A measurement of the di-jet cross-section in single-tagged $\gamma\gamma \rightarrow$ hadrons

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Abstract

A measurement of the inclusive di-jet cross-section measured as a function of $p_T^{Jet}$ in single-tagged $\gamma\gamma$ events has been performed. A cone-based jet algorithm was used. The corrected cross-section is found to be in good agreement with the HERWIG prediction. A theoretical calculation from JetViP does not describe the data well.

Submitted to the ICHEP2000 conference, Osaka
1 Introduction

e^+e^- \rightarrow e^+e^- + \text{hadrons}, with one of the electrons observed (the ‘tag’), can be described as the probing of a nearly real photon originating from the unobserved electron, by a highly virtual photon from the tagged electron (see Figure 1). These tagged \gamma\gamma processes have long been an area of study and are generally analysed in terms of a single scale \(Q^2\) (\(Q^2\) is the negative four momentum squared of the ‘probe’ photon emitted by the tagged electron=-\(q^2\)).

![Figure 1](image-url)

Figure 1: The QPM or direct process for \(e^+e^- \rightarrow e^+e^- + \text{hadrons}\), one of a number of possible diagrams.

An analysis of the jet structure of untagged \(\gamma\gamma\) events involves another natural scale which is the \(p_T^2\) of the hadron jets in the \(\gamma\gamma\) centre of mass frame. For the study of tagged \(\gamma\gamma\) jet production both scales are involved and indeed, for the event selection presented below, they are of a similar order (ie \(Q^2 \simeq p_T^2\)). This is a theoretically more complicated situation for which calculations have recently become available. One such is the JetViP [1] program from B. Pötter. In this paper ALEPH data are compared to the modified [2] HERWIG 5.9 [3] Monte Carlo program using the GRV set 3 [4] parton distribution function for the photon. The jet structure of the accepted events is also examined using a cone-based algorithm and a di-jet cross-section produced. This is compared to a calculation from the JetViP program.

This analysis is based on 53 pb\(^{-1}\) of data taken with the ALEPH detector at the LEP collider in the year 1997 at 183 GeV \(e^+e^-\) centre-of-mass energy. The ALEPH detector is described in detail in [5]. A cluster (the ‘tag’) of more than 70 GeV energy was required in one of the forward luminosity calorimeters (LCAL or SiCAL) within the angular range \(34\text{mrad} < \theta_{\text{tag}} < 155\text{mrad}\). The hadronic system was analysed using the ALEPH energy flow package [6] and cuts similar to those in [7] were applied to the tracks/clusters. The following event selections were made:

- the event must contain at least 3 charged tracks;
- the invariant mass of the hadronic system must be greater than 3.0 GeV/c\(^2\);
- the hadronic energy must be less than 50 GeV;
• a vertex must be reconstructed within 5 cm of the interaction point along the beam direction.

This gave a data sample of 1912 events at a measured $< Q^2 >$ of 26.5 (GeV/c)$^2$ The backgrounds remaining are small and the only significant one is the tagged $\gamma \gamma \rightarrow \tau^+\tau^-$ process. This has been modelled using a program from Vermaseren [8] and subtracted from the data.

2 Theory and Monte Carlo

JetViP (Jets with VIrtual Photons) is a computer program for calculating jet cross-sections in $ep$ and $e\gamma$ scattering. Its predictions have been compared to HERA data [9] and shown to be in reasonable agreement. The Monte Carlo model HERWIG, after simple modification, has been shown to be in reasonable agreement with tagged LEP1 $\gamma\gamma$ data [10] and HERA data [11]. Both are described further below.

2.1 JetViP

JetViP calculates, among other things, the inclusive di-jet cross-section in $e\gamma$ scattering in Leading Order (LO) and Next to Leading Order (NLO) QCD. The calculation is based on the phase-space-slicing method.

Figures 1 and 2(a)-(c) show the four diagrams which JetViP calculates both in LO and NLO. Figure 2(d) shows the Vector Meson Dominance (VMD) diagram which is not included in the calculation. As this tends to lead to a single-jet final state in the lab frame, only the di-jet cross-section has been calculated and compared to the data.

The code contains a user routine giving access to the partons of the calculation. In particular the results are available in the lab frame. This makes comparison with the data much easier as the $\gamma\gamma$ c.m.s. frame is difficult to reconstruct. This is because the events often have forward hadronic energy which is not well measured. The angle and energy of the tag and of the jets in the lab frame can thus be restricted and corresponding cross-sections produced.

