Di-jet production in $\gamma\gamma$ collisions at LEP

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Abstract

The production of two high-$p_T$ jets in the interactions of quasi-real photons at $\sqrt{s_{ee}}$ from 189 GeV to 209 GeV is studied with the data corresponding to an integrated $e^+e^-$ luminosity of 550 $pb^{-1}$. The jets reconstructed by the $k_T$-cluster algorithm are defined within the pseudo-rapidity $\eta$ range of $-1 < \eta < 1$ and the jet transverse momentum $p_T$ above 3 GeV/$c$. The differential di-jet cross section measured as a function of mean jets momentum $\overline{p_T}$ is compared to the leading order Monte Carlo predictions and to next-to-leading order perturbative QCD calculations.

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1 Introduction

The paper presents the results of the study of di-jet events produced in the two-photon collisions in the anti-tagged mode where both scattered electrons escape the setup. Large $p_T$ processes involving quasi-real photons are sensitive to both - quark and gluon - components of the resolved photons. Thus the analysis of the high $p_T$ jet production complements the studies of deep-inelastic scattering of a quasi-real photon which probe the quark distribution. Considered together, they allow to determine the parton density function of the photon. The perturbative QCD scale of the hard interactions is provided by the jet transverse energy to be used in the calculations.

The data used for this analysis were collected by the DELPHI detector [1] at LEP at $\sqrt{s_{ee}}$ from 189 GeV to 209 GeV and an integrated $e^+e^-$ luminosity of 550 $pb^{-1}$. The jets are reconstructed by the $k_T$-cluster algorithm [2] for the transverse momentum above 3 GeV/c and within the pseudo-rapidity range $|\eta| < 1$. The choice of the kinematic limits is conditioned by the desire to suppress the soft $\gamma\gamma$ interactions and to keep jets within the DELPHI acceptance. The cut on jet $p_T$ should not be too large since, besides from the decreasing of the measurement accuracy, it diminishes the contribution coming from the events with the resolved photons involved. The extending of $\eta$ domain results in the increase of the threshold effects since a part of the produced jet particles becomes outside of the setup.

The data are corrected for the detector inefficiency and acceptance effects with the leading order Monte Carlo simulation. It is also used for the estimations of the soft processes accompanying the hard initiated ones and to take into account the influence of the hadronisation. The data, unfolded from the detected particles to the produced hadron, are compared to the next-to-leading order QCD calculations [3].

2 Detector and data

The jets are reconstructed from two kind of the detected objects - the charged particles and photons. The DELPHI apparatus and performance are described in detail in [1].

Charged particles are detected in the barrel tracking system containing 3-layer silicon-strip Vertex Detector, the Inner Detector, the Time Projection Chamber, the Outer Detector and the Forward Chambers in the endcap region. The barrel detectors are located inside the superconducting solenoid providing the uniform magnetic field of 1.23 T parallel to the axis of colliding $e^+/e^-$ beams. The combined momentum resolution provided by the tracking system is few per-miles in the momentum range of the present study.

The final state photons are detected in the electromagnetic calorimeters - High density Projection Chamber in the barrel region and the Forward Electromagnetic Calorimeter in the endcap part of the setup with the polar angle coverage of $(40^\circ \div 140^\circ)$ and $(9^\circ \div 35^\circ, 145^\circ \div 171^\circ)$, respectively.

The following criteria are applied to select data sample:

- **multihadron events:** each event contains at least 5 charged particles. A charged particle is counted if its momentum is greater than 0.2 GeV/c, the polar angle is within the interval from

\footnote{throughout this paper, electron stands for electron and positron}
to 160°, the relative error of the momentum is less than 100% and the impact parameters are smaller than 4 cm in R and 10 cm in z;

- **background suppression:**
  the invariant mass of the system calculated over the charged particles (assuming pion mass) and the photons is below 35 GeV. The sum of the transverse momentum over the charged particles and the photons is below 30 GeV/c. The energy thresholds for the electromagnetic calorimeter clusters are set to 0.5 GeV;

