# HADRON PRODUCTION FROM PHOTON–PHOTON INTERACTIONS IN THE CM ENERGY RANGE FROM 1 TO 5 GeV

PLUTO Collaboration

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We present the first data on photon–photon annihilation into hadrons for CM energies > 1 GeV obtained with the detector PLUTO at the $e^+e^-$ storage ring PETRA. Cross sections are extracted using an inelastic $e\gamma$ scattering formalism. The results are compared to expectations from Regge-like models.

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It was suggested ten years ago [1] that in high energy $e^+e^-$ reactions hadron production via the so called two-photon mechanism (fig. 1) becomes more and more important compared to the usual one-photon mechanism. The significance of experiments covering two-photon processes lies in the fact that one can hope to extract from the measured cross section of the reaction

$$e^+e^- \to e^+e^- + \text{hadrons}\,, \qquad (1)$$

the genuine two-photon cross section for real as well as virtual photons. Depending on different kinematical conditions one can explore either the hadron-like or the point-like behaviour of photon–photon scattering in the same reaction [2]. A measurement of this cross section is also important for the one-photon annihilation process, where the contributions from two-photon collisions appear as a "background" that increases with rising CM energy.

The specific signature of reaction (1) as compared to electron–positron annihilation into hadrons is the occurrence of an electron and a positron in the final state, which are peaked at high energies and very small angles $\theta, \theta'$ [‡1]. In order to select the $\gamma\gamma$ reactions, the PLUTO detector at PETRA has been equipped with two forward spectrometers for identifying ("tagging") the outgoing electrons and positrons. The layout is shown in fig. 2. Each arm of the forward spectrometers consists of a "large angle tagger" (LAT) and a "small angle tagger" (SAT). The LAT covers the polar angle region between 70 and 260 mrad. The energy of electrons and photons is determined with a lead scintillator shower counter of 14.5 radiation length thickness. The position of charged particles is determined by four planes of proportional tube chambers with a wire spacing of 1 cm. The SAT covers the angular region between 23 and 70 mrad. Energy information of electrons and photons is obtained from a lead glass shower counter matrix. It consists of 96 blocks (each with a front area of $6.6 \times 6.6$ cm$^2$), in a concentric arrangement around the beam pipe. The thickness of this counter is 12.5 radiation lengths. Tracking of charged particles is achieved by a set of four planar proportional wire chambers (wire distance 0.3 cm). In a test beam the energy resolution of the LAT was measured to be $11\%/\sqrt{E}$ (rms) and that of the SAT to be $8.5\%/\sqrt{E}$ (rms), $E$ in GeV. These values have been reproduced by analyzing small angle Bhabha scattering. Details on the central part of the PLUTO detector can be found in ref. [3].

‡1 The symbols used for kinematical quantities of process (1) are explained in fig. 1.

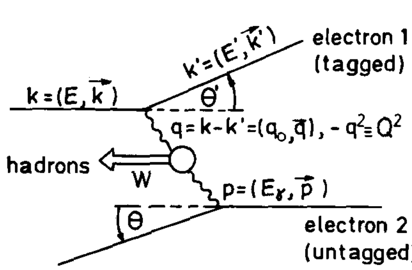


Fig. 1. Kinematics of the reaction $e^+e^- \to e^+e^-$ + hadrons.

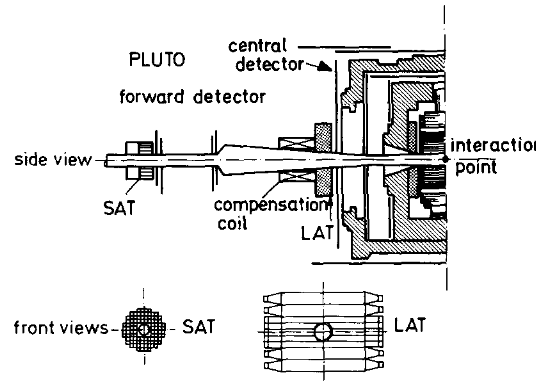


Fig. 2. Layout of one forward detector.

The data reported in this paper have been taken at beam energies of 6.5 and 8.5 GeV with integrated luminosities of 43 nb$^{-1}$ and 88 nb$^{-1}$. Candidates for two-photon induced events were selected by a trigger, which required an energy of more than 3 GeV deposited in one of the forward spectrometers and at least one track with a transverse momentum of more than 300 MeV in the central detector. For the vertex distribution of these events we refer the reader to fig. 2c of ref. [3a]. Most of these events are two prongs and are attributed to QED reactions like $e^+e^- \to e^+e^-\mu^+\mu^-$. A detailed study of these two prongs shows quantitative agreement with the QED expectation.

