OBSERVATION OF HARD PROCESSES IN COLLISIONS OF TWO QUASI-REAL PHOTONS

TASSO Collaboration

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Hard processes in photon–photon collisions are studied using high statistics data without requiring an electron tag. A high yield of hadrons with p_t in the range 1.5–3.0 GeV/c is observed. This yield exceeds the expectation of the Born term by a factor of four.

The experimental study of hard photon–photon collisions probes fundamental QCD processes [1]. Such processes lead to events characterized by the production of hadrons with high p_t, where p_t is the transverse momentum of the hadrons with respect to the electron beam direction. The lowest order process is described by the quark exchange diagram (Born term): $\gamma\gamma \to q\bar{q} \to$ two jets. Some experimental results concerning the above process have already been reported [2–4] [‡1]. These results were based mainly on low statistics single-tag events. They have shown that hard processes in $\gamma\gamma$ scattering are observed at lower CM energies than in hadron–hadron scattering. The rate at which large p_t hadrons are produced was found to be higher than expected by the Born term contribution.

In this paper we present an analysis of hadron production in untagged photon–photon collisions, i.e. where the scattered electrons are not necessarily detected. The use of untagged events is motivated by the need for high statistics. Moreover, untagged events probe in general another physical region ($Q^2 \approx 0$ for both photons where $-Q^2$ is the virtual photon invariant mass squared) and might be sensitive to processes that are suppressed in the single-tag mode where one of the photons has a non-negligible Q^2 ($Q^2 > 0.2$ GeV^2). The use of untagged events has, however, the disadvantage of introducing a large background of e^+e^- annihilation ("1γ") events. We show that with a suitable selection of cuts this background can be reduced to a tolerable level.

We analysed two-photon events measured by the TASSO detector at the e^+e^- storage ring PETRA. A description of the detector has been given elsewhere [6]. The data were collected at beam energies of 15–18.3 GeV with a total integrated luminosity of 71 pb^{-1}. The present analysis includes only charged particles measured in our tracking detector. Detection of scattered electrons in the forward detectors was not required but tagged events were not rejected. Charged tracks were accepted if $|\cos\theta| < 0.87$, where θ is the polar angle between the particle and the positron direction, and if their transverse momenta with respect to the beam axis (p_t) were larger than 0.1 GeV/c. The trigger conditions required for most of the data two tracks with $p_t > 0.25$ GeV/c and for a smaller subsample four such tracks. In order to restrict ourselves to multihadron final states well within the trigger acceptance, event candidates were required to have at least 4 tracks, of which at least one had to have $p_t > 0.3$ GeV/c and $|\cos\theta| < 0.82$, and two others had to have $p_t > 0.2$ GeV/c and $|\cos\theta| < 0.84$.

To reduce the background due to beam gas scattering, tau pair production and e^+e^- annihilation the following cuts were made:

(1) Beam–gas scattering. Events containing at least one proton identified in the inner time of flight counters (with momentum $0.3 < p_{\text{proton}} < 1.4$ GeV/c) were rejected. In addition the event vertex was required to be within 6 cm of the interaction point along the beam direction. These cuts reduced the beam–gas contamination to a level of 1% of the final sample to be defined below.

(2) Tau pair production. Using the sphericity axis each event was divided into two hemispheres. All charge balanced events with topologies of 1 against 3 or 3 against 3 tracks, where the 3 track system had an

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[‡1] Preliminary data from the PLUTO and CELLO collaboration cited in ref. [5].

invariant mass smaller than the tau mass and a net charge $|\Sigma Q| = 1$ were rejected. The remaining sample is almost free from $\tau\bar{\tau}$ contamination originating from the "1γ" process. The fraction of genuine two-photon events lost in the final sample due to those cuts was estimated by Monte Carlo calculations. It amounts to less than 1% of the Born term contribution and to ~6% of the VDM contribution. The contribution of the QED process $\gamma\gamma \to \tau\bar{\tau}$ was calculated by Monte Carlo and found to be less than 5% of the final sample. It was subtracted together with the other backgrounds in the appropriate distributions.

(3) e^+e^- annihilation. For untagged events the contamination by the annihilation process is severe, particularly in the region where particles are produced with high p_t. Whereas annihilation events in general, are characterized by having a total detected energy close to the available CM energy, this is not the case for untagged two-photon events where most of the energy is carried away by the undetected electrons. Hence a cut in the distribution of the measured total energy should allow a separation between the two processes. However, for the present analysis this separation is less effective since "1γ" annihilati n may simulate such high p_t "2γ" events in several ways.

