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# Two Photon Physics at LEP

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## Abstract

LEP offers an excellent opportunity to measure two photon processes over a large kinematical range and thus study the complex nature of the photon. This article reviews the experimental status of "Two Photon Physics" at LEP. The recent results on multi-hadron production and photon structure functions are discussed.

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## 1 Introduction

Over the past decade two photon physics has proven to be a very productive source of information about QED, QCD and hadron spectroscopy. The Feynman diagram responsible for a two photon collision process at LEP is shown in Figure 1, where the high energy incident electrons and positrons split off virtual photons and the scattered electrons take most of the beam energy.

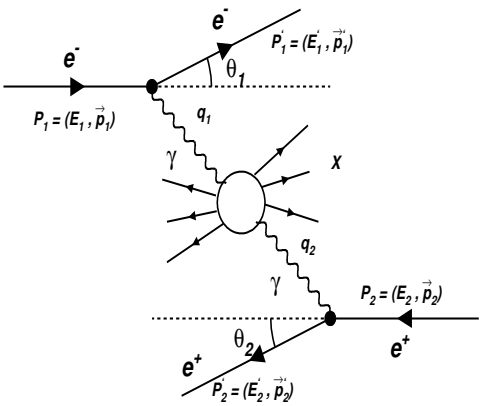



Figure 1: $\gamma\gamma$ *collision in* $e^+e^-$ *scattering*

These two photons then can interact to form a state $X$ with mass $W_{\gamma\gamma}$. The four-momentum transfer $q_i$ to the photons depends on the angle and energy of the scattered electrons[a)]. When neither of the scattered electrons is detected (untagged events), the virtual photons are referred to as nearly real i.e. $q_1^2 \approx q_2^2 \approx 0$. This class of events allows several tests of QCD by studying hadronic resonances, the inclusive hadron cross section and jet production rates. If there is detection of one of the scattered electrons $Q^2 = -q_1^2$ (single tagged events), it is possible to probe the other photon $q_2^2 \approx 0$ regarded as a "target" and study its structure. Finally, if both the scattered electrons are detected $Q_i^2 = -q_i^2, (i = 1, 2)$ (double tagged events), the structure of the reaction of highly virtual photons is probed. In the following sections, a review is given of the $\gamma\gamma$ results obtained at LEP, with special attention to recent results.

## 2 The Two Photon Total Cross-section

At LEP II energies, the two photon process $e^+e^- \rightarrow e^+e^-\gamma^*\gamma^* \rightarrow e^+e^-hadrons$ is a copious source of hadron production. In this reaction the photons either interact as a point-like particle or undergo quantum fluctuation (resolved photon) into a resonant(VMD) or non-resonant virtual states opening up all the possibilities of hadronic interactions as shown in Figure 2. These interactions can be described in terms of Regge poles [1, 2], (Pomeron or Reggeon exchange).
A measurement of the total hadronic cross section as a function of $\sqrt{s}$, improves our understanding of the hadronic nature of the photon. At LEP, using the high energy runs above the Z peak, L3 and OPAL have measured the cross section [3, 4] $\sigma(\gamma\gamma \rightarrow hadrons)$ in the range $5 \leq W_{\gamma\gamma} \leq 145$ GeV as shown in the Figure 3.
The cross-section measurement of the two experiments show a clear rise at high energies, described by a "Soft Pomeron" and the data of the L3 experiment show a fast decrease at low

