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HARD PROCESSES INVOLVING REAL PHOTONS

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Photons, in the same way as leptons, give us a direct look at short-distance phenomena and, through them, access to the manifestation of the basic constituents of matter.

Photons can act as elementary partons directly coupled to the quark electric charge. For such behaviour the number of competing basic processes is smaller and the structure of the event is simpler than in ordinary hard hadronic interactions. A list of such reactions is given in Table 1. In processes (c) and (e) the photon transfers its full energy to large- p_T partons, and the absence of fragmentation products in the forward region gives a very striking topology.

As we know, real high-energy photons generally do not behave that way. They interact by fluctuating into a $q\bar{q}$ pair, and the relevant quantity is the fluctuation time, $\tau = E_\gamma/p_T^2$ for a real γ . (For a virtual one, $\tau = 1/\sqrt{-q^2}$, and such fluctuations are suppressed.) If p_T , the transverse momentum of a created parton, is of the order of the scale parameter Λ of QCD, the fluctuation time is long, the partons of the fluctuating system interact with each other, and globally the photon appears as a superposition of vector mesons with an ordinary (i.e. $\sim 1-x$) quark content. If p_T is larger ($\Lambda \ll p_T \ll E_\gamma^*$), the photon behaves rather as a pair of quasi-independent quark and antiquark. This is quite similar to lepton pair creation. The quark content of the photon is harder than in the previous situation and about flat in x . This corresponds to the well-known and badly named "anomalous" behaviour of the photon. At still larger p_T the point-like picture of the photon takes over.

In Section 1, I will briefly mention, following the excellent review by Zerwas¹⁾, what could be the prompt-gamma physics in e^+e^- collisions. Except for $\gamma\gamma$ hard scattering (see subsections 1c and 3b) this domain is still lacking experimental results.

In Section 2, I will treat, in parallel, the hard photoproduction and processes involving a prompt γ in the final state, and review most of the currently available results in that field.

Section 3 will deal with two-photon processes (QED Compton, $pp \rightarrow \gamma\gamma + X$, $\gamma\gamma \rightarrow$ jets) and discuss the problem of a direct measurement of quark charges. Finally, the application of another original feature of the photon — its ability to produce heavy quarks abundantly — will be described.

1. e^+e^- PHYSICS

For details, the reader should refer to the review by Zerwas¹⁾ and the references therein.

1.1 Quark bremsstrahlung

1.1.1 Quark large-angle bremsstrahlung

This offers the possibility to measure the electroweak charges of the quarks, with a weighting between u and d types which is basically different from the one obtained in the annihilation cross-section measurement. Without going into details (see Fig. 1a), the bremsstrahlung cross-section is proportional to

$$\sum_q e_q^2 R_q = 3 \sum_q e_q^2 \left| e_q - \frac{G_F q^2 (v_e - h_e a_e) (v_q - h_q a_q)}{8\sqrt{2} \pi \alpha (q^2 - m_Z^2 + i m_Z \Gamma_Z) / m_Z^2} \right|^2.$$

The familiar coupling of a Z^0 to a quark can be recognized. Far below the Z^0 this factor reduces to $\sim \sum e_q^4$. With several kinematical cuts giving significance to the Born approximation and eliminating uninteresting configurations, the bremsstrahlung process represents about 1% of the total rate¹⁾ (Fig. 2a). It can be split according to the origin of the photon (Fig. 2b): at the Z^0 , bremsstrahlung from the quarks dominates, and there is, for instance, the interesting relationship

$$\frac{\sigma(q\bar{q}\gamma)}{\sigma(q\bar{q})} = \frac{\sum e_q^2 R_q}{\sum R_q} \frac{\sigma(\mu\mu\gamma)}{\sigma(\mu\mu)}$$

giving access to the original weighting of electroweak charges quoted above.

The background to this process is discussed in Ref. 1.

1.1.2 Smaller-angle bremsstrahlung

The smaller-angle bremsstrahlung (i.e. lower γ - q mass) brings us into the anomalous regime of the photon coupling. The hard-photon structure function²⁾ is here reflected into a hard fragmentation function of a quark into prompt gammas, for the same physical reason. We can therefore expect a spectacular rise of the relative yield of prompt γ at large fractional energies³⁾, as shown in Fig. 3. This should be measurable and complement the study of the γ structure function.

