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PHOTON AND π° PRODUCTION AT THE FNAL $\bar{p}p$ COLLIDER

I. Hinchliffe and R.L. Kelly

Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

ABSTRACT

Direct photon and inclusive π° rates expected at the FNAL 2-Tev $\bar{p}p$ collider are calculated. The direct γ rates are appreciable out to $p_T \sim 50$ GeV, but the γ/π° ratio is less than 5%. Detailed consideration of π° resolution indicates that it will be difficult to measure direct γ's beyond $p_T \sim 20$ GeV. Some tricks are suggested to extend the p_T range.

I. Introduction

This note is concerned with estimates of single photon production at the $\bar{p}p$ collider at FNAL and the problems of observing such photons. The production of direct photons at large p_T in hadronic reactions has long been touted as a good QCD test; at least as reliable as jet production.[1] Recently data have appeared from the ISR which confirm the existence of direct photons at a rate in rough agreement with the QCD expectations.[2]

As is well known from hadronic single particle production at large p_T, the simple QCD picture does not work well (if at all) and needs modification in the form of constituent transverse momentum or addition of higher twist terms (constituent interchange model). It is difficult to know at the ISR energies whether the jet structure is testing QCD or merely fitting parameters associated with these modifications. It is hoped that at the $\bar{p}p$ collider (where one will be able to study jets with p_T in excess of 50 GeV with reasonable event rates) a test of QCD will be possible since the importance of these modifications will have diminished. In this paper we examine the expected photon signal and compare it with the background coming from unresolved π°'s. We conclude that the low luminosity of the $\bar{p}p$ collider coupled with the π° background makes it difficult to study direct photons with $p_T \gtrsim 20$ GeV. The situation is more hopeful at ISABELLE with its higher luminosity. In Section II we discuss the model used for the generation of photons and π°'s; Section III discusses the detector and resolution problems associated with π°'s and photons and the signal to be expected; finally in Section IV we draw some conclusions.

II. QCD Predictions for γ and π° Production

Photons at large transverse momentum can be produced in several ways. Firstly from the so-called direct processes $gq \to \gamma q$ and $q\bar{q} \to \gamma g$. In these processes the photon is produced at the hard scattering vertex, and the cross section is of order $\alpha_S \alpha_{em}$. Such photons will be unaccompanied by other particles at large p_T. We shall exploit this property later in attempting to overcome the π° background. In order to predict the cross section from these processes, one needs the structure functions of the proton and a calculation of the constituent cross section. The structure functions are well known from deep inelastic scattering with the exception of the gluon distribution which can only be inferred indirectly. We used two separate parameterizations of the structure functions; those due to Feynman, Field, and Fox[3] and those due to Baier, Engels, and Petersson.[4] They produce single γ cross sections which agree to within 20%. The constituent cross sections are readily available in the literature;[1] they are

$$\frac{d\sigma_{gq \to \gamma q}}{d\hat{t}} = \frac{1}{3} \frac{\pi \alpha_S \alpha_{em} e_q^2}{\hat{s}^2} \left(\frac{\hat{s}^2 + \hat{u}^2}{-\hat{s}\hat{u}} \right)$$

$$\frac{d\sigma_{q\bar{q} \to \gamma g}}{d\hat{t}} = \frac{8}{9} \frac{\pi \alpha_S \alpha_{em} e_q^2}{\hat{s}^2} \left(\frac{\hat{t}^2 + \hat{u}^2}{\hat{t}\hat{u}} \right) .$$

where $\hat{s}, \hat{t}$ and $\hat{u}$ are the usual Mandelstam variables.

There is an ambiguity here in that the value of Q^2 appearing in $\alpha_S(Q^2)$ and the scale M^2 at which the structure functions are to be evaluated is not known. A calculation of the next order QCD corrections would help to resolve this ambiguity. Tests with different Q^2's and

M^2's indicate that this ambiguity is small compared to the other uncertainties in the calculation. We shall use $Q^2 = M^2 = 4p_T^2$ in what follows. Calculated direct photon yields at $y = 0$ (90°) at FNAL and ISABELLE are shown in Fig. 1. We have not included any constituent transverse momenta (so-called "smerging"). Its effect can be simulated by displacing the p_T-axis by 1-2 GeV. Calculation of the direct photon yield at the CERN $\overline{p}p$ collider ($\sqrt{s}$ = 540 GeV, $\mathcal{L} = 10^{36}/\text{cm}^2\text{yr}$) gives rates less than those shown for FNAL in Fig. 1 by a factor which increases from 2.5 at $p_T \sim 10$ GeV to 10 at $p_T \sim 50$ GeV. This rapidity dependence of the photon yields is shown in Fig. 2.

There are other processes which contribute to the direct photon cross section, in particular $qq \to qq$ which produces a quark at large p_T followed by the bremsstrahlung of a photon from one of the outgoing quarks. This process is expected to be of the order $\alpha_S^2\alpha_{em}$. In order to calculate this process (and others, eg., $gq \to gq(q \to \gamma)$) we need to know the fragmentation function for a quark into a photon, D_q^γ . This is not calculable in QCD (except perhaps in the limit of $z \to 1$ where z = energy of γ/energy of quark) and must be obtained elsewhere. One could get it from $e\overline{e} \to \gamma + X$ but no data so far exists and the best one can do is to make a guess for $D_q^\gamma(z)$. Guesses tend to make these processes produce γ's at about 20% of the rate given by the direct processes discussed above.[5] We do not include these bremsstrahlung processes in our estimates. Two further points should be made; first, the bremsstrahlung photons are part of a jet and so they will be accompanied by other large p_T particles - ISR data indicate that this is not the case so that the brehmsstrahlung

processes are not dominating; second, a significant bremsstrahlung contribution makes a QCD test more complicated because $D_q^{\gamma}(z)$ is not known.* There are also constituent interchange processes (higher twist) but these fall off with a larger power of p_T and so become negligible at large p_T. These effects are not included. In conclusion our direct photon cross sections probably represent a lower bound. The worst uncertainties are for $p_T \lesssim 10$ GeV where "smerging" and CIM processes are important. Our results should be more reliable for large p_T although uncertainties associated with the choice of Q^2 remain.

