MEASUREMENT OF THE INCLUSIVE CHARM PRODUCTION IN $\gamma\gamma$ COLLISIONS AT LEP USING LEPTON TAG

The L3 Collaboration

Abstract

Inclusive charm production in $\gamma\gamma$ collisions has been studied with the L3 detector at the LEP collider. Charmed hadrons were identified by electrons and muons from their semi-leptonic decays. The cross section of charm production has been measured at center of mass energies 91 GeV (LEP1) and 161+172 GeV (LEP2). The results of the cross section measurement are in agreement with QCD prediction.

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1 Introduction

The production of heavy quarks in gamma-gamma collisions consists mainly of charm quarks. The production of beauty quarks is expected to be suppressed by more than two orders of magnitude [1]. The measurement of charm production in $\gamma\gamma$ collisions provides a test of QCD, and it is especially attractive in heavy quark physics where one can rely on perturbative calculations. The "hadronic" nature of photons can be studied more easily with the increase of e^+e^--collider energies. At LEP2 energies "pointlike" and "hadronic" (resolved) photons contribute equally to the cross section [1]. The production rate of the charm quarks in $\gamma\gamma$ collisions depends on the mass of charm quark and the gluon density in the photon. Precise measurements of the process $\gamma\gamma \to c\bar{c}$ could better constrain those important physical parameters. Measurements of the charm production in two-photon collisions were done at PEP, PETRA, TRISTAN and LEP1 energies [2–8]. The published results of different experiments were extrapolated to the total charm cross sections for the purpose of comparison at "Physics at LEP2" workshop [9]. Experiments at TRISTAN have measured higher cross sections than predicted by theory (even with Next to Leading Order(NLO) corrections taken into account). Measurement of charm production rate at LEP1 by ALEPH [8] is compatible with the direct production $\gamma\gamma \to c\bar{c}$ in the Born approximation and with QCD prediction which includes radiative corrections to the direct process and a contribution when one of the photons is first resolved into quark and gluon constituents.

In this paper we present the result of the measurement of $e^+e^- \to e^+e^-c\bar{c}X$ cross section by the L3 experiment at LEP1 and for the first time at LEP2 energies. To identify the presence of charm quark a tagging by electrons and muons from semi-leptonic decays has been used.

2 Measurement of inclusive charm production

Data samples collected by L3 at $\sqrt{s} = 91$ GeV (total integrated luminosity of 80 pb^{-1} in the period 1994-95) and at $\sqrt{s} = 161$, 172 GeV (total integrated luminosity of 21 pb^{-1} in the period 1996) have been analyzed. The L3 detector has been described in detail in Ref. [10].

2.1 Event Selection

The event selection consists of two steps. One needs first to select hadronic final states produced in $\gamma\gamma$ collision and second to tag charm quarks. Hadronic two-photon events are selected by the following cuts: we require at least four tracks in each event, visible energy to be in the range $2 < E_{vis} < 60$ GeV (< 40 GeV at LEP1), energy in the electro-magnetic calorimeter to exceed 0.5 GeV, invariant visible mass to be greater than 3 GeV and thrust to be smaller than 0.95. The invariant visible mass of the event is calculated from the four-momentum vectors of the measured particles. All particles are considered to be pions except for the electro-magnetic clusters identified as photons. The analysis is limited to anti-tagged events which are selected by excluding events where the most energetic cluster in the L3 luminosity monitor has an energy greater than 0.43 E_{beam}. Two more cuts are applied to the LEP1 data. We require the number of calorimetric clusters to be greater than ten and transverse momentum imbalance to be smaller than 5 GeV/c (to suppress further $\tau\tau$ background).

This selection leaves 63330 events in the LEP2 data. Monte Carlo prediction at this stage is 65986 $\gamma\gamma \to$ hadrons events (PYTHIA [11]) and 0.3% of events in total of other types ($qq, ee\tau\tau, \tau\tau, WW$). For LEP1 data corresponding numbers are 137320 events in the data,

Table 1: Background composition for muon tag.

