Inclusive single-particle production in two-photon collisions at LEP II with the DELPHI detector

DELPHI Collaboration

1. Introduction

The inclusive production of hadrons in $\gamma^*\gamma^*$ interactions can be used to study the structure of two-photon collisions [1]. These photons are radiated by beam electrons which scatter at very small angles and most of them are not detected. The untagged photons are quasi-real with a mass $Q^2 \sim 0$. At LEP II these collisions are the main source of hadron production, providing a good opportunity for such an investigation and thus to check the predictions of leading and next-to-leading order (NLO) perturbative QCD computations.

The L3 and OPAL Collaborations have published results of their analyses of the inclusive production of charged hadrons in two-photon collisions [2,3]. While L3 observes a pion production cross-section largely exceeding the NLO QCD predictions at high transverse momenta (5 GeV/c < $p_T$ < 17 GeV/c), OPAL finds a good agreement with them, in the $p_T < 10$ GeV/c range of its analysis.

In this Letter we present the inclusive production of charged hadrons in collisions of quasi-real photons. Section 2 describes the selection criteria for the event sample collected for this study. The inclusive single-particle transverse momentum spectrum and the measurement of the differential charged hadrons cross-section are presented in Section 3. They are compared to theoretical QCD predictions and published results in Section 4.

2. Experimental procedure

The analysis presented here is based on the data taken with the DELPHI detector [4,5] in 1996–2000, covering a range of centre-of-mass energies from 161 GeV to 209 GeV, with a luminosity-weighted average centre-of-mass energy: 195.5 GeV. The selected data set corresponds to the period when the Time Projection Chamber (TPC), the main tracking device of DELPHI, was fully operational thus ensuring good particle reconstruction. The corresponding integrated luminosity used in this analysis is 617 pb$^{-1}$.

The charged particles were measured in the tracking system of DELPHI, which consists of the microVertex Detector (VD), the Inner Detector (ID), the TPC, the Outer Detector (OD) in the barrel, and the Forward Chambers FCA and FCC in the endcaps of DELPHI, all embedded in a homogeneous 1.2 T magnetic field. The following selection criteria are applied to charged particles:

- transverse momentum $p_T > 150$ MeV/c;
- impact parameter of a trajectory transverse to the beam axis $\Delta y < 0.4$ cm;
- impact parameter of a trajectory along the beam axis $\Delta z < 2$ cm;
- polar angle of a track with respect to the $e^-$ beam $10^\circ < \theta < 170^\circ$;
- track length $l > 30$ cm;
- relative error of its momentum $\Delta p/p < 100\%$.

The measurement of neutral particles is made using the calorimeter information provided by the electromagnetic calorimeters, the High Density Projection Chamber (HPC) in the barrel and Forward Electromagnetic Calorimeter (FEMC) in the forward (backward) regions and by the hadronic calorimeter (HAC). Events with photons tagged by the DELPHI luminometer (STIC), i.e. with high $Q^2$ values, have been rejected. The calorimeter clusters, which are not associated to charged particle tracks, are combined to form the signals from the neutral particles ($\gamma$, $\pi^0$, $K^0_L$, n). The following thresholds are set on the measured energy: 0.5 GeV for showers in the electromagnetic calorimeters and 2 GeV for showers in the hadronic calorimeter. Furthermore the polar angle of neutral tracks was required to be in the range $10^\circ < \theta < 170^\circ$.

To extract the hadronic events from the collisions of quasi-real photons the following cuts are applied:

- energy deposited in the DELPHI luminometer (STIC: $2.5^\circ < \theta_{STIC} < 9^\circ$) $\text{ESTIC} < 30$ GeV;
- number of charged-particle tracks $N_{\text{ch}} > 4$;
- visible invariant mass, calculated from the four-momentum vectors of the measured charged and neutral particles, assuming the pion mass for charged particles, 5 GeV/c$^2 < W_{\text{vis}} < 35$ GeV/c$^2$.

The first condition eliminates the so-called single and double-tagged $\gamma^*\gamma^*$ events. The condition on the charged track multiplicity as well as the lower limit on $W_{\text{vis}}$ reduce the background from $\gamma^*\gamma^* \rightarrow \tau^+\tau^-$ events. The upper limit on $W_{\text{vis}}$ cuts down the background from the $e^+e^- \rightarrow q\bar{q}(\gamma)$, $e^+e^- \rightarrow \tau^+\tau^-$ and four-fermion processes. The comparison of the $W_{\text{vis}}$ distributions (Fig. 1) for the data and the Monte Carlo (MC) generated samples of events, described below, illustrates the effects of the $W_{\text{vis}}$ cuts.

