

PROMPT PHOTONS FROM HADRON COLLISIONS

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ABSTRACT

Prompt photons have been observed over a wide momentum range, from tens of MeV/c up to and beyond 10 GeV/c. Experimental evidence for these processes is reviewed and—where possible—comparison with theory is made. New bands of the photon spectrum are being studied, such as the few hundred MeV/c region and their possible connection with low- p_T leptons, and the production of pairs of photons.

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INTRODUCTION

Photons and leptons are privileged probes of interactions of hadron constituents. *Large-transverse-momentum photons* are radiated in the scattering of quarks on gluons or antiquarks, processes predicted by QCD and confirmed experimentally. More recently, the comparison with theory was extended by data on the dependence of the inclusive cross-section on the centre-of-mass energy, the rapidity, the quark composition of the colliding hadrons, and measurements on the associated event structure.

Whilst the production of high-mass lepton pairs (“Drell–Yan”) has been investigated for many years, the observation of a prompt *diphoton continuum* is of more recent date. This process, although related to the Drell–Yan production, is of interest in its own right as it is sensitive to QCD diagrams, which are not easily measurable otherwise.

Soft prompt photons, with transverse momenta of less than a few hundred MeV/c, are thought to be abundantly produced in hadronic collisions, although unambiguous detection has eluded experimentalists so far. The possible connection with the abundant low- p_T electron production is one of the intriguing puzzles being actively investigated. The understanding of it in hadronic production will be a prerequisite for using it as a signature of possible phase transition to a quark–gluon plasma in ultra-relativistic heavy-ion collisions.

In this note I will concentrate on current research in these topics. A detailed review, with emphasis on experimental results, is given by Ferbel and Molzon¹⁾; the theoretical status, with emphasis on two-photon processes, has most recently been presented by Berger, Braaten and Field²⁾.

PRODUCTION OF PHOTONS WITH LARGE ($p_T > 3 \text{ GeV/c}$) TRANSVERSE MOMENTUM

The interest of pursuing detailed studies of prompt photon production is evident when considering the diagrams contributing, to leading order, to this process (fig. 1):

- i) the point-like coupling of the photon is well understood and facilitates the interpretation of the underlying quark–gluon dynamics;
- ii) in the hard-scattering process the photon represents the complete “jet” with well-defined momentum; therefore, one would expect the photon to be unaccompanied by other particles and to show a p_T dependence similar to that of jets;
- iii) photon production is either initiated by a gluon or accompanied by gluon emission. This offers a rather direct way of investigating the structure and fragmentation function of the gluon.

Not surprisingly, as in the case of Drell–Yan lepton production, higher-order contributions cannot be ignored for photon production; the effect on the total cross-section and our theoretical understanding of these contributions is comparable to the “K-factor” in the Drell–Yan case. One particular plausible process is the radiation of photons off the incoming or outgoing quarks, the “bremsstrahlung” process (fig. 1c).

The status on *inclusive* γ -production³⁾ is summarized and compared with inclusive π^0 production in fig. 2. At moderate transverse momenta, $p_T \sim 4$ to 5 GeV/c , photons are produced at a level of a few percent compared with π^0 s, rising with increasing p_T and approaching the π^0 level for $p_T \geq 10 \text{ GeV/c}$. Also shown is a recent calculation with individual yields of the two major subprocesses contributing to the total γ -rate²⁾. Whereas for $pp \rightarrow \gamma X$ the quark–gluon Compton diagram is the major component, the annihilation diagram $q\bar{q} \rightarrow \gamma g$ is expected to dominate in $p\bar{p} \rightarrow \gamma X$ (fig. 3) above $p_T \geq 6$ to 8 GeV/c . We have still to wait for this crucial test, which could best be carried out at the ISR in the immediate future. At that machine, an integrated luminosity of $\sim 100 \text{ nb}^{-1}$ could be reached during a two-week run and the γ spectrum probed out to $\sim 10 \text{ GeV/c}$, as indicated in fig. 3. Should our theoretical expectations be born out by the data, it would provide — besides increased confidence in our understanding of this process — a very cleanly tagged sample of *gluon jets*.

Information exists also on the \sqrt{s} dependence of photon production, mostly based on work at the CERN Intersecting Storage Rings (ISR)³⁾ and on results from Fermilab⁴⁾. It is summarized in fig. 4 together

with the result of a fit to the form $E(d^3\sigma/dp^3) = C(1-x_T)^m \cdot p_T^{-n}$, for which the values $C = 48 \pm 18 \mu\text{b}/\text{GeV}^2$, $m = 8.4 \pm 1.0$, and $n = 6.6 \pm 0.3$ were obtained¹⁾. This coefficient n is about two units smaller compared with single high- p_T meson production: the scaling violating effects of constituent fragmentation are absent, which is reflected in a smaller deviation from the “naïve” parton scattering value $n = 4$. Not surprisingly, then, a similar value of $n = 5.3 \pm 0.2$ is reported⁵⁾ for hadronic jet production in the CERN ISR and $p\bar{p}$ Collider energy range, and hence the ratio photon/jet as a function of p_T is approximately constant (fig. 5).