- **anti-tagging condition:**
  there is no clusters in the luminosity monitor STIC with the energy greater than 25 GeV (anti-tagging condition). This keeps the virtualities of the photons small;

- **di-jet event selection:**
  there are two jets reconstructed by the $k_{\perp}$-cluster algorithm (see below). The pseudo-rapidity $\eta$ of each jet must be in the range $-1 < \eta < 1$ and the jet transverse momentum $p_T$ is above 3 GeV/c. Besides from these two hard process initiated jets, the event may contain jet(s) outside the pseudo-rapidity domain mentioned above. It will be quoted as a 'remnant' jet(s);

- **$p_T$ asymmetry of jets:**
  The additional cut on the average of the jet transverse momenta $\overline{p_T} > 4$ GeV/c provides the asymmetry of the jet $p_T$. The cut is introduced for the comparison with the NLO QCD calculations which are unstable for the symmetric case.

The above criteria select a data sample of 5147 events.

### 2.1 Monte Carlo simulation and background estimation

The leading order MC generator PYTHIA (version 6.205) [4] is used for the simulation of the hadrons production in $\gamma\gamma$ interactions. The program contains an interface to the external library of the parton density functions (PDF) of photon [5]. The default SaS1D PDF is taken. The soft underlying events is modeled through the multiple interactions (MIA) with several parton pairs which interact at the same event. An event with both photons resolved may contain, besides from hard initiated process and corresponding remnant jets, this additional MIA contribution.

The main background process ($e^+e^- \to$ hadrons) is simulated by the KK2f event generator (version 4.14) [6]. Its contribution is estimated to (500 ± 5) events to the selected data sample. The contamination of $\tau$ pairs produced in the two-photon interactions is evaluated to (43 ± 3) events using the BDKRC program [7]. The background of $\tau$ pairs produced in the annihilation is negligible. The events with produced W, Z bosons contribute to (38 ± 4) events.

The events of interest are triggered by several components of the DELPHI trigger system [8] and the resulting efficiency is estimated to be close to the unit.

### 3 $\gamma\gamma$ collisions and jet composer

The $\gamma\gamma$ collisions express the behavior typical to the hadron-hadron interactions, i.e. the c.m. frame of the hard scattering is moving in the $\gamma\gamma$ c.m. frame. In order to
emphasize the invariance under boosts along the beam axis, the natural variables for the jet analysis are transverse momentum $p_T$, the azimuthal angle $\phi$ and pseudo-rapidity $\eta = -\ln(\tan(\theta/2))$ of the particle.

The hadron production in the collisions of quasi-real photons, each having a pointlike and a hadron-like components, is described by a set of the leading order diagrams presented in figure 1. The interactions of bare photons (direct term) are described by the Born-box diagram within the quark-parton model (QPM). If one or both photons are resolved into a partonic structure, the process is called as a single- or double-resolved, respectively. A part of double-resolved interactions with both photons resolved into a bounded quark-pair system is described by the vector dominance model (VDM). The relative contributions depend on the kinematic regime.

The important point is an expected difference in the event topology. A QPM-like event should contain (almost) all produced hadrons inside the reconstructed jets while events with resolved photons involved are accompanied by the remnant jets. The variables sensitive to such difference are [10]

$$x^+_\gamma = \frac{\sum_{jet} (E_{jet} + p_{z,jet})}{\sum_{part} (E_{part} + p_{z,part})} \quad \text{and} \quad x^-_\gamma = \frac{\sum_{jet} (E_{jet} - p_{z,jet})}{\sum_{part} (E_{part} - p_{z,part})}$$

They are the estimators of the photon's momentum fraction involved into the hard interaction. The photons in the QPM-like events participate in the interaction entirely and both $x^+_\gamma$ and $x^-_\gamma$ should be equal to one. While the presence of the remnant (single-resolved photon) moves $x^+_\gamma$ or $x^-_\gamma$ to some lower values. For the double-resolved case, both variables are far from one. Whole $(x^+_\gamma - x^-_\gamma)$ space is split into four quadrants with the value $x_\gamma$ of 0.85. The chosen value keeps approximately equal statistics of the domains studied below. One can combine three kinematic regions: both $x^+_\gamma$ and $x^-_\gamma$ greater than 0.85 (it will be quoted as 'Dir' domain), both values are below 0.85 (double-resolved domain, 'DR') and the rest when one variable is below while another one is above (single-resolved, 'SR'). The notations are conditional and reflect the expectations that, for instance, 'Dir' domain is mostly saturated by the direct (QPM-like) events.

