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HIGH MOMENTUM PARTICLE AND JET PRODUCTION IN PHOTON–PHOTON COLLISIONS*

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Jet and particle production have been studied in collisions of quasi-real photons collected during the LEP2 program. OPAL and DELPHI report good agreement of NLO perturbative QCD with the measured differential di-jet cross sections, which reach a mean transverse energy of the di-jet system of 25 GeV. L3, on the other hand, finds drastic disagreement of the same calculation with single jet production for transverse jet momenta larger than about 25 GeV. L3 observes similar disagreement between data and NLO QCD in their measurements of charged and neutral particle production at high transverse momenta of the particles. A recent measurement performed by DELPHI of the same quantities does not confirm this observation.

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1. Introduction

The large amount of hadronic photon–photon interactions at high energies recorded by the LEP collaborations during the LEPII program has led to several measurements that permit us to investigate the validity of perturbative QCD for such processes. The emerging picture confirms QCD as the correct theory to describe these interactions. There are, however, several disagreements that still need to be understood. This article will review the current state of affairs and highlight areas where more work needs to be done. Many more observables than can be discussed here are available in the original publications. In all measurements discussed in this article the photons entering the photon–photon collisions are quasi-real.

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2. Di-jet production

DELPHI [1] and OPAL [2] have studied the production of di-jets at e^+e^- centre-of-mass energies $\sqrt{s_{ee}}$ from 189 to 209 GeV, with a total integrated luminosity of 550 pb^{-1} and 593 pb^{-1}, respectively. Di-jet events are of particular interest, as the two jets can be used to estimate the fraction of the photon momentum participating in the hard interaction, x_γ, which is a sensitive probe of the structure of the photon. The $k_\perp$-clustering algorithm [3] is used for the measurement of the differential cross-sections, because of the advantages of this algorithm in comparing to theoretical calculations [4].

In leading order (LO) QCD, neglecting multiple parton interactions, two hard parton jets are produced in $\gamma\gamma$ interactions. In single- or double-resolved interactions, these jets are expected to be accompanied by one or two remnant jets. A pair of variables, x_γ^+ and x_γ^-, can be defined that estimate the fraction of the photon's momentum participating in the hard scattering:

$$x_\gamma^\pm \equiv \frac{\sum_{\mathrm{jets}=1,2} (E^{\mathrm{jet}} \pm p_z^{\mathrm{jet}})}{\sum_{\mathrm{hfs}} (E \pm p_z)} , \qquad (1)$$

where p_z is the momentum component along the z axis of the detector and E is the energy of the jets or objects of the hadronic final state (hfs). In LO, for direct events, all energy of the event is contained in two jets, *i.e.*, $x_\gamma^+ = 1$ and $x_\gamma^- = 1$, whereas for single-resolved or double-resolved events one or both values are smaller than 1. Differential cross sections as a function of x_γ or in regions of x_γ are, therefore, a sensitive probe of the structure of the photon.

The experimental results are compared to a perturbative QCD calculation at next-to-leading order (NLO) [5] which uses the GRV HO parametrisation of the parton distribution functions of the photon [6]. OPAL applies the average of the hadronisation corrections estimated by PYTHIA [7] and HERWIG [8] to the calculation for this comparison. DELPHI estimates the hadronisation corrections with PYTHIA and applies them to the data.

The differential di-jet cross-section as a function of the mean transverse momentum or energy of the di-jet system is shown in Fig. 1. Both DELPHI and OPAL observe good agreement with NLO QCD when integrating over x_γ. The cross section predicted for the case x_γ^+ or $x_\gamma^- < 0.75$ is also in good agreement with the OPAL measurement. OPAL observes a significantly softer spectrum for $x_\gamma^\pm < 0.75$ than for the full x_γ^+–x_γ^--space, as expected from the dominance of resolved processes in this region. The cross section predicted by NLO QCD is here below the measurement. It should be noted that in this region the contribution from the underlying event, not included

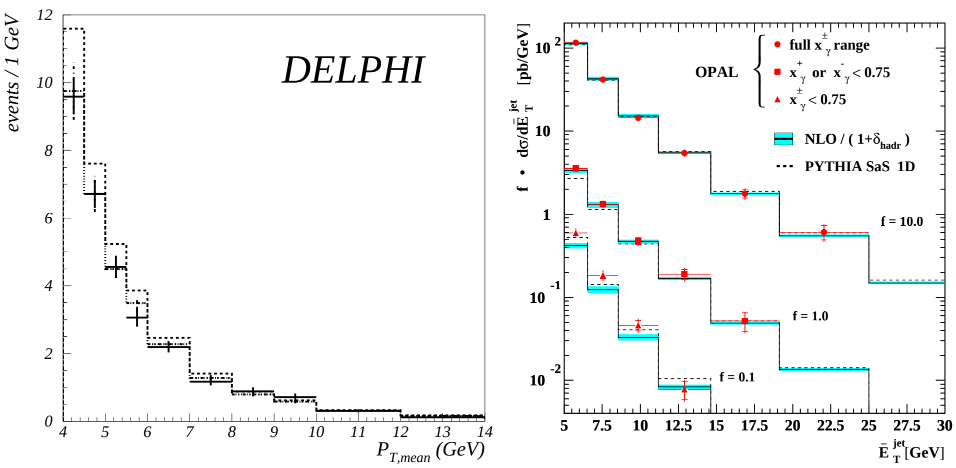

Fig. 1. Left: The di-jet cross section as a function of $P_{\mathrm{T,mean}}$ as measured by DELPHI, compared to the LO (dashed) and NLO (dotted) QCD calculation [5]. Right: The di-jet cross-section as a function of $\bar{E}_{\mathrm{T}}^{\mathrm{jet}}$ as measured by OPAL, for the three regions in x_γ^+–x_γ^--space given in the figure. The factor f is used to separate the three measurements in the figure more clearly.