In the following, information on the rapidity dependence and on the structure of the charged particles associated with γ production is summarized.

Results⁶⁾ from a dedicated experiment to measure γ/π^0 in the rapidity range from 2 to 2.75 at the highest ISR energy, $\sqrt{s} = 63 \text{ GeV}$, are shown in fig. 6. This experiment was suggested⁷⁾ as a sensitive search for possible higher-order contributions, such as higher twist, which were estimated⁷⁾ to contribute more strongly than the basic QCD diagram in this rapidity interval. Experimentally, the yield of photons relative to that of π^0 s is comparable to the yield at $y = 0$ and at a level consistent with leading-order QCD.

Significant differences between the event topologies associated with π^0 and γ production have been observed for some time and have demonstrated irrefutably the reality of prompt photons. The rather striking differences⁸⁾, naïvely expected on the basis of the lowest-order QCD diagrams, are shown in fig. 7. The high- p_T photon is essentially unaccompanied by other charged (and neutral) particles. Based on these studies an upper limit on bremsstrahlung was derived⁸⁾, which was measured to be consistent with zero and less than 30% at the 2σ confidence level: $\gamma_{\text{brems}}/\gamma_{\text{all}} < 0.3$ at 2σ CL. A similar observation is made by the CCOR⁹⁾ Collaboration, who report, however, an indication for increased production of photons accompanied by charged particles beyond $p_T > 10 \text{ GeV}/c$.

An obvious charge correlation is expected for the quark–jet recoiling against the high- p_T photon, which in pp collisions should result in a u-jet/d-jet ratio of 8:1 (a factor of 4 from the square of u/d-charge ratio; a factor of 2 from u/d abundance). Experimentally, the ratio of positive to negative *leading* particles on the recoil side is determined, but with such a devastating reduction of the useful data sample that a statistically meaningful result has not yet been obtained. There is a hint given in the data^{8,9)} that suggests a difference in the charge ratio compared with the detailed QCD estimate¹⁰⁾.

In the future it may be possible to use the γ data to extract the gluon distribution function. In this respect, information on the complete event, i.e. hard photon together with information on the recoil jet, would be of particular value. It also may still be possible to get *one* $p\bar{p}$ run at the ISR, which would allow a useful study of the γ production via the annihilation mechanism. However, “Thanks to the closing of the ISR, this domain of research will be in the hands of the SPS and Fermilab in the near future”¹¹⁾.

There are four experiments running at the CERN Super Proton Synchrotron (SPS), one of which will run on $p\bar{p}$, using an internal H_2 jet target during the CERN $p\bar{p}$ Collider operation. Two experiments are being planned for the Fermilab Tevatron, and one small experiment is being proposed to look for photons at large rapidities at the CERN $p\bar{p}$ Collider.

EVIDENCE FOR A $\gamma\gamma$ CONTINUUM

The production of the photon–pair continuum has been repeatedly discussed¹²⁾ and has recently been reviewed²⁾. Although related to the production of the lepton–pair continuum, it probes different QCD diagrams, not otherwise accessible, such as the “box diagram” of $gg \rightarrow \gamma\gamma$ which is estimated to contribute at ISR energies at a level of 50% relative to the second-order $q\bar{q}$ annihilation diagram. Of conceptual interest is the possibility that a precise measurement of single- to double-photon production may afford a precise measurement of the strong coupling constant α_s , as reviewed in ref. 2. This is based on the fact that the cross-section for the purely QED annihilation process $q\bar{q} \rightarrow \gamma\gamma$ is identical to $q\bar{q} \rightarrow \gamma g$, except for the differences in couplings and colour factors:

$$[d\hat{\sigma}/d\hat{\tau}(q\bar{q} \rightarrow \gamma\gamma)]/[d\hat{\sigma}/d\hat{\tau}(q\bar{q} \rightarrow \gamma g)] = (3e_q^2/4)(a_{em}/a_s).$$

Given the pivotal role of a precision determination of a_s within the QCD framework, a feasibility study of such a hadronic a_s determination through a $\gamma/\gamma\gamma$ measurement appears to be of very topical interest.

The modest experimental information¹³⁾ existing today is summarized below,

$$d^2\sigma/dm_{\gamma\gamma}dy|_{y=0} = (8 \pm 4) \times 10^{-35} \text{ cm}^{-2}/\text{GeV} \quad \text{for } 8 < m_{\gamma\gamma} < 11 \text{ GeV},$$

$$\gamma\gamma/e^+e^- = 1.7 \pm 1 \quad \text{for } p_T(\gamma,e) > 3 \text{ GeV}/c,$$

$$\gamma\gamma/\pi^0\pi^0 = (1.2 \pm 0.6) \times 10^{-3} \quad \text{for } p_{T\gamma} > 3 \text{ GeV}/c.$$

“SOFT” PROMPT PHOTONS

The information on soft photons in the momentum range $\sim 10 \text{ MeV}/c$ to a few hundred MeV/c is very limited, mostly based on indirect evidence, and the physical interpretation is debatable.

