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Particle Correlations in $e^+e^- \rightarrow W^+W^-$ 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 189 and 206 GeV. Evidence for Bose-Einstein correlations was observed in all three cases.

The event mixing technique was used to determine correlations between particles arising from *different* Ws in fully hadronic WW decays. An excess of like-sign particle pairs with low four-momentum difference in fully hadronic WW events is observed, consistent with the effect expected from correlations between identical particles from different Ws.

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 $\mathrm{e^+e^-} \to \mathrm{WW}$ events allow a comparison of the characteristics of the W hadronic decays when both Ws decay hadronically in the reaction $\mathrm{e^+e^-} \to \mathrm{W^+W^-} \to q_1\overline{q}_2q_3\overline{q}_4$ (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 $\mathrm{e^+e^-} \to \mathrm{W^+W^-} \to q_1\overline{q}_2\ell\nu$ (denoted $(2q)$ mode for brevity). Since the distance between the $\mathrm{W^+}$ and $\mathrm{W^-}$ 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 1998, 1999 and 2000 at centre-of-mass energies of 189–206 GeV with integrated luminosity 155 $\mathrm{pb^{-1}}$, 228 $\mathrm{pb^{-1}}$ and 164 $\mathrm{pb^{-1}}$, respectively, with total statistics of 547 $\mathrm{pb^{-1}}$.

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 $Q^2 = -(p_1 - p_2)^2 = M^2_{\pi\pi} - 4m^2_\pi$, 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

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

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, the version of the LUBOEI code, BE_{32}, 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 λ=PARJ(92)=1.35 and $r = 0.58$ fm, which corresponds to model parameter R=PARJ(93)=0.34 GeV. 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).

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. Events were selected using a run quality flag, requiring all detectors essential for the analysis of the different decay channels of the W's to be fully operationl and efficient. In the event selection, charged particles were selected if they had a polar angle between 10° and 170°, momentum between 0.2 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. The information Time Projection Chamber of DELPHI was used to reconstruct the track, which implicit track length cut of 25 cm. Only tracks with polar angle θ between 30° and 150° were accepted. The impact parameters in the transverse and longitudinal plane were required to be smaller than 0.4 cm and 1 cm/sin θ. The energetic isolated charged particle of the mixed decay channel was not included in the analysis.

$\sqrt{s}$	Number of events	Purity(%)	Efficiency(%)
189 GeV	829	89.1	60.0
192 –200 GeV	1136	89.8	53.2
202 –206 GeV	771	90.5	49.6

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

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

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, $e^+e^- \rightarrow q\bar{q}(\gamma)$, especially the radiative return to the Z peak, $e^+e^- \rightarrow Z\gamma \rightarrow q\bar{q}\gamma$. For each event passing the above criteria, all particles were clustered into jets using the LUCLUS algorithm [3] with the resolution parameter $d_{join} = 8$ 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 $E_{cm}\times 0.79$. 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.

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. Events were used only if the variable D was larger than 0.006 rad.GeV^{-1}.

A total of 2736 events were selected. The detector effects on the analysis were estimated using samples of WW events generated with EXCALIBUR [10] for all four-fermion final states,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$\rightarrow q\bar{q}q\bar{q}$, estimated using simulated events, were about 90% and 54%, respectively(see table 1).

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.

$\sqrt{s}$	Number of events	Purity(%)	Efficiency(%)
189 GeV	600	95.2	51.8
192 – 200 GeV	926	96.6	51.1
202 – 206 GeV	643	97.2	48.0

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

Events were selected by requiring six or more charged particles and a missing momentum of more than 5% 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 17 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 $|\cos\theta_{\rm miss}| < 0.96$.

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

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

A kinematical fit was performed on the selected events. The four-vectors of the two jets, 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, 2169 events were selected. The purity and efficiency of the selection, estimated using simulated events, were about 96% and 50%, respectively(see 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 EXCALIBUR without BEC after full simulation of the DELPHI detector and after the same selection criteria as for real data. The $P_0(Q)$ reference distribution was normalised on number of pairs in $P(Q)$ distribution.

The presence of bin-to-bin and inside-bin correlations influences the errors on the $R(Q)$ distribution [16]. 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. The covaruiance matrix technique was used to measure the parameters. Covariance matrix was calculated from the data themselves. The method is based on classical statistics(see for details [14]). 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. The fits below were performed using the inverted V_{jk} matrix.

4.1 Correlation Between Particles in Z events

Correlations between particles in Z events produced during the 1998 calibration run were investigated. The track selection for the analysis was the same as above. The event selection was similar to the one in [15]. The number of selected events amounted to 24681.

The $R(Q)$ distribution for like-sign combinations is shown in figure 1a. The fit using the expression (3) yielded:

$$\lambda_Z = 0.712 \pm 0.021(stat) \quad (5)$$

$$r_Z = 0.888 \pm 0.040(stat) \text{ fm}. \quad (6)$$

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:

$$\lambda_{Z-no\ b\bar{b}} = 0.913 \pm 0.027(stat) \quad (7)$$

$$r_{Z-no\ b\bar{b}} = 0.893 \pm 0.047(stat)\ \text{fm}\,. \quad (8)$$

The λ and r parameters in the LUBOEI BE_{32} code was tuned to the correlation function measured at the Z for like-sign pairs. The tuned parameters $\lambda = 1.35$ and $r = 0.58$ fm were obtained. (PARJ(92)=1.35 and PARJ(93)=0.34). The $R(Q)$ distributions for the data for Z events are compared with the LUBOEI predictions in figure 1a–1b. The good agreements between data and model were found.

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

The $R_{2q}(Q)$ and $R_{4q}(Q)$ distributions for the data are shown in figure 2. A fit to the correlation functions $R(Q)$ using equation (3) yielded the values:

$$\lambda_{2q} = 0.791 \pm 0.096(stat) \quad (9)$$

$$r_{2q} = 1.177 \pm 0.121(stat)\ \text{fm} \quad (10)$$

for the mixed hadronic-leptonic channel and

$$\lambda_{4q} = 0.725 \pm 0.053(stat) \quad (11)$$

$$r_{4q} = 1.117 \pm 0.070(stat)\ \text{fm} \quad (12)$$

for the fully hadronic decay channel.

4.2.1 Background Subtraction in WW$\rightarrow$ $4q$ Events

Averaged over all energies, the selected WW fully hadronic events contained 10% of $q\bar{q}$ events (Table 1). The correction for these background contributions to the fully hadronic sample was done in following way.

The sample of $q\bar{q}$ events was generated with BEC included according to LUBOEI BE_{32} with parameters λ=1.35 and r=0.58 fm as was tuned at Z-peak. 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.

We verified the agreement between data and simulated events at Z-peak for 4 jet samples selected by using the d_{join} requirement.

The comparison of Q-distributions for data and simulated Z events are shown in Fig. 3 for all events (Fig. 3a) and for 4 jet events (Fig. 3b, 3c and 3d for $d_{join} > 4$, $d_{join} > 5$ and $d_{join} > 6.5$, respectively). The agreement for all events is satisfactory (as was shown also in section 4.1), while the model is strongly overestimates the correlations at low-Q for selected 4 jet samples.

We used also the alternative simulated sample at Z-peak with reduced parameter of λ=0.90 (instead of λ=1.35). The all other model parameters were the same. The comparison of Q-distributions for data and these simulated Z events are shown in Fig. 4.

The resulting Q plot for background $q\overline{q}$ events was corrected for the discrepancy between the data and the simulated sample at Z-peak shown in figure 3c. This distribution, properly weighted by the percentage of the background, was subtracted from the experimental WW (4q) distribution. Alternatively, the contribution of background $q\overline{q}$ events were subtracted using the simulated sample with parameter λ=0.90.(without corrections). These two prosedures yield practically the same background subtracted distributions.

The Q-distributions for real WW fully hadronic events and for background events, calculated as described above, are shown in figure 5a. Figure 5b presents the $R(Q)$ distributions for WW (4q) events without (closed circles) and with background subtraction (triangles).

