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UPDATE ON PHOTON-PHOTON COLLISIONS

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Abstract

This Report is the continuation of the "Update" of last year ([illegible] 79-3, March 1979, in French).

In Part I, the structure functions of the photon in QCD are examined. It is shown that, while large p_T hadron production is similar to some extent in $\gamma\gamma$ collisions and in hadron-hadron collisions, the point-like nature of the photon introduces new terms which are entirely calculable, providing new means to test the dynamics of strong interactions.

In Part II, problems of analysis in $\gamma\gamma$ experiments are discussed. [illegible] and cons of various options with regard to the [illegible] electrons (non-tagging, finite-angle tagging, [illegible]). It is shown that (i) non-tagging may be [illegible] of processes only; (ii) finite-angle tagging counters allow for various possibilities (double-tagging, single-tagging, double anti-[illegible]), [illegible] them is entirely satisfactory; (iii) [illegible] tagging at 0°, [illegible] the tagging counters can be solved.

Résumé

Le présent rapport est la suite de la "[illegible]" [illegible] ([illegible], en Français).

Dans la partie I, les auteurs examinent les fonctions [illegible] ton en chromodynamique quantique. Ils montrent que [illegible] hadron [illegible] similaire dans les collisions $\gamma\gamma$ [illegible] hadron-hadron, mais que la nature ponctuelle du photon entraîne [illegible] tion de nouveaux termes, entièrement calculables, qui [illegible] possibilités de vérification de la dynamique [illegible].

Dans la partie II, les auteurs étudient les problèmes [illegible] expériences $\gamma\gamma$. Ils comparent les avantages et les [illegible] options concernant la [illegible] des électrons [illegible] ([illegible], étiquetage à angle, étiquetage à 0°). Ils montrent que (i) [illegible] solution sans étiquetage ne peut être appliquée qu'à un nombre limité de processus; (ii) il existe diverses applications des compteurs d'étiquetage à angle (double étiquetage, simple étiquetage, double "anti-étiquetage"), mais aucune n'est entièrement satisfaisante; (iii) l'expérience idéale est celle fondée sur le double étiquetage à 0°, pour autant que le [illegible] de saturation des compteurs d'électrons par le rayonnement de freinage puisse être résolu.

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THE STRUCTURE FUNCTIONS OF THE PHOTON IN Q.C.D.

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THE STRUCTURE FUNCTIONS OF THE PHOTON IN Q.C.D.

It has been suggested(1), quite a time ago, to study the structure functions of the photon in the e^+e^- colliding beams, by looking at the $e^+e^- \longrightarrow e^+e^-$ hadrons reaction, where one of the exchanged photons is highly virtual (q_1^2 large), while the other one is quasireal ($q_2^2 \simeq 0$). The dominant graph in this case, is the box diagram, shown in figure 1a. From this graph we can extract the free parton model quark distribution whithin a photon:

$$q_B^\gamma(x,Q^2) = 3\frac{\alpha}{2\pi} e_q^2 \left[x^2+(1-x)^2\right] \log\frac{Q^2}{\Lambda^2} \qquad (1)$$

Since we have a serious candidate theory for strong interactions, namely Quantum Chromodynamics (Q.C.D.), it is interesting to examine how strong interactions renormalize the free parton model result (fig. 1b). This question was first treated by Witten(2), in terms of the operator product expansion. His crucial remark is that in addition to the operators encountered when we are dealing with a hadron target, we have also a photon operator. This new operator, whose matrix element is known, differentiates in a striking manner the photon structure functions from the hadronic structure functions (see below). Identical results are obtained also within the diagrammatic approach(3). We will follow here a generalization of Altarelli-Parisi(AP) equations(6).

Similarly to the hadronic case, the quark (gluon) distribution within a photon q^γ (g^γ) is given by an AP-type equation :

$$\frac{dq_i^\gamma(x,t)}{dt} = \frac{1}{2\pi}\Big[\alpha_s(t) q_i^\gamma(x,t) \otimes P_{qq}(x) + \alpha_s(t) g^\gamma(x,t) \otimes P_{qg}(x) + \alpha e_i^2 \, \gamma^\gamma(x,t) \otimes P_{q\gamma}(x)\Big] \qquad (2)$$

$$\frac{dg^\gamma(x,t)}{dt} = \frac{1}{2\pi}\Big[\alpha_s(t) \sum_{i=1}^{2f} q_i^\gamma(x,t) \otimes P_{gq}(x) + \alpha_s(t) g^\gamma(x,t) \otimes P_{gg}(x)\Big] \qquad (3)$$

The symbol A $\otimes$ B stands for the convolution

$$A(x)\otimes B(x)=\int_x^1 \frac{dy}{y}\, A(y)\, B(x/y) \tag{4}$$

and $t = \log Q^2/\Lambda^2$

The new element is the appearance of the transition $\gamma \to q$ in equ. 2. Given the smalness of α, we solve the above equations to lowest order in α but to all orders in α_s. In this case

$$\gamma^{\gamma}(x,t)=\delta(x-1) \tag{5}$$

$$P_{q\gamma}(x) = 3\,[x^2+(1-x)^2] \tag{6}$$

Taking the moments we find :

$$\frac{dq_i^{\gamma}(n,t)}{dt}=\frac{\alpha}{2\pi}e_i^2 P_{q\gamma}(n)+\frac{\alpha_s(t)}{2\pi}\left[q_i^{\gamma}(n,t)P_{qq}(n)+g^{\gamma}(n,t)P_{qg}(n)\right] \tag{7}$$

$$\frac{dg^{\gamma}(n,t)}{dt}=\frac{\alpha_s(t)}{2\pi}\left[\sum_{i=1}^{2f} q_i^{\gamma}(n,t)P_{gq}(n)+g^{\gamma}(n,t)P_{gg}(n)\right] \tag{8}$$

After diagonalization, we get a set of algebraic equations and the final solution for $q_i^{\gamma}(n,t)$, $g^{\gamma}(n,t)$ is given by :

$$q_i^{\gamma}(n,t)=\frac{\alpha}{2\pi}e_i^2 P_{q\gamma}(n)\,t\left[\frac{1-\langle e^2\rangle/e_i^2}{1+d_{qq}(n)}+\frac{\langle e^2\rangle}{e_i^2}\frac{1+d_{gg}(n)}{(1+d^{+}(n))(1+d^{-}(n))}\right] \tag{9}$$

$$g^{\gamma}(n,t)=\frac{\alpha}{2\pi}\langle e^2\rangle P_{q\gamma}(n)\,t\,(2f)\,(-d_{gq}(n))\Big/(1+d^{+}(n))(1+d^{-}(n)) \tag{10}$$

Similar AP-type equations hold for the fragmentation functions of a quark (gluon) into a photon $\gamma^{q}(x,t)$ $(\gamma^{g}(x,t))$. After taking the moments, these equations become :

$$\gamma^{q_i}(n,t)=\frac{\alpha}{2\pi}e_i^2 P_{\gamma q}(n)t\left[\frac{1-\langle e^2\rangle/e_i^2}{1+d_{qq}(n)}+\frac{\langle e^2\rangle}{e_i^2}\frac{1+d_{gg}(n)}{(1+d^+(n))(1+d^-(n))}\right] \quad (11)$$

$$\gamma^{g}(n,t)=\frac{\alpha}{2\pi}\langle e^2\rangle P_{\gamma q}(n)t\ \frac{(-d_{qg}(n))}{(1+d^+(n))(1+d^-(n))} \quad (12)$$

The different $d(n)$ appearing in the above equations, are the usual anomalous dimensions which can be found in the literature[3,4]. Comparing the distributions q^{γ}, γ^{q} (equs. 9, 11) with the corresponding Born terms (e.g. equ. 1) we remark that the Q^2 dependence is unmodified, while the x dependence is modified by the presence of the terms in the square brackets. Also due to the transition $\gamma\to q\to g$ $(g\to q\to\gamma)$ a non-zero g^{γ} (γ^{g}) distribution has been developed. Unlike the hadronic structure functions, the structure functions of the photon, since the photon is a weakly interacting particle, are entirely calculable. It is instructive to determine the exact behaviour of the structure functions at the end points $x = 0,1$.

