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

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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.

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 ($5\ \text{GeV}/c < p_T < 17\ \text{GeV}/c$), OPAL finds a good agreement with them, in the $p_T < 10\ \text{GeV}/c$ range of its analysis.

In this Letter we present the DELPHI study of 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 FCB 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 $p_T > 150\ \text{MeV}/c$;
- impact parameter of a trajectory transverse to the beam axis $\Delta_{xy} < 0.4$ 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 (γ, π^0, K_L^0, 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: $2.5^\circ < \theta_{\text{STIC}} < 9^\circ$) $E_{\text{STIC}} < 30$ GeV;
- number of charged-particle tracks $N_{ch} > 4$;
- visible invariant mass, calculated from the four-momentum vectors of the measured charged and neutral particles, assuming the pion mass for charged particles, $5\ \text{GeV}/c^2 < W_{\text{vis}} < 35\ \text{GeV}/c^2$.

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_{vis} reduce the background from $\gamma^*\gamma^* \to \tau^+\tau^-$ events. The upper limit on W_{vis} cuts down the background from the $e^+e^- \to q\bar{q}(\gamma)$, $e^+e^- \to \tau^+\tau^-$ and four-fermion processes. The comparison of the W_{vis} distributions (Fig. 1) for the data and the Monte Carlo (MC) generated samples of events, described below, illustrates the effects of the W_{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 $\gamma^*\gamma^* \to$ *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 $e^+e^- \to q\bar{q}(\gamma)$ channel has been estimated from a PYTHIA 6.125 sample. The simulations of the $e^+e^- \to$ four-fermion, the $\gamma^*\gamma^* \to \tau^+\tau^-$ and of the $e^+e^- \to \tau^+\tau^-$ backgrounds were based on the EXCALIBUR [7], BDKRC [8] and KORALZ 4.2 [9] genera-

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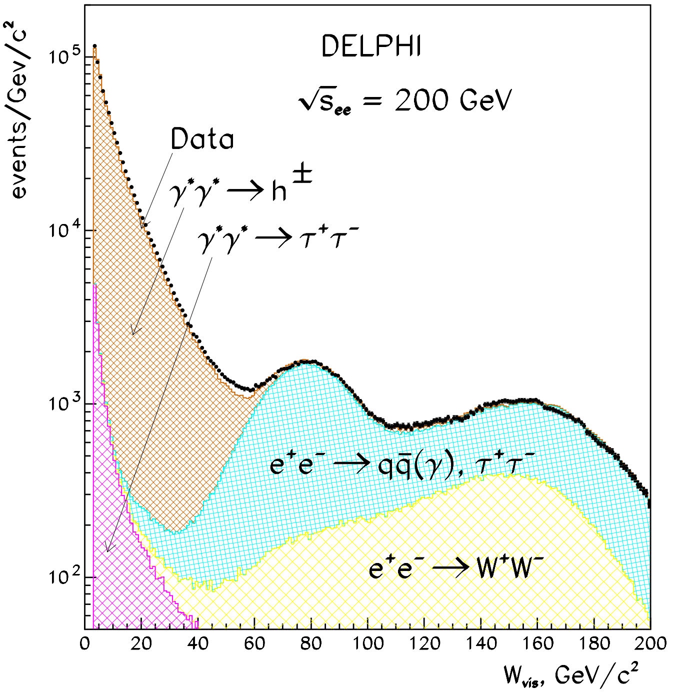

Fig. 1. $W_{\rm vis}$ distributions for the data and for the simulated $\gamma^*\gamma^* \to$ *hadrons* (medium cross-hatching), $\gamma^*\gamma^* \to \tau^+\tau^-$ (second largest cross-hatching), $e^+e^- \to q\bar{q}(\gamma)$, $\tau^+\tau^-$ (small cross-hatching) and $e^+e^- \to W^+W^-$ (largest cross-hatching) events at $\sqrt{s_{\rm ee}} = 200$ GeV.

