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Particle Correlations in $e^+e^-\to W^+W^-$ and $q\bar{q}$ Events

Preliminary

DELPHI Collaboration

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Abstract

The correlation functions R for like-sign and unlike-sign particle pairs were measured for fully hadronic and for mixed decay WW channels using the data collected by the DELPHI detector at LEP at center-of-mass energy of 183 GeV. The correlation functions for particle pairs in $q\bar{q}$ events at high energy were also measured.

The data indicate that R in semileptonic events is larger than in fully hadronic WW decays, supporting a scenario where Bose-Einstein correlations between particles from different Ws are suppressed. It is also larger than between hadrons coming from the decay of Z bosons (even if the contribution from the hadronization of b quarks is removed), and than the correlation function between hadrons produced in the hadronization of $q\bar{q}$ pairs at 183 GeV.

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1 Introduction

The possible presence of interference due to colour reconnection and Bose-Einstein Correlations (BEC in the following, see for example [1, 2, 3, 4, 5, 6, 7] and [8, 9] for a review) in hadronic decays of WW pairs has been discussed on a theoretical basis, in the framework of the measurement of the W mass: this interference [8] can induce a systematic uncertainty on the W mass measurement in the 4-jet mode comparable with the expected accuracy of the measurement. The subject became very pressing due to the prediction [6] that BEC could shift by 100 MeV the measured W mass.

The BEC between identical bosons have been studied extensively in different types of reactions and for different bosons species. Although many studies exist we still miss a complete understanding of the influence of this quantum mechanical effect on a multi-particle system generated in a high energy collision. The description itself for a given multi-particle system is complicated by the fact that one would need to symmetrize the amplitude for the system, which is computationally difficult. One must thus make approximations and build models [10].

How to investigate experimentally the effects of BEC? The observable most often used for the investigation of the BEC in multi-particle final states is the two-particle correlation function. Other observables are affected and can also be exploited; BEC could for instance slightly increase the multiplicity for $(4q)$ events in some models [7]. The WW events allow a comparison of the characteristics of the W hadronic decays when both Ws decay in fully hadronic modes (in the following we shall often refer to this as to the $(4q)$ mode) with the case in which the other W decays semileptonically ($(2q)$ mode for brevity). In the absence of interference between the products of the hadronic decay of the Ws, the single particle distributions in $(4q)$ mode should be equal to twice the $(2q)$ mode after removing the final state lepton or its decay products. For the two-particle correlation function the situation is different. BEC between the two W decays products can happen. In the absence of interference, the fully hadronic correlation function is expected to be lower than the semileptonic one.

Previous experimental results are based on the statistics collected by LEP experiments during 1996 (see [11] for a review). A complete Bose-Einstein correlation between pions originating from different Ws in the $(4q)$ mode was found to be unlikely. The studies of charged multiplicity and inclusive particle distributions does not indicate at that level of the achieved precision the presence of interconnection effects.

This note presents an analysis of BEC between charged particles in the data sample collected by the DELPHI experiment at LEP during 1997, at a centre-of-mass (c.m.) energy around 183 GeV. For this energy the WW cross section is about 15.9 pb; the main background is given by $q\bar{q}$ events, with a cross section (for an effective centre-of-mass energy larger than 10% of the maximum annihilation energy) of about 105 pb. Measurements of BEC for the $q\bar{q}$ events collected at Z energy and, for the first time, at 183 GeV, are also presented.

2 Investigation of Bose-Einstein Effects

BEC manifest themselves in an enhancement in the production of pairs of identical bosons close in phase space.

To study the enhanced probability for the emission of two identical bosons, the correlation function R is used as a probe. 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 $d(x)$ is the space-time distribution of the source, $R(p_1, p_2)$ takes the form

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

where $G[d(x)] = \int d(x) e^{-\imath(p_1 - p_2)\cdot x}\, dx$ is the Fourier transform of $d(x)$. Thus, by studying the correlations between the momenta of pion pairs, one can determine the distribution of the points of origin of the pions. Experimentally, the effect is often described in terms of the Lorentz-invariant variable Q, defined by $Q^2 = (p_1 - p_2)^2 = M^2(\pi\pi) - 4m_\pi^2$, where M 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

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

In the above equation, the pion source is spherically symmetric and gaussian, the parameter r gives the RMS source radius, λ is the strength of the correlation between the pions and N an overall normalization factor. The data from e^+e^- annihilations from PEP energies to LEP show values of r around 0.5-0.7 fm; the value of λ strongly depends on the analysis technique.

Most of the experimental studies are done inclusively, using all the observed charged tracks measured. Electrons, charged kaons and protons do not correlate with pions and clearly reduce the experimental correlation function. Another reduction of $R(Q)$ is due to non-prompt pions, i.e., pions from decays of particles with lifetime larger than the hadronization scale of around 1 fm/c (like K^0, Λ, -commonly referred as V0s- and b and c hadrons). These pions are not expected to correlate with those from the primary hadronization; in same cases they can be easily rejected, like the decay products of reconstructed V0s. A lower λ is thus expected for events with primary heavy quarks (eg $b\bar{b}$ events in Z decays). A more appropriate parametrization for the spherically symmetric and gaussian pion source would thus be:

$$R(Q) = N\left(1 + f(Q) \cdot \lambda e^{-r^2 Q^2}\right) , \tag{4}$$

where λ is still the strength of the correlation between the pions and $f(Q)$ the true fraction of correlated pions, which in general is a function of Q.

It can be understood from what is said above that in the study of BEC is rather complex and that the main problem is given by a good choice of the reference sample. Normally three reference samples are used in the literature:

- Pairs of particles of opposite sign. The drawback of this choice is that many correlated unlike sign pairs come from resonance decays, and the influence of those on the correlation function has to be corrected for by means of a simulation (with possible biases). Moreover some correlations (sometimes called in the literature "residual BEC") are also expected for pairs of opposite sign as a residual consequence of the BEC.

- Pairs of particles taken from artificial events constructed by mixing particles from different real events. The mixing technique introduces arbitrarity, and possible biases, which have also to be corrected by means of a simulation.

- Monte Carlo events simulated without BEC. This is optimal from the statistical point of view, but it assumes completely the underlying model.

At LEP1 the first two reference samples were used. Since the goal of this paper is mainly to compare the strength of BEC in the different samples, and given the limited statistics at LEP2, we shall make mainly use of the third choice, cross checking with Z events. Care is anyway needed in the interpretation of the results for the WW ($4q$) channel since the presence of colour reconnections (not simulated in the reference sample) could easily influence the result.

3 Modelling BEC in WW decays

We consider two possible scenarios that we will use to compare our results: a linear model, built from simple physical considerations (linear scenario) and the algorithm LUBOEI, fully integrated in the JETSET simulation [12]. Other models (see section 3.3) are still in a test stage.

3.1 LUBOEI

Bose-Einstein correlations can be included in PYTHIA/JETSET by using the LUBOEI code. The values generated for the pion momenta are modified by an algorithm that reduces the differences for pairs of like-sign pions.

This description is clearly quantum mechanically unsatisfactory because it tries to adapt things *a posteriori* rather than properly symmetrizing the amplitudes.

This code has been shown [13] to reproduce well the two particle correlation functions measured in Z decays if Bose-Einstein correlations are switched on with a Gaussian parametrization for pions that are produced either promptly or as decay products of short-lived resonances (resonances with lifetime longer than the $K^*(890)$ lifetime were considered long-lived). and if the parameter values $\lambda = 1$ and $r = 0.5$ fm are used. The measured values of the parameters with a mixing reference sample for such 'direct' pions in Z decays were $\lambda = 1.06 \pm 0.17$, $r = 0.49 \pm 0.05$ fm [13]. The value λ=1 for direct pions corresponds to $\lambda \sim 0.35$ for all pions or $\lambda \sim 0.25$ for all particles [13, 14]. The radius r depends on the reference sample choice. A Monte Carlo reference sample changes r from 0.5 fm to a 25% higher value.

Moreover, when tuned to reproduce the observed two particle correlations, LUBOEI is not able to reproduce the three particle correlations [15].

It is anyway a useful model to test detector effects, and to test the reliability of the experimental techniques.

The LUBOEI algorithm with the same values of λ and r was applied to the generated WW events to calculate predictions for the case where Bose-Einstein correlations are present. Two versions of PYTHIA with Bose-Einstein correlations were used a) original version, where Bose-Einstein correlations were included for particles from the same and from different Ws and b) modified version, where Bose-Einstein correlations were included only for particles from the same Ws [16]. In the version a) Bose-Einstein correlations between particles from different Ws are included in the same way as Bose-Einstein correlations between particles from the same Ws.

3.2 Linear Scenario

Starting from very simple algebra considerations we can write the two particle probability density for $(4q)$ events as the sum of two probability densities, $P_s^{(4q)}(Q)$ (corresponding to particles coming from the same W decay) and $P_d^{(4q)}(Q)$ (corresponding to particles coming from different W decays):

$$P^{(4q)}(Q) = P_s^{(4q)}(Q) + P_d^{(4q)}(Q)$$

and introduce a correlation function $R_d^{(4q)}(Q)$ for particles coming from different W decays as:

$$R_d^{(4q)}(Q) = \frac{P_d^{(4q)}(Q)}{P_{0d}^{(4q)}(Q)} .$$

In the hypothesis of independent decays:

$$\begin{aligned} P_s^{(4q)}(Q) &= 2 \cdot P^{(2q)}(Q) \\ R_d^{(4q)}(Q) &= \frac{P^{(4q)}(Q) - 2 \cdot P^{(2q)}(Q)}{P_{0d}^{(4q)}(Q)} . \end{aligned}$$

Assuming the form (4):

$$\begin{aligned} P_s^{(4q)}(Q) = P_{0s}^{(4q)}(Q) \left(1 + f_s(Q) \cdot \lambda_s e^{-r_s^2 Q^2}\right) \\ P_d^{(4q)}(Q) = P_{0d}^{(4q)}(Q) \left(1 + f_d(Q) \cdot \lambda_d e^{-r_d^2 Q^2}\right) , \end{aligned}$$

then:

$$\begin{aligned} R^{(4q)}(Q) &= \frac{P_s^{(4q)}(Q) + P_d^{(4q)}(Q)}{P_{0s}^{(4q)}(Q) + P_{0d}^{(4q)}(Q)} = \\ &= \frac{P_{0s}^{(4q)}(Q) \left(1 + f_s \cdot \lambda_s e^{-r_s^2 Q^2}\right) + P_{0d}^{(4q)}(Q) \left(1 + f_d \cdot \lambda_d e^{-r_d^2 Q^2}\right)}{P_{0s}^{(4q)}(Q) + P_{0d}^{(4q)}(Q)} \\ &= 1 + f_s \cdot \lambda_s e^{-r^2 Q^2} - \left(\frac{P_{0d}^{(4q)}(Q)}{P_{0s}^{(4q)}(Q) + P_{0d}^{(4q)}(Q)} \right) (f_s \cdot \lambda_s - f_d \cdot \lambda_d)\, e^{-r^2 Q^2} . \quad (5) \end{aligned}$$

In the last step we assumed that $r_s = r_d$. This assumption can help us to understand the size of the effect of BEC from different W decays in the full $R^{(4q)}(Q)$.