1.1.3 Charge asymmetry^{1,4)}

Figure 4 shows the origin of the asymmetry. It is due to the interference between diagrams 4a and 4b in which the hadronic final states have $C = +1$ and $C = -1$, respectively. At the quark level the asymmetry is quite large but there is no direct access to it. It is transmitted into an inclusive charge asymmetry, which can be expressed as

$$\rho = \frac{d\sigma(\gamma\pi^+) - d\sigma(\gamma\pi^-)}{d\sigma(\gamma\mu^+) - d\sigma(\gamma\mu^-)},$$

smaller but probably measurable. The asymmetry is proportional to $\sum e_q^3$ and to the difference between quark and antiquark fragmentation functions. Let us define also

$$\rho' = \frac{d\sigma(\pi^+) + d\sigma(\pi^-)}{d\sigma(\mu^+) + d\sigma(\mu^-)},$$

which gives the sum of these fragmentation functions. When the reduced momentum (p_π/p_q) goes to 1, it can easily be shown that the ratio ρ/ρ' should approach 3/5 in the case of standard fractional-charge quarks. Integer Han-Nambu quarks would give an integral ratio. However, the reader should refer to Section 3 for a "modern" version of the integer-charge assumption.

1.1.4 Bremsstrahlung in lepton-hadron deep-inelastic scattering

Figure 1b shows that for bremsstrahlung processes, e^+e^- collisions and deep-inelastic muon scattering processes are in a one-to-one correspondence. To get the interference term, we have now to change the sign of the incident lepton. This was done in the past at SLAC⁵⁾, but the result was not accurate enough to tell about quark charges.

The EMC Collaboration⁶⁾ has the prospect of extracting the interference term. The experimental problems are severe (for instance, the background of halo muons) and the result is not yet available.

1.2 Decay of orthoquarkonium

Again this is quite speculative since — a heavy mass being needed — it mostly applies to the still undiscovered toponium state.

The rate of the gamma decay of toponium $t\bar{t}$ is presumably large: $O(10-20\%)$.

Second-order processes (Fig. 5) should make it possible to see the gluon self-coupling of Fig. 5c. Figure 6⁷⁾ shows indeed that the properties of the hadronic final state (the mass of which can be tuned by selecting the gamma energy) are dominated by the gluon splitting.

As is well known, another imperative reason for looking at the toponium decays involving a gamma is the search for Higgs bosons. However, one has first to find the toponium and get reasonable statistics on it — and this is not an easy task.

1.3 The photon structure function

Here experimental information and excellent reviews are available⁸⁾.

The basic question is: When one probes a real gamma with a deeply virtual one (Fig. 7), does one find a hadron-like structure or, as expected from the parton model, something similar to the purely leptonic case⁹⁾ (Fig. 8)? The answer is clear^{8,10)}: the gamma structure function looks like the parton model expectation:

$$\frac{F_2(x, Q^2)}{x} = \frac{3\alpha}{\pi} \sum_i e_i^4 [x^2 + (1-x)^2] \ln \frac{Q^2}{m_q^2}.$$

Here QCD would rather suggest replacing m_q by Λ , and higher-order corrections are supposed to modify the low- and high- x regions. Figure 9a¹¹⁾ seems to indicate that a clear distinction between QCD and the naïve parton model is in principle possible: however, Fig. 9b shows that unfortunately, once the level of observed events is reached, the difference between the two models has shrunk to an at present unobservable value. We are still far from proving QCD with the gamma structure function measurement.

2. HARD PHOTOPRODUCTION AND PROMPT-GAMMA PHYSICS

This is a quite active sector of high-energy physics¹²⁾.

Figure 10 illustrates the similarity of the physical content in both situations. The basic processes (Fig. 10a) are the same. The background — an interesting one — has the same origin (Fig. 10b). Both have two-photon processes (Fig. 10c) and higher-twist processes (Fig. 10d) with quite noticeable topologies. Table 2 (from Ref. 12) evaluates the relative merits of these and other processes under various theoretical criteria.

However, the experimental conditions and methods are different. Figure 11 shows that several energy domains should be explored to get all types of parton scattering. Figure 12 reminds us that at SPS energies an E_T trigger is not efficient for uncovering jet structures¹³⁾, and hard scattering

should rather be selected there by triggering on individual particles. This is also true for incident gammas, although they are a potentially richer source of jets¹⁴⁾, as shown in Fig. 13.

