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Charged Particle Production in $e^+e^- \rightarrow W^+W^-$ Events at 172 GeV

Preliminary

DELPHI Collaboration

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Abstract

The single particle distributions were measured for two channels of $e^+e^- \rightarrow W^+W^-$ events at 172 GeV where (a) both Ws decay hadronically and (b) where one W decays hadronically and the other one leptonically. The single particle distributions show an excess of charged particles at low x_p, rapidity and transverse momentum in the fully hadronic decay channel compared to the mixed hadronic and leptonic decay channel.

The correlation functions for like-sign and unlike-sign particle pairs were measured for fully hadronic and for mixed decay WW channels. The correlation strength for like-sign pairs measured in the mixed decay channel is in good agreement with the one measured from Z^0 decays, and is considerably larger than the one measured in the fully hadronic WW decays.

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1 Introduction

As a quarks and gluons carry colour charges [1] the important question is how the confinement mechanism works in processes like $e^+e^- \to q\bar{q}g...g$, when there are identical colour charges. In this case the partons can be connected by a string in several different ways. It's not known if Nature chooses a particular configuration at random, or if some configuration is dynamically favoured [2]. A detailed investigation of particle production from decays of the W boson in $e^+e^- \to W^+W^-$ events can provide important information about effects of colour (re)connection between partons of Ws and effects of interference between decay products of different Ws. The influence of these effects on the measured W mass in the case where both Ws decay into quark jets, predicted by various theoretical approaches, varies from a few tens of MeV to a few hundreds of MeV [3].

Usually, studies of effects related to interference between particles or jets were performed by using various two or multiparticle correlation functions [4], because it is assumed that single particle distributions or average multiplicities are not changed significantly by such effects. The first measurement of correlations in $e^+e^- \to W^+W^-$ events, performed by DELPHI [5] using the traditional method of correlation studies, does not show any enhancement of the correlation function at small values of four-momenta difference between like-sign pions from different Ws at the level of statistics collected at 172 GeV.

It has been shown [6, 7] that the average charge multiplicities and single particle distributions of the fully hadronic WW channel, where both Ws decay into two quark jets, are sensitive to colour reconnection effects. These approaches predict that at present LEP2 energies, particulary at 172 GeV, colour reconnection effects in events where both Ws decay hadronically do lead to a smaller average charged particle multiplicity compared to twice the multiplicity of the hadronically decaying W in mixed decay channels, where one W decays hadronically and the other one leptonically:

$$\frac{< N_{ch}^{(had)}(WW) >}{2 < N_{ch}^{(mix)}(W) >} < 1 \tag{1}$$

A reduction of charged particle multiplicities in the fully hadronic decay channel is expected at the low momentum region, $p < 1$ GeV/c [6].

Also, one can not exclude that at high energies the properties of charged particles can significantly be affected by Bose-Einstein (BE) correlations [8, 9], which, contrary to colour reconnection effects, can lead to an excess of low-momentum particles and/or an increase of the relative probability of generation of high multiplicity events. Introduction of BE correlations by using event weight methods developed in [9, 10, 11, 12, 13] can give such effects.

This analysis describes an investigation of charged particle production for fully hadronic and mixed decay channels of $e^+e^- \to W^+W^-$ events, using data collected with the DELPHI detector [14, 15] at LEP in 1996 at centre-of-mass energy of 172 GeV.

2 Particle and Event Selections

The track and event selections, which are described below, were similar to those in [5, 16].

2.1 Particle Selection

The analysis relied on the information provided by the tracking detectors: the Microvertex Detector, the Inner Detector, the Time Projection Chamber as main tracking detector, the Outer Detector, the Forward Chambers and the Muon Chambers. Neutral particles were detected from their electro-magnetic showers in the High density Projection Chamber, the Forward Electro-Magnetic Chambers and the luminosity monitor, STIC; neutral hadronic showers were measured in the instrumented iron return yoke of the solenoidal magnet.

All charged particles except those tagged as hard leptons in semileptonic events were taken to be pions. Charged particles were selected if they fulfilled the following criteria :

- polar angle between 10° and 170°;
- momentum greater than 0.1 GeV/c and smaller than the beam momentum;
- good quality, assessed as follows:
  - track length greater than 15 cm;
  - impact parameters with respect to the nominal interaction point less than 4 cm (transverse and longitudinal with respect to the beam direction);
  - error on momentum measurement less than 100%.

For neutral particles the following selection criteria were applied :

- energy of the electromagnetic or hadron shower greater than 0.5 GeV;
- additional requirements on shower quality, assessed as follows:
  - showers in the STIC must have deposits in more than one cell;
  - showers in the hadron calorimeter must have an error in the energy of less than 100%.

Electron identification was performed in the polar angle range between 20° and 160° by looking for characteristic energy deposition in the central and forward/backward electromagnetic calorimeters and demanding an energy-to-momentum ratio consistent with unity. For this polar angle range the identification efficiency for high momentum electrons was determined from simulation to be $(77 \pm 2)\%$, in good agreement with the efficiency determined using Bhabha events measured in the detector.

Tracks were identified as due to muons if they had at least one associated hit in the muon chambers, or an energy deposition in the hadronic calorimeter consistent with a minimum ionizing particle. Muon identification was performed in the polar angle range between 10° and 170°. Within this acceptance, the identification efficiency was determined from simulation to be $(92\pm1)\%$. Good agreement was found between data and simulation for high momentum muons in $Z \rightarrow \mu^+\mu^-$ decays, and for low momentum pairs produced in $\gamma\gamma$ reactions.

2.2 Event Selection for Fully Hadronic Final States

The event selection criteria were optimised in order to ensure that the final state was purely hadronic and in order to reduce the residual background, for which the dominant contribution is radiative $q\bar{q}$ production, $e^+e^- \to q\bar{q}(\gamma)$, especially the radiative return to the Z peak, $e^+e^- \to Z\gamma \to q\bar{q}\gamma$.

Only events where the value of the thrust was less than 0.9 were considered. For each event passing the above criteria, all particles were clustered into jets using the LUCLUS algorithm [17] with the resolution parameter $d_{\mathrm{join}} = 6.5$ GeV/c. At least four jets were required, with more than three particles in each jet.

Events from the radiative return to the Z peak were rejected by requiring the effective centre-of-mass energy of the e^+e^- annihilation to be larger than 115 GeV. The effective energy was estimated using either the recoil mass calculated from one or two isolated photons measured in the detector or, in the absence of such a photon, by forcing a 2-jet interpretation of the event and assuming that a photon had been emitted collinear to the beam line.

Events were then forced into a four-jet configuration. The four-vectors of the jets were used in a kinematic fit, which imposed conservation of energy and momentum and equality of masses of two pairs of jets. Events were used only if at least one of the three possible pairings of jets had a fitted mass larger than 75 GeV/c^2 and a fit probability larger than 2.5%.