The following analysis is restricted to events with a single tag in the SAT, thus keeping the $Q^2$ of the tagged photon small, but finite, and leaving the untagged photon almost real. For selecting hadronic events from this data sample we require (a) three or more tracks in the central detector, or (b) two tracks in the central detector and at least one shower which is not associated with the tracks ($E_{neutral} > 350$ MeV, $|\cos\theta^n| < 0.997$). The two tracks are defined by the following conditions: $|\cos\theta_1^h| < 0.743, p_{T_1} > 300$ MeV; $|\cos\theta_2^h| < 0.820$, $p_{T_2} > 80$ MeV, where $p_T$ is the transverse momentum, $\theta^n$ and $\theta^h$ are the polar angles of showers and hadrons relative to the beam axis. To check a possible contribution of higher order QED background in this class, we repeated the total analysis with the data sample of class (a) only, and got consistent results.

The vertex distribution of these hadronic events is given in fig. 3. It shows a clear peak around the interaction point above a background from beam–gas interactions. There are 75 events for $-30 \leqslant z \leqslant +30$ mm. To determine the beam–gas background in this sample we counted the number of events for $-100 \leqslant z \leqslant +40$ mm (24) and $+40 \leqslant z \leqslant +100$ mm (21). Assuming a uniform distribution of beam–gas background, which is supported by our previous observations in high statistics experiments, we are thus left with $52 \pm 9$ events.

In fig. 4a we show the background subtracted total energy distribution ($E_{had}$) of the 8.5 GeV data sample. The distribution rises to a peak around 2 GeV and decreases steeply towards higher energies. This behaviour is expected from the bremsstrahlung spectrum of

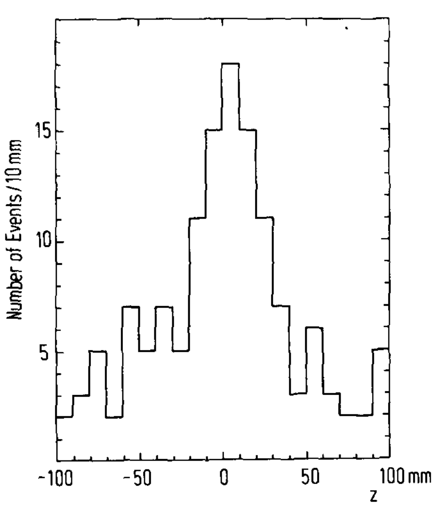


Fig. 3. Vertex distribution for hadronic events with a single tag in the forward spectrometers.

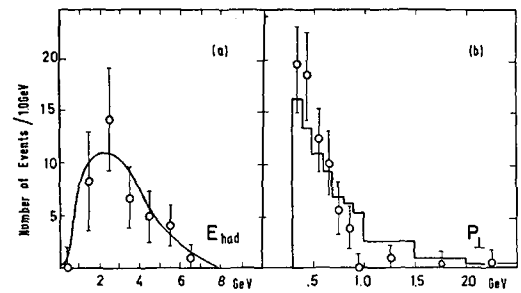


Fig. 4. Distribution of the total hadronic energy ($E_{had}$) per event (a) and the transverse momentum per particle (b). Data points are compared to the model calculation (see text). The histogram (b) was chosen to indicate the varying bin size.

the interacting photons and thus strongly supports the idea that these events originate from two-photon reactions. It excludes the origin from misidentified annihilation events, whose energy as seen in the calorimeter-like detector would peak around $2 \times 8.5$ GeV.

For the question of extracting a hadronic cross section from the measured data we point out that only the photon radiated from the untagged electron ($\langle\theta\rangle \leqslant 20$ mrad) is close to the mass shell. The tagged electron, however, ($\theta > 20$ mrad) radiates photons which have $Q^2 \gg m_\pi^2$ ($\langle Q^2\rangle \approx 0.1$ GeV$^2$). Therefore the proper description of this experimental situation is *electron scattering off a free photon target.* The cross section for e$\gamma$ scattering can be written very similar to inelastic electron–nucleon scattering. Because we want to interpret our data in terms of photon–photon cross sections rather than in terms of structure functions we adopt what is known as "Hand's formula" in electroproduction [4]:

$$d\sigma/d\Omega' dE'|_{e\gamma} = \Gamma_T\{\sigma_T(q^2, W^2) + \epsilon\sigma_L(q^2, W^2)\}\,.$$

$\Gamma_T$ is a flux factor for the virtual photons, $\epsilon$ the polarization parameter and $\sigma_T$ and $\sigma_L$ are the total cross sections for hadron production via virtual transverse and longitudinal photons off a free photon target. The differential cross section for $e^+e^- \to e^+e^-$ + hadrons is then given by

$$d\sigma|_{ee\to ee+hadrons} = \Gamma_T\{\sigma_T + \epsilon\sigma_L\}\, d\Omega' dE' N(E_\gamma)\, dE_\gamma\,, \tag{2}$$

where $N(E_\gamma)\, dE_\gamma$ is the number of photons per electron radiated from the *untagged* lepton. The validity of this approach has been discussed recently by Carimalo et al. [5] ‡2. For vanishing $\sigma_L$ the formula (2) reduces to the one term formula discussed in ref. [6], but with a different flux factor. We have checked the two methods and found that the straightforward application of the Weizsäcker–Williams approximation yields a $\sigma_T$ which is systematically 20% above $\sigma_T + \epsilon\sigma_L$ obtained by the method we propose (see also ref. [7]).

