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A STUDY OF DIRECT SINGLE PHOTONS AND CORRELATED PARTICLES

IN PROTON-PROTON COLLISIONS AT $\sqrt{s}$ = 62.4 GeV

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ABSTRACT

As part of a study of large p_T phenomena in proton-proton collisions at the CERN ISR, a search for direct single photon production has been performed. A statistical division of the data sample into the fraction consistent with single photon production and the fraction due to multi-photon decays of neutral hadrons is accomplished by measuring the average conversion probability for the sample in a one radiation length thick converter. The fraction of the sample attributable to direct single photon production is $<\gamma/\text{all}> = 0.074 \pm 0.012$ for 6 GeV/c $< p_T <$ 10 GeV/c, and $<\gamma/\text{all}> = 0.26 \pm 0.04$ for $p_T >$ 10 GeV/c, with an additional systematic uncertainty of ± 0.05 for both values. It is found that single photons are produced preferentially with no accompanying particles on the same side. The ratio of positive to negative particles on the away side is found to be 3.7 ± 1.2 at high x_E and p_T for the single photon events.

The point-like coupling of the photon to electric charge is well understood and has been exploited for generations as a probe of hadronic structure [1]. Recent interest in direct photon production in proton-proton collisions [2] was stimulated by the experimental observation of a copious yield of prompt leptons [3]. The lepton/pion ratio of $\sim 10^{-4}$ observed for $p_T > 1.0$ GeV/c could have been explained by direct photon production at a level of $\sim$ 10% of π^0.

With the advent of QCD, the relationship between direct photon production and hadron structure could be put on a reasonably quantitative basis [4]. The dominant mechanism for direct photon production at large p_T is thought to be the "QCD Compton Effect", i.e. the reaction gluon + + quark $\rightarrow \gamma$ + quark. In principle, the only unknown quantity is the gluon structure function of the proton. However, the reaction is particularly sensitive to non-scaling effects in the structure functions [5]. There has already been much experimental [6-14] and theoretical work [4,5,15-17] on the subject.

In the experiment reported here, a search for direct single photon production has been performed as part of a study of large p_T π^0 production in proton-proton collisions at the CERN ISR. The apparatus (Fig. 1) consisted of two arrays of lead glass Cerenkov counters, denoted "inside" and "outside", which covered centre-of-mass solid angles about $\theta = 90^o$ of $\Delta\phi \approx \pm 25^o$, $\Delta\theta \approx \pm 30^o$, $\Delta\Omega = .87$ for the inside array and $\Delta\phi \approx \pm 30^o$, $\Delta\theta \approx \pm 38^o$, $\Delta\Omega = 1.42$ for the outside. The arrays were located on either side of a superconducting solenoid magnet containing a barrel hodoscope of 32 scintillation counters (A), and cylindrical drift chambers which were used to measure charged particles. Two hodoscopes of 12 scintillation counters (B) were just outside the solenoid, against the external shell of the cryostat. The total thickness of the coil and cryostat together was 23g/cm^2 (mainly aluminium) corresponding to 1.0 radiation length. Details of the detector have been reported previously [11,18,19].

The trigger for the experiment required the total energy in either lead glass array to exceed a given threshold in coincidence with a signal from any of the A counters. In the analysis, individual π^0's were searched for by looking at clusters of energy in the lead glass arrays. A cluster was defined as an isolated distribution of energy in a matrix of up to 3 x 3 lead glass blocks ($\sim$ 0.1 sr). For transverse momenta $p_T > 3$ GeV/c, the two γ-rays from π^0 decay were unresolved geometrically and appeared as a single cluster. Single clusters could also be formed by isolated single photons or even in many cases by multiphoton decays of neutral particles other than π^0's.

In addition to the cluster criterion given above, two requirements were imposed on the data to ensure that backgrounds from cosmic rays, upstream beam losses, beam-gas and beam-wall interactions were suppressed. These requirements were that an interaction vertex with at least two charged tracks be present and that 4 or more A counters be struck. The efficiencies of the A counter and vertex cuts were measured to be 98% and 95% respectively, In addition, clusters with a charged track projecting to within 30 cm of their centroids were rejected to avoid confusion with correlated charged particles and to ensure that the cluster was caused by a neutral particle. The fraction of events satisfying this cut was high and independent of p_T (Figs. 2a, b). An important test [11] to show that background has been eliminated is that the ratio of clusters at a given p_T for the inside and outside arrays should be independent of p_T. The clusters do satisfy this criterion as seen in Fig. 2c, where this ratio is shown for the final data sample after the additional cuts described below.

A statistical determination of the average number of photons in the sample of clusters could be made by measuring the probability for the photon or group of photons in the cluster to pass through material without any conversion taking place. The coil and cryostat of the solenoid served as the converter. A conversion was defined by the presence of more than 1.5 x single ionization in the two B counters nearest the cluster, after subtracting 1.0 x single ionization for each charged particle track observed.

The non-conversion probability, ν, per photon after a thickness of material t is given by [20]

$$\nu = \mathrm{Exp}\left(- \frac{7}{9} \frac{t}{X_o} (1 - \xi) \right) ,$$

where X_o is the radiation length and ξ is a small energy dependent correction. For a single photon, the non-conversion probability, ν_1, in

1.0 X_o of aluminium varies between 0.474 and 0.462 photon energies from 2 to 13 GeV. For $\pi^0 \to \gamma\gamma$ the nonconverting probability for two photons, ν_2, varies between 0.246 and 0.221 for π^0 energies from 2 to 13 GeV, after averaging over the decay spectrum.

In our previous publication [11)] concerned mainly with the measurement of the inclusive π^0 cross section, the non-conversion fraction for all clusters was studied as a function of p_T. It was concluded from this distribution that the clusters were consistent with all being due to two photons and a single photon contribution of more than 30% could be excluded for the p_T range of 3.5 to 10 GeV/c. This analysis has now been repeated with over three times the data previously available. Data were obtained at $\sqrt{s}$ = 62.4 GeV for four different p_T thresholds of 3, 5, 7 and 9 GeV/c with integrated luminosities of 8.6 x 10^{34}, 1.1 x 10^{36}, 2.0 x 10^{37} and 5.5 x 10^{37} cm^{-2} respectively.

