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**An Experimental Study of  $\gamma\gamma \rightarrow$  hadrons at LEP**

*The ALEPH Collaboration*

**Abstract**

An analysis of  $\gamma\gamma$  interactions has been performed using untagged hadronic data obtained by the Aleph detector at LEP. The data at low transverse momentum ( $p_t$ ) are well reproduced by a model based on the vector meson dominance mechanism (VDM). At high  $p_t$  the presence of hard scattering processes is demonstrated. This component is well described in shape and normalization by a QCD calculation.

*(Submitted to Physics Letters B)*



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## 1 Introduction

In  $e^+e^-$  colliders,  $\gamma\gamma$  processes can be studied via the interaction of virtual photons, produced by electrons in each beam (Figure 1). In the majority of these collisions the electrons are scattered at small angles to the beam and are not detected ‘Untagged’. In this case the colliding photons both have virtual mass ( $Q^2$ ) close to zero and can be regarded as almost real.

The process by which two photons produce hadrons is not described by a single model or theory. Examples of the different contributing process are shown in Figure 2. In principle this is the domain of QCD, however when there is no large energy scale in the interaction it is not currently amenable to calculation, and one is forced to use a less rigorous approach. There are two energy scales which can be important. These are the  $Q^2$  of either photon, and the transverse momentum of any of the partons in the interaction. If either of these becomes sufficiently large then perturbative QCD calculations are expected to be valid. The lowest order diagram in this domain is that of the Quark Parton Model (QPM), Figure 2 (a).

The bulk of the data in this study is however at low  $Q^2$ , and low  $p_t$  (transverse momentum with respect to the  $\gamma\gamma$  direction) and so it must be described by the Vector Dominance Model (VDM) where the photons behave as if they are vector mesons, Figure 2 (b). The cross section is assumed to have the form  $\sigma_{\gamma\gamma}^{had}(W) = A+B/W$ , where  $W$  is the invariant mass of the produced  $\gamma\gamma$  system. There are a number of formulations of this model applied to  $\gamma\gamma$  scattering, the details of which are well described in [1]. VDM does not make detailed predictions about how the available centre of mass energy is transformed into the observed hadrons. One would however expect similar behaviour to that observed in hadron scattering, for example the final state hadrons should show an exponential fall in  $p_t$ .

QCD calculations in this field predict the presence of processes with more than two jets in the final state, examples of which are depicted in Figure 2 (c) and (d). These were first calculated by Brodsky et al.[2] who showed that the rate of production is of the same order as the QPM process. This work has recently been extended by Drees and Godbole [3]. In all these processes there is a subprocess in which two partons scatter at high  $p_t$  which can thus be calculated by perturbative QCD. This subprocess cross section is convolved with the luminosity functions, that give the distribution of virtual photons in an electron, and the photon structure functions that give the distributions of quarks and gluons inside a photon. A critical parameter of the calculation is  $p_t^{\min}$  which is the lower limit of the integration over  $p_t$  of the hard scattering partons. It represents the limit of