Defining :

$$q^{\gamma}(x,t)=\frac{\alpha}{\pi}t\,\phi_{q/\gamma}(x) \quad (13)$$

it is easy to find[4]

$$\phi_{q/\gamma}(x)\simeq\frac{3}{2}\frac{1}{1-B+A\log[1/(1-x)]} \qquad x\to 1 \quad (14)$$

$$\phi_{q/\gamma}(x)\simeq C\,x^{-1.6} \qquad x\to 0 \quad (15)$$

where A, B, C are constants.

Compared to the distributions of quarks in hadrons, which are falling as $(1-x)^n$ $(n \simeq 1-3)$ as $x \to 1$, we observe that the quark distribution in a photon is much flatter in x. This is a consequence of the pointlike quark-photon coupling. The rapid rise at small x on the other hand results from the singular at small x g $\longrightarrow$ g transition. After factoring out the singular behavior at the end points, the structure functions admit a simple parametrization with few polynomial terms[(4)].

The above considerations can be carried over to other colorless particles (say Higgs boson). One has simply to replace the Born term and in the place of the electric charges to put the appropriate coupling constants[(5)].

It is clear that we can view the photon as a source of quarks and gluons. Then for the high-p_T hadron production in $\gamma\gamma$ collisions, we can use the hard-scattering formalism employed to study the high-p_T hadron-hadron cross-section :

$$E\frac{d\sigma}{d^3p}(\gamma\gamma \to jet+X) = \sum_{ab}\int_0^1 dx_a \int_0^1 dx_b\, G_{a/\gamma}(x_a, Q^2)\, G_{b/\gamma}(x_b, Q^2) \times \frac{d\sigma}{d\hat{t}}(ab \to jet+X)\,\frac{\hat{s}}{\pi}\,\delta(\hat{s}+\hat{t}+\hat{u}) \qquad (16)$$

$G_{a/\gamma}$ is the probability to find within the photon constituent a. According to which are the constituents a, b taking part in the hard scattering, we have the following three cases :

i) Both a and b are photons. In that case $G_{\gamma/\gamma}(x) = \delta(x-1)$ and the hard subprocess, at the Born level, is $\gamma\gamma \to q\bar{q}$, giving rise to two large-p_T hadronic jets. No hadronic debris is left along the beam pipes.

ii) One of the constituent is still a photon, while the other is a quark (gluon) emanating from the opposite side photon with a distribution determined through equ. 9 (10). Subprocesses, such as $\gamma q \to g q$ lead to 3 jets structure, 2 jets at large p_T and one jet down the beam direction.

iii) Constituents a and b are quarks or gluons. The structure of these events are very similar to that for hadron-hadron collisions, with a 4-jets signature, two of them at large p_T, the other two along the beam pipes.

In each case we have a distinctive topological jet structure and it will be feasible to separate them with properly designed detectors. Notice also that for each α_s in the subprocess cross-section, there is a logarithm in the fragmentation function and therefore at high energies, all the above jet cross-sections will scale[7] like p_T^{-4}.

Since the quark spectrum in a photon is much harder than the one in a hadron, it will be relatively easier to produce a large p_T jet in $\gamma\gamma$ collisions rather than in hadronic collisions (of course the small value of α operates in the opposite direction). Actual calculations[8] indicate that the jet production with $p_T > 3$ GeV at $\sqrt{s} = 30$ GeV is about 0,05 nb.

Experiments with two high-p_T jets in opposite sides will provide additional information not obtainable with a single jet trigger mode of operation. By varying the jet rapidities we can probe the constituent distribution of the incoming particles. Also in some favorable configurations we can isolate gluonic jets. Quantum numbers correlation will be revealing. It is clear that the subprocess $\gamma\gamma \to q\bar{q}$ will give predominantly opposite-charged pair of hadrons. Therefore the ratio $\pi^+\pi^-/\pi^+\pi^+$ will be a measure of the relative importance of two-jet subprocess, compared to 3-jet, 4-jet and vector-meson dominated collisions.

The most direct way to probe the structure functions of the photon is the deep-inelastic configuration. The electron is tagged now at a large angle and a hadronic jet is observed in the opposite hemisphere. The magnitude of the jet-cross-section is not much less than that coming from the $\gamma\gamma \to q\bar{q}$ subprocess[9].

We can extract more informations about the Q.C.D. jets by studying multiparticle spectra. The distribution, for example, of a quark and a photon within a quark, with momenta fractions x_1, x_2 respectively at scale Q^2, will be given, in the valence approximation, by :

$$f_{q\gamma/q}(x_1,x_2,Q^2) = \int_{\mu^2}^{Q^2} \frac{d\rho^2}{\rho^2} \int dx\,dz\,dw\, f_{q/q}(x,\rho^2,Q^2)\, \hat{P}_{q\gamma/q}(z)\, f_{q/q}(w,\mu^2,\rho^2) \times \delta(x_1 - wzx)\,\delta(x_2 - x(1-z)) \tag{17}$$

Taking double moments we find[10]

$$f_{q\gamma/q}(n_1,n_2,Q^2) = \frac{\alpha}{2\pi} e_q^2 \log\frac{Q^2}{\Lambda^2}\left(B(n_1,n_2-1) + B(n_1+2,n_2-1)\right) \times\left[\frac{1}{1+d(n_1+n_2-1)-d(n_1)}\left\{\left(\frac{\alpha_s(Q^2)}{\alpha_s(\mu^2)}\right)^{d(n_1)} - \left(\frac{\alpha_s(Q^2)}{\alpha_s(\mu^2)}\right)^{1+d(n_1+n_2-1)}\right\}\right] \tag{18}$$

The term in the square brackets represents the Q.C.D. correction to the Born term. For consistency check we can observe the following : integrating $f_{q\gamma/q}(x_1,x_2,Q^2)$ over x_1, we should find the photon distribution within a quark. Indeed, by putting $n_1 = 1$ in equ. 18, we recover, ignoring subleading logarithms, the valence piece of Equ. 11. Similarly we can find the antiquark-quark distribution within a photon [11,12] (in the valence approximation always) :

$$f_{\bar{q}q/\gamma}(n_1,n_2,Q^2) = \frac{\alpha}{2\pi} 3 e_q^2 \log Q^2 \left(B(n_1+2,n_2) + B(n_1,n_2+2)\right) \times\left[\frac{1}{1+d(n_2)-d(n_1)}\left\{\left(\frac{\alpha_s(Q^2)}{\alpha_s(\mu^2)}\right)^{d(n_1)} - \left(\frac{\alpha_s(Q^2)}{\alpha_s(\mu^2)}\right)^{1+d(n_2)}\right\}\right] \tag{19}$$

We can calculate also the spin-polarized structure functions of the photon, within the leading log approximation. We have to replace the spin-averaged functions $P_{i\gamma}(x)$ by the corresponding $P_{i^{\pm}\gamma^{\pm}}(x)$, where the helicities are fixed. A calculation along these lines would be in agreement with the one obtained by the operator formalism(13).

