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Cross Section Measurement of Charm Production in $\gamma\gamma$ Collisions at LEP

The L3 Collaboration

Abstract

Inclusive charm production in $\gamma\gamma$ collisions is studied with the L3 detector at the LEP collider. Data were collected at centre-of-mass energies from 189 GeV to 202 GeV for a total integrated luminosity of 410 pb^{-1}. Hadronic final states containing charm particles are identified by detecting electrons from their semi-leptonic decays. The cross sections $\sigma(\mathrm{e^+e^-} \rightarrow \mathrm{e^+e^-c\bar{c}X})$ and $\sigma(\gamma\gamma \rightarrow \mathrm{c\bar{c}X})$ are measured as a function of the two-photon centre-of-mass energy in the interval 5 GeV $\leq W_{\gamma\gamma} \leq$ 70 GeV. A steeper rise with energy is observed for $\sigma(\gamma\gamma \rightarrow \mathrm{c\bar{c}X})$ as compared to hadron-hadron cross sections and to $\sigma(\gamma\gamma \rightarrow hadrons)$. The data are compared to the expectations of the PYTHIA 5.7 Monte Carlo model. The high energy behaviour of total charm cross section as function of $\gamma\gamma$ centre-of-mass energy is measured for the first time.

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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, $\gamma\gamma \rightarrow q\bar{q}$, 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 (Figure 1). The "hard component" of two-photon interactions can be accessed in measurements of the heavy flavours production. In this case a hard physical scale is given by the c(b)-quark mass [1].

In this paper we present results of the measurement of the $\gamma\gamma \rightarrow \mathrm{c\bar{c}X}$ cross section by the L3 experiment at LEP. The LEP e^+e^- collider is an ideal place to study two photon physics since the background from the annihilation events is very low. Charm quarks have been identified by electrons [1)] from semileptonic charm decays [2]. The data correspond to a total integrated luminosity of $\mathcal{L} = 410\ \mathrm{pb}^{-1}$ collected at centre-of-mass energies from 189 GeV to 202 GeV. The total cross section of $\gamma\gamma \rightarrow hadrons$ has been measured at LEP by L3 [3] and OPAL [4] for $\gamma\gamma$ centre-of-mass energies up to 145 GeV. The charm cross section as a function of the $\gamma\gamma$ centre-of-mass energy is measured here for the first time. It is compared to the model expectations and to the inclusive $\gamma\gamma \rightarrow hadrons$ cross section [3].

2 Total cross section of $\gamma\gamma \rightarrow \mathrm{c\bar{c}X}$.

The event selection is done according to the method developed in [2] with a few modifications.

The analysis is limited to the electrons selected in the barrel region ($|\cos\theta_e| < 0.725$). The electron signal is well identified in the barrel, while it is deteriorated in the endcap region, because of a shorter length of the track and the energy lost in the material in front of the calorimeter. Instead of a fixed window cut on $\mathrm{E_t/P_t}$ [2] a 2 sigma cut is applied in order to take into account different resolution in the data and Monte Carlo.

In order to suppress further γ-conversions a cut on the invariant mass of the electron candidate and of the closest track is applied. The mass must be greater than 0.1 GeV. Figure 2 shows the mass distribution of the data compared to PYTHIA Monte Carlo. A peak corresponding to conversions is observed at small masses. The data and Monte Carlo are in a good agreement. With the application of the cut, the fraction of conversions in the selected sample is reduced from 17.0% to 10.8%. The cut on the conversions improves the charm purity from 63% to 73%.

The analysis is limited to untagged events with small photon virtuality. Events are excluded when the most energetic cluster in the small angle calorimeters (LUMI and ALR) has an energy greater than 0.4 $\mathrm{E_{beam}}$.

The number of selected events is 2455. The background (mainly the annihilation processes and $\gamma\gamma \rightarrow \tau\tau$) is below 1% and is subtracted from the data. The background from $\mathrm{b\bar{b}}$ events is subtracted from the data too. The $\mathrm{b\bar{b}}$ events have been generated by PYTHIA using massive matrix elements calculations with $\sigma(\mathrm{e^+e^-} \rightarrow \mathrm{e^+e^-b\bar{b}X}) = 5$ pb and with equal contribution from direct and resolved process [1]. The preliminary charm production cross section in $\gamma\gamma$ collisions at $\langle\sqrt{s}\rangle = 194$ GeV has been measured to be

$$\sigma^{ee\rightarrow eec\bar{c}X} = 1166 \pm 34\ (\mathrm{stat})\ \pm 128\ (\mathrm{syst})\ \mathrm{pb}$$

1) Electron stands for electron or positron throughout this paper.

The analysis is limited to events with $\mathrm{W_{vis}} > 3$ GeV. The cross section of $\gamma\gamma \rightarrow \mathrm{c\bar{c}X}$ is measured as a function of the photon-photon centre-of-mass energy, determined from the hadronic final state. The visible mass, $\mathrm{W_{vis}}$, of the event is calculated from the four-momentum vectors of the measured particles (tracks and calorimetric clusters including LUMI). A comparison of the visible mass distribution of the data with the expectations of the PYTHIA Monte Carlo at $\sqrt{s} = 189 - 202$ GeV is shown in Figure 3. The Monte Carlo spectrum in Figure 3 includes contribution from all quark flavours calculated with massless matrix elements and is normalized to the data integrated luminosity after rescaling to the measured charm cross section and charm purity.