Note that background contribution does not change practically the Q-distribution for (4q) events (Fig. 5b).

We note also that for WW BEC analysis at LEP, usually, the background contribution in WW fully hadronic channel were estimated using the LUBOEI model tuned at Z-peak, which, as was shown in this section, overestimates the correlations at low-Q for 4 jet samples. It is most important for selections with high background contribution.(which is up to 20% for some of selections used at LEP).

A fit to the $R(Q)$ after the background subtraction with equation (3) yielded the values:

$$\lambda_{4q} = 0.741 \pm 0.065(stat) \tag{13}$$

$$r_{4q} = 1.199 \pm 0.088(stat)\ \text{fm} \tag{14}$$

In the subsequent analyses the $R(Q)$ distributions after the background subtraction were used.

5 Correlations Between Particles from Different Ws

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 sample of $(4q)$-like events was constructed by mixing of two hadronic Ws from the different $(2q)$ events in a following way.

The pairs of Ws were accepted for mixing if they have momentum balance $|\ \overrightarrow{P}_1 + \overrightarrow{P}_2\ | <$ 25 GeV. 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. The mixed event was then constructed from two W candidates by boosting the particles of the individual Ws in opposite directions. The boost vectors were determined taking into account the energy-momentum conservation and the fitted mass of W candidate.

The fully hadronic event selections were applied to mixed events. Some of event shape variables, multiplisities and single particle distributions for fully hadronic and mixed events for data, as well as for MC, are shown in Fig. 6–10. In general good agreement was found.

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

$$R_{4q}(Q)(mixing) = \frac{[P_{2q}(Q) + P_{mix}(Q)]_{data}}{[P_{2q}(Q) + P_{mix}(Q)]_{DELSIM\ no\ BE}}, \tag{15}$$

where $P_{mix}(Q)$ was obtained using the mixing of two $(2q)$ events as described above.

The measured $R_{4q}(Q)$ and $R_{4q}(Q)(mixing)$ are shown in figure 11 for like-sign pairs, indicating the correlations between particles from different Ws.

To perform model independent measurements of correlations between particles from different Ws, the ratio

$$D(Q) \equiv \frac{P_{4q}(Q)}{P_{2q}(Q) + P_{mix}(Q)}, \tag{16}$$

was plotted and fitted by the expression:

$$D(Q) = N\,(1 + \delta Q)\left(1 + \Lambda e^{-RQ}\right). \tag{17}$$

The resulting plots are shown in Fig. 12.

The fit for the prediction of the model with full BEC gave:

$$\Lambda(full\ BE) = 0.227 \pm 0.026(stat) \tag{18}$$

$$R(full\ BE) = 0.895 \pm 0.100(stat)\ \text{fm} \tag{19}$$

$$\delta(full\ BE) = 0.000 \pm 0.002(stat) \tag{20}$$

$$N(full\ BE) = 0.998 \pm 0.004(stat) \tag{21}$$

We fixed the parameter R to the value obtained from the fit of model with full BEC of R=0.895 fm and repeated the fit for the prediction of the model with inside BEC and for the data (with free parameter N). The fits yielded the values:

$$\Lambda(inside\ BE) = -0.002 \pm 0.016(stat) \tag{22}$$

$$\delta(inside\ BE) = 0.001 \pm 0.001(stat) \tag{23}$$

for model with inside Ws BEC, and

$$\Lambda(data) = 0.130 \pm 0.045(stat)^{+0.026}_{-0.020}(syst) \tag{24}$$

$$\delta(data) = 0.000 \pm 0.004(stat) \tag{25}$$

for data.

The systematic error on the measured value of $\Lambda(data)$ in (24) is the sum in quadrature of the following contributions.

- Due to the event mixing technique.

  The systematic error using the model with inside Ws BE was estimated to be ±0.018, i.e. $\Lambda(inside\ BE)$ plus one sigma(equation 22).

  The effects of discrepancies between fully hadronic and mixed events were studied. The weights were assigned to the mixed events which were equal to the ratio of the event shape and single particle distribution variables shown in figures 6–10. The maximum deviation of 0.020 from value (24) was found. The value ±0.020 was used as systematic error due to mixing technique.

– Due to background events. The value of parameter $\Lambda(data)$ without background subtraction was

$$\Lambda(data) = 0.147 \pm 0.043(stat)\,. \tag{26}$$

The difference between the values of (24) and (26), i.e. +0.017, was used as estimation of the systematic error.

The analysis were repeated using the $\alpha > 3^\circ$ requirement, where α is the angle between pairs of particles. The corresponding $D(Q)$ plots are shown in Fig. 13. The fit for the prediction of the model with full BEC gave:

$$\Lambda(full\ BE, \alpha\ cut) = 0.292 \pm 0.037(stat) \tag{27}$$

Note that the $\alpha > 3^\circ$ increases the sensitivity to inter-Ws correlations.(values (18) and (27)).

The fit velues for the prediction of the model with inside BEC and for the data were

$$\Lambda(inside\ BE, \alpha\ cut) = -0.002 \pm 0.021(stat)\,, \tag{28}$$

$$\Lambda(data, \alpha\ cut) = 0.170 \pm 0.055(stat)^{+0.033}_{-0.023}(syst)\,. \tag{29}$$

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 during the 1998, 1999 and 2000 runs with integrated luminosity of 547 pb^{-1} at centre-of-mass energies of 189–206 GeV.

Measurements were performed to extract correlations between pions from different Ws. The event mixing technique was used to constract comparison samples which contain only BEC for particle pairs coming from a single W boson.

The value of parameter $\Lambda(data)$ characterizing the correlations between particles from different Ws is found to be

$$\Lambda(data) = 0.130 \pm 0.045(stat)^{+0.026}_{-0.020}(syst) \tag{30}$$

The value using the $\alpha > 3^\circ$ requirement, where α is the angle between pairs of particles, is found to be

$$\Lambda(data, \alpha\ cut) = 0.170 \pm 0.055(stat)^{+0.033}_{-0.023}(syst)\,. \tag{31}$$

It should be noted that the background subtraction from fully hadronic WW channel practically does not change the Q-distributions.