We can define the function $g(Q)$ to be

$$g(Q) \quad = \quad \left(\frac{P_{0d}^{(4q)}(Q)}{P_{0s}^{(4q)}(Q) + P_{0d}^{(4q)}(Q)} \right) . \tag{6}$$

$g(Q)$ represents the fraction of the pairs coming from different Ws. Asymptotically for large Q, it saturates around 0.6, but in the low-Q region it can be much smaller, due to the fact that the pair from different Ws are in average more distant in phase space than pairs from the same W decay. A small $g(Q)$ in the low-Q region reduces the sensitivity of any correlation function measurement to Bose-Einstein correlations between pions from different Ws. Any increase of the c.m. energy tends to reduce $g(Q)$ at low Q; experimental event selection cuts have the same effect, since they tend to select with larger efficiency events in which the jets are apart.

There are two extreme cases:

1. If there are no BEC from different decays, then $\lambda_d = 0$. Hence:

$$\begin{aligned} R^{(4q)}(Q) &= 1 + (1 - g(Q)) f_s \cdot \lambda_s e^{-r^2 Q^2} \\ &= R^{(2q)}(Q) - g(Q) f_s \cdot \lambda_s e^{-r^2 Q^2} , \end{aligned} \tag{7}$$

   and $g(Q)$ decreases the global correlation. It can be noticed that the same result holds for any r_d.

2. If BEC from different decays are of the same size as BEC inside the decay products of the same W ($\lambda_d = \lambda_s \equiv \lambda$), then:

$$\begin{aligned} R^{(4q)}(Q) &= 1 + [f_s + g(Q)(f_d - f_s)] \cdot \lambda e^{-r^2 Q^2} \\ &= R^{(2q)}(Q) + g(Q)(f_d - f_s) \cdot \lambda e^{-r^2 Q^2} . \end{aligned} \tag{8}$$

   Since from MC studies $f_d > f_s$ for small Q, $R^{(4q)}(Q) \geq R^{(2q)}(Q)$.

3.3 Other Models

The traditional methods of simulation of the Bose-Einstein effect used at LEP (shifting of momenta of particles or re-weighting by empirical formula) are oriented on the reproduction of the experimentally observed enhancement of the particle correlation function, which is just one of the most visible effects related to the Bose-Einstein interference, and they generally fail to address the underlying physical processes.

It is however possible to treat the BE interference in a more rigorous way using the quantum mechanical frame of the Lund fragmentation model developed in [17]. The essential component of this model is the fact that both probability of fragmentation and phase of the process depend on the area spanned by a string during its space-time evolution. The symmetrization of the amplitude of the fragmentation with respect to the exchange of identical bosons then leads to interference terms responsible for the enhancement of the production of pairs/multiplets of close bosons. As there are in principle no additional parameters to tune, the model has high predictive power and may be used to check the validity of the fragmentation model itself. There are two different implementations of this model into MC simulation [18, 19].

We won't use these models in this paper because full predictions are still not available and a careful testing on Z data is needed. However these models suggest a strong suppression or even the absence of Bose-Einstein correlations between particles from different Ws.

4 Data Sample and Event Selection

Data corresponding to a total luminosity of 54 pb^{-1} collected by DELPHI at centre-of-mass energies around 183 GeV during 1997 and about 1 pb^{-1} at centre-of-mass energies around the Z resonance were analyzed. A detailed description of the DELPHI detector can be found in [20]; its performance is discussed in [21].

4.1 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 larger than 0.1 GeV/c and smaller than the beam momentum;
- good quality, assessed as follows:
  - track length larger 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 $(92 \pm 1)\%$. Good agreement was found between data and simulation for high momentum muons in $\mathrm{Z} \to \mu^+\mu^-$ decays, and for low momentum pairs produced in $\gamma\gamma$ reactions.

The detector effects on the analysis were estimated using samples of WW and background events generated with PYTHIA 5.7 [12] with the fragmentation tuned to the DELPHI data at LEP1 [22]. The generated events were passed through the full detector simulation program DELSIM [21].

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

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 [12] with the resolution parameter $\mathrm{d_{join}} = 6.5$ 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 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 fit probability larger than 2.5%. The distribution of the fitted mass of the two jets for all those combinations is shown in Figure 1a, together with the background contribution and the combined expected distribution of the signal and the background. The final cut to select WW events was the requirement of a fitted mass larger than 75 GeV/c^2 for at least one retained combination.

From a data sample corresponding to an integrated luminosity of about 54 pb^{-1}, 205 events were selected. A total of 195 events are expected from simulation. The purity and efficiency of the selection, estimated using simulated events, were about 91% and 47%, respectively.

4.3 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 [12]. 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 $|\cos\theta_{\mathrm{miss}}| < 0.94$.

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 ($|\cos\theta_{\mathrm{miss}}| < 0.85$).

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% and if the fitted mass of the two-jet system was larger than 65 GeV. The distribution of the fitted mass for these events is shown in Figure 1b, together with the background contribution and combined expected signal and background distribution.

From the data sample corresponding to an integrated luminosity of 54 pb^{-1}, 177 events were selected. The purity and efficiency of the selection, estimated using simulated events, were about 96% and 49%, respectively. A total of 185 events is expected from simulation.

4.4 Selection of Hadronic Z Events

The hadronic Z events collected in 1997 have been used in this analysis for consistency checks. The selection of hadronic Z decays is relatively simple, since the cross section for these events at c.m. energy close to the Z mass is considerably higher than the one for other processes. A total of 45,350 hadronic events were selected by requiring that the multiplicity for charged particles (with $p > 100$ MeV/c) was larger than 7 and that the total energy of the charged particles exceeded $0.2\sqrt{s}$.

To check the ability of the simulation to model the efficiency for the reconstruction of charged particles, the average charged particle multiplicity at the Z was measured from this sample to be $20.76 \pm 0.03(stat)$, to be compared with the world average of 21.00 ± 0.13 [23].

Since the fraction of the heavy quark pair that initiated the hadron cascade is different from Z that in W decays, an enriched light flavour sample has also been also used in the comparison. The fraction of $b\bar{b}$ ($c\bar{c}$) has been reduced from the initial 22% (17%) to 1.6% (11%) by requiring that the b-event tagging variable y defined as in Ref. [21] was higher than 0.5. A total of 17,767 events are left after this cut.

4.5 Selection of High Energy $q\bar{q}$ Events

The cross-section for $e^+e^- \rightarrow \mathrm{q\bar{q}}(\gamma)$ above the Z peak is dominated by radiative $\mathrm{q\bar{q}}\gamma$ events; the initial state radiated photons (ISR photons) are generally aligned along the beam direction and not detected. In order to compute the hadronic centre-of-mass energy, the procedure described in [24] was used. Events with reconstructed hadronic centre-of-mass energy ($\sqrt{s'}$) above 160 GeV were used to compute the multiplicity at 183 GeV. A total of 1111 hadronic events were selected by requiring that the multiplicity for charged particles (with $p > 100$ MeV/c) was larger than 9, that the total energy of the charged particles exceeded $0.2\sqrt{s}$, and that the narrow jet broadening [25] was smaller than 0.1.

5 Results

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.

It has to be remarked that using the same data as in the present paper, no difference between measured average multiplicities and momentum distributions for fully hadronic and twice mixed WW channels was obtained [26]. For both fully hadronic and and semileptonic WW events the average multiplicities and momentum distributions were also in a good agreement with those predicted by PYTHIA.

5.1 Correlation Functions for Like-Sign Particles

In this section we present measurements of the correlation functions of like-sign particles, separately for fully hadronic and mixed decay channels.

The reference distribution $P_0(Q)$ was calculated using events generated by PYTHIA (without Bose-Einstein correlations included) after full simulation of the DELPHI detector and after exactly the same selection criteria as for real data. The reference distribution $P_0(Q)$ was normalized on $P(Q)$ distribution in the region $Q > 0.6$ GeV/c^2 where no Bose-Einstein effects are expected. It has to be remarked that using the Monte Carlo reference for the $(4q)$ channel one assumes that colour reconnections effects are negligible.

The measured quantity $R(Q)$ for like-sign combinations of mixed decay WW channels is shown in Figure 1a (open circles). The fit to (3) yielded the values:

$$\lambda = 0.43 \pm 0.09(stat) \pm 0.04(syst) \tag{9}$$

$$r = 0.49 \pm 0.07(stat) \pm 0.02(syst) \text{ fm}. \tag{10}$$

This fit is shown by the upper solid curve in Figure 1a.

The systematic errors in the measured values of λ and r are the sum inm quadrature of the following contributions:

- Background events.
- Variations of the fitted function. The sightly modified function was used in the fit of $R(Q)$:

  $$R(Q) = N\,(1 + \delta Q)\left(1 + f(Q) \cdot \lambda e^{-r^2 Q^2}\right), \tag{11}$$

  were N and δ are left free in the fit.
- Influence of final state Coulomb interaction.

For the full hadronic decay WW channel the measured $R(Q)$ distribution is shown in Figure 1a by closed circles. The fit to the correlation function $R(Q)$ with expression (3) yielded:

$$\lambda = 0.24 \pm 0.08(stat) \pm 0.04(syst) \tag{12}$$

$$r = 0.57 \pm 0.12(stat) \pm 0.06(syst) \text{ fm}. \tag{13}$$

This fit is shown by the lower solid curve in Figure 1a.

The values of the parameter r agree for mixed and fully hadronic decay channels (eqs. 10 and 13), while the correlation strength for the mixed decay channel (eq. 9) is higher than the correlation strength for the fully hadronic decay channel (eq. 12).

The comparisons of model predictions with the data are presented in Figures 3 and 4. As is seen from Figure 2a the model gives a good description of the correlation function for the mixed decay channel. For the fully hadronic WW channel the model with Bose-Einstein correlations only from same Ws(open circles in Figure 2b) agrees with the data (closed circles in Figure 2a), while the model with Bose-Einstein correlations both from the same and from different Ws(stars in Figure 2b) disagrees with the data. The same features are presented in Figure 1b, where model predictions are compared for difference of correlation functions. The model with Bose-Einstein correlations only inside Ws agrees much better with the data (stars in Figure 1b) than the model with full Bose-Einstein correlations (open squares in Figure 1b).