The hadronic final state is not always fully contained in the detector acceptance. An unfolding procedure is applied to go from the measured $\mathrm{W_{vis}}$ to the true $\gamma\gamma$ centre-of-mass energy $\mathrm{W_{\gamma\gamma}}$. Figure 4 shows the correlation of $\mathrm{W_{vis}}$ versus $\mathrm{W_{\gamma\gamma}}$. Up to the highest reconstructed masses there is a linear correlation between $\mathrm{W_{vis}}$ and $\mathrm{W_{\gamma\gamma}}$, while $\mathrm{W_{vis}}$ is on average lower than the true two-photon centre-of-mass energy. The unfolding corrects for acceptance (missing energy) and detector resolution.

The trigger efficiency, is determined directly from the data using a set of independent triggers. The trigger efficiency varies from 94% at $\mathrm{W_{vis}} = 5$ GeV to 98% at $\mathrm{W_{vis}} = 30$ GeV where it becomes constant.

In order to obtain the $\mathrm{W_{\gamma\gamma}}$ distribution, subdivided in seven intervals, the following unfolding relation is used:

$$N(W_{\gamma\gamma}(i)) = \sum_{j=1}^{n=7} A_{ij} N(W_{\mathrm{vis}}(j)) \tag{1}$$

The matrix $\mathrm{A_{ij}}$ is constructed by considering for each Monte Carlo event the measured W_{vis} and its generated $W_{\gamma\gamma}$ value as follows [9]:

$$A_{ij} = \frac{P(W_{\mathrm{vis}}(j)|W_{\gamma\gamma}(i))P(W_{\gamma\gamma}(i))}{\sum_{l=1}^{n=7} P(W_{\mathrm{vis}}(j)|W_{\gamma\gamma}(l))P(W_{\gamma\gamma}(l))} \tag{2}$$

where $P(W_{\mathrm{vis}}|W_{\gamma\gamma})$ is the likelihood of observing the measured W_{vis} given a generated $W_{\gamma\gamma}$value and $P(W_{\gamma\gamma})$ is the initially generated $W_{\gamma\gamma}$ distribution after acceptance cuts.

After unfolding, the events are corrected for efficiency using the ratio between selected and generated charm events in each $W_{\gamma\gamma}$ interval. Table 1 shows the selected data events in bins of W_{vis} and the different contributions from PYTHIA Monte Carlo. The first and the last bin of the W_{vis} distribution are used in unfolding, but they are excluded from the measurement due to the correction factors and high unfolding uncertainty.

From the number of events, corrected with the PYTHIA Monte Carlo in each $W_{\gamma\gamma}$ bin, and the integrated luminosity, the cross section $d\sigma(e^+e^- \rightarrow e^+e^- c\bar{c}X)$ is measured. Figure 5 shows the differential cross section $d\sigma(e^+e^- \rightarrow e^+e^- c\bar{c}X)/dW_{\gamma\gamma}$ as function of $W_{\gamma\gamma}$ measured in the interval 5 GeV $\leq W_{\gamma\gamma} \leq$ 70 GeV.

The unfolding is done using PYTHIA charm events. The PHOJET Monte Carlo generator with all quark flavours is used to estimate the systematic error due to unfolding (Figure 5). The charm production in PHOJET generator is implemented with high p_t threshold which prevents the use PHOJET for charm efficiency studies. The unfolding error is also estimated with PYTHIA using five flavour events instead of charm events.

To extract the $\sigma(\gamma\gamma \rightarrow \mathrm{c\bar{c}X})$ cross section, the photon flux $\mathcal{L}_{\gamma\gamma}$ [7] is calculated and the hadronic two-photon processes are extrapolated to zero $\mathrm{Q^2}$ [3]. For each $W_{\gamma\gamma}$ bin a numerical integration is performed over the unmeasured Q^2 of the scattered electron or positron.

Table 2 gives the efficiencies and the cross section $\sigma(\gamma\gamma \rightarrow \mathrm{c\bar{c}X})$ values together with statistical and systematic errors as a function of $W_{\gamma\gamma}$. Table 3 shows the sources of the systematic error. In addition to the quoted systematic errors, an additional error of 2.9 % due to data-MC resolution difference in the $\mathrm{E_t/P_t}$ variable is added in quadrature.

In Figure 7, the measured cross section $\sigma(\gamma\gamma \rightarrow \mathrm{c\bar{c}X})$ as a function of $W_{\gamma\gamma}$ is shown. A parametrisation by A.Donnachie and P.V. Landshoff [6] of the form $\sigma_{\mathrm{tot}} = A\, s^{\epsilon} + B\, s^{-\eta}$ ('Pomeron + Reggeon') describes well the energy behaviour of all total hadron-hadron cross sections with a universal values $\eta = 0.34 \pm 0.02$ and $\epsilon = 0.095 \pm 0.002$ [5]. The fit in the interval $5 < W_{\gamma\gamma} < 70$ GeV by the 'Pomeron + Reggeon' form gives for the 'Pomeron' slope ϵ

$$
\begin{aligned}
&\epsilon = 0.400 \pm 0.062(\text{stat.}) \pm 0.096(\text{syst.})\\
&A = 1.9 \pm 0.9(\text{stat.})\\
&B = 44.6 \pm 11.0(\text{stat.})\\
&\chi^2 = 9.0/2
\end{aligned}
$$

The sitematic error on ϵ is obtained by fitting with total errors of data points used in the fit. In the fit, the reggeon slope η is fixed to the Particle Data Group value [5] $\eta = 0.34$. The fitted ϵ value is higher than the universal value [5], independent of the Monte Carlo model used to unfold the data.

