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# A STUDY OF CHARGED PARTICLES ASSOCIATED WITH HIGH-$P_T$ PHOTONS AND PIONS

The Axial Field Spectrometer Collaboration

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## ABSTRACT

We report on the distributions of charged particles produced in association with high $p_T$ prompt photons and neutral pions in pp collisions at $\sqrt{s} = 63$ GeV and $\theta = 90°$ in the centre of mass. We find photons to be relatively unaccompanied by other particles at small angles with respect to the photon, and thereby extract a measurement of the fraction of prompt photons due to bremsstrahlung production. The relative density of positive to negative particles in the system recoiling from the photon has been measured and compared with QCD motivated calculations.

The level of production of high $p_T$ prompt photons [1], first established in 1979, is in good agreement with perturbative calculations of this process based on scattering of constituents within hadrons [2]. In particular, recent calculations [3] of the inclusive $\gamma$ cross section are in excellent agreement with the most recent measurements [4]. These model calculations also make firm predictions for the character of events associated with high $p_T$ photons [5].

The present experiment was designed to differentiate between specific mechanisms for $\gamma$ production by studying the associated charged particles. We consider two mechanisms, QCD Compton scattering ($qg \to q\gamma$) and bremsstrahlung production ($qq \to qq\gamma$, $gq \to gq\gamma$) of a photon from a scattered quark. We test the following predictions:

1) In Compton production, the photon is produced alone - it is not a fragment of a jet produced from a scattered parton. The recoil jet is most often due to the fragmentation of a u quark ($u/d \approx 8$, a factor of 4 due to the relative electromagnetic coupling, and a factor of approximately two due to the relative density in the proton).
2) In bremsstrahlung production, the photon is accompanied by charged particles, originating mostly from a scattered u quark ($u/d=8$). The recoil jet is not so strongly dominated by u quarks as it is in Compton production.

Current calculations of the ratio of bremsstrahlung production to Compton production yield about 5-25% [6]. Most model calculations [3] also predict a very small prompt photon contribution from quark-antiquark annihilation ($q\bar{q} \to g\gamma$).

In addition, if Compton production dominates, prompt $\gamma$ triggers should provide a clean sample of quark jets, to be compared with jets produced opposite a $\pi^0$ for example, which are expected often to result from the fragmentation of a scattered gluon. In the present letter we give evidence for $\gamma$ production mechanisms from correlation studies. We defer a detailed analysis of $\gamma$ and $\pi^0$ triggered recoil jets to a later paper.

The experiment was performed with the Axial Field Spectrometer [7] (AFS) at the CERN Intersecting Storage Rings. It used the lead-liquid argon ionization chambers [8], previously used in the measurement of the inclusive prompt photon cross section, to trigger on and identify $\gamma$'s and $\pi^0$'s. The arrangement of the calorimeter in the intersection region was identical to that of the latest data set of Ref. 4; they covered the rapidity range $|y| < 0.28$. As shown in Fig. 1, the result for the raw $\gamma/\pi^0$ signal found in the present data is in good agreement with previous measurements. We do not discuss the prompt $\gamma$ analysis here, but refer the interested reader to Ref. 4 for a detailed discussion of that analysis. We note that the signal/background ratio varies from 0.3 at 4 GeV/c to > 3.0 at 7 GeV/c. Unless otherwise specified, results shown for $\gamma$ triggered events have been corrected for the effects of the meson (mostly $\pi^0$ and $\eta$) induced background in the $\gamma$ sample.

The AFS consists of an open axial field magnet, a set of scintillation counters and a cylindrical drift chamber surrounding the interaction diamond, and counters surrounding the outgoing beams. In addition, there was a set of proportional wire chambers (PWC) and Cerenkov counters subtending about one steradian in the central region opposite the trigger calorimeters. The PWC's could be used in the trigger to require a charged particle of $p_T \geq 0.8$ GeV/c opposite the neutral trigger. The drift chamber gave full azimuthal coverage except for two gaps of 16° each above and below the interaction region (the gaps were in the region between 60° and 120° in azimuth with respect to the trigger).

The apparatus was triggered by the coincidence of a pretrigger (either a "minimum bias" pretrigger given by a coincidence between the downstream scintillation counters or a hit in the scintillators surrounding the intersection region, or the PWC pretrigger discussed above) and a trigger on energy deposition in the lead-liquid argon calorimeter. No significant differences were seen for data sets taken with the minimum bias and PWC pretrigger. Data were collected with both magnet polarities; we discuss below the use of this data in determining possible charge biases in the apparatus. The data set corresponded to an integrated luminosity of $\sim 8 \times 10^{36}$ cm$^{-2}$; it contained $\sim 18000$ $\pi^0$'s, and $\sim 4000$ prompt $\gamma$'s after background subtraction, with $p_T > 4$ GeV/c.

The data were analysed by first using the calorimeters to select a sample of high $p_T$ triggers with very loose cuts on the selection of $\gamma$'s and $\pi^0$'s in order to have sufficient events to study systematic effects in the charged particles. This large sample was then passed through the AFS track reconstruction and fitting programs [9].

