Photon Structure and Heavy Flavour Production in $\gamma\gamma$ Collisions at LEP

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New results reported at the Moriond-QCD 2003 conference from the experiments ALEPH, DELPHI, L3, and OPAL on the structure of the photon as well as heavy quark production in $\gamma\gamma$ collisions are presented. The hadronic structure of the photon is studied in single-tagged events; the interaction of two virtual photons is investigated in double-tagged events. Di-jet events allow, besides constraining the photon structure, investigations on the structure of jets, measurement of the di-jet as well as inclusive and differential cross sections. Inclusive charm and bottom production are investigated at LEP 2 energies. The total and differential cross sections for charm quarks are now measured by all four LEP collaborations, the total bottom by two. Charmonia are detected inclusively via the muonic decay of the $J/\psi$ and separated for the resolved and diffractive processes. Updated results are available for exclusive production of the $\eta_c$ meson. The search for exclusive $\eta_b$ production is presented.

1 Introduction

The hadronic photon structure function is measured in single-tagged events. The structure function separates into two parts, the pointlike part, which is calculated in perturbative QCD and the hadronlike part, which is not accessible in perturbative QCD at low $x$. Here, when the photon fluctuate into a state similar to a light vector meson, the gluon content of the photon is important. Double-tagged events test the interaction of two virtual photons and probe next-to-leading QCD predictions. These topologies might restrict BFKL calculations, where the DGLAP evolution is not applicable. The study of di-jet events gives insight into the structure of the photon as well. The jets may carry a certain fraction $x$ of the momentum of the incoming photon. In the direct process, when the two photons produce a quark anti-quark pair, both jets carry large $x$. For single and double resolved processes, when one or both photon appear resolved, the fractions may be smaller. Di-jet events offer even a richer spectrum of measurements and tests, such as differential cross section, jet shapes etc.
Inclusive heavy flavour production in two-photon collisions is dominated by two processes, the direct and single-resolved process. It therefore reveals the structure of the photon and is sensitive to its gluon content. At LEP 2 energies direct and the single-resolved processes contribute in equal shares to heavy flavour final states. The charm cross section is about two orders of magnitude larger than the bottom production due to the smaller quark mass and higher electric charge. The large quark mass allows the production of heavy flavour to be calculated in perturbative QCD, where the resolved part also depends on the assumed gluon density of the photon.

The exclusive charmonium production has a diffractive contribution at low $p_T^2$ of the vector meson (pomeron exchange) and a resolved contribution at high $p_T^2$ (gluon exchange). The resolved production of $J/\psi$, when calculated in the nonrelativistic QCD, predicts that the colour-octet contribution dominates. Exclusive charmonia and bottomonia production at LEP 2 provides a precise tool to test QCD at low energies. Their two-photon widths and masses are constraint by approaches used in lattice QCD, nonrelativistic QCD and potential models.

In this article we summarize the progress made with respect to last year on the photon structure and in heavy flavour production in two-photon collisions at LEP: improvements, updates and new results are reviewed. The inclusive hadron and pair production are discussed in a separate talk at this conference. For a prior status of two-photon physics, we recommend Ref. 2 for results mentioned in this report but not cited also refer to Ref. 2 and references therein. A short and recent more general overview on two-photon physics and the interaction of the photon can be found in Ref. 3.

2 Photon Structure

2.1 Hadronic Photon Structure Function

Two new results are contributed to this conference, one final publication (ALEPH) and a preliminary result (DELPHI). The photon with the larger momentum transfer $Q^2$, which is radiated by the beam-electron with the larger scattering angle probes the target photon’s structure. The latter is radiated as a real photon such that the scattered beam-electron escapes undetected down the beam-pipe. From the measurement of the invariant mass $W_{\gamma\gamma}$ of the hadronic system produced by the two colliding photons $x = Q^2/(Q^2 + W_{\gamma\gamma}^2)$ can be calculated; then $x$ is the momentum fraction of the parton in the real photon, which is probed. (See Ref. 2 for a general overview on photon structure functions.) New results are consistent with previous measurements at similar $Q^2$ as shown in Figure 1. The data disfavour structure function with large gluon content, which predict a steep rise versus low $x$.