2.2 HERWIG

The generation process in HERWIG starts from a complete matrix element (ME) calculation of electron-quark scattering where the electron is the source of the ‘probe’ photon. The quark is then both evolved ‘forward’ to produce the final state hadrons, and ‘backward’ towards the target photon. This backward evolution dynamically models the various types (direct, resolved, VMD) of events. In the standard HERWIG 5.9 implementation, the VMD component is simulated using a number of partons with their transverse momenta limited and following a gaussian distribution. In the modified HERWIG version studied here the gaussian distribution is replaced by a power law spectrum of the form $dk_T^2/(k_T^2 + k_0^2)$. This increases the average transverse momentum generated at the hadronic coupling and is motivated by the study of photon remnant jet properties from ZEUS [11]. In the ZEUS studies $k_0$ was a fixed scale but here it has been replaced with a dynamic event scale [10].
Figure 2: The diagrams involved in $\gamma\gamma \rightarrow$ hadrons. The JetViP program calculates (a), (b) and (c) where (a) is the single resolved contribution, (c) is the double resolved contribution and in (b) the probe photon is resolved. (d) is the VMD contribution and is not calculated.

3 Comparison of HERWIG Monte Carlo and Data

Figure 3 shows (a) $Q^2$, (b) $W_{VIS}$ (the invariant mass of the final state particles excluding the tag), (c) the number of charged tracks and (d) the energy flow of the final state particles (excluding the tag) as a function of the pseudorapidity $\eta = -\ln[tan(\theta/2)]$, where $\theta$ is the angle with respect to the beam pipe (the tag being in the negative $\eta$ direction). In this last distribution each particle is weighted by its energy and the whole plot is then divided by the total number of events to give an energy flow per event.

In Figure 3 the data, with background subtracted, are represented by the points and the solid histogram is the HERWIG Monte Carlo after full detector simulation. All are in good agreement showing that HERWIG gives a good description of the LEP2 tagged $\gamma\gamma$ data, modelling both the tag and the hadronic final state well.

3.1 Cone Jets

At hadron colliders a number of factors, including the longitudinal boost of the final state and the presence of target remnants and underlying events, has often led to the use of ‘cone’ jet-finding algorithms in preference to the ‘JADE’-type algorithms more commonly used in $e^+e^-$ annihilation physics. As similar arguments apply to $\gamma\gamma$ physics, a cone jet-finding algorithm has been adopted...
Figure 3: Data compared to fully simulated HERWIG Monte Carlo: (a) the $Q^2$ of the probe photon; (b) the measured invariant mass of the final state; (c) the number of charged tracks; (d) the hadronic energy flow.

for this study.

A track was in the cone jet if $R < 1$ where,

$$R = \sqrt{(\eta_{track} - \eta_{cone})^2 + (\phi_{track} - \phi_{cone})^2};$$

$\eta_{cone}$ was defined as the $E_t$-weighted average of the individual $\eta_{track}$,

$$\eta_{cone} = \frac{1}{E^\text{cone}_t} \sum_{\text{tracks} \in R < 1} E^\text{track}_t \eta_{track};$$

where $E^\text{cone}_t$ is the sum of the $E^\text{track}_t$ and $\phi_{cone}$ is similarly defined.

The following requirements were made on jets entering the analysis: $E^{jet}_T > 3.0$ GeV and $N_{\text{particles}}$ in jet $\geq 2$. In addition, for the following plots, the jet was required to lie within $|\eta| < 1.6$ to be in the central region of the detector. The number of jets found in each event is shown in Figure 4(a) and compared to HERWIG. The $p_T$ spectrum for all jets is shown in Figure 4(b).
A good way to check that the various components (direct, resolved, double resolved) have been well modelled is to look at the $x_\gamma$ and $x_{\text{tag}}$ distributions for di-jet events. These are:

$$x_\gamma = \frac{\sum_{\text{jets}} (E + p_z)}{\sum_{\text{hadrons}} (E + p_z)}$$

and

$$x_{\text{tag}} = \frac{\sum_{\text{jets}} (E - p_z)}{\sum_{\text{hadrons}} (E - p_z)}$$