The dashed curve in Figure 7 shows the expectation from the PYTHIA Monte Carlo for the cross section $\sigma(\gamma\gamma \rightarrow \mathrm{c\bar{c}X})$. The expected slope is smaller than the slope observed in the data. The prediction for the charm cross section is only 66 % of the measured cross section. This can be partially attributed to the effect of the next to leading order corrections. The dotted curve in Figure 7 is the measured by L3 total cross section $\sigma(\gamma\gamma \rightarrow \text{hadrons})$ scaled by an arbitrary factor 1/20.

The value of ϵ is in agreement with the measurements of the photoproduction of J/ψ (charm) mesons at HERA, which show about two times bigger slope than the photoproduction total cross section [10, 11].

The fit to the data by the form $\sigma_{\mathrm{tot}} = A\, s^{\epsilon}$ performed in the interval $10 < W_{\gamma\gamma} < 70$ GeV gives for the 'Pomeron' slope

$$
\begin{aligned}
&\epsilon = 0.287 \pm 0.046(\text{stat.}) \pm 0.073(\text{syst.})\\
&A = 4.8 \pm 1.4(\text{stat.})\\
&\chi^2 = 1.7/2
\end{aligned}
$$

Modifications to the parametrization of the total cross section were recently proposed by A.Donnachie and P.V. Landshof [12]. In order to allow for a bigger slope for the high energy behaviour they introduce an admixture of 'hard' and 'soft' Pomeron. Many other models were proposed to describe the hadronic cross sections [13–15]. Our result is the direct measurement of the 'hard' perturbative component of photon-photon collisions.

3 Conclusions

The cross section for inclusive charm production in two-photon collisions, $\sigma(\gamma\gamma \rightarrow \mathrm{c\bar{c}})$ is measured with the L3 detector at $\sqrt{s} = 189 - 202$ GeV. The high energy behaviour of the total charm cross section as a function of the $\gamma\gamma$ centre-of-mass energy is measured for the first time. The cross sections $\sigma(\mathrm{e^+e^-} \rightarrow \mathrm{e^+e^-c\bar{c}X})$ and $\sigma(\gamma\gamma \rightarrow \mathrm{c\bar{c}X})$ are measured in the interval 5 GeV $\leq W_{\gamma\gamma} \leq$ 70 GeV. The fit to the data gives for the 'Pomeron' slope

$\epsilon = 0.29 \pm 0.05(\mathrm{stat.}) \pm 0.07(\mathrm{syst.})$. The data are compared to the expectations of the PYTHIA model. A steeper rise with energy is observed for $\sigma(\gamma\gamma \rightarrow \mathrm{c\bar{c}X})$ as compared to hadron-hadron cross sections and to $\sigma(\gamma\gamma \rightarrow \mathit{hadrons})$.

Acknowledgments

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W_{vis} [GeV]	Selected Data Events	Background Events	b-background Events	uds-bkgd. Events	N_{cc} Events
$5-10$	741	5.3	14.3	172.5	549.0
$10-15$	527	1.3	22.9	107.9	395.0
$15-25$	542	1.1	28.2	124.6	388.0
$25-40$	282	2.7	16.8	51.2	211.0
$40-70$	96	8.7	6.5	20.7	60.0

Table 1: The number of events of the data, background and signal for the process $\gamma\gamma \to c\bar{c}X$ as a function of W_{vis}.

$W_{\gamma\gamma}$ [GeV]	$c\bar{c}$ unfolded Events	Efficiency 10^{-2}	$\sigma_{ee\to eec\bar{c}X}$ [nb]	$\sigma_{\gamma\gamma\to c\bar{c}X}$ [nb]
$5-10$	443.5	0.330 ± 0.013	$0.328 \pm 0.012 \pm 0.031$	$22.0 \pm 0.8 \pm 2.1$
$10-15$	284.1	0.559 ± 0.020	$0.124 \pm 0.004 \pm 0.012$	$20.1 \pm 0.7 \pm 1.9$
$15-25$	427.7	0.695 ± 0.023	$0.150 \pm 0.005 \pm 0.011$	$27.2 \pm 0.9 \pm 2.0$
$25-40$	360.0	0.720 ± 0.027	$0.122 \pm 0.004 \pm 0.011$	$37.4 \pm 1.3 \pm 3.5$
$40-70$	222.8	0.565 ± 0.029	$0.096 \pm 0.004 \pm 0.011$	$45.8 \pm 2.0 \pm 5.1$

Table 2: Cross section values for the process $\gamma\gamma \to c\bar{c}X$ as a function of $W_{\gamma\gamma}$. The first error is statistical and the second is systematic.

$W_{\gamma\gamma}$ [GeV]	$\sigma_{\gamma\gamma\to c\bar{c}X}$ [nb]	Charm eff. [nb]	Unf. PYTHIA [nb]	Unf. PHOJET [nb]	$\sigma_{bb} = 10$ pb [nb]	Charm purity [nb]
$5-10$	22.0	0.9	1.4	1.0	0.2	1.0
$10-15$	20.1	0.7	-0.6	-1.25	0.5	0.9
$15-25$	27.2	0.9	0.3	0.5	1.2	1.3
$25-40$	37.4	1.4	1.3	-1.0	2.1	1.8
$40-70$	45.8	2.3	-1.8	-2.1	3.0	2.1

Table 3: The list of the systematic errors on the total cross section for the process $\gamma\gamma \to c\bar{c}X$.