From a data sample corresponding to an integrated luminosity of 10 pb^{-1}, 24 events were selected.

The detector effects on the analysis were estimated using samples of WW and background events generated with PYTHIA 5.7 [18] with the fragmentation tuned to the DELPHI data at LEP1 [19]. The generated events were passed through the full detector simulation program DELSIM [15]. A total of 24.7 events are expected from simulation. The purity and efficiency of the selection, estimated using simulated events, were about 91% and 41%, respectively. The cut on the fit probability strongly reduces the efficiency of event selection, from 66% to 41%. It was verified with simulated events that the events removed by the cut on the fit probability have practically the same multiplicity distribution as the remaining events.

2.3 Event Selection for Mixed Hadronic and Leptonic Final States

Events in which one W decays into lepton plus neutrino and the other one into quarks are characterized by two hadronic jets, one energetic isolated charged lepton, and missing momentum resulting from the neutrino. The main backgrounds to these events are radiative $q\bar{q}$ production and four-fermion final states containing two quarks and two charged leptons of the same flavour.

Events were selected by requiring six or more charged particles and a missing momentum of more than 10% of the total centre-of-mass energy. Electron and muon tags were applied to the events. In $q\bar{q}(\gamma)$ events, the selected lepton candidates are either leptons produced in heavy quark decays or misidentified hadrons, which generally have rather low momenta and small angles with respect to their quark jets. The momentum of the selected muon, or the energy deposited in the electromagnetic calorimeters by the selected electron, was required to be greater than 20 GeV. The energy not associated to the lepton, but assigned instead to other charged or neutral particles in a cone of 10° around the lepton, is a useful measure of the lepton's isolation; this energy was required to be less than 5 GeV for both muons and electrons. In addition, the isolation angle between the lepton and the nearest charged particle with a momentum greater than 1 GeV/c was required to be larger than 10°. If more than one identified lepton passed these cuts, the one with highest momentum was considered to be the lepton candidate from the W decay. The angle between the lepton and the missing momentum vector was required to be greater than 70°. All the other particles were forced into two jets using the LUCLUS algorithm [17]. Both jets had to contain at least one charged particle.

Further suppression of the radiative $q\bar{q}$ background was achieved by looking for evidence of an ISR (Initial State Radiation) photon. Events were removed if there was a cluster with energy deposition greater than 20 GeV in the electromagnetic calorimeters, not associated with a charged particle. Events with ISR photons at small polar angles, where they would be lost inside the beam pipe, were suppressed by requiring the polar angle of the missing momentum vector to satisfy $|\cos\theta_{\rm miss}| < 0.94$.

The four-fermion neutral current background was reduced by applying additional cuts to events in which a second lepton of the same flavour as the first was detected. Such events were rejected if the energy in a cone of 10° around the second lepton direction was greater than 5 GeV.

If no lepton was identified, the most energetic particle which formed an angle greater than 25° with all other charged particles was considered as a lepton candidate. In this case the lepton was required to have a momentum greater than 20 GeV/c, as before, but tighter cuts were applied to the amount of missing momentum (greater than 20 GeV/c) and to its polar angle ($|\cos\theta_{\rm miss}| < 0.85$).

A kinematical fit was performed on the selected events. The four-vectors of the two jets and of the lepton were used in the fit, which imposed conservation of energy and momentum and equality of the masses of the two-jet system and the lepton-neutrino system, attributing the missing momentum of the event to the undetected neutrino. Events were used only if the fit probability was larger than 0.1%. The final cut was that the fitted mass of the two-jet system had to be larger than 65 GeV.

From the data sample corresponding to an integrated luminosity of 10 pb^{-1}, 30 events were selected. The purity and efficiency of the selection, estimated using simulated events, were about 96% and 49%, respectively. A total of 26.3 events is expected from simulation.

3 Results and Discussion

Charged particles were used in the analysis if they had a momentum $p > 100$ MeV/c, error on the momentum measurement less than 100%, polar angle θ between 30° and 150°, track length greater than 50 cm, and impact parameters with respect to the nominal interaction point less than 4 cm. The energetic isolated charged track of the mixed decay channel was not included in the following analysis.

If the statistical errors for the data on average charged particle multiplicities and single particle distributions were less than the expected errors calculated from simulated events, the latter were used as statistical errors.

3.1 Average Multiplicities of Charged Particles

Fig. 1 shows the charged particle multiplicity distributions for the fully hadronic decay (Fig. 1a) and for the mixed decay (Fig. 1b) channels of $e^+e^- \to W^+W^-$ events. The shaded areas represent the background contributions, the histograms are the sum of the expected signal and background.

The average multiplicities of charged particles measured for fully hadronic and mixed decay WW channels, without correction for background events, inefficiencies due to detector effects and selection criteria, were 34.7 ± 1.5 (stat) and 15.4 ± 0.9 (stat). Correcting for the background contribution using simulated events gave the value 34.9 ± 1.5 (stat) for the average multiplicity for the hadronic decay channel. The same correction for the mixed decay channel had a negligible effect.

To take into account inefficiencies due to detector effects and selection criteria, correction factors were calculated as the ratio of average multiplicities of generated WW events to average multiplicities after full simulation of the DELPHI detector. The corrected values of the average charge multiplicities for hadronic W decays in the fully hadronic and mixed decay channels obtained in the present analysis are:

$$< N_{ch}^{(had)}(WW) > \; = \; 41.7 \pm 1.8 \text{ (stat)}, \tag{2}$$

$$< N_{ch}^{(mix)}(W) > \; = \; 18.2 \pm 1.1 \text{ (stat)}. \tag{3}$$

The numbers (2) and (3) can be compared with the average multiplicities of 38.0 and 19.0 predicted using WW events generated by PYTHIA (where both Ws decay independently), with parameters tuned to the DELPHI data at LEP1.

The values (2) and (3) are consistent with the values

$$< N_{ch}^{(had)}(WW) > \; = \; 40.6 \pm 1.7 \text{ (stat)} \pm 1.0 \text{ (syst)}, \tag{4}$$

$$< N_{ch}^{(mix)}(W) > \; = \; 18.0 \pm 0.9 \text{ (stat)} \pm 0.5 \text{ (syst)}, \tag{5}$$

measured in [20] using the same data sample as in the present analysis but selecting WW events with higher efficiency but lower purity.

3.2 Single Particle Distributions

The dependence of the charged particle multiplicities on momentum, rapidity and transverse momentum (i.e. single particle distributions) were obtained using the same procedure as for the calculation of the total average multiplicities (section 3.1), this procedure being repeated in each momentum, rapidity or transverse momentum interval. The single particle distributions, corrected for detector effects and kinematical cuts, were obtained by bin by bin multiplication of the uncorrected distributions with the ratio of the generated distributions to the distributions after full detector simulation. The single particle distributions shown below were normalized to the number of events and the distribution for the mixed decay WW channel was multiplied by the factor two.