We have simulated this process in a Monte Carlo program. For the spectrum from the untagged photon, $N(E_\gamma)\,dE_\gamma$, we used the standard Weizsäcker–Williams formula [6]. For the flux factor and the polarization parameter we find in the small angle approximation of electroproduction:

$$\Gamma_T = \frac{\alpha}{2\pi^2}\frac{1}{\theta'^2}\frac{1}{(E-E')}(1+E'^2/E^2)(W^2/(W^2+Q^2))\,,$$

$$\epsilon = 2EE'/(E^2+E'^2)\,.$$

The hadronic events were generated with constant cross section in $q^2$ and $W^2$ according to a multi-pion phase space program with limited transverse momentum (300 MeV) along the direction of flight of the CM system. The average multiplicity was taken from annihilation data [8] (parametrized by $n_{ch} = 2 + 0.7\ln W^2$, $W$ in GeV) at the same center of mass energy.

The Monte Carlo simulation reproduces the distribution of the measured hadronic energy (fig. 4a) quite well (solid line). As a further check we compare the model expectation and the observed transverse momentum distribution of the charged hadrons with respect to the direction of flight of the CM system. This is displayed in fig. 4b, again showing a good agreement. Therefore we are confident that we can use the acceptance calculation from the model to compute $\sigma_T(q^2, W^2) + \epsilon\sigma_L(q^2, W^2)$ in different bins of $W_{vis}$. $W_{vis}$ is the *observed* invariant mass of the hadronic system seen in the central detector, calculated by taking pion masses for all charged particles.

The cross section versus $W_{vis}$ (charged and neutral) at $\langle Q^2\rangle \approx 0.1$ GeV$^2$ is shown in fig. 5. The range of true $W$ that contributes to each bin of $W_{vis}$ is indicated by the dashed horizontal bars of the data points. Besides the statistical error, which is given in the figure, we estimate an overall systematic error of ±25% mainly coming from the uncertainty in the acceptance calculation.

‡2 Notice that these authors have two additional terms ($\sigma_P$, $\sigma_I$) which drop by integration over the azimuthal angles of the hadrons in our case.

The solid line in fig. 5 represents the expectation for $\sigma_T(q^2, W^2)$ assuming a pure Regge asymptotic behaviour for $\gamma\gamma$ scattering extrapolated to low energies via duality and factorization [9]. Including a $\rho$ form factor ansatz for the virtual photon one obtains:

$$\sigma_T(q^2, W^2) = (0.24\,\mu b + 0.27\,\mu b/W)\left(\frac{1}{1+Q^2/m_\rho^2}\right)^2\,,$$

($W$ in GeV). At the highest $W$ the data agree with the model. This model has been used earlier [3] to estimate the "background" from two-photon processes in annihilation cross sections. Our measurement, therefore, justifies this procedure.

Towards lower $W$ there is an excess in the measured cross section. It is unlikely that all this excess is due to longitudinal contributions. In a recent paper [10] Greco and Srivastava have argued that both for real and virtual photons one has to include contributions from the point-like coupling of real photons to quarks (quark-loop diagrams). Following this suggestion and assuming an effective quark mass of 100 MeV we calculate a contribution (fig. 5, dashed line) which shows qualitatively the observed increase towards lower energies, but accounts only partially for its magnitude. Inserting lower effective quark masses would improve the agreement.

To summarize, we have for the first time observed a statistically significant sample of hadronic events with $W > 1$ GeV produced in two-photon interactions.

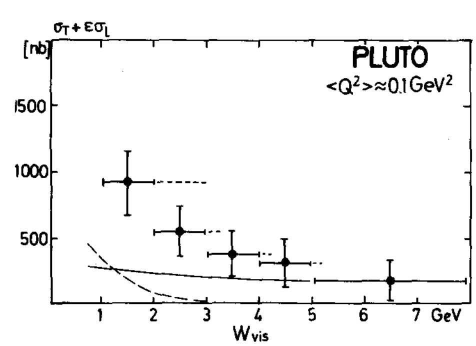


Fig. 5. $\sigma_T + \epsilon\sigma_L$ versus $W_{vis}$ at $\langle Q^2\rangle = 0.1$ GeV$^2$. The dashed part of the error bars indicates the range in $W$ that contributes to the data point. The data points are compared to a Regge-exchange model (solid line) and to contributions from point-like photon–quark couplings (dashed line, see text).

Both energy and $p_T$ distributions agree well with expectations for a two-photon process and are quite inconsistent with annihilation events. We evaluate the cross section using the formalism of inelastic $e\gamma$ scattering which appears to be most appropriate for the momentum transfers used. At high CM energies the data agree with the expectations from a Regge-exchange model. Towards lower CM energies the cross section shows a stronger rise than the extrapolation of the Regge model would predict. The difference may indicate the importance of point-like quark–photon couplings even for almost real photons.

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