The generation of π°'s, which represents background to single photon production is similar. The fundamental scattering processes, $qq \to qq$, $gg \to q\bar{q}$ etc., generate quark and gluon jets which then contain π°'s. The calculation of π°'s requires structure functions as before, the cross sections for the hard scattering processes, and the fragmentation functions $D_q^{\pi^{\circ}}(z,Q^2)$ and $D_g^{\pi^{\circ}}(z,Q^2)$. One must also take into account parton fragmentation into vector mesons which subsequently produce π°'s in their decays, as in the model of Feynman, et al.[3] We have done this in a phenomenological way by rescaling the π° fragmentation functions of Baier, et al.[4] For the quark fragmentation function we use twice that of Baier, et al. with

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* Note to the theorists - It is not strictly correct to distinguish between direct and brehmstrahlung photons since the two processes mix in higher orders of QCD perturbation theory.

Λ = 400 MeV,

$$D_q^{\pi^\circ}(z,Q^2) = D(z,Q^2)/z$$

$$D_Q^{\pi^\circ}(z,Q^2) = (1 - z)\, D(z,Q^2)/z$$

where q = u or d, Q = s or c, and $D(z,Q^2)$ is defined by Baier, et al. The $\pi^\pm$ rates should be rescaled in a similar fashion. These then fit the total charged particle rate seen at PETRA[6] (Fig. 3) assuming a K/π ratio of 3/7 roughly in agreement with the data.[7] The evolution in Q^2 is dictated by the lowest 2 QCD moments. The Q^2 evolution is not very important since it is slow and our jets are roughly the same energy as the PETRA ones. There is a larger problem with $D_g^{\pi^\circ}$ where there are no data. (In order to measure it, one should look at Toponium $\to \pi^\circ + X$). We use 1.5 times the $g \to \pi$ fragmentation functions of Baier, et al. with Λ = 400 MeV. This has a z-dependence near z = 1 like $(1 - z)^{d_2}$ with $d_2 \approx 2$ as determined by counting rules. The normalization is chosen by requiring that in the gluon jet 75% of the momentum is ultimately carried by pions and one-third of these are neutral. Our π° signal is shown in Fig. 1. The uncertainties in the photon signal apply here also, viz., "smerging", higher twist and the Q^2 problem, and in addition there are the uncertainties of the fragmentation functions. It is hoped that some of the uncertainties will cancel out in the γ/π° ratio since they have a common origin. This is particularly likely to be true of the "smerging". It is immediately clear from Fig. 1 that the γ/π° ratio is smaller than the ISR data until $p_T \gtrsim 50$ GeV. However, if we plot the γ/π° as a function of $x_T = 2\, p_T/\sqrt{s}$ our predictions compare reasonably with the ISR results. Note that

the accessible x_T range at FNAL is at most $x_T \lesssim 0.05$, which lies well below the ISR measurements.

III. π^o Detection

We must now estimate the number of π^o's which appear as photons due to the imperfect detector. Since the γ/π^o ratio in the region of p_T where there is a significant number of events is smaller than at the ISR, it is clear that one will have to work harder. The model of a detector we use is as follows; a π^o decaying into two photons will fail to be resolved and will look like a single photon if either of the following criteria are satisfied:

(a) The opening angle between the two photons is less than ϕ_{min}.

(b) One of the two photons has less energy than E_{min}.

Of course, in the latter case the "background photon" will have less energy than the π^o from which it came. ϕ_{min} and E_{min} are detector dependent. For the central detector at FNAL covering the rapidity interval $1 \lesssim y \lesssim -1$, ϕ_{min} will be at least 12 mrad, corresponding to a minimum resolvable shower separation of 2 cm, and may be as large as 23 mrad for asymmetric π^o decays. In our simple detector model with fixed ϕ_{min} we concentrate on an intermediate value of 17 mrad. Reasonable values of E_{min} are in the range of 100-300 MeV.

Figure 4 shows the effect of the detector resolution. It is clear that there is a critical value of p_T beyond which the background is enormous. Even below this value the background is comparable to the signal, but since most π^o's are resolved a background subtraction should be possible. The critical p_T is determined by ϕ_{min} and to increase it ϕ_{min} must be reduced. An obvious solution is to pull back the detector away from the

interaction region so that a fixed resolution will give a smaller ϕ_{min}. Unfortunately, this will entail a loss in acceptance. One segment of the FNAL detector pulled back will only cover 1/24 of the azimuth. It is clear from Fig. 1 that the event rate is too small to make this worthwhile.

One could resolve π^o's out to $p_T \sim 40$ GeV but there are effectively no events for $p_T \gtrsim 25$ GeV in the retracted mode, whereas we can already reach $p_T \sim 20$ GeV in the standard (unretracted) configuration. The situation at ISABELLE is better; even with the limited azmuthal acceptance there is still a reasonable number of events at $p_T \sim 70$ GeV. The increased luminosity enables one to pay a price of azmuthal acceptance in order to resolve π^o's to larger p_T. Figure 2 shows that the direct photon rate has little rapidity dependence, and this is also true of the background. The increased ratio of total to transverse momentum (= cosh y) in the endcap region tends to be compensated by the increased distance from the intersection region so that the π^o resolution characteristics are similar to those in the central detector <u>if</u> E_{min} and the minimum resolvable shower separation are similar. In this case one could also reach $p_T \sim 20$ GeV in the endcaps.