The comparison of the data with the linear model was performed.

The predicted distribution in case of no BEC between the decay products of different Ws was obtained using equation 7. The used $g(Q)$ distribution is presented in Figure 3a (closed circles), which was calculated by PYTHIA after the full detector simulation and exactly the same selection criteria as in the data. The measured values and statistical errors of λ and r for mixed decays channel (eqs. 9 and 10 respectively) were used as input for λ_s and r in equation 7. The predicted $R^{(4q)}(Q)$ distribution is shown in Figure 3b (open circles) together with the measured $R^{(4q)}(Q)$ (closed circles).

The $R^{(4q)}(Q)$ distribution in case of full BEC calculated using equation 5 is shown in Figure 3b (stars). Note that the predicted $R^{(4q)}(Q)$ in case of full BEC can change, because in the present case the linear model ignores residual BEC, which may play a sizeable role for high multiplicity events which could yield a contribution to $R^{(4q)}(Q)$. As it is shown in Figure 3b, even ignoring the residual BEC, the linear model with full BEC predicts higher $R^{(4q)}(Q)$ (stars), than it was measured for data (closed circles).

It also has to be remarked that some of recent theoretical approaches predict strong suppression or even absence of Bose-Einstein correlations between particles from different Ws [18, 19]. Our data supports these predictions.

The possible bias in measured $R(Q)$ distributions due to detector effects and selection criteria were studied using $R(Q)$ distributions for events generated by PYTHIA which were compared with $R(Q)$ distributions for the same generated events but after the full detector simulation and exactly the same selection criteria as for real data. In Figure 4 are shown the obtained distributions for semileptonic events(Figure 4a), for fully hadronic events with full Bose-Einstein correlations (Figure 4b) and for fully hadronic events with Bose-Einstein correlations inside Ws only (Figure 4c). The $R(Q)$ distributions obtained at generated level (stars in the figures) and $R(Q)$ distributions after full detector simulation and selection criteria (closed circles in the figures) are practically the same at $Q > 0.1$ GeV/c^2, i.e. in the region where the present analysis was performed.

It has also to be remarked that the first measurements of BEC in $e^+e^- \to W^+W^-$ events, performed by DELPHI [28] and ALEPH [27] did not show any evidence of correlation between like-sign pions from different Ws at the level of statistics collected at 172 GeV centre of mass energy.

5.2 Correlation Functions for Unlike-Sign Particles

The quantity $R(Q)$ for unlike-sign particle pairs of the mixed decay WW channel are shown in Figure 5a. The same distributions for the fully hadronic decay channel are shown in Figure 5b. As in the case of like-sign combinations, the model with Bose-Einstein correlations included using LUBOEI code gives a reasonable description of the data for the mixed decay channel. For the fully hadronic decay channel the model agrees with the data if Bose-Einstein correlations are present only for pions from the same Ws (open circles in Figure 5b), but disagrees in case of full Bose-Einstein correlations (stars in Figure 5b).

5.3 Correlation Functions for Z decay products

Correlations between particles at Z events produced during calibration run in 1997 were investigated, using the same track selection as in this note and event selection as in [13]. In Figure 6a is shown the correlation function for like-sign particles from Z decays (closed circles) obtained using the same method as for WW events described above. The fit to the correlation function $R(Q)$ with expression (3) yielded:

$$\lambda = 0.22 \pm 0.01 \qquad (14)$$

$$r = 0.61 \pm 0.02 \text{ fm}\,. \qquad (15)$$

This fit is shown by the solid curve in Figure 6a. The measured values (9) and (10) are in agreement with the values measured for 1994 data with the ones measured by DELPHI previously [13, 14]. The $R(Q)$ distribution for unlike-sign particle pairs is shown in Figure 6b. The predictions using events generated by PYTHIA at the Z peak with Bose-Einstein correlations included are shown in Figure 6a and Figure 6b (open circles). Bose-Einstein correlations were included in the same way and with the same parameters as for WW events. As seen in Figure 6a and Figure 6b the model yields good agreement with the data.

6 Compatibility Checks

An alternative analysis was also performed with a stricter track selection in order to check the above results. Charged particles from photon conversions and from decays of V0s were discarded. To extend our sensitivity in the low-Q region, we restricted the analysis by using only tracks with at least 2 VD hits. This allows to use safely also the region of Q from 0 to 100 MeV. In this analysis all results are consistent with a 0.65 fm radius which was then kept fixed in the fits.

First of all the distribution as a function of Q of the numbers of like charge particle pairs found in $(4q)$ and $(2q)$ events was separately studied.

The correlation functions $R^{4q(2q)}(Q)$ are plotted in Figure 7. They show the usual enhancement at low Q which can be fairly described by the form (3). A fit to (3) gives:

$$\lambda^{(4q)} = 0.40 \pm 0.07 \qquad (16)$$

$$\lambda^{(2q)} = 0.68 \pm 0.09\,. \qquad (17)$$

The results obtained for Z events collected in 1997 with the MC reference sample and parametrization (3) are:

$$\lambda^{(Z)} = 0.33 \pm 0.01 \qquad (18)$$

$$\lambda^{(Z-no\ b\bar{b})} = 0.45 \pm 0.02\,. \qquad (19)$$

The definition of the $(Z - no\ b\bar{b})$ sample was given in a previous Section. The different initial quark composition of the W and Z events could thus play an important role. The value of $\lambda^{(Z-no\ b\bar{b})}$ should represent an upper limit to $\lambda^{(2q)}$ since the heavy quark content of the $(2q)$ sample is higher than in the light quark-enriched $q\bar{q}$.

Z events collected in 1994 gave consistent results.

High energy $q\bar{q}$ events were also analyzed and their correlation function measured for the first time. The result is shown in figure 8. Using the parametrization (3), the result on λ is:

$$\lambda^{(q\bar{q},183GeV)} = 0.31 \pm 0.04 \,. \tag{20}$$

This result is consistent with the result obtained at the Z.

In figure 9 the correlation functions $R^{(4q)}(Q)$, $R^{(2q)}(Q)$, $R^{(Z)}(Q)$ and $R^{(Z-no\ b\bar{b})}(Q)$ are shown superimposed. $R^{(4q)}(Q)$ is consistent with $R^{(Z)}(Q)$ while $R^{(2q)}(Q)$ is larger also than $R^{(Z-no\ b\bar{b})}(Q)$, contrary to the expectations (according to the fraction of prompt pion pairs, $R^{(2q)}(Q)$ should be between $R^{(Z)}(Q)$ and $R^{(Z-no\ b\bar{b})}(Q)$).

The ratio $R_{+-}(Q) = N_{\pm\pm}(Q)/N_{+-}(Q)$, where $N_{\pm\pm}$ and N_{+-} are the number of like and unlike sign pairs respectively also shows an enhancement at low Q with respect to the Monte Carlo distribution in which the Bose-Einstein effect was not simulated.

It is clear from these results that the enhancement in $(4q)$ events looks less significant than in $(2q)$. This could be consistent with the hypothesis that BEC between pions from different Ws are less marked than between pions from the same W. It should be noted anyway that the significance of this result is difficult to estimate, since it is not obvious that the functional form (3) applies to pions from different Ws, nor that a spherical source with the same radius as in the case of a single particle can be assumed.

7 Correlations Between Pions from Different Ws

Two techniques were used to extract directly the correlation function between pions from different Ws.

1. The first one is a variation of the technique described in [28]. This uses the unlike-sign reference sample without correcting for the effect of resonances (provided the colour reconnection effects are not large).

   To obtain the two-particle Q distribution for pairs of pions coming from different Ws, the following procedure was used. The Q distribution for pion pairs is measured in $(4q)$ events. This distribution is the sum of the distribution of pion pairs coming from the same W and of that of pion pairs coming from different Ws. The contribution of pairs coming from the same W is subtracted statistically, using the Q distribution obtained from $(2q)$ events. The same procedure is followed for both like-sign and unlike-sign pion pairs to obtain $P(Q)$ and $P_0(Q)$, respectively.

   In the absence of colour reconnection, the two-particle density for unlike-sign pairs coming from different Ws should be identical to the like-sign distribution except for BEC effects, and should not contain pairs from decays of particles or resonances. The ratio of like-sign to unlike-sign pairs is:

$$R'(Q) = \frac{P^{(4q)}_{++}(Q) - a \cdot P^{(2q)}_{++}(Q)}{P^{(4q)}_{+-}(Q) - a \cdot P^{(2q)}_{+-}(Q)} \tag{21}$$

   where a is a normalization parameter. As the fully hadronic decay contains two W decays, we might naively assume that $a = 2 * N_{evt_{4q}}/N_{evt_{2q}}$ would be an appropriate choice, where N_{evt} indicates the size of the event sample. However, slight differences in the charged particle multiplicity can result in a negative difference. Therefore, we choose

$$a = N_{evt_{4q}}/N_{evt_{2q}} * < n_{4q} > / < n_{2q} >$$

from the average charged multiplicities, $< n_{4q} >$ and $< n_{2q} >$. The measured $R'(Q)$ is shown in figure 10. No evidence for correlations between pions from different Ws is seen; the correlation function appears to be smaller than one at small values of Q.

A study based on MC, assuming from simulation both the reference sample (the denominator in eq. 21) and the intra-W distribution, shows that the ultimate statistical sensitivity on λ_d that can be reached with this subtraction method is of the order of $\Delta(\lambda_d) = 0.18$ with the present statistics. Moreover there is a large sensitivity on the normalization.

2. In the second (more sensitive) technique a set of $(4q)$-like events is constructed by mixing pairs of $(2q)$ events. For each real $(4q)$ event each W is replaced by a W from a $(2q)$, flying in the same direction and with the same momentum, and with the two reconstructed jets lying in the same plane. To perform this correctly, from each selected semileptonic event, the hadronic part was boosted to the rest frame of the W candidate. In this "mixed sample" the reference $P^{(mix)}$ for the fully hadronic events was constructed by boosting pairs of such single W candidates in opposite directions according to the velocities and directions of flight of the W candidates in the fully hadronic events. $R(Q)$ constructed with these events as a reference sample should no longer contain correlations due to the hadronization of single Ws.

   The ratios $P^{(4q)}_{++}(Q)/P^{(mix)}_{++}(Q)$ for data and MC are shown in Figure 11a and 11b.

