Total cross-section for real and virtual photons

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Results are presented for measurements of the total cross section $\gamma\gamma \to hadrons$ process by the L3 and the OPAL collaborations at LEP. The QCD predictions are tested with the L3 measurement of total hadronic cross section for virtual $\gamma^*\gamma^*$ collisions and of total cross section for $c\bar{c}$ and $b\bar{b}$ production by quasi-real photons.

1. INTRODUCTION

A quasi-real photon interacts as a hadron due to quantum fluctuations into vector mesons or into quark-antiquark pairs. The $\gamma\gamma$ cross section is composed by a "soft (VDM)" interaction, which can be described by hadronic phenomenology, like the Regge poles, a point like two-photon reaction, $\gamma\gamma \to q\bar{q}$, which is exactly calculable in QED (direct component) and a "hard component" (resolved or anomalous or QCD component) which implies the knowledge of the quark and gluon density in the photon. The "hard component" of two-photon interactions can be accessed in measurements of the heavy flavours production and of a scattering of highly virtual photons. In the first case a hard physical scale is given by $c(b)$-quark mass, while large virtuality Q^2 of the photon provides a hard scale in the second case. The LEP e^+e^- collider is an ideal place to study two photon physics. The background from the annihilation events is normally very low.

2. TOTAL HADRONIC $\gamma\gamma$ CROSS SECTION

The cross section of $\gamma\gamma \to hadrons$ process has been measured at LEP by the L3 [1] and the OPAL [2] for $\gamma\gamma$ centre-of-mass energies up to 145 GeV. The energy of a photon-photon collision is determined from the hadronic final state. The visible mass, W_{vis}, of the event is calculated from the four-momentum vectors of the measured particles (tracks and calorimetric clusters). The hadronic final state is not always fully contained in a detector acceptance. The unfolding procedure is applied to go from the measured W_{vis} to the true $\gamma\gamma$ centre-of-mass energy $W_{\gamma\gamma}$. From the number of events, corrected with Monte Carlo generator (PYTHIA or PHOJET) in each $W_{\gamma\gamma}$ bin, the cross section $\mathrm{d}\sigma(e^+e^- \to e^+e^- hadrons)$ is measured. From the $\mathrm{d}\sigma(e^+e^- \to e^+e^- hadrons)$ the total cross section of two real photons is extracted by calculating the photon flux and extrapolating the hadronic two-photon processes to zero Q^2.

Fig. 1 shows the $\sigma_{\gamma\gamma}$ measurements by L3 and OPAL collaborations. The discrepancy on the cross section reflects the difference on selection efficiency given by the two generators. The L3 measurement (Figs. 1a, 1b) is shown using PHOJET Monte Carlo, which gives somewhat better description of the data. The asymmetric error bars are pointing to the values obtained using PYTHIA generator. The OPAL result is given as average of the two generators. The results from the L3 and OPAL agree within errors when the same generator is used in the analysis, but there is a systematic difference of $\simeq 20\%$ between the two Monte Carlo models. This is mostly due to a different modelling of the diffractive events. A parametrisation by A. Donnachie and P.V. Landshoff [3] of the form $\sigma_{\mathrm{tot}} = A\, s^{\epsilon} + B\, s^{-\eta}$

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describes well the energy behaviour of all total hadron-hadron cross sections. A fit with A, B and ϵ as free parameters (η = 0.4678[4]) gives:
$\epsilon = 0.158 \pm 0.006(\mathrm{st}) \pm 0.028(\mathrm{sys})$ L3, PHOJET,
$\epsilon = 0.143 \pm 0.005(\mathrm{st}) \pm 0.025(\mathrm{sys})$ L3, PYTHIA,
$\epsilon = 0.19 \pm 0.09(\mathrm{st.} + \mathrm{sys.})$ OPAL.

The ϵ value is about a factor two higher than the universal value [4], independent of the Monte Carlo model used to correct the data. The two-photon cross section at high energies can be estimated from proton-proton and photoproduction total cross sections assuming factorization for the Pomeron term: $\sigma_{\gamma\gamma} \approx \sigma^2_{\gamma\mathrm{p}}/\sigma_{\mathrm{pp}}$. The predictions thus obtained are consistent with the two-photon measurement (shaded area in Fig. 1a). While the universal parametrisation of hadron-hadron cross sections fails to describe the fast rise of high energy part in $\gamma\gamma$ collisions, several QCD inspired models are in a qualitative agreement with the data (Fig. 1b).

3. CHARM AND BEAUTY PRODUCTION CROSS SECTIONS

In this paper we present the result of the measurement of the $e^+e^- \to e^+e^- c\bar{c}X, b\bar{b}X$ cross sections by the L3 experiment. Charm quarks have been tagged by electrons and muons from their semi-leptonic decays. Electrons are selected with momentum greater than 0.6 GeV/c, muons with momentum greater than 2.0 GeV/c. The data collected by L3 in the period of 1994 through 1997 at $\sqrt{s}$ = 91-183 GeV have been analyzed for a total integrated luminosity of $\mathcal{L}$ = 165 pb^{-1} [5]. The preliminary result at $\sqrt{s}$ = 189 GeV corresponds to $\mathcal{L}$ = 176 pb^{-1}. The beauty production cross section has been measured at $\sqrt{s}$ = 189 GeV using muon tag.

