DELPHI Collaboration

DELPHI 99-22 CONF 221
March 21, 1999

Bose-Einstein Correlations Between Particles from Different Ws in $e^+e^- \rightarrow$W$^+$W$^-$ Events

Z. Metreveli[1], **R. Moller**[2], **V. Perevoztchikov**[3], **N. Pukhaeva**[4,5], **K.K. Seth**[6], **A. Tomaradze**[6], **N. van Remortel**[5], **F. Verbeure**[5]

DELPHI Preliminary

Abstract

Preliminary results are presented for the correlation functions $R(Q)$ for like-sign particle pairs for $q\bar{q}(\gamma)$ events, for Z^0 events, for fully hadronic WW and for mixed decay WW channels using the data collected by the DELPHI detector at LEP at the center-of-mass energies of 183 and 189 GeV. The parameters λ and r characterizing the Bose-Einstein effect, measured in fully hadronic WW events are in agreement with parameter values in semileptonic WW events, in $q\bar{q}(\gamma)$ and in a sample of Z events enriched in light flavour decay.

The comparison of the distributions for real fully hadronic events and for fully hadronic events where correlations between decay products from different Ws are absent (constructed by an event mixing technique) shows an excess of like-sign particle pairs at low four-momenta difference in the data for fully hadronic events. It can be interpreted as evidence for Bose-Einstein correlations between identical particles from different Ws.

[1] Institute for High Energy Physics of Tbilisi State University, Georgia

[2] Niels Bohr Institute, Copenhagen, Denmark

[3] Brookhaven National Laboratory, Upton, USA

[4] Joint Institute for Nuclear Research, Dubna, P.O. Box 79, RU-101 000, Moscow, Russian Republic

[5] Physics Department, Universiteire Instelling Antwerpen, Universiteitsplain 1, BE-2610, Belgium

[6] Physics Department, Northwestern University, Evanston, IL 60208, USA

1 Introduction

The possible presence of interference due to colour reconnection and Bose-Einstein correlations (BEC) (see for example [1, 2] and references therein) 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 [1] 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 popular due to the prediction [3] that BEC could shift up to 100 MeV the measured W mass.

The effects of Bose-Einstein Correlations between identical bosons have been studied extensively in different types of reactions and for different boson species. Although many studies exist, one still misses 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 know and to symmetrize the amplitude for the system.

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. 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 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.

Previous experimental results are based on the statistics collected by LEP experiments during 1996 and 1997 (see [4] and [5] and references therein).

In the present paper, Bose-Einstein correlations are studied for W-pairs decaying both hadronically and semileptonically. Comparison of these measurements allow one to extract information on Bose-Einstein correlations between decay products of two hadronically decaying Ws. In the absence of interference between the two W systems, the fully hadronic correlation function is expected to be lower than the semileptonic one. Direct comparisons were also performed for real fully hadronic events and fully hadronic events without correlations between products of different Ws constructed by mixing pairs of real $(2q)$ events. The data used for the analysis were collected with the DELPHI detector [6, 7] at LEP in 1997 and 1998 at centre-of-mass energies of 183 and 189 GeV with integrated luminosity of 53.5 pb^{-1} and 155.0 pb^{-1}. The data collected at these two energies were combined for the following analyses.

2 Investigation of 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

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

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 determine the distribution of the points of origin of the pions. Experimentally, the effect is often described in terms of the variable Q, defined by $Q^2 = -(p_1-p_2)^2 = M^2(\pi\pi) - 4m_\pi^2$, 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

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

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

3 Modelling BEC in WW decays.

Bose-Einstein correlations can be included in PYTHIA/JETSET by using the LUBOEI code, where they are introduced as a final state interaction [8]. 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.

This code has been shown [12] 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[1] and if the parameter values $\lambda = 1$ and $r = 0.5$ fm are used. The measured values of the parameters, using a mixed track reference sample, for such 'direct' pions in Z decays were $\lambda = 1.06 \pm 0.17$, $r = 0.49 \pm 0.05$ fm [12]. The value λ=1 for direct pions corresponds to $\lambda \sim 0.35$ for all pions or $\lambda \sim 0.25$ for all particles [12, 13].