Clearly the leading log calculations are valid at asymptotic energies. At moderate energies, non-leading terms might constitute sizeable corrections. Such corrections, have been evaluated(14) for space-like momenta using the operator product expansion. For the time-like region, since no Wilson expansion is available, one has to resort to the cut-vertex formalism(15).

As we have pointed out already, the structure functions of the photon are entirely calculable. However if we want to calculate hadron production in $\gamma\gamma$ collisions, we have to use the fragmentation functions into hadrons, which are not entirely calculable and they are extracted from other experiments. We can bypass this problem by measuring jet cross-sections. We can define for example a cross-section for producing two opposite-side jets in $\gamma\gamma$ collisions(16) (*à la Sterman-Weinberg*). Such jet cross-section, have been shown(17) to be finite to all orders in α_s .

Apart from tests of perturbative Q.C.D., $\gamma\gamma$ collisions can be a good testing ground for non-perturbative aspects of strong interactions. A study of the p_T-dependence of single inclusive reactions (namely the values of the exponent n in $E\frac{d\sigma}{d^3p} = p_T^{-n} f(x_T)$), or of the interplay between VMD and parton model will provide valuable informations about the confinement physics. We have assumed throughout that it is feasible to have beams of quasi-real photons. Some experimental difficulties in achieving this are discussed in the second part of this report and possible ways to overcome these difficulties are also suggested. Altogether we think that $\gamma\gamma$ collisions due to the dual nature of the photon as a pointlike particle and as a superposition of vector mesons, appear as a very effective tool to further unravel the dynamics of strong interactions at short and long distances.

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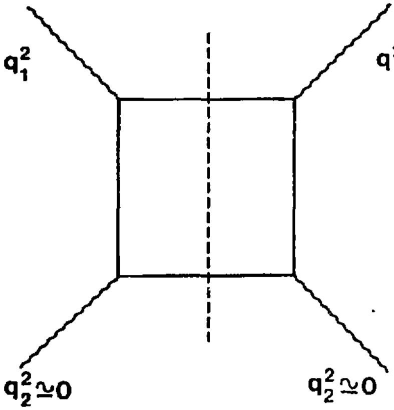

Fig. 1a

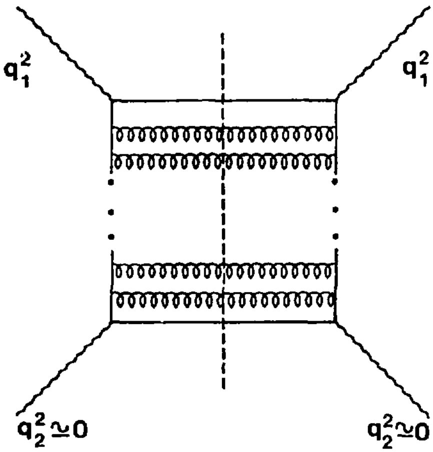

Fig. 1b

NEW UPDATE ON PHOTON-PHOTON COLLISIONS

PART II. PROBLEMS OF ANALYSIS

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Contents

1. Introduction

While a number of exciting QCD applications are proposed nowadays by theorists (see part I of this report), and while a few quite interesting $\gamma\gamma$ experiments were performed last year (involving, for the first time, non-negligible counting rates for hadronic states produced) [1,2], it is obvious to everybody that there is still a wide gap left between theory and experiment, dream and reality, brilliant speculations in some preprints and hard facts in the laboratory.

Of course such a gap may be found, more or less, in any field of physics, but it must be emphasized that photon-photon collisions have their specific complexity. Basically, as we feel it, this complexity is due to the fact that the colliding particles (the off-shell photons) cannot be directly measured; among any other collision processes of known particles, only neutrino-neutrino collisions (if they were investigable) would be comparable in this respect.

Therefore, at the border between theory and experiment, problems of analysis - i. e., extraction of the physically interesting information from measurements - are a field of research by itself. It must be said that, to some extent, these problems were already considered in the past, in particular in the extensive report by Budnev et al. [3], and also in some more recent studies for specific machines [4]. However, they are so complex, and they evolve so quickly at present, that the authors feel it might be useful to consider them again, in the context of experiments to be performed with existing or future high-energy electron-positron storage rings, i. e. PETRA and PEP as well as LEP.

Part of the discussion here presented can be found in various papers recently written by some of the authors [5,6]. This report is a kind of synthesis of these papers and includes some additional considerations.

2. To tag or not to tag?

From the very beginning, those of the authors who were involved in studying photon-photon collision processes (fig. II.1) considered as self-evident that in practical measurements both outgoing electrons should be tagged at 0° (i. e., inside a cone of very small opening angle: a few milliradians or at most a few degrees) [7]. Other authors were more flexible [8];

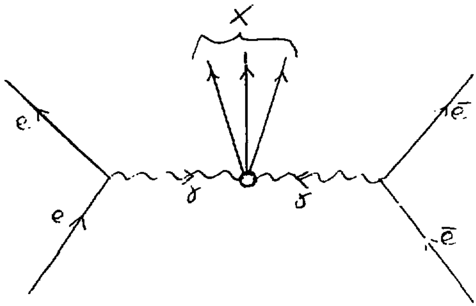

Fig. II.1

they did not consider electron tagging as absolutely unavoidable. Indeed, recent experiments [1,9] have shown that, in some cases at least, measurements may be performed and correctly analyzed without any tagging. It should also be emphasized that, in addition to making experiments easier and less costly, non-tagging measurements have two important advantages: They allow for maximal counting rates and they may be analyzed, roughly, with the double equivalent-photon approximation [illegible].

Therefore, it is a crucial question: How far is tagging really necessary? To answer that question, two criteria should be considered: a. background rejection; b. reconstitution of events.

a. <u>Background rejection</u>

Various sources of background are to be considered.

(i) <u>Theoretical background</u>. The main source of theoretical background is the heavy-photon bremsstrahlung diagram of fig. II.2 (plus the symmetric one). Actually, this background was the main concern of some of the authors when they started their work many years ago [7]; they then showed that it may be practically reduced to nothing by tagging the electrons at 0°. However, it soon appeared that, even without any tagging, such a background generally remains small (typically of the order of a few percent) [3]. By the way, it tends to become smaller when the beam energy is increased.

(ii) <u>Beam-gas reactions</u> +). In principe, it is possible to get rid of this background by using the vertex distribution of events along the beam axis; other criteria (such as coplanarity in the case of 2-body production, or $\Sigma p_{\perp} \simeq 0$) may also be used [1,9]. One may also get an estimation of this background, to be subtracted, by letting the machine run with only one beam.

+) and possibly other garbage from the machine

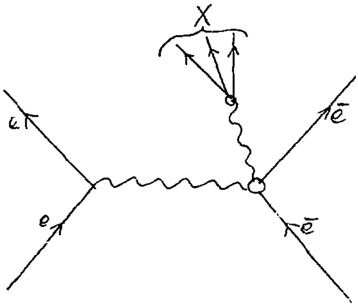

Fig II. 2

(iii) <u>$e^+ e^-$ annihilation with degraded visible energy</u>. A risk of contamination proceeds from those $e^+ e^-$ annihilation events where a large part of the total energy (or invariant mass) is "lost" by leaving some of the final particles undetected; either because they are undetectable, as neutrinos are, or because of the restricted acceptance and efficiency of the detecting device. In particular, hard photons emitted by the electrons roughly in their own direction may escape detection. Even more than the single-bremsstrahlung diagram of fig. II.3(a) (which, in case of hard-photon emission, is characterized by a rather asymmetric final-particle distribution), it is the double-bremsstrahlung process (fig. II.3 (b)) that may become a dangerous background; indeed, kinematically, it "simulates" the $\gamma\gamma$ process rather well.