An indication for soft photons, with $p_T < 100 \text{ MeV}/c$, has been obtained in exposures of bubble chambers to a $10 \text{ GeV}/c \pi^-$ beam¹⁴⁾ and a $70 \text{ GeV}/c K^+$ beam¹⁵⁾. In both cases a statistically significant excess of photons at very small values of $x < 0.01$ was observed, which could not be explained as originating from the decays of known hadrons. The level of production was found to be consistent with the QED process of “inner bremsstrahlung”, i.e. radiation from the hadrons produced in the reaction.

The decay of soft *virtual* photons into lepton pairs provides a cleaner experimental signature, and in a number of experiments such evidence was found in the mass range $200 \text{ MeV}/c^2 \leq M_{\ell\ell} \leq 600 \text{ MeV}/c^2$, as summarized¹⁶⁾ in fig. 8. It is striking to note that the data, which were obtained at a variety of beam energies, favour a $1/M^2$ -dependence, similar to bremsstrahlung processes in this mass region, but more intense by a factor of $\gtrsim 5$. In connection with low-mass lepton pairs one remembers also the long-standing “ e/π ” mystery observed at the ISR, fig. 9, namely the dramatic increase in lepton production for $p_T \leq 500 \text{ MeV}/c$ ¹⁷⁾. Several experiments have seen this trend of e/π , although the absolute level of production has large systematic errors due to the uncertainty in subtracting Dalitz pairs from π^0 's and η 's and biases against leptons from prompt low-mass pairs. Preliminary data from the AFS confirm this rise, extending the p_T range to below $200 \text{ MeV}/c$. The contribution of the dilepton continuum to the e/π level is also estimated in fig. 9 (dashed line), using the data shown in fig. 8 and extrapolating the measurements as $\sim 1/M^2$ down to $M \sim 100 \text{ MeV}/c^2$, independent of \sqrt{s} . This indicates that lepton pairs can account for a major fraction of the inclusive lepton spectrum below $p_T \sim 500 \text{ MeV}/c$. However, these lepton pairs do not originate from hadronic bremsstrahlung¹⁸⁾; other processes, such as the annihilation of quark-antiquark pairs created during the space-time development of hadronic collisions¹⁹⁾, may be responsible for the observations. This is a relatively new domain of physics: the experimental status is rudimentary, and decisive experiments which will measure the production of single electrons and electromagnetic pairs of electrons and its dependence on the hadronic environment of the collision (e.g. production with large transverse energy), are only in a preparatory stage²⁰⁾. The physics interpretation belongs to the complicated realm of non-perturbative phenomena. However, the interest of these studies is intense, as understanding of the “simple” pp case is a prerequisite to using such signatures in the search for phase transitions from a hadron gas to a quark-gluon plasma²¹⁾.

CONCLUSIONS

The study of hadronic photon production has developed into a diverse field. Hard photons provide one of the cleanest tests of QCD, which has honourably passed the first round of confrontation. The present generation of fixed-target experiments may hopefully contribute, particularly through the possibility of the control of the quark content of the beam.

Evidence for the $\gamma\gamma$ continuum at the QCD level has been observed. The experiment which could use this signature as a powerful tool has not yet been designed; but when it is, a respectable determination of α_s may be the reward.

Soft photons may be abundantly produced, and would have to be carefully studied as it could be a powerful searchlight in the jungle of "non-perturbative" physics.

The results reported here have to a large extent been obtained by the R806, R807, and R808 (Axial Field Spectrometer) Experimental Groups at the ISR, and I am appreciative of the many years of fruitful collaboration. H. Specht and M. Winik discussed with me the AFS data on low- p_T electrons and prepared figs. 8 and 9.

The organizers are to be thanked for a stimulating meeting covering the rich spectrum of collider physics.

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Figure captions

Fig. 1 Principal diagrams contributing to prompt photon and photon-pair production: a) QCD analogue of the Compton diagram; b) quark–antiquark annihilation resulting in a photon recoiling against a gluon; c) bremsstrahlung of an outgoing quark; d) “box diagram” for 2γ production; in addition, pairs may be produced by $q\bar{q}$ annihilation, as in fig. 1b, with the gluon replaced by a photon.

Fig. 2 Inclusive production of photons and π^0 's measured at the highest ISR energy (ref. 3). Also shown is the QCD result for γ production, calculated to be dominantly qg scattering plus a small contribution from q -bremsstrahlung (ref. 2).