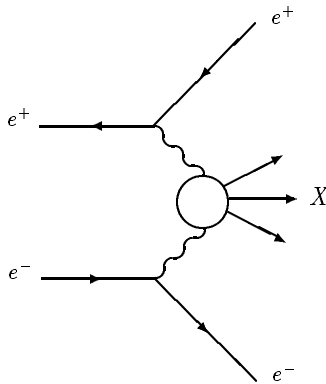


Figure 1:  $e^+e^- \rightarrow e^+e^-X$



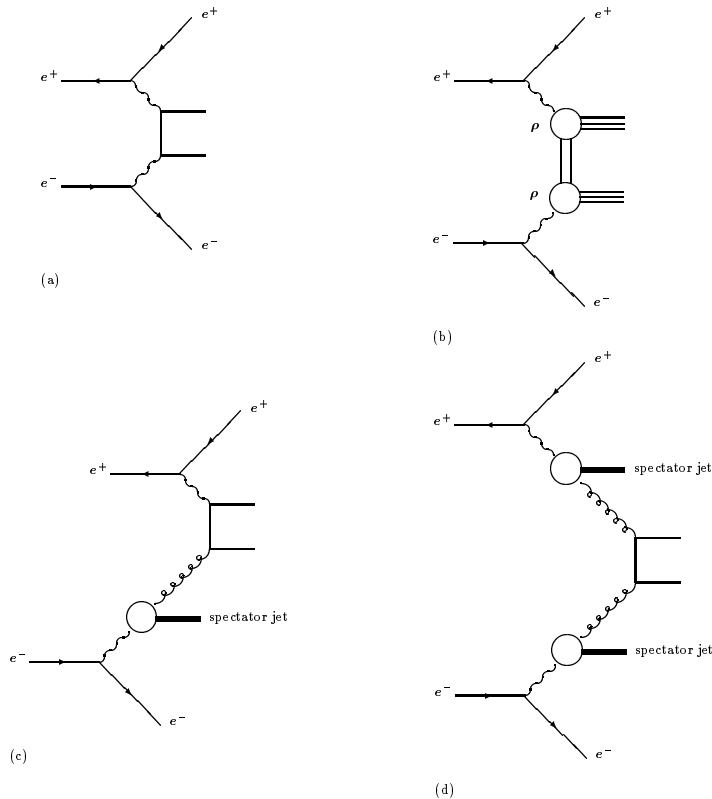


Figure 2: Examples of processes important in  $\gamma\gamma \rightarrow \text{hadrons}$ . a) Direct (QPM) process b) VDM c) Single resolved process d) Double resolved process

validity of current perturbative QCD calculations, and might thus be expected to lie in the range 1-3 GeV/ $c$ . The photon structure function is not well measured experimentally and, in particular, the gluon content of the photon is almost completely unknown. A number of different formulae are available in the literature [4-8] to describe it. The multijet processes, however, as well as providing a clear test of QCD, could be responsible for large backgrounds at proposed high energy  $e^+e^-$  machines [3, 9], so a determination of their magnitude can have a critical bearing on the design of such machines.

The first studies of the topology of multihadronic  $\gamma\gamma$  events at PETRA found evidence for two high- $p_t$  jets consistent with a contribution from the QPM in addition to the dominant VDM contribution [10]. Furthermore there was evidence in untagged and low  $Q^2$  tagged data of a third component that was consistent with neither the QPM nor VDM models. It was suggested that this was due to the presence of the additional QCD processes discussed above [11, 12]. More recently, experiments at TRISTAN have reported seeing even larger excesses [13, 14].

## 2 Apparatus and triggering

The data were collected at LEP using the ALEPH detector which has been described in detail elsewhere[15]. The sample in this study was selected from 19.1 pb $^{-1}$  of data taken during 1990, and 1991. These data were collected at beam energies between 44 and 47.5 GeV, with the primary purpose of studying the  $Z^0$  boson.

The main trigger for the data used in this study requires a track detected by the inner tracking chamber (ITC) (which implies a minimum  $p_t$  of 300 MeV/ $c$ ) to be found pointing towards an energy deposition of greater than 200 MeV in a segment of the electromagnetic calorimeter; the trigger is therefore sensitive to minimum ionizing particles. At the second trigger level a corresponding track must be found in the fast track-finding performed in

the time projection chamber (TPC), using a hard-wired processor[16].

### 3 Track cuts and event selection

The purpose of the following cuts was to select a large sample of events of the type  $\gamma\gamma \rightarrow$  hadrons, with low background from other sources.

Charged tracks were required to pass the following cuts:

- At least 4 hits in the TPC;
- distance of closest approach to the mean interaction point less than 2.5 cm in the radial direction and less than 20.0 cm along the beam direction;
- momentum greater than 100 MeV/c;
- $|\cos \theta| < 0.96$  where  $\theta$  is the angle between the track and the  $e^+$  beam direction.

Calorimeter clusters were required to pass the following cuts:

- $|\cos \theta| < 0.96$  ;
- no associated charged track;
- energy greater than 250 MeV in the electromagnetic calorimeter, or 600 MeV in the hadron calorimeter.

The following criteria were then applied to select the events:

- $2.0 < W_{\text{vis}} < 25.0 \text{ GeV}/c^2$ , where  $W_{\text{vis}}$  is the invariant mass of the observed tracks and clusters, which is typically around half of the true invariant mass  $W$ ;
- total energy in calorimeters  $< 25.0 \text{ GeV}$ ;
- total energy of charged tracks  $< 25.0 \text{ GeV}$ ;
- $\geq 3$  charged tracks ;
- a vertex close to the interaction point (within 14cm along the beam direction, and 1.5 cm in the radial direction);
- $p_t^{\text{tot}} < 2.0 \text{ GeV}/c$ , where  $p_t^{\text{tot}}$  is the transverse component with respect to the beam direction of the vector sum of the momenta of charged tracks in the event;
- thrust  $< 0.998$ , thrust was calculated using all the charged tracks and calorimeter clusters in the event, boosted into their centre of mass;
- no cluster with energy greater than 24.0 GeV in the luminosity calorimeters (‘anti-tag’ condition). This restricts the  $Q^2$  of the data to be less than  $7 (\text{GeV}/c^2)^2$ . From the Monte Carlo simulation (section 5), the mean  $Q^2$  in the data is found to be  $0.23 (\text{GeV}/c^2)^2$ .
- at least one track with  $p_t > 250 \text{ MeV}/c$ ;
- no particle identified as a deuteron (using the dE/dx information provided by the TPC).

