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Correlations Between Particles in $e^+e^- \to W^+W^-$ Events

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Abstract

Preliminary results are reported on the two-particle correlation function $R(Q)$ in hadronic Z decays, fully hadronic WW decays and mixed hadronic-leptonic WW decays using data collected by the DELPHI detector at LEP at energies between 183 and 202 GeV.

Evidence for Bose-Einstein correlations was observed in all three cases; the parameters λ and r characterizing the correlation in fully hadronic WW events agree with those in mixed hadronic-leptonic WW events, as well as in a sample of Z decays in which the contribution from $b\bar{b}$ pairs was depleted.

Two techniques were used to determine correlations between particles arising from *different* Ws in fully hadronic WW decays. Having different degrees of model dependence, these techniques show an excess of particle pairs with low four-momentum difference in fully hadronic WW events, consistent with the effect expected from correlations between identical particles from different Ws.

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1 Introduction

The possible presence of colour reconnection effects and Bose-Einstein correlations in hadronic decays of WW pairs has been discussed on a theoretical basis, in relation to the measurement of the W mass (see for example [1, 2] and references therein). These effects can induce a systematic uncertainty on the W mass measurement in the fully hadronic channel [1] comparable with the expected accuracy of the measurement.

Bose-Einstein correlations (BEC) originate from the symmetrization of the production amplitude for identical bosons. The effects of BEC between identical bosons have been studied extensively in different types of reactions and for different boson species. Although many studies exist, there is still no complete understanding of the influence of this quantum mechanical effect on a multiparticle system generated in a high energy collision. The description of a given multiparticle system itself is complicated by needing to know the amplitude for the system and symmetrize it.

The observable most often used for the investigation of BEC in multiparticle final states is the two-particle correlation function.

The $e^+e^- \to$ WW events allow a comparison of the characteristics of the W hadronic decays when both Ws decay hadronically in the reaction $e^+e^- \to W^+W^- \to q_1\overline{q}_2q_3\overline{q}_4$ (in the following we shall often refer to this as the $(4q)$ mode) with the case in which one of the Ws decays leptonically in the reaction $e^+e^- \to W^+W^- \to q_1\overline{q}_2\ell\nu$ (denoted $(2q)$ mode for brevity). Since the distance between the W^+ and W^- decay vertices is considerably smaller than the typical hadronisation distance, their decay products are expected to overlap in space and time and identical bosons from *different* Ws can be subject to Bose-Einstein correlations. In the framework of LUBOEI, the Bose-Einstein algorithm embedded in JETSET, [3], the authors of [2] concluded that BEC between identical bosons from the decays of different Ws could strongly influence the measured mass of the W. On the other hand some authors (see e.g. [4]) argue that such inter-W correlations should not exist. It is therefore important to establish whether such correlations exist.

A rigorous mathematical treatment of correlations between pions from different Ws is given in [5]. Bose-Einstein correlations are incorporated in a space-time parton-shower model for e^+e^- annihilation into hadrons in [6].

In the present paper, Bose-Einstein correlations are studied for Ws in $(4q)$ and in $(2q)$ events. Such a combined study allows us to extract information on BEC between decay products of the two hadronically decaying Ws. The data used for the analysis related to Ws were collected with the DELPHI detector [7, 8] at LEP in 1997, 1998 and 1999 at centre-of-mass energies of 183, 189 and 192–202 GeV with integrated luminosity of 54 pb^{-1}, 155 pb^{-1} and 228 pb^{-1}, respectively, with total statistics of 437 pb^{-1}.

The layout of the paper is the following. Section 2 summarizes the general properties of BEC. Section 3 describes the particle and event selection criteria. Sections 4 presents the measurements of correlation functions in Z, fully hadronic and mixed hadronic-leptonic WW events. Section 5 describes measurements of of correlations between particles from different Ws in fully hadronic WW events. A summary is given in Section 6.

2 Bose-Einstein Effects

BEC manifest themselves as an enhancement in the production of pairs of identical bosons close in phase space. To study the enhanced probability for emission of two identical bosons, the correlation function R is used. For pairs of particles, it is defined as

$$R(p_1, p_2) = \frac{P(p_1, p_2)}{P_0(p_1, p_2)}\,, \tag{1}$$

where $P(p_1, p_2)$ is the two-particle probability density, subject to Bose-Einstein symmetrization, p_i is the four-momentum of particle i, and $P_0(p_1, p_2)$ is a reference two-particle distribution which, ideally, resembles $P(p_1, p_2)$ in all respects, apart from the lack of Bose-Einstein symmetrization.

If $f(x)$ is the space-time distribution of the source, $R(p_1, p_2)$ takes the form

$$R(p_1, p_2) = 1 + |G[f(x)]|^2\,,$$

where $G[f(x)] = \int f(x) e^{-\imath(p_1-p_2)\cdot x}\,dx$ is the Fourier transform of $f(x)$. Thus, by studying the correlations between the momenta of pion pairs, one can study the distribution of the points of origin of the pions. Experimentally, the effect is often described in terms of the variable Q, defined by $Q^2 = -(p_1 - p_2)^2 = M_{\pi\pi}^2 - 4m_\pi^2$, where $M_{\pi\pi}$ is the invariant mass of the two pions. The correlation function can then be written as

$$R(Q) = \frac{P(Q)}{P_0(Q)}, \tag{2}$$

which is frequently parametrized by the function

$$R(Q) = \gamma(1 + \delta Q)\left(1 + \lambda e^{-r^2 Q^2}\right)\,. \tag{3}$$

In the above equation, in the hypothesis of a spherically homogeneous pion source, the parameter r gives the radius of the source and λ is the strength of the correlation between the pions.

Bose-Einstein correlations can be included in PYTHIA/JETSET [9] by using the LUBOEI code, where they are introduced as a final state interaction [2, 3]. After the generation of the pion momenta, the values generated for all identical pions are modified by an algorithm that reduces their momentum vector differences according to equation 3. For the present analysis, only the original version of the LUBOEI code, now sometimes called BE_0, was used. For the comparison with the data, BEC were switched on in LUBOEI with a Gaussian parametrization for pions that are produced either promptly or as decay products of short-lived resonances (resonances with decay width less than 45 MeV were considered long-lived), with parameters set to $\lambda = 0.85$ (see Section 4.1) and $r = 0.5$ fm. It should be noted that the measured values for λ and r, corresponding to all particles, do not reproduce the above LUBOEI input values which correspond to primary particles or particles from short lived resonance decays only.

The correlation function was also studied in Z decays. Since the fraction of heavy quark pairs initiating the hadronic final state differs in Z and in W events and especially b quarks are practically absent in W decays, a Z sample depleted in $b\bar{b}$ pairs has also been studied.

Two scenarios were considered for the study of BEC in W pairs.

(a) BEC were included for particles from the same and from different Ws (hereafter called *full* BE). In this case, BEC between particles from different Ws are treated in the same way as BEC between particles from the same W.

(b) BEC were included only for particles from the same Ws (hereafter called *inside* BE).