At high energies, the direct and resolved photon processes are predicted to give comparable contributions to the charm and beauty production cross section [6]. The single-resolved photon cross section is dominated by the photon-gluon fusion diagram $\gamma g \to c\bar{c}, b\bar{b}$. The production rate of the c- and b-quarks in two-photon collisions depends on the mass of the c- and b-quark and on the gluon density in the photon. In Figure 1c, the event energy flow is plotted together with PYTHIA predictions as a function of the pseudorapidity, $\eta = -\ln(\tan(\frac{\theta}{2}))$, where θ is the polar angle of the particle. A clear difference in shape can be seen between the distributions for the direct and resolved processes for $|\eta| > 1$, where the direct process alone is insufficient to describe the data. The most sensitive distributions where predictions for direct and resolved processes are different are found to be the visible mass, the track multiplicity, the transverse momentum of the lepton and the energy flow spectra. The preliminary L3 result on charm production at $\sqrt{s}$ = 189 GeV is $\sigma(e^+e^- \to e^+e^- c\bar{c}X) = 1378 \pm 55(\mathrm{st}) \pm 134(\mathrm{sys})$ pb.

The beauty production in $\gamma\gamma$ collisions has been estimated by selecting muons with a high transverse momentum with respect to the closest jet and a high momentum ($p_\mu > 2.5$ GeV, $p^{jet}_{T\mu} >$ 1.5 GeV). The number of events in the data is equal to 49, b-purity of the sample is 34% and b-efficiency is 1%. The preliminary L3 result on beauty production at $\sqrt{s}$ = 189 GeV is $\sigma(e^+e^- \to e^+e^- b\bar{b}X) = 10.3 \pm 4.6(\mathrm{st}) \pm 3.3(\mathrm{sys})$ pb. The beauty production in $\gamma\gamma$ collisions is measured for the first time. The total inclusive charm and beauty production cross sections are plotted in Fig. 1d together with previous measurements. The data are compared to the theory predictions of Ref. [6]. The dashed line corresponds to the direct process, NLO QCD calculation, while the solid line shows the QCD prediction for the sum of the direct and the resolved processes calculated to NLO accuracy (m_c = 1.3 GeV and m_b = 5.0 GeV). The cross section increases with energy as expected by QCD predictions.

4. TOTAL HADRONIC $\gamma^*\gamma^*$ CROSS SECTION

The double-tag events, collected with the L3 detector, correspond to integrated luminosity of 140 pb^{-1} at 91 GeV, 52 pb^{-1} at 183 GeV [7] and 176 pb^{-1} at 189 GeV. Scattered electron and positron are detected by the small angle electromagnetic calorimeters with polar angle between 25 and 69 mrad on each side of the detector. The cross-section of $\gamma^*\gamma^*$ collisions has been measured at $\langle Q^2\rangle$ = 3.5 GeV^2, $\langle Q^2\rangle$ = 14 GeV^2 and

$\langle Q^2 \rangle = 14.5$ GeV^2, correspondingly. The centre-of-mass energy of the two virtual photons, $W_{\gamma^*\gamma^*}$, is measured by the energies and angles of tagged electron and positron and ranges from 2 GeV to 75 GeV. The numbers of selected double tagged events are 137, 34 and 108, respectively. In Fig. 1e the measured cross section $e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^- hadrons$ is plotted together with prediction for direct (QPM) process estimated with JAMVG Monte Carlo generator of J.A.M. Vermaseren and with the prediction of QCD Monte Carlo model implemented in PHOJET generator of R. Engel. The cross section is plotted as function of variable $Y = \ln(s/s_0) \simeq \ln(W_{\gamma^*\gamma^*}/Q_1Q_2)$. The QPM cross section lies below the data, while QCD prediction is in a reasonable agreement with the data. An alternative QCD approach is based on the BFKL equation [8]. Here the highly virtual two-photon process, with $Q_1^2 \simeq Q_2^2$, are considered as the "golden" process where the calculation can be verified without phenomenological inputs [9,10]. In this scheme the cross-section for the collision of two virtual photons is $\sigma_{\gamma^*\gamma^*} \approx \sigma_0/\sqrt{Q_1^2Q_2^2Y}\left(W_{\gamma^*\gamma^*}/\sqrt{Q_1^2Q_2^2}\right)^{\alpha_P-1}$, where α_P is the "hard Pomeron" intercept. In Fig. 1f the data fitted with α_P as free parameter are shown together with the leading order BFKL prediction and subleading cross section of the one-gluon exchange. The fit gives:
$\alpha_P - 1 = 0.28 \pm 0.05$ at $\sqrt{s} \approx$ 91 GeV,
$\alpha_P - 1 = 0.40 \pm 0.07$ at $\sqrt{s} \approx 183$ GeV.
$\alpha_P - 1 = 0.29 \pm 0.03$ at $\sqrt{s} \approx 189$ GeV.