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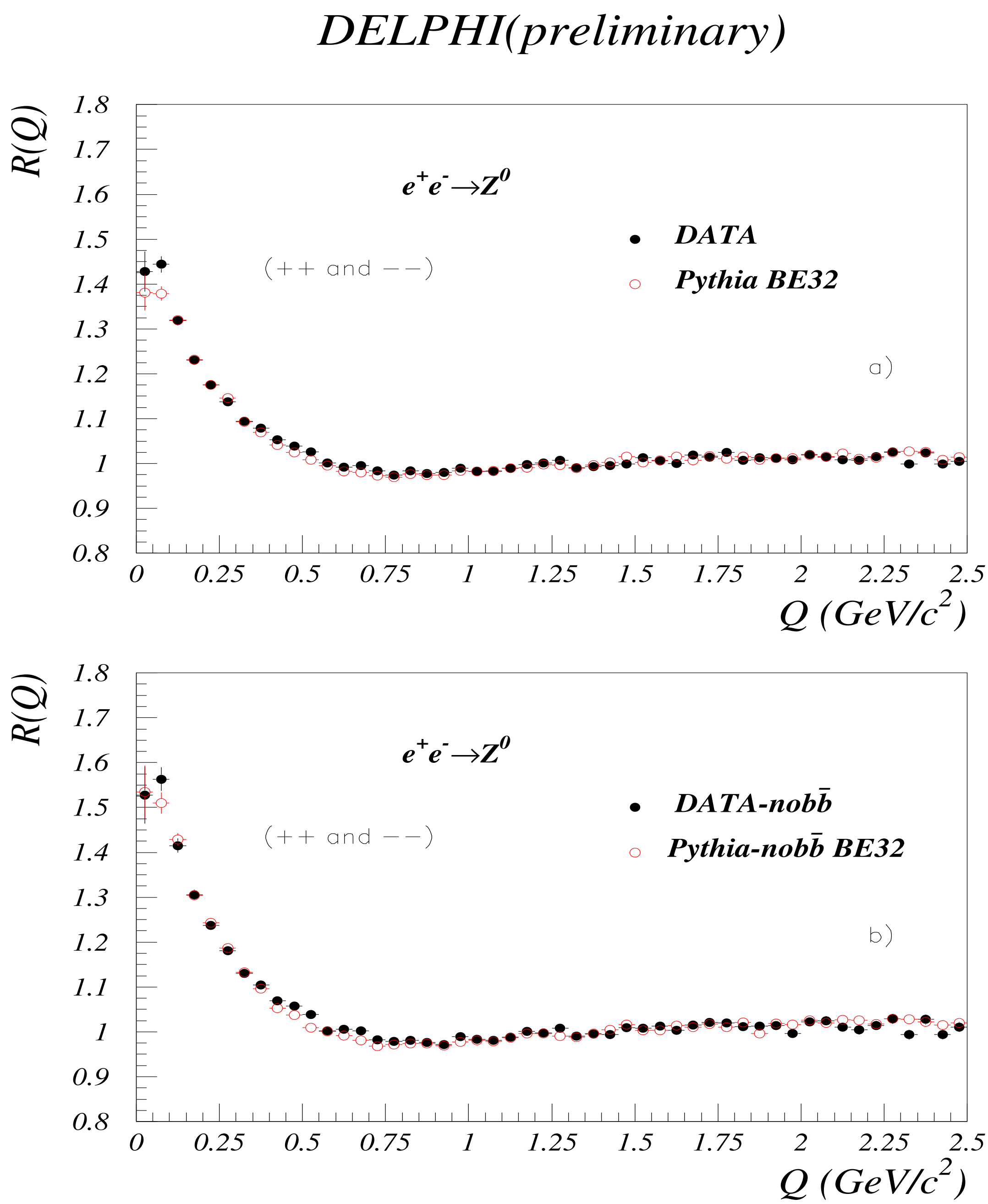

Figure 1: (a) Measured correlation functions $R(Q)$ for like-sign pairs in Z decays data (closed circles) and the PYTHIA Monte Carlo model tuned at the Z peak (open circles). (b) Same as in (a), for Z events depleted in $b\bar{b}$ production

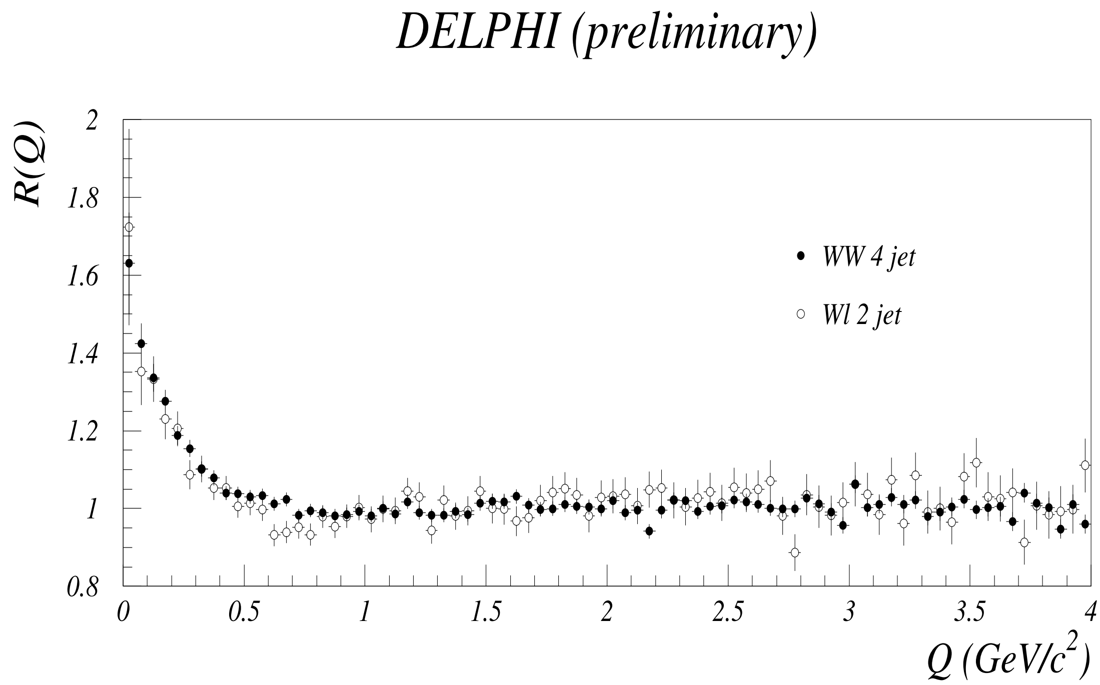

Figure 2: Measured correlation functions $R_{2q}(Q)$ (open circles) and $R_{4q}(Q)$ (closed circles) for like-sign pairs.