[a)] Electron stands for electron and positron throughout this article

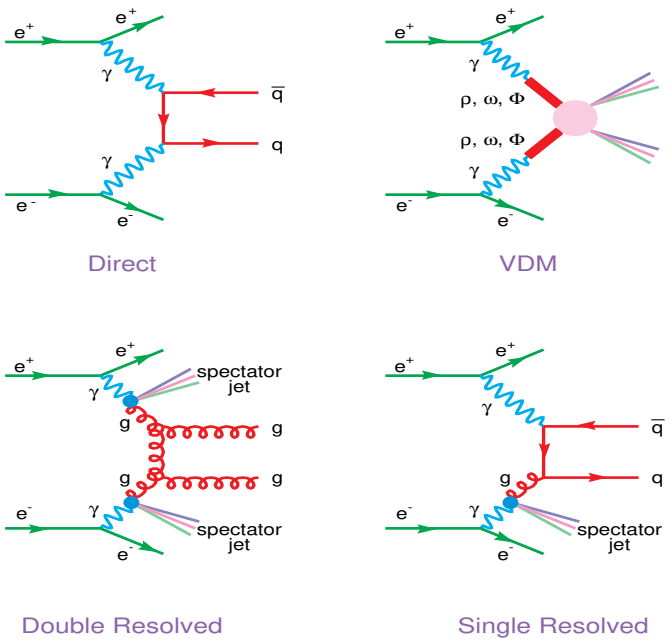



Figure 2: *Some diagram contributing to hadron production in $\gamma\gamma$ collisions at LEP.*

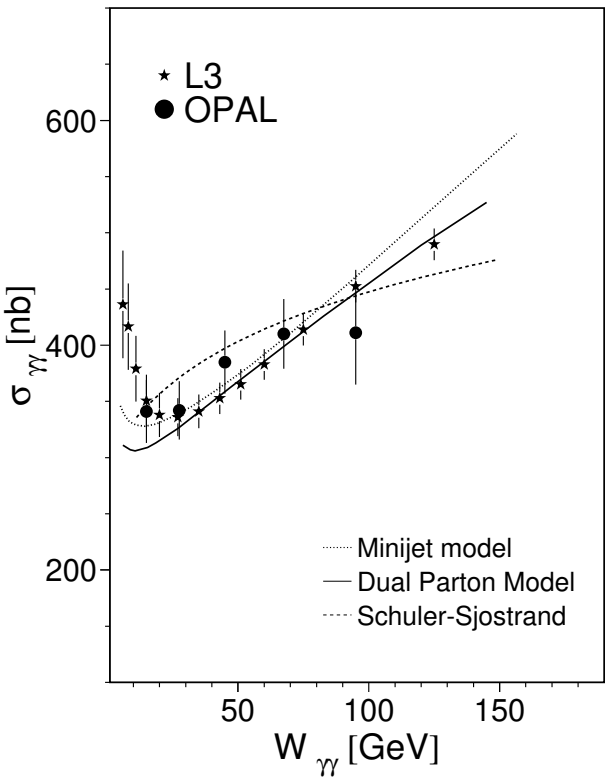



Figure 3: *The measured cross-section $\sigma(\gamma\gamma \to hadrons)$ as a function of $W_{\gamma\gamma}$.*

energies due to "Reggeon exchange". The rise of $\sigma_{\gamma\gamma}$ is faster than the one observed in hadron-hadron or $\gamma$p collisions; a simple factorization ansatz [5] $\sigma_{\gamma\gamma} = \sigma^2_{\gamma p}/\sigma_{pp}$ is excluded as can be seen in Figure 3 from the predictions of Schuler and Sjostrand [6]. The data are rather well described by the dual parton model of Engel and Ranft [7] or by analytical calculations which take into account the importance of QCD effects at high transverse momentum. In Figure 3, the mini-jet model of Godbole and Pancheri [8] is also represented. One has to notice that all models has some dependence which can change the cross section predictions by 10-30%. The Monte Carlo models PYTHIA and PHOJET which are used to correct the data, differ by ≈20% in the absolute normalization. In future, improvements in the theoretical predictions especially the description of diffractive processes are desirable.