This left a sample of 41154 events. Small corrections for the trigger inefficiency have been applied to the data. These amount to 5% at  $W_{\text{vis}}$  of  $2.5 \text{ GeV}/c^2$ , falling to zero for  $W_{\text{vis}}$  above  $4.0 \text{ GeV}/c^2$ .

## 4 Backgrounds

The main background in this sample is from beam-gas collisions. These produce events that are very similar in topology to  $\gamma\gamma$  events, but are distinguished by being produced equally at all positions along the beam. These events were subtracted statistically using the sidebands of the  $z_{\text{vertex}}$  distribution. The fraction of beam-gas events in the sample is found to be 2%. As a check on this procedure, it was confirmed that the  $z_{\text{vertex}}$  distribution of events containing a deuteron was indeed flat.

Background due to annihilation events which have visible energy much less than  $\sqrt{s}$  can potentially represent a serious background, in particular at high  $W_{\text{vis}}$ . These events can occur either due to the emission of hard radiation which goes undetected or because they lie partially inside the beam pipe. Monte Carlo studies showed that only the latter process is important in this case. As the data for this study were taken around the  $Z^0$  pole it provides a direct means to measure the size of this background. Plotting the measured number of events per unit luminosity as a function of  $\sqrt{s}$  will reveal the presence of any sizeable annihilation background by the presence of a peak at the  $Z^0$  mass. For events with  $W_{\text{vis}}$  between  $6 \text{ GeV}/c^2$  and  $30 \text{ GeV}/c^2$  the resulting plot was consistent with the nearly flat  $\gamma\gamma$  luminosity function and enables the background to be estimated to be less than 1%, both in this region and in the whole sample. Similar results were found from Monte Carlo studies. This background has been subtracted.

The background due to  $e^+e^- \rightarrow e^+e^-\tau^+\tau^-$  was calculated by Monte Carlo to be 0.7 % of the sample and was subtracted from the data. For  $e^+e^- \rightarrow Z^0 \rightarrow \tau^+\tau^-$  the background was estimated to be no more than one or two events and was therefore neglected.

## 5 Monte Carlo Models of $\gamma\gamma$ Interactions

In order to compare the selected data sample with the various theories applicable to the process  $\gamma\gamma \rightarrow \text{hadrons}$ , a number of Monte Carlo samples were produced. These are described in the following sections.

### 5.1 QPM

The program of J.A.M. Vermaseren[17] was used to produce events containing u,d,s or c quarks via the Quark Parton Model. This is a lowest order QED calculation of the process  $e^+e^- \rightarrow e^+e^-f\bar{f}$ . It correctly describes a sample of  $e^+e^- \rightarrow e^+e^-e^+e^-$  events selected from the ALEPH data. For the QPM simulation the quarks were subsequently fragmented using the JETSET program[18].

### 5.2 VDM

For the Vector Dominance Model simulation, the luminosity function of reference [19] was folded with a Generalized Vector Dominance Model form factor [20], and either a constant or a  $1/W$  cross section term. The GVDM form factor was preferred to the simple  $\rho$  pole form factor because in previous experiments[11, 21, 22], where the scattered electron was measured, it has been shown to provide a better description of the data.

A new model has been developed to simulate the production of the final state hadrons in VDM, which is expected to be similar to the scattering of two  $\rho$  mesons. In this model the available energy is divided between two pairs of quarks, where each pair represents a meson. Working in the  $\gamma\gamma$  centre of mass system the momenta of the four quarks was chosen as follows. Each of the four quarks was given momentum transverse to

the  $\gamma\gamma$  direction according to the formula:

$$\frac{d\sigma}{dp_t^2} \sim \exp(-\alpha p_t^2)$$

with  $\alpha$  set to 5 (GeV/c)<sup>-2</sup> as used by PLUTO [12]. These momenta were then adjusted so that there was no net transverse momentum by subtracting one quarter of their net momentum in both x and y directions. The remaining momentum, available to each pair along the  $\gamma\gamma$  direction ( $p_l$ ), was shared between them using a flat distribution. A rotation and boost was then applied to the quarks to transform them to the laboratory centre of mass frame. Finally the quarks were fragmented using the LUND string scheme [18].

Certain parameters of the fragmentation process were tuned to obtain agreement between the model and the data in the low  $p_t$  region. The parameter controlling the  $p_t$  of hadrons with respect to the jet direction ( $\sigma_{p_t}$ ) was set at 490 MeV/c. The parameters  $a$  and  $b$  that control the shape of the LUND string fragmentation function were set to 0.18 and 0.44. Their choice reflects current knowledge of soft hadronic physics; the use of significantly different values cannot be accommodated within the standard framework of vector dominance.