The data was then examined to determine whether the clusters are consistent with all being due to two photons or whether some single photon component can be accomodated. The non-conversion fraction as a function of p_T for the inside and outside arrays is given in Figs. 3a and b. The non-conversion fraction is affected by charged or other neutral particles traversing the relevant B counters and simulating a conversion - the main cluster intercepts only 1/5 the length of the B counters. Thus, an additional cut was made to require that no charged track or neutral cluster (apart from the main cluster) overlap the two B counters of interest. There is very little p_T dependence in the fraction of events that satisfy this cut (Figs. 2d, e).

The non-conversion fractions for the events satisfying this "no overlap" cut are shown separately for the inside and outside arrays in Figs. 3c and d. They are both increased relative to the results without the cut. The residual systematic difference in the non-conversion fractions for the inside and outside arrays is consistent with the value expected from the poorer track finding efficiency and larger c.m.s. solid angle of the B counters on the outside. These effects are not p_T dependent as demonstrated by all the cuts involving associated charged tracks (Figs. 2a, b, d, e). The curves drawn on the data are the non-conversion fractions ν_1 for a pure single photon sample, and ν_E to be expected from all processes other than direct single photon production that can produce good clusters (Table I) [21,22]. The acceptances for these processes were calculated by a Monte Carlo program. The values of ν_E were then calculated using their production cross sections. The η^0/π^0 ratio has been measured to be independent of p_T [23]. The cross sections of the other particles relative to π^0 were assumed to be independent of p_T, so that the p_T dependent effects of these decays on the non-conversion fraction are due entirely to the acceptance of the cluster algorithm.

The fraction of the clusters ascribed to direct single photons can be calculated from the non-conversion fractions observed, and the values for pure single photons and for all other processes:

$$f_\gamma = \frac{\gamma}{\text{all}} = \frac{\nu_{obs} - \nu_E}{\nu_1 - \nu_E} .$$

However, since the outside data are systematically below the expected values, an additional procedure must be used. Previous measurements [10] indicate that

$$< \gamma/\pi^0 > = 0.021 \pm 0.012 \quad \text{for} \quad 3.5 < p_T < 5.0 \text{ GeV/c}.$$

Thus, we take this p_T region as a calibration for a small but known direct single photon signal, and renormalize the expected non-conversion fractions accordingly. An additional advantage of this procedure is that it eliminates two other possibilities of systematic error. These relate to the absolute value of the converter thickness and the absolute value of the apparent energy loss in the converter by converting photons that shower. The latter point needs some elaboration. The response of a lead glass array to electrons of various energies passing through a model of the coil and cryostat at various angles was carefully measured during extensive calibration runs at the CERN PS. The apparent fractional energy loss for converting photons and π^0 could then be computed and amounted to between 4% and 3% over the energy range covered in this experiment. Since only the conversions are corrected, the absolute value of the non-conversion fraction depends on the absolute value of this correction. However, the p_T dependence of this effect is negligible since the cross-section is nearly a pure power law in p_T over the range covered [11].

The fraction of the clusters attributed to direct single photon production was computed separately for the inside and outside arrays according to the above procedure. The results for f_γ obtained in the two arrays were in agreement, indicating the validity of the calibration procedure, so they were averaged to obtain the final result (Fig. 4a). The errors shown are statistical. In addition there is an overall additive systematic uncertainty of $\pm$ 0.053 by which all the values of f_γ may be adjusted together. This error is the resultant of three components : the systematic errors for the apparent energy loss correction and the multi-photon decay correction, taken as half the amount of the correction to f_γ in each case, and the statistical uncertainty at the calibration point. The values of the systematic errors for all three effects are $\pm$ 0.028, $\pm$ 0.037, $\pm$ 0.026 respectively, for a total of $\pm$ 0.053 as given above.

The results of Fig. 4a clearly show that for $p_T < 10$ GeV/c the fraction of clusters not due to π^0 or other known multi-photon decays (Table I) is small. The average value for the range $6 < p_T < 10$ GeV/c is

$$< \gamma/\text{all} > \; = \; < f_\gamma > \; = \; 0.074 \pm 0.012 \pm 0.053 \quad \text{(systematic)}.$$

However, for $p_T > 10$ GeV/c the average f_γ is

$$< f_\gamma > \; = \; 0.26 \pm 0.04 \pm 0.05 \quad \text{(systematic)}.$$

It must be realized that most sources of background would not tend to convert and thus would behave similarly to single photons. However, the values of f_γ obtained in the inside and outside arrays agree in all cases, which indicates that background is not an important effect. A recent experiment [12,14] with the capability of geometrically resolving the two photons from π^0 decay has made a strong claim for the existence of direct single photons in the range $6 < p_T < 9$ GeV/c. Taking the present results for f_γ as a measure of direct single photon production , the approximate composition of our clusters for $6 < p_T < 10$ GeV/c is 7% direct γ, 62% π^0 and 31% multi-γ (Table I). If the direct photon measurements of reference 14 are restated in terms of f_γ , the result for $6 < p_T < 9$ GeV/c is $f_\gamma \approx 0.17$ which is higher but not in serious disagreement with the results presented here (Fig. 4a), considering the large systematic uncertainties of both experiments.

According to QCD ideas [4,5,15-17], direct photons are not accompanied by fragments of jets on the same side, whereas π^0 and other hadrons are. Thus, the no-overlap cut on the B counters may artificially enhance the direct photon component of the clusters. The possible enhancement factor may be measured by using a sample of minimum bias triggers [24], in random overlap with an artificial cluster. Conversely as fewer tracks would be present in direct photon events than π^0 events the reconstruction efficiency of the former may be reduced. If all direct photns are produced unaccompanied by same side jet fragments, the inclusive ratio may be obtained by multiplying the values of f_γ in Fig. 4a by an estimated factor of 0.8.