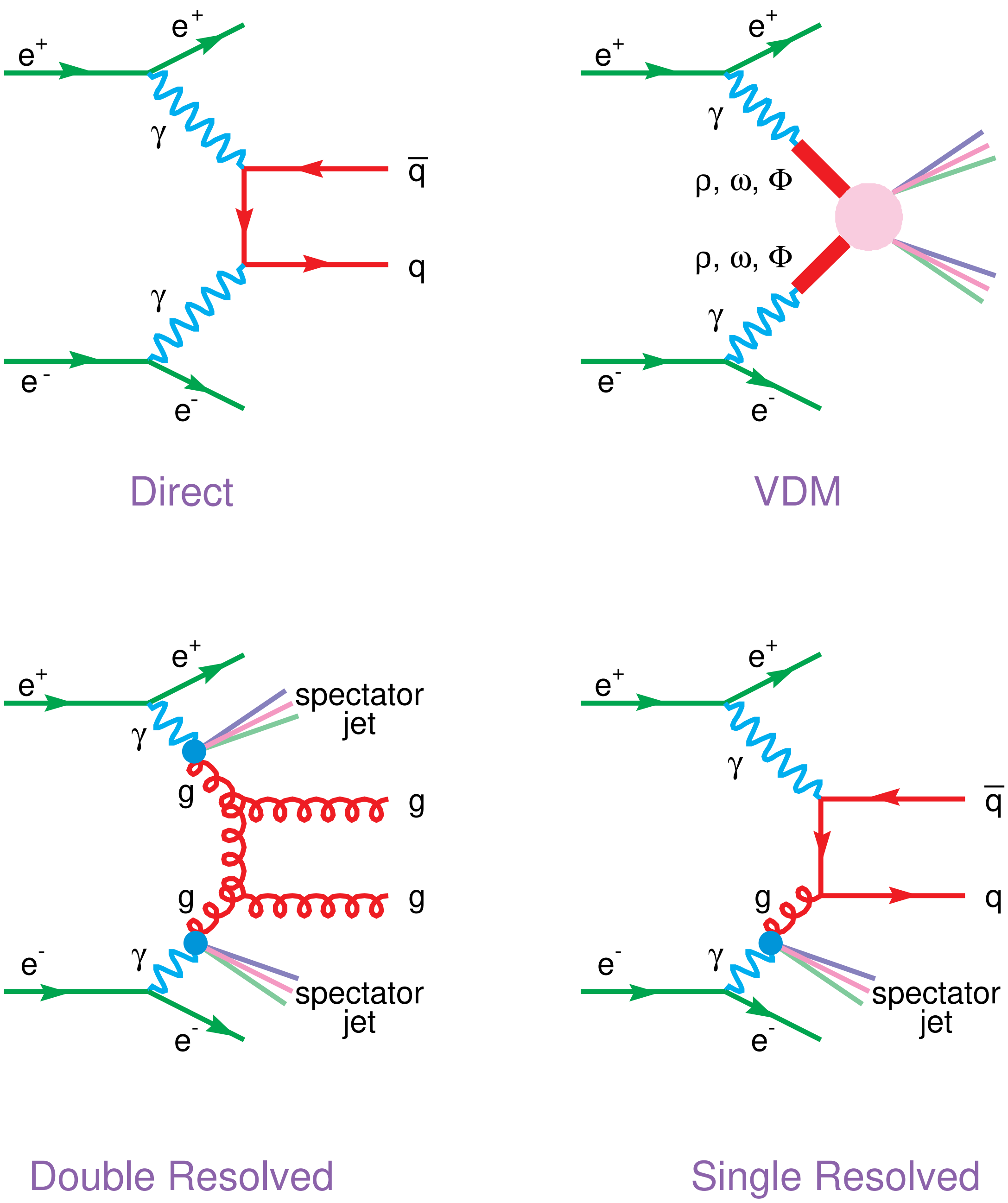

Figure 1: Production of hadrons in two-photon collisions at e^+e^- colliders.