A further signature will evidently be needed if one is to separate direct photons at $p_T \gtrsim 20$ GeV. It has already been remarked that the π^o's are members of jets whereas the photons are unaccompanied. One might be able to clean up the signal by imposing a cut on the particles accompanying the candidate photon. For illustration let us try requiring that the accompanying energy be less than a fixed value, E_{cut}. In estimating the values of E_{cut}

which can be used two factors should be borne in mind.

(i) The photons are not really unaccompanied. There are low p_T particles associated with the beam jets. One can estimate how much energy they deposit in the detector at $y = 0$. We will define the accompanying energy to be energy carried by particles within $\frac{1}{2}$ unit of rapidity (polar angle between $60^\circ - 120^\circ$) and 20° of azimuth of the photon. Assuming the multiplicity to be approximately 10 per unit rapidity our photon at $y = 0$ will be accompanied by about 1 particle and assuming that each has an energy of 1 GeV (the average p_T of the beam jets) we arrive at an average accompanying energy of 1 GeV. We are assuming that there is only one event; it is possible that there could be several interactions during the sampling time of the detector. If this is true then the accompanying energy is correspondingly increased. For the FNAL detector low p_T events can be expected at the rate of about 10^5/sec, so this coincidence effect should not be a problem. For ISABELLE with its higher luminosity this effect could be increased and the resulting accompanying energy could be large.

(ii) In the FNAL detector all the photon energy will not be deposited in the shower counter. Some of it will leak through and be deposited in the calorimeter.

In view of resolution and fluctuations in the accompanying energy it seems unlikely that E_{cut} could be much less than 5 GeV in practice. Figure 6 shows the effect of this cut on the background. For E_{cut} = 5 GeV and $p_T \gtrsim 35$ GeV the background is under control and there are still a reasonable number of events. Note that the cut is beneficial even at small p_T where it significantly reduces the

background (cf. Figs. 4 and 5). A detailed analysis is not possible without a Monte-Carlo including details of the detector. There is one real problem estimating the effect of the cut; the background with a cut is sensitive to the shape of the (unknown) gluon fragmentation function $D_g^{\pi^o}(z)$ in the limit of large z. Figure 6 shows the effect of a change in $D_g^{\pi^o}(z)$. The hard gluon curve comes from renormalizing our gluon fragmentation function by multiplying it by $\frac{2}{3}(1 - z)^{-1}$. In addition we show the effect of $D_g^{\pi^o}(z) = 0$. In the former case the background falls below the signal for $p_T \sim 45$ GeV and $E_{cut} \sim 5$ GeV. At such p_T values the event rate is starting to become small.

The simplest procedure in this large p_T region would be to measure the $(\gamma + \pi^o)$ rate and the $(\pi^+ + \pi^-)$ rate with the same cuts. Then,

$$\gamma = (\gamma + \pi^o) - \frac{(\pi^+ + \pi^-)}{2}$$

The problem with this is that the CDF detector has no particle identification. So the only hope is to measure all charged particles and form,

$$\gamma = (\gamma + \pi^o) - \frac{(\text{charged particles})}{C} ,$$

where $C \approx 2 - 3$ depending on one's ideas about the K/π ratio. Clearly, this procedure has substantial errors unless the background is small.

An alternative procedure would be to measure the photon signal and background at fixed p_T as a function of E_{cut}. As E_{cut} is reduced a plateau should be reached once the π^o background falls below the photons; the cross-section in this plateau is the direct photon signal. This method may be difficult to use in practice as shown in Fig. 8. This shows the total event rate, photon signal plus π^o background, as a function of E_{cut} at several p_T values. The plateau

structure as $E_{cut} \rightarrow 0$ is not visible, because the π° background does not fall sufficiently fast. Actual data, affected by statistical noise and E_{cut} resolution, would show even less of an effect. Simple extrapolations of the solid curves in Fig. 7 tend to give values for the photon yields which are in error by about a factor of two. Although the extrapolation method may be a start, it seems clear that at high p_T one will need additional signatures to distinguish π°'s and γ's reliably.

IV. Conclusions

We have examined the possibilities of detecting single large p_T photons at the FNAL collider. The γ/π^0 ratio for $p_T \leq 20$ GeV is found to be 1 - 2%, subject to uncertainties in the parton structure and fragmentation functions. However, the π^0 background can be tolerable in this range although, depending on the energy threshold of the shower counters, a subtraction may be required. There seems to be no advantage in pulling back a small section of the detector so as to increase the accessible p_T range since the loss in acceptance produces an unacceptable loss in event rate. A procedure involving a cut on the energy accompanying the candidate photon is useful for $p_T \leqslant 20$ GeV, but does not appear to be sufficient in itself to extend the transverse momentum range. The accessible p_T range at ISABELLE will probably be larger since it should be possible to resolve π^0's out to 50 GeV with smaller azimuthal acceptance and still have a reasonable photon signal due to the increased luminosity.

The significance of direct photon yields below 20 GeV is difficult to assess ahead of time. Certain types of deviations from our simple QCD predictions could be easily explained away. Overall normalization is subject to uncertainties in the sea distributions; the momentum scale can be shifted by "smerging"; higher twist effects would tend to increase the rate and steepen the p_T dependence; there are probably significant higher order QCD corrections (particularly at low x_T) as in all other hadronically initiated processes.[8] However, there is also some possibility that for 10 GeV $\leq p_T \leq$ 20 GeV these effects

will be brought under control (e.g., better deep inelastic scattering data and Z^0 production cross sections will help constrain the sea distributions) and one will be able to test QCD at low x_T.

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FIGURE CAPTIONS

Fig. 1 Photon and π^{o} event rate at FNAL ($\bar{p}p$ at $\sqrt{s}$ = 2000 GeV) and photon rate at ISABELLE (pp at $\sqrt{s}$ = 800 GeV). The luminocities used are $10^{36}/cm^{2}\cdot$year and $10^{39}/cm^{2}\cdot$year at FNAL and ISABELLE, respectively. Photon rates with both full and limited (pulled-back mode) azimuthal acceptances are shown.