   The double ratio:

$$R''(Q) = \frac{P^{(4q)}_{++}(Q)/P^{(mix)}_{++}(Q)}{P^{(MC,4q)}_{++}(Q)/P^{(MC,mix)}_{++}(Q)} \tag{22}$$

   is shown in figure 12. Also in this case no evidence for correlations between pions from different Ws is seen; the correlation function appears again to be smaller than one.

8 Conclusions

The correlation function R of like-sign hadron pairs produced in hadronic and semileptonic WW decays, and in the hadronization of $q\bar{q}$ pairs at 183 GeV, has been studied as a function of the 4-momentum difference, Q. A reference sample taken from the simulation without Bose-Einstein effects was used.

The data indicate that R in semileptonic events is larger than in fully hadronic WW decays. It is also larger than between hadrons coming from the decay of Z bosons (even if the contribution from the hadronization of b quarks is removed), and than the correlation function between hadrons produced in the hadronization of $q\bar{q}$ pairs at 183 GeV.

The fact that the enhancement due to BEC in $(4q)$ events is smaller than in $(2q)$, together with other tests presented in the paper, indicates that BEC between pions from different Ws are less marked than between pions from the same W. Care is anyway needed in the interpretation of the results for the WW ($4q$) channel since the presence of colour reconnections (not simulated in the reference sample) could easily influence the result.

The data were compared to predictions of the PYTHIA model with Bose-Einstein effect included (LUBOEI). The model yields agreement with the measured correlation functions for the mixed decay WW channel. For the fully hadronic decay WW channel the model agrees with the data if Bose-Einstein correlations are present only for particles from the same Ws, while it disagrees with the data if Bose-Einstein correlations are also present between particles from different Ws.

The data were also compared to the prediction from a linear model. Also in this case the correlation function is smaller than what expected in case of complete BEC between pions from different Ws.

Finally, two independent techniques to measure correlations between pions from different Ws yielded a correlation function smaller than one at small Q values.

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References

[1] T. Sjöstrand and V.A. Khoze, Z. Phys. **C62** (1994) 281.

[2] G. Gustafson and J. Häkkinen, Z. Phys. **C64** (1994) 659.

[3] M.F. Watson and N.K. Watson, hep-ph/9709216.

[4] B.R. Webber, "QCD Event Generators", in "Physics at LEP2", eds. G. Altarelli, T. Sjöstrand and F. Zwirner, CERN 96-01 Vol 2 (1996) 161.

[5] J. Ellis and K. Geiger, Phys. Lett. **B404** (1997) 230.

[6] L. Lönnblad and T. Sjöstrand, Phys. Lett. **B351** (1995) 293.

[7] V. Kartvelishvili, R. Kvatadze and R. Möller, Phys. Lett. **B408** (1997) 331.

[8] "Physics at LEP2", eds. G. Altarelli, T. Sjöstrand and F. Zwirner, CERN 96-01 (1996).

[9] A. Ballestrero et al., "Report of the Working Group on W Mass and QCD", hep-ph/9709283 (September 1997).

[10] L. Lönnblad and T. Sjöstrand, hep-ph/9711460, November 1997.

[11] A. De Angelis, "Interconnection Effects in Multiparticle Production from WW Events at LEP", CERN-OPEN/97-024 and hep/ex/9805005, to be published in Proc. XXVIII International Symposium on Multiparticle Dynamics, Frascati, September 1997.

[12] T. Sjöstrand, "PYTHIA 5.7 / JETSET 7.4", CERN-TH.7112/93 (1993); T. Sjöstrand, Comp. Phys. Comm. **82** (1994) 74.

[13] DELPHI Coll., P. Abreu *et al.,* Z. Phys. **C63** (1994) 17.

[14] DELPHI Coll., P. Abreu *et al.,* Phys. Lett. **B286** (1992) 201.

[15] DELPHI Coll., P. Abreu *et al.,* Phys. Lett. **B355** (1995) 415.

[16] L. Lönnblad and T. Sjöstrand, private communications.

[17] B. Andersson and W. Hoffmann, Phys. Lett. **B169** (1986) 364.

[18] Š. Todorova-Nová, J. Rameš, "Simulation of the Bose-Einstein effect using space-time aspects of Lund string fragmentation model", preprint IReS 97/29, PRA-HEP 97/16.

[19] B. Andersson, M. Ringnér: "Correlations in the Lund Model", preprint LU TP 97-07.

[20] DELPHI Coll., P. Abreu *et al.,* Nucl. Instr. Meth. **A303** (1991) 233.

[21] DELPHI Coll., P. Abreu *et al.,* Nucl. Instr. Meth. **A378** (1996) 57.

[22] P. Abreu et al. (DELPHI Coll.), Z. Phys. **C73** (1996) 11.

[23] C. Caso et al. (Particle Data Group), The European Physical Journal **C3** (1998) 1.

[24] DELPHI Coll., P. Abreu *et al.,* Phys. Lett. **B372** (1996) 172.

[25] Yu.L. Dokshitzer, Phys. Lett. **B305** (1993) 295;
P. Nason and B.R. Webber, in "Physics at LEP2", eds. G. Altarelli, T. Sjöstrand and F. Zwirner, CERN 96-01 Vol 1 (1996) 256.

[26] DELPHI Coll., P. Abreu *et al.,* DELPHI Note 97-177 PHYS 751, Contributed to the early 1997 conferences and to the HEP Conference, Vancouver 1998.

[27] ALEPH Coll., Paper #590 contributed to the HEP Conference, Jerusalem 1997.

[28] DELPHI Coll., P. Abreu *et al.,* Phys. Lett. **B401** (1997) 181.

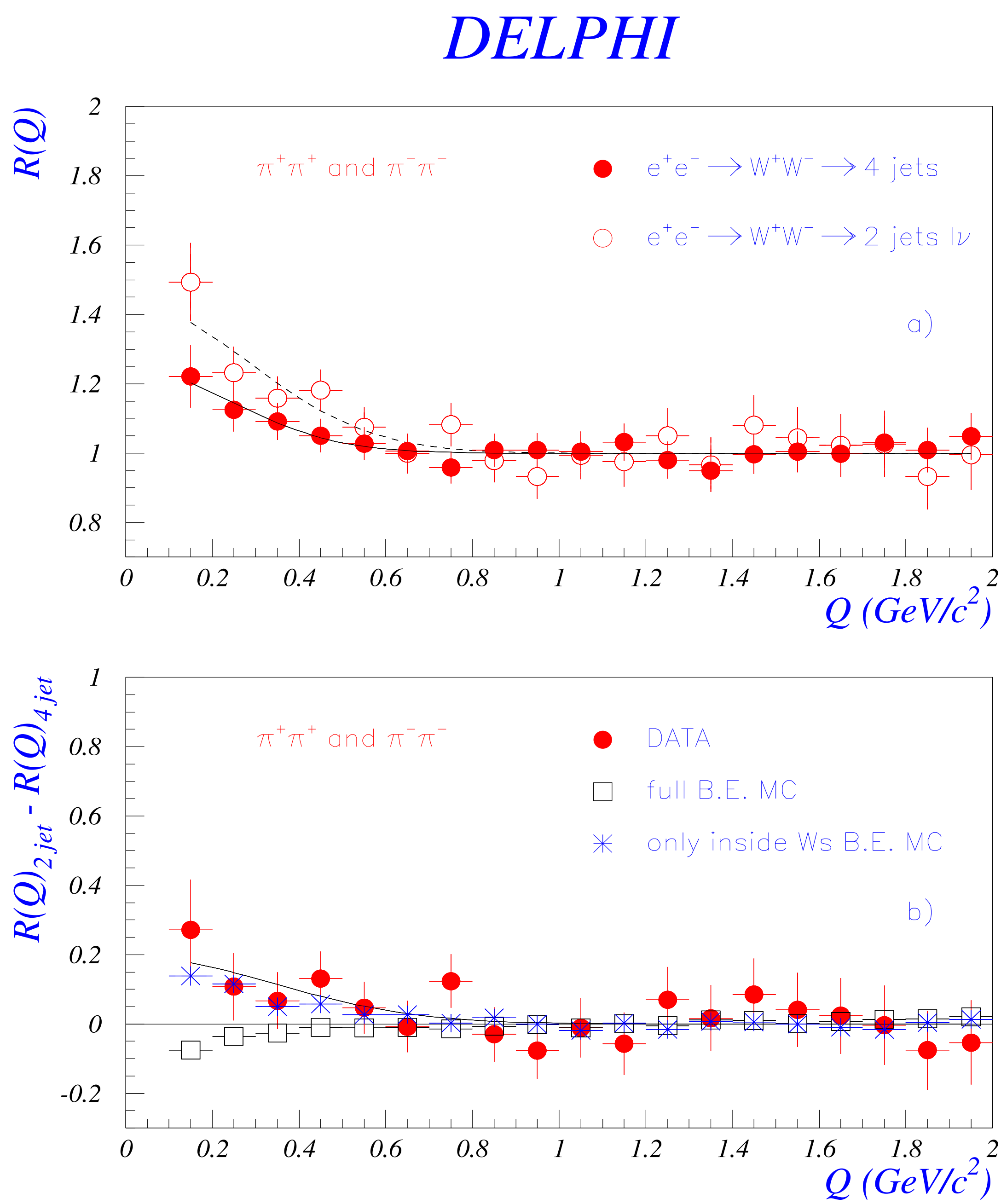


Figure 1: (a) The measured correlation functions $R(Q)$ for like-sign pairs for the mixed decay channel (open circles) and for fully hadronic decay channel (closed circles). The full lines represents the fit by eq. 3. (b) The difference between correlation functions shown in Figure 1(a).