Before specifying the data selection and the various analyses, a general comment on BEC is appropriate. The observation of correlations between like-sign pairs of particles alone does not insure that the observed correlations owe their origin to Bose-Einstein correlations. They could, for example, arise from final state interactions between pions with small relative momenta. It turns out that it is possible to discount this possibility by virtue of the small correlations between unlike-sign pions, which could arise from final state interaction effects. As will be shown in the following, the unlike-sign pairs show a small amount of correlation. The like-sign pions necessarily are in an isospin I=2 state and the unlike-sign pions are dominantly in the isospin I=0 state. The scattering length for I=2 is more than a factor three smaller than the one for I=0 [10]. This insures that the final state interaction effects for like-sign pion pairs are expected to be nearly an order of magnitude smaller than those observed in unlike-sign pions. Even if all the correlations observed for unlike-sign pions were attributed to final state effects, then essentially none of the correlation effects observed in like-sign pairs can be attributed to final state interactions and can be ascribed to BEC.

3 Particle and Event Selections

The present analysis relies on the information provided by the tracking detectors: the micro-Vertex Detector, the Inner Detector, the Time Projection Chamber as main tracking detector, the Outer Detector, the Forward Chambers and the Muon Chambers. The calorimeters were used for lepton identification and to detect neutral particles. All charged particles except those tagged as hard leptons in semileptonic events were taken to be pions and assigned the pion mass.

In the event selection, charged particles were selected if they had a polar angle between 10° and 170°, momentum between 0.1 GeV/c and the beam momentum, and good quality, i.e. track length greater than 15 cm, transverse and longitudinal impact parameters less than 4 cm (as measured from the nominal interaction point with respect to the beam direction) and error on the momentum measurement less than 100%.

Neutral particles were considered in the analysis, if they were associated to an electromagnetic or hadron shower with energy greater than 0.5 GeV and had a relative error on the energy measurement less than 100%.

Electron identification in the polar angle range between 20° and 160° used the characteristic energy deposition in the central and forward/backward electromagnetic calorimeters and demanded a nominal 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 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 $(92 \pm 1)\%$. Good agreement was found between data and simulation for high momentum muons in $Z \to \mu^+\mu^-$ decays, and for lower momentum muons produced in $\gamma\gamma$ reactions.

In this analysis, more restrictive cuts were used, and only tracks with polar angle θ between 30° and 150° and track length greater than 50 cm were accepted. The energetic isolated charged particle of the mixed decay channel was not included in the analysis.

3.1 Fully Hadronic Channel (WW$\to 4q$)

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, $e^+e^- \to Z\gamma \to q\bar{q}\gamma$.

For each event passing the above criteria, all particles were clustered into jets using the LUCLUS algorithm [3] with the resolution parameter $d_{\mathrm{join}} = 6.5$ GeV/c. At least four jets were required, with at least 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 colinear to the beam line.

The remaining events were then forced into a four-jet ($4j$) 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. The variable D was defined as [11]

$$D = \frac{E_{min}}{E_{max}} . \frac{\theta_{min}}{(E_{max} - E_{min})}, \tag{4}$$

where E_{min}, E_{max} are the minimum and maximum jet energies and θ_{min} is the smallest interjet angle after the constrained fit. As shown in figure 1 of [11], this variable allows an efficient separation of WW events from background events. Events were used only if the variable D was larger than 0.006 rad.GeV^{-1}.

A total of 2891 events were selected. The detector effects on the analysis were estimated using samples of WW and background events generated with PYTHIA 5.7 [9] with the fragmentation tuned to the DELPHI data at LEP1 [12]. The generated events were passed through the full detector simulation program DELSIM [8]. The purity and efficiency of the selection of WW$\to q\bar{q}q\bar{q}$, estimated using simulated events, were about 82% and 69%, respectively. The expected number of events selected with these criteria amounted to 2822. The composition of the background is shown in table 1.

$\sqrt{s}$	Number of events	Z/γ	ZZ	Zee	Purity	Efficiency
183 GeV	353	15.1	2.8	0.11	82.0	75.4
189 GeV	1071	14.0	4.4	0.21	81.4	72.2
192-202 GeV	1467	11.8	6.2	0.23	81.8	64.3

Table 1: The numbers of events selected, the percentages of background of Zγ, ZZ and Zee events, the purity of the samples and the efficiency at the different energies for WW ($4q$).

3.2 Mixed Hadronic-Leptonic Channel (WW$\rightarrow 2q.l\nu$)

Events in which one W decays into a lepton plus neutrino ($l\nu$) 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 nominal 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 the corresponding quark jet. 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 isolation of the lepton; 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 [3]. 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 Initial State Radiation (ISR) photon. Events were removed if there was a cluster with energy deposition greater than 20 GeV in the electromagnetic calorimeters, and it could not be attributed to 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)

$\sqrt{s}$	Number of events	Z/γ	ZZ	Zee	Purity	Efficiency
183 GeV	178	3.5	0.8	1.7	94.0	49.8
189 GeV	508	2.8	0.8	2.7	94.5	45.0
192-202 GeV	763	2.5	1.0	1.1	95.4	42.6

Table 2: The numbers of events selected, the percentages of background of Zγ, ZZ and Zee events, the purity of the samples and the efficiency at the different energies for WW ($2q$).

and to its polar angle ($|\cos\theta_{\mathrm{miss}}| < 0.85$).

A kinematical fit was performed on the selected events. The four-vectors of the two jets, of the lepton and of the missing momentum 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%.

In total, 1449 events were selected. The purity and efficiency of the selection, estimated using simulated events, were about 95% and 44%, respectively. The number of expected events amounted to 1492. The composition of the background at the various energies is given in table 2.

4 Correlation Functions for Z, WW$\rightarrow$ $4q$, and WW$\rightarrow$ $2q.l\nu$ Events

To compute the correlation function $R(Q)$ (equation 2), the two-particle probability density $P(Q)$ was calculated; the reference $P_0(Q)$ came from PYTHIA without BEC after full simulation of the DELPHI detector and after the same selection criteria as for real data. The $R(Q)$ distributions were normalised to unity in the region $Q > 0.8$ GeV/c^2 where no Bose-Einstein effects are expected. The use of a Monte Carlo reference sample for the WW fully hadronic channel implies the assumption that color reconnection effects [13], not present in PYTHIA, are negligible.

The presence of bin-to-bin and inside-bin correlations influences the errors on the $R(Q)$ distribution [15]. If there are N charged particles in an event, each track has (N-1) entries in the two-particle density $P(Q)$, contributing to different bins of the histogram. Due to the finite size of the bins, the same track can contribute several times to the same bin, which is a source of inside bin correlations. To correct for such effects, the errors of $R(Q)$ were scaled by appropriate factors, computed as follows. A total of 500 sets of WW events were generated by PYTHIA with BEC included, using for each set the same statistics as for real data, and the $R(Q)$ distributions were determined for each set. The error scaling factors were then calculated for the fitted values of λ and r in equation (3). They are 1.35 ± 0.04 and 1.50 ± 0.05 for λ and r of the fully hadronic WW channel and 1.25 ± 0.04 and 1.33 ± 0.05 for λ and r of the mixed WW channel[1]. The errors presented below are given after the corrections with these factors.

[1]The error scaling factors for the BEC parameters, as calculated above, are model dependent. Namely, for the parameter λ of the fully hadronic WW channel this factor is 1.45 ± 0.06 in the case of *full* BEC and 1.25 ± 0.05 in the case of *inside* Ws BEC. The average value was used in the present analysis.

