Review of Two-Photon Interactions

David Urner
Cornell University

Abstract. Presented are recent results of two-photon interactions. Topics include photon structure functions, inclusive hadron production, differential cross sections derived from tagged $\gamma\gamma$ fusion events and results in exclusive hadron production, particularly the observations of the $\eta'$. Two-photon interactions provide a unique opportunity to study a large variety of physics topics. In electron positron machines two photons are emitted producing the photon-photon interaction. One can use this process to examine the structure and interaction of the photon. Two-photon data allow for a large number of tests of perturbative QCD and the exploration of non-perturbative phenomena in the light meson sector.

PHOTON STRUCTURE FUNCTION

Two photon interactions are instrumental to extract the hadronic structure function of the photon, which is related to the quark densities in the photon. It is measured in single tagged events, which means that one of the photons is real, and the other has a large momentum transfer much larger than $\Lambda_{QCD}$. This process can be viewed as deep inelastic electron $e^{-}\gamma$ scattering, where a quasi real photon is probed by a virtual photon with high $Q^2$. The differential cross section $F^T_2(x, Q^2)$ is related to the hadronic structure function:

$$\frac{d^2\sigma_{e^-\gamma\rightarrow\gamma X}}{dx dQ^2} = [(1 + y)^2 F^T_2(x, Q^2) - y^2 F^L_2(x, Q^2)] \frac{2\pi\alpha^2}{xQ^2} \quad \text{with} \quad x \sim \frac{Q^2}{Q^2 + W^2}, \quad y = \frac{E_{tag}}{E_{beam}} \cos^2 \theta.$$

The longitudinal term can usually be neglected since $y^2$ is small. The LEP2 data has considerably extended the reach towards small $x$. The present level of precision starts to challenge current structure function parameterizations. The newest result comes from ALEPH in the $Q^2$ range of 17.3 and 67.2 GeV$^2$ [1].

HEAVY QUARK PRODUCTION

Heavy quark production, provides important tests of perturbative QCD as well as probing the partonic densities in the photon. Recent results include a $D^*$ measurement of ALEPH [2] and a muon semileptonic measurement by DELPHI [3]. ALEPH shows that besides $W$, also the transverse momentum and the differential cross section in $p_T$ and $\eta$ are in good agreement with NLO QCD. DELPHI added a preliminary third measured point of the total bottom cross section, which agrees well with results from OPAL and L3. The large quark mass should allow good accuracy in perturbative calculations.
However the current status of NLO QCD underestimates the cross sections by about a factor of 3. This discrepancy cannot be tuned away by changing the b-quark mass.

**INCLUSIVE MESON PRODUCTION**

L3 has complemented their earlier result in inclusive π⁰ production with an inclusive charged pion and kaon production measurement [4], using the LEP2 data in the region of $W_{\gamma\gamma} < 5$ GeV and $Q^2 < 8$ GeV², see Figure 1b. There is a good agreement between data and NLO QCD below a $p_T$ of 3 GeV, but above about 5 GeV the data clearly surpass the expectation similar to the excess previously observed in the π⁰ and $K_s$ spectra. In the inclusive single jet production the data is compared to a NLO QCD calculation [5], which agrees well with many inclusive observables for the older OPAL data. However for the L3 data, see figure 1b), which go to a higher $p_T$, there is again a clear deviation observed [6].

**EXCLUSIVE HADRON PAIR PRODUCTION**

For small photon virtualities, large s and large momentum transfer from the photons to the hadrons, treating the $\gamma\gamma \rightarrow hh$ system in leading twist perturbation theory, the transition amplitude factorizes into a hard scattering amplitude $\gamma\gamma \rightarrow q\bar{q}q\bar{q}$ + a single hadron distribution for each hadron [7]. The handbag model adds a soft 2-hadron distribution amplitude in what is basically a power correction.

**Untagged $\gamma\gamma \rightarrow \pi\pi, KK$, Baryon-Antibaryon**

The handbag model predicts the ratio $\frac{\gamma\gamma \rightarrow \pi\pi}{\gamma\gamma \rightarrow KK} = 1$ [8], while the leading twist calculation would predict a ratio of 2. Aleph, Delphi [9], and with higher statistics, but still preliminary, BELLE [10] have measured these decays and find indeed that the ratio is around 1 over the full W range. The handbag model also predicts a $1/\sin^4(\theta)$ behavior for the differential cross section, which agrees well with the data.