The $k_T$-cluster algorithm, implemented in the KTCLUS program [2], operates with the objects (they may be either detected particles or partons) and tries to join them into jets in a recursive way. The following variables are calculated for each object and a pair of the objects $i$ and $j$:

$$d_i = E_{T,i}^2 \quad \text{and} \quad d_{ij} = \min(d_i, d_j) \left[ (\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2 \right] / R^2$$

with $R$ is usually set to one. If the smallest value ($d_{min}$) in this sample is $d_{i,j}$ value of a pair, then these two objects are joined into a new object and its $E_T$, $\phi$ and $\eta$ is recalculated. Otherwise ($d_{min} = d_i$), the corresponding object is not mergeable, it is moved from the object list to the jet list. The procedure continues until there are no more objects.

4 Analysis and results

Figure 2 illustrates the features of the various parts of the $\gamma\gamma$ interactions mentioned above on the example of the total energy outside the reconstructed jets $E_{out}$. 
The 'Dir' domain (figure 2b) is saturated by the QPM-like events on 94%, the contribution of the double-resolved subprocesses to the 'DR' domain (figure 2d) is around 54%, while the 'SR' domain (figure 2c) is filled by all three types in nearly equal parts. It is seen that the model doesn’t describe the data in the part of the $(x_1^\gamma - x_2^\gamma)$ space where the contribution of the resolved processes is essential. It is also clear that the simple one-parameter renormalization of whole model is not adequate since its components must be tuned separately with the different factors.

The 3-parameters fit of the data is performed simultaneously on the following distributions: $E_{out}$, the transverse momentum balance ($\sum |p_{T,i}|$) and the total invariant mass of the detected particles. The distributions are fitted in each $(x_1^\gamma - x_2^\gamma)$ domain separately. The obtained parameters (the scale factors for each component) are $\alpha_{qpm} = (0.86\pm0.02)$, $\alpha_{s-res} = (1.49\pm0.09)$ and $\alpha_{d-res} = (1.93\pm0.05)$. The errors of the fit are included to the systematic uncertainties in the following. Figure 3 presents the background subtracted data compared to the $\gamma\gamma$ simulation for the variables which were not involved into the performed fit. The data now agree with the simulation. The fitted MC set consist of 33% QPM-like, 23% single-resolved and 44% double-resolved events. The later is subdivided into no-MIA (75%) and with MIA (25%) contributions (see below).

### 4.1 Multiple parton interactions

The modeling of the double-resolved events includes a so-called multiple parton interaction (MIA) part. Since the photons are composite objects, consisting from many partons, it is assumed that different pairwise interactions may take place during one $\gamma\gamma$ collision. It was shown that the inclusion of MIA part improves the description of the data [11]. The amount of MIA part in PYTHIA is determined by a cutoff parameter on the parton transverse momentum and the default value of 1.6 $GeV/c$ is used. MIA results in two ways. The hard process alone does not provide two jets passing through the selection criteria but being combined with MIA it provides. In other case when hard initiated jets satisfy the criteria, MIA systematically increases the jet transverse energy. The MIA contribution coming from the former is the background and it has to be estimated and subtracted from the data. For that PYTHIA was run in the mode with MIA switched off. It is found that 27% of double-resolved $\gamma\gamma$ interactions with MIA contributed would not pass the di-jet selection criteria if MIA is absent. Note that the double-resolved part of the model is fitted in a coherent way, i.e. without its splitting on MIA and no-MIA subsamples. In summary to the MIA influence, the model predicts the background coming from MIA as 7% (3%) of double-resolved part (total model prediction) while 18% double-resolved events are affected by MIA in an increase of the jet transverse momentum.