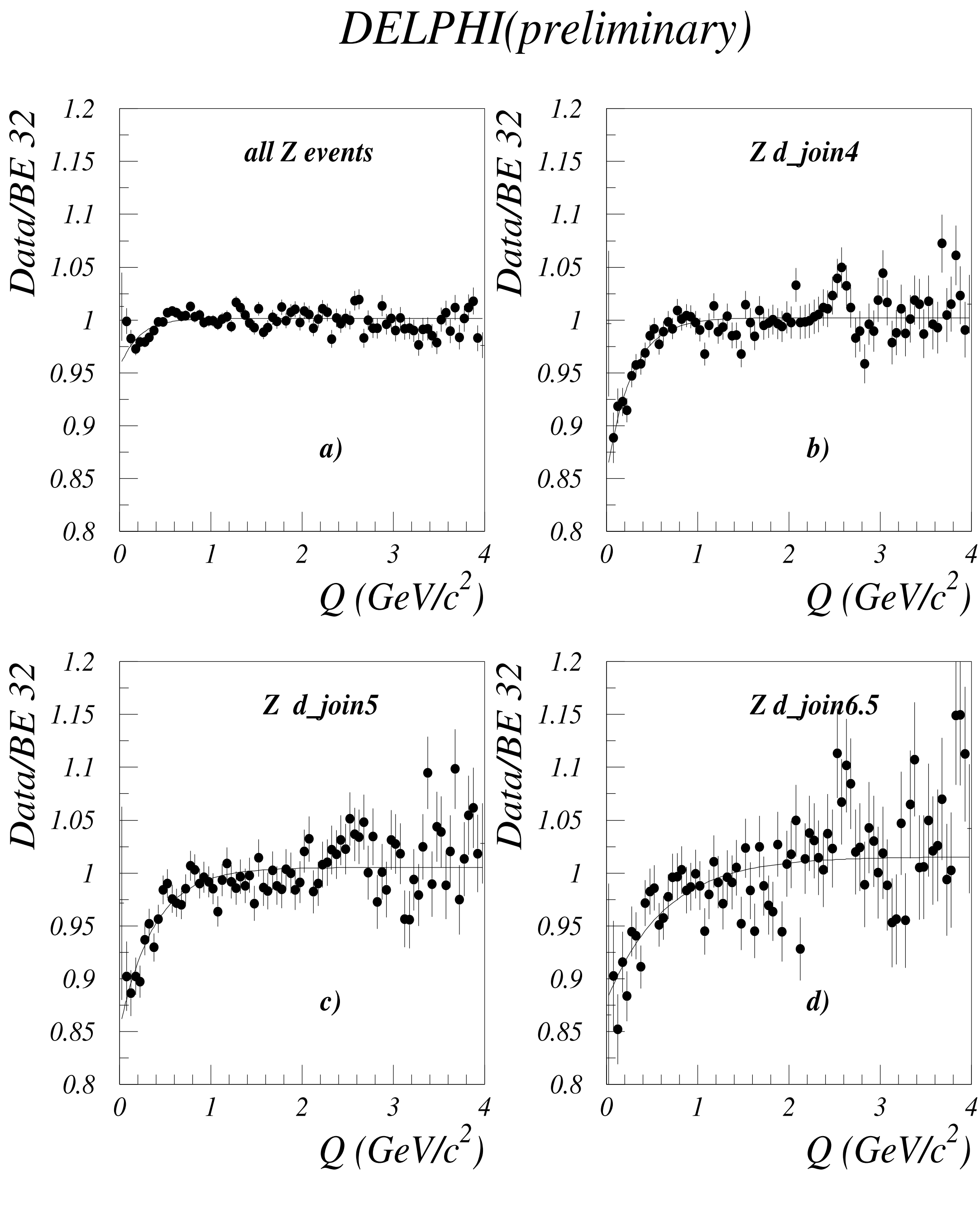

Figure 3: The ratio of Q-plots for real and simulated events in Z decays data (a) for all Z events and for selected Z 4 jet events, with (b) $\mathrm{d_{join}} > 4$, (c) $\mathrm{d_{join}} > 5$, (d) $\mathrm{d_{join}} > 6.5$. The model parameters were $\lambda = 1.35$ and $r = 0.58$ fm.

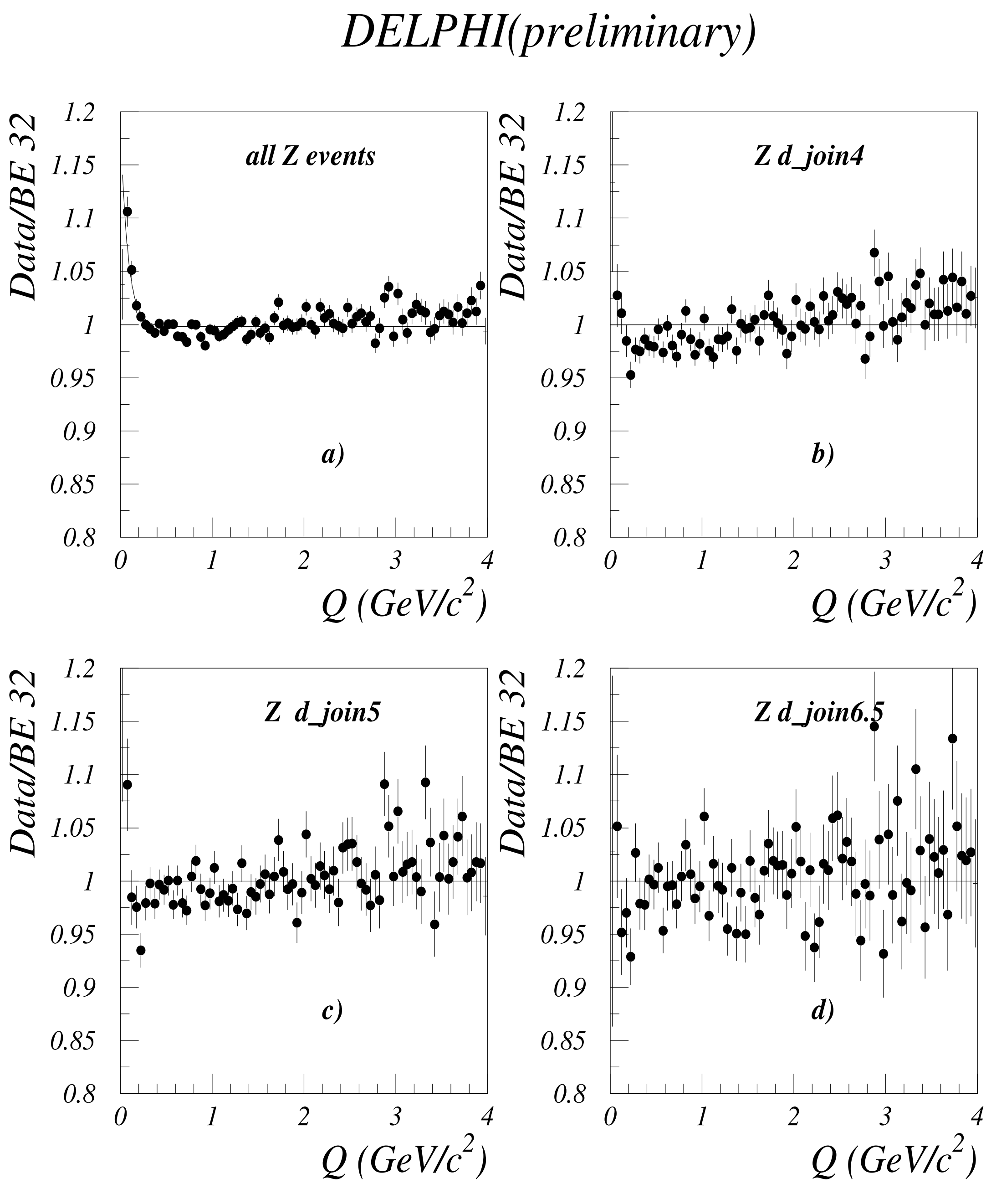

Figure 4: Same as in figure 3 but for simulated events with parameters of $\lambda = 0.90$ instead of $\lambda = 1.35$.