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

In the present analysis the LUBOEI algorithm with the same values of λ and r was applied to generate WW events to calculate predictions for the case where Bose-Einstein correlations are present. Various modifications of the LUBOEI code, i.e. the original version, version BE_3 and version BE_{32} were used in the present analyses. The versions BE_3 and BE_{32} differ in the rescaling procedures of momentum and energy after modification of the particle momenta. For more details on the LUBOEI code and the modifications,

[1]Resonances with lifetime longer than the $K^*(890)$ lifetime were considered long-lived.

see [2]. For each version, two scenarios were considered: a) where Bose-Einstein correlations were included for particles from the same and from different Ws (herafter called full BE) and b) where Bose-Einstein correlations were included only for particles from the same Ws (hereafter called inside BE) [9]. 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.

4 Particle and Event Selections

The track and event selections, which are described below, were similar to those in [10, 15].

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 Calorimetrs and the luminosity monitor, STIC; neutral hadronic showers were measured in the instrumented iron return yoke of the solenoidal magnet.

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

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

For neutral particles the following selection criteria were applied :

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

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

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

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

For each event passing the above criteria, all particles were clustered into jets using the LUCLUS algorithm [8] 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 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. The variable D was defined as [10]

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

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 GeV(-1).

From a data sample corresponding to a total integrated luminosity of 208.5 pb^{-1}, 1427 events were selected.

The detector effects on the analysis were estimated using samples of WW and background events generated with PYTHIA 5.7 [18] with the fragmentation tuned to the DELPHI data at LEP1 [19]. The generated events were passed through the full detector simulation program DELSIM [7]. The purity and efficiency of the selection, estimated using simulated events, were about 87% and 73%, respectively.

4.3 Event Selection for Mixed Hadronic and Leptonic Final States

Events in which one W decays into a 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 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 [8]. 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%.

From the data sample corresponding to a total integrated luminosity of 208.5 pb^{-1}, 686 events were selected. The purity and efficiency of the selection, estimated using simulated events, were about 96% and 49%, respectively.

5 Results and Discussion

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

5.1 Correlation Functions for Like-Sign Particles for Fully Hadronic and for Mixed Decay WW channels

To compute the correlation function $R(Q)$ (Eq. 2), the two-particle probability density $P(Q)$ was calculated and $P_0(Q)$, the reference two-particle distribution. 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 the same selection criteria were applied 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 (Fig. 1a). It has to be remarked that the use of a Monte-Carlo reference sample for the WW fully hadronic channel implies the assumption that color reconnection effects [11] are negligible.

The uncorrected $R(Q)$ distributions for like-sign combinations of mixed decay and fully hadronic WW channels is shown in Fig. 1a.

Possible bias in the measured $R(Q)$ distributions due to detector effects and selection criteria were studied using $R(Q)$ distributions for events generated by PYTHIA and $R(Q)$ distributions for the same generated events but after the full detector simulation and the same selection criteria as for real data. The original version of LUBOEI code was used.

In Fig. 2 the model predictions are shown for the semileptonic events (Fig. 2a), for fully hadronic events with full Bose-Einstein correlations (Fig. 2b) and for fully hadronic events with Bose-Einstein correlations inside Ws only (Fig. 2c). It was checked that the $R(Q)$ distributions for the semileptonic channel are in complete agreement for the versions with full and with inside Ws BEC, as expected.

The ratio of the $R(Q)$ distributions obtained at generator level (open circles in the figures) and $R(Q)$ distributions after full detector simulation and selection criteria (closed circles in the figures) was used as correction factor for the $R(Q)$ of the data. In the case of the fully hadronic decay channel the correction factor for full BEC is larger than for inside Ws BEC (see figures 2b and 2c), which is due to the event selection criteria of fully hadronic events[2]. The mean value of these two correction factors (obtained for full and inside Ws BEC) was used for the following analyses and half of the difference was considered as a systematic error.