An alternative method was used to check the estimation of the effect of bin-to-bin and inside-bin correlations on the measured values of the parameters λ and r. No error increasing factors were used, but the covariance matrix was calculated from the data themselves. The method is based on classical statistics. Let us consider the i-th event from the set of n events and the two-particle probability density P which is presented in the histogram h^i with N_p bins.

The histogram $H = \sum_{i=1}^{n} h^i$ and values

$$c_{jk} = \sum_{i=1}^{n} (h^i_j - H_j/n)(h^i_k - H_k/n)(1+1/n)$$

were calculated event by event. Here j and k are the bin numbers for the histograms. The correlations and errors for one event are not known but the different events are uncorrelated. Considering bin values of the histogram made for one event as a random vector with unknown distribution, one has an uncorrelated ensemble of these vectors and hence the covariance matrix can be estimated statistically.

For all events the resulting histogram H for the two-particle probability density $P(Q)$ and $V_{jk} = c_{jk} \cdot n/(n-1)$ covariance matrix for this histogram were calculated. A fit to the correlation functions $R(Q)$ by expression (3) using the inverted V_{jk} matrix yielded the results in agreement with those obtained using the error increasing factors(see below).

4.1 Correlation Between Particles in Z events

Correlations between particles in Z events produced during the 1999 calibration run were investigated. The track selection for the analysis was the same as above. The event selection was similar to the one in [14]. The $R(Q)$ distributions, obtained using the same method as for WW events, are shown in figure 1a for like-sign combinations. The fit using the expression (3) yielded:

$$\lambda_Z = 0.233 \pm 0.007(stat) \quad (5)$$

$$r_Z = 0.573 \pm 0.016(stat) \text{ fm}. \quad (6)$$

Since the fraction of heavy quark pairs that initiated the hadron cascade is different in Z and in W decays, a light flavour enriched Z sample has been used for comparison. The $b\bar{b}$ fraction has been reduced from the original 22% to about 2% by removing a large fraction of $b\bar{b}$ events using a b-event tagging procedure (see [8] for details). The correlation functions for this sample are shown in figure 1b for like-sign combinations. The fit results are:

$$\lambda_{Z-no\ b\bar{b}} = 0.306 \pm 0.009(stat) \quad (7)$$

$$r_{Z-no\ b\bar{b}} = 0.585 \pm 0.016(stat) \text{ fm}. \quad (8)$$

The λ parameter in the LUBOEI code was adjusted to the correlation function measured at the Z for like-sign pairs. The parameter r in the model was fixed at the value $r = 0.5$ fm and the best match was found for $\lambda = 0.85$. The $R(Q)$ distributions for the data for Z events are compared with the LUBOEI predictions in figure 1a–1b.

4.2 Correlation Between Particles from any Ws in WW→ $4q$ and WW→ $2q.l\nu$ Events

The $R_{2q}(Q)$ and $R_{4q}(Q)$ distributions for the data are shown using 100 MeV bins in figure 2a for like-sign pairs.

A fit to the correlation functions $R(Q)$ using equation (3) yielded the values:

$$\lambda_{2q} = 0.288 \pm 0.038(stat) \quad (9)$$

$$r_{2q} = 0.569 \pm 0.055(stat) \text{ fm} \quad (10)$$

for the mixed hadronic-leptonic channel and

$$\lambda_{4q} = 0.281 \pm 0.020(stat) \quad (11)$$

$$r_{4q} = 0.634 \pm 0.030(stat) \text{ fm} \quad (12)$$

for the fully hadronic decay channel. The fit results are shown by the curves in figure 2a. An analysis using 50 MeV bins gave results fully compatible for all quoted values (9) to (12).

The fitted values of λ and r using the covariance matrix technique as an alternative to the error scaling were λ_{2q} = 0.298±0.038(stat), r_{2q} = 0.548±0.048(stat) fm for ($2q$) events and λ_{4q} = 0.282± 0.018(stat) , r_{4q} = 0.630± 0.029(stat) fm for ($4q$) events, to be compared to the values (9)–(12).

Averaged over all energies, the selected WW fully hadronic events contained 13% of $q\overline{q}$ events and 5% of ZZ events(Table 1). The correction for these background contributions to the fully hadronic sample was done in two ways.

In the first way, the influence of the background events on $R(Q)$ in the ($4q$) channel was corrected by subtracting the Q-distributions for the $q\overline{q}$ and ZZ contributions from the experimental Q-distribution. The Q-distributions for the background events were estimated as follows. The Q-distributions of simulated $q\overline{q}$ and ZZ events without BEC which passed the WW (4q) selection criteria were multiplied by the form (3) with λ and r the same as the experimental values for selected high energy $q\overline{q}$ events and Z events, i.e. λ=0.247±0.017 and r=0.595±0.039 fm for $q\overline{q}$ and the values (5)–(6) for ZZ events. The $q\overline{q}$ events used for this purpose were selected requiring the sum of the energies of the charged particles to be larger than 20% of the beam energy, at least 9 charged tracks in the event, the effective centre-of-mass energy to be larger than 160 GeV, and the narrow jet broadening parameter to be less than 0.03. The track selection was identical to the one for WW events. It was verified that the λ value for $q\overline{q}$ events did not change by more than one standard deviation between all selected($n_{ch} \geq 9$) and high ($n_{ch} > 25$) charge multiplicities. The Q-distributions for real WW fully hadronic events and for background events, calculated as described above, are shown in figure 3a. Figure 3b presents the $R(Q)$ distributions for WW (4q) events without (closed circles) and with background subtraction (open circles). A fit to the correlation functions $R(Q)$ after the background subtraction using equation (3) yielded the values:

$$\lambda_{4q} = 0.289 \pm 0.026(stat) \quad (13)$$

$$r_{4q} = 0.679 \pm 0.059(stat) \text{ fm} \quad (14)$$

For the second method to correct for the background, a sample of $q\overline{q}$ events was generated with BEC included according to LUBOEI with parameters λ=0.85 and r=0.5 fm.

These events were subjected to the same event and track selection criteria as the fully hadronic sample and the Q-distribution of the background was calculated from the events passing the selection. The Q-distribution was corrected for the discrepancy between the data and the simulation in figure 1a. This distribution, properly weighted by the percentage of the background, was subtracted from the experimental distribution. A fit to the correlation functions $R(Q)$ after the background subtraction using equation (3) yielded the values:

$$\lambda_{4q} = 0.292 \pm 0.029(stat) \quad (15)$$

$$r_{4q} = 0.746 \pm 0.069(stat) \text{ fm.} \quad (16)$$

In the subsequent analyses the $R(Q)$ distributions after the background subtraction for both methods were used. No correction was made for the small percentage of background in the mixed hadronic-leptonic sample.

5 Correlations Between Particles from Different Ws

In section 4.2 results were presented for correlations between particles from any Ws in WW$\rightarrow 4q$ events. In this section two methods are used to determine whether correlations between particles from *different* Ws exist.