To isolate a given hard process, for instance Compton scattering or the fusion diagram, one has to make differences between cross-sections, namely:

- for photoproduction, the difference between inclusive final-state distributions for particles of both signs should be considered¹⁵⁾ (see Fig. 14);
- for prompt-gamma physics with hadrons, the differences between cross-sections obtained with projectiles of both signs should be used (Fig. 15).

Up to now the field has been dominated by ISR prompt-gamma measurements. These are described by Figs. 16¹⁶⁾. The prompt gamma signal around 90° is clear (Fig. 16a). The prompt gamma prefers to be unaccompanied (Fig. 16b). The charge of the away system is rather positive, which seems to indicate that indeed inverse Compton scattering, predominantly involving u quarks, plays a role (Fig. 16c). The bremsstrahlung contribution seems to be weak, if not zero (Fig. 16d). Results at small angles¹⁷⁾ are quite compatible with the large-angle ones (Fig. 16e). The theoretical understanding seems to be satisfactory¹⁸⁾.

Results from fixed-target experiments¹⁹⁾ are still preliminary (Fig. 17) but many groups are currently working along these lines (Table 3). These experiments are quite difficult because the identification of a prompt gamma (among π^0/η and various halo backgrounds) is a delicate task.

In the case of photoproduction, preliminary results have come from the NA14 group at CERN²⁰⁾. This experiment at the Super Proton Synchrotron uses the most intense e^- beam available, the E12 (Fig. 18), which is a very pure, tagged beam ($\sigma_E \sim 3$ GeV). The NA14 (Fig. 19) is an open-geometry spectrometer with wide coverage (up to 135° c.m.) for charged particles and photons. The structure of the electromagnetic calorimeters is adequate enough to allow for an excellent γ - π^0 separation, and they are well protected against the background from halo muons. The π^0 's and η 's are measured in the calorimeters (Fig. 20) and their reconstruction efficiency is well understood. Inclusive π^0 distributions are shown in Fig. 21. The normalization obtained by several methods, which agree well (beam counting, Bethe-Heitler μ pairs, ψ , etc.), has an uncertainty of $\sim 20\%$. The sensitivity in Fig. 21 is above one event per picobarn. In addition to the normal hadronic contribution inferred from pion scattering²¹⁾, Fig. 21a and, to a lesser extent, Fig. 21b show that photon hard-scattering terms are needed. The total sum reproduces data quite well. A recent and preliminary computation²²⁾ indicates that higher-order terms will modify the QCD estimate: one will go to the uppermost curve in Fig. 21. The fact that in the data of Fig. 21b, around 90° c.m., the QCD terms have a smaller relative contribution than in the forward region (Fig. 21a) is in good agreement with QCD prediction.

As already quoted, the right way to isolate QCD Compton scattering is by taking the difference between π^+ and π^- inclusive distributions. This work is under way. In 1983 the NA14 experiment will complete its data-taking and increase its statistics by a large factor. We will come back to this in subsection 3.3.

3. TWO-GAMMA PROCESSES

Two-gamma processes involve the fourth power of quark charges, and in principle are quite sensitive to the numerical value of these.

It may be appropriate here to recall that models with integer charges are still frequently advocated in the literature²³⁾. They are mostly based on an $SU(3)_C \times U(1)$ symmetry, with a

spontaneous breaking of colour symmetry in the large distance (i.e. strong coupling) regime but without giving up confinement. The gluons get a non-zero Lagrangian mass. If this mass is small enough (≤ 200 MeV or so), the authors²³⁾ claim that no experiment, except two-gamma processes with real gammas, can tell the difference between this and the standard model, at least with the accuracies at present available. Indeed, the quark charge behaves as:

$$Q = Q_1^{\text{fract. charge}} + Q_8 \frac{m_g^2}{q^2 + m_g^2}.$$

At $q^2 = 0$, $Q_1 + Q_8$ reproduces the old Han-Nambu integer charge assignment. But at even moderate q^2 ($q^2 \gg m_g^2$), the octet part fades away and the fractional charge results are recovered. Furthermore, any single-photon process—since, apart from the “tinted” gamma, only colour singlets are involved—will always project the photon onto its singlet component. Quasi-reality ($q^2 \lesssim m_g^2$) and the presence of more than one gamma are therefore needed in order to feel the octet part of the charge. Discussions on controversial points can be found elsewhere^{24,25)}. Let us now turn to experiments.