Note that the quantity $f_\gamma = \gamma/\text{all}$ (Fig. 4a) is really the fraction of our previously published π^0 cross section [11,25] that can be attributed to direct single photons. The exact details of the cluster composition can be avoided if the data for f_γ are multiplied by the inclusive cross section [25] of reference 11 to obtain an estimate of the direct single photon invariant cross section (Fig. 4b). The factor of 0.8 has not been included. The errors shown are statistical while the broken curves are smoothed curves showing the effect on the data of the ± 0.05 systematic uncertainty in f_γ. In addition, it should be noted that the absolute p_T scale is uncertain to ± 5%.

Our results for the single γ cross sections favour the QCD calculation with scale violation included [5], rather than the higher yield given by calculations of the gluon-quark process without scale vialation [16,17].

Further analysis of this apparent production of single γ's gives the following preliminary results. In some models, directly produced photons are expected to be unaccompanied by particles on the same side. Thus the value of $f_\gamma = \gamma/\text{all}$ should be enhanced for such events. By a method similar to the above, f_γ has been obtained separately for two classes of events. Those in Fig. 5a have at least one charged or neutral particle other than the trigger in the trigger hemisphere, while those in Fig. 5b do not. The f_γ for the accompanied trigger particles are consistent statistically with zero for $p_{Ttrig} < 11$ GeV/c. However, for the unaccompanied particles, f_γ clearly rises with p_{Ttrig}, and for $7 < p_{Ttrig} < 11$ GeV/c, 20% ± 2% (statistical) of this sample may be attributed to direct single γ's.

If the process yielding direct single photons is $gq \to \gamma q$ then theory predicts that because of the quark charges and abundances in the proton the quark involved will be a u quark eight times more often than a d quark. This large excess of positive to negative in the parent quark should be reflected in the structure of the 'jet' opposite to the single γ [26]. This has been investigated by the measurement of the charge ratio R = positive particles/negative particles in the hemisphere opposite the trigger, as a function of $x_E = - \vec{p}_{Ttrig} \cdot \vec{p}_{Ttrack}/|p_{Ttrig}|^2$. It should be noted that the ratio R is difficult to measure accurately. A small relative misalignment of the drift chamber modules can cause a small difference in the relative p_T^2 scales of positive and negative tracks, causing a large systematic error in R. However, a difference in R between subsets of the same data sample should not be affected by these uncertainties. Figure 6 shows R as a function of x_E for four trigger bands and two subsets of the data. Subset (a) consists of those events where the trigger particle has converted and is accompanied by a same side particle. As shown above these events contain essentially no single γ's. Conversely, subset (b) comprises of those events where the trigger particle has not converted and is not accompanied by a same side particle. These events have an enhanced single-γ content. There is no systematic difference in the value of R between these two subsets below 7 GeV/c. However, above 7 GeV/c there is an indication that there is an excess of high x_E positive particles in the single-γ enhanced sample. From the values of f_γ shown in Fig. 5, and the non-conversion probabilities for γ's and for other particles, it is possible to extract R for single-γ events. The value obtained for 7 GeV/c $< p_{Ttrig} <$ 13 GeV/c, $0.3 < x_E < 1.05$ is $R = 3.7 \pm 1.2$ (statistical). This result favours the idea that the process $gq \to \gamma q$ is significant in the process of high p_T single photon production.

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TABLE I

Neutral Particles with Multiphoton Decays

Particle	Assumed Production/π^0	Decay	$c\tau$ (cm)	Branching Ratio	Monte Carlo calculated acceptance for $p_T \gtrsim 7$ GeV/c
π^0	1.00	$\gamma\gamma$	0	1.0	0.99
η^0	0.55	$\gamma\gamma$	0	0.38	0.80
η^0	0.55	$\pi^0\pi^0\pi^0$	0	0.30	0.64
K_s^0	0.40	$\pi^0\pi^0$	2.68	0.31	0.85
ω^0	0.50	$\pi^0\gamma$	0	0.09	0.51
η'	1.0	$\eta^0\pi^0\pi^0$ $\hookrightarrow \gamma\gamma$	0	0.22 x 0.38	0.43
η'	1.0	$\eta^0\pi^0\pi^0$ $\hookrightarrow \pi^0\pi^0\pi^0$	0	0.22 x 0.30	0.28

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22) The overlap of a π^0 with an otherwise good cluster was computed using the correlation function measured for charged particles. The fraction of good clusters with an additional π^0 overlap varied between 1.5% and 0.5%. This changed the predicted value of ν_E by approximately -0.002 which is negligible.

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25) In reference 11) all the clusters were taken to be two photons and and the invariant cross section was computed. The effect on the conclusions of that paper from the small direct photon component (Fig. 4a) is negligible. A potentially more serious problem comes from the K_s^o, ω^0 and η' multiphoton decays, since an exact correction would require detailed knowledge of the $\sqrt{s}$ and p_T dependence of the K/π^0, ω/π^0 and η'/π^0 ratios. Under the assumptions of Table I, the fraction of clusters contributed by the multiphoton decays of these particles varies slowly from 12% at p_T = 7 GeV/c to 15% at p_T = 12 GeV/c. Barring a pernicious variation of the $\sqrt{s}$ and p_T dependence of the true cross section ratios for these particles, the effect on the scaling parameter n is also negligible.

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Figure captions

Fig. 1 : A view of the apparatus normal to the beams.

Fig. 2 : a) Fraction of clusters with no charged track projecting to within 30 cm of their centroids as a function of cluster p_T for the inside detector.

b) Same for outside.

c) Ratio of clusters at a given p_T for the two arrays, inside/outside . (The final data sample is used).

d) Fraction of events for which no charged track or additional neutral cluster overlap the two relevant B counters as a function of p_T for the inside detector.

e) Same for outside.