## 3 Single Particle and Jet Production

Inclusive production of charged hadrons, $K^0_s$ mesons and jets has been studied at LEP by the OPAL experiment. Figure 4(a) shows a measurement of the differential cross-section for charged hadrons produced in collision of the two quasi-real photons in the range 10 GeV< $W_{\gamma\gamma}$ <125 GeV as a function of transverse momentum [9] $p_T$ . The results are reasonable agreement to NLO perturbative QCD calculations [10]. These data demonstrate the dominance of the direct component at large $p_T$.

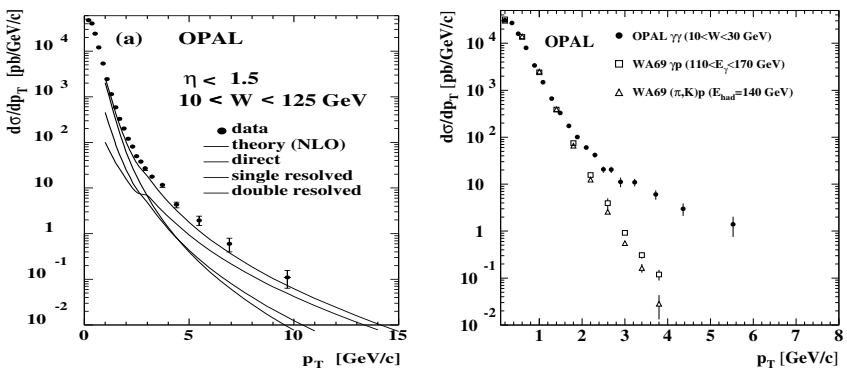



Figure 4: *a) Differential inclusive charged hadron cross-section and b) the* $p_T$ *distribution measured in* $\gamma\gamma$ *interactions compared to the* $\gamma p$ *and* $(\pi,K)p$ *interactions.*

Also shown in figure 4(b) is the comparison of the $\gamma\gamma$ data to $p_T$ measured in $\gamma$p and $(\pi, K)$p interactions normalised at the same value at low $p_T$. It can be seen that there is a significant increase of rates in the $\gamma\gamma$ process above a $p_T$ of 2 GeV. The clear deviation from the hadronic interactions shows the effect of the direct component in the $\gamma\gamma$ interactions. Similar studies of $p_T$ distributions of the $K^0_s$ mesons are in reasonable agreement with NLO calculations [9].

The OPAL experiment has performed a very nice measurement of dijet production in two-photon collisions at $\sqrt{s}$ = 161 and 172 GeV. Their results [12] demonstrate that it is possible to distinguish between direct and resolved processes in the dijet events with the help of the variable $x_\gamma$, which is the estimator of the fraction of the target photon's momentum carried by the parton which produces jets. Figure 5 shows the measured distribution of the parton scattering angle $\theta^*$ for direct and double-resolved processes, compared to the relevant QCD matrix element calculations [13]. One observes a clear distinction between the direct process $\gamma\gamma \to q\bar{q}$ ($x_\gamma > 0.8$), where a quark is exchanged in the t channel and the doubly resolved one ($x_\gamma < 0.8$), dominated by the gluon exchange. The strong rise in cos$\theta^*$ distribution near cos$\theta^*$=1 is due to a large double-resolved contribution, as expected from QCD.

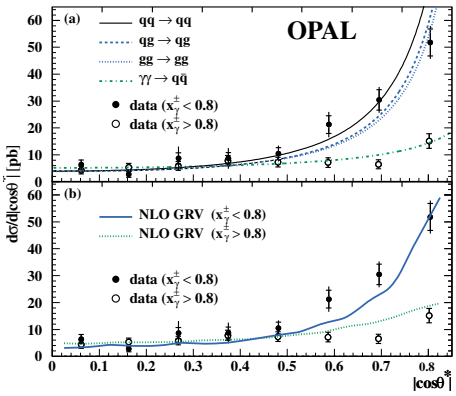



Figure 5: *The angular distribution in the dijet center-of-mass system for "Direct" and "Resolved" events*