LEP energy $[GeV]$	Number of expected events	Background source
$\sqrt{s} = 91$	10.9 ± 1.4	$e^+e^- \to e^+e^-q\bar{q}$
	5.4 ± 2.7	$e^+e^- \to q\bar{q}$
	1.2 ± 0.5	$e^+e^- \to e^+e^-\tau^+\tau^-$
$\sqrt{s} = 161, 172$	8.2 ± 1.1	$e^+e^- \to e^+e^-q\bar{q}$
	7.0 ± 0.8	$e^+e^- \to e^+e^-\tau^+\tau^-$
	0.8 ± 0.1	$e^+e^- \to \tau^+\tau^-$
	0.6 ± 0.3	$e^+e^- \to q\bar{q}$
	0.2 ± 0.1	$e^+e^- \to W^+W^-$

125482 events $\gamma\gamma \to$ hadrons (PYTHIA) and 4.1% of events in total of other types ($qq, ee\tau\tau, \tau\tau$). A comparison of different distributions also shows good agreement between data and Monte Carlo. In Figure 1a) we plot the measured visible mass spectrum for LEP2 data after hadronic events selection ($c\bar{c}$ purity is only 10 % at this step).

Tagging of charm quarks in this analysis is based on two methods: the detection of muons in the L3 muon chambers and the tagging of electrons using L3 tracking and calorimetry.

2.2 Muon tag result

Muon selection implies a lower cut on momentum of 2 GeV/c as only such muons can penetrate through calorimeters to muon chambers. In order to suppress a contribution of muons from annihilation processes we require the muon momentum to be smaller than 7 GeV/c for LEP1 and 15 GeV/c for LEP2 data. Figure 1b) shows the transverse momentum of muon track spectrum for LEP2 data after all selection cuts have been applied.

After applying all cuts, 43 inclusive muon events have been observed in the LEP1 and 29 events in the LEP2 data. One event in LEP1 data has two (same sign) muon candidates. Monte Carlo prediction is 32.6 events for LEP1 and 28.8 events for LEP2 luminosities. It accounts for contributions from two-photon process $e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-q\bar{q}$ and annihilation process $e^+e^- \to Z, \gamma \to hadrons$ (both simulated with PYTHIA), $e^+e^- \to \tau^+\tau^-$ (KORALZ [12]), $e^+e^- \to e^+e^-\tau^+\tau^-$ (Vermaseren [13]) and at LEP2 also $e^+e^- \to W^+W^-$ (KORALW [14]). Cosmic ray events were rejected by visual scan. All the contributions are listed in Table 1.

Total cross section of inclusive charm production was obtained by using selection efficiency and $c\bar{c}$ purity of $\gamma\gamma \to$ hadrons events given by the PYTHIA Monte Carlo, which includes contributions from direct and resolved processes. The charm quark mass was assumed to be 1.35 GeV/c^2. In total, 25.5$\pm$6.6($stat$) (LEP1) and 12.2$\pm$5.4($stat$) (LEP2) events remained after background subtraction. Selection efficiencies were estimated to be (0.60 ± 0.14) 10^{-3} at LEP1 and (0.73 ± 0.17) 10^{-3} at LEP2 energies. Trigger efficiencies were derived from the data itself using a set of independent triggers. Trigger efficiencies were found to be 95.7 ± 1.2 % for LEP1 and 93.5$\pm$0.7 % for LEP2 data. Altogether total cross section measurement is $553 \pm 142(stat) \pm 141(syst)$ pb at LEP1 and $848 \pm 373(stat) \pm 231(syst)$ pb at LEP2 energies. Systematic errors arise from uncertainty on background subtraction and selection efficiencies. We have also made an estimate of $c\bar{c}$ selection efficiency using the MC program [13] of J.A.M. Vermaseren for the Quark Parton Model (QPM) production of charm quarks which were $(0.43 \pm 0.05)\ 10^{-3}$ at LEP1 and $(0.79 \pm 0.11)\ 10^{-3}$ at LEP2 energies. This is compatible within errors with PYTHIA numbers and provides an estimate for possible systematics from model dependence. Vermaseren Monte Carlo uses the exact $2 \rightarrow 4$ matrix elements calculation for $e^+e^- \rightarrow e^+e^- f\bar{f}$ via $\gamma\gamma$ collisions (direct process only).