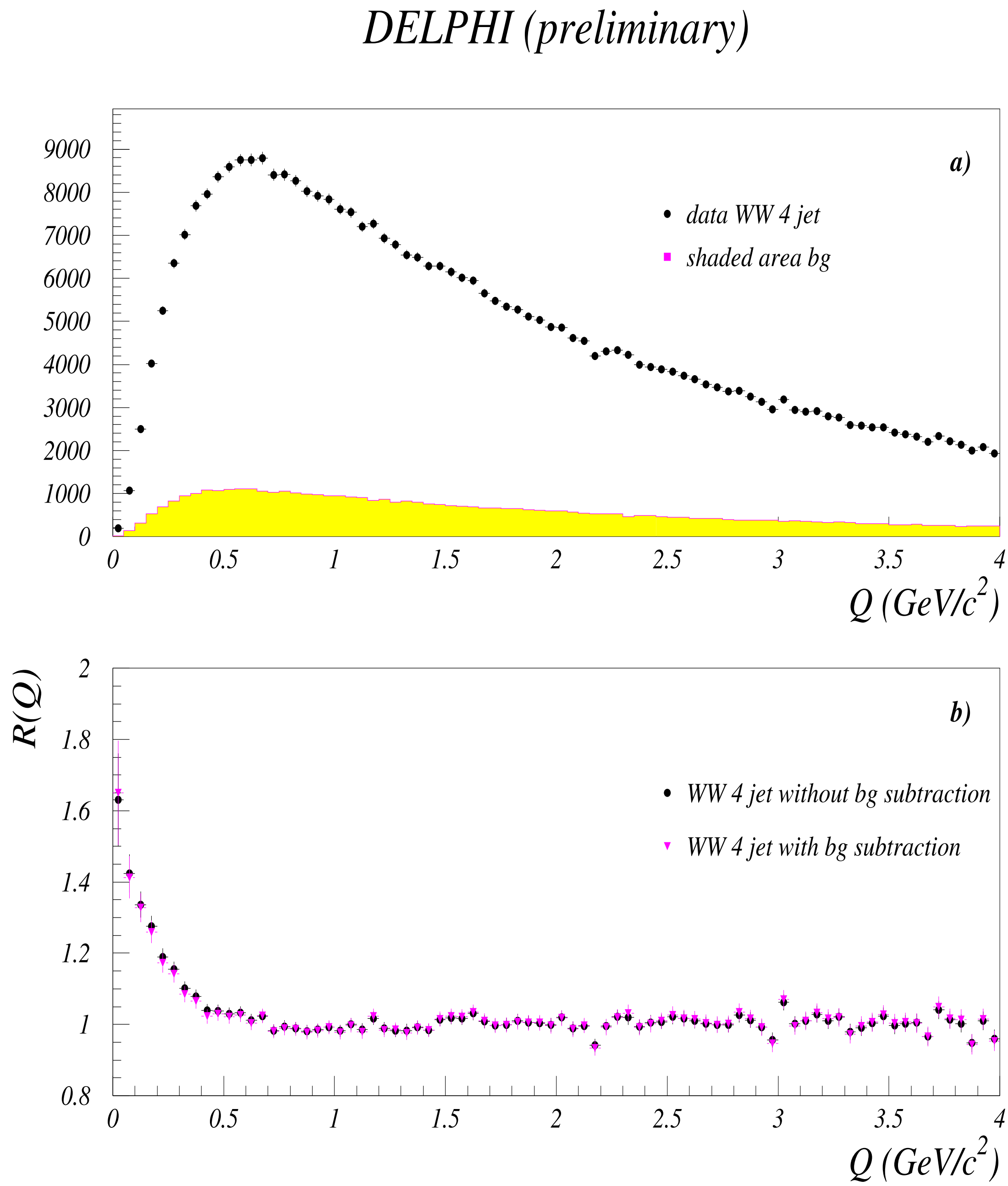

Figure 5: (a) Q-distributions for real (4q) events and for background events for like-sign pairs. (b) measured $R_{4q}(Q)$ distributions for (4q) before and after background subtraction (closed circles and triangles, respectively).

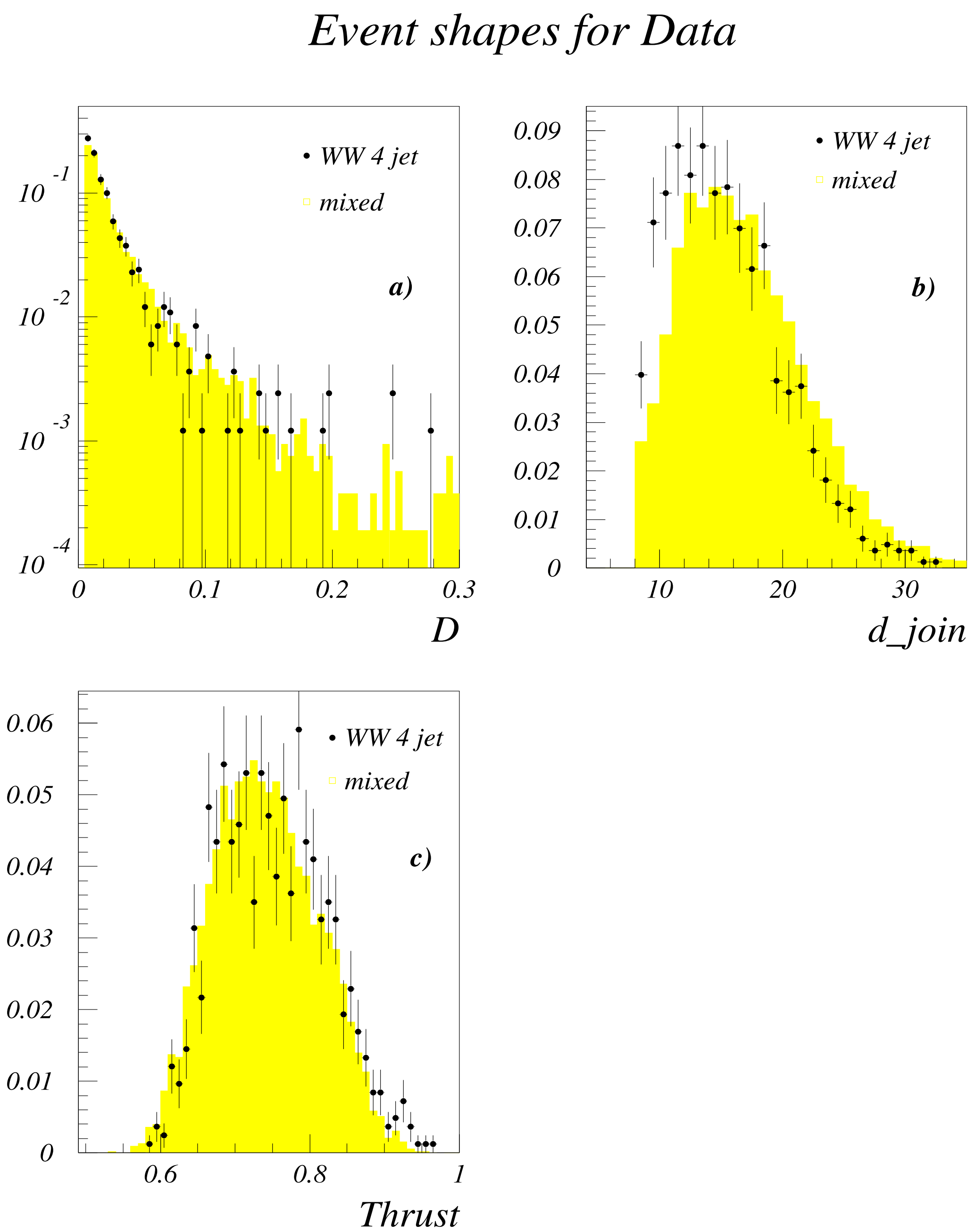

Figure 6: Comparison of events shape variables for real (4q) and mixed events for 1998 data.