## 4 Heavy Quark Production

The study of heavy quark (c,b) production in two photon collisions at LEP provides not only an excellent test of perturbative QCD but also gives an estimate of the gluon density in the photon. At LEP energies, the direct and resolved photon processes are predicted to give comparable contributions to the charm and beauty quark production cross-sections [14]. The resolved process is dominantly quark-gluon fusion: $\gamma g \to q\bar{q}$ so that these measurements provide information about the gluon content of the photon. The cross-section of the processes $e^+e^- \to e^+e^- c\bar{c}, b\bar{b}$ X has been measured by the L3 [15] and OPAL [16] experiments. At L3, the charm and beauty quark are identified by tagging leptons $(e, \mu)$ from semileptonic charm and beauty decays. Charm quark were also identified by the reconstruction of $D^{\pm *}$ meson decays, where $D^* \to D^0\pi^\pm$, and OPAL tags charm quark with $D^* \to D^0\pi^\pm$ and $D^0 \to K^-\pi^+, K^-\pi^+\pi^o, K^-\pi^+\pi^-$.

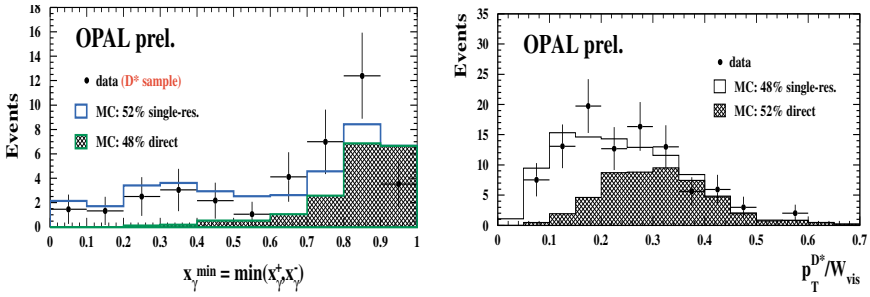



Figure 6: *The $x_\gamma$ distribution of dijet events containing a $D^*$ and the $p_T$ distribution of the $D^*$ normalised to the visible mass of the event.*

A good separation of direct and resolved processes is obtained by associating the $D^*$ to a dijet analysis or by inspection of the $p_T$ distribution of the $D^*$ (See figure 6). As predicted the direct and resolved processes contribute roughly equally to the observed distribution. The differential $D^*$ cross section agrees well with the NLO predictions and is independent of the Monte Carlo models used to correct the data over the range of detector acceptance. The total inclusive cross-sections are plotted in Figure 7 together with previous measurements. The data are compared to NLO QCD calculations [14]. The direct process $\gamma\gamma \to c\bar{c}, b\bar{b}$, shown with dotted line, is insufficient to describe the data, even if real and virtual gluon corrections are included. The cross sections requires contributions from the resolved processes which are dominantly $\gamma g \to c\bar{c}, b\bar{b}$. The data therefore requires a significant gluon content in the photon.

The $b\bar{b}$ cross section is measured for the first time in two photon collisions by the L3 experi-

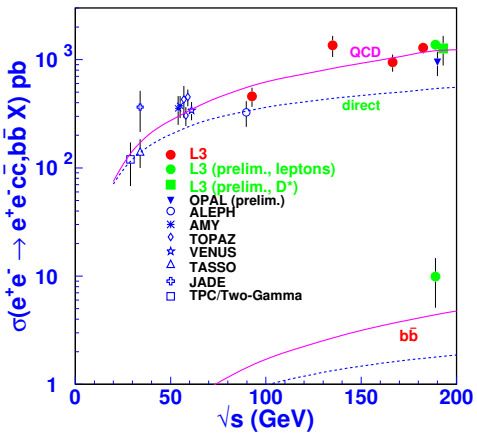



Figure 7: *The cross-section for heavy quarks production as measured at LEP and at previous* $e^+e^-$ *colliders*

ment. The preliminary value of b cross section lies somewhat above QCD predictions.