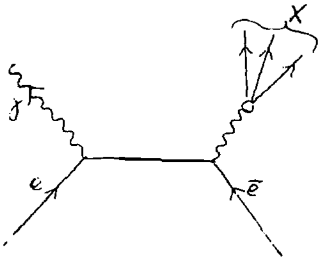

Fig. II. 3 (a)

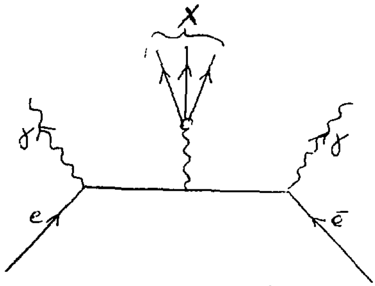

Fig. II. 3 (b)

However, from fig. II.4 (11), it appears that photon-photon collisions on one hand, $e^+ e^-$ on the other hand, have their ranges well separated in total visible energy (the distribution in total visible invariant mass would probably be very similar); actually, there seems to be a gap between those two ranges. Therefore, one may hope that, with an appropriate higher cut-off in total visible energy (or visible invariant mass), one would not keep too much of the annihilation background when studying $\gamma\gamma$ processes. (Due to the energy-behaviour of both processes, this should become all the more true when the beam energy is increased). In order to further improve the signal-to-noise ratio, the same kinematic criteria as in (ii) may as well be useful here (coplanarity, $\Sigma p_\perp \simeq 0$; however, contributions to background like those shown in fig. II.3 would not be eliminated by using such criteria).

Background (iii) would of course be entirely suppressed if one were able to use $e^- e^-$ or $e^+ e^+$ (as with some lower-energy machines like [illegible] (7) and presumably DORIS). However, PETRA and [illegible] are one-ring machines allowing only for $e^+ e^-$ collisions; the same will be true for [illegible].

We conclude from the above discussion that, although background [illegible] must be very seriously considered in non-tagging experiments, it should be possible to keep them under control; thus [illegible] may not be a decisive argument in favour of tagging. However, to be cautious, we would say that this conclusion may be valid for some $\gamma\gamma$ channels and not for others.

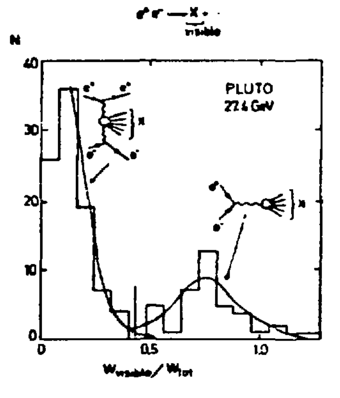

Fig. II 4

Distribution of the total visible energy as observed by PLUTO at 27.4 GeV. The curves indicate the shape of the contributions expected from two photon exchange and one photon annihilation.

b. Event reconstitution

Since there is no detecting apparatus covering the full solid angle of 4π with total efficiency +), one cannot make sure, in $\gamma\gamma$ experiments without tagging, that all particles produced are really seen. Thus, in particular, reconstitution of the most fundamental parameter, i. e. of the invariant mass produced or c. m. energy of the $\gamma\gamma$ collision, will in general involve some amount of uncertainty.

Let us emphasize that it would not be enough to have a detector covering "almost 4π", i. e. the full solid angle except for a small cone around 0° and 180° with respect to the beam axis. The point is that, precisely, particles produced in $\gamma\gamma$ processes are mostly emitted forward and backward, both for dynamic reasons (according, at least, to relevant theories and models: QED, QCD, Regge-pole theory) and for kinematic ones (i. e., because of the Lorentz boost between the $\gamma\gamma$ c. m. frame and the laboratory). Therefore, a criterion like $\sum p_\perp \simeq 0$ cannot help too much either.

Nevertheless, it should be possible to analyze correctly, without tagging, some simple processes where there are good chances, for theoretical reasons, of not having any additional particles escaping detection. Such processes are:

(i) lepton pair production at not too high invariant mass (as in the D. C. I. experiment (9));

(ii) hadron pair production ($\gamma\gamma \to \pi^+\pi^-$, $K^+ K^-$, $K_s^0 K_s^0$) near threshold;

(iii) production of resonances decaying with a large branching ratio into channels involving only a few particles (as in the experiment performed at SPEAR (1)).

All those reactions basically involve low invariant masses (or $\gamma\gamma$ collision energies); for obvious experimental reasons, they are rather to be studied with machines of not too high energy.

Now, what can be done, without tagging, with electron-positron collision rings of very high energy like LEP? Not much, we are afraid. Perhaps, the process $\gamma\gamma \to q\,\bar{q}$ (producing two jets at large $p_\perp$) provides such a possibility. But even here, the analysis may be very difficult, as fig. 1.5,6 (13) show: bremsstrahlung background on the right-hand side of these diagrams, and on the left-hand side contamination from processes with 2 large-$p_\perp$ jets plus one or more beam-pipe jets (the latter may remain unseen), leaves only a rather small range where the process to be looked for appears to distinctly predominate; by the way, we should not forget that perturbative QCD, as used here, is just a model for the time being.

+) and it is not certain at all that there may be one in the future.

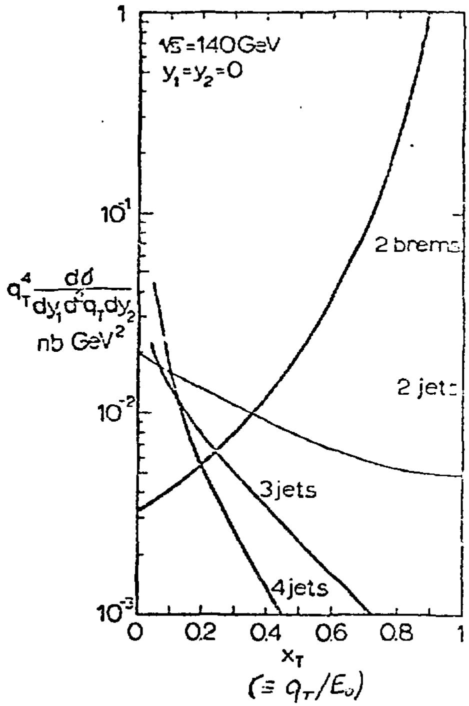

Fig. II. 5

Various contributions to a measurement of two jets with large transverse momentum q_T ($\equiv p_\perp$ in this report), emitted at 90° in the laboratory ("2 brems." = diagram of fig. II.3 (b) in this report; "3 jets", "4 jets" = 2 large-q_T jets plus one or two beam-pipe jets).