Fig. 3 Calculated cross-section for γ production in $p\bar{p}$ collisions at $\sqrt{s} = 63$ GeV (ref. 2). The solid triangle indicates the $q\bar{q}$ annihilation contribution, which exceeds γ production by qg scattering above $p_T \sim 8$ GeV/c. The right ordinate indicates the corresponding rates expected from a two-week run at the ISR with an integrated luminosity of 100 nb^{-1} (solid dots).

Fig. 4 Results on γ production at two values of \sqrt{s} . The dashed line is a fit to the inclusive cross-section $E(d^3\sigma/dp^3) = C(1-x_T)^m \cdot p_T^{-n}$, with $n = 6.6 \pm 0.3$ (see text).

Fig. 5 The ratio γ/jet at $\sqrt{s} = 63$ GeV (refs. 3 and 5).

Fig. 6 The level of photon production at large rapidities, found to be comparable to γ/π^0 at $y \cong 0$ (ref. 6). Curve (a) represents the leading-order QCD result, whilst (b) contains an admixture of CIM diagrams.

Fig. 7 Azimuthal distribution of tracks with $p_T > 1.0$ GeV/c relative to a triggering π^0 or γ . The trigger particle had $p_T > 5.5$ GeV/c (ref. 8).

Fig. 8 The mass dependence of lepton pair production, produced with pions and protons at different beam energies. The data favour a $1/M^2$ -dependence (solid line). The levels of ρ and ϕ production have been plotted assuming the same x -dependence as was measured for the dilepton continuum.

Fig. 9 Summary of ISR data on prompt electron production relative to pions. The dashed line is based on the level of pair production given in fig. 8 and assuming a $1/M^2$ -dependence down to $100 \text{ MeV}/c^2$. It has been simulated in detail for the pair recognition capability of the AFS data and indicates that a substantial part of the inclusive yield is of pair origin.