(a) A hard photon is radiated from the initial state.

(b) Many of the charged particles escape the acceptance of the tracking devices.

(c) The neutral to charged energy ratio of the event is large.

(d) Double bremsstrahlung takes place in the initial state.

To reduce the contamination due to (a), all events with a momentum component along the beam axis (Σp_z) satisfying $|\Sigma p_z| > 0.3\, p_b$, where p_b is the incoming electron beam momentum, were rejected. The contamination due to (b) and (c) was reduced by requiring that accepted events should have a total charge balanced within two units and the net momentum component perpendicular to the beam direction ($\Sigma \boldsymbol{p}_t$) satisfying $|\Sigma \boldsymbol{p}_t| < 0.25\, p_b$. The effect of these cuts on the number of detected two photon events is small (loss of 13% of the final sample). The contribution of (d) was estimated using the equivalent photon approximation. It was found to be less than 2% of the final sample and is therefore neglected.

In addition to the background processes (1)–(3) another potential contributor is Bhabha scattering

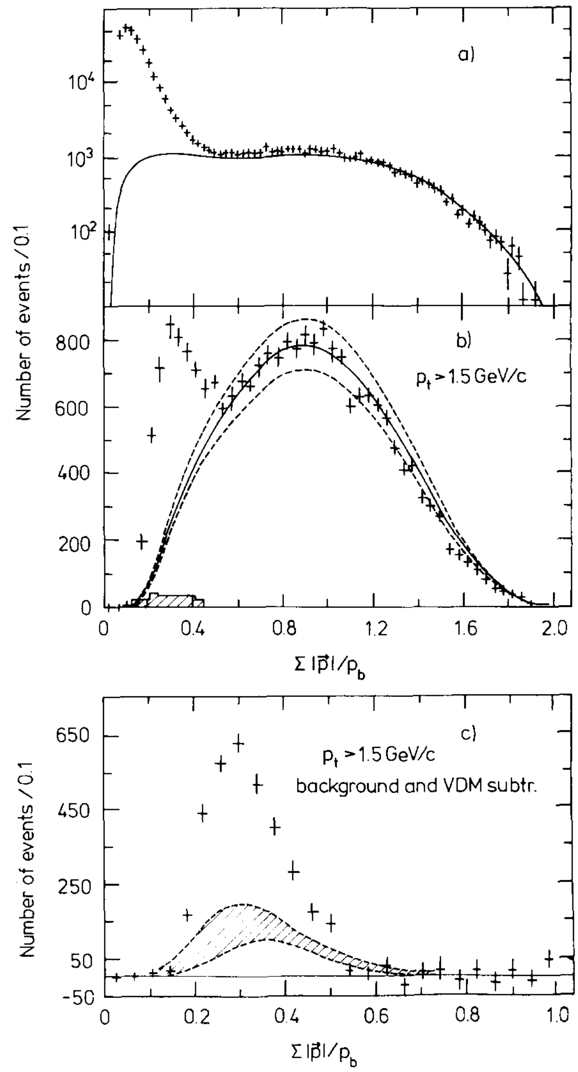

Fig. 1. (a) ($\Sigma|\boldsymbol{p}|/p_b$) distribution for all events. The solid line is the expected contribution of the "1γ" events. (b) ($\Sigma|\boldsymbol{p}|/p_b$) distribution for all events containing one or more tracks with $p_t > 1.50$ GeV/c. The solid line is the expected contribution of the "1γ" events and the dashed lines indicate the systematic uncertainty. The shaded area represents the "1γ" events produced with a hard bremsstrahlung photon such that the effective mass of the hadronic system is below 12 GeV. (c) As (b) but after subtracting the "1γ", $\gamma\gamma \to \tau\bar{\tau}$, and VDM contributions. The band shows the maximal variation that can be obtained by varying the fragmentation parameters in the Born term calculation.

with a virtual photon converting into a hadronic system. The contribution of this process was estimated following ref. [7] and was found to be smaller than 1.5% of the final sample.