Only events with a reconstructed vertex within the intersection diamond were accepted. A set of track selection cuts was then applied. It consisted of cuts on the number of hits per track, the track length, the $\chi^2$ per degree of freedom for the track fit, the assignment of the track to the vertex, and the level of agreement between the initial momentum fit and the momentum fit constraining the track to the vertex. In addition, only tracks with $|y| < 0.8$ and $p_T > 0.3$ GeV/c were retained for most of the analysis. Various systematic checks were performed to ensure that incorrectly measured tracks were not biasing the results presented. In particular, as a check, a more stringent set of cuts was applied, accepting about 80% of the tracks passing the above cuts. These cuts did not significantly alter the momentum or charge distribution of the accepted tracks. The data were recorded in three widely spaced intervals in time and under varying conditions; these data sets were compared in detail. No significant differences were found; checks on specific aspects of the analysis are discussed below. After verifying that the data samples were consistent, they were added and analysed together. The data have been corrected for the effects of the gaps in azimuthal coverage in the chamber. They have not been corrected for tracking efficiency, cut acceptance, or measurement errors. These corrections are estimated to be less than 20% for $p_T > 0.3$ GeV/c independent of angle, charge, momentum, or trigger particle.

We first discuss the distribution in charged particle density and charged energy flow with respect to the neutral trigger. In Fig. 2a-c we show the particle density as a function of the difference in azimuthal angle ($\Delta\phi$) between the particle and the trigger, for different intervals of particle momentum. The density opposite the trigger is very similar for $\gamma$ and $\pi^0$ triggers; the width of the away side peak narrows with increasing particle $p_T$. In a region of approximately 30° around trigger $\pi^0$'s, there is a clear enhancement in the track density over that at ∿ 70°; the $\pi^0$ is frequently produced as a fragment of a jet. In the $\gamma$ triggered sample we see no significant excess particles in this angular region. We conclude that the data are qualitatively in agreement with predictions that prompt $\gamma$'s in this $p_T$ range are produced predominantly unaccompanied.

We have attempted to determine quantitatively the ratio of bremsstrahlung to total prompt γ production, $R^{brems}$, from this data. This analysis is necessarily model dependent since the expected particle density accompanying bremsstrahlung γ's or $\pi^0$'s are not well known and may be different; the fragmentation functions are not identical. We have minimized the model dependence in our calculations of $R^{brems}$ by comparing the measured ratio of energy accompanying a γ or $\pi^0$ with that expected for bremsstrahlung γ's or $\pi^0$'s. $R^{brems}$ can then be extracted from the relationship:

$$< E^{\gamma}_{acc}>/<E^{\pi^0}_{acc}> = R^{brems} <E^{brems\ \gamma(expected)}_{acc}>/<E^{\pi^0}_{acc}\ (expected)>$$

where $<E^{\gamma(\pi^0)}_{acc}>$ is the amount of associated energy accompanying the trigger particle. We implicitly assume that corrections to the measured accompanying energy due to inefficiencies, undetected neutral particles, and the cut on particle momentum at 0.3 GeV/c cancel in the ratio.

As an approximation to $dE/d\Delta\phi$ we form the sum $\Sigma|p_T|_i$ in intervals of $\Delta\phi$. Fig. 3 shows for different trigger bins the mean value of $\Sigma|p_T|_i$ in each $\Delta\phi$ interval. A clear enhancement at small $\Delta\phi$ is seen for $\pi^0$'s which is not seen for γ's. We take $<E^{\gamma\ \pi^0}_{acc}>$ to be the excess in the first three bins ($\Delta\phi < 36°$) in this distribution above the unassociated level. This level has been estimated in two ways: by taking the level associated with "minimum bias" triggers (the dashed line shown in Fig. 3), and by assuming the level at ∿70° is the same as that at 0°. "Minimum bias" in this instance is taken to be non-diffractive events with at least one charged particle in the region $|y| < 1.5$.

If $Z_{tr}$ is defined as the fractional energy of the parent constituent taken by the γ or $\pi^0$, then $<E_{acc}>$ is related to $Z_{tr}$ by the relation $<Z_{tr}> = p^{\gamma(\pi^0)}/(p^{\gamma(\pi^0)} + <E_{acc}>)$. For bremsstrahlung γ's we have estimated $<Z_{tr}>$ by convoluting the fragmentation function for this process, $(1+(1-Z)^2)/Z$, with the cross section for quark production in this momentum range ($\approx p_T^{-n}$, $n = 6-8$). The mean value of $Z_{tr}$ is calculated to be .87 ± .03, and is not sensitive to the production spectrum assumed, yielding $<E_{acc}^{brems\ \gamma}$ expected$>/p^{\gamma}$ $= .15 \pm .05$. For $\pi^0$'s we estimate $<E_{acc}^{\pi^0}$ expected$>$ from our data by measuring the change in charged energy in a cone of half angle 45° around the $\pi^0$ as the trigger momentum is changed. Correcting for inefficiencies and for the loss of neutral particles, we find $<E_{acc}^{\pi^0}>/p^{\pi^0} = .11 \pm .04$, in good agreement with a previous result [10] using the same technique. Using a different technique, a recent experiment [11] has measured a value of $<E_{acc}^{h\pm}>/p^{h\pm} = .25 \pm .06$ for triggers near $\theta = 45°$. We note that our result implies a non-zero intercept for the fragmentation function at $Z = 1.$, while a value of 0.25 implies an intercept of zero. To allow for the model dependence indicated by these results, in the following analysis we assume a value $<E_{acc}^{\pi^0}(\text{expected})>/p^{\pi^0} = .18 \pm .06$. The expected ratio of energy accompanying bremsstrahlung $\gamma$'s to that accompanying $\pi^0$'s is then .85 ± .34.