in the calculation, is expected to be largest, as shown below. PYTHIA 6.161 is in good agreement with the OPAL data using the SaS 1D [9] parton densities. PYTHIA includes a model of the underlying event using multiple parton interactions (MIA).

The three plots on the left hand side of Fig. 2 show the differential cross section measured by OPAL as a function of x_γ for the three regions in x_γ^+–x_γ^--space described above. The shaded histogram on the bottom of each of the three plots indicates the contribution of MIA to the cross section as obtained from the PYTHIA MC generator. It is evident especially for $x_\gamma^\pm < 0.75$ that the MIA contribution is of about the same size as the discrepancy between the measurement and the NLO prediction. Furthermore, it is interesting to observe that there is next to no MIA contribution to the cross section if either x_γ^+ or x_γ^- is required to be less than one, while the sensitivity to the photon structure at small x_γ is retained. As one would expect also the agreement of the NLO calculation with the measurement is best in this case. For large x_γ the NLO calculation does not agree well with the data. However, it has been pointed out that the calculation of the cross section becomes increasingly problematic when approaching $x_\gamma = 1$ [10, 11].

Especially with these last measurements one is able to disentangle the hard subprocess from soft contributions and make the firm statement that NLO perturbative QCD is adequate to describe di-jet production in photon–photon collisions in the regions of phase space where the calculation can be

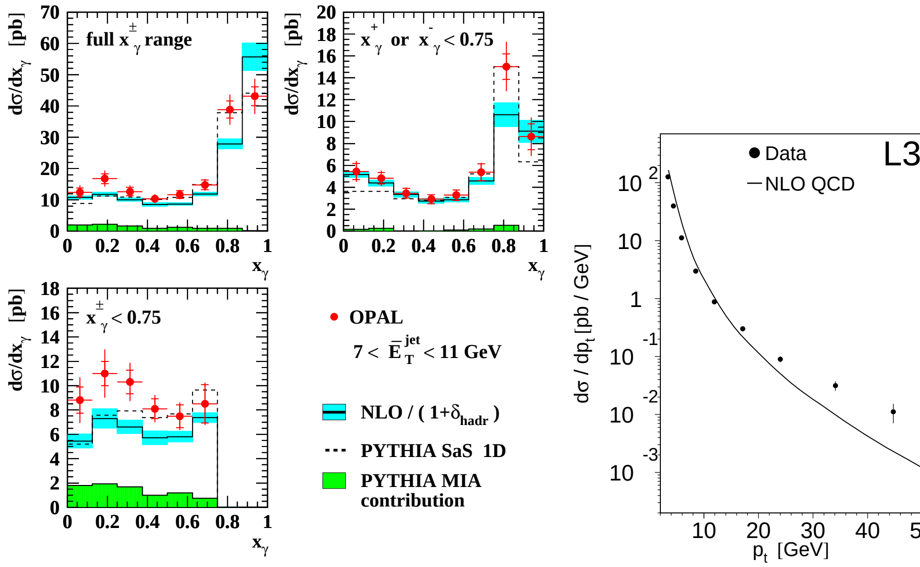

Fig. 2. Left: The di-jet cross-section measured by OPAL as a function of x_γ and for the regions of the mean transverse energy $\bar{E}_{\mathrm{T}}^{\mathrm{jet}}$ and $x_\gamma^\pm$ of the di-jet system indicated in the figures. Right: The inclusive single jet cross section as measured by L3 compared to NLO QCD. The theoretical scale uncertainty is less than 20%.

expected to be complete and reliable, *i.e.* where MIA contributions are small and for x_γ not too close to unity. At the same time a different sub-set of observables can be used to study in more detail the nature of the soft processes leading to the underlying event.

3. Single jet inclusive production

The L3 collaboration has measured inclusive jet production in photon–photon interactions [12]. A total integrated luminosity of 560 pb^{-1} recorded at e^+e^- centre-of-mass energies $\sqrt{s_{ee}} = 189$–209 GeV is used. Jets are reconstructed using the $k_\perp$-clustering algorithm and analysed in the pseudo-rapidity range $|\eta| < 1$ for jet transverse momenta $3 < p_{\mathrm{t}} < 50$ GeV. The remaining background from other processes after event selection increases from about 5% at low p_{t} to about 20% at high p_{t}. This background is subtracted bin-by-bin from the data before corrections for selection efficiency and detector acceptance are applied. The differential cross section as a function of p_{t} is shown in Fig. 2. The distribution can be described by a power law function Ap_{t}^{-B} with $B = 3.6 \pm 0.1$. A comparison to an NLO perturbative QCD calculation [10] using the GRV HO parton density functions fails to describe the data for jet transverse momenta larger than about 25 GeV.