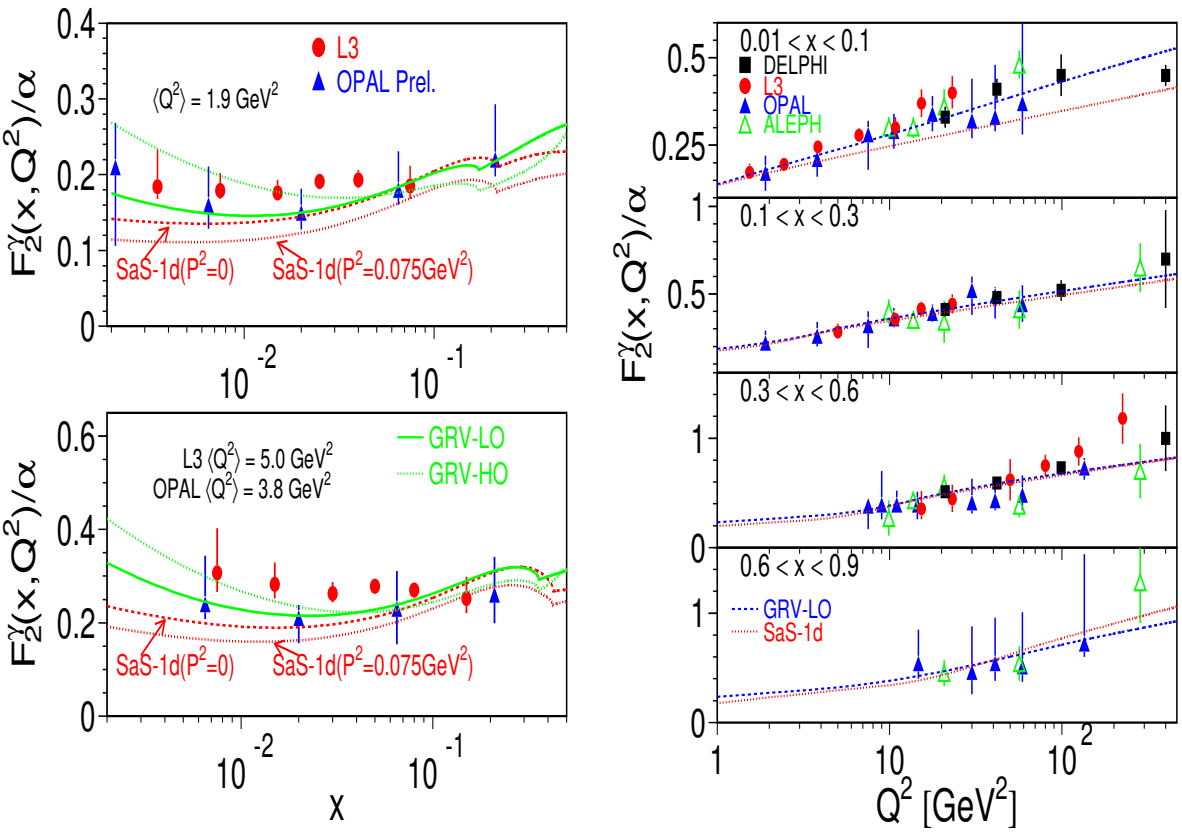
## 5 Hadronic structure function $F_2^{\gamma,QCD}$