In Fig. 4 we show, as a function of trigger momentum, the value of $R^{brems}$ extracted using the above technique. Results are shown for both assumptions for the unassociated background. $R^{brems}$ is seen to be consistent with zero everywhere; for $5.5 < p_T < 8.0$, where the errors are predominantly statistical, the two standard deviation limit is $R^{brems} < 0.2$. Also shown are two predictions for this ratio [6].

We have checked that our result is not sensitive to the prompt $\gamma$ analysis, particularly to a requirement that the calorimeter containing the shower(s) contains no energy other than that assigned to the shower(s). This cut was removed for the $\pi^0$ triggered sample, resulting in the level of associated energy in the first bin in $\Delta\phi$ increasing by 15%. Correcting the associated energy in this bin by 15% of its measured value for both $\gamma$ and $\pi^0$ triggered events resulted in a negligible change in $R^{brems}$.

Bremsstrahlung production of $\gamma$'s should be dominantly from u quarks and thus be reflected in an excess of positive particles in the jet accompanying the trigger. Since the trigger has taken most of the momentum of the fragmenting parton, we would expect a charge asymmetry at low $X_E$ ($X_E \equiv (p^{h\pm} \cdot p^{\gamma\ \pi^0})/|p^{\gamma\ \pi^0}|^2$). If bremsstrahlung production is absent, accompanying particles should show the same characteristics as those in minimum bias triggers. We show in Fig. 5 the ratio of positive to negative particles with $\Delta\phi < 90^\circ$ as a function of $X_E$. For $\gamma$ triggers, few tracks remain after subtracting the background from mesons, and the ratio is consistent with that measured for minimum bias events with a fake $\gamma$ trigger.

We next discuss the system of recoiling particles, selected with $\Delta\phi > 90$. The distribution in $X_T \equiv -[(p_T^{h\pm} \cdot p_T^{\gamma\ \pi^0})/|p_T^{\gamma\ \pi^0}|^2)]$ is shown in Fig. 6a. There is no significant difference for $\gamma$ and $\pi^0$ triggered events. Fig. 6b shows the distribution in

$$X_T^{JET} \equiv -[(p_T^{h\pm} \cdot p_T^{JET})/|p_T^{JET}|^2)],$$ where

$p_T^{JET}$ is the vector sum of the trigger momentum and the momenta of all charged particles within a cone of half angle 45° around the trigger. The associated particle momenta have been added with a weight to account for cut efficiencies (a factor of 1.5) and missing neutral particles (a factor of 1.7). Again, we do not observe a significant difference in the $\gamma$ and $\pi^0$ triggered distributions. The present measurement agrees well with that for $\pi^0$'s recoiling against a $\pi^0$ trigger as measured in a previous experiment [12]. The different data sets have been compared, and agree very well, giving us further confidence that we have no significant bias in high $p_T$ particles due to the varying conditions and triggers used during the data collection.

Finally, we discuss the charge distribution of recoiling particles. A measurement of the absolute ratio $R^{+/-}$ of the density of positive to negative particles on a steeply falling distribution is very susceptible to systematic biases in the detector. We have collected data with about equal luminosities for each sign of the analysing magnetic field, which cancels many sources of instrumental bias. From these data, we have also deduced a limit on charge bias in our data of $\delta(R^{+/-})/R^{+/-} < .015 * p_T$ (GeV/c) at 95% c.l. In addition, we have checked the charge distributions in the different data sets, and they agree.

Fig. 7 shows the extracted value of $R^{+/-}$ for different bins in trigger momentum as a function of $X_T$. For both $\gamma$'s and $\pi^0$'s $R^{+/-}$

increases with $X_T$, the effect being stronger for $\gamma$ triggered events. Superimposed is a QCD motivated prediction for $R^{+/-}$ for prompt photon triggered events (predominantly the Compton process). Particularly in the region $0.2 < X_T < 0.5$, where we have excellent momentum resolution and the sample is not contaminated by background particles, the agreement is not good. Correcting the theoretical points for a possible 20% admixture of bremsstrahlung events (using the $\pi^0$ triggered sample to estimate $R^{+/-}$ opposite bremsstrahlung $\gamma$ triggers) does not significantly improve the agreement.