The corrected x_p distributions of charged particles for fully hadronic and mixed decay WW channels, where $x_p \equiv 2p/\sqrt{s}$, are shown in Fig. 2a. In Fig. 2b the difference of the x_p distributions is shown as closed circles. An excess of low momentum particles is observed for the fully hadronic decay channel in the region $x_p < 0.01$, which corresponds to the momentum region $p < 0.86$ GeV/c. This difference amounts to

$$3.9 \pm 1.5 \text{ (stat)} \pm 0.7 \text{ (syst)}, \tag{6}$$

where the systematic error is the sum in quadrature of the contributions due to background events (0.54), variation of selection criteria (0.38) and limited Monte-Carlo statistics(0.10).

The difference between the distributions for fully hadronic and twice the mixed decay channel for events generated by PYTHIA (stars in Fig. 2b), where both Ws decay independently, is practically zero in all momentum regions, as expected.

It has been shown [6] that comparison of particle properties of fully hadronic and mixed decay WW channels with respect to the thrust axis, where the thrust axis is defined from all particles in the event, can be sensitive to interference of decay products of different Ws for the fully hadronic decay channel. The thrust, major and minor axis in the present analysis was obtained using the fitted directions of four objects (four quark jets in the case of fully hadronic decay channel and two quark jets, the lepton and the neutrino for the mixed decay channel).

In Fig. 3, Fig. 4a and Fig. 4b are shown the corrected distributions of rapidity, p_t^{in} and p_t^{out}, respectively. The rapidity, p_t^{in} and p_t^{out} of the particles were defined with respect to the thrust, major and minor axis. As in the case of the x_p distributions, a considerable excess of charged particle multiplicities in the fully hadronic decay channel (closed circles) is observed, as compared to twice the mixed decay channel multiplicities (open circles). This excess is concentrated in the low rapidity and transverse momenta regions. It was verified by the simulated events that the correction factors do not introduce any bias which could lead to discrepancy between distributions of fully hadronic and mixed decay WW channels.

3.3 Correlation Functions for Like-Sign Particles

In ref. [5] DELPHI measured the correlations between like-sign pions from different Ws in $e^+e^- \to W^+W^-$ events. No enhancement of the correlation function was observed at small Q values, where $Q^2 = M^2(\pi\pi) - 4m_\pi^2$. In this section we present measurements of the correlation functions of like-sign pions, separately for fully hadronic and mixed decay channels.

The correlation function can be written as

$$R(Q) = \frac{P(Q)}{P_0(Q)}, \tag{7}$$

where $P(Q)$ is the two-particle probability density and $P_0(Q)$ is the reference two-particle distribution. The term $P(Q)$ in this analysis represents the Q distribution of two like-sign particles. The reference distribution $P_0(Q)$ was calculated using four-vectors of particles randomly selected from different events (event mixing technique). The momentum components of particles for measuring $P_0(Q)$ were calculated with respect to the thrust axis, which was obtained using the fitted directions of four objects, as explained in section 3.3.

In [21, 22, 23] it was shown that the mixing event technique generates kinematical and so called "methodological" correlations at low Q values. The same ratio (7) calculated from Monte-Carlo events (without Bose-Einstein correlations included) takes into account both the kinematical and methodological correlations [21, 22, 23]. Consequently, the ratio

$$R'(Q) = \frac{R^{\mathrm{data}}(Q)}{R^{\mathrm{MC}}(Q)} \tag{8}$$

is a measurement of dynamical correlations [23].

The quantity $R(Q)$ for like-sign combinations of fully hadronic decay WW channels is shown in Fig. 5a for data (closed circles) and for Monte-Carlo events after full simulation of the DELPHI detector (open circles). The ratio $R'(Q)$ is shown in Fig. 5b.

A fit to the correlation function $R'(Q)$ using the expression

$$R'(Q) = 1 + \lambda e^{-r^2 Q^2} \tag{9}$$

was performed, where the parameter r represents the source size and λ the strength of the correlation between the pions. As in ref. [5], the parameter r was fixed to the value r=0.5 fm, as measured in Z^0 decays [23]. The fit yielded the value:

$$\lambda \quad = \quad 0.09 \pm 0.06 \text{ (stat)} \tag{10}$$

with $\chi^2 = 14$ for 14 degrees of freedom. This fit is shown by the solid curve in Fig. 5b. For verification of stability of the results, another mixing method was used, where the momentum components of the particles were calculated with respect to the event axis for the calculation of $P_0(Q)$. The measured value of λ was practically the same as the value (10).

For the mixed decay WW channel the same quantities are shown in Fig. 6. The fit to the correlation function $R'(Q)$ with expression (9) and with fixed value r=0.5 fm yielded:

$$\lambda \quad = \quad 0.41 \pm 0.13 \text{ (stat)}\,, \tag{11}$$

with $\chi^2 = 26$ for 14 degrees of freedom [1]. This fit is shown by the solid curve in Fig. 6b. The stability of the results was verified by using another mixing method, i.e. for the calculation of $P_0(Q)$ the momentum components of the particles were calculated with respect to the thrust axis which was obtained using particles from hadronically decaying Ws of the mixed decay WW channel. The measured value of λ was in good agreement with the value (11).

The correlation strength obtained for like-sign pions from hadronic W decays in the mixed decay channel (eq. 11) is compatible with the corresponding values reported in [21] (λ=0.40$\pm$0.02) and in [22] (λ=0.35$\pm$0.04) for like-sign pions from Z^0 decays using a mixed-event reference sample.

The correlation strengths of like-sign pions in fully hadronic and mixed decay channels must be equal if the correlation strength of like-sign pions from different Ws equals the correlation strength of like-sign pions from the same Ws. The present measurement shows a difference: the measured correlation strenght for the full hadronic decay channel (eq. 10) is much smaller than the value obtained for the mixed decay channel (eq. 11) and smaller than the values measured at the Z^0 peak in [21, 22]. This confirms the result of [5] where no enhancement of the correlation function between like-sign pions from different Ws was observed at small Q values (with a measured value of λ=–0.20$\pm$0.22$\pm$0.08).