The corrected $R(Q)$ distributions for like-sign combinations of mixed decay and fully hadronic WW channels is shown in Fig. 1b. A fit to the correlation functions $R(Q)$ using

[2]The large fraction of ($4q$) events removed by the event selection criteria are the events where the jets from different Ws are roughly in the same directions. Thus, the event selection criteria reduces the fraction of those WW events which are likely to show the largest BEC for particles from different Ws and, correspondingly, the larger BEC for the fully hadronic decay channel.

the expression

$$R(Q) = 1 + \lambda e^{-r^2Q^2} \tag{5}$$

was performed, where the parameter r represents the source size and λ the strength of the correlation between the particles. The fit yielded the values:

$$\begin{aligned} \lambda_{2q} &= 0.399 \pm 0.048(stat) & (6)\\ r_{2q} &= 0.622 \pm 0.051(stat)\ \text{fm}\,. & (7) \end{aligned}$$

for the semileptonic channel and

$$\begin{aligned} \lambda_{4q} &= 0.365 \pm 0.024(stat) & (8)\\ r_{4q} &= 0.622 \pm 0.028(stat)\ \text{fm}\,. & (9) \end{aligned}$$

for the fully hadronic decay channel. The fit results are shown by the solid curves in Fig. 1b.

The presence of bin-to-bin correlations influences the errors on the values of λ and r. To estimate the effect of bin-to-bin correlations, 300 sets of WW events were generated by PYTHIA with BEC included, using approximately the same number of events for each set as there were in the data. Using the fit by expression (5) the values and errors of the parameters λ and r were obtained and the average fitted errors were calculated. The variations of λ and r from the average value were plotted for these 300 sets (not shown) and the gaussian widths of the distributions were obtained. The statistical errors were multiplied by a factor equal to the ratio of the gaussian widths to the average fitted errors. These factors were equal to 1.26 and 1.20 for the errors in λ and r for the semileptonic channel, and 1.50 and 1.51 for the errors in λ and r for the fully hadronic channel. Using these corrections for the errors the final value of parameters were

$$\begin{aligned} \lambda_{2q} &= 0.399 \pm 0.060(stat) \pm 0.026(syst) & (10)\\ r_{2q} &= 0.622 \pm 0.061(stat) \pm 0.022(syst)\ \text{fm}\,. & (11) \end{aligned}$$

for the semileptonic channel and

$$\begin{aligned} \lambda_{4q} &= 0.365 \pm 0.036(stat) \pm 0.047(syst) & (12)\\ r_{4q} &= 0.622 \pm 0.042(stat) \pm 0.031(syst)\ \text{fm}\,. & (13) \end{aligned}$$

for the fully hadronic decay channel.

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

- Due to variation of the event selection criteria. The systematic errors were 0.019 and 0.015 fm for λ_{2q} and r_{2q}, and 0.024 and 0.021 fm for λ_{4q} and r_{4q}.

- Due to background events. The obatained systematic errors were 0.010 and 0.011 fm for λ_{2q} and r_{2q}, and 0.018 and 0.014 fm for λ_{4q} and r_{4q}.

- Due to normalization of the reference distributions. The systematic errors were 0.014 and 0.012 fm for λ_{2q} and r_{2q}, and 0.017 and 0.018 fm for λ_{4q} and r_{4q}.

- choice of Monte Carlo model, full versus inside Ws only: 0.033 for λ_{4q}.

The comparisons of the predictions of various modifications of the LUBOEI procedure with the data are presented in Fig. 3. The version BE_{32} with full BEC included reproduces reasonably well the data for both the semileptonic and fully hadronic decay channel (Fig. 3a and Fig. 3b). The version of the model with BEC inside Ws only disagrees with the data for the fully hadronic channel (Fig. 3c).

5.2 Correlation Functions for $q\bar{q}(\gamma)$ events

The same track and event selections were applied for the $q\bar{q}(\gamma)$ events as in [20]. Charged particles were selected if they fulfilled the following criteria :

- polar angle between 20° and 160°;
- momentum larger than 0.1 GeV/c and smaller than the beam momentum;
- impact parameters smaller dan 4 cm in the plane perpendicular to the beam axis and along the beam axis;
- error on momentum measurement less than 100%.