Fig. 2 Rapidity dependence of photon event rates at FNAL.

Fig. 3 Fit to DESY inclusive charged particle production using effective quark fragmentation functions as described in the text.

Fig. 4 Background event rates with thresholds of E_{min} = 100 and 300 MeV. Photon and total π^{o} event rates are shown for comparison.

Fig. 5 Background event rates subject to cuts on accompanying energy of E_{cut} = 10 GeV and 5 GeV. The detector parameters are ϕ_{min} = 17 mrad, E_{min} = 100 MeV.

Fig. 6 E_{cut} = 5 GeV background as in Fig. 5 but with modified gluon contributions as described in the text.

Fig. 7 E_{cut} dependence of the total event rate at p_T values where π^{o}'s cannot be resolved.

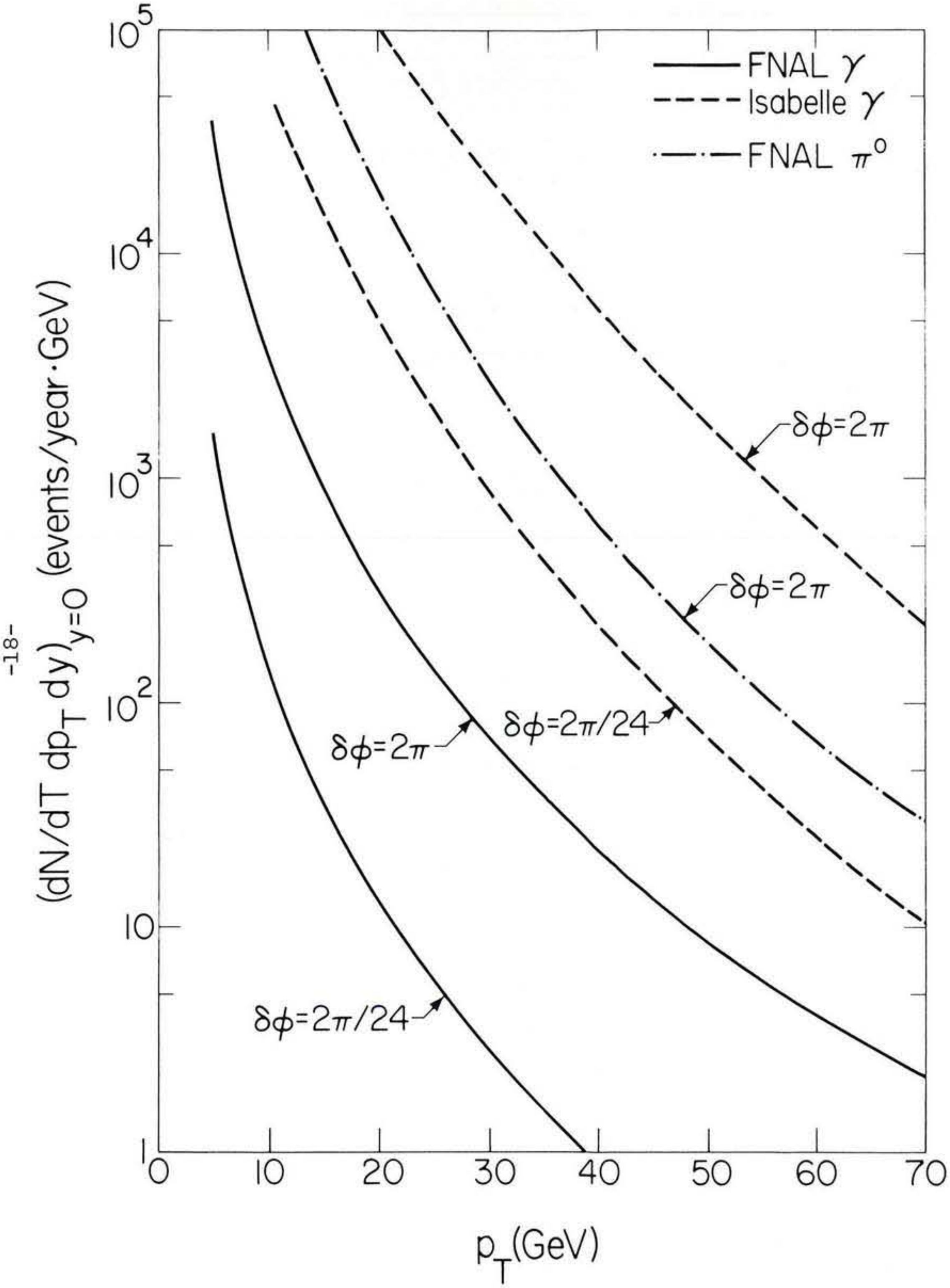
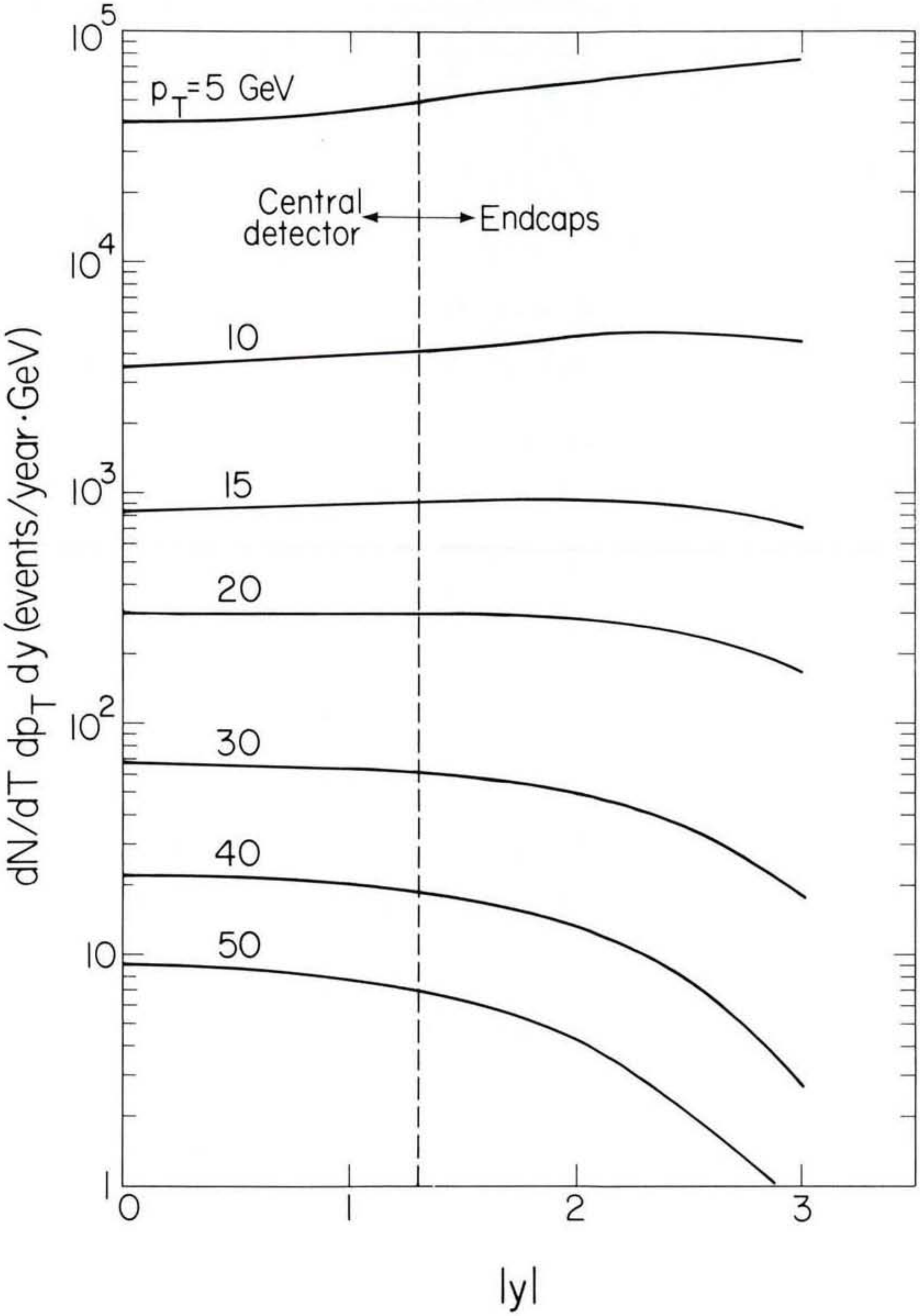
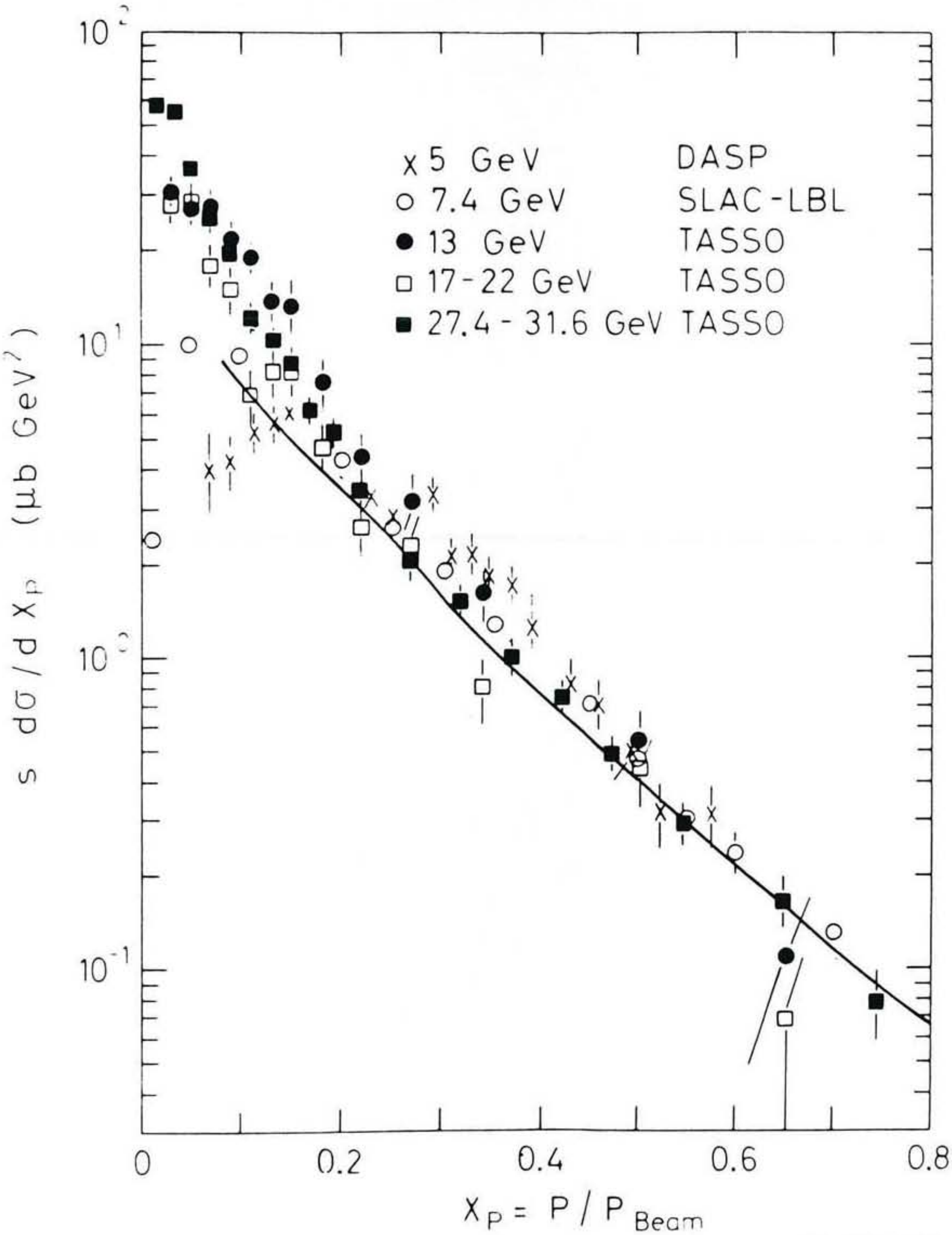