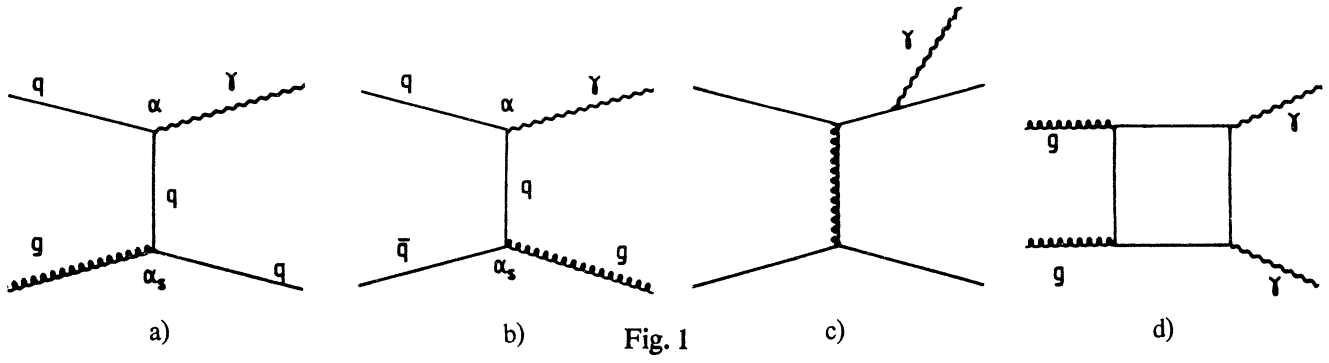


Fig. 1

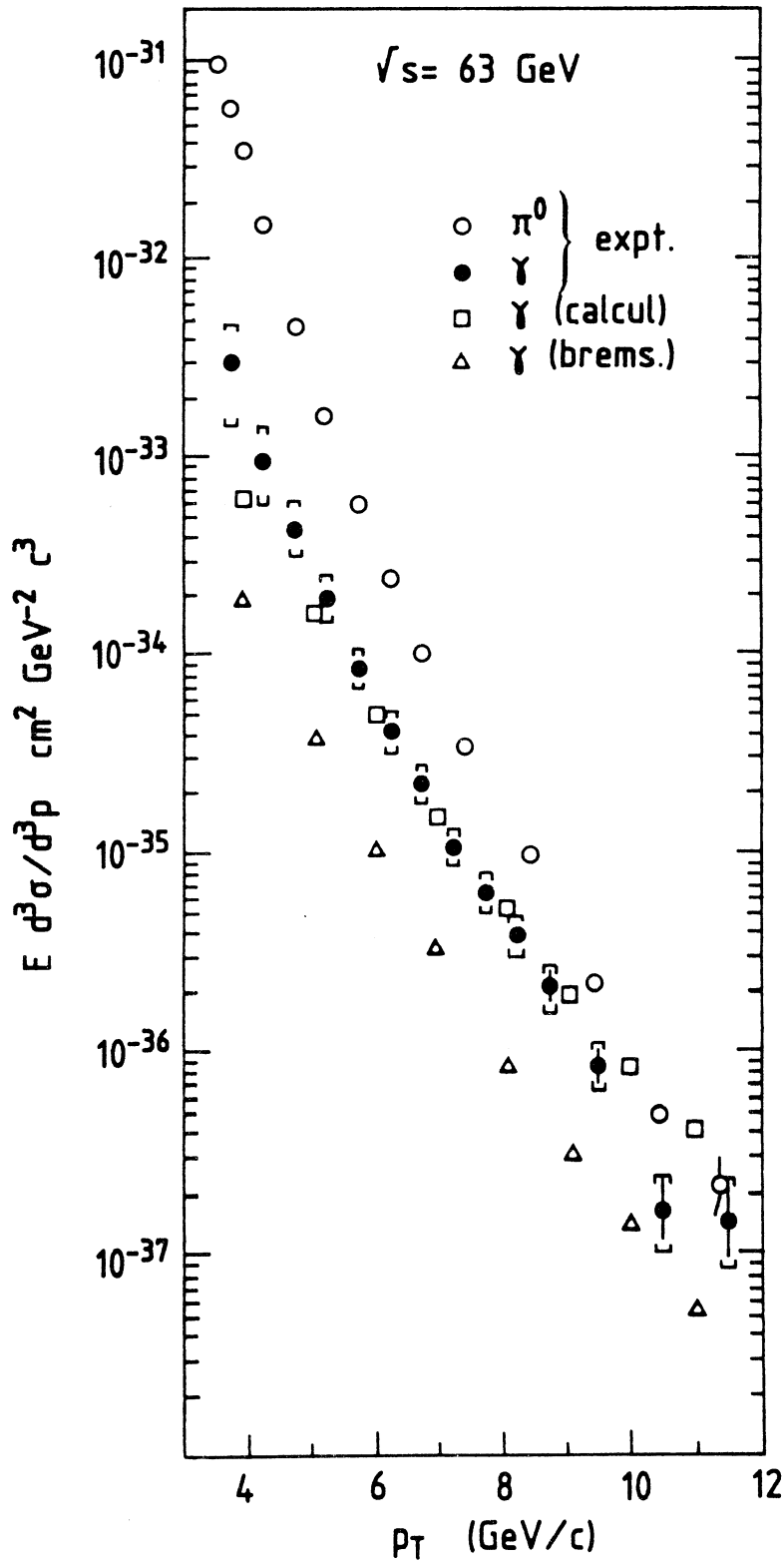


Fig. 2