3.4 Correlation Functions for Unlike-Sign Particles

The quantities $R(Q)$ and $R'(Q)$ for unlike-sign particle pairs of the fully hadronic decay channel are shown in Fig. 7. The same distributions for the mixed decay channel are shown

[1]The fitted values of the parameters with unfixed r were λ=0.52$\pm$0.21 and r=0.58$\pm$0.14 fm, both in good agreement with the corresponding values obtained in [5] using a different event mixing method.

in Fig. 8. As seen from these figures, the $R'(Q)$ distributions for both channels (Fig. 7b for fully hadronic and Fig. 8b for mixed decay) are compatible with one in the full Q region, indicating that, at the present level of statistical precision, no additional correlations were observed from the data for unlike-sign particle configurations except those which are included in the Monte-Carlo model. On the other hand the obtained $R'(Q)$ distributions for unlike-sign configurations (Fig. 7b and Fig. 8b) confirm the validity of the used event mixing reference samples for like-sign combinations.

4 Summary

Charged particle production was studied for two decay channels of $e^+e^- \to W^+W^-$ events at centre of mass energies of 172 GeV, using data collected with the DELPHI detector during the 1996 run.

The momentum, transverse momentum and rapidity distributions of charged particles for fully hadronic and mixed decay channels were measured. The transverse momentum and rapidity distributions were measured with respect to the thrust axis of all particles of the event. At low momentum, rapidity and transverse momentum regions an excess is observed of the number of charged particles in the fully hadronic decay channel in comparison with twice the mixed decay channel (figures 2, 3 and 4). The difference between the average multiplicities of hadronic W decays in fully hadronic and twice the mixed decay channels for $x_p < 0.01$ ($p < 0.86$ GeV/c) is:

$$3.9 \pm 1.6 \text{ (stat+syst)}\,. \tag{12}$$

The correlation functions for like-sign and unlike-sign particle pairs were measured separately for fully hadronic and for mixed decay channels. For unlike-sign pairs no additional correlations except those which are included in the model, are observed from the data.

The measured correlation strength between like-sign particles from hadronic W decays in the mixed WW decay channel is in good agreement with the same values measured for like-sign particles from Z^0 decays and these values are higher than the correlation strength of like-sign particles measured for the fully hadronic decay WW channel. Consequently, the present analysis confirms the results of the analysis in [5] where, at the present level of statistics, no enhancement was found at small Q values of the correlation function of like-sign particles from different Ws for the fully hadronic WW decay channel.

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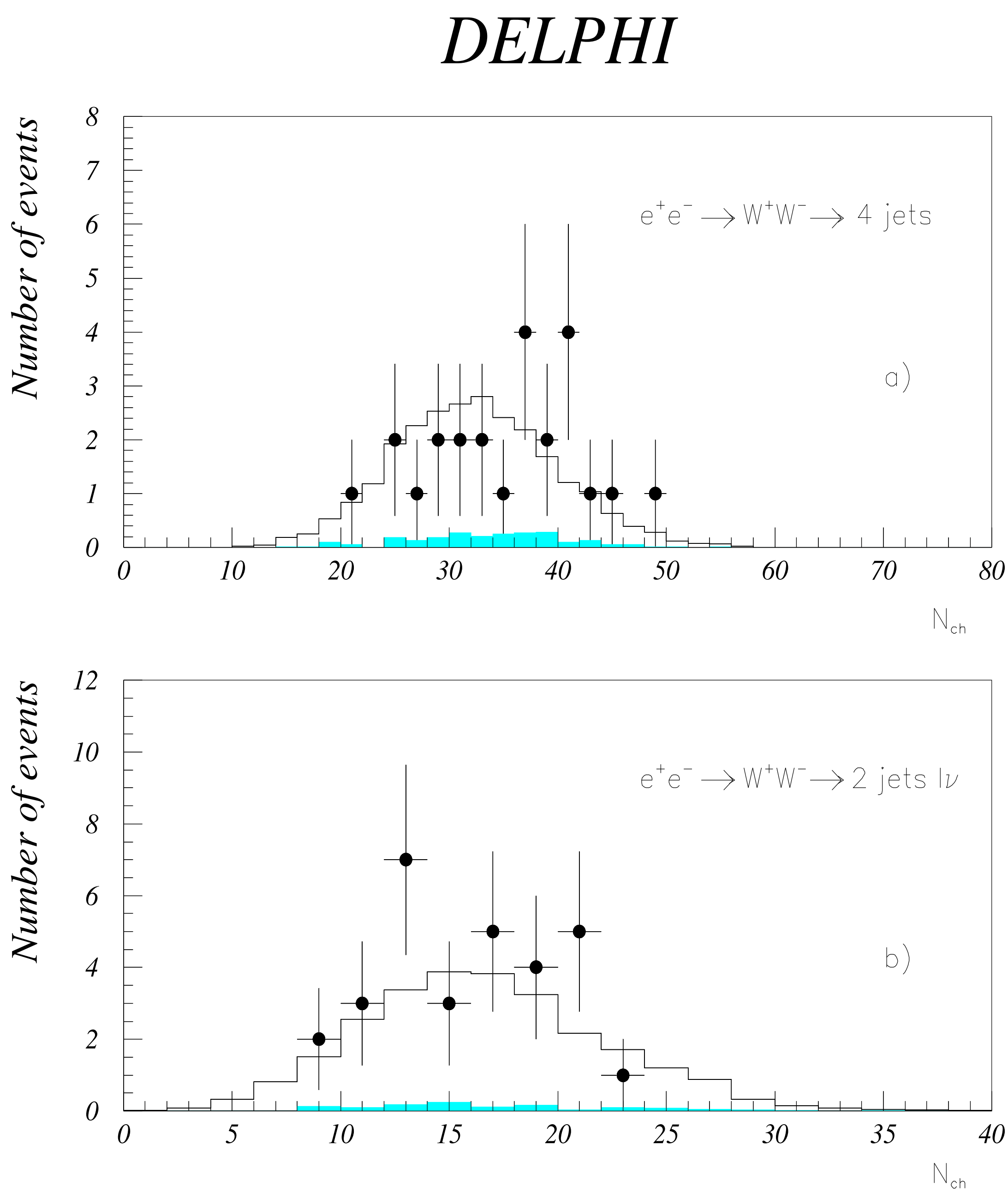

Figure 1: Charged particle multiplicity distributions: **(a)** fully hadronic (4-jet) final states and **(b)** mixed hadronic and leptonic (jet-jet-lepton-neutrino) final states. The shaded areas represent the background contributions. The histograms are the sum of the expected signal and background.