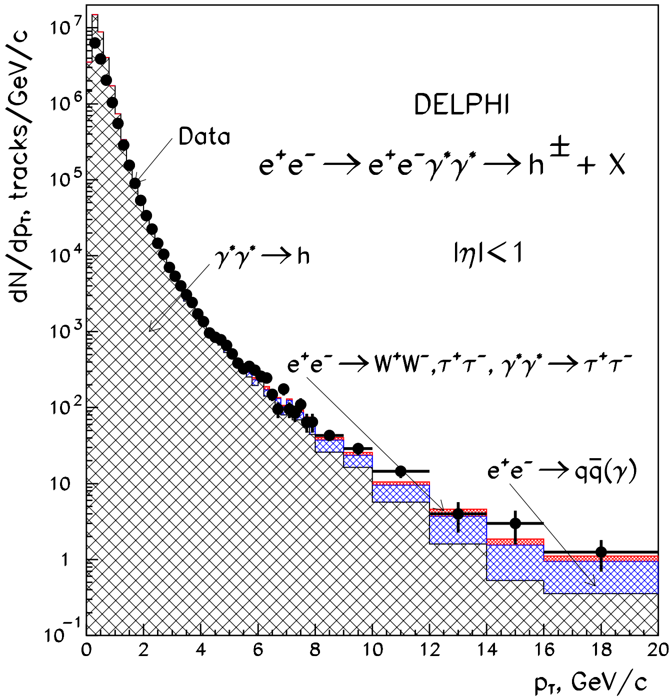

Fig. 2. p_T distribution of charged particles of the selected sample of events, for $|\eta| < 1$ together with the Monte Carlo generated contributing processes: $\gamma^*\gamma^* \to$ *hadrons* (largest cross-hatching), $e^+e^- \to q\bar{q}(\gamma)$ (medium cross-hatching), $e^+e^- \to W^+W^-$, $\tau^+\tau^-$, $\gamma^*\gamma^* \to \tau^+\tau^-$ (small cross-hatching).

tors, respectively. The Monte Carlo generated events were then passed through the standard DELPHI detector simulation and reconstruction 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 selected events is presented in Fig. 2, for tracks with pseudo-rapidity $|\eta| < 1$ ($\eta = -\ln\tan(\theta/2)$),[2] i.e. well measured tracks including TPC information. The expected Monte Carlo generated contributions, normalized to the data integrated luminosity are also shown. The data are well reproduced by the sum of the simulated samples of events for $p_T > 1.6$ GeV/c and the $e^+e^- \to q\bar{q}(\gamma)$ channel is the main contributor for $p_T > 12$ GeV/c. There is a lack of data at $p_T < 1.6$ GeV/c, becoming substantial at $p_T < 1$ GeV/c. This is caused by the trigger efficiency which was not accounted for in the Monte Carlo simulation and which is low for low p_T tracks and low multiplicities [10]. For this reason, the following comparison with theoretical predictions is presented for $p_T > 1.6$ GeV/c only.

The differential $d\sigma/dp_T$ cross-section distribution of the inclusive production of charged hadrons in the process $\gamma^*\gamma^* \to$ *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 $\gamma^*\gamma^* \to$ *hadrons* in Monte Carlo events. This ratio is of the order of 50–60% for $1.6\ \text{GeV}/c < p_T < 4\ \text{GeV}/c$ and drops to about 20% for $p_T > 10$ GeV/c, the upper bound on $W_{\rm vis}$ being mainly responsible 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 also shown. It agrees very well with the data for $p_T > 1.6$ GeV/c up to large p_T values.

Table 1
Differential inclusive $d\sigma/dp_T$ of charged particles produced in $\gamma^*\gamma^* \to$ *hadrons* collisions, for $|\eta| < 1$, $|\eta| < 1.5$ and $p_T > 1.6$ GeV/c. The first error is statistical, the second is the systematic uncertainty. The data are background subtracted and corrected for detector inefficiency and selection cuts.