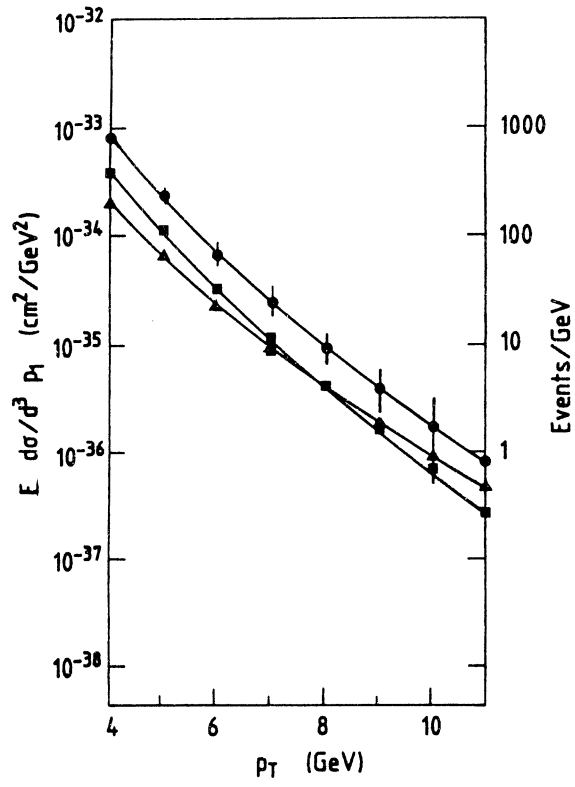


Fig. 3

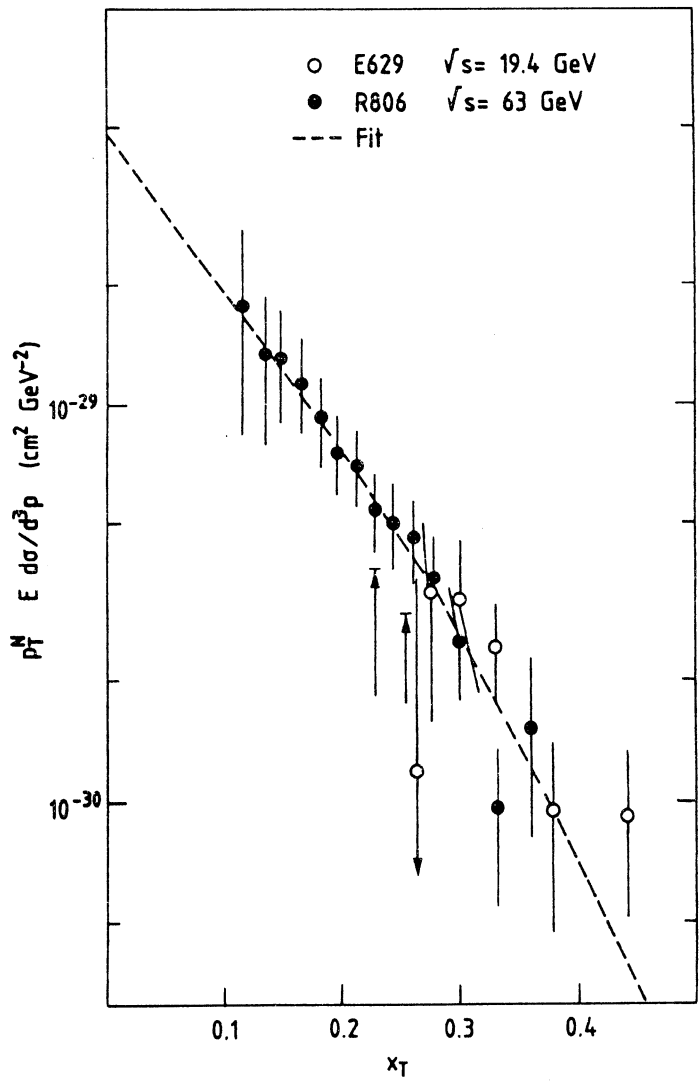


Fig. 4

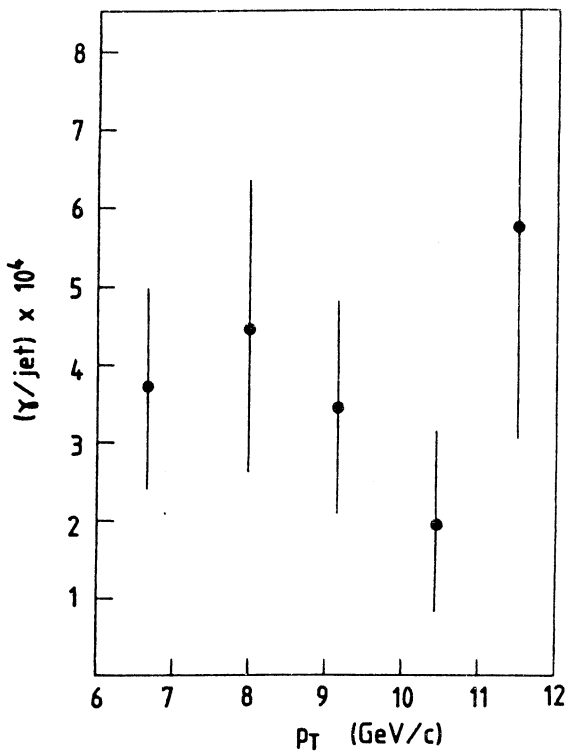