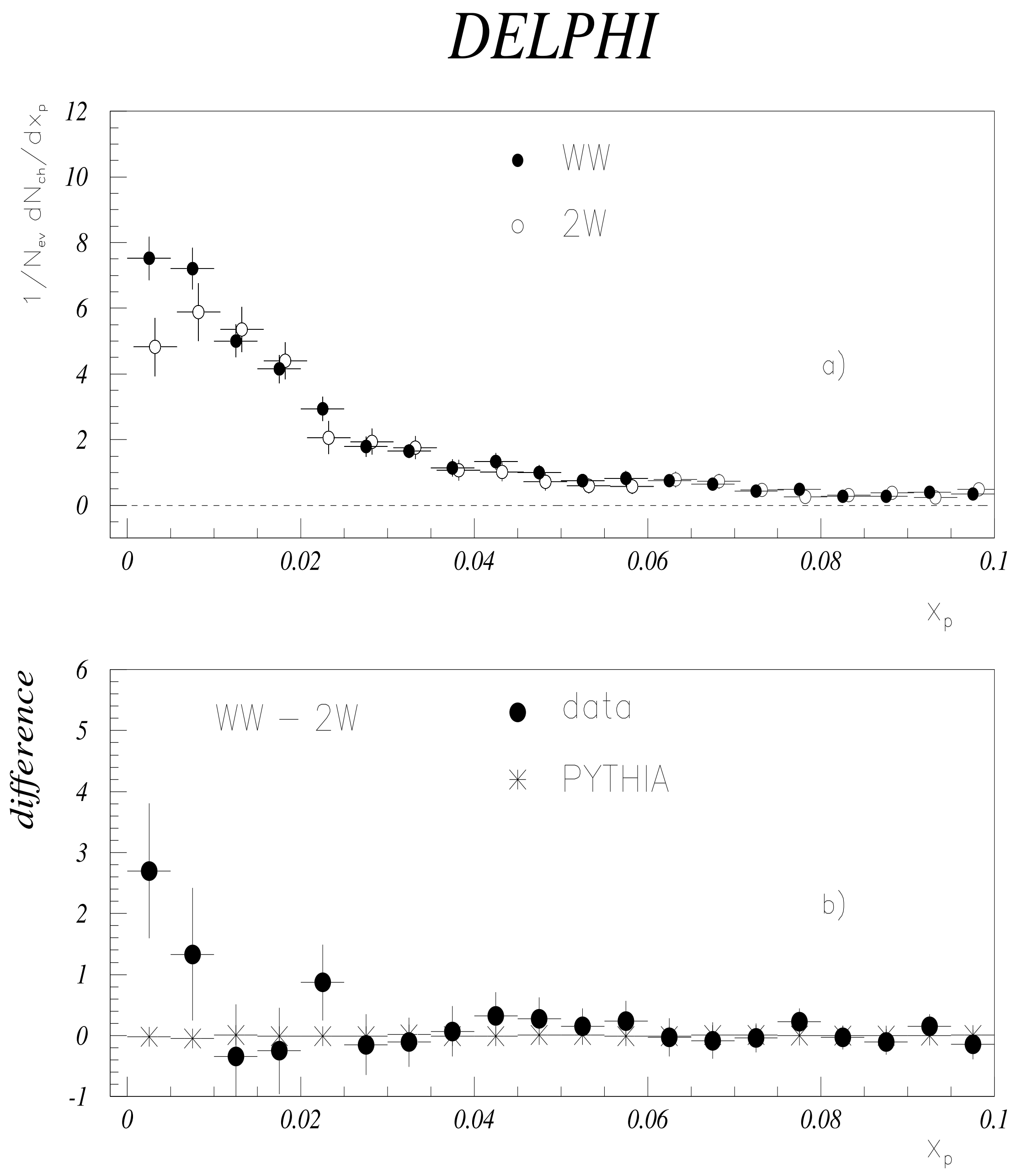

Figure 2: **(a)** The corrected x_p distributions for charged particles from hadronic W-decays for fully hadronic final states (closed circles) and twice the mixed hadronic and leptonic final states (open circles). The distributions are normalized to the number of events. **(b)** The difference between the distributions in Fig. 3a (closed circles). The predicted difference obtained by using events generated with PYTHIA is shown by stars.

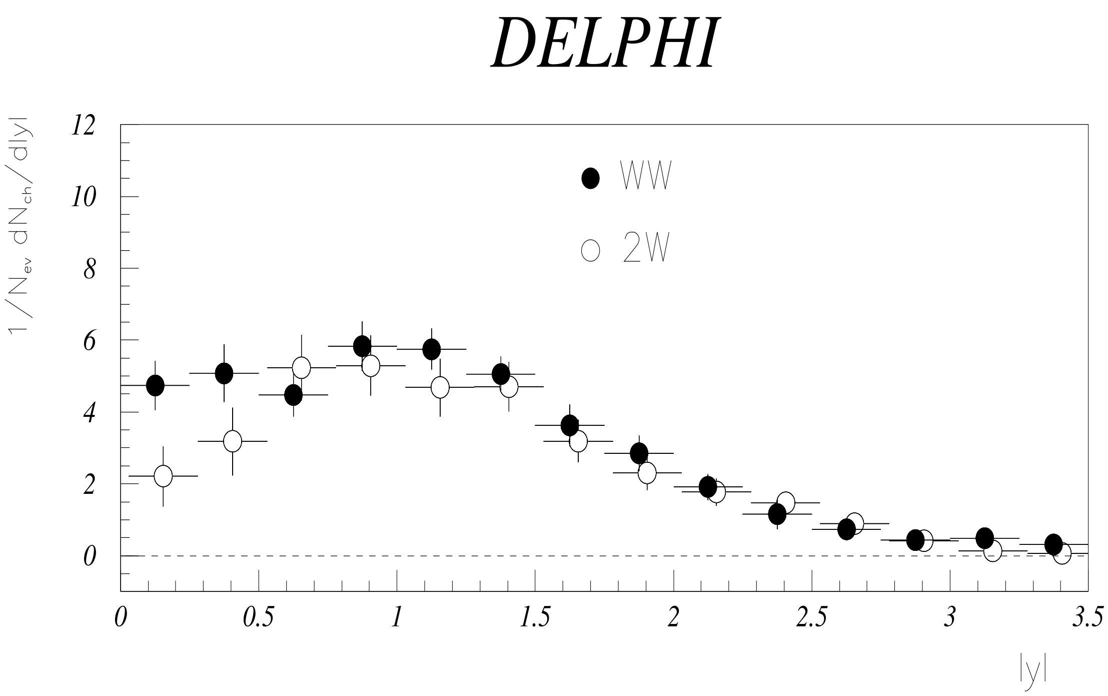

Figure 3: The corrected rapidity distributions for charged particles from hadronic W-decays for fully hadronic final states (closed circles) and twice the mixed hadronic and leptonic final states (open circles). The distributions are normalized to the number of events.