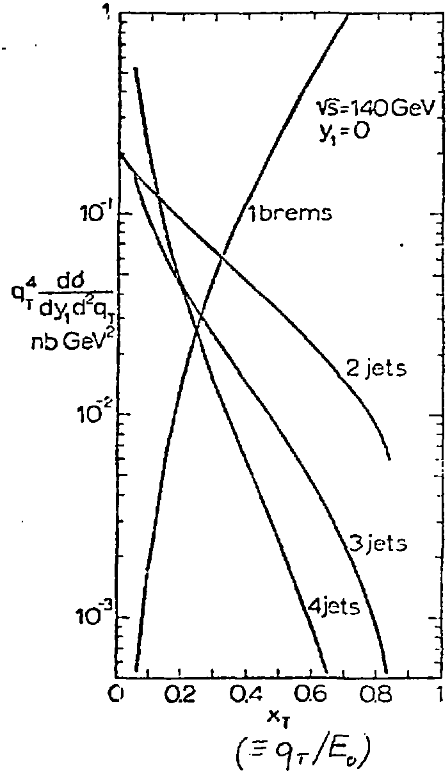

Fig. II.6

Various contributions to an inclusive measurement of one jet with large transverse momentum q_T ($\equiv p_\perp$ in this report), emitted at 90° in the laboratory ("1 brems." = diagram of fig. II.3 (a) in this report; "2 jets" = 2 large-q_T jets; "3 jets", "4 jets" = 2 large-q_T jets plus one or two beam-pipe jets).

We conclude that, in particular because of problems in event reconstitution, the non-tagging option <u>cannot</u> be systemically used for studying $\gamma\gamma$ collision processes.

3. <u>The drama of finite-angle tagging</u>

As is well known, at the existing high-energy $e^+ e^-$ machines, tagging at 0° (i. e., in the range of a few milliradians) is impossible, since in this range the tagging counters would be saturated by bremsstrahlung. Therefore, at PETRA and PEP, the minimal tagging angle is ≃ [illegible] mrad; at LEP, hopefully, it would be somewhat lower, but would not go to 0° either [14].

That fact involves two very unfortunate consequences, as regards counting rates on one hand, and back-factorization on the other hand.

a. <u>Counting rates</u>. Obviously, most of the events are lost for measurement, since the angular spectrum of either outgoing electron is given (in the [illegible]) by

$$N(\theta)\,d\theta = \frac{\theta^3\,d\theta}{(\theta^2+\theta_c^2)^2} \simeq \frac{d\theta}{\theta} \quad \text{for } \theta \gg \theta_c$$

(where $\theta_c \approx m_e/E_0$, m_e being the electron mass and E_0 the beam energy); only the tail of the angular spectrum is kept. Integrating over the tagging-angle θ, the factor $\log E_0/m_e$ (appearing in non-tagging or 0°-tagging experiments) should be replaced in principle by $\log \theta_{max}/\theta_{min}$ where θ_{min} and θ_{max} are the experimental limits provided by the tagging system; but only in principle, since (see ref. [illegible]), there is a kinematic constraint which further reduces the spectrum at finite angles, so that actually the integrated angular spectrum becomes (roughly):

$$\int N(\theta)\,d\theta \approx \log \frac{\min(\theta_{max},\, M/E_0)}{\min(\theta_{min},\, M/E_0)}$$

where M is the invariant mass produced. Since that drastic reduction of the angular spectrum takes place at both electron vertices, it follows that, under typical conditions existing at PETRA ($E_0 \simeq 15$ GeV, $\theta_{min} \simeq 20$ mrad), one thus looses about two orders of magnitude in counting rate at $M \approx 1$ GeV.

b. <u>Back-factorization</u>. Not only one looses most of the events, but also <u>the best</u> of them from the point of view of back-factorization, i. e. of extracting the desirable information on the process $\gamma\gamma \to X$ from the experimentally measured differential cross section bearing on $e^+ e^- \to e^+ e^- X$.

Back-factorization has been studied in ref. [5]. In the Feynman diagram of fig. II.1, the central vertex is characterized, a priori, by the fourth-rank tensor $C^{\mu\nu\rho\sigma}$, i. e. 256 different terms; obviously no experiment will ever allow one to separate them properly. Using the helicity formalism plus some general physical principles (gauge invariance, hermiticity), one is brought down to 36 terms. Restricting oneself to 2-body (or quasi-2-body) reactions, the number of independent terms for $\gamma\gamma \rightarrow X$ is reduced to 20, as shown many years ago by Carlson and Tung [15]. It is clear that this is still much too much, i. e. no experimentalist will be able to disentangle those 36 or 20 terms properly.

Integration over the full solid angle (4π) of the central detector would allow one to further reduce the above numbers to 8 or 6 respectively. However, as long as such a procedure doesn't really correspond to the conditions of the experiment (and it hardly will), it would require (considering hadron production or, more generally, any process which is not pure QED) a model-dependent extrapolation that would be tainted with doubt in most cases.

It has been shown [5] that the helicity formalism leads to only one term, i. e. to the double equivalent-photon approximation, provided following condition is satisfied:

$$\varepsilon, \varepsilon' \ll 1$$

defining: $\varepsilon = 2Q/M \simeq 2E_c\theta/M$, $\varepsilon' = 2Q'/M \simeq 2E_c\theta'/M$

Numerical checks of the double E. P. A. have been performed, considering the reaction $e\bar{e} \longrightarrow e\bar{e}\ell^+\ell^-$. The relative error Δ, with respect to an exact calculation, on the differential cross section has been computed, after integration over the azimuthal angles, keeping the following quantities fixed: $\varepsilon, \varepsilon'$ (or θ, θ'); x, x' defined as

$$x = (E_c - E)/E_c \quad , \quad x' = (E_c - E')/E_c$$

where E, E' are the energies of the outgoing electrons, and where one notices:

$$x x' \simeq M^2/(4 E_c^2)$$

Finally, the last independant variable, i. e. the emission angle ψ of one of the leptons produced, has been varied between 30° and 150°. Tables 1 and 2 show the range of Δ thus obtained for two different configurations (x = 0.1, x' = 0.1; x = 0.1, x' = 0.4). It should be noticed that those results become independent of beam energy, as far as the mass of the leptons produced may be neglected.

$x=0.1$, $x'=0.1$	$\varepsilon=1/100$ ($\theta\simeq1$ mrad)	$\varepsilon=1/30$ ($\theta\simeq3$ mrad)	$\varepsilon=1/10$ ($\theta\simeq10$ mrad)	$\varepsilon=1/3$ ($\theta\simeq30$ mrad)
$\varepsilon'=1/100$ ($\theta'\simeq1$ mrad)	$-1\%<\Delta<+1\%$	$-1\%<\Delta<+1\%$	$-4\%<\Delta<+1\%$	$-33\%<\Delta<+5\%$
$\varepsilon'=1/30$ ($\theta'\simeq3$ mrad)	$-1\%<\Delta<+1\%$	$-1\%<\Delta<0$	$-3\%<\Delta<+1\%$	$-33\%<\Delta<+4\%$
$\varepsilon'=1/10$ ($\theta'\simeq10$ mrad)	$-4\%<\Delta<+1\%$	$-3\%<\Delta<+1\%$	$-3\%<\Delta<0$	$-33\%<\Delta<+2\%$
$\varepsilon'=1/3$ ($\theta'\simeq30$ mrad)	$-33\%<\Delta<+5\%$	$-33\%<\Delta<+4\%$	$-33\%<\Delta<+2\%$	$-26\%<\Delta<-6\%$