The first measurement of Bose-Einstein correlations in $e^+e^-\rightarrow$W$^+$W$^-$ events, performed by DELPHI [16] using a subtraction method, did not show any evidence of correlations between like-sign pions from different Ws at the level of statistics collected at 172 GeV centre-of-mass energy. Similar results were obtained by ALEPH using the same method at 172 and 183 GeV centre-of-mass energies [17] and by OPAL [18]. The subtraction method appears to be less sensitive to BEC between different Ws than the methods used in the present analysis. Moreover it is very sensitive to the normalization. Using the formalism of [5] the L3 Collaboration found no evidence for inter-W correlations [19]. The ALEPH Collaboration concluded [20] that their data are not compatible with a model, tuned at the Z^0 and extrapolated to WW events, with full BEC.

To perform direct measurements sensitive to BEC between particles from different Ws, analyses were made using comparison samples which contain only BEC for particle pairs coming from a single W boson, but not for particle pairs from different Ws. Such comparison samples were constructed by the following two techniques:

1. using an event mixing method;

2. using a correlation function calculated from R_{2q} (called the Linear Scenario).

In the event mixing method (section 5.1) the mixed hadronic-leptonic data are used to construct a comparison sample and the model dependence is minimal in the sense that only standard Monte Carlo events are used without BEC. In the linear scenario (section 5.2) extra input from simulations is needed, in particular the fraction of pairs from different Ws as a function of Q.

5.1 Event Mixing Technique

A comparison sample of $(4q)$-like events was constructed by mixing two $(2q)$ events. From each selected semileptonic event, the hadronic part was boosted to the rest frame of the

W candidate. The rest frames of the W candidates were determined using the energy and momenta of the Ws obtained from the kinematical fits. An event was then constructed from two W candidates by boosting the particles of the individual Ws in opposite directions. The boost vectors were determined separately for each W taking energy-momentum conservation and the fitted W candidate mass into account. The expected R_{4q} when there are no correlations between Ws, constructed from the experimental values of P_{2q} and from the mixed sample P_{mix}, can be written as

$$R_{4q}(Q)(mixing) = \frac{[P_{2q}(Q) + P_{mix}(Q)]_{data}}{[P_{2q}(Q) + P_{mix}(Q)]_{DELSIM\ no\ BE}}, \qquad (17)$$

where $P_{mix}(Q)$ was obtained using the mixing of all available combinations of two $(2q)$ events. The pairing of all semileptonic Ws yields $(n \times (n-1)/2)$ WW pairs, where n is the number of semileptonic Ws, while the number of WW pairs used for the reconstruction of the $P_{2q}(Q)$ distribution in equation (17) equals $n/2$. Therefore, the Q distribution between Ws was divided by the factor $(n \times (n-1)/2)/(n/2){=}(n-1)$ to obtain $P_{mix}(Q)$. We define the difference

$$\Delta\lambda(mixing) = \lambda_{4q} - \lambda_{4q}(mixing), \qquad (18)$$

where λ_{4q} is the correlation strength for real $(4q)$ events (equation 11), and $\lambda_{4q}(mixing)$ is the correlation strength for $(4q)$-like events obtained using the $R_{4q}(Q)(mixing)$. A difference of $\Delta\lambda$ from zero would indicate the presence of correlations between particles from different Ws in real $(4q)$ events. The error increasing factors due to bin-to-bin and inside bin correlations were calculated in the same way as described in section 4 and found to be 1.21 ± 0.04 for $\Delta\lambda$.

The mixed events were not submitted to the selection criteria of the fully hadronic WW events. It was verified using simulated events with *inside* Ws BEC and exactly the same selections and method, that the $R_{4q}(Q)(mixing)$, calculated using the event mixing method, was practically the same as $R_{4q}(Q)$, as expected (see figure 4). Fitting both distributions in figure 4 simultaneously using equation (3) and five free parameters, $\Delta\lambda$, λ_{4q}, r,γ and δ, an insignificant difference in λ of $\Delta\lambda$=0.007±0.010 was observed.

The measured $R_{4q}(Q)$ and $R_{4q}(Q)(mixing)$ are shown in figure 5a for like-sign pairs and in figure 5b for unlike-sign pairs. The aim was to compare the $R_{4q}(Q)$ from the data with the $R_{4q}(Q)(mixing)$ and to deduce the $\Delta\lambda$ (equation 18). Therefore a combined fit was made of equation (3) to both distributions with the five free parameters($\Delta\lambda$, λ_{4q}, r,γ and δ). The value of the parameter of interest was:

$$\Delta\lambda(mixing) = 0.067 \pm 0.024(stat) \qquad (19)$$

for the first background subtraction method and

$$\Delta\lambda(mixing) = 0.056 \pm 0.025(stat) \qquad (20)$$

for the second one. Taking the average of both measurements and assigning half the difference as a systematic error yields

$$\Delta\lambda(mixing) = 0.062 \pm 0.025(stat) \pm 0.021(syst) \qquad (21)$$

The systematic error on the measured value of $\Delta\lambda_{4q}(mixing)$ is the sum in quadrature of the following contributions.

– Due to the event mixing technique. The systematic error was conservatively estimated to be 0.017, i.e. the $\Delta\lambda$ obtained from simulated events plus one sigma (see above).

– Due to background events. Half the difference of the $\Delta\lambda$ obtained with the two background subtraction methods, i.e. 0.006 was used.

– A systematic error of 0.010 was assigned due to the fitting procedure. This number was the largest difference found when fitting the $R(Q)$ distributions when using either the error increasing factor or the covariance matrix.

Another method was also used to compare the $R_{4q}(Q)$ from the data with the $R_{4q}(Q)(mixing)$. The integral of the Bose-Einstein signal $I_{BE}{=}\int \lambda e^{-r^2Q^2}dQ{=}\frac{\sqrt{\pi}}{2}\frac{\lambda}{r}$ was included in the fit as a free parameter. Both the parameters I_{BE} and r for both distributions were left free. The fitted values were I_{BE}(4q)=0.0775±0.0039(stat) and $I_{BE}(mixing)$=0.0591±0.0049(stat), yielding the difference $\Delta I_{BE}(data){=}I_{BE}$(4q)–$I_{BE}(mixing)$ =0.0184±0.0063(stat).[2].

5.2 Linear Scenario

The two particle probability density for the $(4q)$ channel can be written as the sum of two probability densities, $P^{(s)}_{4q}(Q)$ and $P^{(d)}_{4q}(Q)$ (corresponding to particles coming from the same and from different W decays, respectively):

$$P_{4q}(Q) = P^{(s)}_{4q}(Q) + P^{(d)}_{4q}(Q) \tag{22}$$

and

$$R_{4q}(Q) = \frac{P^{(s)}_{4q}(Q) + P^{(d)}_{4q}(Q)}{P^{(0s)}_{4q}(Q) + P^{(0d)}_{4q}(Q)}\,, \tag{23}$$

with $P^{(0s)}_{4q}(Q)$ and $P^{(0d)}_{4q}(Q)$ the corresponding distributions of a reference sample where no BEC from different Ws are present.
In the case of independent decays of the two Ws, and therefore only BEC inside the Ws,

$$P^{(s)}_{4q}(Q) = 2\cdot P_{2q}(Q) = 2\cdot R_{2q}(Q)\cdot P^{(0s)}_{2q}(Q) = R_{2q}(Q)\cdot P^{(0s)}_{4q}(Q)\,. \tag{24}$$