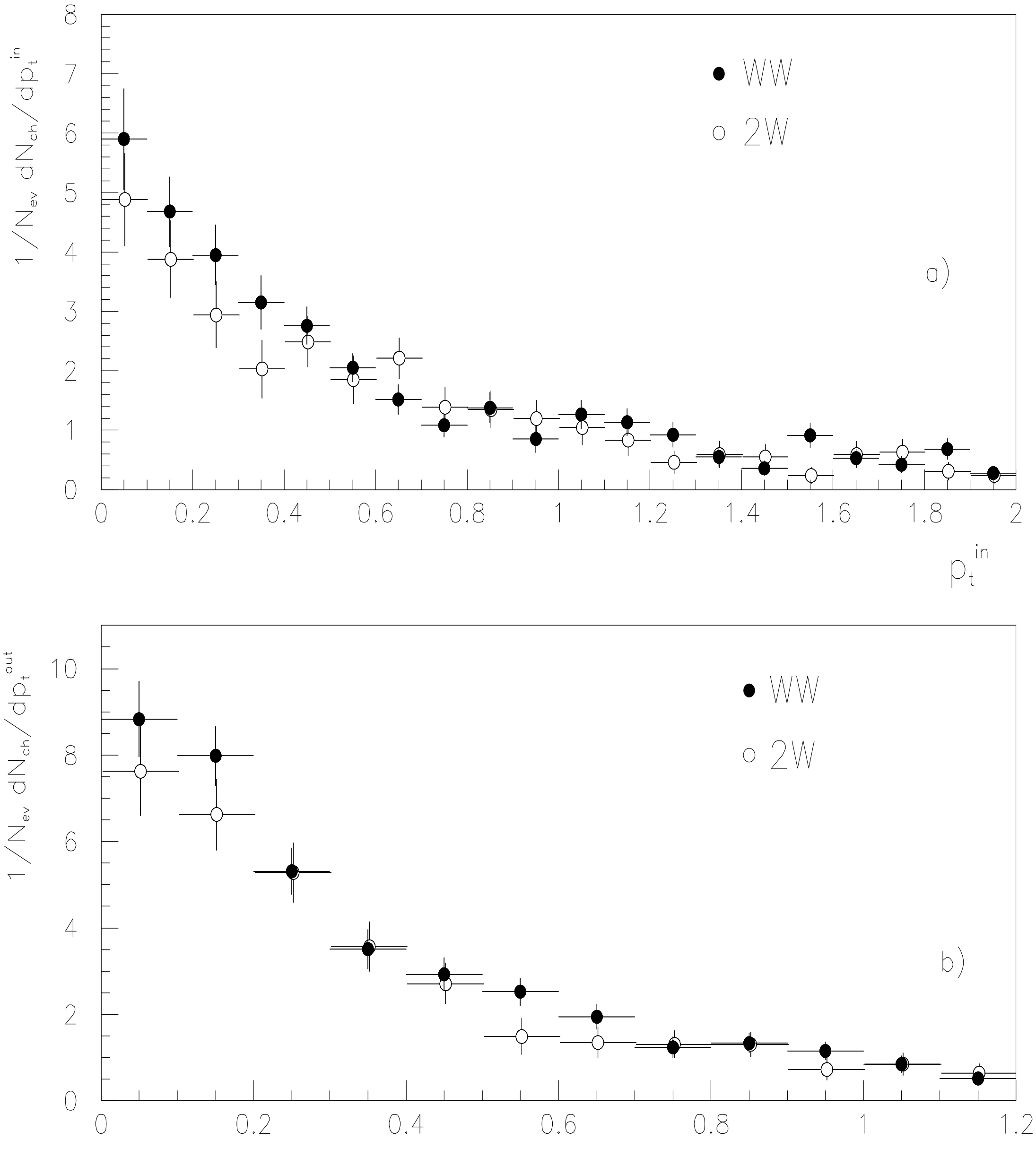

Figure 4: The corrected **(a)** p_t^{in} and **(b)** p_t^{out} distributions for charged particles from hadronic W-decays for fully hadronic final states (closed circles) and twice the mixed hadronic and leptonic final states (open circles). The distributions are normalized to the number of events.