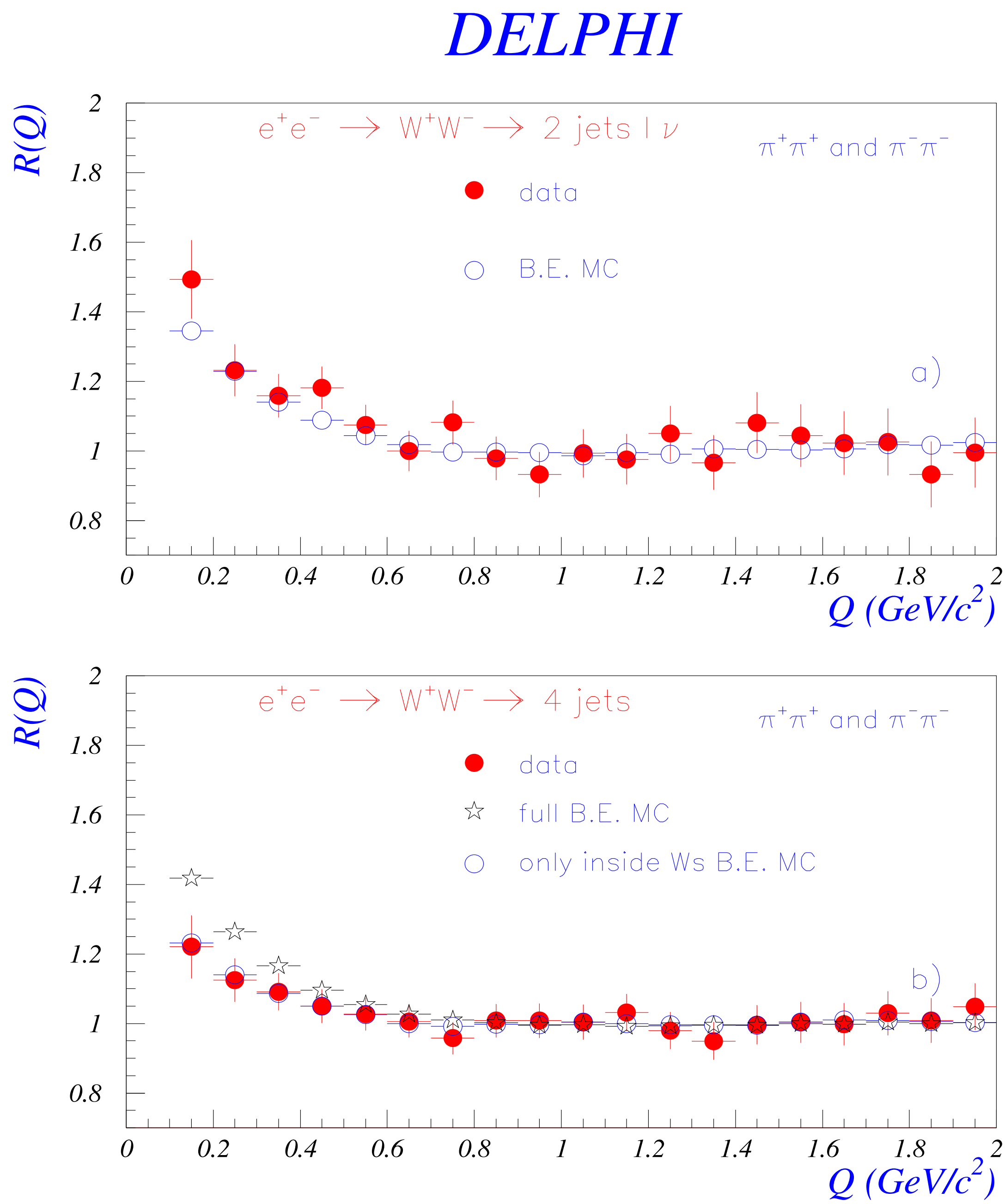


Figure 2: (a) The measured correlation functions $R(Q)$ for like-sign pairs for the mixed decay channel (closed circles). The prediction of PYTHIA with BEC included using LUBOEI is shown by open circles. (b) The measured correlation functions $R(Q)$ for like-sign pairs for fully hadronic decay channel (closed circles). The prediction of PYTHIA with two version of BEC included using LUBOEI are shown by open circles and by stars (see text and figure).

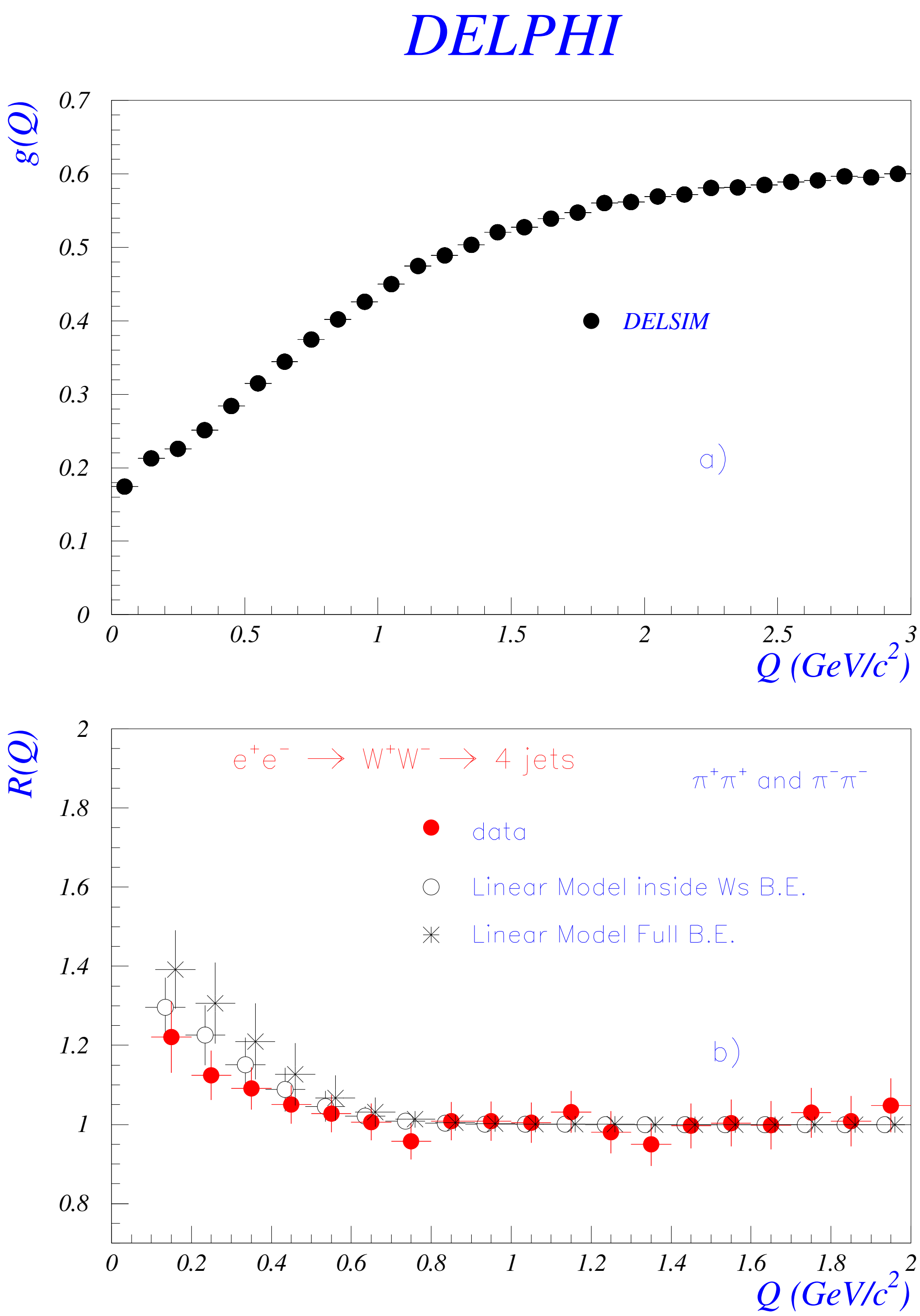


Figure 3: (a) The function $g(Q)$ (see text). (b) The expected correlation function $R(Q)$ in (4q) events in the linear model assuming complete BEC between pions from different Ws (stars) and no correlation (open circles) compared with the measured $R^{(4q)}(Q)$ (closed circles).

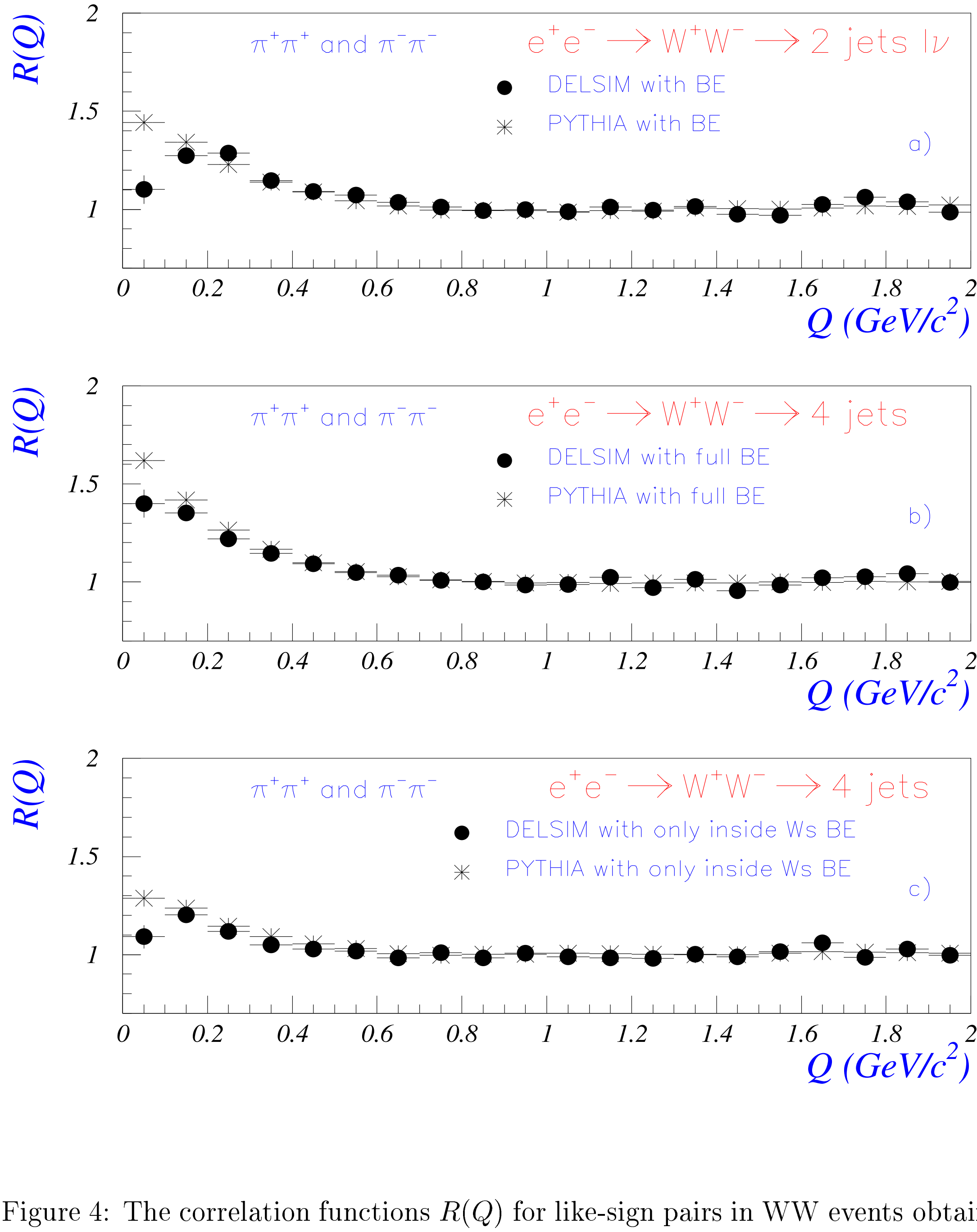


Figure 4: The correlation functions $R(Q)$ for like-sign pairs in WW events obtained using events generated by PYTHIA(stars) and using the same generated by PYTHIA events which were passed throught full detector simulation and were subject of the same selection criteria as for data (closed circles).