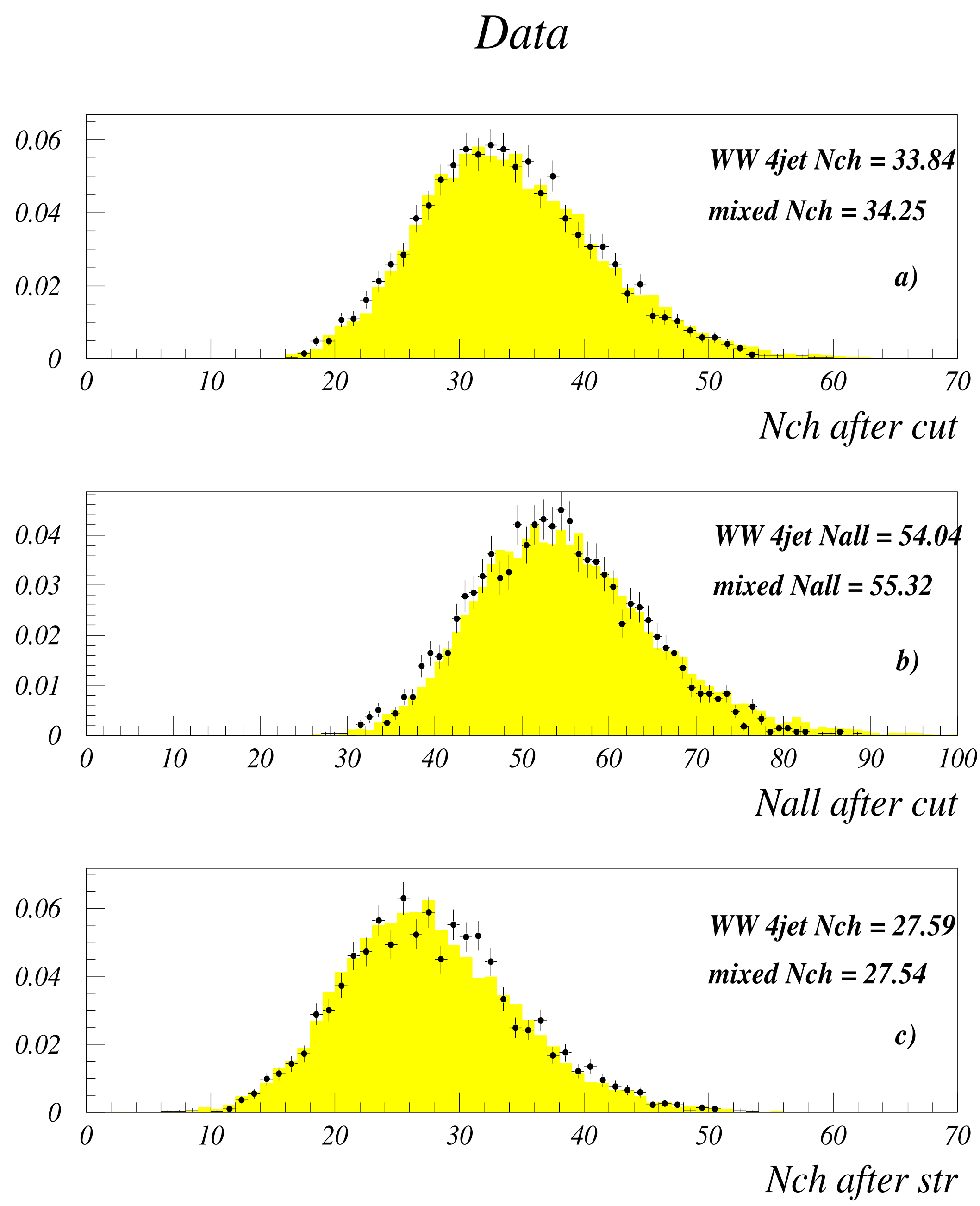

Figure 7: Comparison of multiplicity distributions for real (4q) and mixed events for 1998 data for a) all charged particles used for event selections, b) all particles includilng neutrals, c) charged particles used for analysis of Q-distributions.

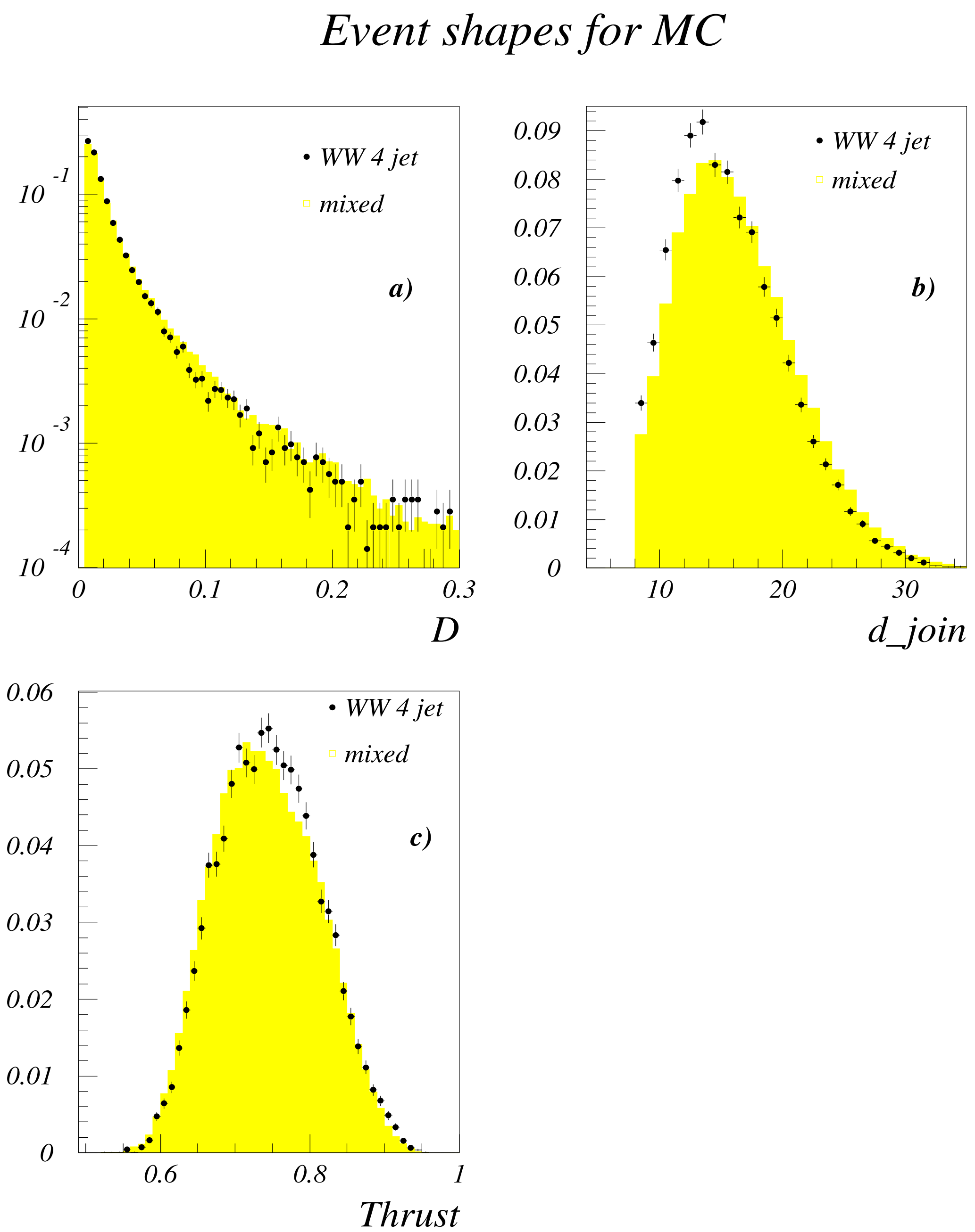

Figure 8: Comparison of events shape variables for (4q) and mixed events for simulated data.