It has been noticed that with the improved understanding and larger statistics due to the LEP measurements a value for the strong coupling constant is extracted, competitive and compatible with other measurements.

2.2 Double-Tagged Events

The interaction of two virtual photons is investigated using double-tagged events. In the new contribution from the ALEPH collaboration, which is being published, the measurements are compared to Monte-Carlo predictions, a next-to-leading order (NLO) calculations and to the BFKL approach. The data are consistent with previous measurements. Monte-Carlo models describe the shape of various distributions of the data quite well. The NLO calculation predicts a cross section lower than is measured, while the shape follows the data in most distributions. Little room is left for further contributions, especially at high $Y$, with $Y = \ln(s_\text{in}/s_0) \approx W_{\gamma\gamma}^2/\sqrt{Q_T^2Q_\gamma^2}$ (Where this approximation requires that the invariant mass of the hadronic system $W_{\gamma\gamma}$ is larger...
that the individual momentum transfers $Q_i$, i.e., $W_{\gamma\gamma}^2 \gg Q_i^2$): LO-BFKL is therefore ruled out. NLO-BFKL is in reasonable agreement with the measurements.

2.3 Di-Jet Production

The study of di-jet production by OPAL in collisions of two quasi-real photons^9 is a rich laboratory both for the investigation of the structure of the photon, jet properties and physics associated with jet production in general. Only a small part can be indicated here. From the energies and momenta of the hadrons and jets, the data sample can be separated into direct, single- and double-resolved processes calculating $x_\gamma$, like $x$ before, an estimate of the momentum fraction of the parton in the real photon. The inclusive di-jet cross section as function of the mean transverse jet energy extracted is nicely described by NLO, when PYTHIA or HERWIG is used for hadronization correction. Deviations are only seen for the double-resolved events. This might be a hint for multiple interactions. Jet-profiles are reproduced by Monte-Carlo models. The angle between the di-jet axis and the incoming partons shows evidence for the quark and gluon exchange contributions. The first measurement of the differential cross section of function of $x_\gamma$ is shown. Again disagreement is observed for double-resolved events: the difference of data and NLO prediction is just as large as the contribution predicted by the model for multiple interaction of the partons in the photon.

3 Heavy Flavour Production

3.1 Inclusive $D^{\pm}$ Production

All four LEP experiments measure now the inclusive charm production using most of their LEP 2 statistics (corresponding to an integrated luminosity of $\approx 700 \text{ pb}^{-1}$) at energies around $\sqrt{s} \approx 200 \text{ GeV}$ with fully reconstructed $D^{\pm}$ mesons in no-tag events; a new publication from ALEPH is contributed to Moriond^{10} (Also added in the total cross section diagramm is the update of L3^{11} using leptons as charm tag.), see Figure 2.

The experiments provide differential distributions in pseudorapidity. The distributions are found to be flat in this variable, what is in agreement with the expectation for NLO calculations. The distribution in transverse momentum to the beam axis as predicted in NLO calculations in the massive approach agrees with the data. (More recent calculations^{12} using massive or massless charm quarks also describe the data well.)

Direct and single-resolved contribution can be separated using the fact that in the resolved one the remnant jet carries away a part of the invariant mass available in the $\gamma\gamma$ collision. The relative contribution fitted with the data of the ALEPH experiment are found in agreement with the NLO prediction and with previous measurements.

3.2 Total Charm Cross Section

Extrapolated to the full phase space, the measurements using the $D^{\pm}$ as the charm tag, can be compared to NLO QCD calculations and other measurements, see Figure 2 All data are consistent. If only the direct contribution is considered the prediction at LEP 2 would be lower by a factor two. It should be noted that for the measurements with leptonic final state a light charm quark mass is slightly preferred.