3.1 $pp \rightarrow \gamma\gamma X$

This process has been measured at the ISR in experiment R806²⁶⁾. Its very small cross-section and the value of the ratio $\gamma\gamma/\pi^0\pi^0 \approx 10^{-3}$ indicate how difficult this is. The $\gamma\gamma$ cross-section is expected to be about equal to e^+e^- pair production by the Drell-Yan process, and the ratio of both cross-sections is a meaningful quantity to consider. Figure 22 shows the ability for neutral identification of the calorimeter: at high p_T (i.e. high p), merging neutral pions can simulate gammas. Figure 23 shows that if one compares the measured points with the Monte Carlo expectation in the absence of a $\gamma\gamma$ source, such a contribution is present. The error on the final result

$$\gamma\gamma/e^+e^- = 1.7 \pm 1.0$$

reflects the statistical and systematic limitations of the measurement.

3.2 $\gamma\gamma \rightarrow \text{jet-jet}$

Figure 24 summarizes the available data in this field of two-gamma physics²⁷⁾.

In particular, it can be seen that “no tag” results are now available²⁸⁾.

When comparing these with various expectations, it should be remembered that

- isolating such a final state is not an easy experimental task, and therefore systematic errors could be difficult to avoid;
- in the colour-breaking model the q^2 domain of the exploration matters a lot. Jarayaman et al.²⁹⁾ have analysed this problem and give the value of the increase of the two-jet cross-section to be expected in such a theory (Table 4).

Clearly, the experimental results tend to be above the simple standard QCD predictions. However, at this stage, both the experimental and the theoretical uncertainties, such as the contribution of non-leading terms and of different mechanisms in the standard model, preclude the drawing of conclusions and make premature the reference to non-standard quark charges. It is nevertheless a crucial point to follow up.

3.3 QED Compton scattering

This process, which has long been advocated as a basic test, has been measured by the NA14 group. However, data are still preliminary³⁰⁾.

The prompt-gamma spectrum in gamma hadronic final states, identified as such by the spectrometer, is shown in Fig. 25. The band represents the estimated contamination of π^0 's and other neutral mesons. Since π^0 's have been measured in the same exposure (Fig. 21), this contamination estimate is normalization-independent. The band width includes systematic uncertainties in the acceptance and identification, as well as statistical effects. Both the slope and the absolute level indicate that a prompt-gamma signal, increasing in relative value with p_T , is present. Adding the QED standard term, with higher-order corrections³¹⁾ and the box diagram (Fig. 10c) contribution, roughly reproduces the data. They have some tendency to lie above the expected curve, both at small and intermediate p_T . Subsequent measurements and a complete study of the exclusive features of the events will strengthen the reliability of the data and tell us whether this effect is confirmed.

4. HEAVY-FLAVOUR PHOTOPRODUCTION

At least one thing is known: more charm seems to be produced, in relative value, by photons than by hadrons. Heavy-flavour photoproduction is interesting in two respects:

- i) for understanding the production mechanism;
- ii) for providing spectroscopic information on the heavy-flavoured states.

I will be very brief, since these points have been discussed in great detail at the recent Fixed-Target Workshop at CERN¹²⁾.

4.1 Production mechanism

Photon-gluon fusion is claimed to provide a relevant description of hidden and open charm photoproduction. Many reviews on the subject are available³²⁾. An interesting remark³³⁾ is that if indeed the ψ excitation curve, for instance, measures the gluon distribution, it would be interesting, in the same experiment, to photoproduce ψ 's on various materials to see whether differences due to the EMC effect are observed.

4.2 Information on heavy-flavoured states

This is relevant for the measurement of lifetimes and for pure spectroscopic information.

Clearly the e^+e^- rings, on the "charm factory", will be much better for D's than will any other set-up. But for F's and charmed baryons the combination of an active target and a powerful spectrometer can bring us much information. Table 5, taken from a CERN proposal³⁴⁾, gives an idea of what can be achieved in a photoproduction experiment using the E12 beam. Compared to a hadronic exposure, the gain is obviously related to the better signal/background, which itself reflects the higher relative yield of charmed events.