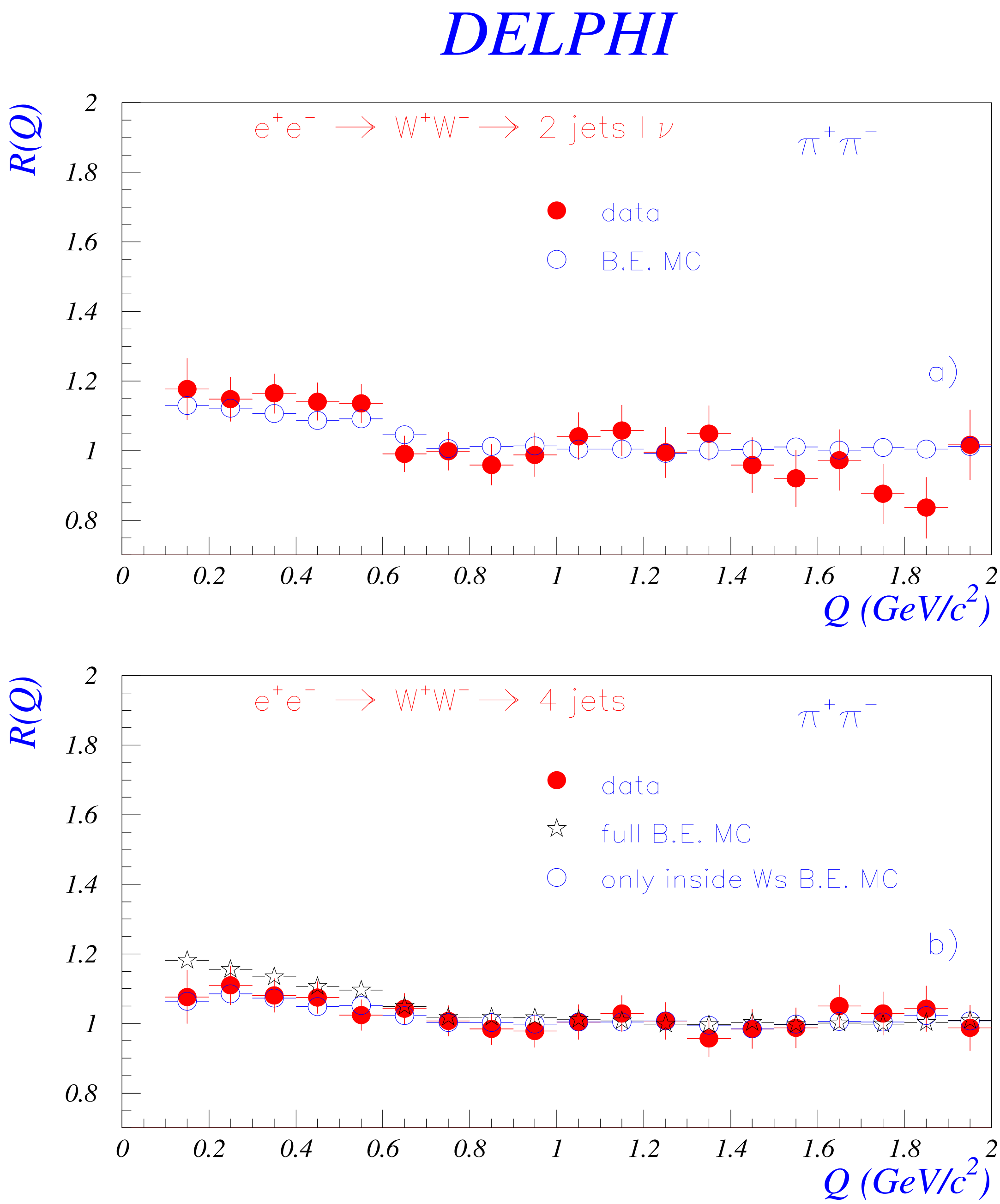


Figure 5: The same distributions as in Figure 2 but for unlike-sign pairs.

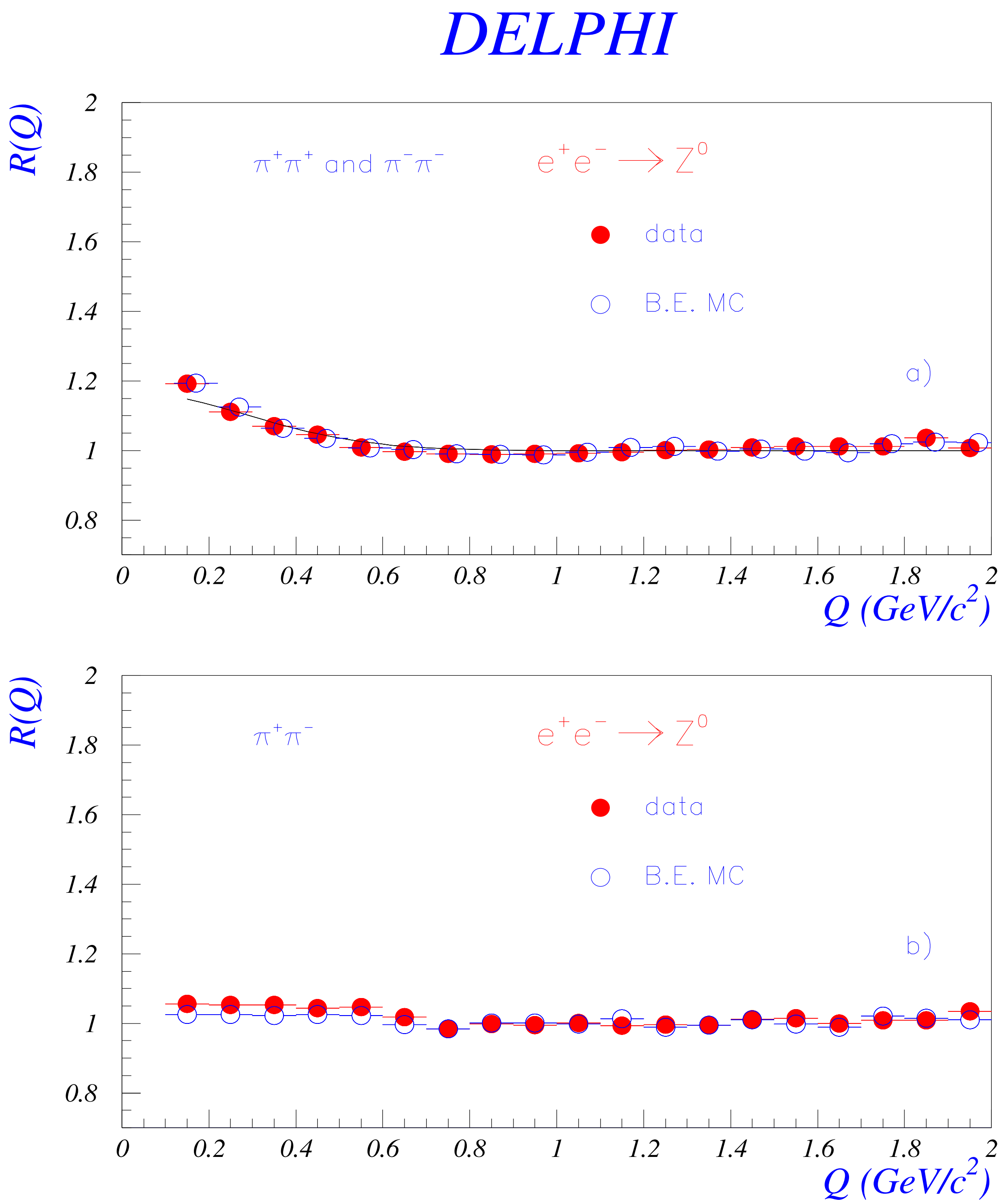


Figure 6: (a) The measured correlation functions $R(Q)$ for like-sign pairs for particles from Z decays (closed circles). The full line represents the fit by eq. 2. The prediction of PYTHIA with Bose-Einstein correlations included using LUBOEI is shown by open circles. (b) The same as in Figure 6a but for unlike-sign pairs.