In summary, we have shown that prompt photons are predominantly produced without nearby accompanying particles, and have placed a two standard deviation limit on bremsstrahlung $\gamma$ production of prompt photons of $\sigma^{\text{brems}\gamma}/\sigma^{\text{total }\gamma} < 0.3$ in the momentum range $5.5 < p_T < 8.0$ GeV/c at $\theta = 90°$. Theoretical calculations of this ratio depend sensitively on the value of the strong coupling constant, on how the effective quark mass radiating the photon is treated and on the gluon and quark distribution functions. Coupled with our measurements of the inclusive cross sections for $\pi^0$ and prompt photon production, our measurement of $R^{\text{brems}}$ provides a good test of these parameters in a consistent calculation. The charge ratio in the recoiling jet shows a value of $N^+/N^-$ of about 2 for $X_T > .5$, with a somewhat smaller value for $\pi^0$ triggered events; it does not agree quantitatively with a simple QCD motivated calculation of u quark fragmentation and the agreement is not significantly improved by the inclusion of the maximum bremsstrahlung production component allowed by the data. A reevaluation of either the sources of unaccompanied prompt photon production or the charge distribution in the fragmentation is necessary to improve the agreement. Finally, we do not observe differences in the recoil jet momentum distributions between $\gamma$ and $\pi^0$ triggered events even though one expects a different admixture of quark and gluon jets in the two cases.

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## FIGURE CAPTIONS

Fig. 1 The detected $\gamma/\pi^0$ ratio at $\sqrt{s}$ = 63 GeV for the present data set and for the data of Ref. 4. For the present data, only statistical errors are shown. For the previously published data, the inner error bars are statistical, and the outer error bars contain the error due to a possible non-linearity in the calorimeter. The band is the calculation of the background in the $\gamma/\pi^0$ ratio due to meson decays.

Fig. 2 For $p_T$ of the trigger greater than 4.5 GeV/c and for different bins in charged particle momentum, the distribution in the difference in azimuthal angle ($\Delta\,\phi$) between the neutral trigger and a charged track. The $\gamma$ triggered data have been corrected for the effects of the meson induced background.

Fig. 3 For different bins in the neutral trigger momentum, the distribution in the variable $\Sigma|p_T|_i$ as a function of $\Delta\phi$. The $\gamma$ triggered data have been corrected for the effects of the meson induced background.

Fig. 4 The value of $\sigma^{\text{brems}\ \gamma}/\sigma^{\gamma}$, the fraction of all prompt photon events due to bremsstrahlung production, for two assumptions for the level of energy in charged particles near the neutral trigger not associated with the hard scattering process. Inner error bars are statistical; outer error bars include systematic uncertainties added in quadrature.The curves are the results of QCD motivated calculations of $R^{\text{brems}}$ from Ref. 6.

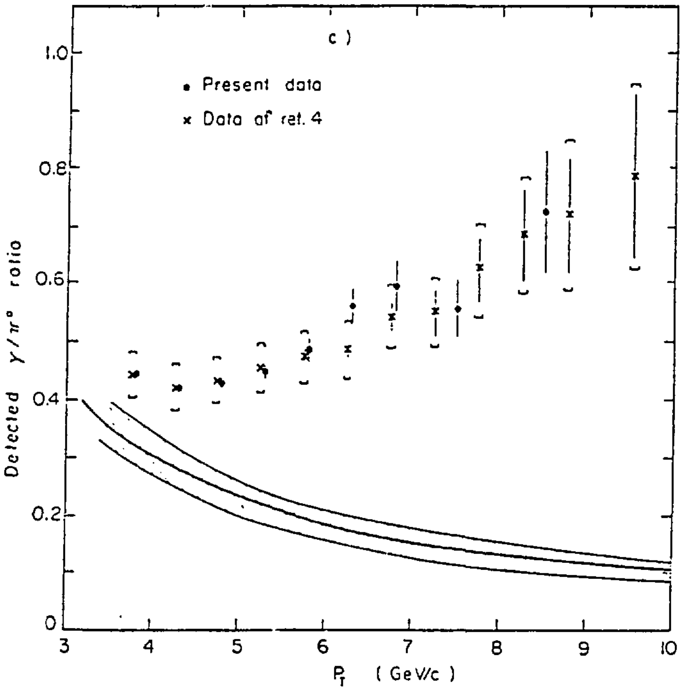
a) H. Dechanstreiter et al. and

b) Aurenche and Lindfors - the two curves are for different parameterizations of the gluon structure function.

Fig. 5 The ratio of the density of positive to negative particle density with $\Delta\phi < 90°$ as a function of $X_E$ for $\gamma$ and $\pi^0$ triggers with $p_T$ greater than 4.5 GeV/c. The $\gamma$ triggered data have been corrected for the effects of meson induced background.