About 910k events are selected after application of the above selection criteria.

3. Data analysis and results

Monte Carlo samples of the various final states present in the data were generated for comparison with these data. The simulation of the process $\gamma^*\gamma^* \rightarrow \text{hadrons}$ was based on PYTHIA 6.143 [6] in which the description of the hadron production encompasses the processes described by the Quark Parton Model (QPM) (direct process), the Vector Dominance Model (VDM) and the hard scattering of the hadronic constituents of quasi-real photons (resolved photon process). The MC sample of events used is 2.7 times larger than the data. The main background coming from the inclusive $e^+e^- \rightarrow q\bar{q}(\gamma)$ channel has been estimated from a PYTHIA 6.125 sample. The simulations of the $e^+e^- \rightarrow$ four-fermion, the $\gamma^*\gamma^* \rightarrow \tau^+\tau^-$ and of the $e^+e^- \rightarrow \tau^+\tau^-$ backgrounds were based on the EXCALIBUR [7], BDKRC [8] and KORALZ 4.2 [9] genera-

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**ABSTRACT**

A study of the inclusive charged hadron production in two-photon collisions is described. The data were collected with the DELPHI detector at LEP II. Results on the inclusive single-particle $p_T$ distribution and the differential charged hadrons $d\sigma/dp_T$ cross-section are presented and compared to the predictions of perturbative NLO QCD calculations and to published results.

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The data are well reproduced by the sum of the simulated sam-
tions, normalized to the data integrated luminosity are also shown.
The expected Monte Carlo generated contribu-
tions, respectively. The Monte Carlo generated events were then
passed through the standard DELPHI detector simulation and re-
construction programs [5]. The same cuts were applied on the
reconstructed MC events as on the data.
The $dN/dp_T$ distribution of the charged particles of the se-
lected events is presented in Fig. 2, for tracks with pseudo-rapidity
$|\eta| < 1$, together with the Monte Carlo generated contributing processes: $\gamma^* \gamma^* \rightarrow$ hadrons (largest cross-hatching), $e^+e^\rightarrow q\bar{q}(\gamma)$, $\tau^+\tau^-$ (small cross-hatching) and $e^+e^\rightarrow W^+W^-$ (medium cross-hatching).

The differential inclusive $d\sigma/dp_T$ cross-section distribution of the inclusive production of charged hadrons in the process $\gamma^* \gamma^* \rightarrow$ hadrons has been obtained by subtracting the background contributions from the experimental $dN/dp_T$ data. The resulting distribution has been corrected, bin-by-bin, by a factor which is the inverse of the ratio of the numbers of reconstructed to generated tracks of $\gamma^* \gamma^* \rightarrow$ hadrons in Monte Carlo events. This ratio is of the order of 50–60% for 1.6 GeV/c $< p_T < 4$ GeV/c and drops to about 20% for $p_T > 10$ GeV/c, the upper bound on $W_{\text{vis}}$ being mainly re-
ponsible for the drop in efficiency on large $p_T$ tracks. The $d\sigma/dp_T$ distribution is shown in Fig. 3 for different sets of selection criteria as described below. The PYTHIA prediction is shown in Fig. 3 for different sets of selection criteria.

Fig. 1. $W_{\text{vis}}$ distributions for the data and for the simulated $\gamma^* \gamma^* \rightarrow$ hadrons
(medium cross-hatching), $\gamma^* \gamma^* \rightarrow \tau^+\tau^-$ (second largest cross-hatching), $e^+e^\rightarrow q\bar{q}(\gamma)$, $\tau^+\tau^-$ (small cross-hatching).

Fig. 2. $p_T$ distribution of charged particles of the selected sample of events, for $|\eta| < 1$.