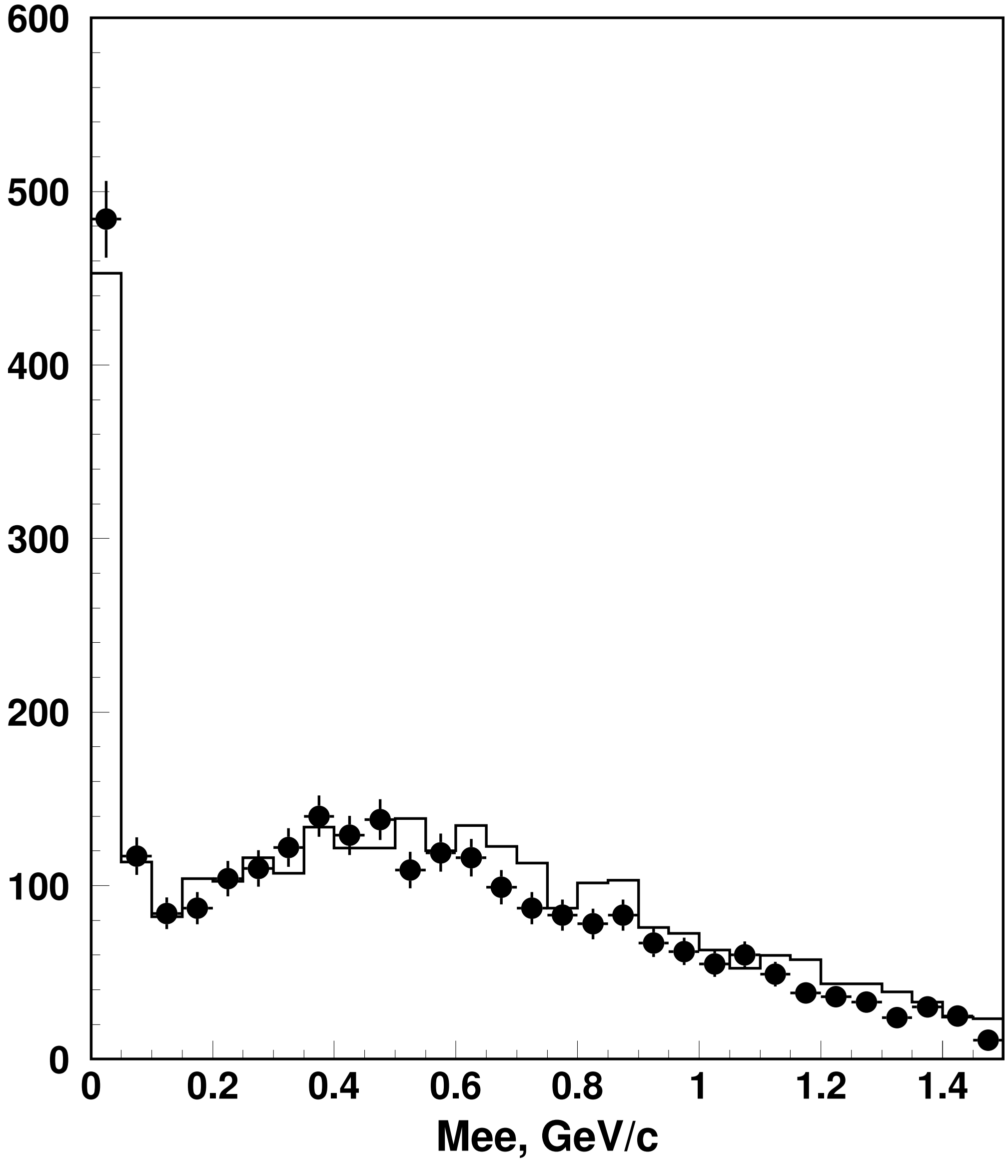

Figure 2: Mass of the electron candidate and the closest track. The requirement on the mass to be greater than 0.1 GeV suppresses γ-conversions. The points are the data at at $\sqrt{s} = 189 - 202$ GeV, the histogram is the PYTHIA Monte Carlo normalized to the same number of events as in the data.

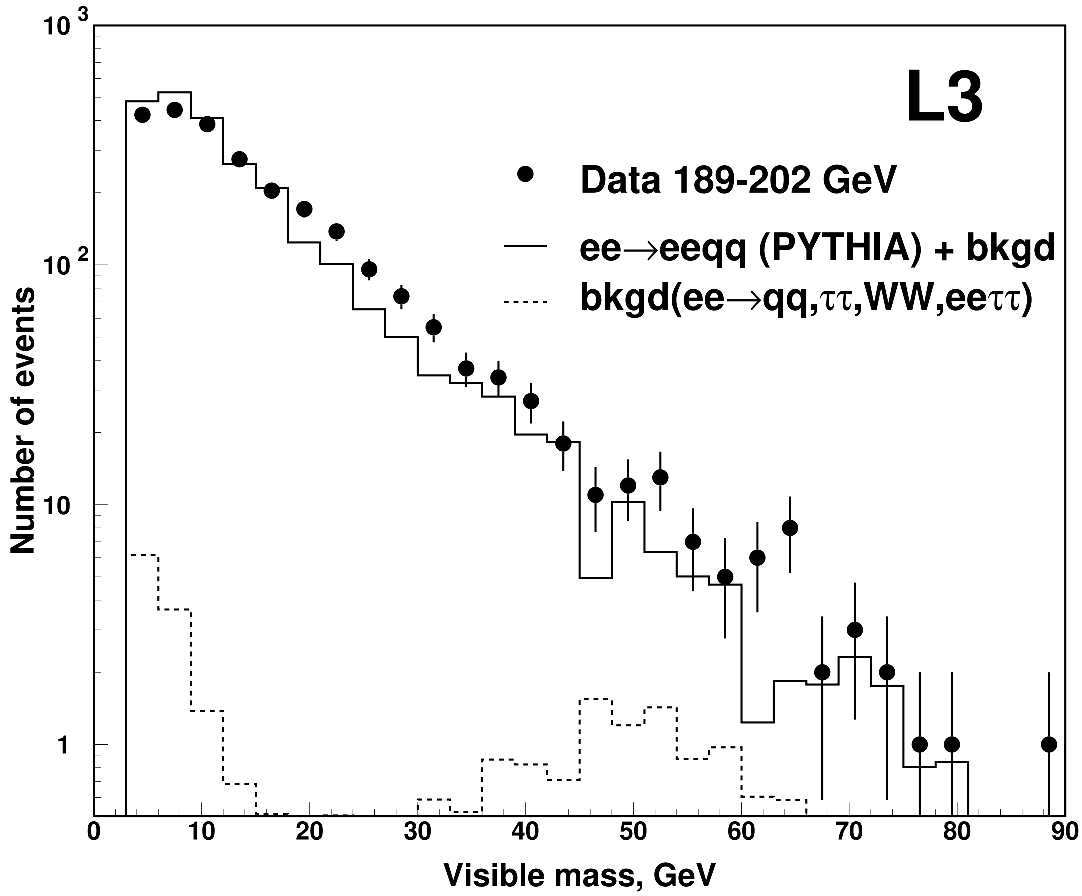

Figure 3: The visible mass spectrum for the inclusive electron data at $\sqrt{s} = 189 - 202$ GeV compared to PYTHIA events generated with massless matrix elements. The Monte Carlo spectrum with all flavour contributions is normalized to the data integrated luminosity after scaling to the measured charm cross section and purity.