Fig. 3 : a) Non-conversion fraction as a function of p_T for the inside array.

b) Same for outside.

c) Non-conversion fraction as a function of p_T for those events with no overlap in the B counters (inside array).

d) Same for outside.

Fig. 4 : a) The fraction of clusters attributed to direct single photon production as a function of p_T. In addition to the errors shown, there is an overall additive systematic uncertainty of $\pm$ 0.053 by which all the points may be adjusted together.

b) Inclusive cross section attributed to direct single photon production. The errors shown are statistical. The broken curves are smoothed curves showing the effect on the data of the $\pm$ 0.05 systematic uncertainty in f_γ.

Fig. 5 : a) The fraction of clusters attributed to direct single photon production, for those events where the trigger was accompanied by a same side particle.

b) The same for those events where the trigger was not accompanied by a same side particle.

Fig. 6 : a) The charge ratio R for away side particles, as a function of x_E, for those events where the trigger particle did convert and was accompanied by a same side particle.

b) The same for those events where the trigger particle did not convert and was not accompanied by a same side particle.

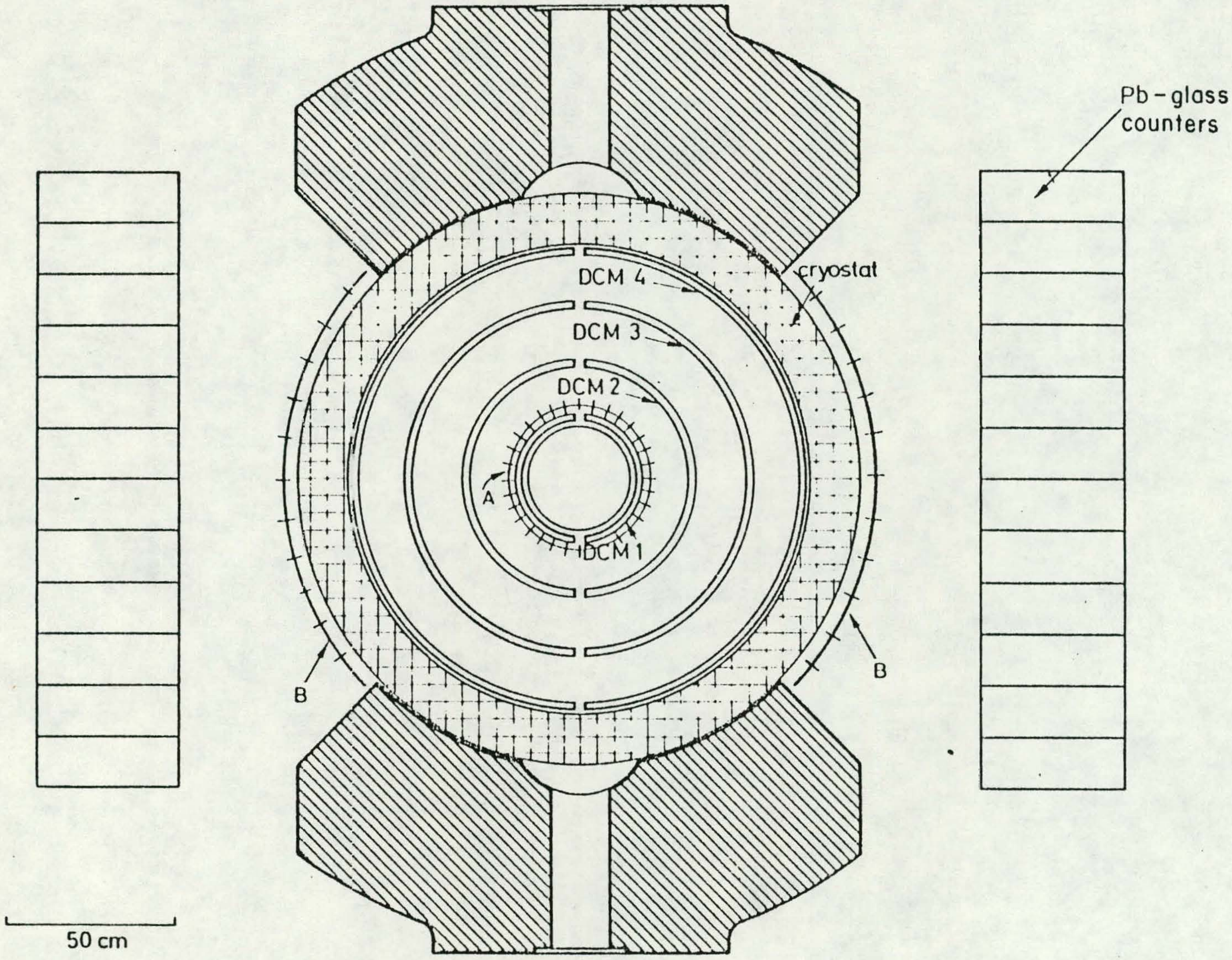
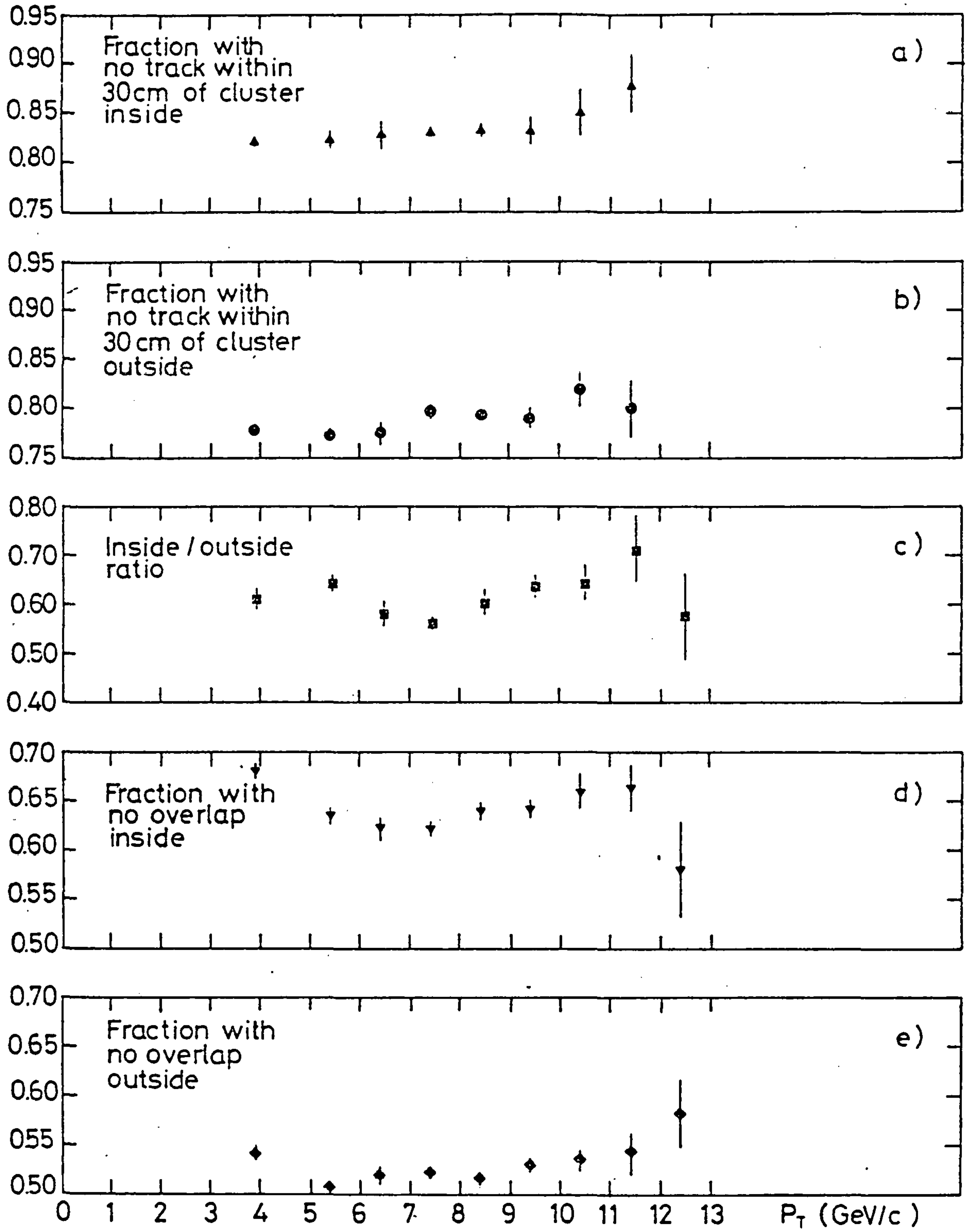
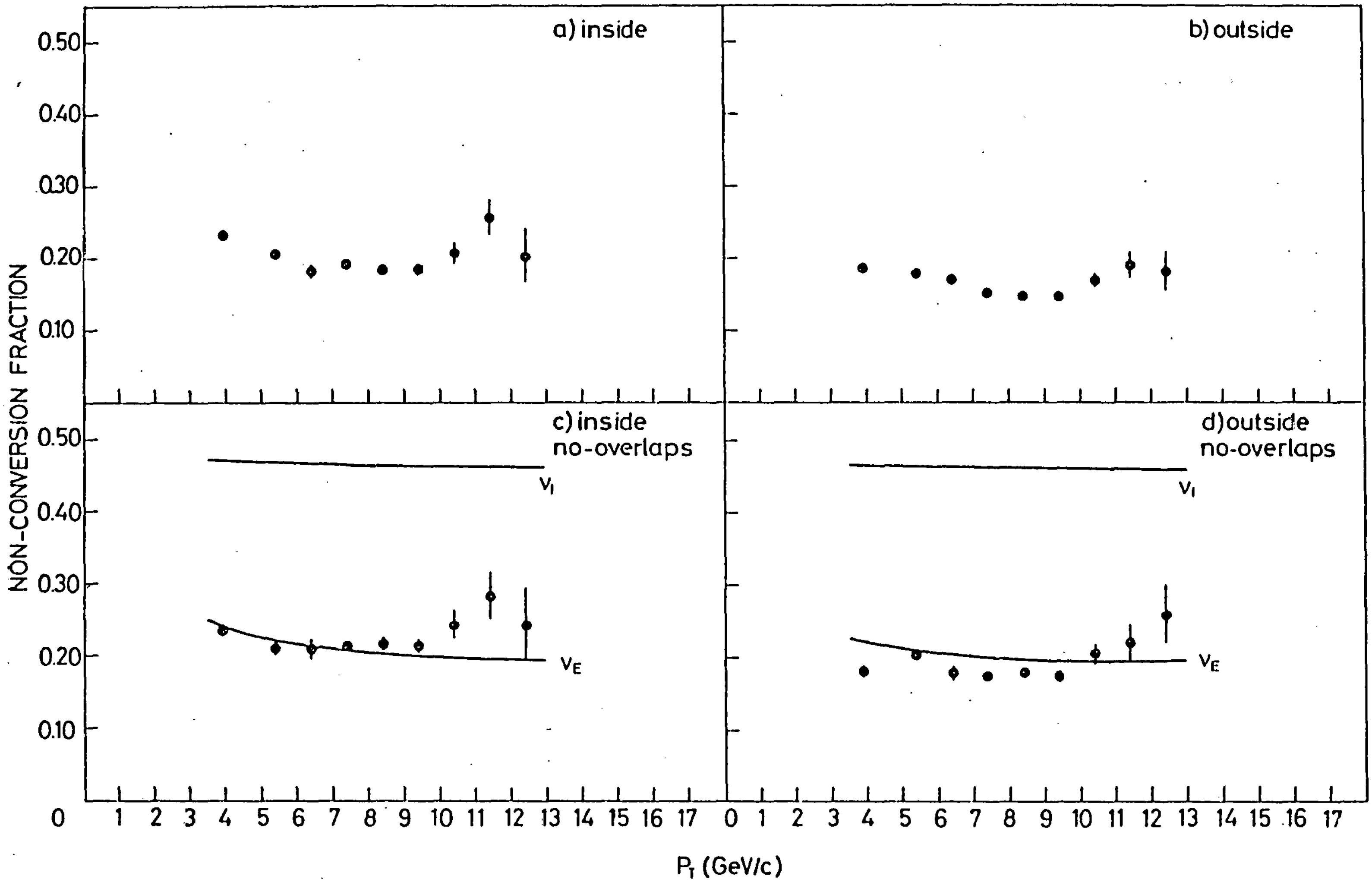