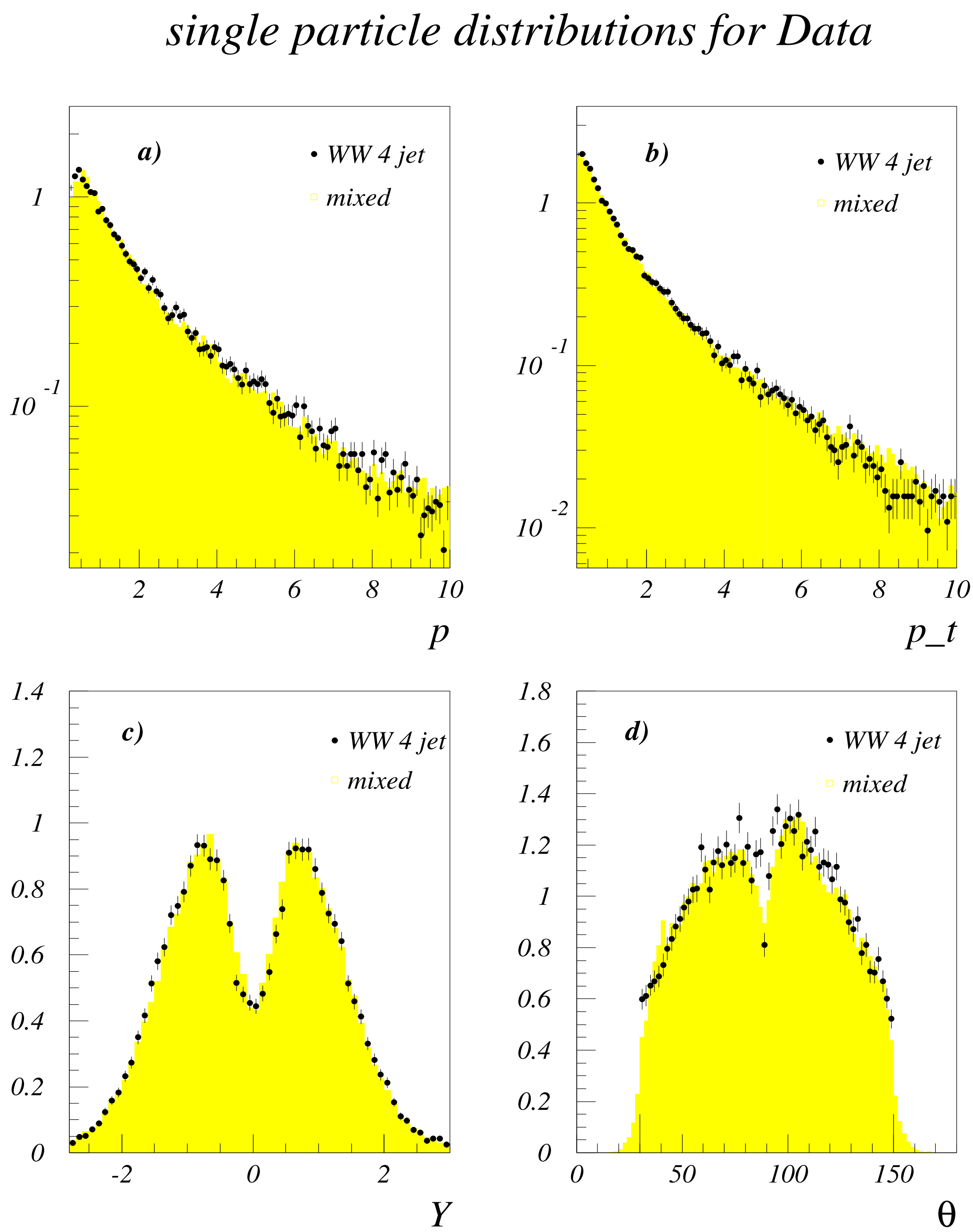

Figure 9: Comparison of single particle distributions for real(4q) and mixed events for 1998 data.

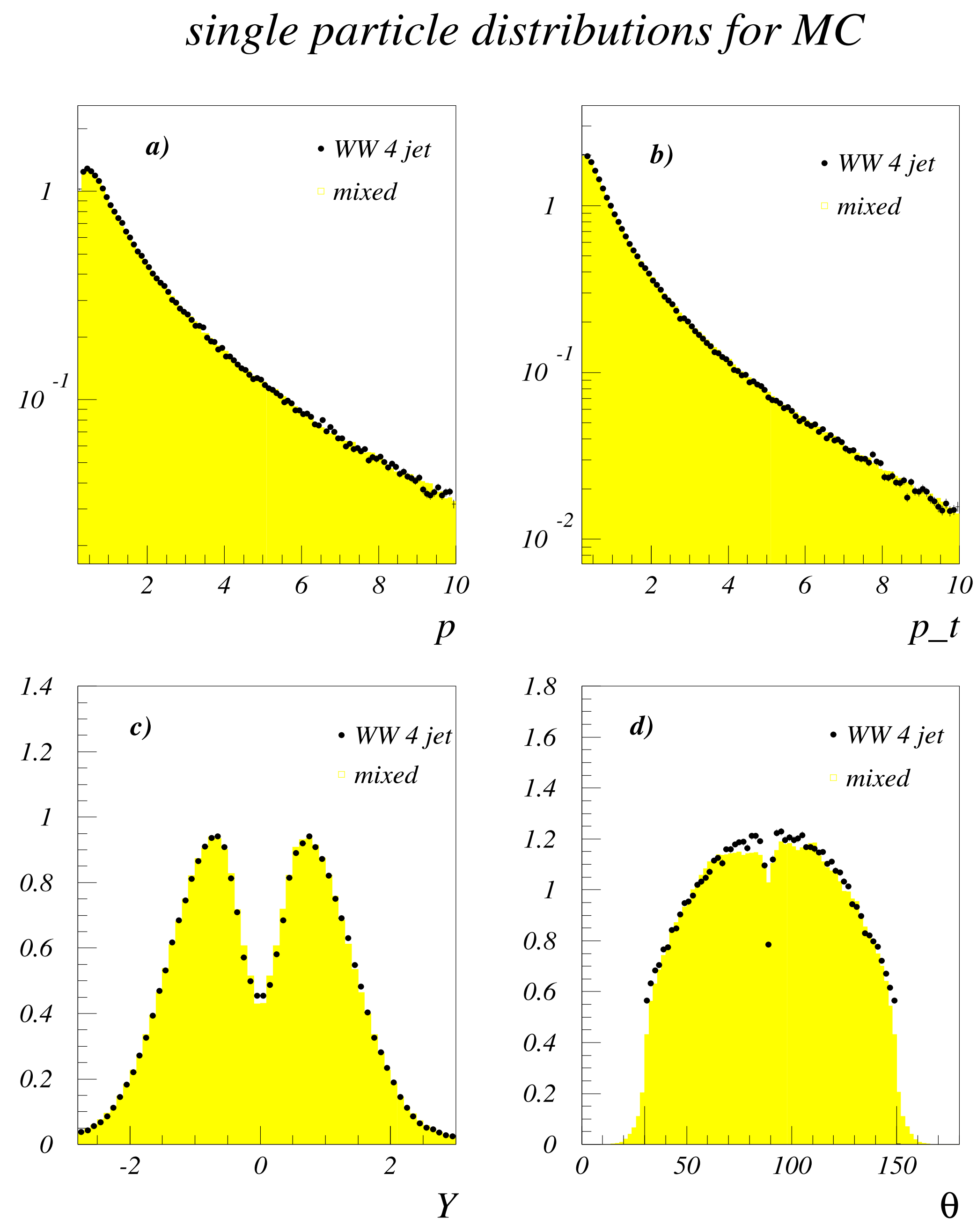

Figure 10: Comparison of single particle distributions for real(4q) and mixed events for simulated data.

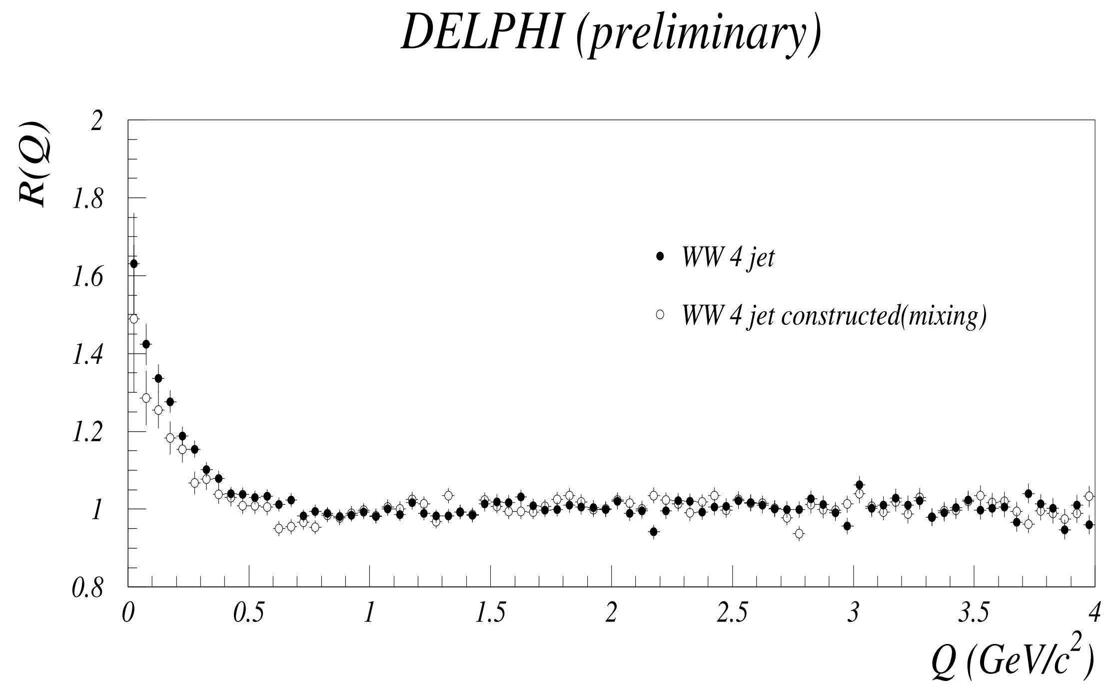

Figure 11: Measured correlation functions $R_{4q}(Q)$ (closed circles) and $R_{4q}(Q)(constructed)$ (open circles) computed from (2q) events using the mixing technique.