This calculation was shown to be in agreement with the calculation compared to the di-jet observables above. There is clearly a need here for additional data to be published to confirm or contradict the observed discrepancy.

4. Hadron production

L3 has studied the production of charged and neutral pions in 414 pb^{-1} of data recorded at e^+e^- centre-of-mass energies $\sqrt{s_{ee}} = 189$–$209\,\mathrm{GeV}$. The right plot in Fig. 3 shows the transverse momentum spectrum of charged pions. It is evident that the corresponding calculation in NLO QCD fails to describe the data for momenta larger than about 4 GeV. At the highest charged particle momenta measured the theory underestimates the data by more than an order of magnitude. A similar measurement by L3 of neutral pion production [15] leads to the same conclusions. Yet the presence of high momentum particles should indicate the presence of a hard scale, and the perturbative calculation should be reliable. The discrepancy can, therefore, not easily be understood in terms of the NLO calculation on parton level. Furthermore, at high momenta the interaction of two photons is expected to be dominated by the so-called direct process, *i.e.* the exchange of a fermion, such that uncertainties in the knowledge of the photon structure are not expected to be very important. The experimental background at the largest momenta measured has been estimated from MC to be about 20%, and is subtracted from the data before the comparisons with theory are carried out. To compare the parton level calculation to the data, it is folded with the

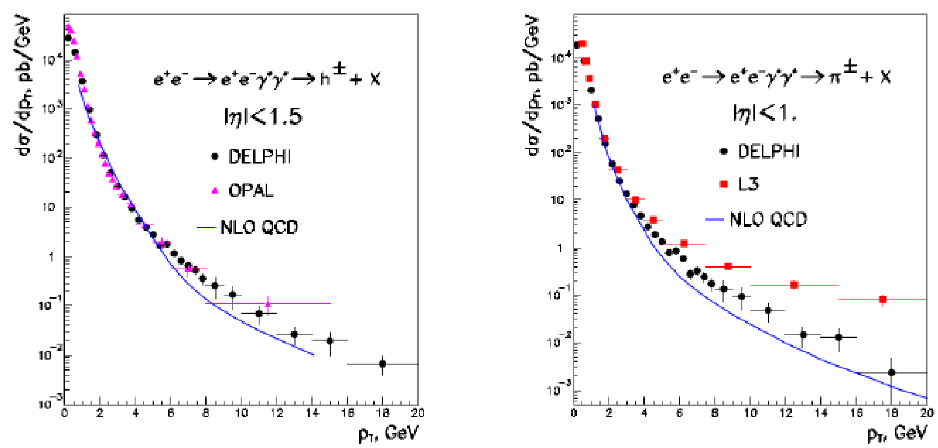

Fig. 3. Transverse momentum spectra of charged hadrons as measured by DELPHI and OPAL (left) and of charged pions as measured by DELPHI and L3 (right). In both cases the measurement are compared to a calculation in NLO QCD [13]. Figure taken from [14].

appropriate fragmentation function. It is not expected that fragmentation effects could explain discrepancies of this magnitude. Furthermore, in the study of single jet production described above, which is sensitive to the same partonic processes, no fragmentation functions are used in comparing data and theory. Hadronisation corrections in the upper half of the transverse momentum spectrum shown in the right plot of Fig. 2 are estimated to be below 10%. One has to conclude that these discrepancies seen in the L3 data are very significant, and at present not understood.

DELPHI has performed a similar measurement of charged hadron production in 617 pb^{-1} of data with centre-of-mass energies $\sqrt{s_{ee}}$ = 161–209 GeV [16]. The right plot in Fig. 3 shows the DELPHI data in comparison with L3 and the prediction of NLO QCD. The DELPHI measurement is clearly incompatible with the L3 data and in much better agreement with NLO QCD, if still somewhat above the calculation at larger transverse momenta. In studying the background especially at the largest available transverse momenta DELPHI finds that a more restrictive event selection is needed in their case to reduce the background to an acceptable level. This concerns in particular the upper limits on the total energy or on the total invariant hadronic mass in the event used to suppress background from hadronic decays of the Z^0. When modelling their selection on the one used by L3, DELPHI observes the high transverse momentum region to be dominated by this background. While this may serve as an indication of the difficulties involved in measuring the hadron spectra in the region of large transverse momenta, it should be noted that the level of background to a signal process remaining after a set of selection criteria have been applied depends to some extend on the experimental apparatus, and hence cannot be directly compared across experiments.

The left plot in Fig. 3 compares the DELPHI data to an older measurement of OPAL [17] at lower energies. The OPAL data do not yet reach high enough in transverse momentum to contribute to the discussion of the data-theory discrepancies observed by L3. Measurements of high momentum hadron production from ALEPH and OPAL using the full LEPII data set would clearly be very interesting to see.

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