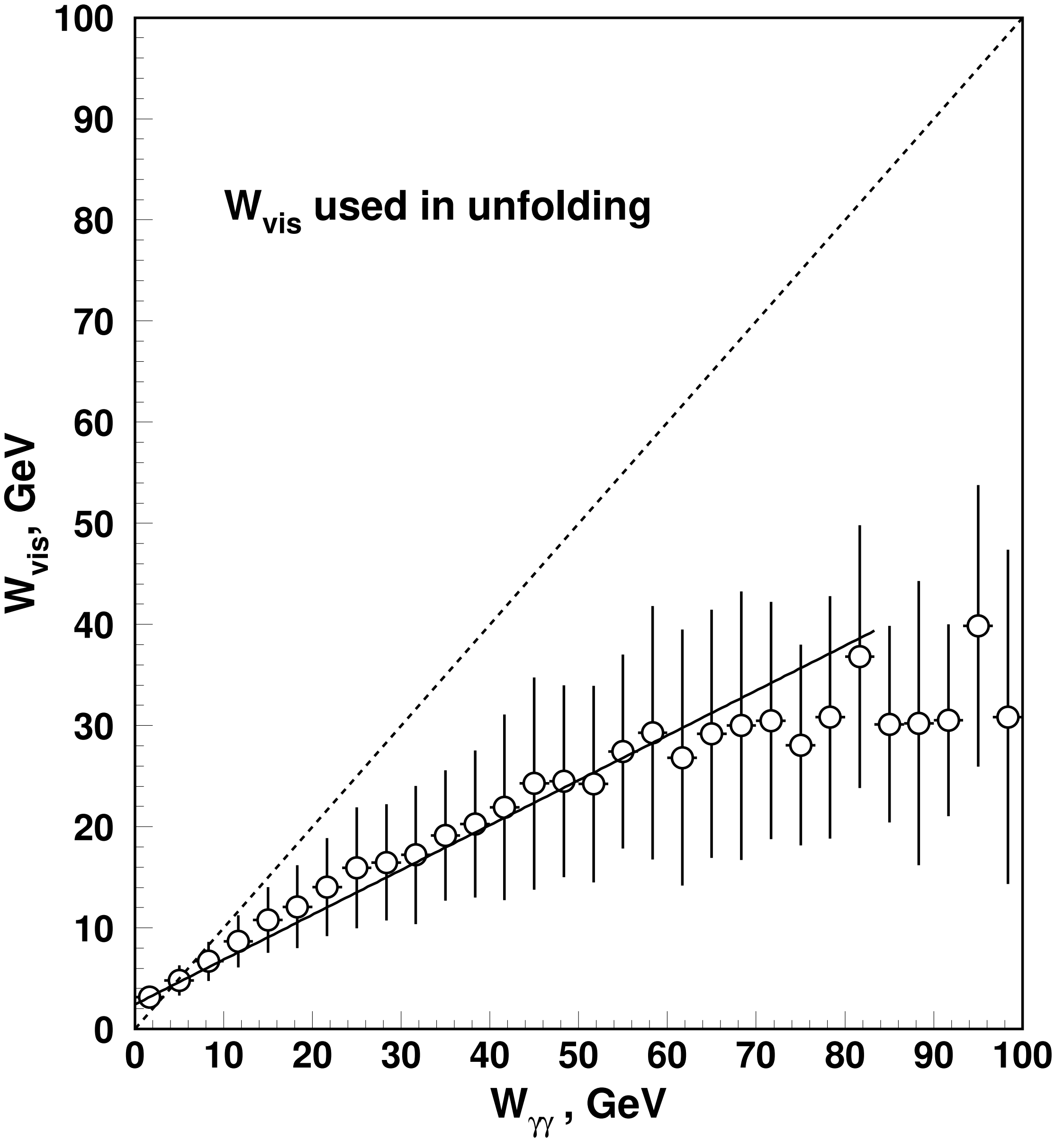

Figure 4: W_{vis} versus $W_{\gamma\gamma}$ using PYTHIA Monte Carlo. The unfolding corrects for acceptance (missing energy) and detector resolution.