### 5.3 QCD (multijets)

Within the last two years, following the increased interest in the subject of multijet production in  $\gamma\gamma$  physics, a number of Monte Carlo programs have been produced to simulate the process. Two of these, PYTHIA[23] and HERWIG[24], are additions of the  $\gamma\gamma$  initial state to existing general purpose generators. In addition the KEK experiments AMY and TOPAZ have produced purpose-written generators. When comparing these generators to the Aleph data the Drees and Grassie parameterization of the Photon Structure Function has been used[8]. The models successfully describe the  $p_t^{\text{thrust}1}$  distribution above about 2.0 GeV/c, but some differences were found in other distributions, particularly  $W_{\text{vis}}$ . In general the models from AMY and TOPAZ gave a better description of the data than PYTHIA or HERWIG. As a result of this comparison the model from TOPAZ was chosen as the QCD generator for the present analysis.

While a full QCD treatment will naturally contain QPM as its simplest diagram, for the purposes of this study they are treated separately. One reason for this is that the Vermaseren QPM generator (section 5.1) is an explicit Born term calculation for the process of Figure 2(a) and so does not require a  $p_t^{\text{min}}$  parameter. The QCD processes considered here lead to 3 or 4 jets in the final state, in contrast to the 2-jet QPM final state.

## 6 Analysis - comparison of Data and Models

The cross-section  $\sigma_{\gamma\gamma}^{\text{had}}$  can be expressed as a sum of two VDM terms, a QCD and a QPM term:

$$\sigma_{\gamma\gamma}^{\text{had}} = A + B/W + \sigma_{\text{QCD}}(W, p_t^{\text{min}}) + \sigma_{\text{QPM}}(W) \quad (1)$$

---

<sup>1)</sup>  $p_t^{\text{thrust}}$  is more commonly referred to in the literature by the name  $p_t^{\text{JET}}$ . It is intended to characterize the  $p_t$  of the original partons in a situation where jet finding is expected to be difficult. It is calculated by first boosting all observed charged tracks and neutral clusters into their centre of mass. The event is then divided into two hemispheres separated by the plane which lies at 90 degrees to the thrust axis, and  $p_t^{\text{thrust}}$  is defined by taking the vector sum of all tracks in one hemisphere and finding its component in the direction transverse to the beam direction.

A	110	$\pm 10$	$\pm 28$ nb
B	1000	$\pm 70$	$\pm 180$ nb GeV/c <sup>2</sup>
$p_t^{\min}$	2.5	$\pm 0.1$	$\pm 0.3$ GeV/c

Table 1: Fitted values of VDM cross section and  $p_t^{\min}$ .  
The first error is statistical and the second is systematic.

While the QPM term has a fixed normalization, the terms A and B of the VDM and  $p_t^{\min}$  of the QCD model can be regarded as free parameters. In order to determine these parameters a fit of the models to the data has been performed. The resulting values are shown in Table 1. The fit was repeated using different sets of input variables and the systematic errors shown are determined from the resulting range of values. Figure 3 shows the shape of  $\sigma_{\gamma\gamma}^{had}$  as a function of W using the fitted parameters. The shape of the QCD part was calculated using the formula given by Drees [25]. The value of  $p_t^{\min}$  found (2.5 GeV/c) is larger than that used by AMY and TOPAZ who favour values between 1.4 and 1.6 GeV/c [13, 14]. Our value for  $p_t^{\min}$  does however agree with the recent results on total photoproduction cross sections and hard scattering from the HERA collaborations [26].

The influence of  $p_t^{\min}$  on  $\sigma_{\gamma\gamma}^{had}$  is indicated by the upper curve on Figure 3 which shows how much more rapidly the QCD part of the cross section grows with a  $p_t^{\min}$  of 1.6 GeV/c compared to 2.5 GeV/c. It is believed that the difference in  $p_t^{\min}$  between the current analysis and the KEK results could derive from differences in treatment of the VDM part. The KEK experiments used results from earlier experiments or theory to fix their VDM models, and were thus left with only one free parameter,  $p_t^{\min}$ , whereas in the present analysis the VDM model has been tuned and normalized to the Aleph low  $p_t$  data.

The figures show how the data are described by combining the VDM, QPM, and QCD models using the best fit parameters. Figures 4, 5(a), and 5(b) show the distributions of  $W_{\text{vis}}$ ,  $p_t^{\text{thrust}}$  and charged track  $p_t^2$  for all the data compared to the various components and their sum. At low  $p_t$  and  $W_{\text{vis}}$  the data are well described by vector dominance, while at high  $p_t$  and  $W_{\text{vis}}$  where VDM falls below the data, they are well described by the sum of the QCD and QPM models.