p_T, GeV/c	$\langle p_T\rangle$, GeV/c	$d\sigma/dp_T$, pb/GeV/c	
		$\|\eta\| < 1$	$\|\eta\| < 1.5$
1.6–2.0	1.76	$(2.36 \pm 0.02^{+0.88}_{-0.41}) \times 10^2$	$(3.00 \pm 0.02^{+0.42}_{-0.60}) \times 10^2$
2.0–2.4	2.17	$(8.98 \pm 0.11^{+3.24}_{-1.18}) \times 10^1$	$(1.15 \pm 0.01^{+0.09}_{-0.17}) \times 10^2$
2.4–2.8	2.58	$(4.05 \pm 0.07^{+1.30}_{-0.58}) \times 10^1$	$(5.23 \pm 0.08^{+0.27}_{-0.82}) \times 10^1$
2.8–3.2	2.98	$(2.10 \pm 0.05^{+0.82}_{-0.27}) \times 10^1$	$(2.66 \pm 0.06^{+0.30}_{-0.38}) \times 10^1$
3.2–3.6	3.38	$(1.24 \pm 0.04^{+0.44}_{-0.17}) \times 10^1$	$(1.61 \pm 0.05^{+0.05}_{-0.25}) \times 10^1$
3.6–4.0	3.78	$(7.31 \pm 0.34^{+2.92}_{-1.06})$	$(9.41 \pm 0.35^{+1.03}_{-1.69})$
4.0–4.4	4.18	$(4.29 \pm 0.26^{+2.07}_{-0.47})$	$(5.54 \pm 0.27^{+0.85}_{-0.54})$
4.4–4.8	4.59	$(2.95 \pm 0.22^{+1.36}_{-0.46})$	$(3.89 \pm 0.24^{+0.42}_{-0.47})$
4.8–5.2	4.99	$(2.22 \pm 0.19^{+1.05}_{-0.12})$	$(2.78 \pm 0.20^{+0.29}_{-0.10})$
5.2–5.6	5.39	$(1.33 \pm 0.16^{+0.62}_{-0.05})$	$(1.65 \pm 0.16^{+0.19}_{-0.06})$
5.6–6.0	5.79	$(1.36 \pm 0.17^{+0.41}_{-0.25})$	$(1.70 \pm 0.19^{+0.12}_{-0.24})$
6.0–6.4	6.19	$(9.70 \pm 1.42^{+4.04}_{-1.20}) \times 10^{-1}$	$(1.16 \pm 0.15^{+0.15}_{-0.14})$
6.4–6.8	6.59	$(4.57 \pm 1.01^{+3.26}_{-0.88}) \times 10^{-1}$	$(8.34 \pm 1.36^{+0.47}_{-2.66}) \times 10^{-1}$
6.8–7.2	6.98	$(5.44 \pm 1.11^{+5.96}_{-3.03}) \times 10^{-1}$	$(6.65 \pm 1.12^{+2.52}_{-2.90}) \times 10^{-1}$
7.2–7.6	7.38	$(5.13 \pm 1.04^{+1.18}_{-0.92}) \times 10^{-1}$	$(5.43 \pm 1.09^{+0.28}_{-0.23}) \times 10^{-1}$
7.6–8.0	7.78	$(2.93 \pm 0.91^{+1.70}_{-1.57}) \times 10^{-1}$	$(3.67 \pm 0.92^{+0.38}_{-1.42}) \times 10^{-1}$
8.0–9.0	8.44	$(1.56 \pm 0.68^{+3.48}_{-1.33}) \times 10^{-1}$	$(2.65 \pm 1.23^{+1.94}_{-2.30}) \times 10^{-1}$
9.0–10.0	9.47	$(1.08 \pm 0.59^{+1.76}_{-0.89}) \times 10^{-1}$	$(1.71 \pm 0.86^{+1.41}_{-1.30}) \times 10^{-1}$
10.0–12.0	10.87	$(0.53 \pm 0.22^{+1.68}_{-0.44}) \times 10^{-1}$	$(0.68 \pm 0.28^{+1.37}_{-0.49}) \times 10^{-1}$
12.0–16.0	13.53	$(0.16 \pm 0.05^{+0.26}_{-0.02}) \times 10^{-1}$	$(0.23 \pm 0.07^{+0.43}_{-0.14}) \times 10^{-1}$

To study the systematic uncertainty coming from the selection criteria, we have varied them, in particular the $W_{\rm vis}$ upper limit and the track polar angle (θ) cuts. A smaller upper bound of $W_{\rm vis}$ has the advantage of minimizing the background contribu-

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[2] The angular selection of tracks (Table 1 and Figs. 2–5) is expressed in terms of $|\eta|$ cuts for comparison with published results [2,3].