Table 1

$x=0.1$, $x'=0.4$	$\varepsilon=1/100$ ($\theta\simeq2$ mrad)	$\varepsilon=1/30$ ($\theta\simeq7$ mrad)	$\varepsilon=1/10$ ($\theta\simeq20$ mrad)	$\varepsilon=1/3$ ($\theta\simeq70$ mrad)
$\varepsilon'=1/100$ ($\theta'\simeq3$ mrad)	$-1\%<\Delta<+1\%$	$-1\%<\Delta<+1\%$	$-1\%<\Delta<+1\%$	$-4\%<\Delta<+7\%$
$\varepsilon'=1/30$ ($\theta'\simeq9$ mrad)	$-2\%<\Delta<+1\%$	$-2\%<\Delta<+1\%$	$-1\%<\Delta<+1\%$	$-4\%<\Delta<+6\%$
$\varepsilon'=1/10$ ($\theta'\simeq26$ mrad)	$-12\%<\Delta<+1\%$	$-12\%<\Delta<+1\%$	$-12\%<\Delta<0$	$-5\%<\Delta<+3\%$
$\varepsilon'=1/3$ ($\theta'\simeq86$ mrad)	$-54\%<\Delta<+1\%$	$-54\%<\Delta<+1\%$	$-51\%<\Delta<+1\%$	$-28\%<\Delta<-3\%$

Table 2

From Tables 1 and 2, it may be concluded that, if one wishes to avoid reaching a range where the error Δ may exceed a factor of ≈ 2, one should restrict oneself to $\mathcal{E} \lesssim 1/3$. (It should be remarked that, by integrating over ψ, one would certainly get smaller error values, due to averaging, and partly to cancellation between positive and negative values of Δ; however, one might be interested in studying angular distributions).

We thus notice that there is a "limit of back-factorization" (or limit of validity of the E. P. A., or limit of quasi-reality of the photons), and that this limit is even much more drastic than the kinematic constraint (roughly described by the cut-off $\theta \lesssim M/E_0$) mentioned above.

What happens when *the limit of back-factorization is violated?* Any direct extraction of the information on the $\gamma\gamma$ process from the experiment becomes impossible (or would be very misleading). The possibility then remains to do model-fitting: i. e., choosing a model to calculate the tensor $C^{\mu\nu\rho\tau}$, factorizing with both second-rank tensors for the external (electron-photon) vertices, possibly integrating over some variables, and then comparing with the experimental data for the total *process ($e\,\bar{e} \longrightarrow e\,\bar{e}\,X$) as they are. For hadron production, an utterly* heavy and hazardous procedure!

We thus conclude: Finite-angle tagging is a real drama. Most of the events are just thrown away, and those few that remain are only partly analyzable in a simple way, i. e. by back-factorization.

4. <u>Single-tagging, a solution?</u>

Measurements where only one electron is tagged appear as a compromise between non-tagging and double-tagging. Actually, "compromise" is not exactly the word; single-tagged events will always appear in experiments with finite-angle tagging counters, together with the double-tagged ones and in much larger numbers. The experimentalist will be happy to have them, and try to analyze them.

Are they more satisfactory? Let us consider them, using the various criteria defined above.

a. <u>Counting rates</u>. As we just said, they will be much larger than for double-tagged events, since the factor $\log E_0/m_e$ is kept on one side (that of the untagged electron). At PETRA, for instance, even with a still rather low luminosity, they appear sufficient to study hadron production [(2)].

b. <u>Back-factorization</u>. The back-factorization constraint ($\theta \ll W/E_0$) remains only on one side, i. e. where the electron is tagged. Thus the proportion of events that may be analyzed with the double W. W. A. is higher than in the double-tagging case.

On the other hand, as has been observed in the third paper of ref. [5] (see also ref. [2]), such events may be treated - in first approximation, at least - as "electroproduction on a real-photon target". The helicity formula is then reduced to 6 terms in the general case, and to 4 terms in the case of a 2-body (or quasi-2-body) $\gamma\gamma$ reaction. The 4-term formula has a quite familair structure (the same as, for instance, in electroproduction of a pion from a proton target [16]):

$$d\sigma_{e\gamma \to e\gamma X} \sim \frac{d\sigma_U^{\gamma\gamma}}{d\Omega} + \eta \frac{d\sigma_L^{\gamma\gamma}}{d\Omega} + \eta \frac{d\sigma_P^{\gamma\gamma}}{d\Omega} \cos 2\varphi + \sqrt{2\eta(\eta+1)} \frac{d\sigma_I^{\gamma\gamma}}{d\Omega} \cos\varphi$$

where η is the virtual photon's polarization parameter; φ is - in the c. m. frame - the relative azimuthal angle between the tagged electron and one of the particles produced, whereas Ω is the solid angle of the latter particle.

We checked that formula under conditions quite close to those of the PLUTO Collaboration experiment at PETRA [2], considering the process $e\bar{e} \to e\bar{e}\, \ell^+\ell^-$. Tables 3 and 4 show the range of the relative error Δ found (with respect to an exact calculation) when W and θ (the tagged electron's scattering angle) were fixed and all other independent variables were varied in wide limit (with, however, the restriction: $40° < \psi, \psi' < 140°$, ψ and ψ' being the angles of the leptons produced). The angle of the untagged electron was integrated over between 0 and a minimal tagging angle of 23 mrad (assuming total efficiency of the tagging counters, here acting as veto counters, above that angular value). One notices that, except for some extreme situations (W/E_0 small, θ large), the approximation is excellent.

Extrapolating the central detector's acceptance to 4π, a 2-term formula would be obtained; but here again, for hadron production, such a procedure would generally be model-dependent and therefore rather doubtful.

From a. and b., it results that single-tagged events are indeed better than double-tagged ones both from the point of view of abundance and of back-factorization (although even a 4-term formula may be hard to disentangle). But on the other hand, one might wonder whether the shortcomings of the non-tagging experiments would not show up again, to some extent, in single-tagging. Let us thus consider, here again, the criteria introduced in sect. 2 above.

θ \ M	0.3 GeV	0.5 GeV	1 GeV	2 GeV and above
23 mr	$-5\% < \Delta < +5\%$	$-6\% < \Delta < +3\%$	$-1\% < \Delta < +3\%$	$\lvert\Delta\rvert < 2\%$ everywhere
45 mr	$-1\% < \Delta < +10\%$	$-5\% < \Delta < +3\%$	$-1\% < \Delta < +1\%$	
70 mr	$-1\% < \Delta < +17\%$	$-2\% < \Delta < +3\%$	$-3\% < \Delta < +1\%$	
120 mr	$-4\% < \Delta < +23\%$	$-1\% < \Delta < +11\%$	$-3\% < \Delta < +2\%$	
250 mr	$-1\% < \Delta < +28\%$	$-1\% < \Delta < +13\%$	$-1\% < \Delta < +4\%$	

Table 3 $(E_0 = 8.5$ GeV$)$

θ \ M	0.5 GeV	1 GeV	2 GeV	3 GeV and above
23 mr	$-3\% < \Delta < +5\%$	$-5\% < \Delta < +3\%$	$-1\% < \Delta < +3\%$	$\lvert\Delta\rvert < 3\%$ everywhere
45 mr	$-1\% < \Delta < +12\%$	$-4\% < \Delta < +2\%$	$-1\% < \Delta < +3\%$	
70 mr	$-1\% < \Delta < +13\%$	$-2\% < \Delta < +3\%$	$-2\% < \Delta < +2\%$	
120 mr	$-6\% < \Delta < +24\%$	$-1\% < \Delta < +9\%$	$-3\% < \Delta < +2\%$	
250 mr	$0 < \Delta < +28\%$	$-2\% < \Delta < +15\%$	$-1\% < \Delta < +3\%$	

Table 4 $(E_0 = 16$ GeV$)$

c. <u>Background rejection</u>

(i) As was shown by one of us some time ago [17], the theoretical background should become dangerous in general, under single-tagging conditions, only at rather large tagging angles; this conclusion was then reached for beam energies of a few GeV, but the authors later checked that it remains valid at higher energies (as was expected).