Fig. 5

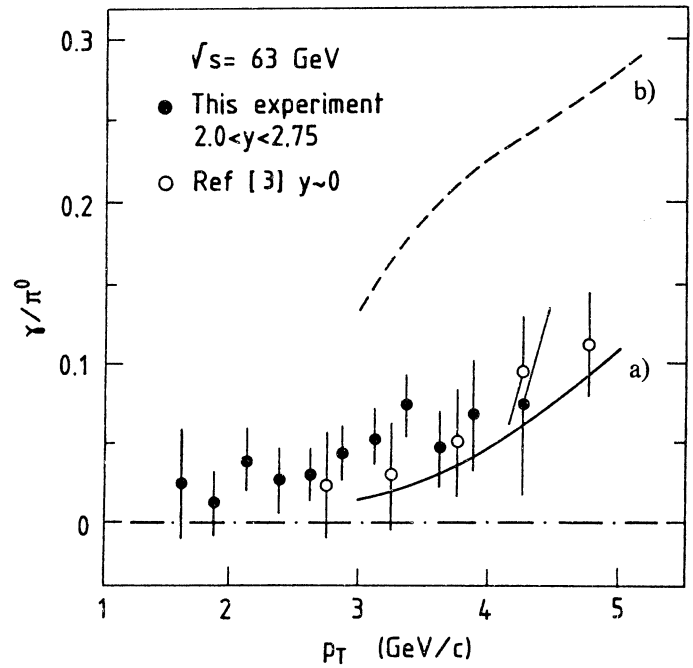


Fig. 6

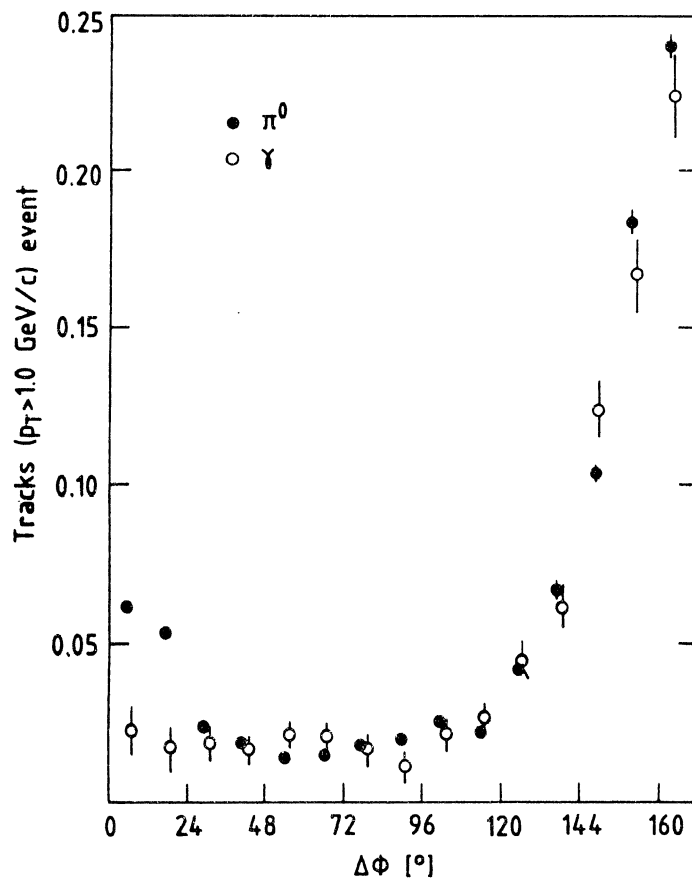