With such an intense beam, which is necessary to reach the sensitivity quoted, the only viable solution for an active target is the use of silicon devices. The proposal of Ref. 34, following the pioneering work of other groups^{*)}, suggests the arrangement shown in Fig. 26, which is under test.

*) Especially the NA1 and NA11 groups.

The recent claim that beauty has a long lifetime ($\sim 10^{-12}$ s) makes us very hopeful of detecting it in such experiments. The present upper limits on its production cross-section are given in Fig. 27³²⁾. If the photoproduction cross-section is not too far below the quoted number — an occurrence which can be reasonably expected — an exposure of 1 event per picobarn could provide enough events for beauty identification and study.

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Table 1

Large- p_T processes with photons in the initial or in the final state (Ref. 1)

a) $e^+e^- \rightarrow \gamma X$	$e^+e^- \rightarrow q\bar{q}$ $\rightarrow \gamma$ brems.	
b) $(Q\bar{Q}) \rightarrow \gamma X$	$(Q\bar{Q}) \rightarrow \gamma GG$ $\rightarrow \gamma GGG$	
c) $\gamma N \rightarrow \text{large-}p_T \text{ jet} + X$	$\gamma q \rightarrow Gq$ $\gamma G \rightarrow q\bar{q}$	QCD Compton fusion $\downarrow$
d) Direct γ in hadron coll. $AB \rightarrow \gamma X$	$Gq \rightarrow \gamma q$ $q\bar{q} \rightarrow \gamma G$	inverse
e) Deep inelastic Compton $\gamma N \rightarrow \gamma X$	$\gamma q \rightarrow \gamma q$ $\gamma G \rightarrow \gamma G$	QED Compton via box
f) Large- p_T hadrons in $\gamma\gamma$ $\gamma\gamma \rightarrow \text{large-}p_T \text{ jets}$	$\gamma\gamma \rightarrow q\bar{q}$ $\gamma\gamma \rightarrow GG$	via box
g) Two high- $p_T \gamma$ in hadron coll. $AB \rightarrow \gamma\gamma X$	$q\bar{q} \rightarrow \gamma\gamma$ $GG \rightarrow \gamma\gamma$	

Table 2

Theoretical merits of different processes (from R. Petronzio, Ref. 12).
The stars have the usual Michelin meaning, $(*)^{-1}$ is a new concept.

	Subprocesses	K factors	Intrinsic p_T
DY	***	***	/
DY _{p_T}	**	***	***
Direct γ	**	** (?)	**
Photoproduction	**	/	***
Deep Compton	***	**	***
hh $\rightarrow$ jet/ π^0	*	/	$(*)^{-1}$

Table 3

List of approved prompt-photon experiments at the CERN SPS and at Fermilab
(from F. Costantini and K.P. Pretzl)

Expt.	Start of data-taking	Beam	Energy (GeV)	Physics goals stated in Proposal	Photon calorimeter	Photon calorimeter resolution $\sigma(E)/E$	Two-shower separation Δx (mm)	Hadron measurement	Sensitivity (events per nb per day)
SPS									
NA3	82	$\pi^{\pm}, p$	200	$hh \rightarrow \gamma X, hh \rightarrow \gamma\gamma X$, q and g fragmentation, g structure function.	Scintillator/lead + shower chamber	$< 0.21/\sqrt{E}$	< 50	Magnet spectrometer, Cherenkov.	600
NA24	83	$\pi^{\pm}, p$	200 300	"	Proportional tube/ lead + scintillator/ lead	$< 0.24/\sqrt{E}$	15	Segmented hadron calorimeter.	800
WA70	83	$\pi^{\pm}, p$	200 300	"	Liquid scintillator/ lead	$0.16/\sqrt{E}$	15	Ω' spectro- meter, RICH counter.	800
UA6	84	$\bar{p}, p$	270	$hh \rightarrow \gamma X, \pi^0 X$, Drell-Yan e^+e^- pairs, and Λ and $\bar{\Lambda}$ production.	Proportional tube/ lead	?	$\gtrsim 15$	Magnet spectrometer, dE/dx , transition radiation.	40 ($\bar{p}p$) (if they are main user) and 300 (pp)
FNAL									
E705	84	$p, \bar{p}, \pi^{\pm}$	300	Charmonium $hh \rightarrow \chi X$, $hh \rightarrow \gamma X, hh \rightarrow \gamma\gamma X$.	Scintillating lead- glass	?	50	Magnet spectrometer Cherenkov.	~ 120
E706	85	$\pi^{\pm}, p$	400 530 800	$hh \rightarrow \gamma X, hh \rightarrow \gamma\gamma X$, Drell-Yan e^+e^- pairs, $hh \rightarrow \pi^0 \gamma \eta^0 \gamma$, $\pi^0 \eta^0 + X$.	Liquid argon	$0.14/\sqrt{E}$	?	Magnet spectrometer, calorimeter, RICH counter, silicon micro-strips.	$\sim 10^3$