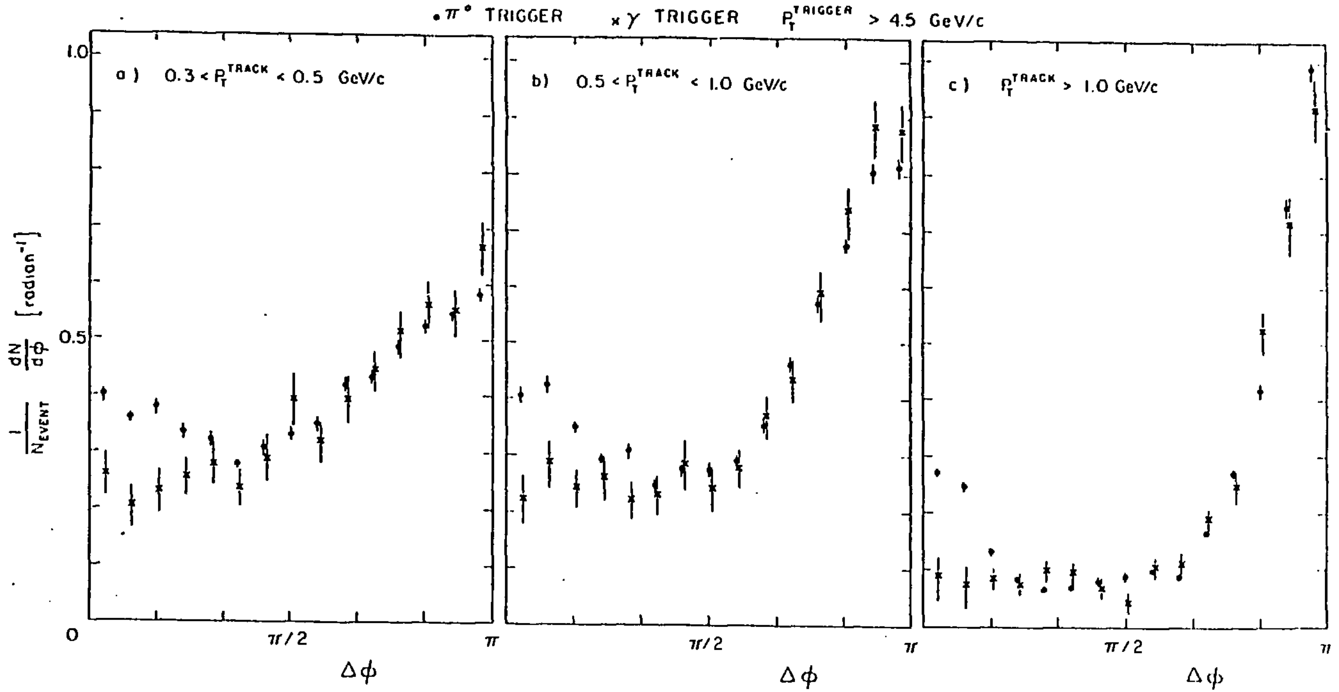
Fig. 6 The density of recoil particles ($\Delta\phi > 90°$) versus $X_T$ (part a) or $X_T^{JET}$ (part b) for $p_T$ of the trigger greater than 4.5 GeV/c The $\gamma$ triggered data have not been corrected for the effects of meson induced background.

Fig. 7 For two bins in trigger momentum, the ratio of the density of positive to negative tracks with $\Delta\phi > 90°$ as a function of $X_T$. The $\gamma$ triggered events have been corrected for the effects of meson induced background. The curves shown in part b are from the calculation of Ref. 5 for $p_T = 6.0$ GeV/c. The data have $< p_T > = 5.8$ GeV/c. The curves are for extreme variations in the gluon fragmentation in the small quark-antiquark annihilation contribution to the prediction for prompt photon production. Including scale breaking effects in the fragmentation raises the predicted charge ratio slightly everywhere.



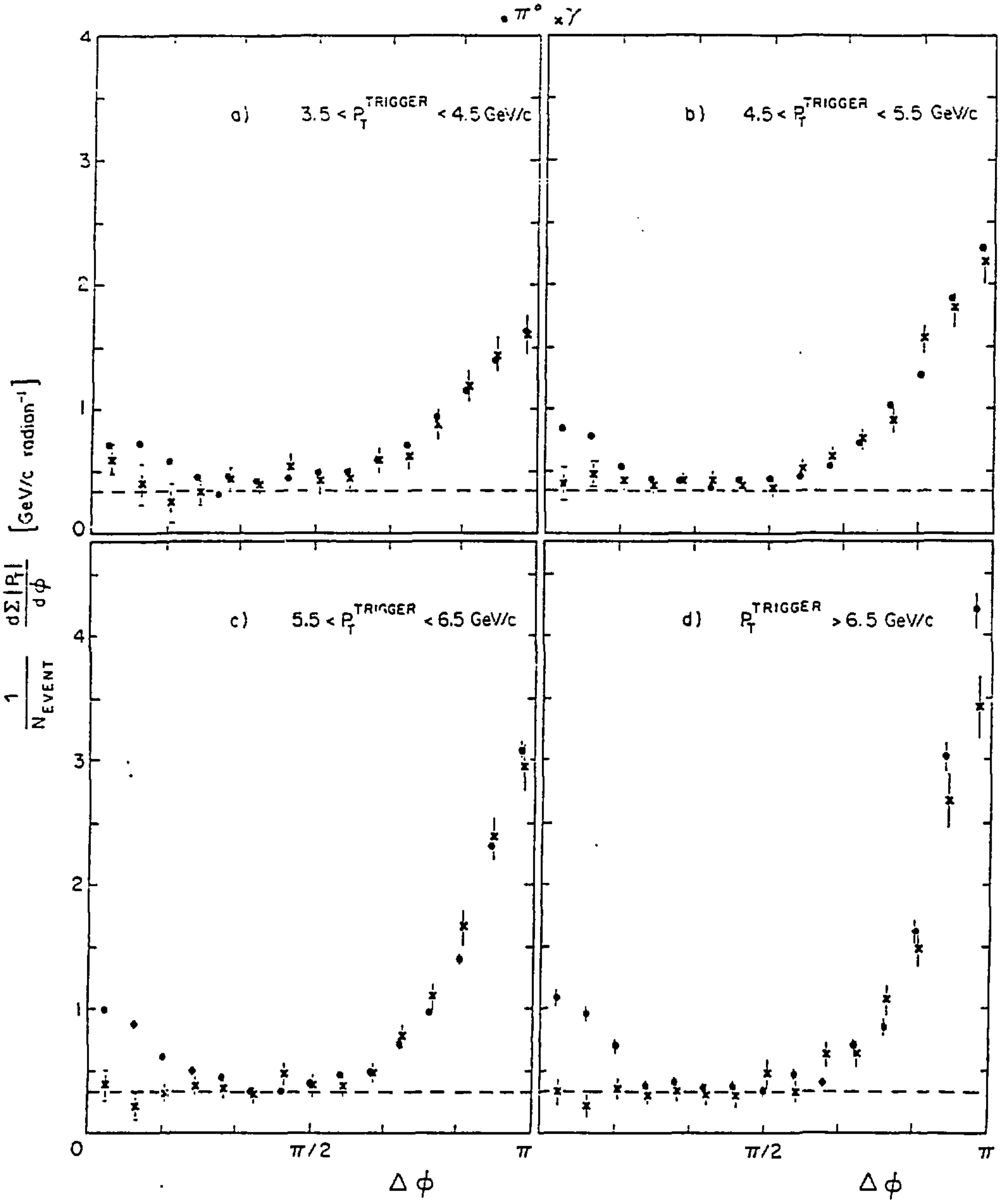
c )
• Present data
× Data of ret. 4
Detected γ/π° ratio
1.0
0.8
0.6
0.4
0.2
0
3
4
5
6
7
8
9
10
$P_T$ ( GeV/c )