FNAL γ
Isabelle γ
FNAL π^0
$\delta\phi=2\pi$
$\delta\phi=2\pi$
$\delta\phi=2\pi/24$
$\delta\phi=2\pi$
$\delta\phi=2\pi/24$
$(dN/dT\ dp_T\ dy)_{y=0}$ (events/year·GeV)
p_T(GeV)
XBL 812-289

Fig. 1



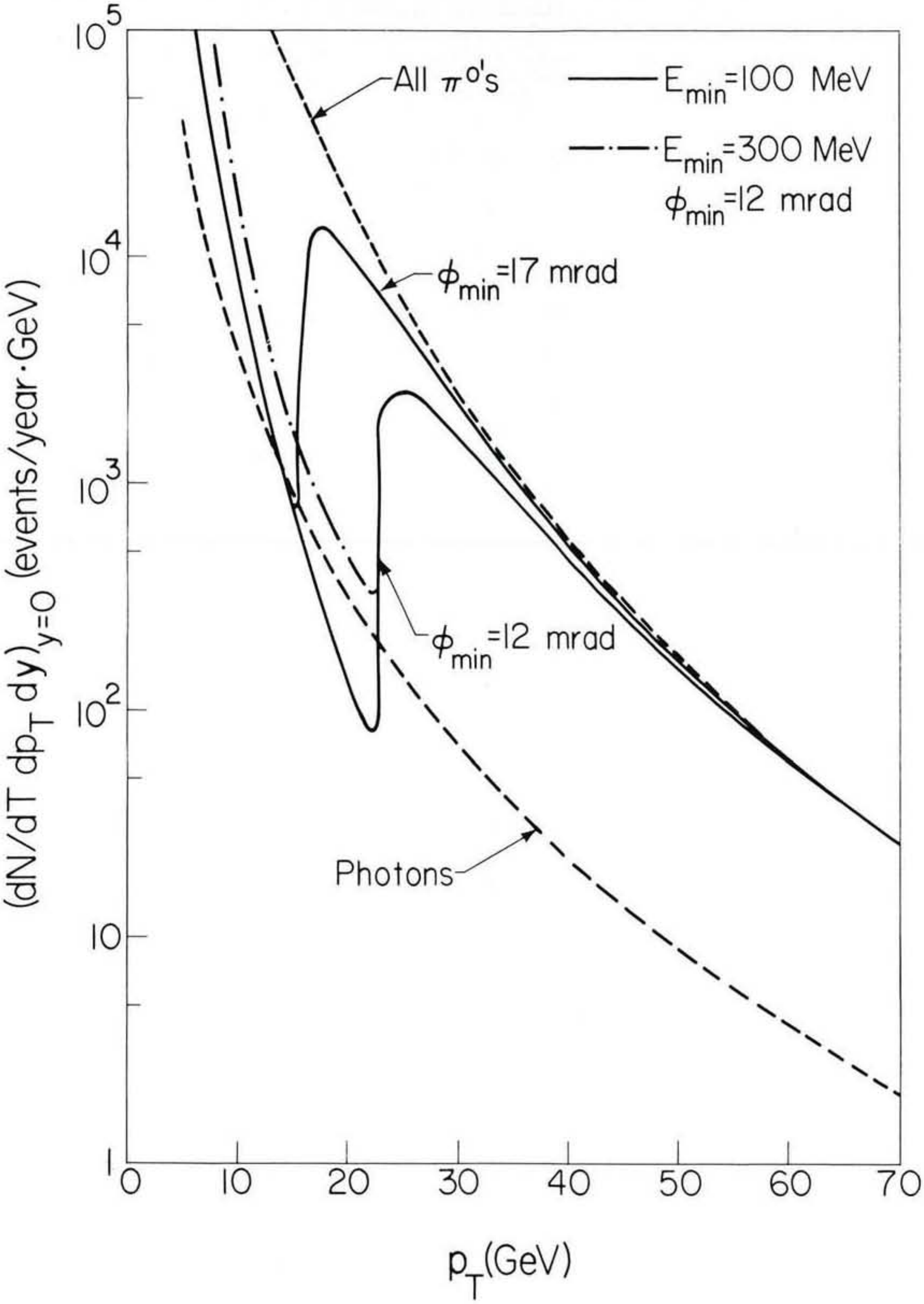
XBL 812-286

Fig. 2



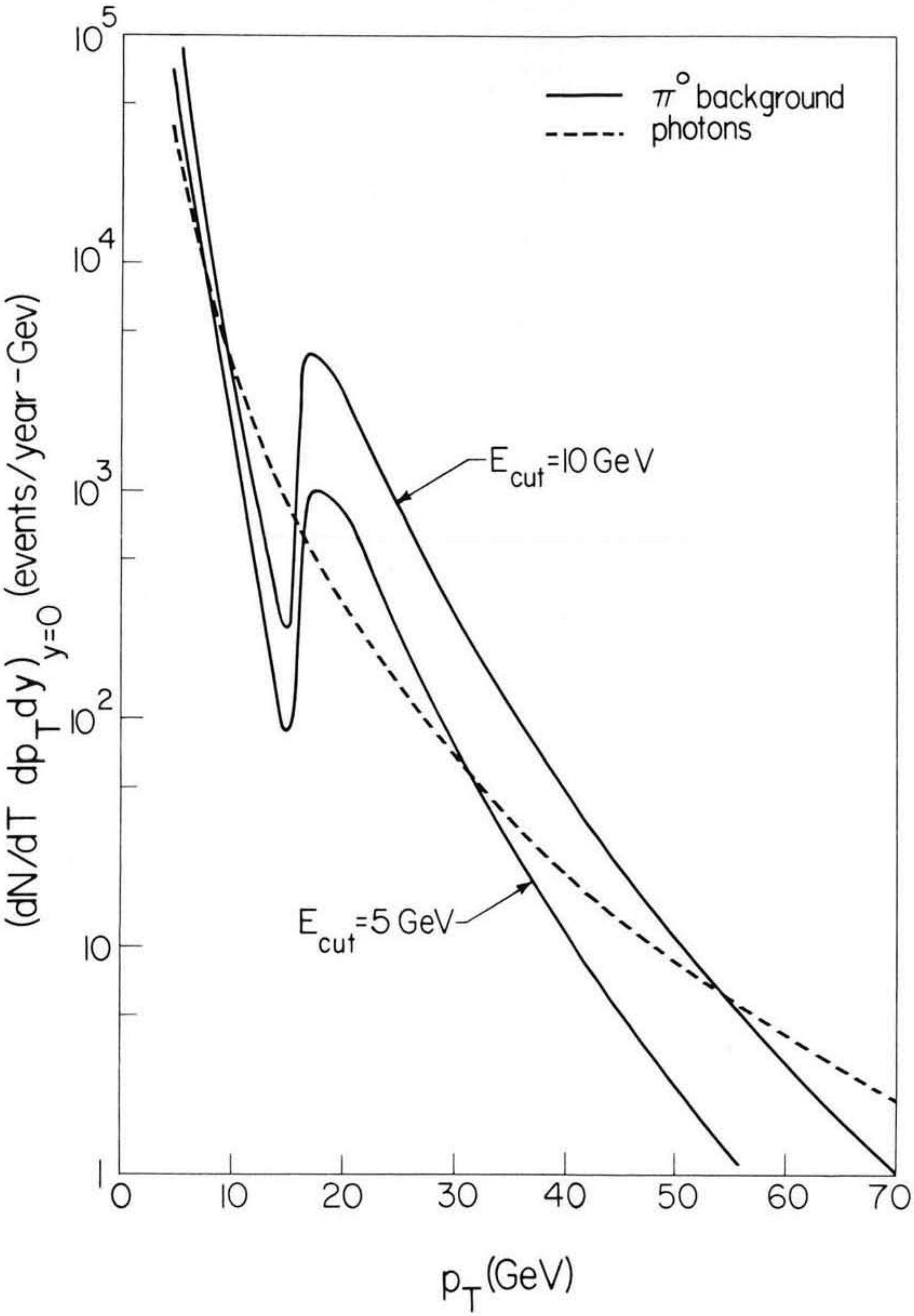
XBL 813-8329

Fig. 3



XBL 812-284

Fig. 4



XBL 812-287

Fig. 5

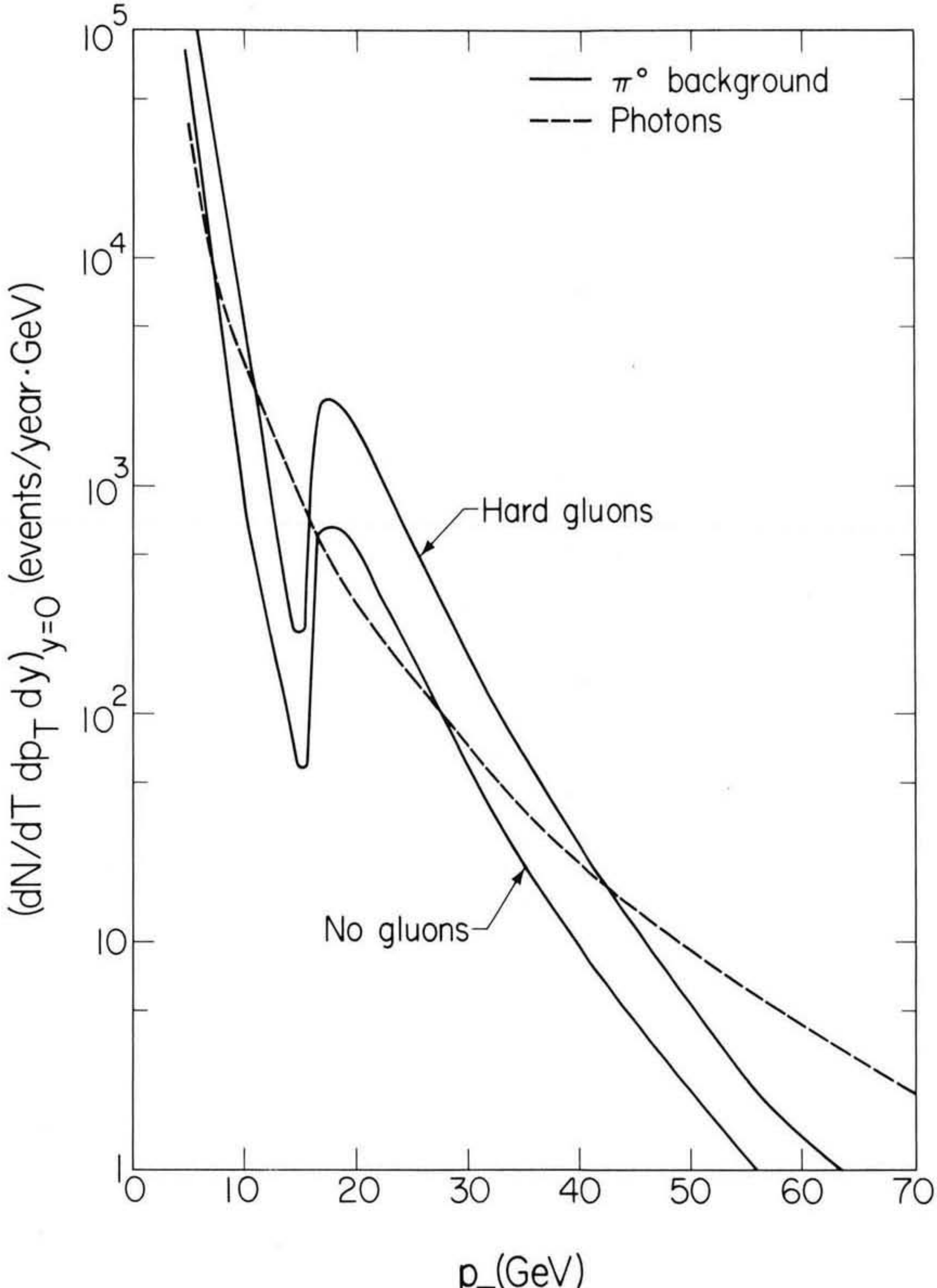