The measurement of the hadronic structure function, $F_2^{\gamma,QCD}$ has been performed at LEP in the range $0.0025 < x < 1$ and $1.2\ \mathrm{GeV}^2 < Q^2 < 279\ \mathrm{GeV}^2$ [20, 21, 22, 23]. The physical interest in the analysis of the hadronic photon structure function is twofold. Firstly, to measure the shape of $F_2^\gamma$, especially at small values of $x$, at fixed $Q^2$, where HERA experiments observe a strong rise of the proton structure function. Secondly the $Q^2$ evolution of $F_2^\gamma$ is investigated. The $F_2^\gamma$ measurements from L3 and OPAL are shown in Figure 8 (a) in the $Q^2$ interval from 1.2 to 9.0 $\mathrm{GeV}^2$. The $x$ range is $0.002 < x < 0.1$ at $\langle Q^2 \rangle = 1.9\ \mathrm{GeV}^2$ and $0.005 < x < 0.2$ at $\langle Q^2 \rangle = 5.0\ \mathrm{GeV}^2$. For the low values of $x$, the data agree better with the parton density prediction of GRV [17], whereas SaS-1d [19] prediction is lower.

A compilation of the results for different experiments on the $Q^2$ evolution of $F_2^\gamma$ in various ranges of $x$ are shown in Figure 8 (b). The measured values of $F_2^\gamma$ show clearly the linear growth with $\ln Q^2$ expected by QCD. The predictions of the GRV-LO [17] and SaS-1d [19] models are also shown. With all the statistics available at the end of LEP data taking, one hopes to extract the effective scale parameter $\Lambda_{QCD}$ at large x.

## 6 $\gamma^*\gamma^*$ Collisions

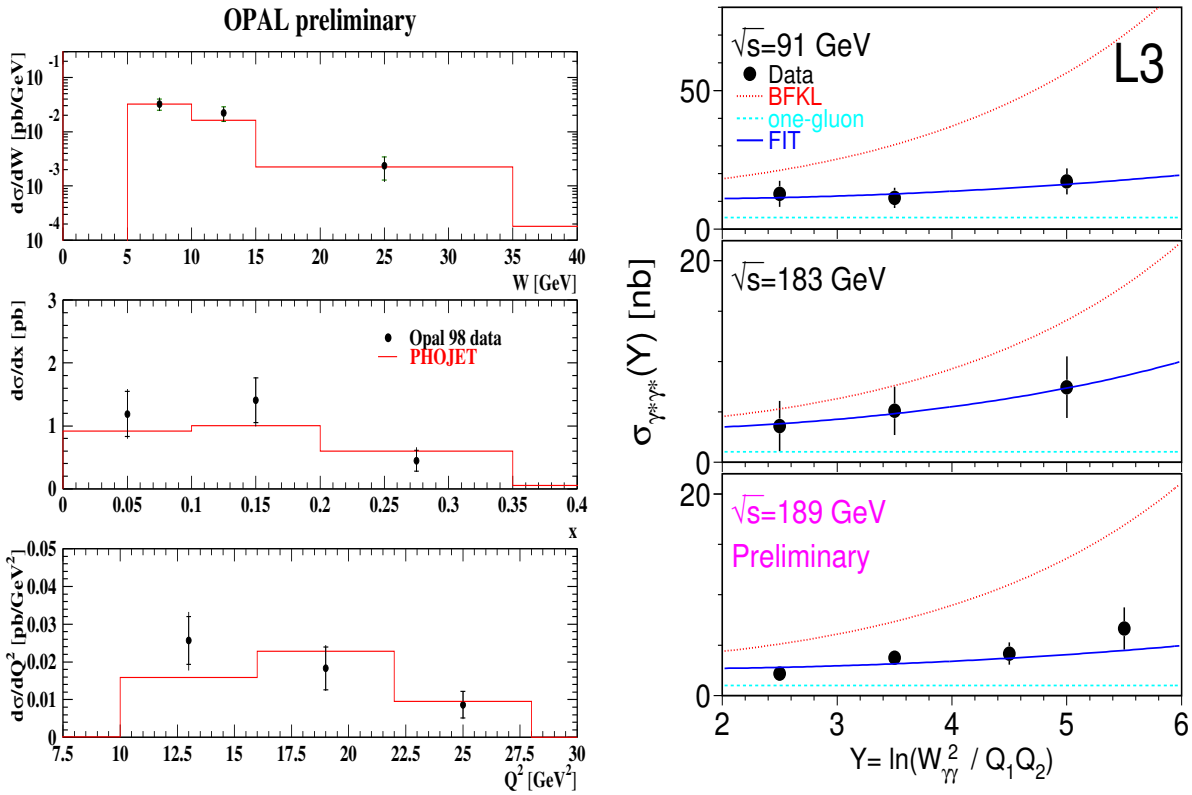
The cross-section of $\gamma^*\gamma^*$ collisions has been measured at LEP with L3 [24] and OPAL [25] experiments in the range of $3\ \mathrm{GeV}^2 < \mathrm{Q}^2_{1,2} < 37\ \mathrm{GeV}^2$. Since the two photons are highly virtual and – unlike the proton – they do not contain constituent quarks with an unknown density distribution, one may hope to have a complete perturbative QCD calculation under particular kinematical conditions. An alternative QCD approach is based on the BFKL equation [26]. Here the highly virtual two-photon process, with $Q_1^2 \simeq Q_2^2$, is considered as the "golden" process where the calculation can be verified without phenomenological inputs [27, 28]. The $\gamma^*\gamma^*$ interaction can be seen as the interaction of two $\mathrm{q\bar{q}}$ pairs scattering off each other via multiple gluon exchange. In this scheme the cross-section for the collision of two virtual photons [27, 28] depends upon the "hard Pomeron" intercept $\alpha_P - 1 = 0.53$ [27, 28] in the LO, whereas in the next-to-leading order the BFKL contribution is calculated to be smaller, $\alpha_P - 1 \simeq 0.17$ [29]. The results from L3 and OPAL (figure 9(a)) show that the events are well described by the