Using (24) in (23) gives

$$\begin{aligned} R_{4q}(Q)(linear) &= \frac{R_{2q}(Q)\cdot P^{(0s)}_{4q}(Q) + P^{(d)}_{4q}(Q)}{P^{(0s)}_{4q}(Q) + P^{(0d)}_{4q}(Q)} \\ &= R_{2q}(Q) - g(Q)\left(R_{2q}(Q) - \frac{P^{(d)}_{4q}(Q)}{P^{(0d)}_{4q}(Q)}\right)\,, \end{aligned} \tag{25}$$

where

$$g(Q) = \left(\frac{P^{(0d)}_{4q}(Q)}{P^{(0s)}_{4q}(Q) + P^{(0d)}_{4q}(Q)}\right)\,, \tag{26}$$

[2]The simulation sample for inside Ws BEC yielded $\Delta I_{BE}(inside)$ =0.0033±0.0033(stat).

where $g(Q)$ represents the fraction of pairs coming from different Ws. Calculations using DELSIM show that $g(Q)$ equals $\sim$0.2 at $Q = 0$, and increases up to $\sim$0.6 at $Q = 2.5$ GeV/c (see figure 6a).

The measured $R_{4q}(Q)$ and the expected $R_{4q}(Q)(linear)$ are shown in figure 6b. For the calculation of $R_{4q}(Q)(linear)$ in equation (25) the measured $R_{2q}(Q)$ was used, the $g(Q)$ was calculated by PYTHIA with full detector simulation and the ratio $P^{(d)}_{4q}(Q)/P^{(0d)}_{4q}(Q)$ was estimated using the LUBOEI code[3]. Again, similarly as in section 5.1, a simultaneous fit was performed to $R_{4q}(Q)$ and $R_{4q}(Q)(linear)$, which yielded

$$\Delta\lambda(linear) \equiv \lambda_{4q} - \lambda_{4q}(linear) = 0.082 \pm 0.025(stat) \qquad (27)$$

with the first background subtraction and

$$\Delta\lambda(linear) \equiv \lambda_{4q} - \lambda_{4q}(linear) = 0.071 \pm 0.026(stat) \qquad (28)$$

with the second background subtraction.

For the verification of the method the same procedure, as applied in previous section to the simulated events with inside Ws BEC, was used. The value of $\Delta\lambda(linear)$=0.000$\pm$0.011 was obtained, supporting the method.

Averaging both results and taking half the difference as a systematic error due to the background subtraction, the linear scenario yielded the result

$$\Delta\lambda(linear) \equiv \lambda_{4q} - \lambda_{4q}(linear) = 0.077 \pm 0.026(stat) \pm 0.020(syst)\,, \qquad (29)$$

The systematic error on the measured value of $\Delta\lambda(linear)$ in (29) is the sum in quadrature of the following contributions.

- Due to the linear technique used. The systematic error assigned was 0.011, i.e. the error on the $\Delta\lambda$ obtained with the simulated events with inside Ws BEC.
- The systematic error due to background events was 0.006.
- A systematic error of 0.012 was estimated for the uncertainty due to the model dependences of the function $g(Q)$ and the ratio $P^{(d)}_{4q}(Q)/P^{(0d)}_{4q}(Q)$.
- A systematic error of 0.010 was assigned due to the fitting procedure, as for the previous method.

The other method of comparison of $R_{4q}(Q)$ from the data with the $R_{4q}(Q)(linear)$, described in section 5.1, gave I_{BE}(4q)=0.0794$\pm$0.0038(stat), $I_{BE}(linear)$=0.0578$\pm$0.0049(stat) and the difference $\Delta I_{BE}(data)$=0.0216$\pm$0.0062(stat).[4]

6 Summary

The correlation functions for like-sign particles were measured in hadronic Z decays, in mixed and in fully hadronic WW channels using data collected with the DELPHI detector

[3] In the simulation the ratio $P^{(d)}_{4q}(Q)/P^{(0d)}_{4q}(Q)$ fluctuates by $\pm$0.05 around unity.

[4] The value for simulated events with inside Ws BEC was $\Delta I_{BE}(inside)$=0.0013$\pm$0.0037(stat).

during the 1997, 1998 and 1999 runs with integrated luminosity of 437 pb^{-1} at centre-of-mass energies of 183, 189 and 192–202 GeV.

Measurements were performed to extract correlations between pions from different Ws. Using a model independent event mixing technique, the difference between the correlation strengths of like-sign pairs for real WW ($4q$) events and for a comparison sample which contains only correlations coming from the same W boson was

$$\Delta\lambda(mixing) = 0.062 \pm 0.025(stat) \pm 0.021(syst)\,. \tag{30}$$

Another measurement of $\Delta\lambda$ obtained using a comparison of R_{4q} and R_{2q} (the linear scenario) makes use of model dependent input, in particular the fraction of pairs from different Ws as a function of Q, yielding

$$\Delta\lambda(linear) = 0.077 \pm 0.026(stat) \pm 0.020(syst) \tag{31}$$

Both measurements yield compatible results. Our overall conclusion is that our data support the hypothesis of correlations between like-sign pions coming from different Ws at the level of about two standard deviations.

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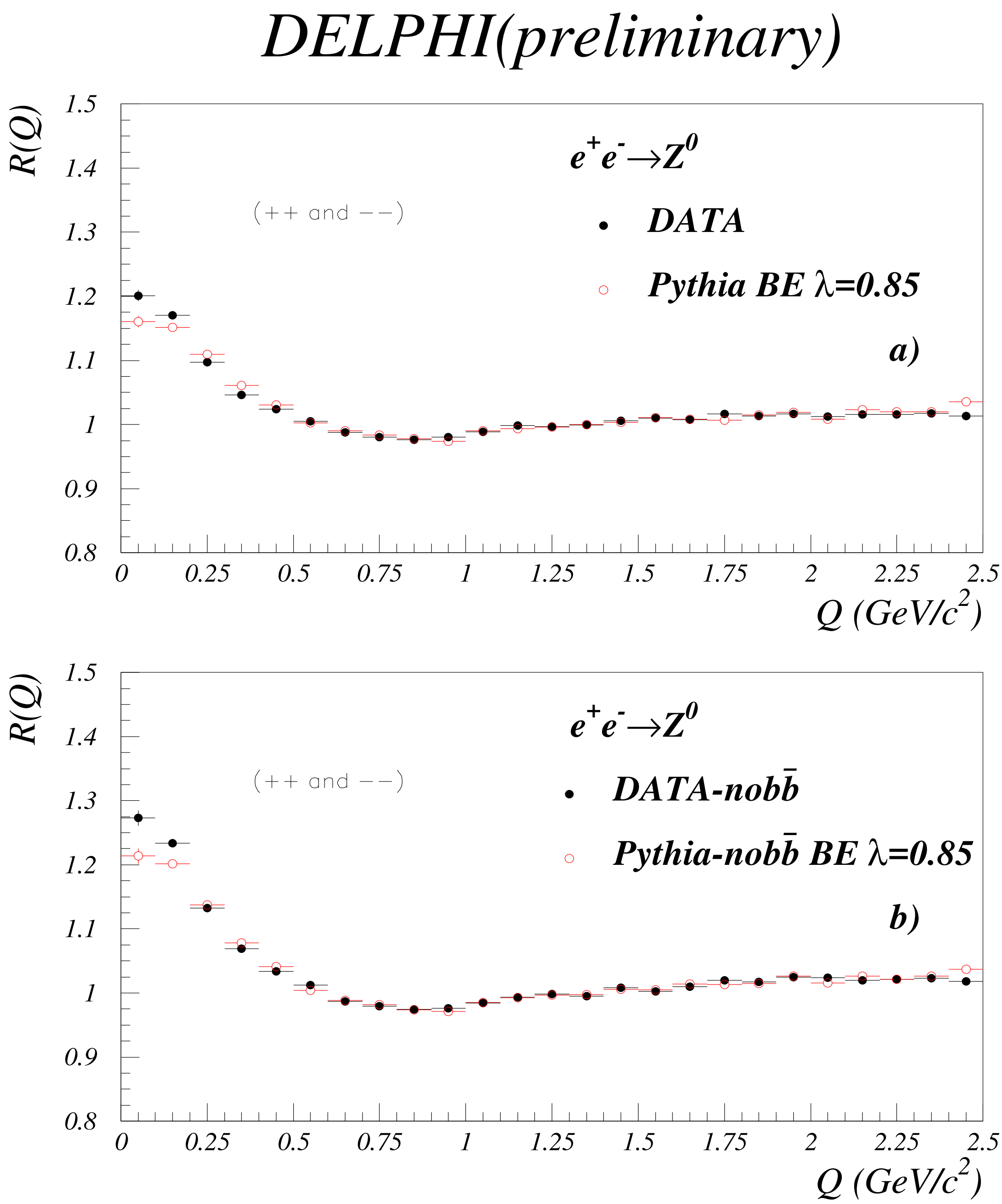