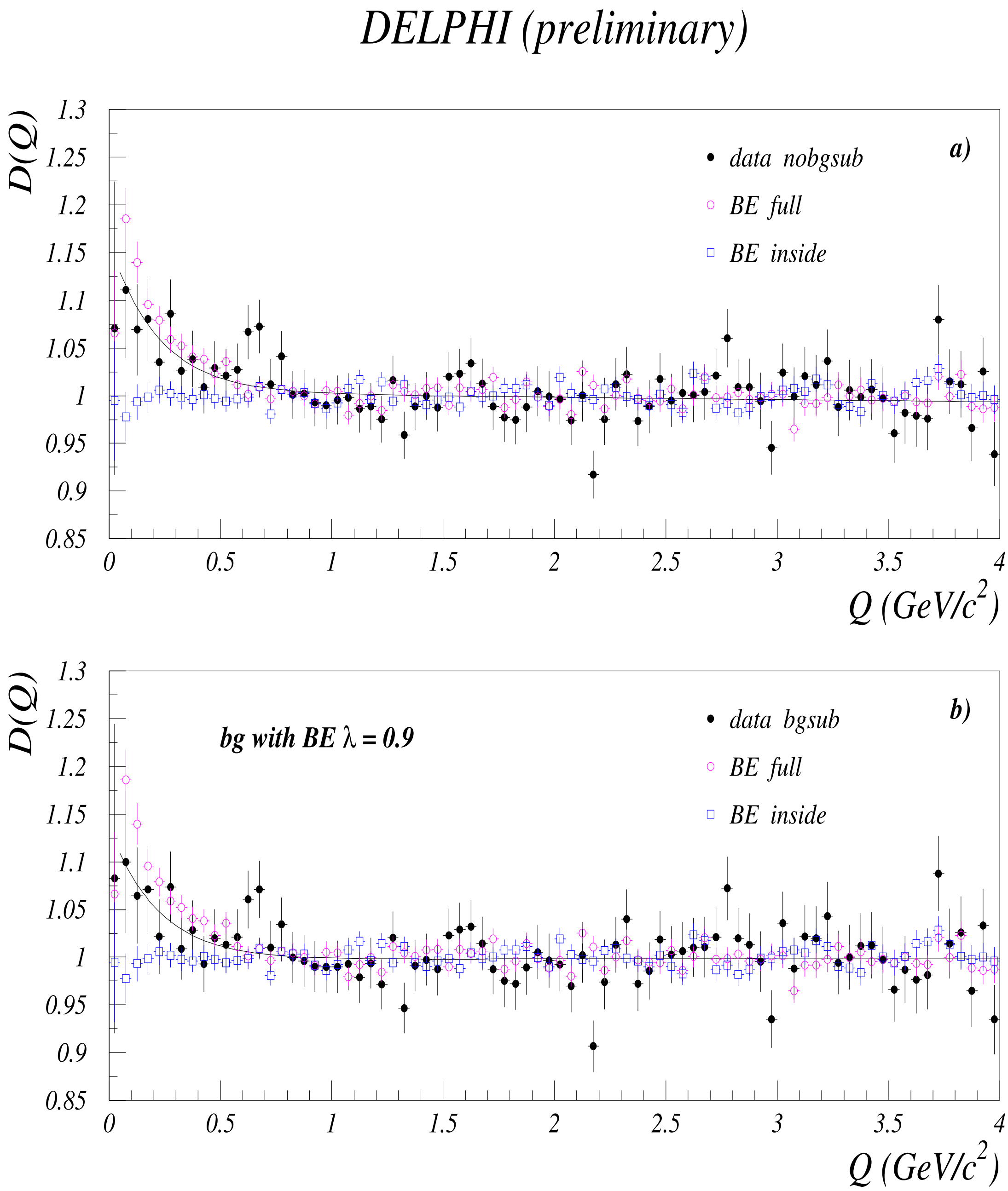

Figure 12: (a) The ratio $D(Q)$ of full hadronic to mixed events for data, for *full* BEC and for *inside* BEC. (b) same as (a) but after background subtraction from the data. The curves in figures show the best fit to expression (17) for data.

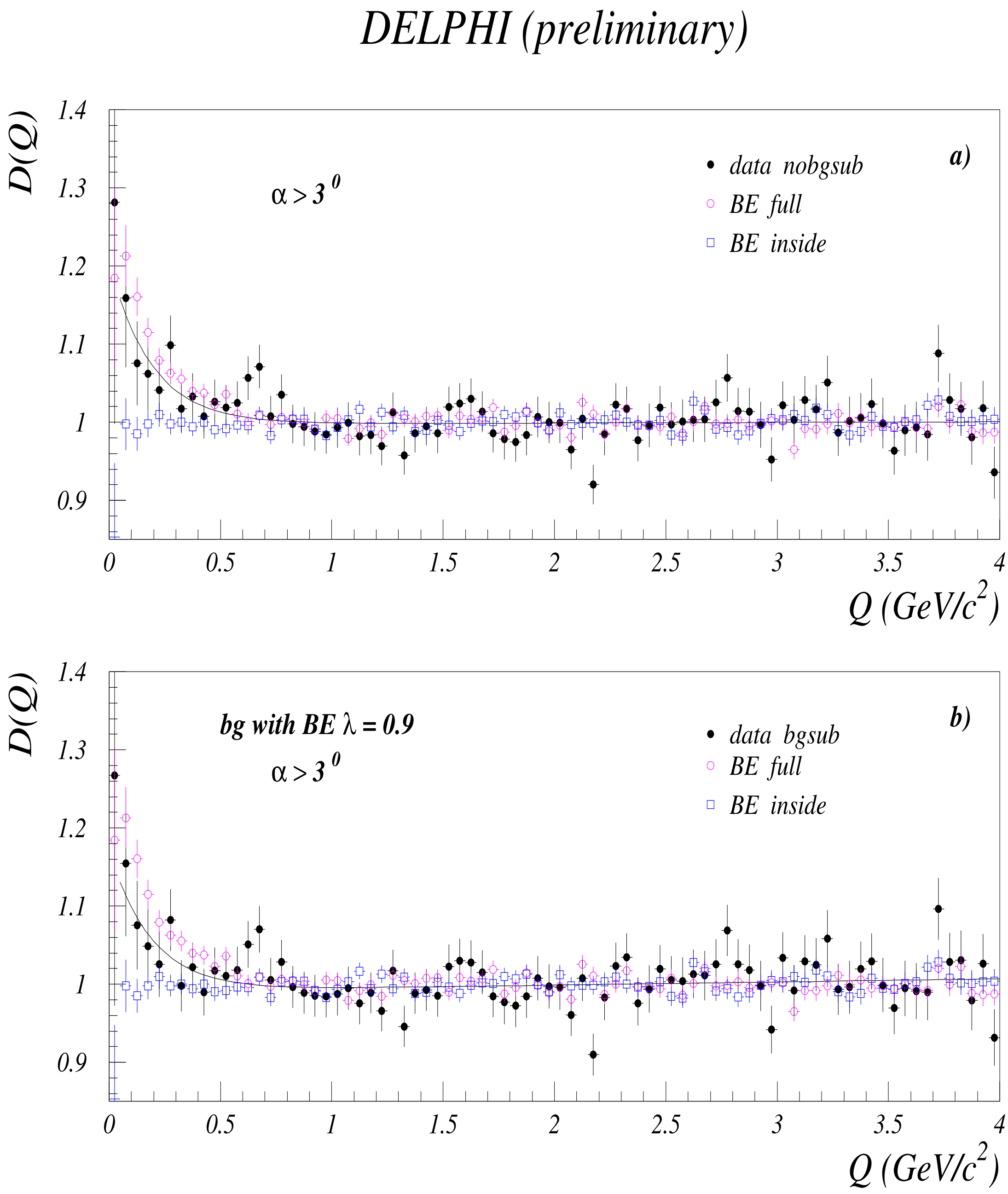

Figure 13: Same as in figure 12 but for $\alpha > 3^{\circ}$ cut.