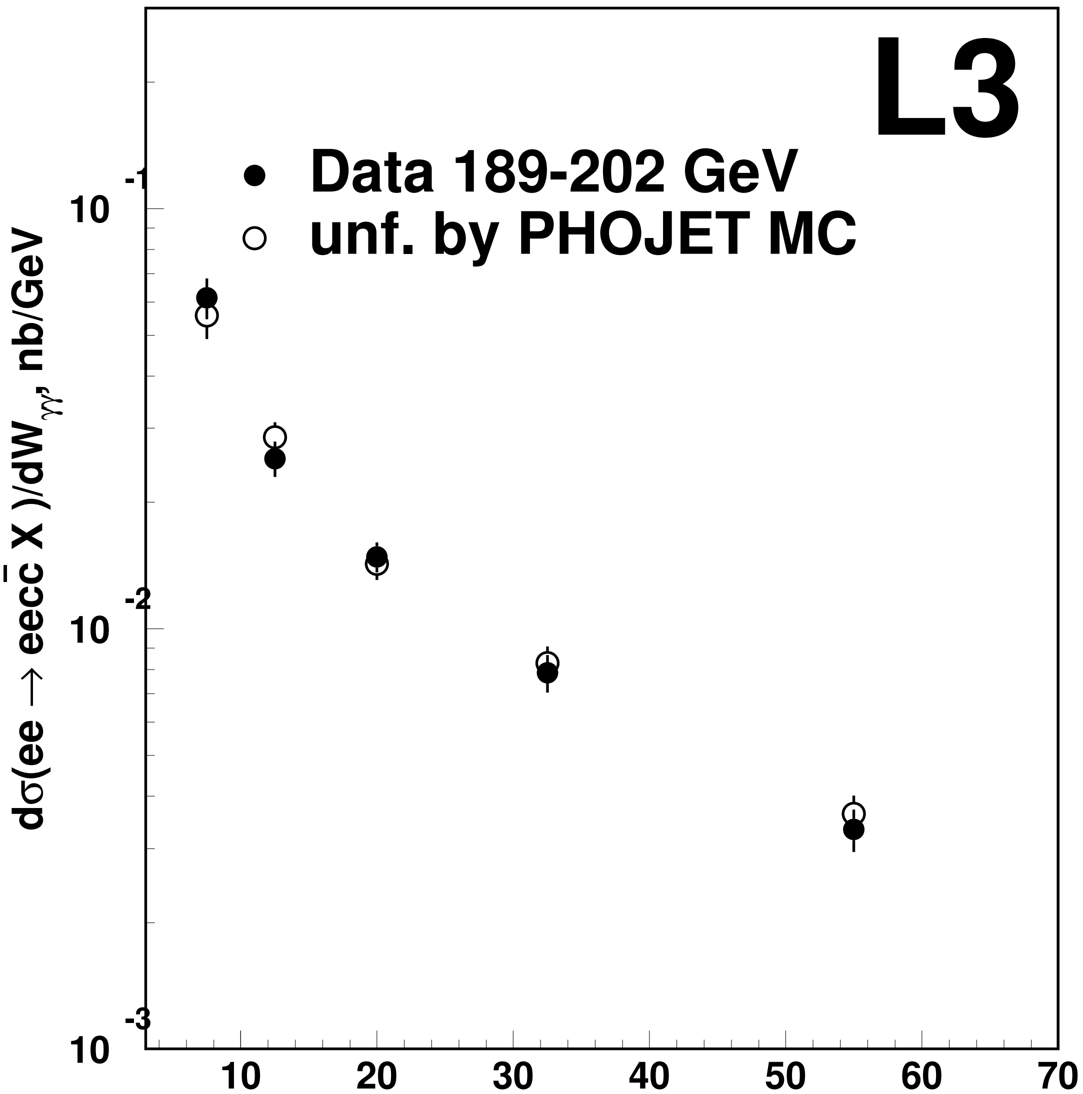

Figure 5: The differential cross section ee $\rightarrow$ eec$\bar{\mathrm{c}}$ as function of $W_{\gamma\gamma}$ at $\sqrt{s} = 189 - 202$ GeV. The unfolding have been done with PYTHIA Monte Carlo. Open dots show the cross section values when PHOJET is used for unfolding.