Fig. 1a shows the sum of the absolute momenta for detected charged particles, normalized to the beam momentum ($\Sigma|\boldsymbol{p}|/p_b$) for events satisfying the above mentioned cuts. The solid line is the background estimation due to the "1γ" annihilation process. For this purpose we have used the Hoyer et al. [8] event generator with first order QCD corrections and including QED radiative effects [9]. The generated particles were then traced through our detector. It can be seen from fig. 1a that the observed charged energy for annihilation events is typically high, hence a cut of $\Sigma|\boldsymbol{p}|<0.4$ p_b was applied.

As was mentioned above, hard processes are expected to dominate in final states containing particles produced with high p_t. Fig. 2a shows the distribution of dN/dp_t^2 as a function of p_t^2 of the charged tracks for accepted events. In the low p_t region the data exhibit a strong fall with increasing p_t. This feature is expected from peripheral $\gamma\gamma$ scattering as predicted by the Vector Dominance Model (VDM), which describes two-photon processes in terms of the scattering of two vector mesons. This process was simulated by generating a multipion phase space with limited transverse momentum. The p_t dependence was described by an exponential in p_t of the form $d\sigma/dp_t^2 = a \exp(-bp_t)$; the average charged multiplicity was parametrized by $n = c_1 + c_2 \exp[c_3 (\ln 4 W_{\gamma\gamma}^2)^{1/2}]$ where $W_{\gamma\gamma}$ is the $\gamma\gamma$ CM energy. Best agreement of this model with the data for p_t smaller than 1 GeV/c was obtained by choosing b = 4 GeV^{-1}, c_1 = 3.96, c_2 = 0.0029, c_3 = 2.85 and the ratio of neutral to charged multiplicity of $\frac{1}{2}$. The dashed line in fig. 2a shows the prediction of this parametrization and the dashed–dotted line shows the results of the "1γ" computation. It can be seen that the data exceed the sum of these contributions for $p_t > 1.50$ GeV/c. The same conclusion can also be reached from fig. 2b where the p_t^2 distribution is plotted after subtracting the "1γ" contribution and compared again to the VDM (dashed line). The large excess of events in the high p_t region was found to be insensitive to variations of the VDM Monte Carlo parameters. This was checked by varying (a) the p_t parametrization (the b parameter was varied between 4.0 to 6.0 GeV^{-1} [‡2]), (b) the multiplicity (c_1 was varied

[‡2] Our data for p_t < 1 GeV/c are consistent with a b parameter of 5 GeV^{-1}. To obtain a conservative estimate on the VDM contribution at large p_t, we used a b value of 4 GeV^{-1}. If instead the p_t distribution of VDM is assumed to follow the ISR data of ref. [10] and normalized to our data at p_t = 1 GeV/c, also less events are predicted by VDM in the large p_t region.