The tracks coming from V^0 decays and secondary interactions were alsoused if they passed the previous track selection. Events were selected if they had a value of $\sqrt{s'}/\sqrt{s}$ above 0.9, a charge multiplicity larger than 9, a total transverse energy of the charged particles larger than $0.2\sqrt{s}$ and a narrow jet broadening [21] smaller than 0.065. Following these criteria a total of 3383 events selected from the data at 189 GeV. From simulation it were calculated that the expected background from WW and ZZ was 419 and 48 events respectively. The contribution from radiative returns to the Z (considered as events with $\sqrt{s'}/\sqrt{s}$ below 0.9 at generator level) was estimated to be 214 events. With this selection a purity and efficiency of our sample of 79.5% and 79% respectively were obtained. The WW and ZZ background were taken into account by adding them to the reference Monte-Carlo sample. The statistical error on λ and r was corrected for bin-to-bin correlations according to the same method as used for the WW analysis in section 5.1.

The corrected $R(Q)$ distribution for likesign combinations is shown in Fig. 4. Using eq. 5 to fit the $R(Q)$ distribution for likesign combinations, the parameter values

$$\lambda_{q\bar{q}(\gamma)} = 0.326 \pm 0.025(stat) \pm 0.04(syst) \quad (14)$$

$$r_{q\bar{q}(\gamma)} = 0.632 \pm 0.032(stat) \pm 0.08(syst) \text{ fm}. \quad (15)$$

were obtained. The systematic error was computed as the sum in quadrature of the following contributions:

- Due to variation of the fit range and the number of parameters in the expression for the fit ($R(Q)$ was also fitted to eq. 5, multiplied by a factor $(1+\delta Q)$), a systematic error of 0.010 and 0.061 fm for λ and r, respectively, was obtained.
- Due to variation of the event and track selection cuts an error of 0.016 and 0.040 fm for λ and r, respectively, was computed.
- A 0.004 and 0.006 fm systematic error for λ and r, respectively, was found due to limited Monte-Carlo statistics.
- A systematic error on λ and r of 0.025 and 0.044 fm was obtained by using a different $q\bar{q}(\gamma)$ Monte-Carlo reference sample obtained with a HERWIG [22] simulation.

5.3 Correlation Functions in Z^0 events

Correlations between particles in Z events produced during the calibration run in 1998 were investigated. The track selection for the analysis was the same as above. The event selection was similar as in [12]. The corrected $R(Q)$ distribution, obtained using the same method and correction procedures as for WW events, is shown in Fig. 5a as closed circles. The fit using the expression (5) yielded:

$$\lambda_Z = 0.297 \pm 0.013(stat) \tag{16}$$
$$r_Z = 0.575 \pm 0.014(stat) \text{ fm}\,. \tag{17}$$

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 [14] for details). The correlation functions for this sample are shown in Fig. 5a by open circles. The measured values of λ and R using the fit with expression (5) gave

$$\lambda_{Z-no\ b\bar{b}} = 0.358 \pm 0.020(stat) \tag{18}$$
$$r_{Z-no\ b\bar{b}} = 0.616 \pm 0.022(stat) \text{ fm}\,. \tag{19}$$

The $R(Q)$ distribution for the data for Z events together with the LUBOEI predictions with BEC are shown in Fig. 5b. Bose-Einstein correlations were included in the same way and with the same parametres as for WW events. As in the case of WW events, the version BE_{32} yields good agreement with the data.

The agreement between the $R(Q)$ for the fully hadronic, the semileptonic WW channel and the light flavour enriched Z sample (eq. 10 – 13 and 18 – 19) forms an indication of the presence of BEC between particles from different Ws, but direct evidence of BEC between particles from different Ws is necessary for any quantitative conclusions.

5.4 Measurement of BEC Between Particles from Different Ws Using an Event Mixing Technique

The first measurements of Bose-Einstein correlations in $e^+e^- \rightarrow W^+W^-$ events, performed by DELPHI [15] using a subtraction method, do not show any evidence of correlation between like-sign pions from different Ws at the level of statistics collected at 172 GeV center-of-mass energy. Similar results were obtained by ALEPH using the same method at 172 and 183 GeV center-of-mass energy data [16] and by OPAL [17]. The above mentioned method appears to be less sensitive to BEC between different Ws than an event mixing method used in the present analysis. Moreover the subtraction method has a large sensitivity to the normalization.

To perform a direct measurement sensitive to BEC between particles from different Ws, an analysis was made using a reference sample which contains only BEC for particles coming from a single W boson, not for particle pairs from different Ws. Such reference sample was constructed by an event mixing technique using the selected real semileptonic events.