The LO BFKL prediction for the slope ($\alpha_P - 1 \approx 0.53$) and for the normalization is not in agreement with the L3 measurement. Next-to-Leading-Order BFKL predictions are closer to the data [11], while the intercept $\alpha_P - 1 \approx 0.16$ is significantly lower than the measurement. Next-to-Leading-Order corrections to the BFKL evolution have been determined phenomenologically in [12] and are in a perfect agreement with the L3 data.

5. SUMMARY

The observed slope of the rise of the $\sigma(\gamma\gamma \to hadrons)$ with energy is by factor two bigger than expected from the universal Regge behaviour of total hadronic cross sections. The data on charm and beauty production are in agreement with QCD prediction and demonstrate clear evidence for the gluon density in the photon. The beauty production in $\gamma\gamma$ collisions has been measured by the L3 for the first time. Leading order BFKL predictions failed to describe L3 data on $\gamma^*\gamma^*$ collisions.

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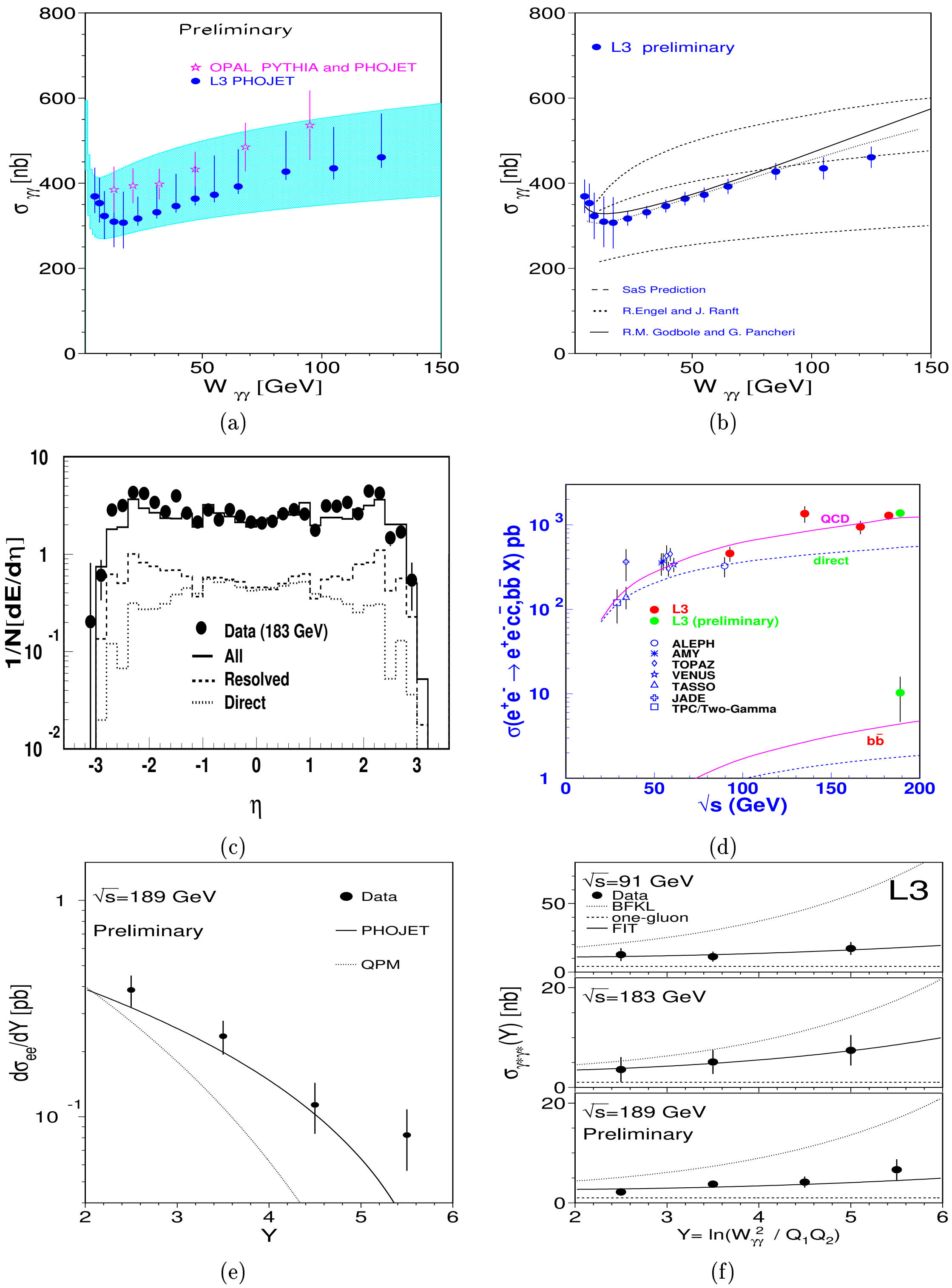

Figure 1. The results on total cross section for real and virtual photons.