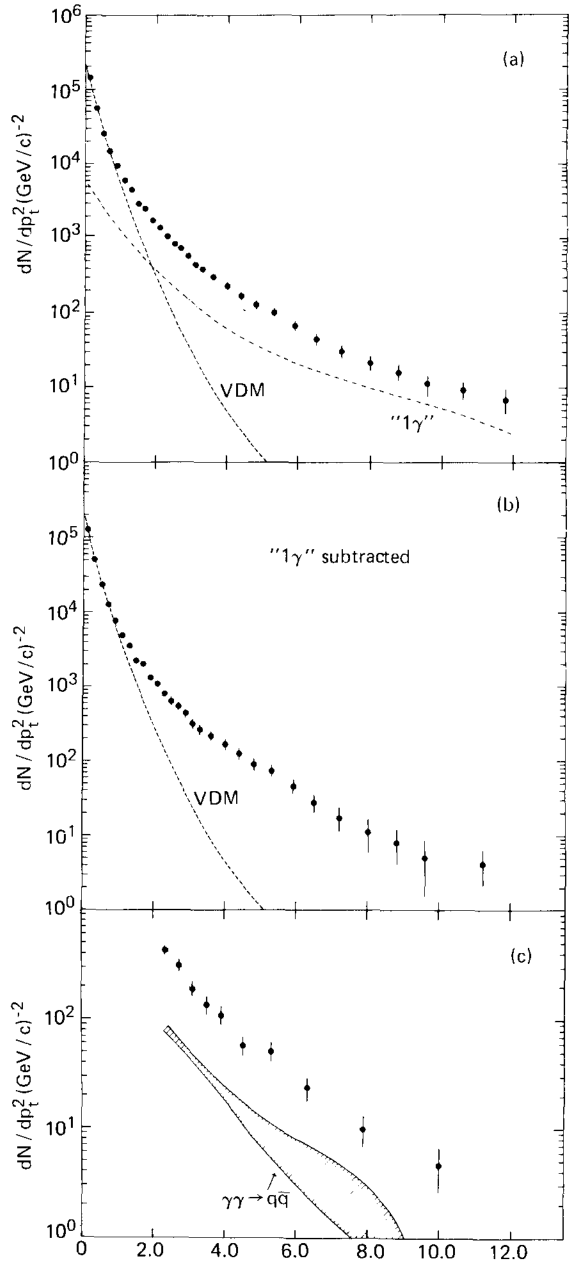

Fig. 2. (a) dN/dp_t^2 versus p_t^2 distribution of all the tracks in the event. The events are required to have $\Sigma|p|/p_b < 0.4$. The dashed line is the expected VDM contribution (see text) and the dashed-dotted line describes the 1γ calculation. (b) Same as (a) but after subtracting the "1γ" contribution. The dotted line is the expected VDM contribution. (c) Same as (b) but after subtracting the $\gamma\gamma \to \tau\bar{\tau}$ and the VDM contributions. The band shows the maximal variation that can be obtained by changing the fragmentation parameters in the Born term calculation.

between 3 to 4.5), (c) the ratio of neutral to charged particle production (this ratio was varied between $\frac{1}{3}$ to $\frac{1}{2}$) and by using (d) a gaussian p_t dependence instead of the exponential one. To investigate hard $\gamma\gamma$ processes we shall hence restrict our final sample to events having at least one particle with $p_t > 1.50$ GeV/c. This leaves a total of 1491 events [‡3].

Fig. 1b shows again the $(\Sigma|\boldsymbol{p}|/p_b)$ distribution for events containing at least one track with $p_t > 1.50$ GeV/c. The two peak structure demonstrates that the separation between "1γ" and "$\gamma\gamma$" processes is possible even for events containing high p_t tracks. For comparison the same distribution is shown for the "1γ" Monte Carlo simulation (solid line). The "1γ" distribution was normalized in the region of $\Sigma|\boldsymbol{p}|/p_b > 0.50$, where it agrees well with the shape of the high $\Sigma|\boldsymbol{p}|/p_b$ peak. This procedure agrees with the absolute normalization of the "1γ" Monte Carlo to within 2% which is well within our systematic error of 10% (band width of the "1γ" curve in fig. 1b) for this background. The estimation of the systematic error comes from a Monte Carlo study of the "1γ" channel in which different values of the fragmentation and QCD parameters were used. The ratio of events having $\Sigma|\boldsymbol{p}| < 0.4\, p_b$ to those with $\Sigma|\boldsymbol{p}| > 0.5\, p_b$ was calculated and found to be, within 10%, constant under reasonable changes of the strong coupling constant α_s, and of the fragmentation parameters a_f, σ_q and $P/(P+V)$, as defined in the Field–Feynman prescription.

Initial state bremsstrahlung is highly reduced by the above mentioned Σp_z cut. Nevertheless it could still be the source of additional systematic errors if the hadronic final state is produced in an energy region that might not be well described by our "1γ" event generator. However, at most 10% of the generated and accepted "1γ" events in the $\Sigma|\boldsymbol{p}| < 0.4\, p_b$ (shaded area in fig. 1b) had an effective e^+e^- CM energy below 12 GeV. It is therefore concluded that the main contribution to the "1γ" background comes from events in which the two jets are produced along the beam direction and only a fraction of the particles are within the geometrical acceptance. This type of background, being geometrical in origin, can be reliably computed with the "1γ" Monte Carlo.

The simplest diagram of a hard "$\gamma\gamma$" process is the Born term leading to the production of two jets. The Vermaseren event generator [11] was used to simulate this process where instead of producing lepton pairs, fractionally charged quarks were generated. The final state hadrons were generated by fragmenting the quarks using the Field–Feynman prescription and tracing them through the detector. The quark masses are free parameters in this procedure. The values used were 300, 300, 500 and 1500 MeV for u, d, s and c quarks, respectively. Although large differences in the total cross section are obtained for different quark masses, the number of accepted events after detector simulation and the cuts mentioned above is approximately constant down to light quark masses of 10 MeV. Other variables in this model are the standard fragmentation parameters $[a_f, \sigma_q$ and $P/(P+V)]$. Since the fragmentation characteristics of low energy jets are not well known, the parameters were varied in the following range: a_f and $P/(P+V)$ between 0.25 and 0.70; and σ_q between 0.3 to 0.5 GeV/c. The Born term calculations are therefore given as bands corresponding to the extreme values obtained with these fragmentation parameters.