Table 4

Predictions for $R_{\gamma\gamma}$ in the various cases considered in the text (Ref. 29)

Model	$R_{\gamma\gamma}$
FCQ	1.26
ICQ ($m_g = 0.2 \text{ GeV}$) ^{a)}	1.82
ICQ ($m_g = 0.1 \text{ GeV}$) ^{a)}	1.45
ICQ ($m_g = 0.05 \text{ GeV}$) ^{a)}	1.34
ICQ ($m_g = 0$) ^{a)}	1.31
ICQ with Higgs ($m_g = m_H = 0$) ^{a)}	1.51
ICQ ($m_g = 0$) above threshold	2.19

a) Below colour threshold.

Table 5

Number of useful decays for lifetime measurement (S/B means signal/background).
20 M events registered with minimum bias trigger sensitivity $\sim 1 \text{ evt/pb}$.

	0.26 $F/\bar{F}$ per charmed event $F \rightarrow K^+ K^- \pi$	0.2 $\Lambda_c/\bar{\Lambda}_c$ per charmed event $\Lambda_c \rightarrow p K^\pm \pi^\mp$
BR?	5%	5%
for spectroscopy	260	130
S/B	0.25	0.3
for τ measurement	124	62
S/B	1.2	1.6
+ visible jump in active target	50	25

Figure captions

- Fig. 1 : Gamma wide-angle bremsstrahlung: a) in e^+e^- collision; b) in lepton-hadron deep-inelastic scattering.
- Fig. 2a : Cross-section for gamma production in e^+e^- collisions (from Ref. 1): thrust ≤ 0.975 ; $z \leq x_q$ or $x_{\bar{q}}$; $45^\circ \leq \theta \leq 135^\circ$. See Fig. 1 for notation (drawn from Ref. 1).
- Fig. 2b : Decomposition of the cross-section with respect to the γ sources (from Ref. 1).
- Fig. 3 : γ/π^0 ratio in e^+e^- annihilation (from Ref. 3).
- Fig. 4 : The sources of prompt gammas.
- Fig. 5 : Gamma decays of orthoquarkonium (Ref. 7).
- Fig. 6 : Thrust distribution of the final hadronic state in gamma decay of orthoquarkonium (Ref. 7).
- Fig. 7 : Kinematics of $\gamma\gamma$ scattering.
- Fig. 8 : $\gamma\gamma \rightarrow \mu^+\mu^-$.
- Fig. 9 : The photon structure function: prediction of various models: a) the structure function itself; b) the number of observable events.
- Fig. 10 : The physics of hard photoproduction and prompt-gamma hadroproduction.
- Fig. 11 : The fraction of various parton-parton subprocesses predicted from a QCD model as a function of $x_T = 2p_T/\sqrt{s}$. The kinematic ranges covered by experiments studying jet physics at the SPS, ISR, and $p\bar{p}$ Collider are shown.
- Fig. 12 : Comparison of the predictions of a QCD parton-shower Monte Carlo model with data from NA5 for both small- and large-aperture calorimeter triggers. The solid and dashed curves are the predictions at the hadron and parton level, respectively.
- Fig. 13a : Cross-sections predicted by a QCD-model calculation for the reaction $\gamma p \rightarrow \text{jet} + X$ at $\sqrt{s} = 19.4$ GeV.
- Fig. 13b : Cross-sections predicted by a QCD-model calculation for $\gamma p \rightarrow \text{jet} + X$ compared with $pp \rightarrow \text{jet} + X$.
- Fig. 14 : QCD-model calculations of the inclusive π^+ cross-section and the difference of the inclusive cross-sections $\pi^+ - \pi^-$ for the reaction $\gamma p \rightarrow \pi^+ X$ and $\gamma p \rightarrow \pi^- X$ are shown. The contribution of the point-like behaviour of the photon (Born term) is shown as a solid line, the anomalous in dashed-dotted, the hadronic or VDM in small-dashed, and higher twist in big-dashed lines.
- Fig. 15 : How to isolate a given process by subtraction.
- Fig. 16a : Left: Experiment R806. Observed ratio γ/π^0 as a function of p_T . Right: Experiment R108. Ratio γ/all as a function of p_T .
- Fig. 16b : Experiment R108. Ratio γ/all for events with particles accompanying (left) and not accompanying (right) the photon in its hemisphere.
- Fig. 16c : Experiment R807. Ratio R of positive to negative particles in the hemisphere opposite to the trigger and for two p_T intervals as a function of x_T . Solid lines are QCD predictions of R .
- Fig. 16d : Experiment R807. Fraction of bremsstrahlung events as a function of the p_T of the direct γ . The calculation is made by assuming two kinds of level for the unassociated background: the minimum-bias events or the level at 70° in $\Delta\phi$ from the trigger. The solid lines are QCD predictions for this ratio.