2.3 Electron tag result

We searched for an electron (or positron) to tag charm-quark production for momentum $p > 0.5$ GeV/c. We used a time-expansion chamber (TEC) for tracking and a BGO calorimeter to measure electro-magnetic (EM) showers. This analysis was restricted to the barrel region ($|cos| < 0.725$) in order to improve the quality of track measurements.

Electron candidates were selected by combining the information from the E_t/p_t ratio, dE/dx and the EM shower ratios of E_1/E_9 and E_9/E_{25}, where E_1/E_9 is the ratio of the energy deposited in the crystal at the shower center to the energy of the surrounding 9, and E_9/E_{25} is the ratio of the energy deposited in the 9 crystals around the shower center to the energy of 25 crystals. The ratio (E_t/p_t) of the transverse energy measured by the BGO and the transverse momentum measured by the TEC has the power to separate 99% of the hadrons (primarily pions) from the electrons. We fixed the range to $0.9 < E_t/p_t < 1.20$. In Fig. 2a-b, the E_t/p_t distributions of electrons and non-electrons are plotted separately for Monte Carlo (PYTHIA) events at $\sqrt{s} =$ 161 GeV. The high energy electrons (p > 0.5 GeV/c) have a mean value for dE/dx of 1 MeV/cm, so we made a cut of $0.85 < dE/dx < 1.20$. In Fig 2c, we plotted the transverse momentum of tracks (2c) for both data and MC at $\sqrt{s} = 161$ GeV after final selection. The lateral shower shape of the BGO cluster must be consistent with that of an EM shower: $E_1/E_9 > 0.4$ and $E_9/E_{25} > 0.95$. The number of crystals associated with the BGO cluster must be greater than three. To suppress the contamination from photon conversions, we required the distance of closest approach (DCA) of each electron candidate to the event vertex in the x-y plane to be less than 0.5 mm.

After applying all cuts, 471, 125 and 136 inclusive events have been observed at $\sqrt{s} = 91$, 161 and 172 GeV energies respectively. Monte Carlo prediction is 515, 135 and 119 events respectively. All the background contributions for the electron tag are listed in Table 2. The selection efficiency was estimated (PYTHIA) to be $(0.70 \pm 0.05)\ 10^{-2}$, $(1.30 \pm 0.12)\ 10^{-2}$ and $(0.90 \pm 0.09)\ 10^{-2}$ at the same respective center of mass energies. Total cross section measurement is $425 \pm 40(stat) \pm 57(syst)$ pb at $\sqrt{s} = 91$, $586 \pm 85(stat) \pm 131(syst)$ pb at $\sqrt{s} = 161$, and $783 \pm 133(stat) \pm 163(syst)$ pb at $\sqrt{s} = 172$ energies. The combined result for LEP2 is $679 \pm 75(stat) \pm 145(syst)$ pb.

2.4 Discussion of results

In Figure 3 we show the results for the measurement of the total inclusive charm production cross section compared to other measurements [9] and to the predictions of Ref. [1]. Dashed lines correspond to the QPM prediction while solid lines show the QCD prediction calculated to the NLO accuracy. Our results are in agreement with QCD predictions.

Uncertainty for the theory prediction is due to charm mass variation. The highest values of prediction come from using a charm mass of 1.3 GeV/c^2; the lowest values correspond to a charm mass of 1.7 GeV/c^2. The open $c\bar{c}$ threshold energy is set to 3.8 GeV. The QPM (Born direct process) prediction depends only on the heavy-quark mass and the QCD coupling

Table 2: Background composition for electron tag.