(ii) Again the beam-gas background may be suppressed by various means, in particular by analyzing the vertex distribution along the beam axis [2].

(iii) The background from $e^+ e^-$ annihilation is suppressed (except for accidental coincidences).

We conclude that background problems can in principle be handled properly (certainly better than in the non-tagging case).

d. <u>Event reconstitution</u>

As in the non-tagging case, this is a weak point. Here again, there is in general a risk that some particles produced - in particular, in the forward or backward direction - may escape detection. And here again, a kinematic criterion such as $\sum p_\perp \simeq 0$ - whatever useful it may be - doesn't warrant absolute security against that risk (notice, by the way, that here the transverse momentum of the tagged electron should be included in $\sum p_\perp$). +)

A priori, one might believe that, looking for the missing mass, one would be able to decide whether missing particles include either the untagged electron alone, or the latter plus something else (which might be one or more particles emitted in the $\gamma\gamma$ process, leaving radiative corrections aside). However, an elementary calculation shows [4] that one has a large uncertainty on the missing mass, due to the momentum resolution of the tagged electron. Even assuming that the central detector is perfect as far as resolution is concerned (i. e., measures the energy and momentum of every particle with 100% accuracy), one gets:

$$\Delta(MM^2) \simeq 4E_c^2\, \Delta E/E \quad \text{i.e.} \quad \Delta(MM) \simeq 2E_c\, (\Delta E/E)^{1/2}$$

With the rather optimistic assumption $\Delta E/E = 1\%$, one thus gets: $\Delta(MM) \simeq$ 3 GeV at PETRA ($E_o \simeq 15$ GeV) and $\Delta(MM) \simeq 14$ GeV at LEP ($E_o \simeq 70$ GeV).

We thus conclude that, here again, reconstruction of events will be correctly performed, basically, only where theoretical reasons will lead one to assume that no particle has been "lost".

+) Additional kinematic criteria may here be used, but they don't ensure complete security either.

5. Double anti-tagging, as an improvement of non-tagging

Since, with finite-angle tagging systems, double-tagged events are scarce and to a large extent hardly analyzable, and since on the other hand the single-tagged ones don't provide a decisive improvement with respect to the non-tagging option as far as event reconstitution is concerned, the question may legitimately be raised: Was it worth while to build finite-angle tagging counters for PETRA and PEP, and is it worth while to do the same thing for LEP?

To some extent, it was (or it is), nevertheless. Three arguments may be given here:

(i) Such counters must necessarily be used in large-Q^2 experiments, some of which may be of extreme theoretical importance. Of course, all the shortcomings and difficulties mentioned will show up in such double- or single-tagging measurements.

(ii) Finite-angle tagging counters, when used for triggering in coincidence with the central detector, allow for a preselection of events supposed to be $\gamma\gamma$.

(iii) There is still another use for those counters, namely double anti-tagging. In 1974, one of us wrote in his Ph. D. Thesis ( ): "For those collision rings where the detection of electrons scattered at 0° would be technically impossible or too difficult or too costly, we consider the possibility of studying nevertheless, under certain conditions, events of the type 'photon-photon collisions' with two quasi-real photons. That is 'tagging by absence': Instead of checking that either electron is <u>present</u> inside a cone centered on its initial direction and of opening angle θ_{max}, one would check that either electron is <u>missing</u> everywhere outside of those two cones, i. e. in the whole angular range $\theta_{max} < \theta, \theta' < \pi - \theta_{max}$."

The obvious condition for "tagging by absence" or "anti-tagging" is that the tagging counters (thus used as veto counters) should be of 100% (or almost 100%) efficiency in a range starting from the minimal tagging angle and extending to some large angle where the electron's scattering probability becomes practically zero. If this condition is satisfied, single-tagging may be treated (as, actually, we have already seen above) as "single anti-tagging", in the sense that the untagged electron will be considered as scattered into a narrow cone around 0°. Double anti-tagging, on the other hand, may obviously be considered an improved version of non-tagging: At the price of loosing a rather small fraction of events, one selects the "good" photons (the quasi-real ones) on both sides, just as in the case of double tagging at 0°; and the double W. W. A. formula becomes about as accurate as in that case.+)

6. The ideal experiment: double tagging at 0°

Only double tagging at 0° is satisfactory in every respect (provided the problem of saturation by bremsstrahlung can be solved).

a. Counting rates. In spite of the unavoidable lower cut in the energy loss of the electrons (reasonably, $x_{min} \gtrsim 10^{-2}$; electrons [illegible] a smaller proportion of their energy would continue turning around in closed orbits inside the ring), counting rates would [illegible] in general ([illegible]).

b. Back-factorization. The double W. W. A., i. e. back-factorization with only one term, can be used with an accuracy of $\approx$ [illegible] ([illegible]), and ([illegible]).

c. Background rejection. (i) The theoretical [illegible] cally zero ([illegible]). (ii) The beam-gas background, [illegible] annihilation, are suppressed (apart from accidental [illegible]).

d. Event reconstitution. The invariant mass [illegible] ([illegible] $\gamma\gamma$ collision in its c. m. frame) is obtained by missing mass. [illegible] mentioned cut-off at x_{min} automatically warrants that the error [illegible] this missing mass, due to the resolution of both electrons in momentum, [illegible] limited and under control. On the other hand, each event can be reconstituted in the $\gamma\gamma$ c. m. frame by simple Lorentz transformation along the beam axis; angular distributions, etc., in that frame [illegible] rather easily.

Table 5 contains a comparison of the advantages and disadvantages of the various tagging options here considered. Clearly, double tagging at 0° would be by far the best of all.

It should be remarked that, with a 0° tagging device, double-tagged events will again always be accompanied by single-tagged ones (due, in particular, to electrons remaining untagged because they undergo an energy loss $x < x_{min}$). However, the latter will be less useful for the sake of analysis than the former, again because event reconstitution may become difficult or doubtful in the single-tagging case.

+) On the other hand, nothing is changed, practically, with respect to the non-tagging option, as regards background rejection and event reconstitution.

Options / Criteria		Counting [illegible]	Back-factorization	Background rejection	Event reconstitution
	Non-tagging	maximal	1 term (D.E.P.A.) (rough)	possible (with kinematic cuts) at least in some $\gamma\gamma$ channels	uncertain, except for specific channels
Finite angle tagging	Double anti-tagging	almost maximal	1 term (D.E.P.A.) (highly accurate)		
	Single-tagging	still large	6 or 4 terms (when q^2 not $\ll m^2$)	reasonably good	still uncertain, except for specific channels
	Double-tagging	small	16 or 8 terms (when q_1^2, q_2^2 not $\ll m^2$)	optimal	good
Double-tagging at 0° (assuming that a solution is found for bremsstrahlung saturation)		still large	1 term ([illegible]) (highly accurate)		

7. A word on radiative corrections

Radiative corrections in photon-photon collision processes are expected to be significant in general (four external electron lines in the Feynman diagram!). They cannot be derived, even roughly, from any standard formulas to be found in the literature. They differ widely, according to the experimental configuration considered, and in particular according to the solution chosen as regards tagging. In any case, they involve a lot of complicated computations that must be performed with great care.