3.3 Charm Structure Function $F^{\gamma}_{c,2}$

When one of the scattered beam particles is detected, the event can be used to determine the charm structure function $F^{2}_{\gamma,c}$. With $55.3 \pm 11.0$ such single-tagged events with a $D^{\pm}$ meson
from the full LEP 2 statistics, the OPAL collaboration published a measurement in two bins of $x$ with $\langle Q^2 \rangle \approx 20 \text{GeV}^2$\textsuperscript{13}. The comparison with the calculations shows that a point-like contribution is not sufficient to describe the data. A hadron-like part is needed. The data even exceed the models, though the measurement errors are still too large to be conclusive.

### 3.4 Inclusive Bottom Production

Open bottom production is measured by the L3 and the OPAL collaborations at LEP 2 energies. For this conference L3 updates their result to the full integrated luminosity at LEP 2\textsuperscript{11}. Their analysis procedures exploit the fact, that the momentum as well as the transverse momentum of leptons with respect to the closest jet is higher for muons and electrons from bottom than from background, which is mainly charm. Therefore, leptons with momenta of more than 2 GeV are selected and their momentum distribution with respect to the closest jet is investigated.

The total cross section measurements for open bottom production are compared to NLO calculations, showing that the calculations underestimate the data by a factor three corresponding to three to four standard deviations.

### 3.5 Inclusive J/ψ

DELPHI investigates the inclusive J/ψ production in $\gamma\gamma$ collisions at LEP 2 energies\textsuperscript{14} with a clean signal of $36\pm7$ muonic J/ψ decays. From a fit of the diffractive and resolved contribution, as taken from the PYTHIA simulation, a value of $74\pm22\%$ is extracted to originate from the resolved process: a clear indication for the gluon in the photon. In a recent paper the octet production of J/ψ in association with jets has been discussed\textsuperscript{15} and found to be needed for an agreement with the DELPHI measurements.

### 3.6 Exclusive $\eta_c$

The formation of the $\eta_c$ in exclusive production in two-photon production is a good test of QCD (See Ref.\textsuperscript{16} for a short summary of the present status of studies of exclusive particle production
in two-photon events). A preliminary study of ηc production at LEP 2 is contributed by the DELPHI collaboration to this conference.\(^{17}\) Nice signals are found in the decay modes of the ηc to π⁺π⁻K⁺K⁻, K⁺K⁻K⁺K⁻, and K_{S}K⁺π⁻. No signal, however, is seen in the π⁺π⁻π⁺π⁻ decay mode, though it is expected when the branching fraction of Ref.\(^{18}\) are implied. An upper limit on the two-photon width for this channel is given, while for the other three a value somewhat higher than the world average\(^{18}\) and recent measurements\(^{10}\) is extracted.

### 3.7 Exclusive ηb

As reported at last year’s Moriond conference, the ALEPH experiment published a search for the still undiscovered ηb pseudoscalar meson in γγ collisions via exclusive production, i.e., all decay products are observed in the detector. A preliminary search from L3\(^{19}\) is presented here.

The mass of the ηb can be extracted, e.g., from potential models, pQCD, NRQCD, and lattice calculations. While the production can reliably be estimated the branching ratios of the meson are guessed from an MLLA combined with LPHD and using isospin invariance\(^{20}\). Including detector efficiency and acceptance about one to two signal events are expected; background events about one.

The meson has been search for in four different decay channels by L3. Three candidates are found (while ALEPH had found one candidate, but with a better mass resolution), which are compatible with the background expectation. Limits are given for the product of the particle width times branching ratio of a few hundred eV.

### 4 Summary

In this article we summarize the ten contributions on the structure of the photon and of heavy flavour production in two-photon collisions submitted to the Moriond-QCD 2003 conference. The space being limited, we recommend the reader to consult the papers in the bibliography and references therein for the very details.

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