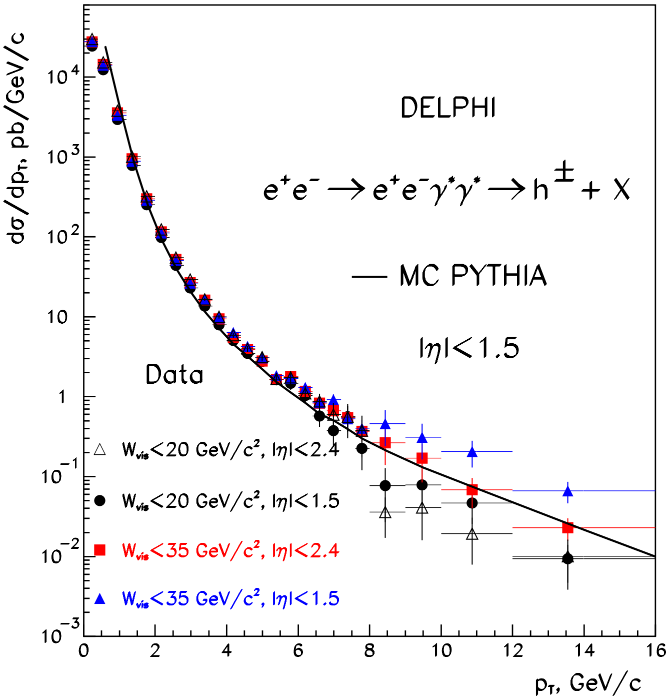

Fig. 3. Differential inclusive $d\sigma/dp_T$ distributions of charged particles with $|\eta| < 1.5$, produced in $\gamma^*\gamma^*$ collisions, for different sets of initial selection criteria. (The lower limit of W_{vis} was $W_{\text{vis}} > 5\ \text{GeV}/c^2$.) The data are background subtracted and corrected for detector inefficiency and selection cuts. The line is the corresponding PYTHIA prediction for $\gamma^*\gamma^* \to$ *hadrons*.

tions especially 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 $\gamma^*\gamma^* \to$ *hadrons* channels. Hence a tight (θ) cut can reduce significantly the number of selected charged-particle tracks (N_{ch}) of a given event and consequently its computed visible energy W_{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_{vis}:

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

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 $\gamma^*\gamma^* \to$ *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

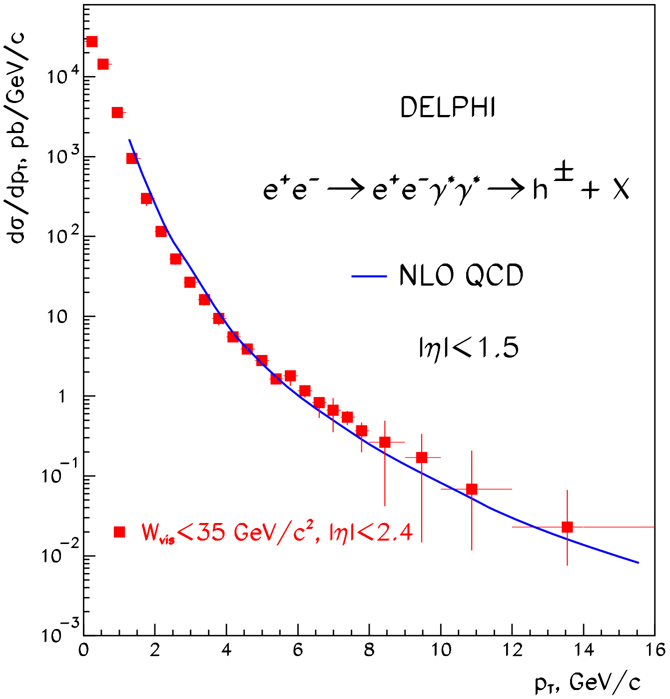

Fig. 4. Differential inclusive $d\sigma/dp_T$ distribution of charged particles produced in $\gamma^*\gamma^*$ collisions for $|\eta| < 1.5$ and $5\ \text{GeV}/c^2 < W_{\text{vis}} < 35\ \text{GeV}/c^2$. The original data sample used to extract this cross-section included tracks with $10^\circ < \theta < 170^\circ$ ($|\eta| < 2.4$). The data are shown as points with statistical + systematical error bars. They are background subtracted and corrected for detector inefficiency and selection cuts. The line is the NLO QCD prediction of [13] for $\gamma^*\gamma^* \to$ *hadrons*.