Fig. 1



Fraction with no track within 30cm of cluster inside
a)
Fraction with no track within 30cm of cluster outside
b)
Inside / outside ratio
c)
Fraction with no overlap inside
d)
Fraction with no overlap outside
e)
0.95
0.90
0.85
0.80
0.75
0.70
0.60
0.50
0.40
0.65
0.55
0 1 2 3 4 5 6 7 8 9 10 11 12 13
P_T (GeV/c)

Fig. 2



a) inside
b) outside
c) inside no-overlaps
d) outside no-overlaps
NON-CONVERSION FRACTION
0.50
0.40
0.30
0.20
0.10
0
ν_I
ν_E
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17
P_T (GeV/c)

Fig. 3

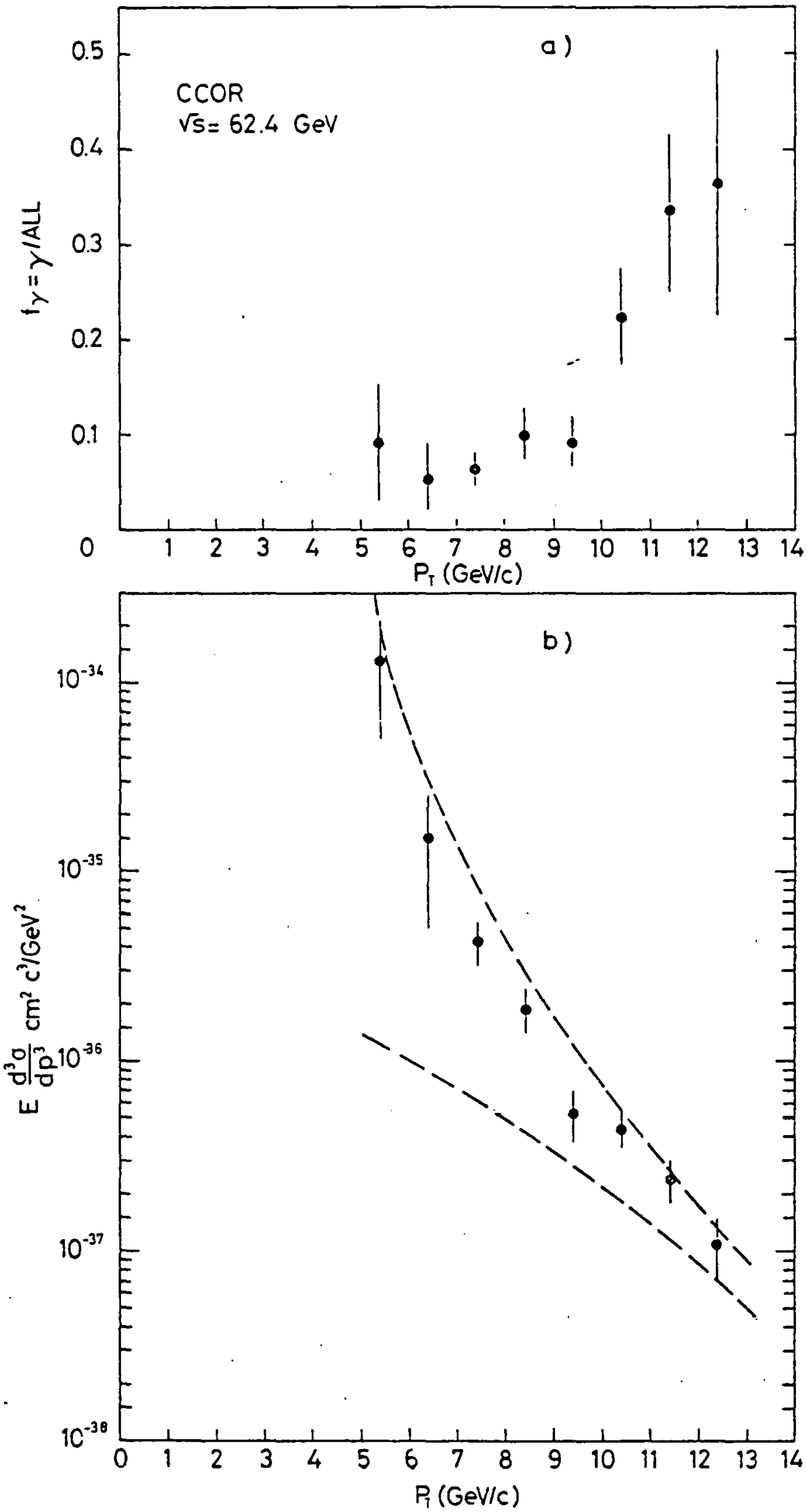
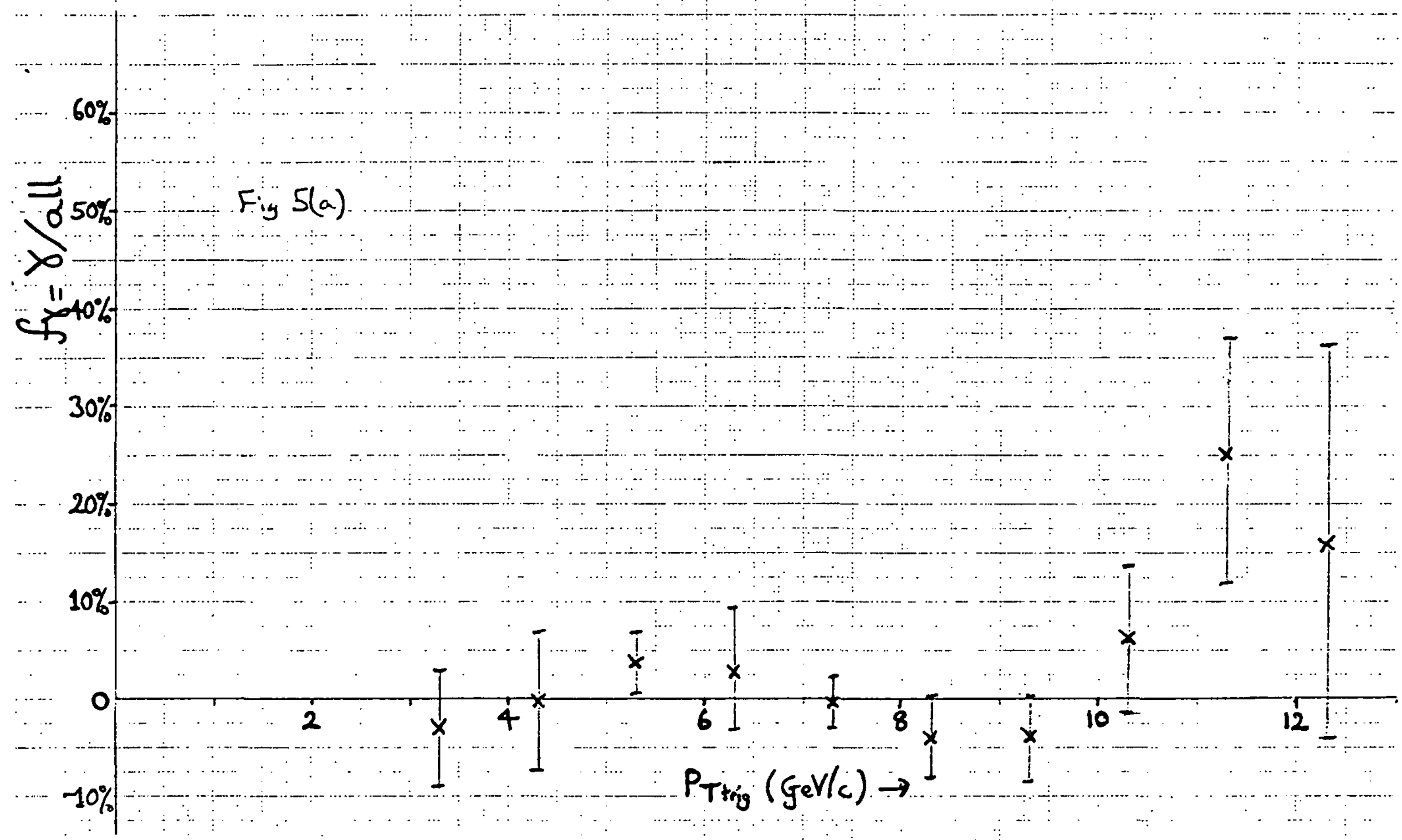