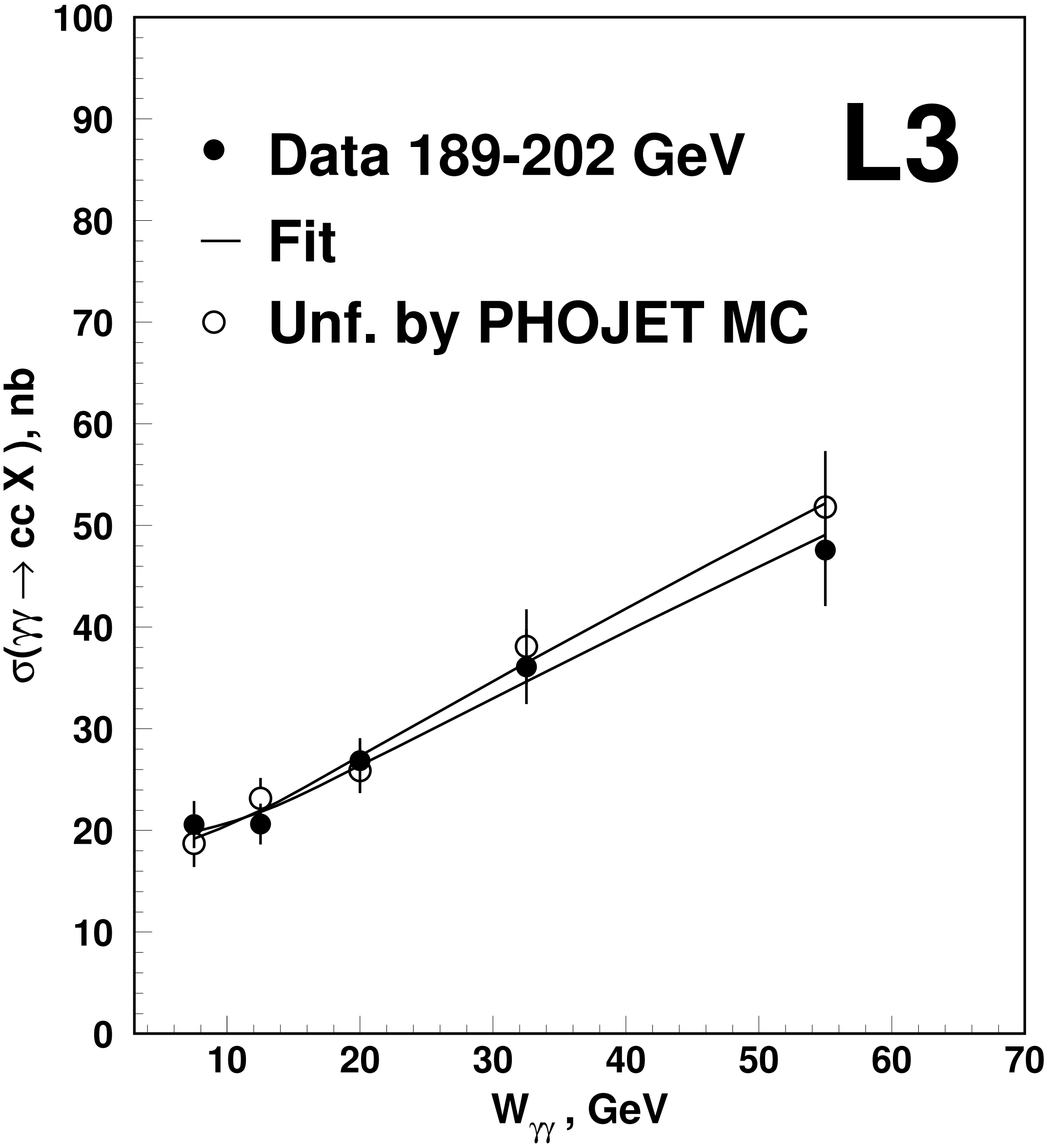

Figure 6: The cross section $\gamma\gamma \rightarrow c\bar{c}$ as function of $W_{\gamma\gamma}$ at $\sqrt{s} = 189 - 202$ GeV. The lines are the Regge fits, with fixed value of η as described in the text. The unfolding have been done with PYTHIA (full dots) and PHOJET (open dots) Monte Carlo.

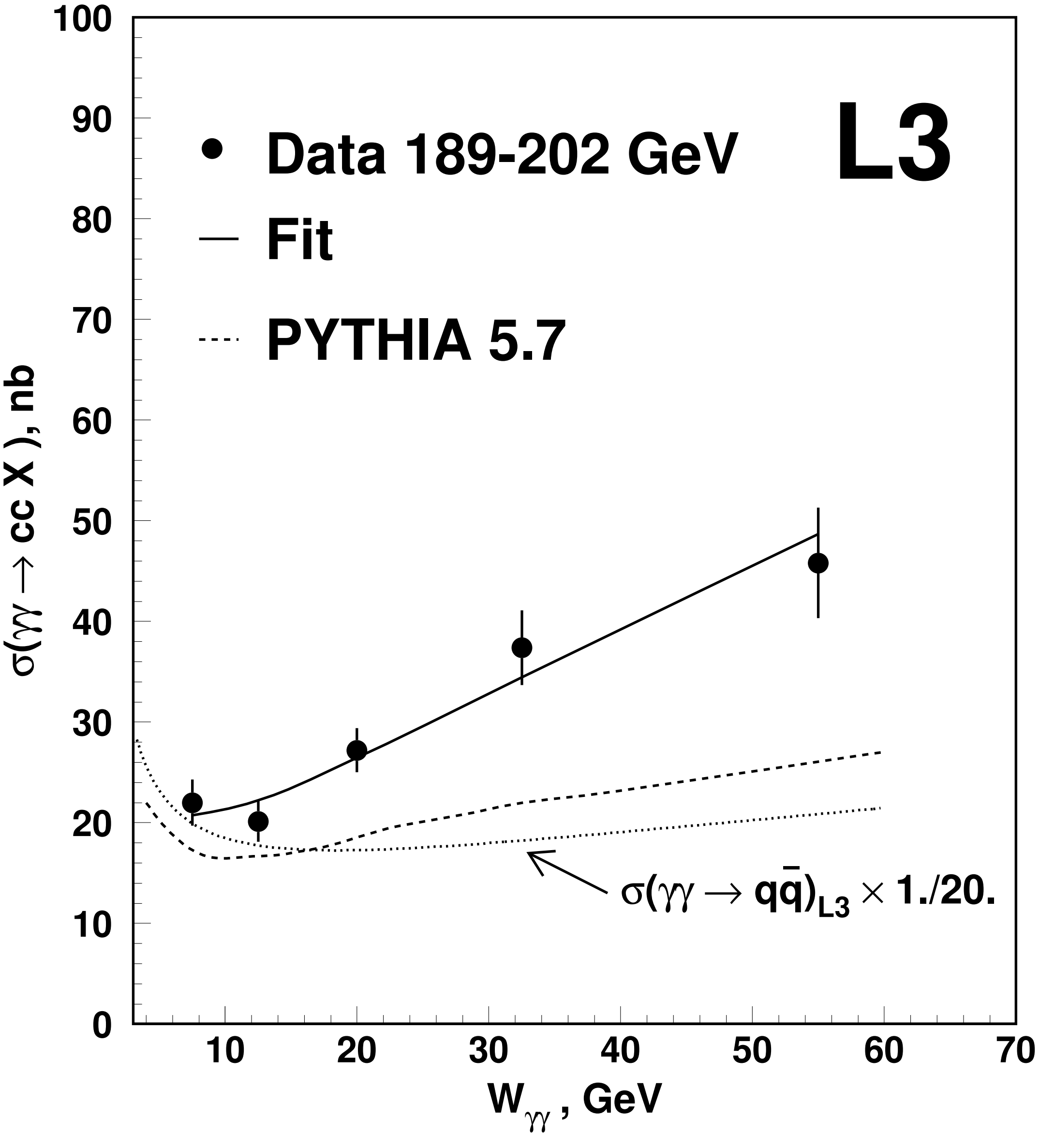

Figure 7: The cross section $\gamma\gamma \to c\bar{c}$ as function of $W_{\gamma\gamma}$ at $\sqrt{s} = 189-202$ GeV. The continuous line is the Regge fit, with fixed value of η as described in the text. The unfolding is done with PYTHIA Monte Carlo. The dashed curve shows the expectation from the PYTHIA model. The dotted curve is the total cross section $\sigma(\gamma\gamma \to \text{hadrons})$ measured by L3 scaled by an arbitrary factor 1/20.