A reference 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. An event was constructed from two single Ws by boosting the particles of such single W candidates in opposite directions using the velocities and directions of flight of the W candidates according to energy-momentum conservation using the values of fitted W mass of these single Ws. Note that no informations from real ($4q$) events were used to constract ($4q$)-like events in order to avoid the introduction of the possible biases from interconnection effects which may exist in real ($4q$) events. These mixed events have an average hadronic multiplicity which is exactly twice that of Ws from semileptonic events. The inclusive momentum spectra of the mixed events are fully consistent with the spectra of ($4q$) events and with the spectra of ($2q$) events multipled by two (not shown).

We define the ratio

$$g(Q) = \frac{P(Q)_{4q}}{P(Q)_{mix}}, \tag{20}$$

where $P(Q)_{4q}$ is the Q-distribution of real ($4q$) events and $P(Q)_{mix}$ is the Q-distribution of ($4q$)-like events obtained by mixing two real ($2q$) events. The function $g(Q)$ does not have the usual meaning of correlation function between particles from different Ws, because pairs from different Ws were not isolated. Note that a deviation of $g(Q)$ from unity would indicate a fractional excess or lack of the number of pairs in real ($4q$) events.

To ensure that the event mixing did not introduce artificial distortions, the analyses were repeated with a full simulation sample without BEC. The double ratio

$$g'(Q) = \frac{g(Q)}{g^{MCnoBE}(Q)}, \tag{21}$$

should have any distortion removed.

The ratio $g(Q)$ obtained for the data is shown in Fig. 6a (closed circles) together with the prediction of DELSIM where no BEC were included (open circles). The double ratio $g'(Q)$ is shown in Fig. 6b. A BE-like excess in the number of pairs is seen in the low Q region.

The bias due to detector effects and selection criteria was studied using events generated by PYTHIA and using the same generated events which were passed through the full detector simulation and were subject to the same selection criteria as the data. The $g(Q)$ distributions for these events are shown in Fig. 7a for full BEC, in Fig. 7b for inside Ws BEC, and in Fig. 7c for no BEC. The $g(Q)$ distributions show a remarkable sensitivity for BEC between particles from different Ws (the enhancement at low Q in Fig. 7a). No enhancement is seen for inside Ws BEC (Fig. 7b), nor for no BEC (Fig. 7c), as expected. Similar features are present for the double ratio $g'(Q)$ shown in Fig. 8 [3]. Note that, in case of full BEC, the $g'(Q)$ (as well $g(Q)$) in PYTHIA is higher than in DELSIM (Fig. 8a). No such effect is seen in the case of inside Ws BEC(Fig. 8b). This effect, as discussed in section 5.1 (footnote 2), is due to the event selection criteria of fully hadronic WW events.

The ratio of the functions $g'(Q)$ obtained at generator level and after full detector simulation and selection criteria, was used as a correction factor for the $g'(Q)$ of the data. The average value of the two correction factors (obtained for full and inside Ws BEC) was used and half the difference was considered as a systematic error. The corrected $g'(Q)$ for the data is shown in Fig. 6b by open circles. The $g'(Q)$ were fitted to the gaussian shape

$$g'(Q) = 1 + \Delta e^{-k^2Q^2} \,. \tag{22}$$

[3]The double ratio $g'(Q)$ for the model with no BEC is equal to unity by definition.

where Δ and k were free parameters. Δ represents the fractional excess of number of pairs in fully hadronic ($4q$) events at Q=0 [4]. The multiplication factor for the error of Δ has been estimatied to be 1.5 from the values for the fully hadronic and semileptonic channels (see section 5.1) using error propagation. This last value was used for the following analysis. Thus, the final value of the parameter Δ is

$$\Delta = 0.073 \pm 0.025(stat) \pm 0.018(syst). \tag{23}$$

The systematic error is the sum in quadrature of the following contributions.