### 4.2 Unfolding of the data and hadronisation corrections

To compare the data to theoretical predictions, two more steps must be done. One needs to transform (unfold) the data from the level of detected particles to the hadrons produced in $\gamma\gamma$ interactions. The loss of a part of the produced hadrons in the event which escaped the setup, results in two ways - some events do not satisfy the selection and thus are lost, and the observed distributions in the selected events are distorted. To take into account the detector resolution effects, the RUN unfolding program [12] has been used. It uses the simulation of events in order to get the correlation between the
produced and detected $p_T$ values. For each simulated event the program determines a weight in order to reach the best fit of the data distribution. The unfolded result is then represented in the form of the histogram with the number of bins chosen to minimize their statistical correlations.

The Monte Carlo partons are considered in the leading-order and are not identical to the NLO partons in the theoretical calculations. They have to be corrected on the hadronisation effects for the comparison with the unfolded data. The corrections have been estimated by using the PYTHIA results - the $p_T$ distribution as obtained with $k_T$-cluster algorithm on the parton level is divided by one obtained on the level of the produced hadrons. Figure 4 shows the corrections depending on jet $p_T$ for both cases with MIA contribution and without it. Note that the corrections are independent on the presence of multiple parton interactions and thus the later do not introduce essential systematic uncertainties for the di-jet cross section measurement.

The data are corrected on the acceptance and the hadronisation, and the total di-jet cross section is measured as $(17.1 \pm 0.3) \text{pb}$. The expectations are $(20.2 \pm 0.1) \text{pb}$ and $(17.8 \pm 0.1) \text{pb}$ for the calculations made in the leading and next-to-leading order, respectively. The differential cross section is shown in figure 5 together with the predictions mentioned above. Note that we present the measured cross section for the $p_T$ below 14 GeV/c since the data are limited by this value.

5 Conclusions

In summary, the production of two high-$p_T$ jets in the interactions of quasi-real photons is studied with the DELPHI data taken at LEP2 at an integrated $e^+e^-$ luminosity of 550 $\text{pb}^{-1}$. The jets reconstructed by the $k_T$-cluster algorithm are defined within the pseudorapidity range of $-1 < \eta < 1$ and the jet transverse momentum $p_T$ above 3 GeV/c. The total and differential di-jet cross sections are measured for the mean jets momentum $p_T$ between 4 GeV/c and 14 GeV/c. The total cross section agrees with the next-to-leading order perturbative QCD calculations within the experimental uncertainties while they are 18% below the calculations carried out in the leading order. The measured differential di-jet cross section is also found in good agreement with NLO QCD predictions.

References


Figure 1: Main diagrams corresponding to the hadron production in $\gamma\gamma$ interactions.
Figure 2: Comparison of the total energy outside the reconstructed jets $E_{out}$ with the simulation for the all data (a), 'Dir' (b), 'SR' (c) and 'DR' (d) phase space domains. The dashed histograms correspond to the sum of the di-jet $\gamma\gamma$ interactions as predicted by PYTHIA and the background processes. The contributions of different $\gamma\gamma$ subprocesses are shown by dotted (QPM term), dashed-dotted (single-resolved) and solid (double-resolved) histograms.
Figure 3: Comparison of the background subtracted data with the simulation after the fit for the charged multiplicity (a), the invariant mass calculated with the charged particles only (b), the mean value of jet transverse momentum $\overline{p_T}$ (c) and the mean number of particles in the reconstructed jets (d). The simulation plots sum all three model components scaled with the factors above.
Figure 4: Hadronisation corrections as a function of mean jet transverse momentum $\overline{p_T}$. 
Figure 5: Differential cross section of di-jet production in quasi-real $\gamma\gamma$ interactions. The jets are reconstructed by the $k_T$-cluster algorithm within the pseudo-rapidity range of $-1 < \eta < 1$ and the jet transverse momentum $p_T$ above 3 GeV/c. Histogram shows the leading (dotted) and next-to-leading (dashed) order calculations [3].