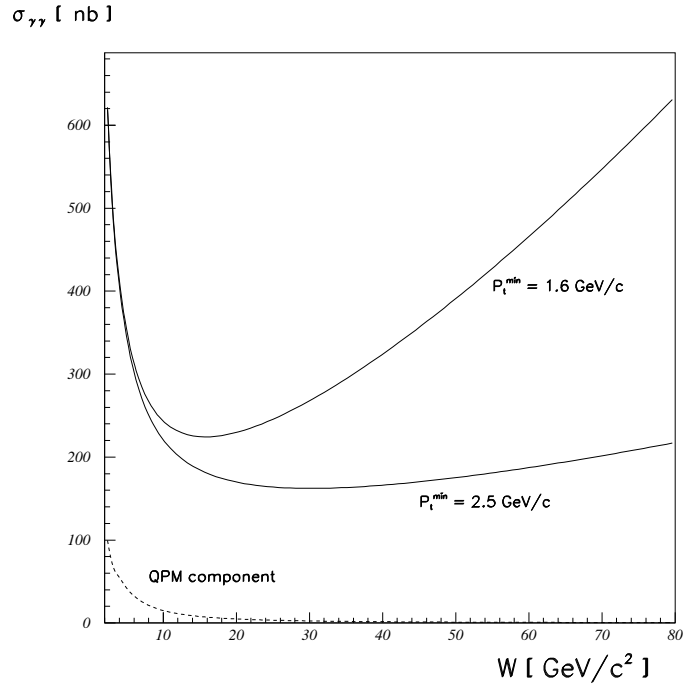


Figure 3:  $\sigma_{\gamma\gamma}^{had}$  using fitted parameters shown in Table 1. Also shown is the