Fig. 1



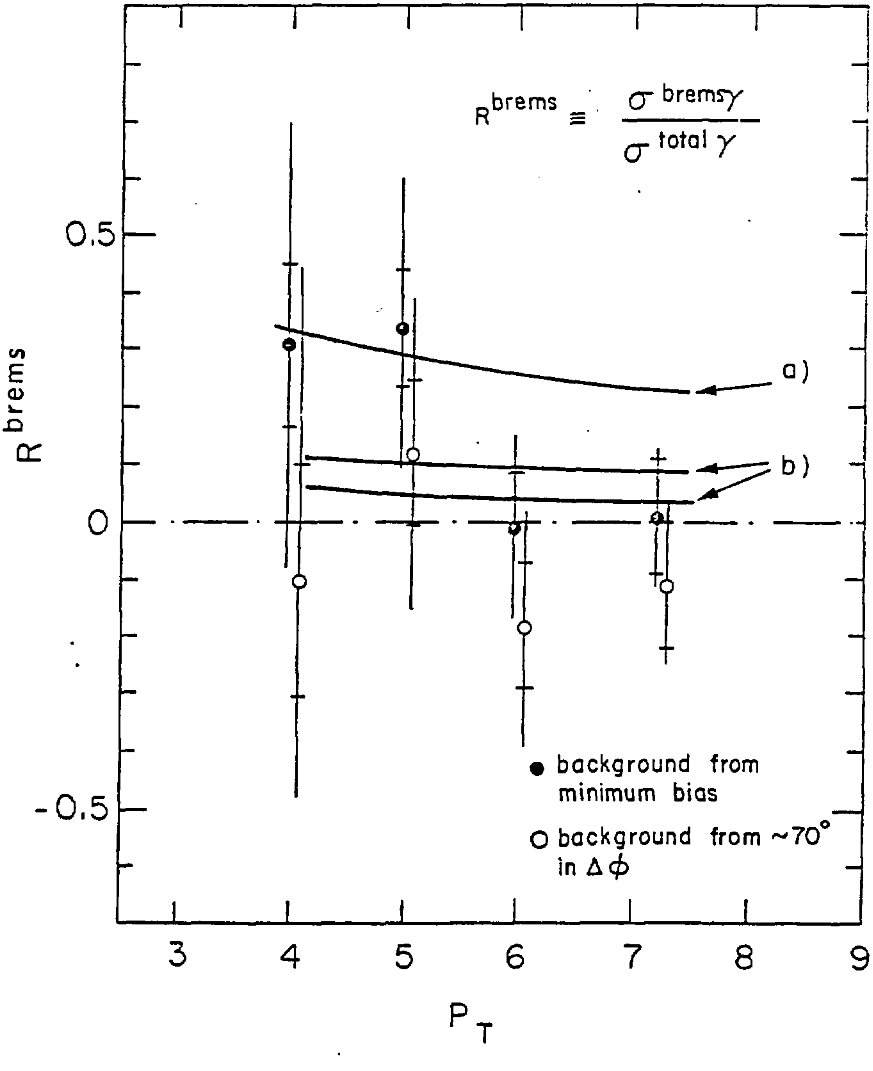
• $\pi^0$ TRIGGER × $\gamma$ TRIGGER $P_T^{TRIGGER}$ > 4.5 GeV/c
a) $0.3 < P_T^{TRACK} < 0.5$ GeV/c
b) $0.5 < P_T^{TRACK} < 1.0$ GeV/c
c) $P_T^{TRACK} > 1.0$ GeV/c
$\frac{1}{N_{EVENT}} \frac{dN}{d\phi}$ [radian$^{-1}$]
1.0
0.5
0
$\pi/2$
$\pi$
$\Delta\phi$