Comparing predictions made in the framework of the hard scattering approach [7] with the $\gamma\gamma \rightarrow$ Baryon-Antibaryon cross section one is sensitive to the quark structure of the baryon. Reasonable agreement with the quark-diquark model [13] is found by the L3, OPAL, CLEO and BELLE [11] experiments in the $p\bar{p}$, $\Lambda\bar{\Lambda}$ and $\Sigma\bar{\Sigma}$ final states, see figures 1b)-1d), although the BELLE data starts to challenge the diquark model, while three-quark model [12] predictions are too low. The $\gamma\gamma \rightarrow p\bar{p}$ spectra can be used to fit the parameters of the handbag model, and hence make predictions for the cross sections of all other baryon octet members [14], using one additional parameter $\rho$ - a ratio of form factors of the proton. They agree with the $\Lambda\bar{\Lambda}$ and $\Sigma\bar{\Sigma}$ measurement by CLEO and L3 [15], see figure 1b). One notes that for $W_{\gamma\gamma}$ below 2.6 GeV there are experimental discrepancies between the BELLE and CLEO experiments for the $p\bar{p}$ [1b]) and between the L3 and CLEO experiments for the $\Lambda\bar{\Lambda}$ [1c] final states, which should be resolved.
The L3 experiment measured $\gamma\gamma \rightarrow \rho^0\rho^0$ and $\gamma\gamma \rightarrow \rho^+\rho^-$ processes \[17\]. A simple partial wave analysis was performed on the 4-pion final states, including only $\rho\rho$ partial waves plus a 4 $\pi$ isotropic background, fitting the data separately for each W bin. The only contributing waves have a $J^P, J_Z$ of 0$^+$ and 2$^+, 2$ as shown in figure 2. From this result one would conclude, that the isospin ratio of the $\rho\rho$ cross sections is incompatible with either I=0 or I=1.

The L3 experiment also analyzed the two-photon production of $\rho^0\rho^0$ in the single tagged mode at $\sqrt{s} = 89-209$ GeV \[17\], which allow a test of the qq, gg $\rightarrow$ meson-pair mechanism. The $\rho^0\rho^0$ signal was separated from the $\rho^0\pi^+\pi^-$ and 4$\pi$ backgrounds with the box method. Figure 2(c) shows the $\gamma^*\gamma$ differential cross section as a function of $Q^2$, which agrees well with the generalized vector dominance model.

**Single Tagged $\gamma^*\gamma \rightarrow \pi^0\pi^0$**

In tagged two-photon decays the process $\gamma^*\gamma \rightarrow \pi\pi$ in the region of large $Q^2$ but small W factorizes into a perturbatively calculable part dominated by short distance scattering \[7\]: $\gamma^*\gamma \rightarrow q\bar{q}$ or, $\gamma^*\gamma \rightarrow gg$ and non perturbative matrix elements measuring the transitions $q\bar{q} \rightarrow \pi\pi$ and $q\bar{q} \rightarrow gg$, called generalized distribution amplitudes \[16\]. CLEO has a preliminary measurement of the $\gamma^*\gamma \rightarrow \pi^0\pi^0$ cross sections for different $Q^2$ and W bins shown in figure 2(d).

**FIGURE 1.** L3 experiment: Inclusive $\pi^-$ (a) and single jet production (b) cross section. Exclusive $\gamma\gamma \rightarrow \Lambda\bar{\Lambda}$ (c) and $\gamma\gamma \rightarrow \Sigma\bar{\Sigma}$ (d) cross section and comparison with handbag and diquark models. BELLE experiment: Exclusive $\gamma\gamma \rightarrow \rho\bar{\rho}$ cross section (e) and comparison with diquark model.
\[ \gamma\gamma \rightarrow \eta(1440) \]

Until recently \( \eta(1440) \) has only been seen in gluon rich environments such as \( \bar{p}p \) annihilation or \( J/\psi \) decay. Although quenched lattice calculations indicate a mass of the \( 0^{++} \) glueball around 2 GeV, some glueball content of the \( \eta(1440) \) can presently not be excluded. The L3 experiment reported a first observation of the \( \eta(1440) \) in two-photon collisions \cite{18} with a \( \Gamma_{\gamma\gamma}(\eta_{1440}) \cdot BR(\eta_{1440} \rightarrow K_s K^+ \pi^-) = 49 \pm 12 \text{eV} \). Since two-photon partial width of glueballs should be very small, this would indicate that the \( \eta(1440) \) is mostly not a glueball.

CLEO has analyzed 13.8 fb\(^{-1} \) of data collected around the \( \Upsilon(4S) \) energies and searched for \( \gamma\gamma \rightarrow \eta(1440) \rightarrow K_s K^+ \pi^- \) decays \cite{19}. There is no \( \eta(1440) \) resonance observed and an upper limit for the two-photon partial width of 14.4 eV is obtained. This result, which includes all systematic errors, is 2.9 \( \sigma \) below the L3 result. Figure 3a) shows the CLEO data with the fit result and overlayed the signal (line) with errors (dashed), as expected from the L3 result.