- Fig. 16e : The γ/π^0 ratio at the ISR in the forward region.
- Fig. 16f : Detail of the background contributions to the observed γ/π^0 ratio. The curves represent: a) background from π^0 ; b) from η ; c) from η' ; d) from ω ; e) from merging π^0 ; f) sum of (a) to (e), where the bound gives the statistical and systematic errors on the calculation.
- Fig. 17a : FNAL data on $pp \rightarrow \gamma + X$ (from Ref. 19a).
- Fig. 17b : FNAL data on $pC \rightarrow \gamma + X$ and $\pi^+C \rightarrow \gamma + X$ at 200 GeV/c (from Ref. 19b).
- Fig. 17c : FNAL data on the ratio γ/π^0 (from Ref. 19c).
- Fig. 18 : The E12 beam layout.
- Fig. 19 : The NA14 spectrometer.
- Fig. 20 : $\gamma\gamma$ invariant masses in the NA14 calorimetry.
- Fig. 21 : π^0 inclusive spectra in NA14: a) forward calorimeter (Olga); b) 90° c.m. calorimeter (IC).
- Fig. 22 : Neutral identification in the ISR calorimeter. Monte Carlo calculated probability (including detection and reconstruction efficiency) for a) a π^0 , with both decay photons incident on a calorimeter, to be accepted as a single shower (open circles) or a π^0 (solid dots); b) a single photon to be identified as a single shower.
- Fig. 23 : Evidence for a $\gamma\gamma$ source: the observed and the Monte Carlo calculated R_s/R_π ratio for three different p_T thresholds.
- Fig. 24 : $\gamma\gamma \rightarrow \text{jet} + X$ in various set-ups: a) TASSO, b) JADE, c) PLUTO.
- Fig. 25 : Single-gamma inclusive spectra in NA14: a) forward calorimeter (Olga); b) 90° c.m. calorimeter (IC).
- Fig. 26 : The target arrangement in the NA14 proposal.
- Fig. 27 : Cross-section of $B\bar{B}$ pair photoproduction versus ν . Also shown are the data of the EMC for $C\bar{C}$ pairs. The curves represent the prediction of the γ -g fusion model (leading order, $m_c = 1.5$ and $m_b = 5$ GeV).

Fig. 1a

Fig. 1b

Fig. 2a

Fig. 2b

Fig. 3

Fig. 4a

Fig. 4b

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9a

Fig. 9b

Fig. 10

Fig. 11

Fig. 12

Fig. 13a

Fig. 13b

Fig. 14

Fig. 15

Fig. 16a

Fig. 16b

Fig. 16c

Fig. 16d

Fig. 16e

Fig. 16f

Fig. 17a

Fig. 17b

Fig. 17c

H: Scintillator Hodoscopes
 V: MUON VETO HODOSCOPES
 M: MULTIWIRED PROPORTIONAL CHAMBERS
 BC, IC, FC : EM. CALORIMETERS

Fig. 19

Fig. 20

Fig. 21b

Fig. 21a

Fig. 22

Fig. 23

Fig. 24a

Fig. 24b

Fig. 24c

Fig. 25a

Fig. 25b

Fig. 26

Fig. 27