Fig. 2



• $\pi^0$ × $\gamma$
a) $3.5 < P_T^{TRIGGER} < 4.5$ GeV/c
b) $4.5 < P_T^{TRIGGER} < 5.5$ GeV/c
c) $5.5 < P_T^{TRIGGER} < 6.5$ GeV/c
d) $P_T^{TRIGGER} > 6.5$ GeV/c
$\frac{1}{N_{EVENT}} \frac{d\Sigma|P_T|}{d\phi}$ [GeV/c radian$^{-1}$]
0
1
2
3
4
0
$\pi/2$
$\pi$
$\Delta\phi$

Fig. 3



$R^{brems} \equiv \frac{\sigma^{brems\,\gamma}}{\sigma^{total\,\gamma}}$
$R^{brems}$
0.5
0
-0.5
a)
b)
● background from minimum bias
○ background from ~70° in $\Delta\phi$
3
4
5
6
7
8
9
$P_T$

Fig. 4

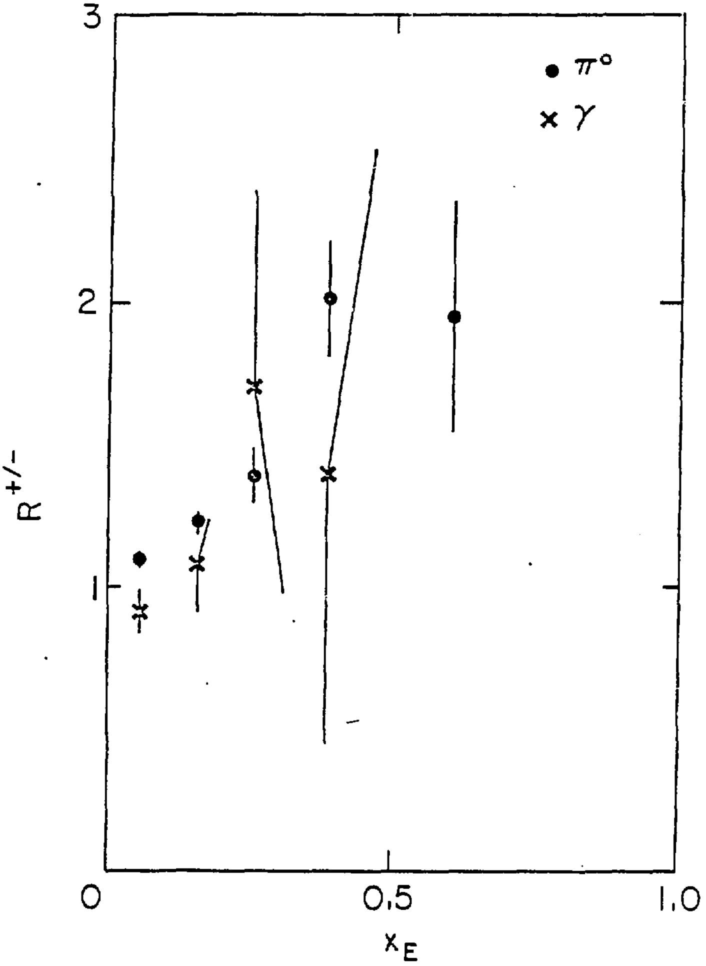


Fig. 5

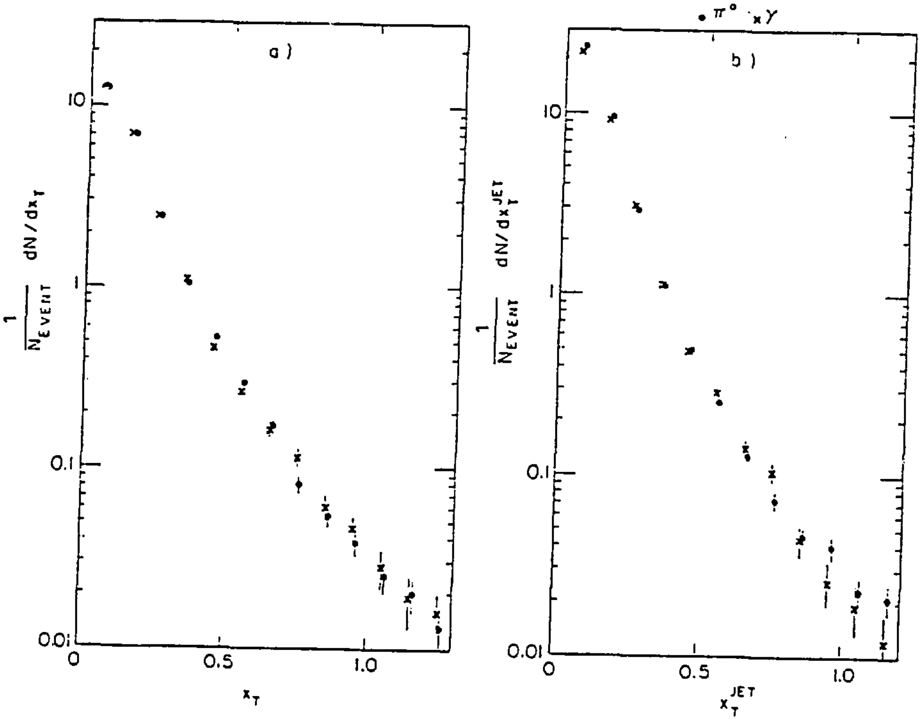

a)
b)
● π° x γ
$\frac{1}{N_{EVENT}} \; dN/dx_T$
$\frac{1}{N_{EVENT}} \; dN/dx_T^{JET}$
10
1
0.1
0.01
0
0.5
1.0
$x_T$
$x_T^{JET}$

Fig. 6

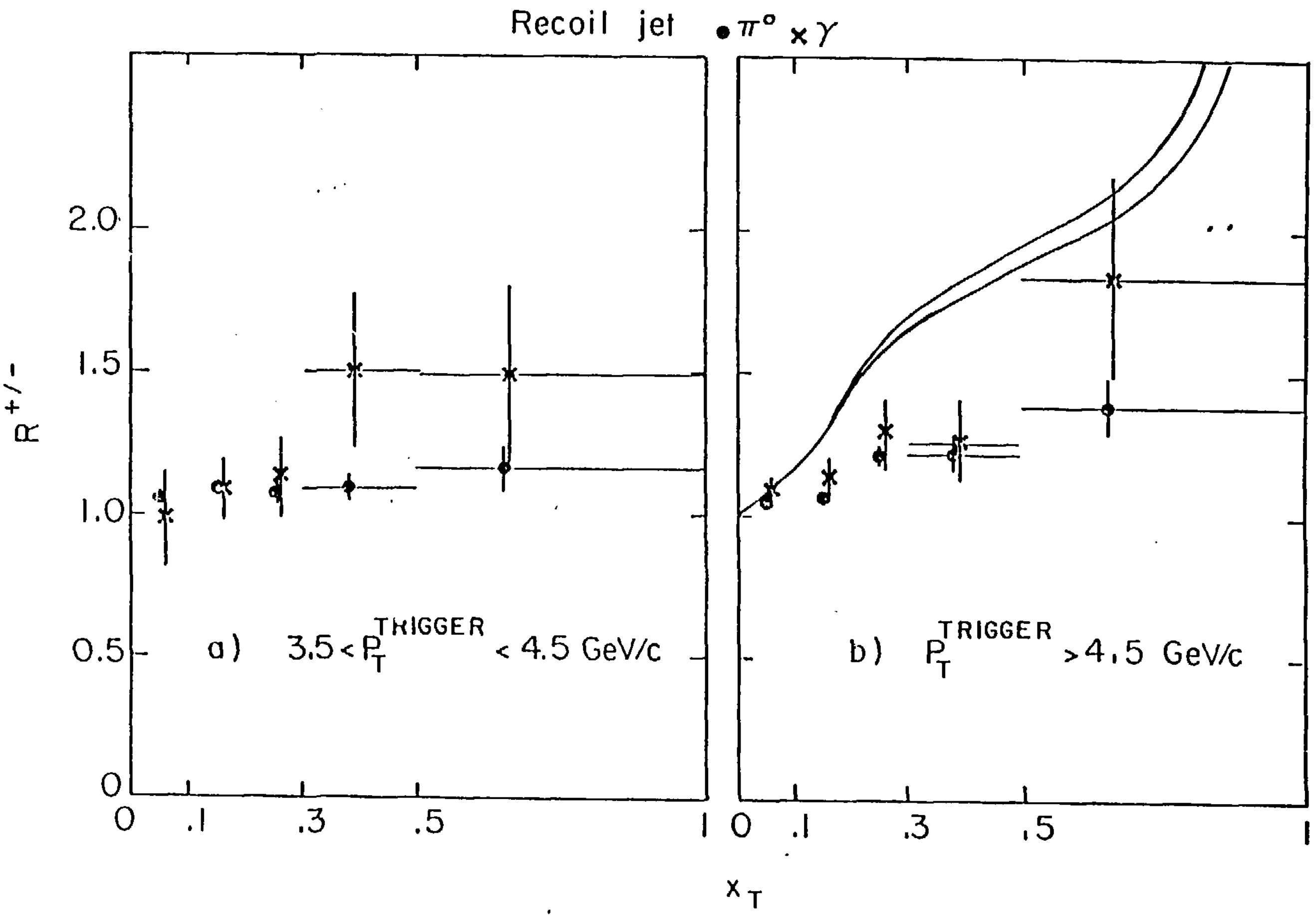

Recoil jet ● $\pi^o$ × $\gamma$
$R^{+/-}$
2.0
1.5
1.0
0.5
0
0
.1
.3
.5
1
a) $3.5 < P_T^{TRIGGER} < 4.5$ GeV/c
b) $P_T^{TRIGGER} > 4.5$ GeV/c
$x_T$

Fig. 7