LEP energy $[GeV]$	Number of expected events	Background source
$\sqrt{s} = 91$	197.8 ± 8.7	$e^+e^- \rightarrow e^+e^-q\bar{q}$
	36.5 ± 11.0	$e^+e^- \rightarrow q\bar{q}$
	7.8 ± 2.5	$e^+e^- \rightarrow \tau^+\tau^-$
	4.5 ± 1.0	$e^+e^- \rightarrow e^+e^-\tau^+\tau^-$
$\sqrt{s} = 161$	41.4 ± 2.3	$e^+e^- \rightarrow e^+e^-q\bar{q}$
	4.8 ± 0.5	$e^+e^- \rightarrow e^+e^-\tau^+\tau^-$
	3.9 ± 0.3	$e^+e^- \rightarrow \tau^+\tau^-$
	0.7 ± 0.3	$e^+e^- \rightarrow W^+W^-$
	0.2 ± 0.1	$e^+e^- \rightarrow q\bar{q}$
$\sqrt{s} = 172$	59.2 ± 4.1	$e^+e^- \rightarrow e^+e^-q\bar{q}$
	4.5 ± 0.5	$e^+e^- \rightarrow e^+e^-\tau^+\tau^-$
	3.7 ± 0.3	$e^+e^- \rightarrow \tau^+\tau^-$
	0.6 ± 0.3	$e^+e^- \rightarrow W^+W^-$
	0.2 ± 0.1	$e^+e^- \rightarrow q\bar{q}$

constant. The plotted theory prediction was calculated with the photon structure function of Glück-Reya-Vogt [15]. Using parametrization by Drees-Grassie [16] for the quark and gluon densities of the photon results in a decrease of the cross section by 3% for high mass and by 9% for low mass. The renormalization scale was chosen to be the charm mass. The change in the renormalization scale from m_c to $2m_c$ decreases the QCD prediction by 30% (15%) for $m_c = 1.3$ (1.7) GeV$/c^2$. These uncertainties indicate that it is not possible to measure the mass of the c-quark simply by measuring the total $c\bar{c}$ cross section. However, the direct process does not suffer from them and therefore further study of differential distributions leading to a separation of the direct and resolved photon contribution to the cross section should enable the c-quark mass to be measured in the future.

3 Conclusions

The cross section of inclusive charm production in $\gamma\gamma$ collisions has been measured with L3 detector at LEP1 and for the first time at LEP2 energies. The values using muon tag have been found to be:

$$\sigma_{LEP1}^{ee\rightarrow eeccX} = 553 \pm 142 \text{ (stat) } \pm 141 \text{ (syst) pb}$$

$$\sigma_{LEP2}^{ee\rightarrow eeccX} = 848 \pm 373 \text{ (stat) } \pm 231 \text{ (syst) pb.}$$

The values of the cross sections from electron tag have been found to be:

$$\sigma_{91}^{ee\rightarrow eeccX} = 425 \pm 40 \text{ (stat) } \pm 57 \text{ (syst) pb}$$

$$\sigma_{161}^{ee\rightarrow eeccX} = 586 \pm 85 \text{ (stat) } \pm 131 \text{ (syst) pb}$$

$$\sigma_{172}^{ee\rightarrow eeccX} = 783 \pm 133 \text{ (stat) } \pm 163 \text{ (syst) pb}$$

$$\sigma_{LEP2}^{ee \to eeccX} = 679 \pm 75 \text{ (stat) } \pm 145 \text{ (syst) pb.}$$

The results are consistent with QCD predictions.

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3 Charm production cross section in two-photon collisions. Dashed lines correspond to the QPM prediction while solid lines show the QCD prediction calculated to the NLO accuracy [1]. The lowest values of prediction come from using a charm mass of 1.7 GeV/c^2; the highest values correspond to a charm mass of 1.3 GeV/c^2. The change in the renormalization scale from m_c to $2m_c$ decreases the QCD prediction by 30% (15%) for $m_c = 1.3$ (1.7) GeV/c^2. The points at TRISTAN and LEP1 energies were artificially split by 1 GeV to avoid merging.