Figure 1: (a) Measured correlation functions $R(Q)$ for like-sign pairs in Z decays data (closed circles) and the PYTHIA Monte Carlo model tuned at the Z peak (open circles). (b) Same as in (a), for Z events depleted in $b\bar{b}$ production

DELPHI(preliminary)

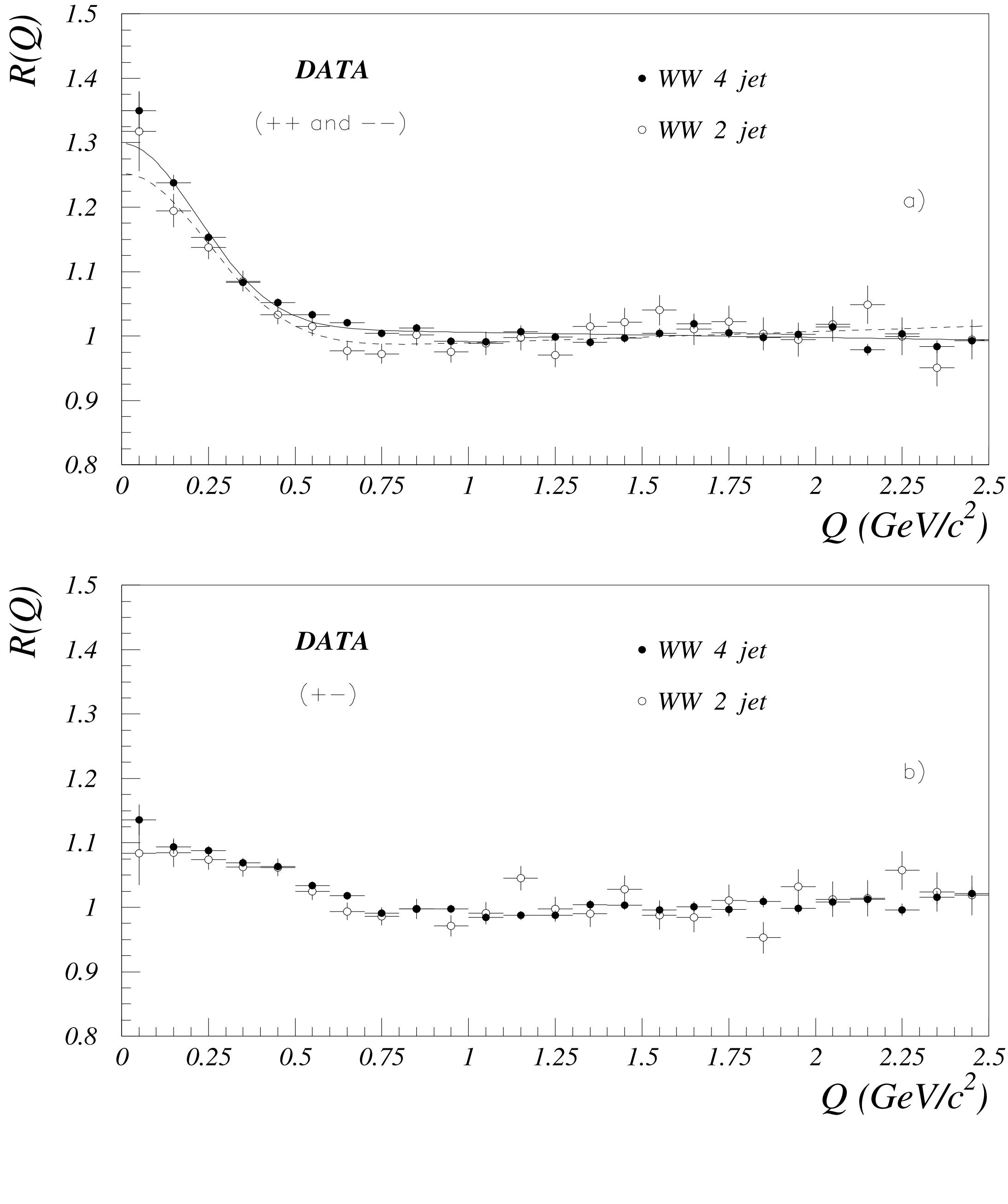

Figure 2: (a) Measured correlation functions $R_{2q}(Q)$ (open circles) and $R_{4q}(Q)$ (closed circles) for like-sign pairs. (b) Same as in (a), for unlike-sign pairs. The full curve shows the best fit to expression (3) for the $(4q)$, the dashed curve for the $(2q)$ correlation functions.