Fig. 2c shows the dN/dp_t^2 distribution as a function of p_t^2 after subtracting besides the "1γ" and the $\gamma\gamma \to \tau\bar{\tau}$ also the VDM contribution. The band describes the expectation of the hard processes due to the Born terms as discussed above. It can be seen that both distributions have similar shapes however the data exceed the Born term calculations by a factor of about four for $1.5 < p_t < 2.3$ GeV/c. This large disagreement is not due to events having a large number of high p_t tracks, since a similar excess occurs also in the distribution whereas only the highest p_t track in the event is considered.

Fig. 1c compares the $\Sigma|\boldsymbol{p}|/p_b$ distribution for the subtracted data with that expected for the Born term (shaded band). The largest disagreement with the Born term is found in the region of low visible energy, $0.25 < \Sigma|\boldsymbol{p}|/p_b < 0.4$. The large excess of events over the

‡3 In the present analysis the Q^2 distribution can only be inferred from Monte Carlo simulations and has been checked with the forward detectors. This estimation has been done conservatively using the Born term, since this gives the weakest Q^2 dependence. This computation predicts that for 75% of the events the maximum Q^2 will be smaller than 0.2 GeV^2. Moreover, the simulation predicts that 7% and 5% of the events will be tagged in the forward and end cap detectors, respectively. These rates are found to be consistent with the results obtained from the subsample of the data which could be checked in this way.

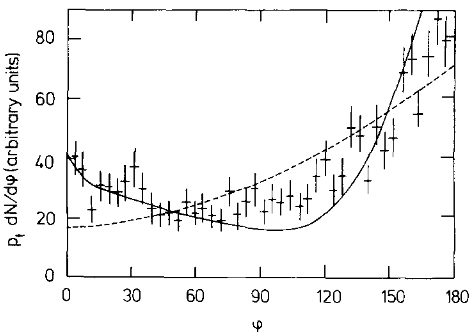

Fig. 3. p_t dN/dφ distribution where φ is the angle in the plane perpendicular to the beam direction between the highest p_t track in the event and all other tracks weighted by their p_t. The background due to "1γ" and $\gamma\gamma \to \tau\bar{\tau}$ as well as the VDM contribution is subtracted. The solid line represents the Born term behaviour and the dotted line is obtained from the VDM calculations, both normalized to the data.

Born term expectation could be due to QCD corrections and other hard scattering contributions like multi-jet production [1,12] and higher twists [1,13]. However, to our knowledge, there exists no full computation of those terms in a form that can be compared to our data. Preliminary data for a similar excess over the Born term prediction have been presented in ref. [5].

Searching for jets in $\gamma\gamma$ events is more difficult than in one photon annihilation due to the fact that the jets are boosted along the beam direction and carry only a small fraction of the available CM energy. In order to minimize these problems and find out whether the production of high p_t particles is correlated with jet production, we searched for clusters in the plane perpendicular to the beam direction. Fig. 3 shows, for events containing at least one track with $p_t > 1.50$ GeV/c, the distribution of the azimuthal angle (φ) between the highest p_t track in the event (trigger track) and all the other tracks weighted by their p_t (p_t dN/dφ). The background contributions from "1γ" and $\gamma\gamma \to \tau\bar{\tau}$ as well as the VDM part are subtracted. For comparison two models have been used, one having two high p_t clusters (Born term) the other having no high p_t clusters (VDM). The solid line represents the shape expected for this distribution from the Born term contribution, while the dotted line shows the shape as expected by our VDM calculation. It can be seen that for small φ, while the VDM gives a poor description of the data the shape of the Born term distribution agrees with it. This suggests that the large rate for high p_t tracks may be correlated with the production of particle clusters.

In summary, we have studied the p_t distribution of hadrons produced in untagged $\gamma\gamma$ collision. The yield of hadrons with p_t between 1.5 and 3 GeV/c exceeds the expectation of the Born term by a factor of four, indicating that other diagrams are also important in quasi-real two-photon interactions in this p_t range.

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