**FIGURE 3.** CLEO experiment: Search for \( \gamma\gamma \rightarrow \eta(1440)(\eta(1440) \rightarrow K_s K\pi) \) (a), the expected L3 signal (line) with errors (dashed) is superimposed. Observation of \( \eta' \) decaying to \( K K \pi \) final state for CLEO II (b) and CLEO III (c) data sets.
The total existing experimental knowledge of the hyperfine splitting in any meson system is the $\Delta M = M(J/\psi' - M(\eta_c)) = 117 \pm 2$ MeV. The measurement of $\Delta M = M(\psi') - M(\eta_c)$ is important for the understanding of the spin-spin interaction in the confinement region. Theoretical predictions based on potential model calculations are $M(\eta_c) \sim 3594$-3629 MeV, with a two-photon partial width ratio of $\Gamma(\eta_c)/\Gamma(\psi') \sim 0.7$. A Crystal Ball measurement [20] at 3594 $\pm$ 5 MeV could not be confirmed by other searches [21]. Recently the BELLE experiment published an $\eta_c'$ observation in $B \rightarrow K(K_sK^+\pi^+)$ [22] with a mass of 3654$\pm$6$\pm$8 MeV and a significance of more than 6$\sigma$. The BELLE experiment also observed a $\eta_c'$ signal in the mode $e^+e^- \rightarrow J/\psi(X)$ [23] with a mass of 3622$\pm$12 MeV and a significance of 3.4$\sigma$. The BABAR experiment has presented a preliminary $\eta_c'$ signal [24] in two-photon decays with a mass of 3633$\pm$5$\pm$1.8 MeV.

The CLEO experiment has analyzed 13.9fb$^{-1}$ taken with the CLEO II detector [25], see figure 3b) and finds a signal at a mass of 3642.7$\pm$4.0 MeV with a significance of 4$\sigma$, a significance which assumes the mass or width of the resonance not to be known. CLEO confirmed this observation using 9.2fb$^{-1}$ of data from the CLEOIII detector [25], see figure 3c), finding a mass of 3642.5$\pm$3.4 MeV (no systematic error included) and a significance of 5.7$\sigma$. The ratio $\frac{\Gamma(\eta_c')_{B(\eta'_c \rightarrow K}\rightarrow K_sK^+\pi)}{\Gamma(\eta_c)_{B(\eta_c \rightarrow K}\rightarrow K_sK^+\pi}} = 0.17 \pm 0.06$ (CLEO II) 0.29 $\pm$ 0.09 (CLEO III), with statistical errors only. All results are preliminary.

REFERENCES

1. ALEPH collaboration, paper in preparation.
2. ALEPH collaboration, *Eur. Phys. J.* C28 437-449 (2003).
3. DELPHI collaboration, presented at PHOTON 2003 in Frascati.
4. L3 collaboration *Phys. Letters.* B554 105-114 (2003).
5. L. Bertora *hep-ph/0306167* (2003).
6. L3 collaboration, presented at PHOTON 2003 in Frascati.
7. G.P. Lepage and S. J. Brodsky, *Phys. Rev. D* 22 2157 (1980).
8. M. Diehl, et al. *Phys. Lett. B532* 99-110 (2002).
9. K. Grezlak Proceedings to PHOTON 2001 in Ascona *World Scientific.*
10. BELLE collaboration presented at PHOTON 2003 in Frascati.
11. L3 collaboration *hep-ex/0306017*, submitted to *Phys. Lett. B*, OPAL collaboration *hep-ex/0209052* (2002), CLEO collaboration *Phys. Rev. D* 50 5484 (1994), VENUS *Phys. Lett B* 407 185 (1997).
12. Farrar et al. *Nucl. Phys. B* 259 702 (1985).
13. C. F. Berger and W. Schweiger, *hep-ph 0212066* (2002).
14. M. Diehl et al. *hep-ph 0206288* (2002).
15. CLEO collaboration *Phys. Rev D* 56 2485 (1997), L3 collaboration *Phys. Lett. B* 536 24 (2002).
16. M. Diehl et al. *Phys Rev. D* 62 073014 (2000).
17. L3 collaboration presented at PHOTON 2003 in Frascati.
18. L3 collaboration *Phys. Lett. B* 501 1-11 (2001).
19. CLEO collaboration *hep-ex/0212046* (2002).
20. Crystal Ball collaboration *Phys. Rev. Lett* 48 70. (1982).
21. E760 Fermilab *Phys. Rev. D* 52 4839 (1995), E835 Fermilab *Phys. Rev. D* 64 052033 (2001).
22. BELLE collaboration *Phys. Rev. Lett.* 89 102001 (2002).
23. BELLE collaboration *Phys. Rev. Lett.* 89 142001 (2002).
24. BABAR collaboration G. Wagner *hep-ex/0305083* (2003).
25. CLEO collaboration *hep-ex/0306060* (2003).