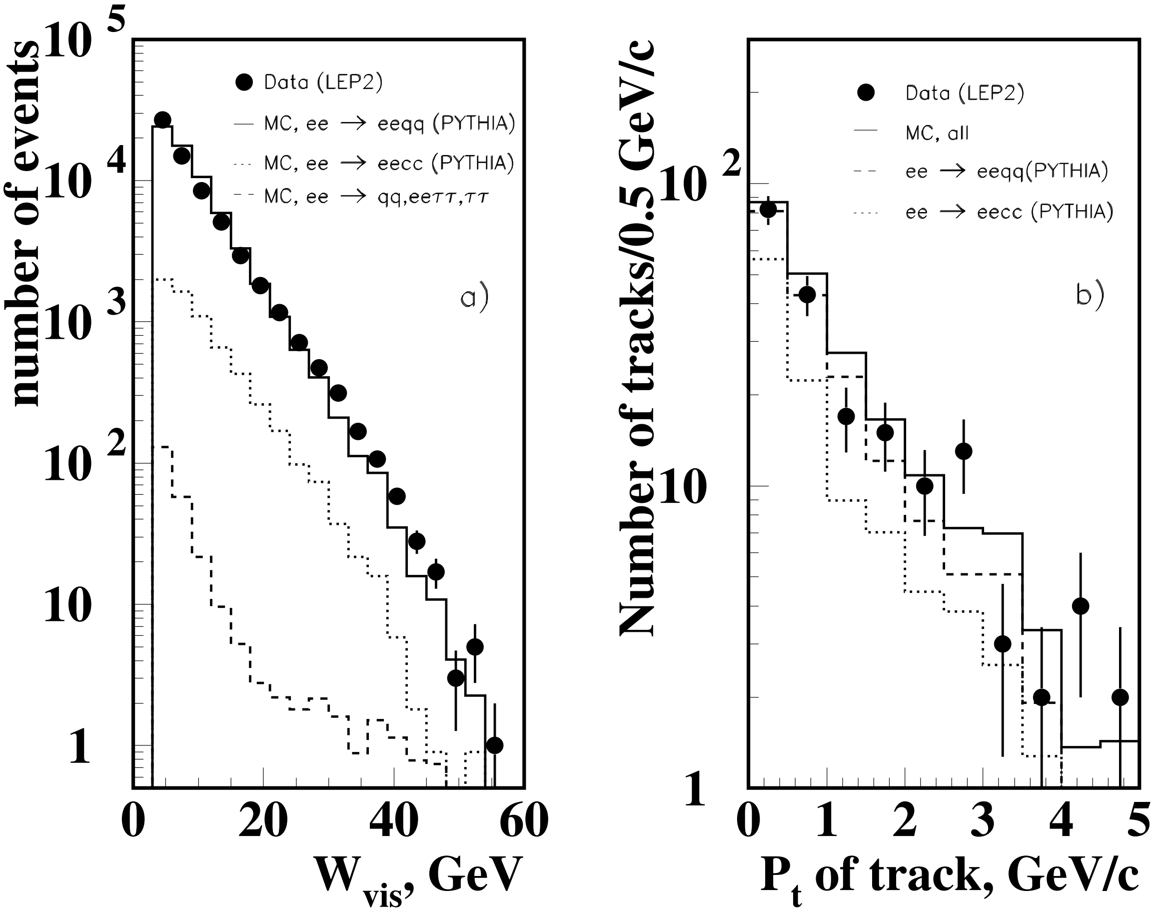

Figure 1: Spectra of visible mass of events after hadronic selection (1a) and transverse momentum of tracks after final selection for the muon tag (1b).