(a) (b)

Figure 8: *(a) The measured $F_2^\gamma$ at $\langle Q^2 \rangle = 1.9\ GeV^2$ and 5.0 $GeV^2$ and (b) evolution of $F_2^\gamma$ as a function of $Q^2$ for different range of $x$ values.*

PHOJET Monte Carlo model which uses the GRV-LO parton density in the photon and leading order perturbative QCD. The LO BFKL calculations shown in the figure 9(b) with dotted line are too high. By leaving $\alpha_P$ as a free parameter in the LO calculations, a combined fit to the L3




(a) (b)

Figure 9: *(a) The differential cross-section of double tag events compared to PHOJET Monte Carlo predictions and (b) the two photon cross-sections at LEP1 and LEP2 compared to LO-BFKL calculations after subtraction of the direct contribution*

data obtained at $\sqrt{s} \approx 91$, 183 and 189 GeV gives a value of $\alpha_P - 1 = 0.29 \pm 0.025$ with $\chi^2$/d.o.f =7/9.

## 7 Outlook

Progress in the field of the two photon physics at LEP is significant, most notable are multi-hadron production and photon structure functions. With the statistics of 500 pb$^{-1}$ luminosity available at the end of LEP II data taking the experimental measurements will reach a high level of precision such that an improvement from the theoretical point of view will be desirable in order to have reliable interpretations of the experimental results.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## References