Table 1

| $p_T$, GeV/c | $|p_T|$, GeV/c | $d\sigma/dp_T$, pb/GeV/c |
|--------------|---------------|-------------------------|
| $|p_T| < 1$   |               |                         |
| $1.6-2.0$    | $1.76$        | $(2.36 \pm 0.02) \times 10^8$ |
| $2.0-2.4$    | $2.17$        | $(8.98 \pm 0.11) \times 10^7$ |
| $2.4-2.8$    | $2.58$        | $(4.05 \pm 0.07) \times 10^7$ |
| $2.8-3.2$    | $2.98$        | $(2.10 \pm 0.05) \times 10^7$ |
| $3.2-3.6$    | $3.38$        | $(1.24 \pm 0.04) \times 10^7$ |
| $3.6-4.0$    | $3.78$        | $(7.31 \pm 0.34) \times 10^6$ |
| $4.0-4.4$    | $4.18$        | $(4.29 \pm 0.26) \times 10^6$ |
| $4.4-4.8$    | $4.59$        | $(2.95 \pm 0.22) \times 10^6$ |
| $4.8-5.2$    | $4.99$        | $(2.22 \pm 0.19) \times 10^6$ |
| $5.2-5.6$    | $5.39$        | $(1.33 \pm 0.16) \times 10^6$ |
| $5.6-6.0$    | $5.79$        | $(1.01 \pm 0.17) \times 10^6$ |
| $6.0-6.4$    | $6.19$        | $(0.70 \pm 0.14) \times 10^6$ |
| $6.4-6.8$    | $6.59$        | $(0.57 \pm 0.12) \times 10^6$ |
| $6.8-7.2$    | $6.98$        | $(0.44 \pm 0.11) \times 10^6$ |
| $7.2-7.6$    | $7.38$        | $(0.13 \pm 0.04) \times 10^6$ |
| $7.6-8.0$    | $7.78$        | $(0.03 \pm 0.01) \times 10^6$ |
| $8.0-9.0$    | $8.44$        | $(0.06 \pm 0.02) \times 10^6$ |
| $9.0-10.0$   | $9.47$        | $(0.08 \pm 0.03) \times 10^6$ |
| $10.0-12.0$  | $10.87$       | $(0.10 \pm 0.03) \times 10^6$ |
| $12.0-16.0$  | $13.53$       | $(0.16 \pm 0.05) \times 10^6$ |

To study the systematic uncertainty coming from the selection
criteria, we have varied them, in particular the $W_{\text{vis}}$ upper
limit and the track polar angle ($\theta$) cuts. A smaller upper bound
of $W_{\text{vis}}$ has the advantage of minimizing the background contribu-
tematic uncertainties have been added quadratically in Table 1. The corresponding uncertainty has been defined as PYTHIA and HERWIG [12] predictions for the $e^+e^- \to q\bar{q}(\gamma)$ one. Tracks at low polar angle are missing TPC measurements and are thus less well measured. On the other hand most contributing processes correspond to the emission of tracks peaked in the forward (backward) regions, in particular the $e^+e^- \to q\bar{q}(\gamma)$ and even more the $\gamma^*\gamma^* \to \text{hadrons}$ channels. Hence a tight ($\theta$) cut can reduce significantly the number of selected charged-particle tracks ($N_{\text{ch}}$) of a given event and consequently its computed visible energy $W_{\text{vis}}$. Fig. 3 shows the $d\sigma/dp_T$ distributions, calculated using tracks with $|\eta|<1.5$, for four sets of selection criteria varying the polar angle selection imposed on charged tracks and the cut on the visible invariant mass $W_{\text{vis}}$:

1. $10^\circ < \theta < 170^\circ$ ($|\eta| < 2.4$), $5$ GeV/c$^2 < W_{\text{vis}} < 20$ GeV/c$^2$;
2. $25^\circ < \theta < 155^\circ$ ($|\eta| < 1.5$), $5$ GeV/c$^2 < W_{\text{vis}} < 20$ GeV/c$^2$;
3. $10^\circ < \theta < 170^\circ$ ($|\eta| < 2.4$), $5$ GeV/c$^2 < W_{\text{vis}} < 35$ GeV/c$^2$;
4. $25^\circ < \theta < 155^\circ$ ($|\eta| < 1.5$), $5$ GeV/c$^2 < W_{\text{vis}} < 35$ GeV/c$^2$.

The spread of the measurements is relatively small for $p_T < 7$–8 GeV/c but increases for high $p_T$ values where the $e^+e^- \to q\bar{q}(\gamma)$ background dominates. The corresponding systematic uncertainty has been estimated as half of the spread of the four sets of measurements.

The other source of uncertainty comes from the Monte Carlo modeling. It has been estimated by comparing the PYTHIA and TWOGAM [11] predictions for the $\gamma^*\gamma^* \to \text{hadrons}$ processes and PYTHIA and HERWIG [12] predictions for the $e^+e^- \to q\bar{q}(\gamma)$ process. It was found that the relative difference on the efficiencies calculated from the various generators depends on $p_T$ but never exceeds 10%. The corresponding uncertainty has been defined as half of the difference between two generator contributions. All systematic uncertainties have been added quadratically in Table 1.

Table 1 gives the values of $d\sigma/dp_T$ as a function of $p_T$, for the selection criteria described in Section 2, the pseudo-rapidity ranges.
that if cuts such as those used in [2] are applied, $q\bar{q}$ background dominates at large $p_T$, making it difficult to draw conclusions on two-photon processes.

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**References**