One of us has computed those corrections in his Thesis (21) for the non-tagging case. Only corrections at the electron vertices were taken into account. More precisely, looking at fig. II.7: The contribution of diagrams II.7 (a) plus 7 (b) was computed, and the interference between diagrams II.7 (c) plus 7 (d) and the uncorrected diagram of fig. II.1 was added to that contribution. The infrared divergence thus cancels out, as could be foreseen.

By comparing a double equivalent-photon approximation set up ad hoc (i. e., treating both photons as real at the central vertex $\gamma\gamma \to$, just as in the double E. P. A. for the uncorrected process) with a simple one (i. e., using the Williams-Weizsäcker spectrum on the right-hand side of fig. II.1 and fig. II.7 (a)-(d), and computing everything else exactly), the author of ref. (21) was able to show that all usual formulae for the double E. P. A. can be validly used to a first order approximation. That formula is written as

$$d\sigma^{corr}_{e\bar{e}\to e\bar{e}X} \simeq N_{corr}(x)\,dx\;\sigma_{\gamma\gamma}(M^2)\;N(x')\,dx' \quad \left(\text{with } xx' \simeq \frac{M^2}{4E_c^2}\right)$$

where $N(x')$ is the usual Williams-Weizsäcker spectrum and $N_{corr}(x)$ is an equivalent-photon spectrum including radiative corrections. At fixed M, relating the above formula to the differential cross section for the uncorrected process (simply expressed by the double Williams-Weizsäcker approximation), one gets

$$\frac{d\sigma^{corr}_{e\bar{e}\to e\bar{e}X}}{dM} \Bigg/ \frac{d\sigma^{uncorr}_{e\bar{e}\to e\bar{e}X}}{dM} = 1 + \delta/2$$

where δ is the relative correction (the factor 1/2 is there to remind one that a factor of 2 must be introduced because of symmetry between left-hand and right-hand electron). It is then easily seen that δ is independent, in such an approximation, of the particular process ($\gamma\gamma \to X$) considered.

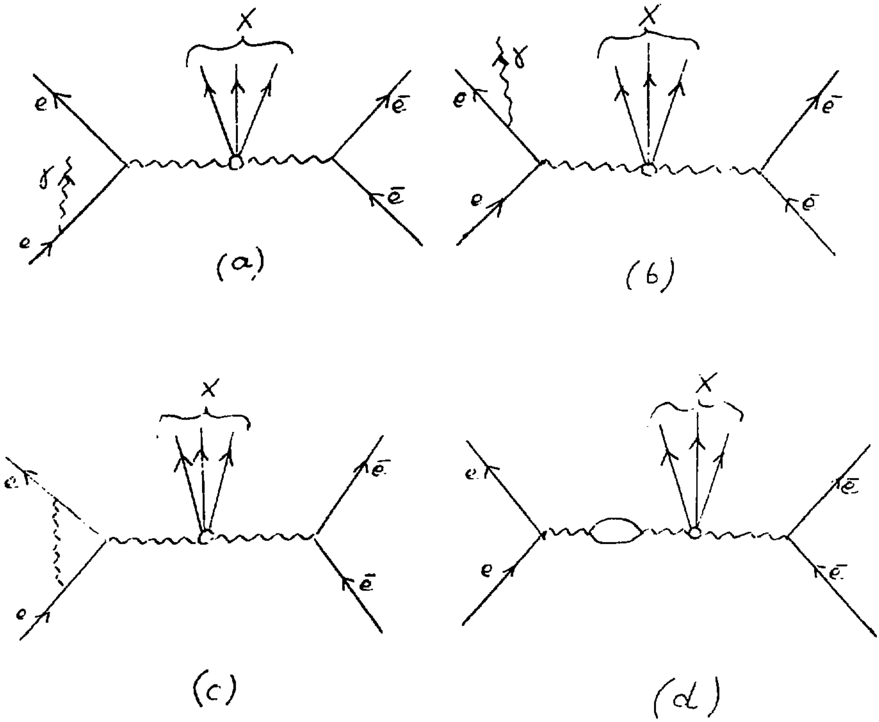

Fig. II.7

Values of δ were computed for various beam energies (fig. II.8). It appears that δ is positive and large, as was to be expected for the non-tagging case (where hard photons with energies ranging almost up to the beam energy can be emitted).

An improvement of that computation, taking account of a restricted acceptance of the central detector, is presently being performed by M. Defrise [22].

Another calculation was performed by two of the authors for the double-tagging case, more precisely for the conditions of the second stage of the D. C. I. experiment [9]. It was shown [23] that there the radiative correction is negative and rather small (a few percent). This is not surprising since here the emission of hard photons is sharply limited by the overall energy balance.

Obviously, the study of radiative corrections for photon-photon collisions is only in its beginning.

8. Conclusion

Apart from our short digression on radiative corrections, this study was mainly devoted to discussing the various options of tagging or non-tagging of the outgoing electrons in $\gamma\gamma$ experiments. One of our conclusions is that finite-angle tagging systems, as they exist at PETRA and PEP (and as they are foreseen at LEP), are rather unfit for a systematic and accurate investigation of photon-photon collision processes.

The ideal measurement is double-tagging at 0°. Perhaps some day it will be decided to have a "$\gamma\gamma$ machine", i. e. an electron storage ring facility with the specific technology (a large number of scarcely populated bunches, probably in two separate rings) allowing for this kind of tagging.

As their final conclusion, the authors would like to add the following remark: In spite of their strong convictions on some points, they are aware that this Report is probably not the last word on problems of analysis in photon-photon collisions. That terribly complex subject will certainly be discussed in much detail by experimentalists and theorists who will meet at the forthcoming "Workshop on $\gamma\gamma$ collisions". Additional problems, not even mentioned in this Report, may show up and prove important. On the other hand, it may be hoped that new ways of thinking, new ideas, new solutions may come out in what appears nevertheless one of the most fascinating areas of high-energy physics.

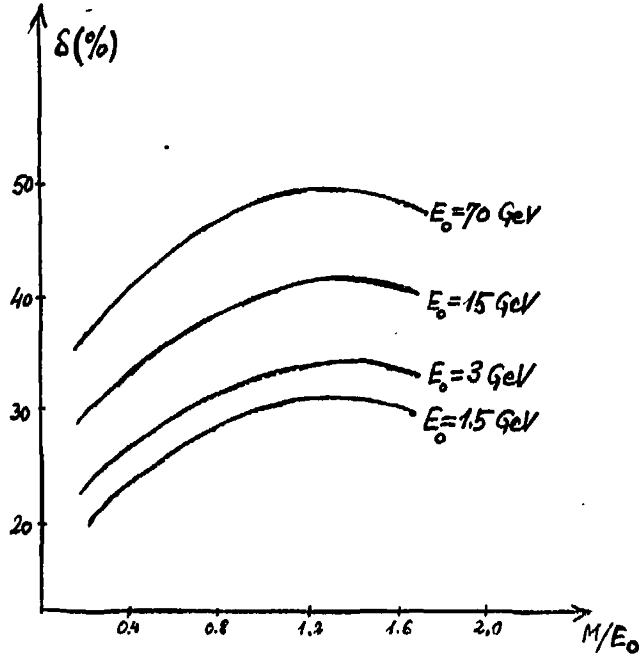

Fig II. 8

<u>References of part II</u>

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