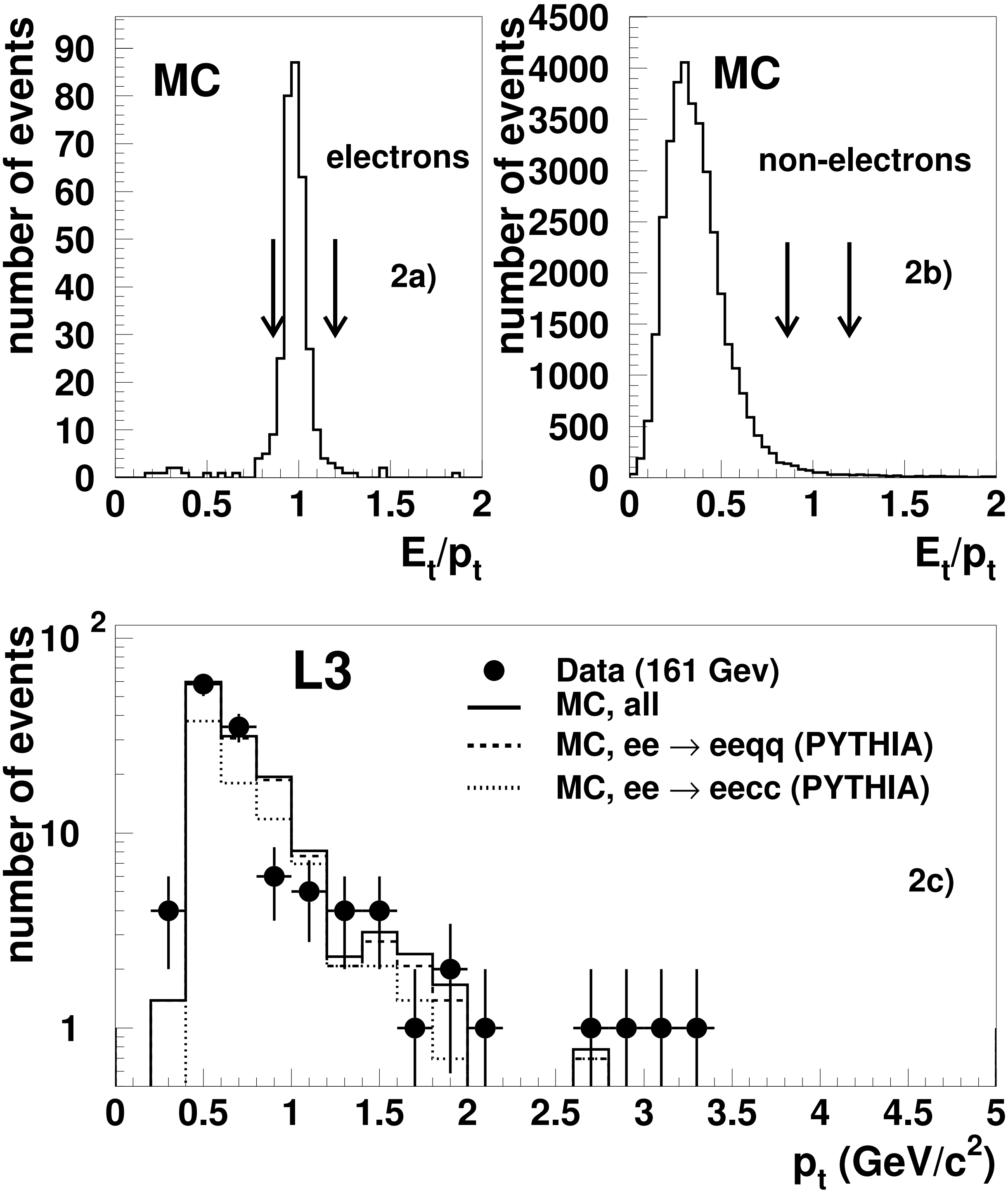

Figure 2: E_t/p_t distribution of tracks for electrons (2a) and non-electrons (2b) for Monte Carlo (PYTHIA [11]), $\sqrt{s} = 161$ GeV. The transverse momentum of tracks (2c) is plotted for both data and MC at $\sqrt{s} = 161$ GeV after final selection.