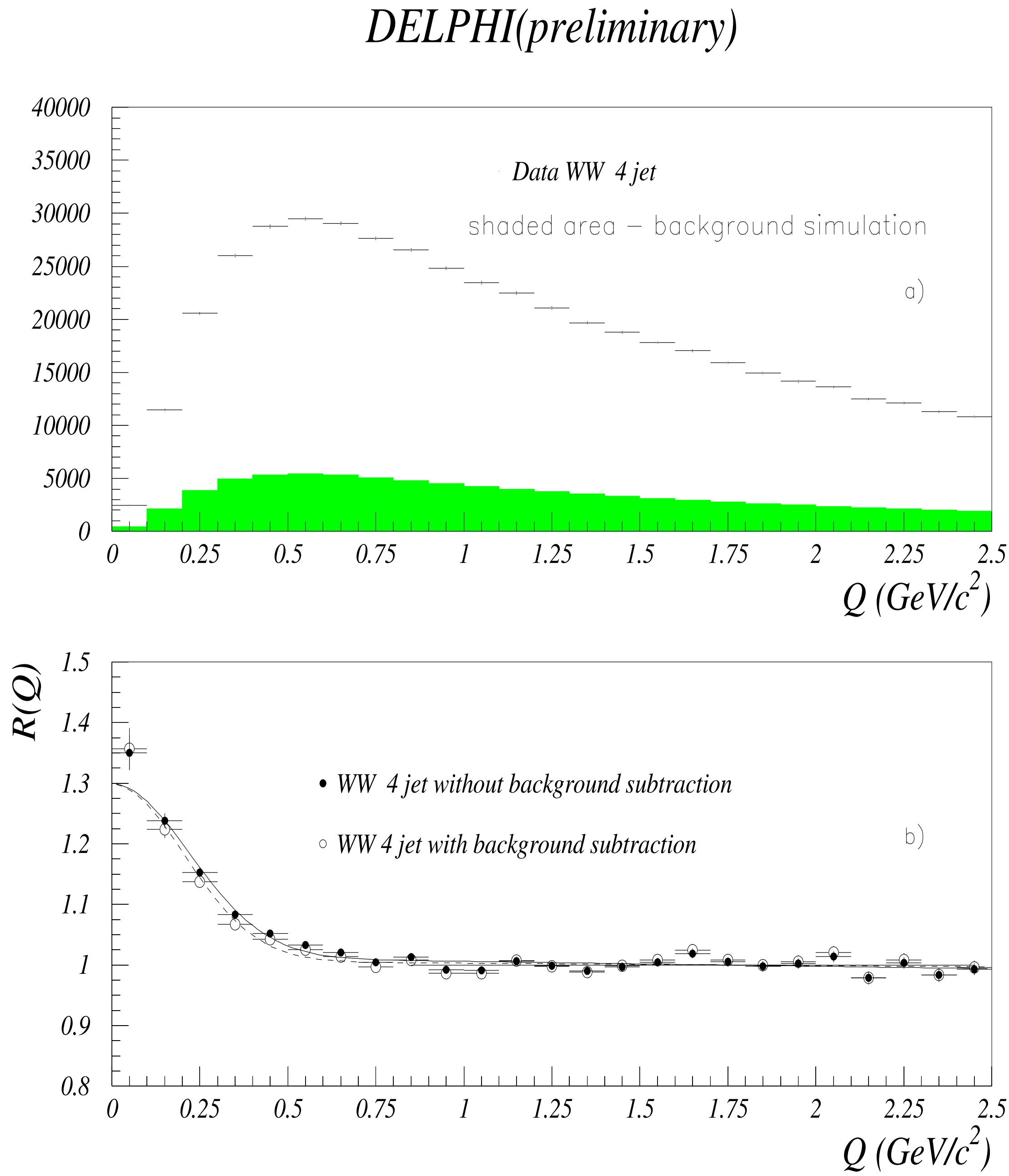

Figure 3: (a) Q-distributions for real (4q) events and for background events for like-sign pairs. (b) measured $R_{4q}(Q)$ distributions for (4q) before and after background subtraction (closed and open circles, respectively). The curves show the fit results to expression (3).

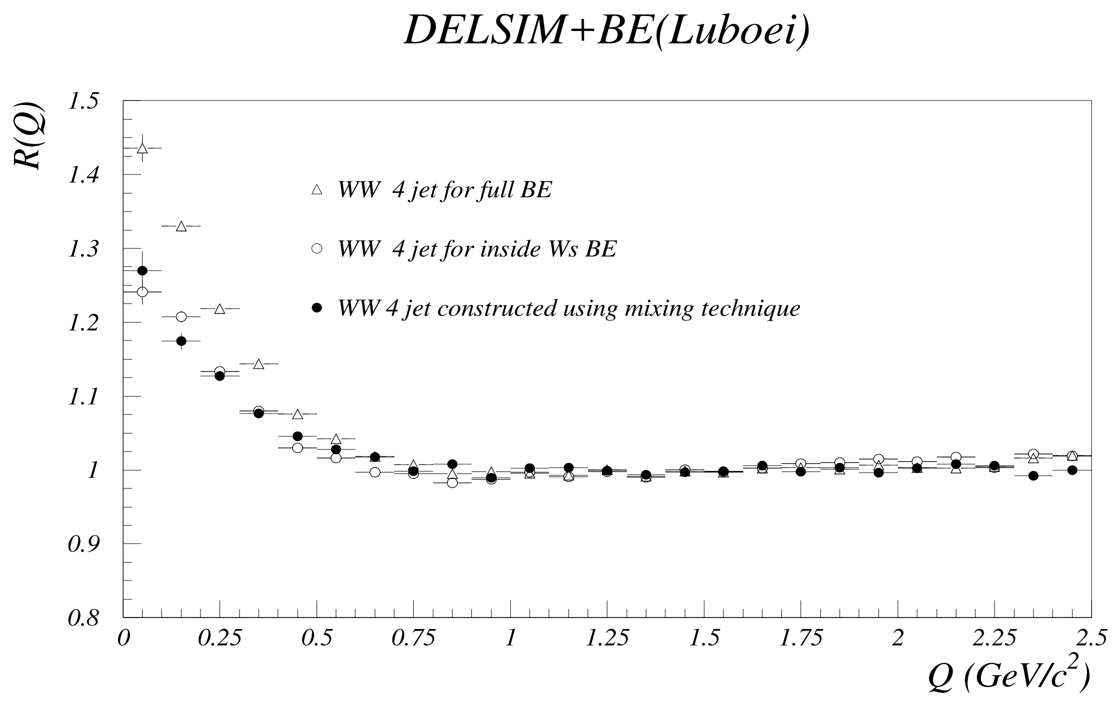

Figure 4: $R(Q)$ for fully hadronic WW events from simulated events with *inside* Ws BEC (open circles) and for reconstructed events using the mixing technique (full circles). The $R(Q)$ for fully hadronic WW simulated events with *full* BEC is also shown (triangles). The original version of LUBOEI was used for the plots shown in this figure with input parameters λ=1.0 and r=0.5 fm.