[1] P. D. B. Collins, Introduction to Regge theory (Cambridge U.P., Cambridge, 1977)
[2] Review of Particle Physics, *Phys. Rev.* D **54**, 191 (1996)
[3] L3 Coll., M. Acciarri et al., *Phys. Lett.* B **408**, 450 (1997);
L3 Coll., M. Acciarri et al., Submitted to EPS, Tampere, 1999
[4] OPAL Coll., G. Abbiendi et al., CERN-EP/99-076.
[5] V. N. Gribov and L. Ya. Pomeranchuk, *Phys. Lett.* B **8**, 343 (1962).
[6] G. A. Schuler and T. Sjöstrand, *Nucl. Phys.* B **407**, 539 (1993);
G. A. Schuler and T. Sjöstrand, *Z. Phys.* C **73**, 677 (1997)
[7] R. Engel, *Z. Phys.* C **66**, 203 (1995);
R. Engel and J. Ranft, *Phys. Rev.* D **54**, 4246 (1996)
[8] R.M.Godbole and G.Pancheri, hep-ph/9903331 (1999)
[9] OPAL Coll., K. Ackerstaff et al., *Eur. Phys. J* **C6**, 253 (1999)
[10] J. Binnewies, B. A. Kniehl and G. Kramer, *Phys. Rev.* D **53**, 6110 (1996)
[11] OMEGA Coll., R. J. Apsimon et al., *Z. Phys.* C **43**, 63 (1989)
[12] OPAL Coll., K. Ackerstaff et al. , *Z. Phys.* C **73**, 433 (1997);
OPAL Coll., G. Abbiendi et al. , *Eur. Phys. J* **C 6**, 253 (1999)
[13] H. Kolanoski, Two-Photon Physics at $e^+e^-$ Storage Rings, Springer-Verlag(1984);
B. L. Combridge et al., *Phys. Lett.* B **70**, 234 (1977);
D. W. Duke and J. F. Owens, *Phys. Rev.* D **26**, 1600 (1982)
[14] M. Drees et al., *Phys. Lett.* B **306**, 371 (1993)
[15] L3 Coll., M. Acciarri et al., Submitted to EPS, Tampere, 1999
[16] OPAL Coll., G. Abbiendi et al. , Submitted to EPS, Tampere, 1999
[17] M. Glück, E. Reya and A. Vogt,*Phys. Rev.* D **45**, 3986 (1992);
M. Glück, E. Reya and A. Vogt,*Phys. Rev.* D **46**, 1973 (1992)
[18] H. Abramowicz, K. Charchula and A. Levy, *Phys. Lett.* B **269**, 458 (1991)
[19] G. A. Schuler and T. Sjöstrand, *Z. Phys.* C **68**, 607 (1995);
G. A. Schuler and T. Sjöstrand, *Phys. Lett.* B **376**, 193 (1996)
[20] ALEPH Coll., R.Barate et al., *Phys. Lett.* B **458**, 152 (1999)
[21] DELPHI Coll., Igor Tyapkin in " Workshop on Photon Interactions and the Photon structure", LUND 1998
[22] L3 Coll., M. Acciarri et al., *Phys. Lett.* B **436**, 403 (1998);
L3 Coll., M. Acciarri et al., *Phys. Lett.* B **447**, 147 (1999)
[23] OPAL Coll., K. Ackerstaff et al., *Z. Phys.* C **74**, 33 (1997);
OPAL Coll., K. Ackerstaff et al., *Phys. Lett.* B **411**, 387 (1997);
OPAL Coll., K. Ackerstaff et al., *Phys. Lett.* B **412**, 225 (1997). OPAL Coll., G. Abbiendi et al., Submitted to EPS, Tampere, 1999
[24] L3 Coll., M. Acciarri et al., *Phys. Lett.* B **453**, 333 (1999);
L3 Coll., M. Acciarri et al., Submitted to EPS, Tampere, 1999
[25] OPAL Coll., G. Abbiendi et al. , Submitted to EPS, Tampere, 1999
[26] E.A. Kuraev, L.N. Lipatov and V.S. Fadin, Sov. Phys. JETP **45** (1977) 199;
Ya.Ya. Balitski and L.N. Lipatov, Sov. J. Nucl. Phys. **28** (1978)822
[27] S.J. Brodsky, F. Hautmann and D.E. Soper, *Phys. Rev.* D **56**, 6957 (1997)

[28] J. Bartels, A. De Roeck and H. Lotter, *Phys. Lett.* B **389**, 742 (1996);
J. Bartels, A. De Roeck, C. Ewerz and H. Lotter, hep-ph/9710500
[29] S.J. Brodsky, V.S. Fadin, V.T. Kim, L.N. Lipatov and G.B. Pivovarov, hep-ph/99101229