effect of changing  $p_t^{\min}$  from 2.5 to 1.6 GeV/c.

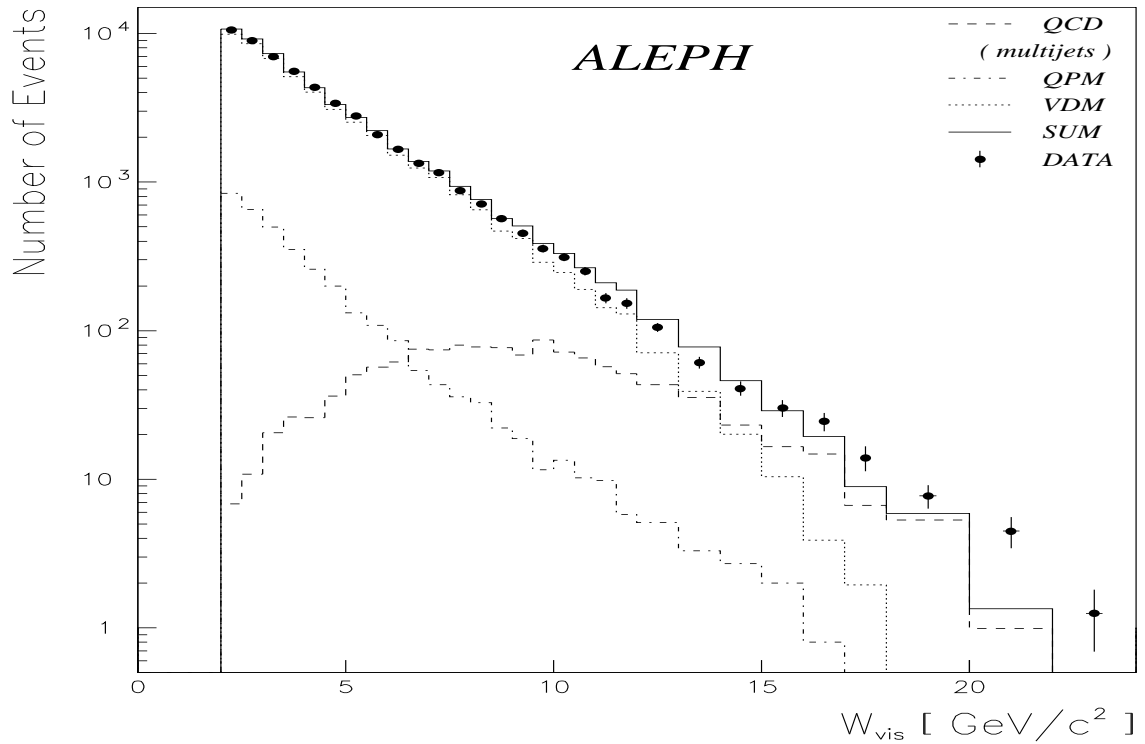
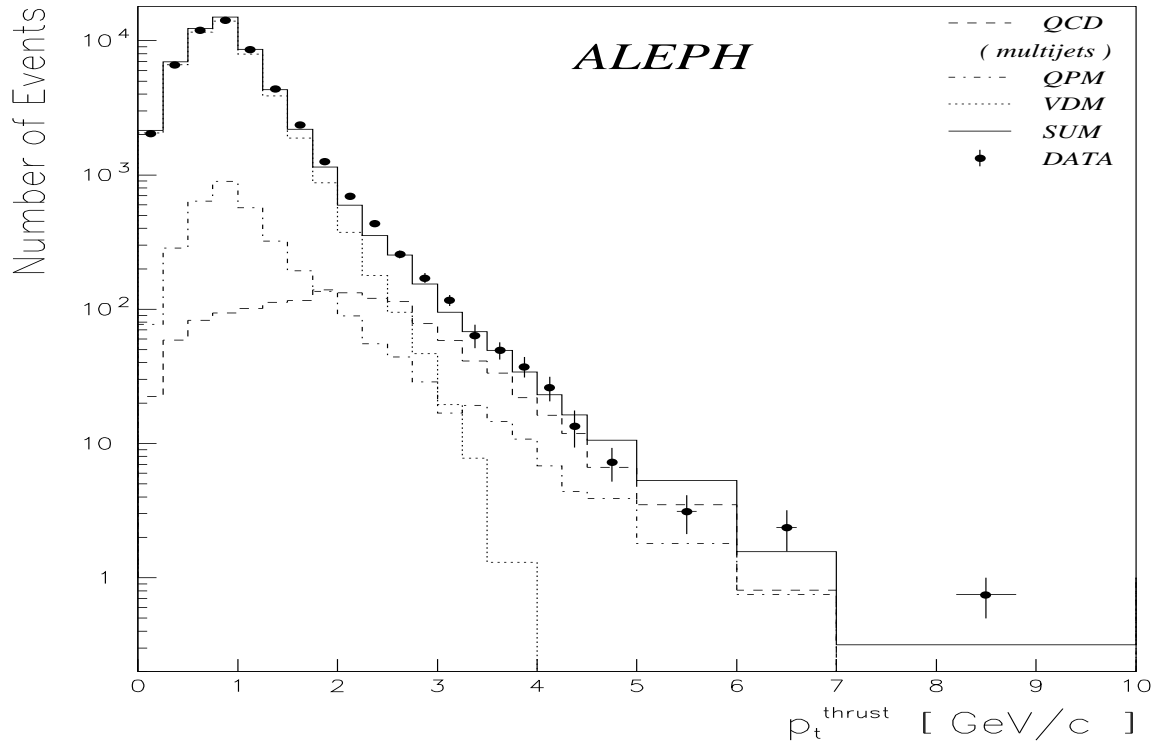