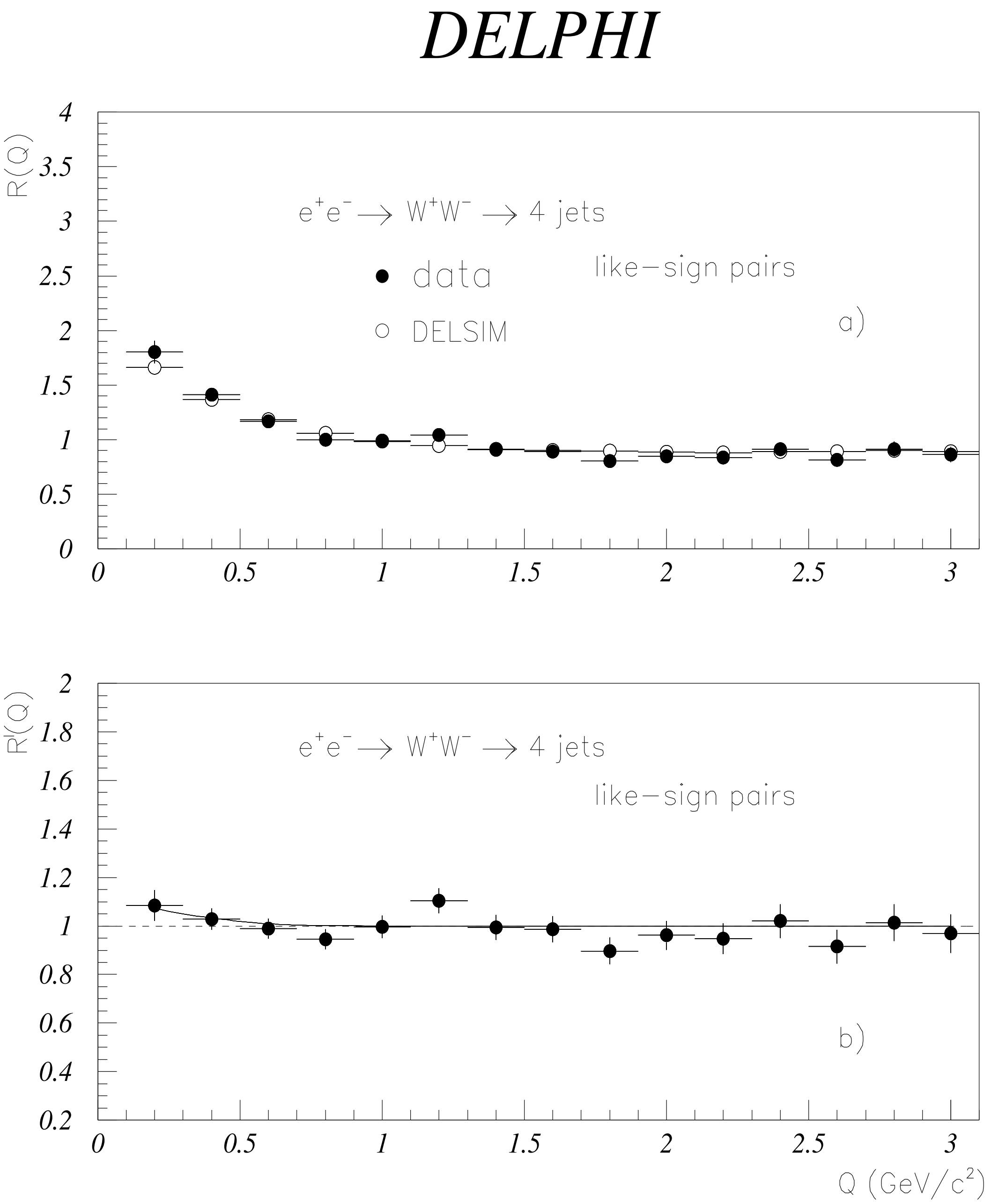

Figure 5: **(a)** The $R(Q)$ distributions for like-sign combinations in fully hadronic decay WW channels for data (closed circles) and Monte-Carlo events (open circles). **(b)** The ratio $R'(Q)$ for like-sign combinations for fully hadronic decay WW channels.

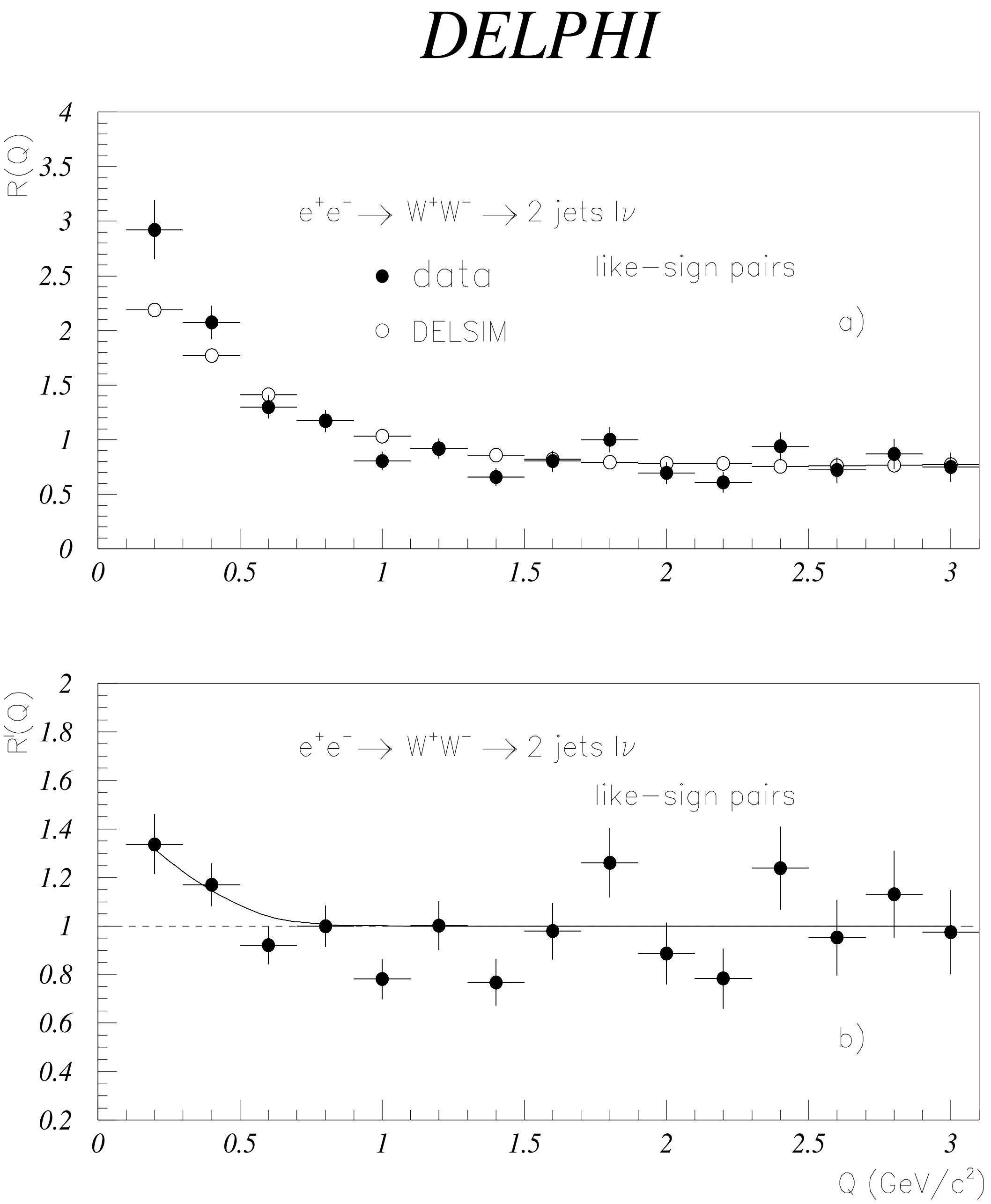

Figure 6: **(a)** The $R(Q)$ distributions for like-sign combinations in mixed decay WW channels for data (closed circles) and Monte-Carlo events (open circles). **(b)** The ratio $R'(Q)$ for like-sign combinations for mixed decay WW channels.