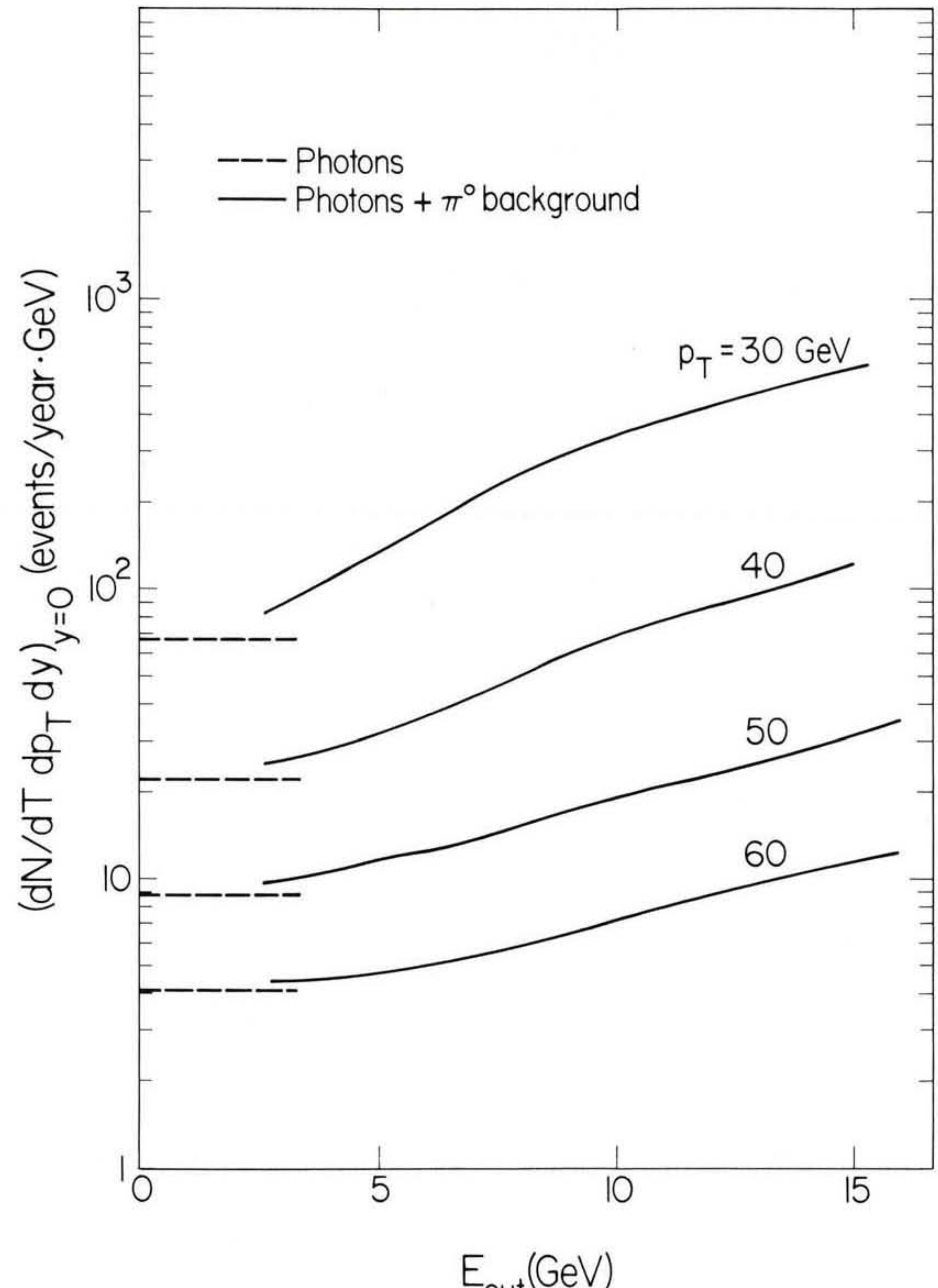

$\pi°$ background
Photons
Hard gluons
No gluons
$(dN/dT\ dp_T\ dy)_{y=0}$ (events/year·GeV)
p_T(GeV)
10^5
10^4
10^3
10^2
10
1
0
10
20
30
40
50
60
70
XBL 812-288

Fig. 6



XBL 812-285

Fig. 7