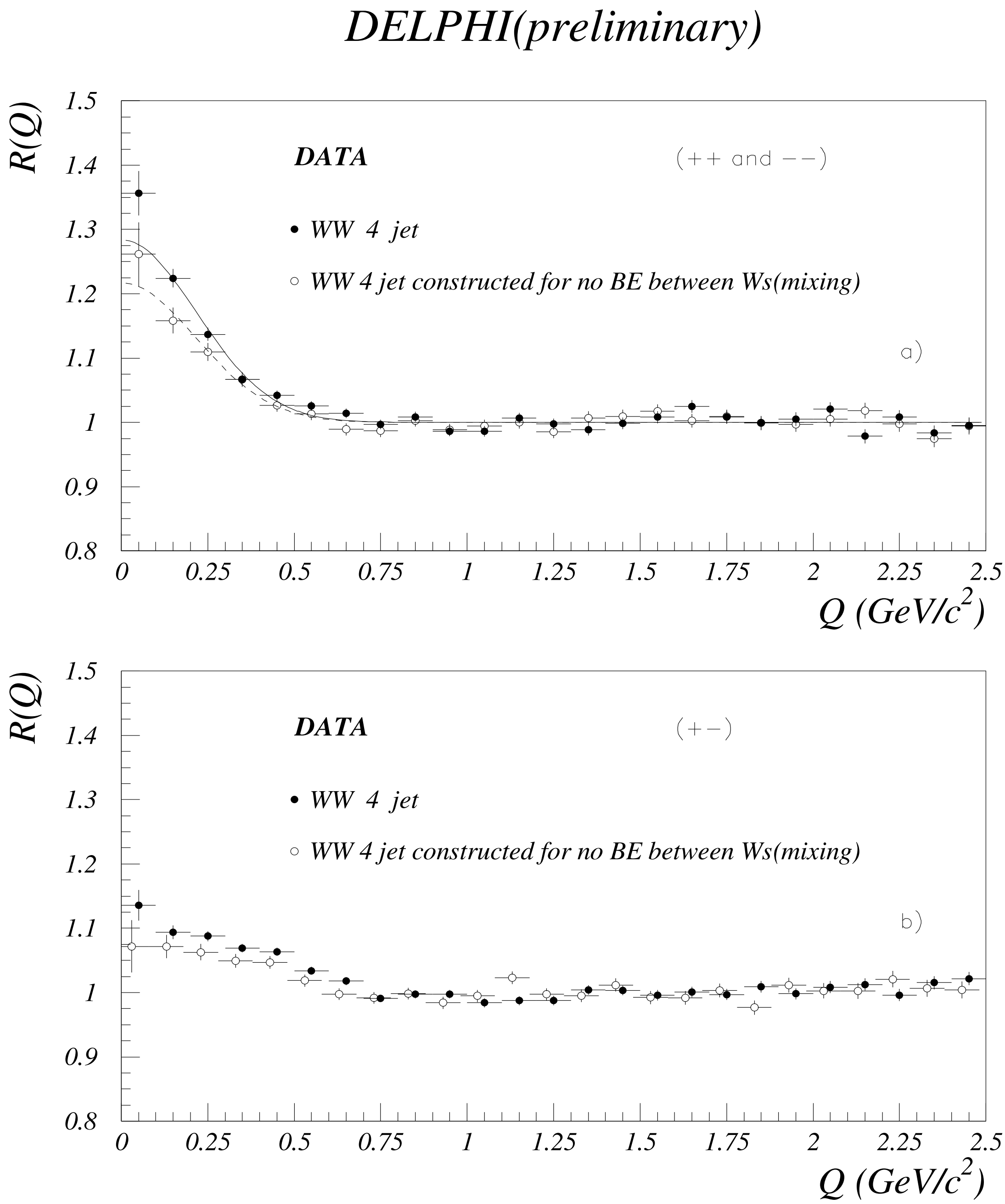

Figure 5: (a) Measured correlation functions $R_{4q}(Q)$ (closed circles) and $R_{4q}(Q)(constructed)$ (open circles) for like-sign pairs. (b) Same as in (a), for unlike-sign pairs. $R_{4q}(Q)(constructed)$ was computed from events constructed from 2-jet events using the mixing technique. The full curve shows the best fit to expression (3) for the data sample, the dashed curve for the constructed sample.

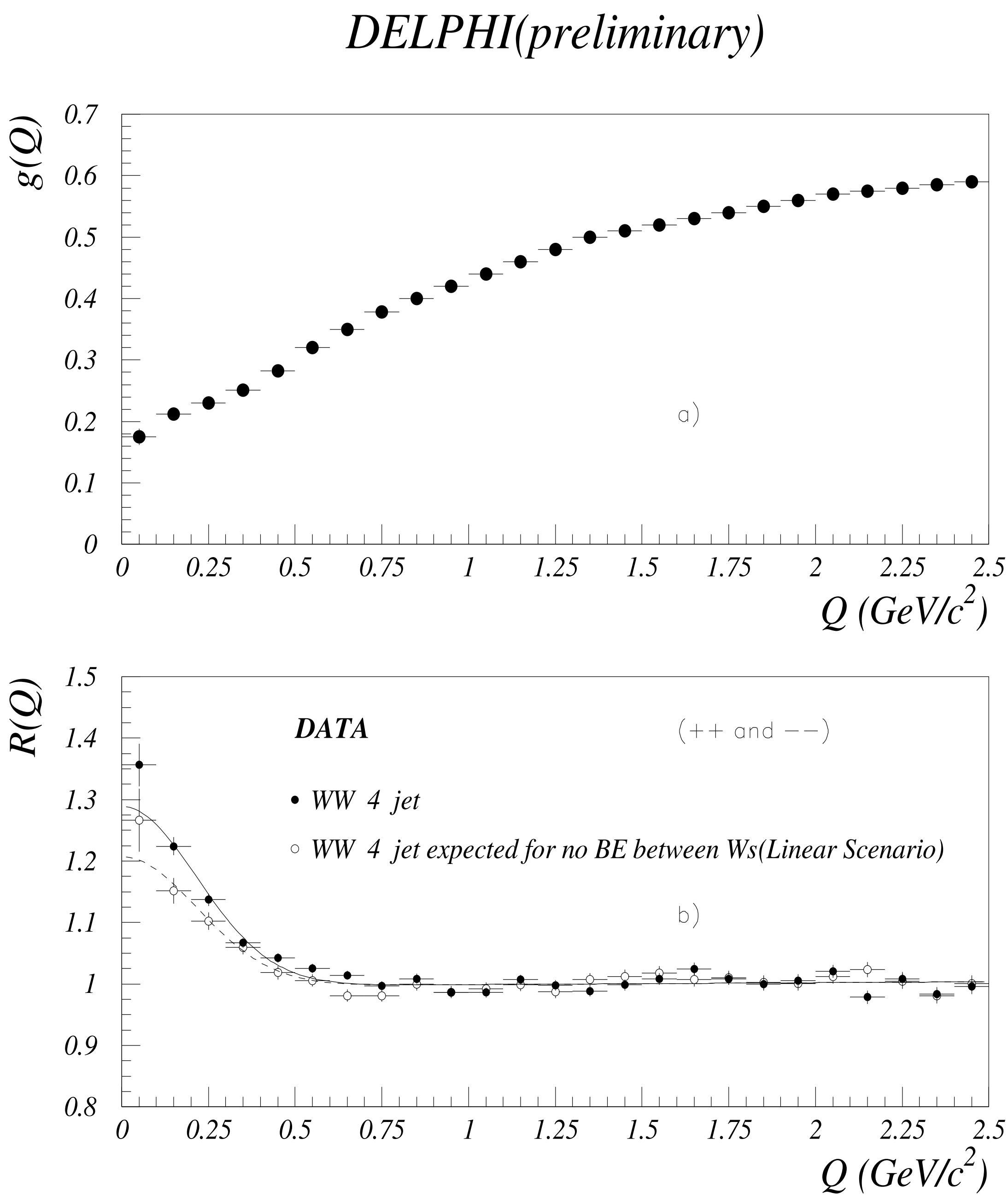

Figure 6: (a) The function $g(Q)$ at 189 GeV. (b) Measured correlation functions $R_{4q}(Q)$ (closed circles) and $R_{4q}(Q)(expected)$ (open circles) for like-sign pairs. The full curve shows the best fit to expression (3) for the data sample, the dashed curve for the expected sample.