a)
CCOR
√s= 62.4 GeV
0.5
0.4
0.3
0.2
0.1
0
$f_\gamma = \gamma$/ALL
1 2 3 4 5 6 7 8 9 10 11 12 13 14
P_T (GeV/c)
b)
10^{-34}
10^{-35}
10^{-36}
10^{-37}
10^{-38}
$E\frac{d^3\sigma}{dp^3}$ cm² c³/GeV²
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14
P_T (GeV/c)

Fig. 4


60%
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$f_\gamma = \gamma/all$
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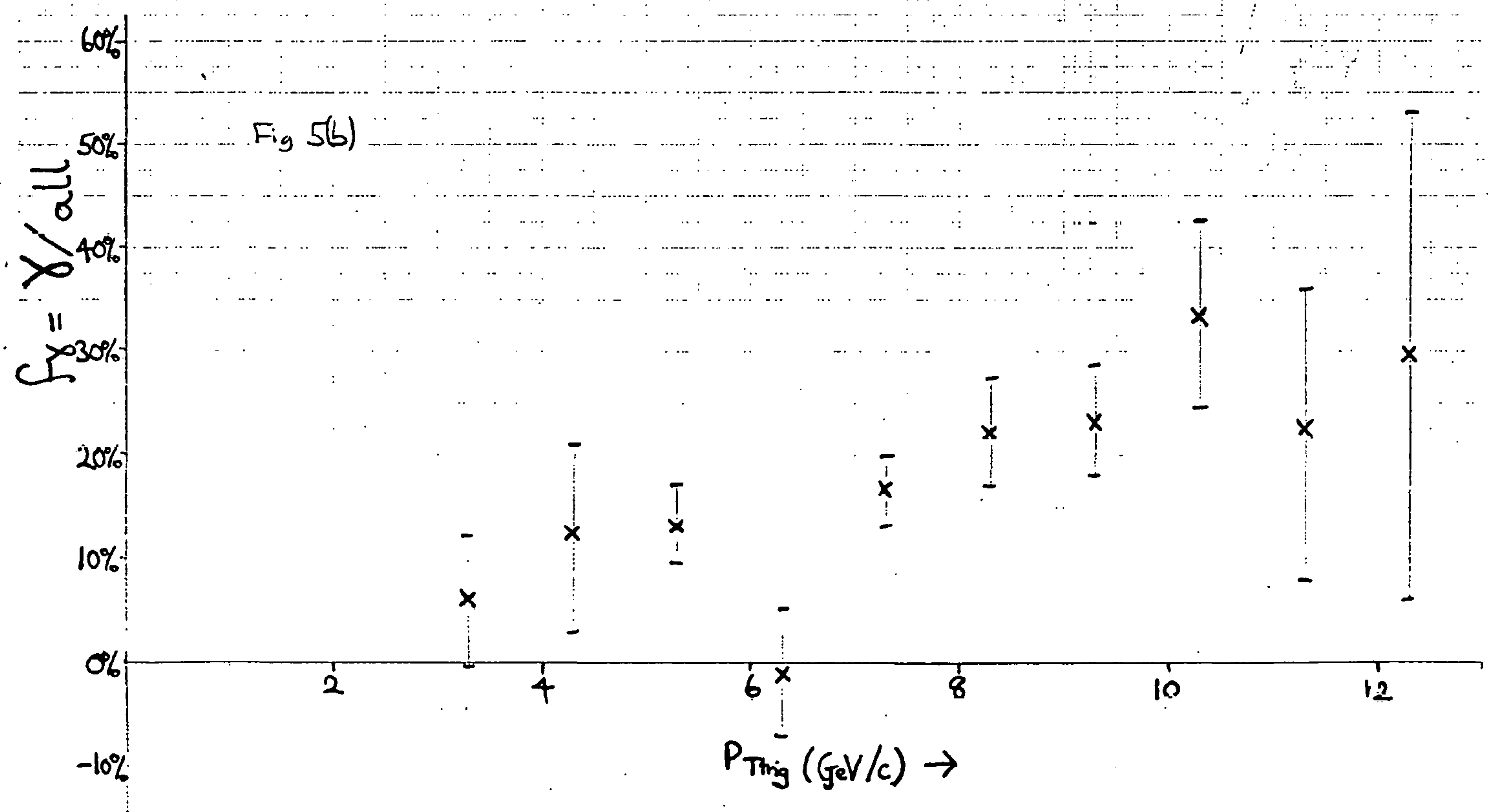
12
$P_{T\,trig}$ (GeV/c) →