where the tag defines the negative $p_z$ direction. Direct events where all the energy is in (or near) the two jets will have both $x_\gamma$ and $x_{\text{tag}}$ values near 1. Single resolved processes (which should have two high transverse momentum jets and one jet away from the tag) should have a low value of $x_\gamma$, but a high value of $x_{\text{tag}}$. Double resolved processes, with one beam-pipe jet in each direction, should have both low $x_\gamma$ and low $x_{\text{tag}}$. The measured $x_\gamma$ distribution is shown in Figure 4(c). The cross-hatched area shows events which were generated as QPM-like and the hatched area comes from events which were single resolved in nature. The remaining events are not easy to classify because HERWIG actually generates the events dynamically. It can be seen that the measured $x_\gamma$ distribution provides some distinction between direct and resolved events and is well modelled by HERWIG. The measured $x_{\text{tag}}$ distribution, shown in Figure 4(d), has a lower tail at lower values of $x$, indicating that there are few events where the tag photon is resolved. HERWIG again is in good agreement with the data.

4 Extracting the Di-Jet Cross-Section

The previous sections have shown that HERWIG is a good model for the data. It describes the tag, the hadronic final state and the jet system well. It is thus a suitable tool to use to correct the data for detector effects to produce a final di-jet cross-section. Figure 5(a) shows, for the selected events, the number of jets at hadron level compared to that at fully-simulated (detector) level: 80% of detector level di-jet events come from hadron level di-jet events. For the events with two jets at each level, Figure 5(b) shows the $p_T$ resolution with the jet matching done by the cone metric, $R$. This plot shows a high correlation (86%) between the $p_T$ at detector level and that at hadron level and suggests that a bin width of 3 GeV is suitable at low $p_T$ to avoid large bin-to-bin migration. A simple bin-by-bin correction can then be used to produce the final cross-section.

Figure 6(a) shows the raw di-jet $p_T$ spectrum with one entry per jet, and Figure 6(b) shows the final cross-section corrected back to hadron level. This is compared to the HERWIG Monte Carlo hadron level prediction and the JetViP calculation. It can be clearly seen that HERWIG and the data agree well, while the JetViP cross-section has a different shape. The effect of correcting back to HERWIG parton level is at most a 10% effect in the extreme bins, acting to flatten the result slightly. This therefore does not explain the discrepancy.

The measured cross-section only includes statistical errors. As HERWIG has thus far been the only model to reasonably match tagged $\gamma\gamma$ data, the systematic error from model dependence has tended to be dominant in previous structure function analyses [7]. Pythia 6.122 [12] has a preliminary version of tagged di-jet-production within it. This only generates di-jet events and is, in general, not in good agreement with the data. However the analysis has been repeated using this Monte Carlo program to produce a corrected cross-section and the full difference between the results has been included as a systematic error (Figure 7). This does not change the conclusion with respect to the theoretical calculation.
Figure 4: Data compared to fully simulated HERWIG Monte Carlo. (a) The number of cone jets. (b) The $p_T$ of all cone jets. For two jet events: (c) $x_\gamma$ and (d) $x_{tag}$. In (c) the cross-hatched area comes from HERWIG events which are QPM-like before detector simulation and the hatched area is single resolved events.

Figure 5: (a) The number of jets for selected events with two or more jets at detector level or hadron level. (b) for events with two jets at both levels, the $p_T$ correlation with jets matched in R.
Figure 6: (a) The $p_T$ spectrum for di-jet events and (b) the resulting corrected cross section compared to HERWIG (dashed) and JetViP (dotted).

Figure 7: The corrected di-jet cross-section with a conservative systematic error for model dependence is shown compared to the JetViP calculation.
5 Conclusions

Single-tagged ALEPH $\gamma\gamma$ have been studied and the data are found to be in good agreement with the HERWIG Monte Carlo generator. This generator was used to correct the data to produce a di-jet cross-section. The corrected cross-section is not found to be in agreement with a theoretical prediction from the JetViP program.

Acknowledgments

We are grateful to Bjorn Pötter for providing the JetViP program and for much help in understanding the problems involved; and to Mike Seymour for providing the modified HERWIG model and for many $\gamma\gamma$-related discussions. We wish to thank our colleagues from the accelerator divisions for the successful operation of LEP. We are indebted to the engineers and technicians in all our institutions for their contribution to the good performance of ALEPH. Those of us from non-member countries thank CERN for its hospitality.

References


[10] LEP $\gamma\gamma$ working group, Comparison of Deep inelastic Electron-Photon Scattering Data with Herwig and Phojet MC models, to be published.