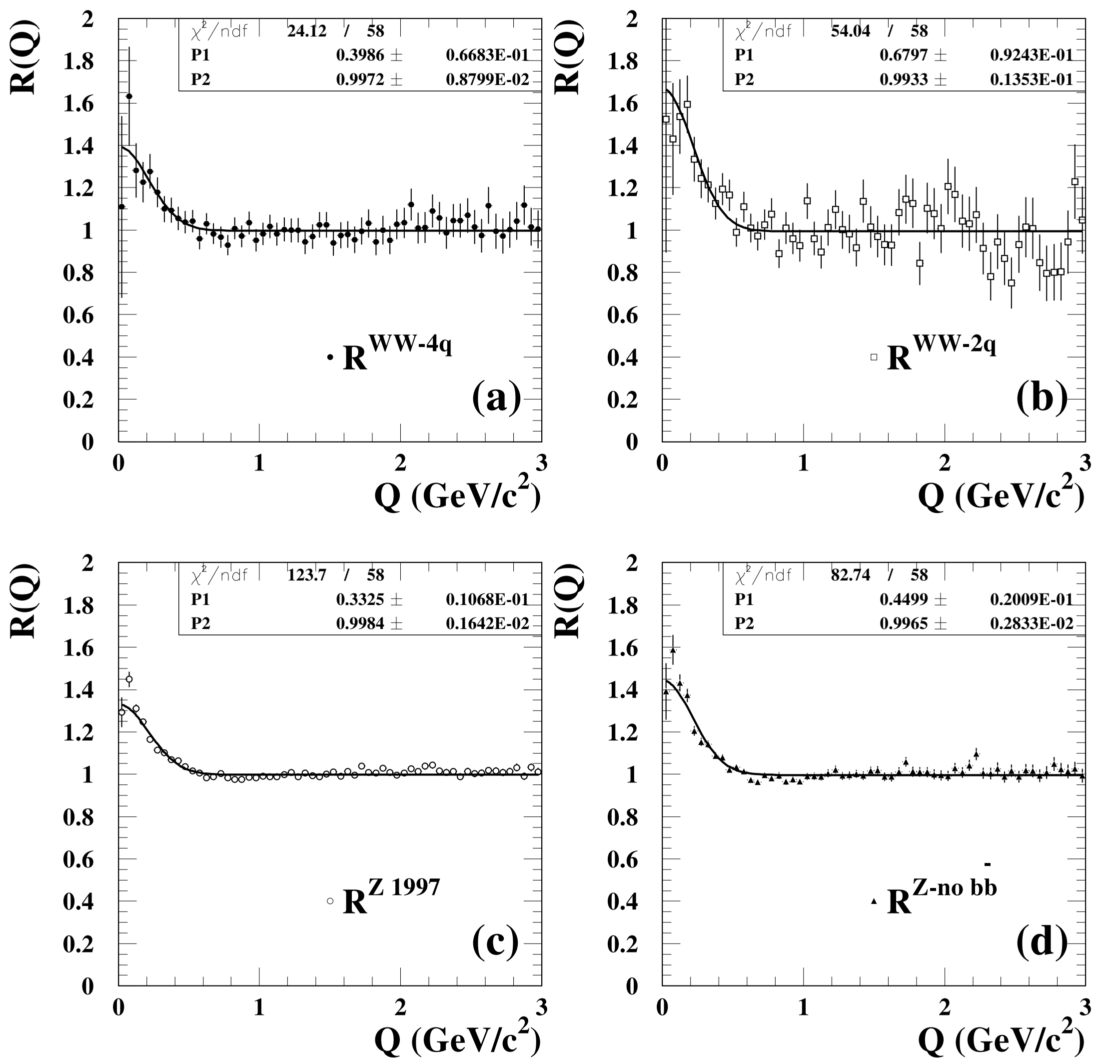


Figure 7: The correlation function $R(Q)$ for like-sign particles in $(4q)$ events (a), in $(2q)$ events (b), in Z events (c) and enriched light flavour sample (d) for pair of track having at least 2 VD hits per track. Fits to the expression (3) are superimposed with r fixed to 0.65 fm and the full Q range used in the fit.

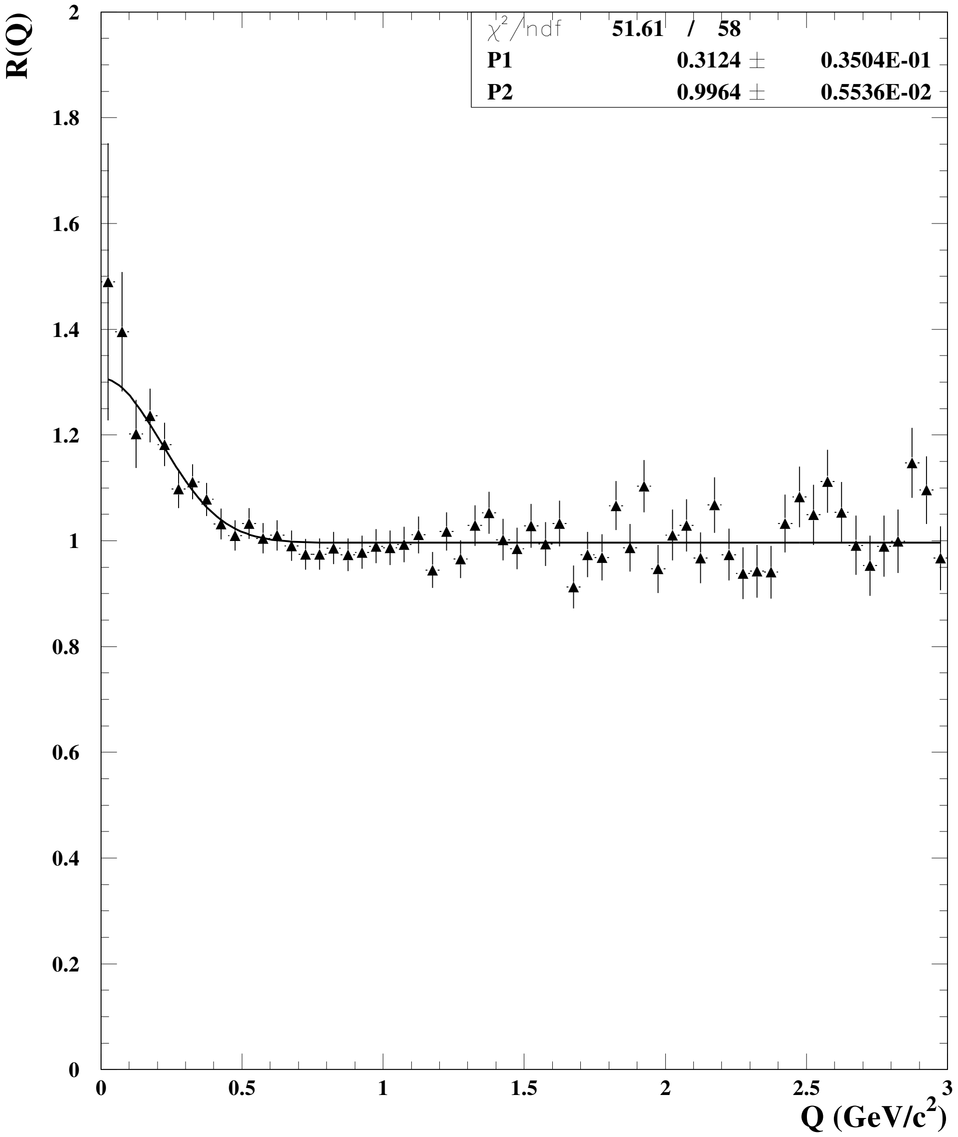


Figure 8: The correlation function $R(Q)$ for like-sign particles in high energy $q\bar{q}$ events; the fit to the expression (3) is superimposed with r fixed to 0.65 fm and the full Q range used in the fit.

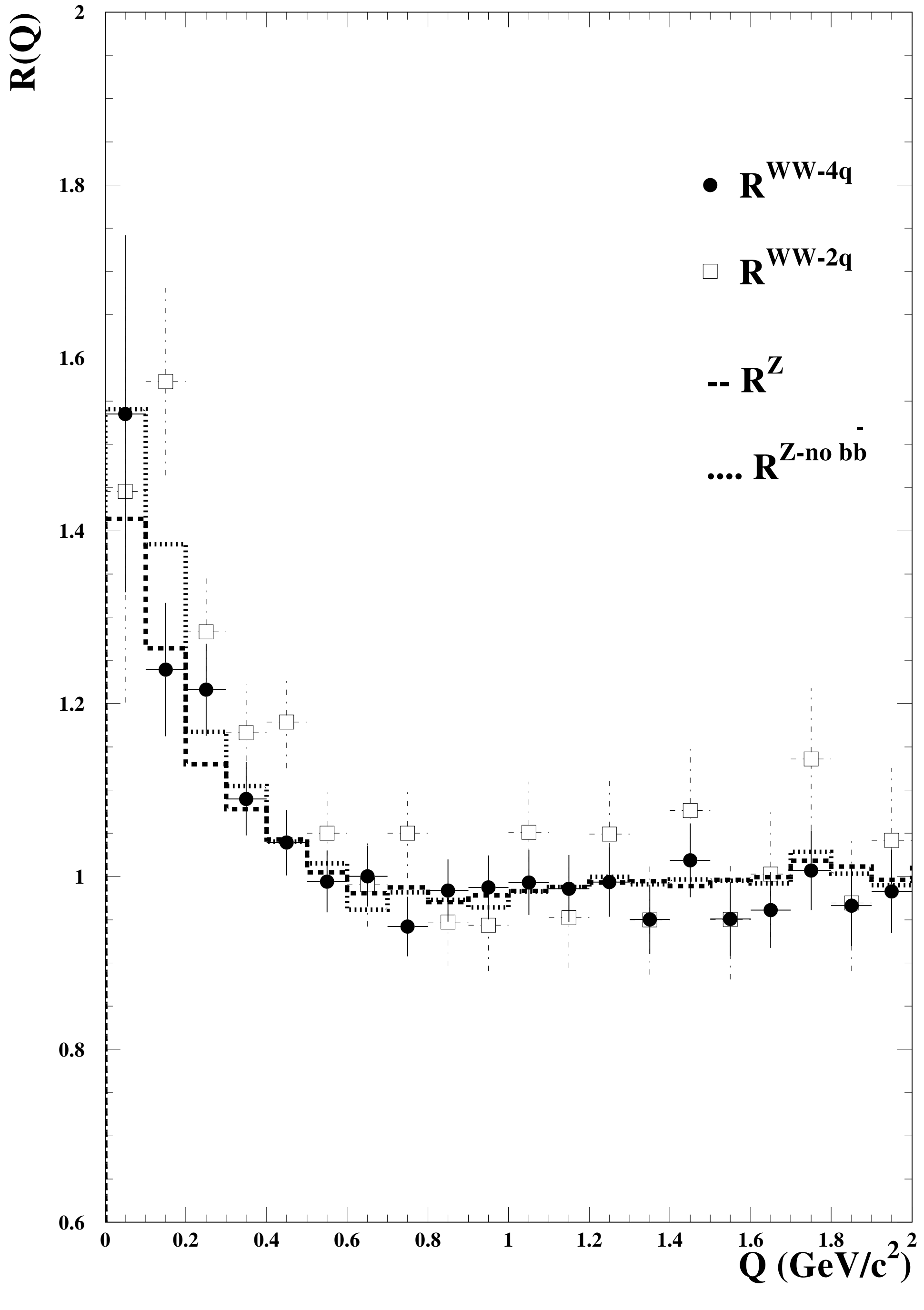


Figure 9: The correlation function $R(Q)$ for like-sign particles in $(4q)$ events (bullets) and in $(2q)$ events (open squares) The correlation function for Z events is superimposed for comparison (dashed line) together with the correlation function for the enriched light flavour sample (dotted line).