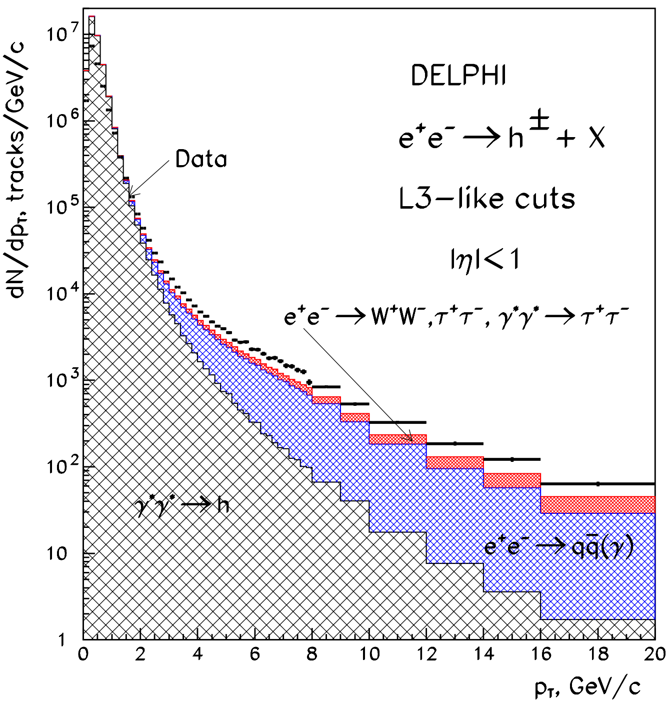

Fig. 5. p_T distribution of charged particles of the event sample after application of the "L3-like" selection criteria, for $|\eta| < 1$ and $5\ \text{GeV}/c^2 < W_{\text{vis}} < 78\ \text{GeV}/c^2$, together with the Monte Carlo generated contributing processes: $\gamma^*\gamma^* \to$ *hadrons* (largest cross-hatching), $e^+e^- \to q\bar{q}(\gamma)$ (medium cross-hatching), $e^+e^- \to W^+W^-$, $\tau^+\tau^-$, $\gamma^*\gamma^* \to \tau^+\tau^-$ (small cross-hatching).

$|\eta| < 1$ and $|\eta| < 1.5$ and for $p_T > 1.6$ GeV/c where the event trigger efficiency is close to 100%. The first error is statistical and the second one is the overall systematic uncertainty. Fig. 4 shows the comparison of the $d\sigma/dp_T$ distribution for $|\eta| < 1.5$ with the NLO QCD prediction of [13]. The theoretical computation tends to be slightly lower than the measurements at high p_T values although staying compatible with them within errors.

4. Discussion of results

Our measurement of the $d\sigma/dp_T$ cross-section of the inclusive production of hadrons in $\gamma^*\gamma^*$ interactions appears to agree well with both PYTHIA and NLO QCD predictions.

The L3 experiment has performed a similar analysis [2] and has observed that the p_T spectrum of charged hadrons is slightly below the PYTHIA MC prediction while the derived $d\sigma/dp_T$ cross-section considerably exceeds the NLO QCD prediction at high p_T values. We have repeated our analysis, adopting a "L3-like" set of selection criteria which, compared to ours, corresponds to a less tight W_{vis} cut ($W_{\text{vis}} < 78$ GeV/c^2 instead of 35 GeV/c^2) and a higher threshold of the total number of particles including neutrals (5 instead of 4). The looser W_{vis} cut has the effect of increasing significantly the $e^+e^- \to q\bar{q}(\gamma)$ background (see Fig. 1) which now dominates at large p_T values. The resulting dN/dp_T spectrum of charged particles for the "L3-like" events is presented in Fig. 5 together with the contributing channels. One observes an excess of data over the PYTHIA MC prediction. This disagreement between MC and data is likely to come from charged particles of background channels as these are introduced in much larger quantities than charged particles from $\gamma^*\gamma^* \to hadrons$, when the W_{vis} cut is relaxed up to 78 GeV/c^2, as can be checked by comparing Fig. 5 with Fig. 2. It legitimates, *a posteriori*, our $W_{\text{vis}} < 35$ GeV/c^2 cut to minimize the contamination of charged particles from background channels.

The OPAL experiment has measured the differential $d\sigma/dp_T$ cross-section of the inclusive production of charged hadrons [3] for different intervals of W, the hadronic invariant mass corrected for detector effects. In the (10 GeV/$c^2 < W < 30$ GeV/c^2) interval, the cross-section is compatible with the NLO prediction.

5. Conclusions

The study of the inclusive charged hadron production in two-photon collisions has been carried out at the DELPHI detector at LEP II. Measurements of the inclusive single-particle p_T distribution and of the differential inclusive $d\sigma/dp_T$ cross-section have been extracted. The differential inclusive $d\sigma/dp_T$ cross-section is found to be compatible, within errors, with the PYTHIA and NLO QCD predictions up to high p_T, although systematic uncertainties limit the accuracy of the comparison in this region. It is shown 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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