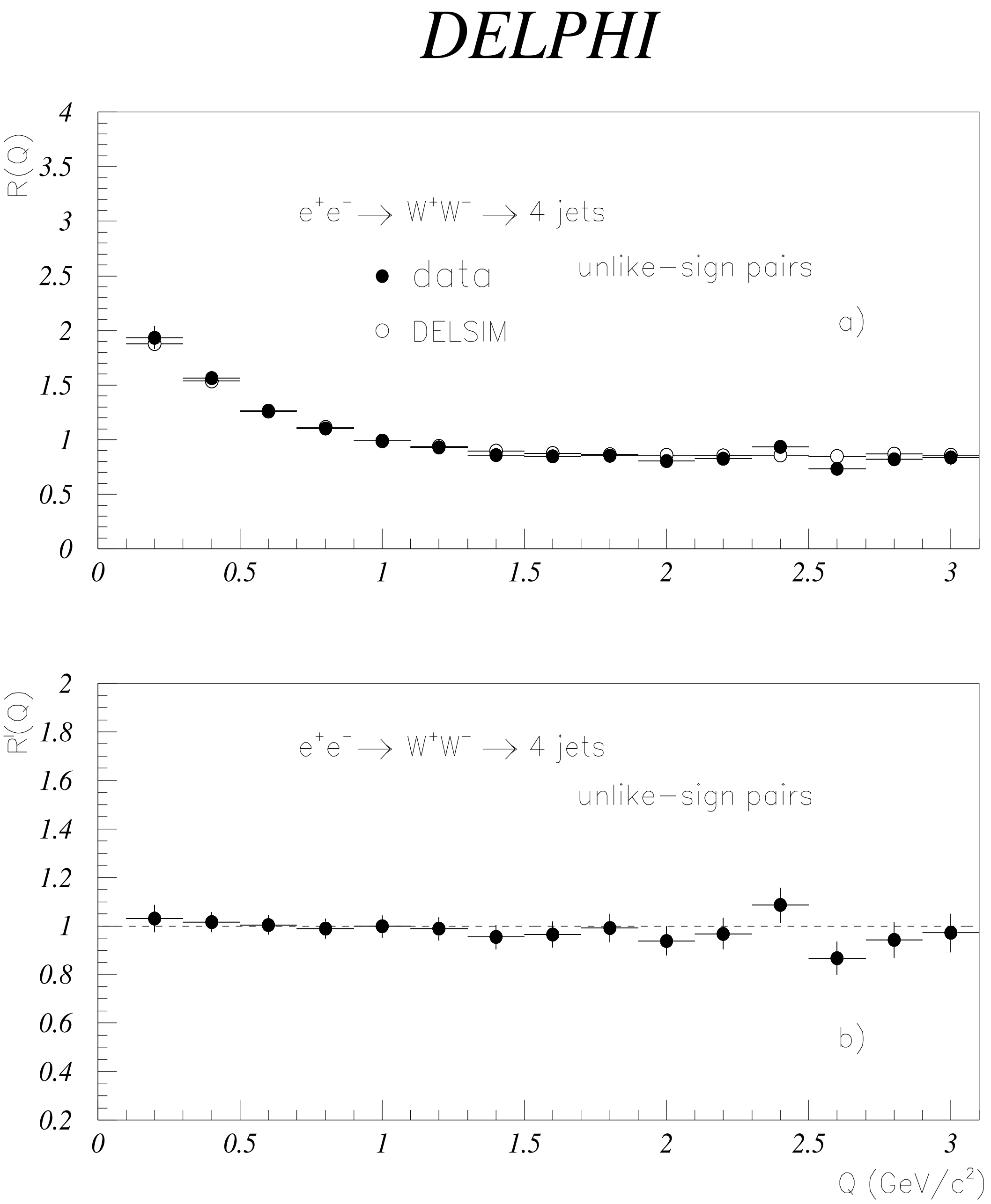

Figure 7: **(a)** The $R(Q)$ distributions for unlike-sign combinations in fully hadronic decay WW channels for data (closed circles) and Monte-Carlo events (open circles). **(b)** The ratio $R'(Q)$ for unlike-sign combinations for fully hadronic decay WW channels.

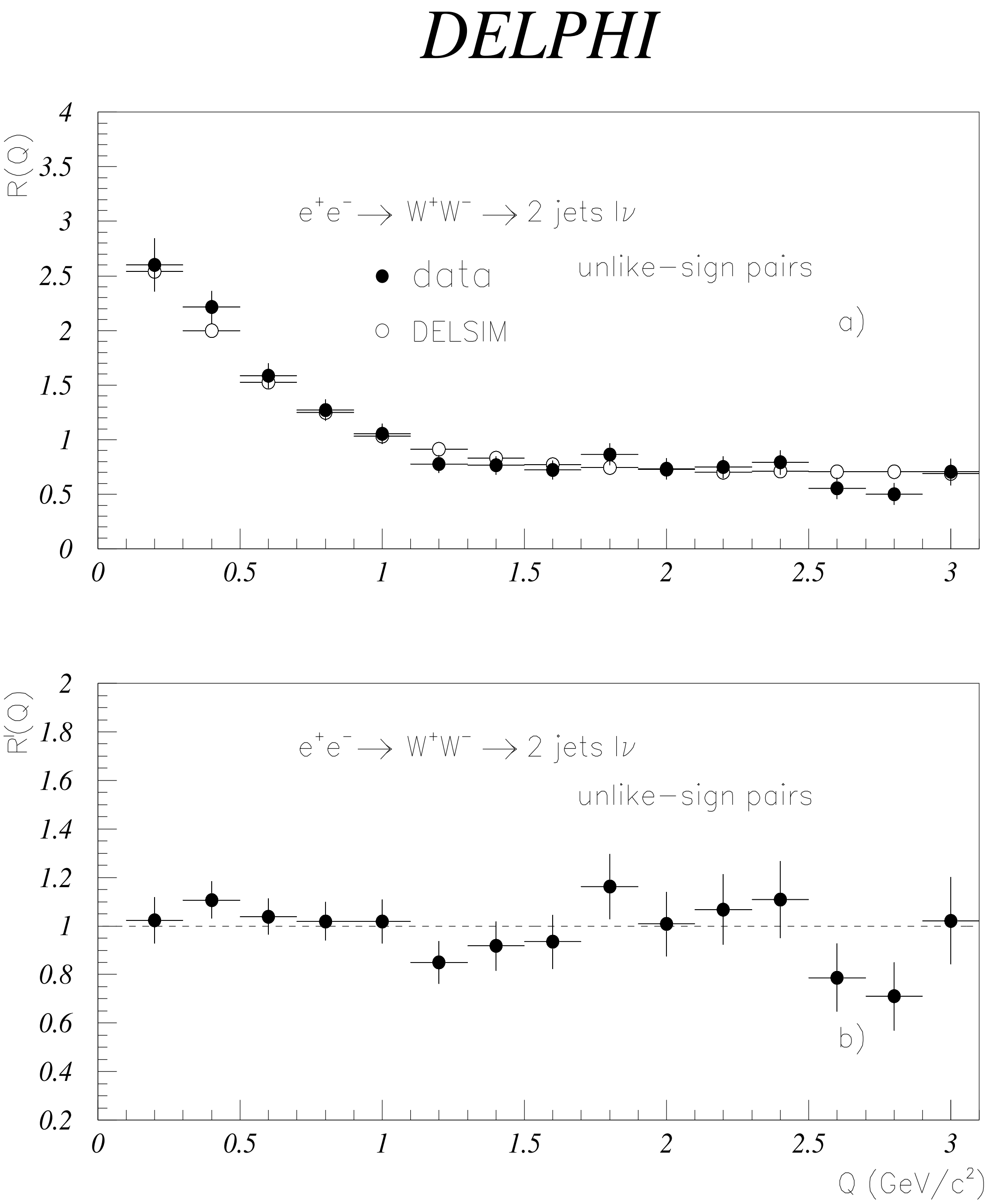

Figure 8: **(a)** The $R(Q)$ distributions for unlike-sign combinations in mixed decay WW channels for data (closed circles) and Monte-Carlo events (open circles). **(b)** The ratio $R'(Q)$ for unlike-sign combinations for mixed decay WW channels.