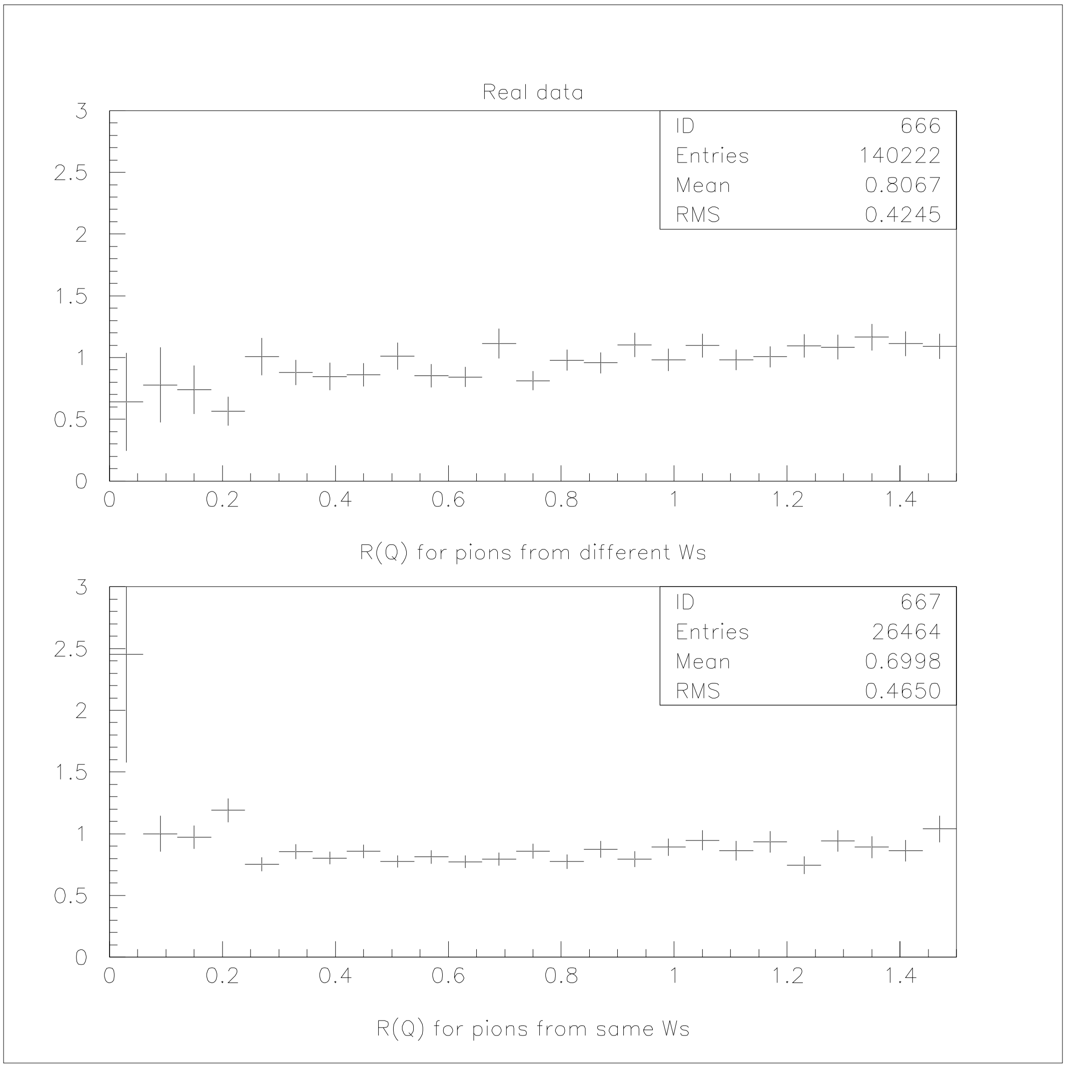
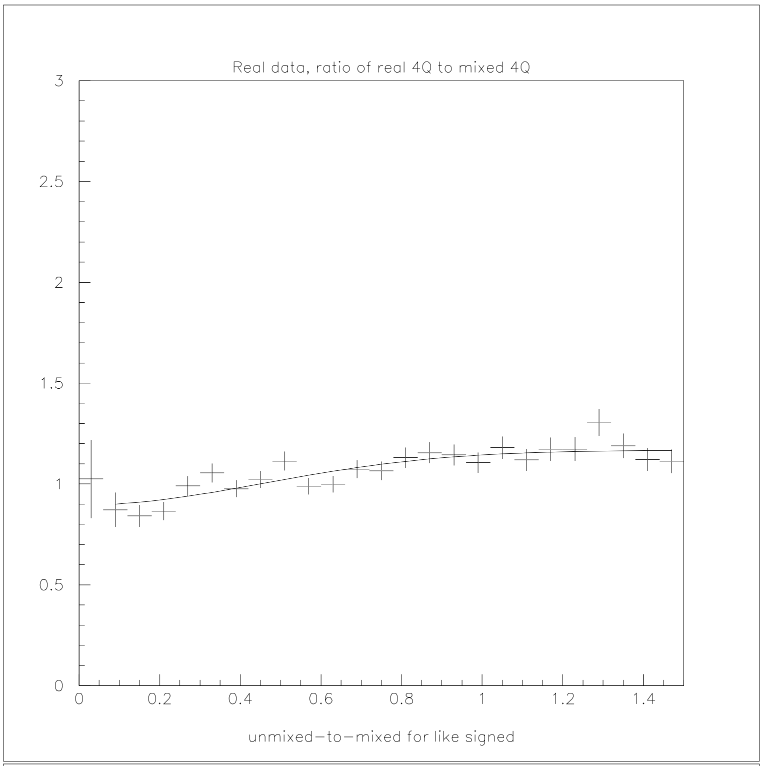


Figure 10: The correlation function $R'(Q)$ (see text) for like-sign particles arising from different Ws (upper plot) and for same Ws (lower plot) using opposite-sign particles as a reference sample.



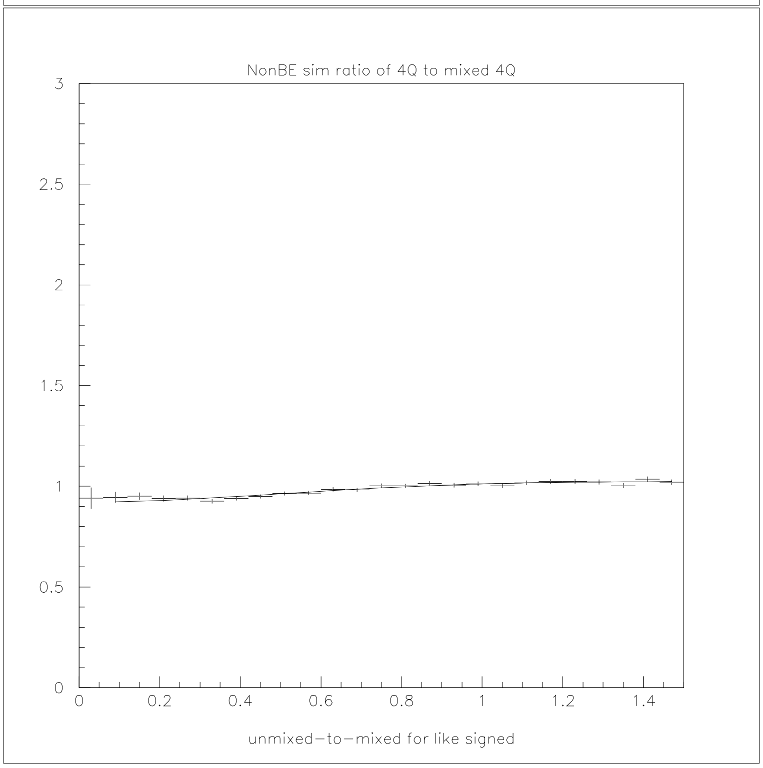


Figure 11: The correlation function for like-sign particles in $(4q)$ events, normalized to the mixed reference sample in data (upper plot) and in a simulated sample without BEC (lower plot).

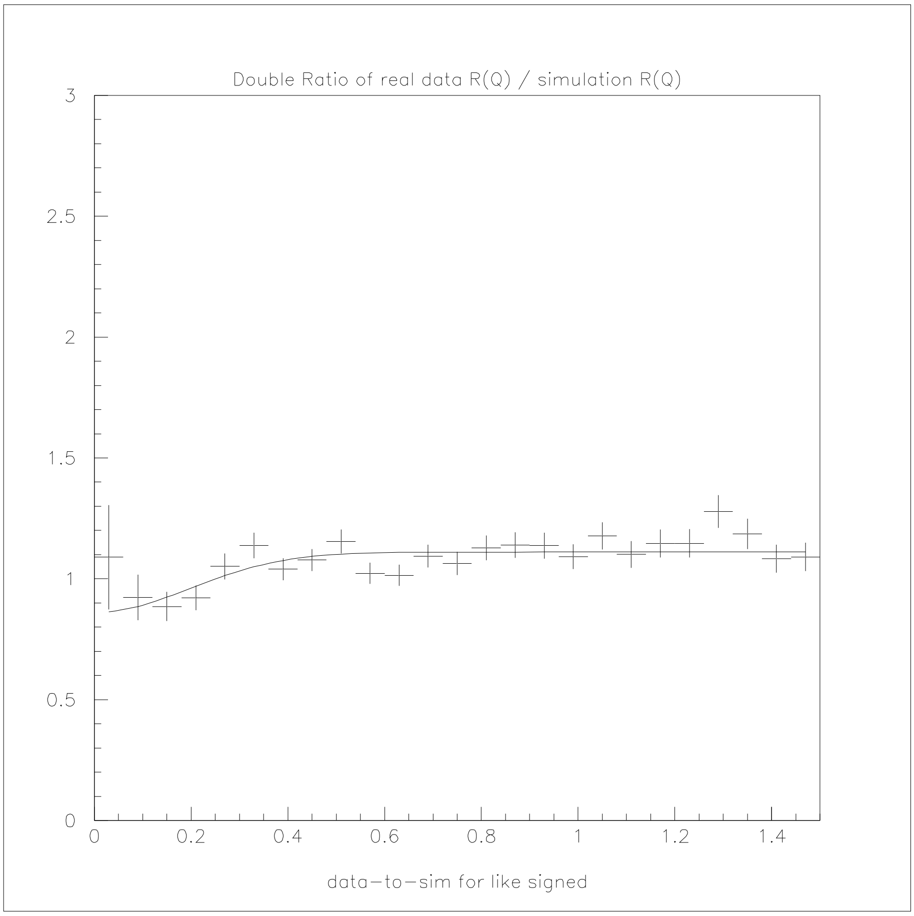


Figure 12: The correlation function $R''(Q)$ (see text) for like-sign particles in $(4q)$ events, normalized to the mixed reference sample.