Fig. 7

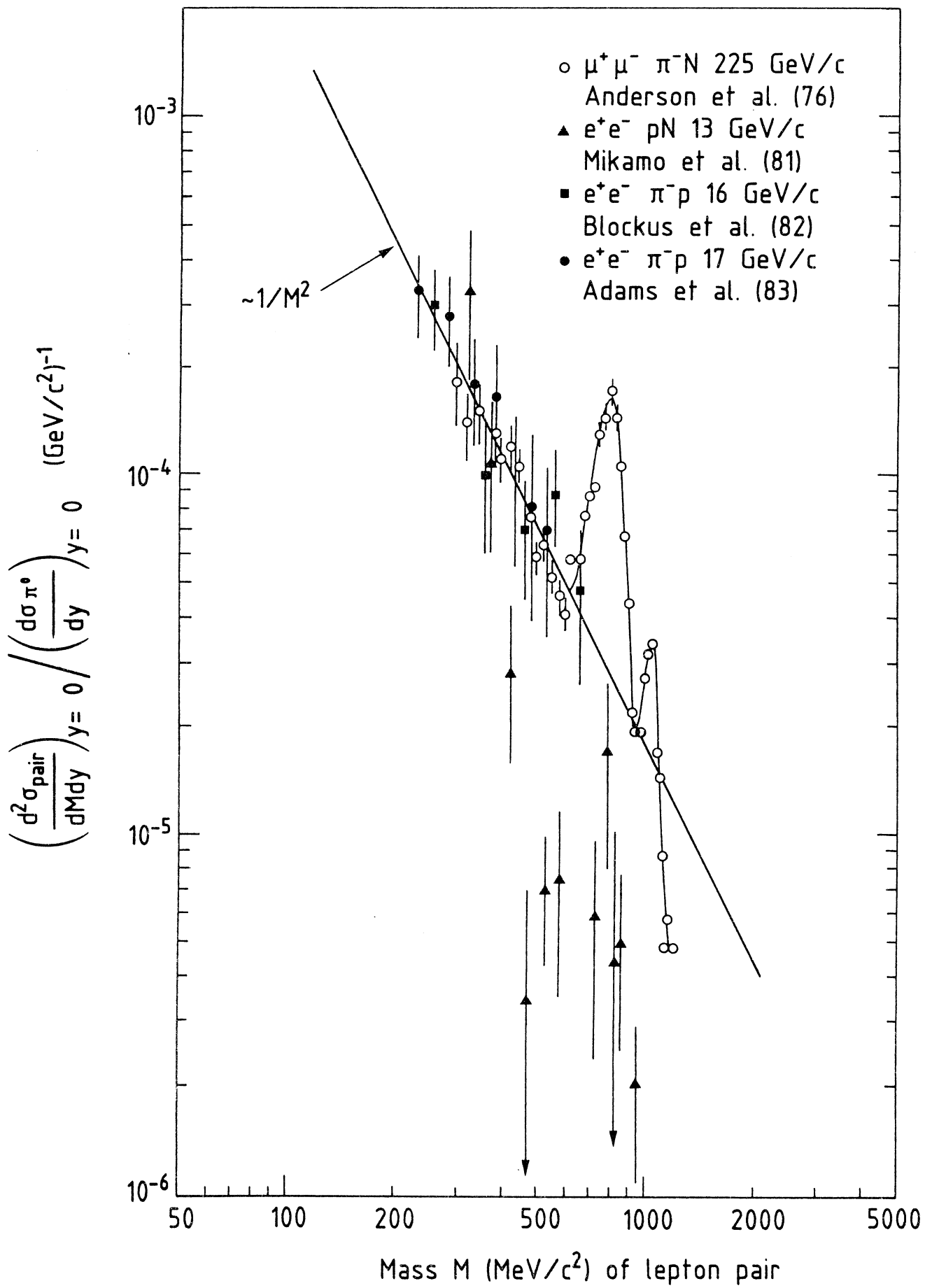


Fig. 8

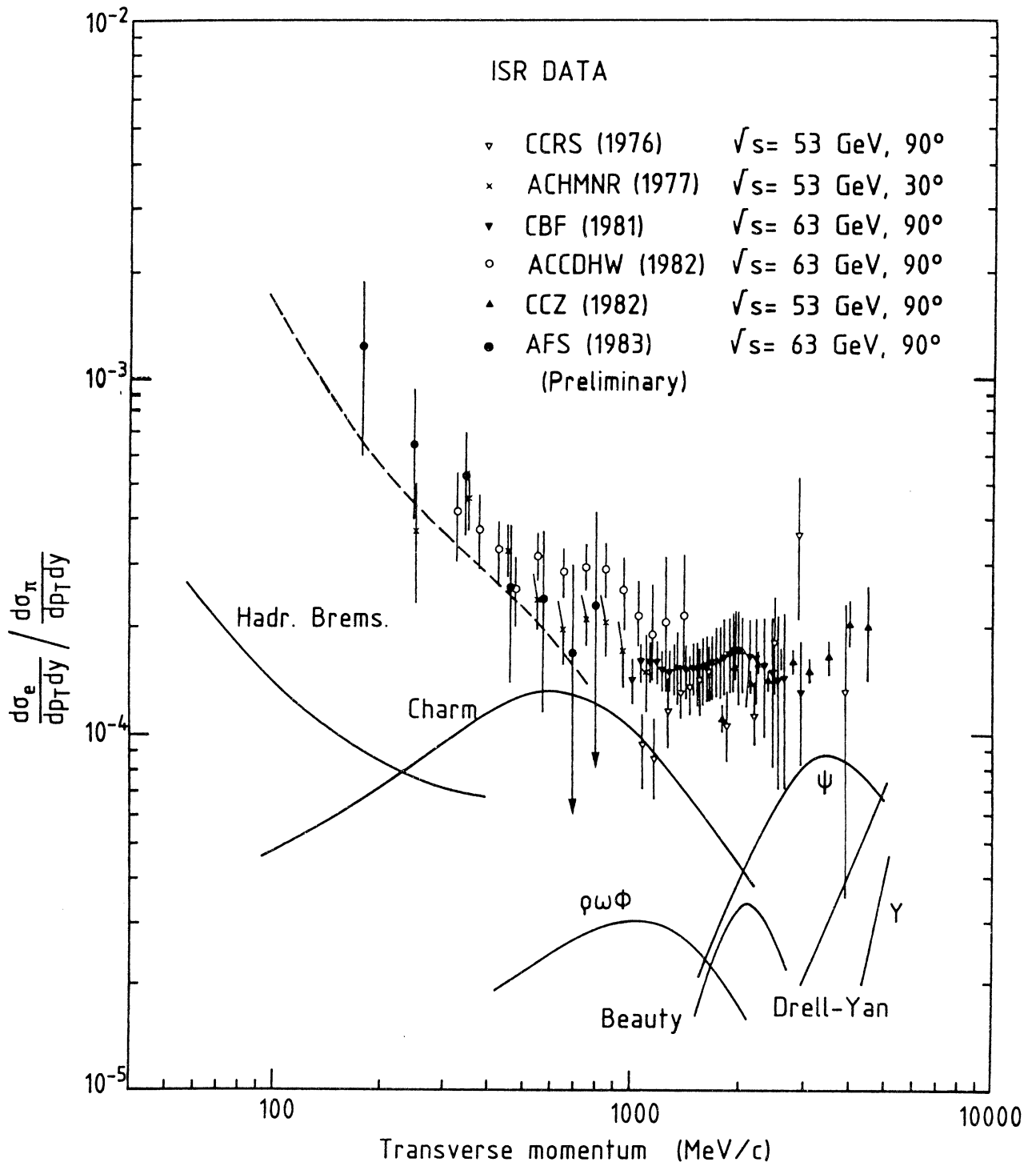


Fig. 9