Fig 5(a)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20%
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0%
-10%
$f_\gamma = \gamma/all$
2
4
6
8
10
12
$P_{T\,trig}$ (GeV/c) →

Fig 5(b)

Figure 6(a)

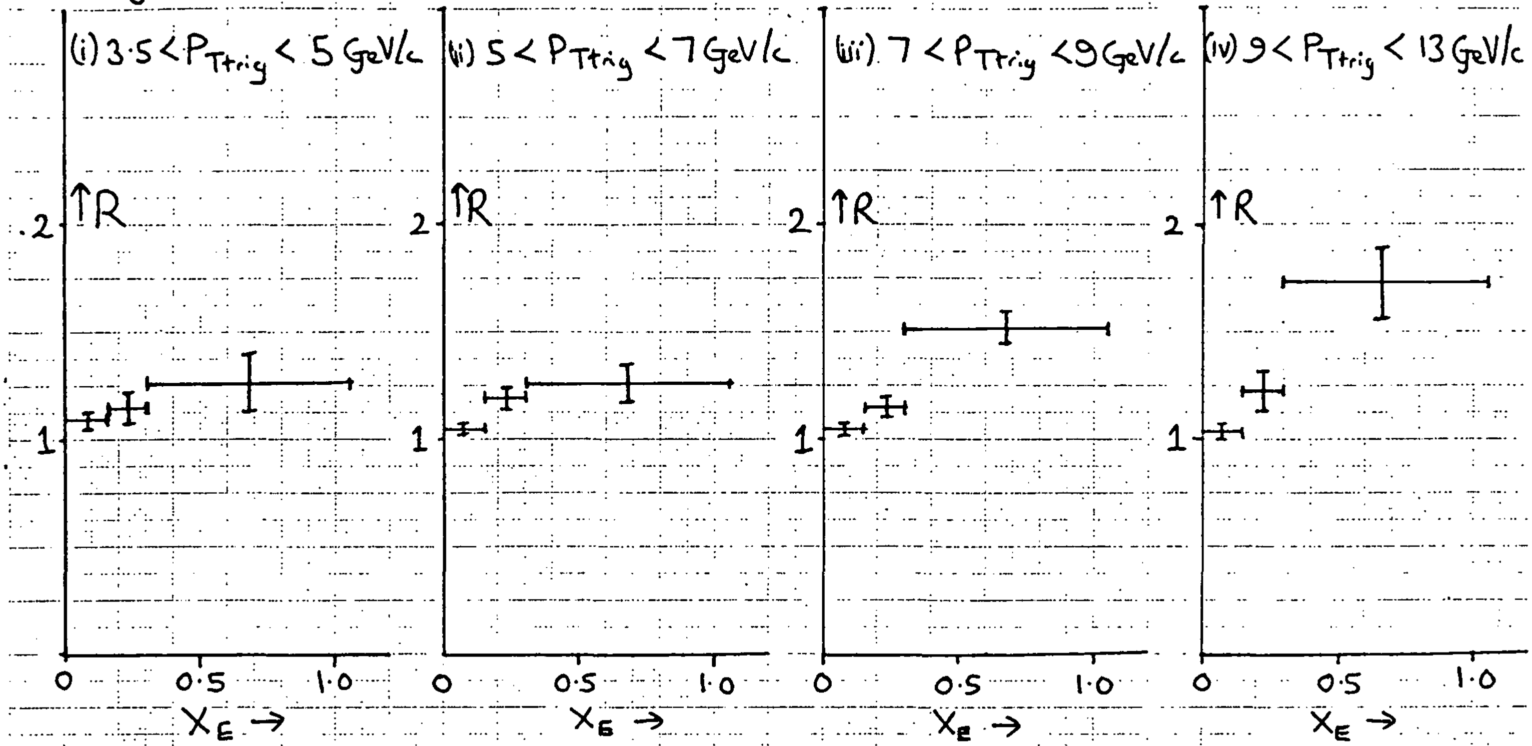

Figure 6(b)