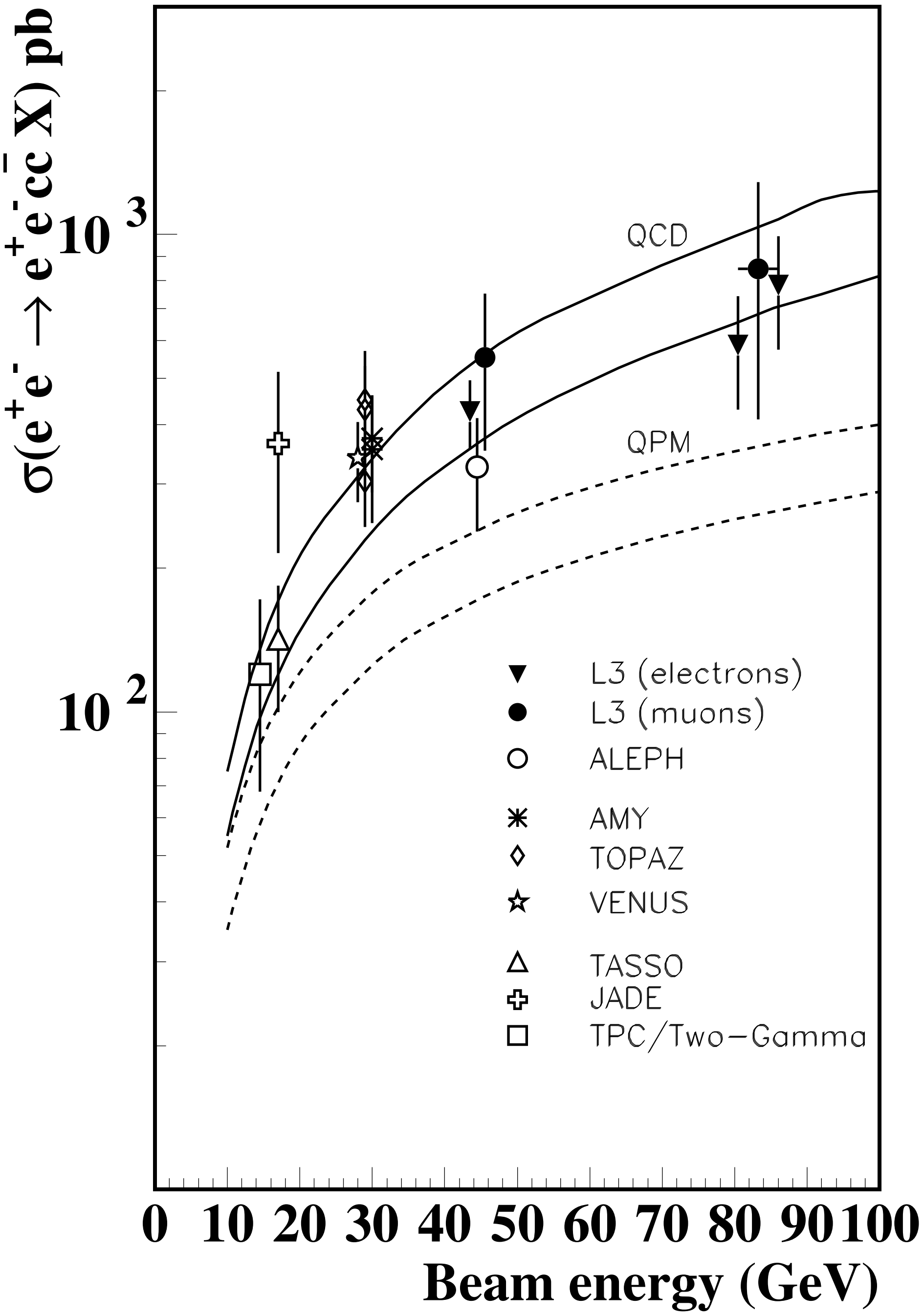

Figure 3: Charm production cross section in two-photon collisions. Dashed lines correspond to the QPM prediction while solid lines show the QCD prediction calculated to the NLO accuracy [1]. The lowest values of prediction come from using a charm mass of 1.7 GeV/c^2; the highest values correspond to a charm mass of 1.3 GeV/c^2. The change in the renormalization scale from m_c to $2m_c$ decreases the QCD prediction by 30% (15%) for $m_c = 1.3$ (1.7) GeV/c^2. The points at TRISTAN and LEP1 energies were artificially split by 1 GeV to avoid merging.