Figure 4:  $W_{vis}$  distribution.

(a)



(b)

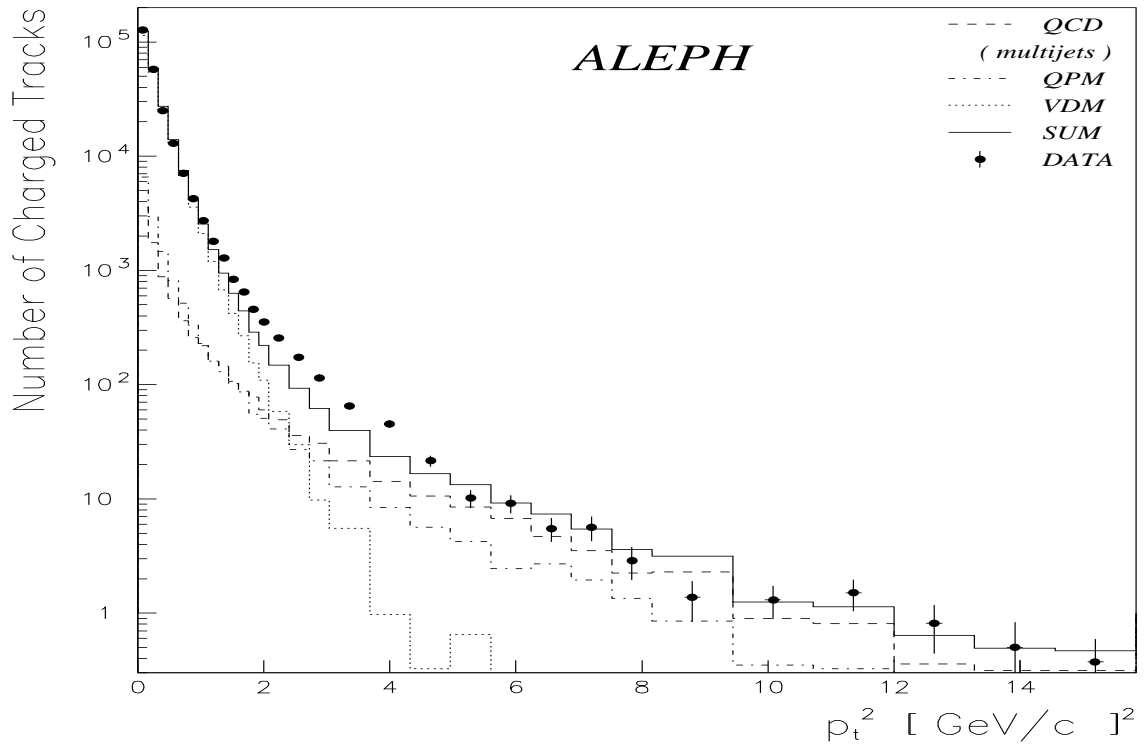


Figure 5: (a)  $p_t^{\text{thrust}}$  distribution. (b) Inclusive  $p_t^2$  distribution of charged tracks measured relative to beam direction.

The QCD contribution can be studied in more detail by selecting events with  $p_t^{\text{thrust}} > 3.0 \text{ GeV}/c$  where there is a negligible VDM contribution. Figures 6 (a) and (b) show the  $W_{\text{vis}}$  and thrust distributions for the 366 events in this region. The background subtraction here consists of 20 events from  $e^+e^- \rightarrow e^+e^-\tau^+\tau^-$ , all at high thrust, 2 events from  $e^+e^-$  annihilation, and 1 beam gas event. The QPM gives a small but significant contribution, but this is not sufficient to explain the data, particularly at low thrust. However when the large contribution from the multijet QCD diagrams is added there is good agreement with the data. Fitting the value of  $p_t^{\text{min}}$  to this subset of the data gives the result :

$$p_t^{\text{min}} = 2.5 \pm 0.4 \pm 0.4 \text{ GeV}/c$$

where the first error is statistical and the second is systematic. The systematic error was estimated by using different variables to perform the fit as before and also varying the size of the VDM component between zero and twice the value obtained in the previous fit to the full data sample.

## 7 Conclusions

A sample of the process  $\gamma\gamma \rightarrow \text{hadrons}$  has been selected. The data are well described by a combination of three models, namely VDM, QPM and QCD. The bulk of the data is at low  $p_t$ , and is well described by VDM, however at high  $p_t$  and  $W_{\text{vis}}$  there is a large excess of events over the sum of VDM and QPM alone. The data thus require an additional component at high  $p_t$  which is well described in shape and normalization by a model incorporating QCD multijet processes. A fit of the different contributions to the data yields a value of  $2.5 \pm 0.1 \pm 0.3 \text{ GeV}/c$  for the minimum  $p_t$  for hard scattering in the QCD multijet processes. This is higher than the values previously obtained at TRISTAN but consistent with recent HERA photoproduction results. Such a value substantially reduces the predicted rate of such processes at high energy colliders.

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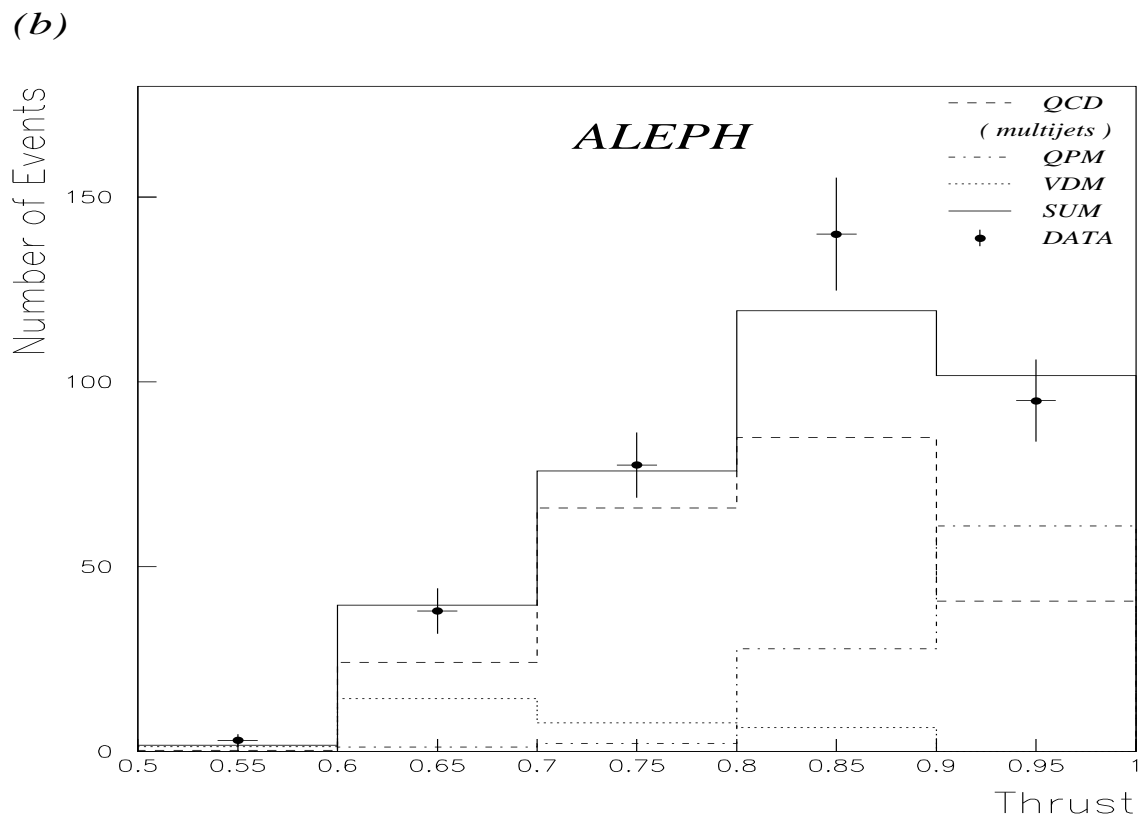
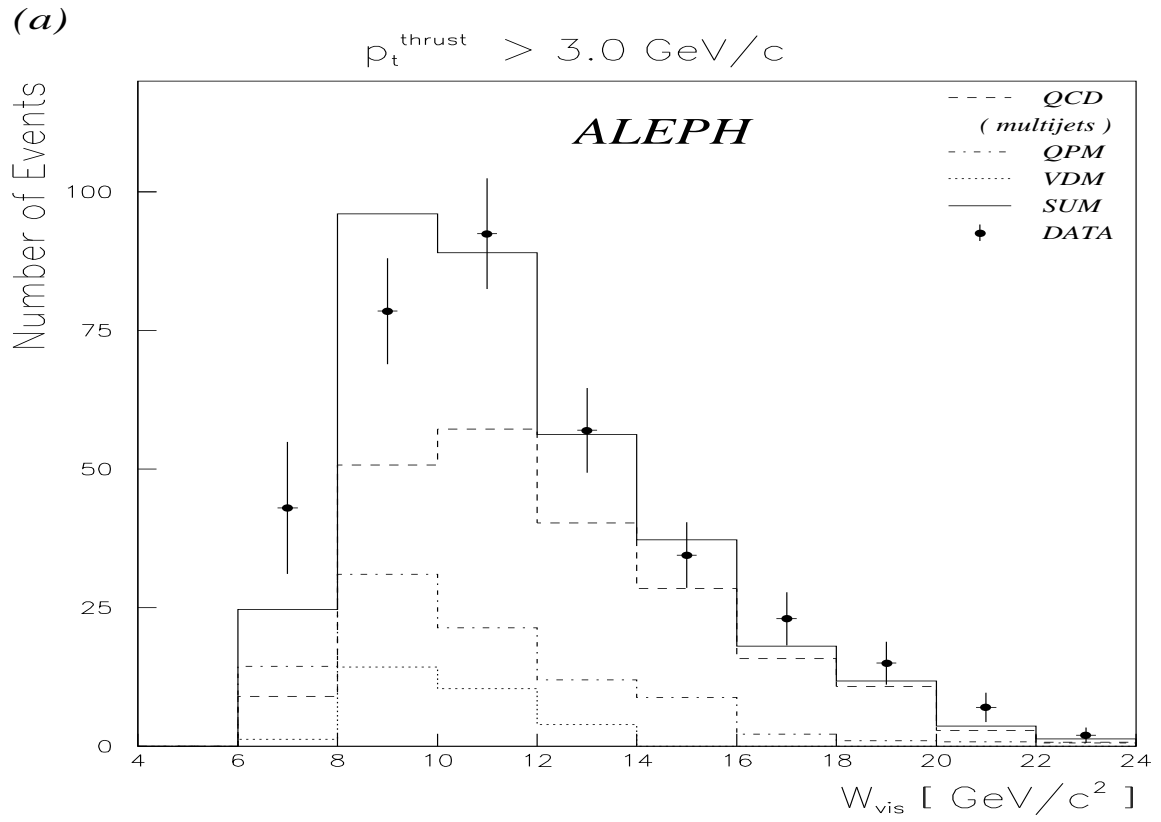


Figure 6: Distributions for events with  $p_t^{\text{thrust}}$  greater than  $3.0 \text{ GeV}/c$ ; (a)  $W_{\text{vis}}$  (b) Thrust.

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