- Due to the difference in multiplicities and momentum distributions between fully hadronic and twice the semileptonic channel arising from the possible presence of color reconnection or/and by statistical fluctuations. Weights were assigned to each particle in the ($4q$) events depending on their momenta to make the charge multiplicity and momentum distributions in the ($4q$) channel exactly the same as in twice the ($2q$) channel, and the analyses were repeated. The value thus obtained was $\Delta = 0.079 \pm 0.019$. The difference with the value (23), i.e. ± 0.006, was considered as systematic error due to this source.
- Due to variation of the event selection criteria. The systematic error due to this source was found to be ± 0.005.
- A systematic error of ± 0.003 was found due to the normalization of the $g'(Q)$ distribution.
- A ± 0.003 systematic error was estimated due to limited Monte-Carlo statistics.
- A ± 0.016 error was computed due to the difference between Monte Carlo models (full BEC versus inside Ws only).

The parameter Δ can be written as the product of the correlation strenght λ_{diff} between particles from different Ws and the fraction f of like-sign particle pairs from different Ws in the fully hadronic WW channel at low Q,

$$\Delta = \lambda_{diff} \times f. \tag{24}$$

The fraction f in this equation, calculated by PYTHIA, was found to be 0.201. Thus the λ_{diff}, calculated from (24) using the value of f predicted by PYTHIA and the measured value of Δ (expression 23), approximately equals to 0.36 , a number which is in good agreement with the values of λ_{2q} and λ_{4q} (expressions 10 and 12).

The measured $g'(Q)$ distribution and model predictions are shown in Fig. 9. The data points are at uncorrected level, the corresponding distributions were also used for the model predictions. The model modifications vary in the range indicated by the shaded area (upper shaded area for full BEC and lower one for inside BEC). The predicted $g'(Q)$ for BEC inside Ws only are below the measured $g'(Q)$, while the model with full BEC is in good agreement with the data.

[4] The value of the parameter k obtained was $1.74 \pm 0.39 GeV^{-1}$

6 Summary

The correlation functions for like-sign and unlike-sign particles were measured for mixed and for fully hadronic WW channels using data collected with the DELPHI detector during the 1997 and 1998 run with integrated luminosity of 208.5 pb^{-1} at center-of-mass energies of 183 and 189 GeV. The values of Bose-Einstein correlation (BEC) strenght(λ) and radius(r) were

$$\lambda_{4q} = 0.365 \pm 0.036(stat) \pm 0.047(syst) \quad (25)$$
$$r_{4q} = 0.622 \pm 0.042(stat) \pm 0.031(syst)\ \mathrm{fm}\,. \quad (26)$$

for the fully hadronic decay channel and

$$\lambda_{2q} = 0.399 \pm 0.060(stat) \pm 0.026(syst) \quad (27)$$
$$r_{2q} = 0.622 \pm 0.061(stat) \pm 0.022(syst)\ \mathrm{fm}\,. \quad (28)$$

for the mixed decay channel.

The values for the channel $q\overline{q}(\gamma)$ were

$$\lambda_{q\overline{q}(\gamma)} = 0.326 \pm 0.025(stat) \pm 0.04(syst) \quad (29)$$
$$r_{q\overline{q}(\gamma)} = 0.632 \pm 0.032(stat) \pm 0.08(syst)\ \mathrm{fm}\,. \quad (30)$$

The values for the light flavour enriched Z^0 sample were

$$\lambda_{Z-no\ b\bar{b}} = 0.358 \pm 0.020(stat) \quad (31)$$
$$r_{Z-no\ b\bar{b}} = 0.616 \pm 0.022(stat)\ \mathrm{fm}\,. \quad (32)$$

The λ and r values for the fully hadronic decay channel are consistent with those for the mixed decay channel, for the $q\overline{q}(\gamma)$ channel and for the light flavour enriched Z^0 sample, indicating the existence of BEC between particles from different Ws.

A direct measurement of correlations between pions from different Ws was performed using an event mixing technique to construct a reference sample which contains only correlations for particles from a single W boson. An excess of like-sign particle pairs of

$$\Delta = 7.3 \pm 2.5(stat) \pm 1.8(syst) \quad \% \quad (33)$$

was found in the fully hadronic decay channel at low four-momenta difference.

The predictions of the LUBOEI model with full BEC agree with the data.

Acknowledgments

We thank L. Lönnblad and T. Sjöstrand for very useful discussions. We are greatly indebted to our technical collaborators and to the funding agencies for their support in building and operating the DELPHI detector, and to the members of the CERN-SL Division for the excellent performance of the LEP collider.

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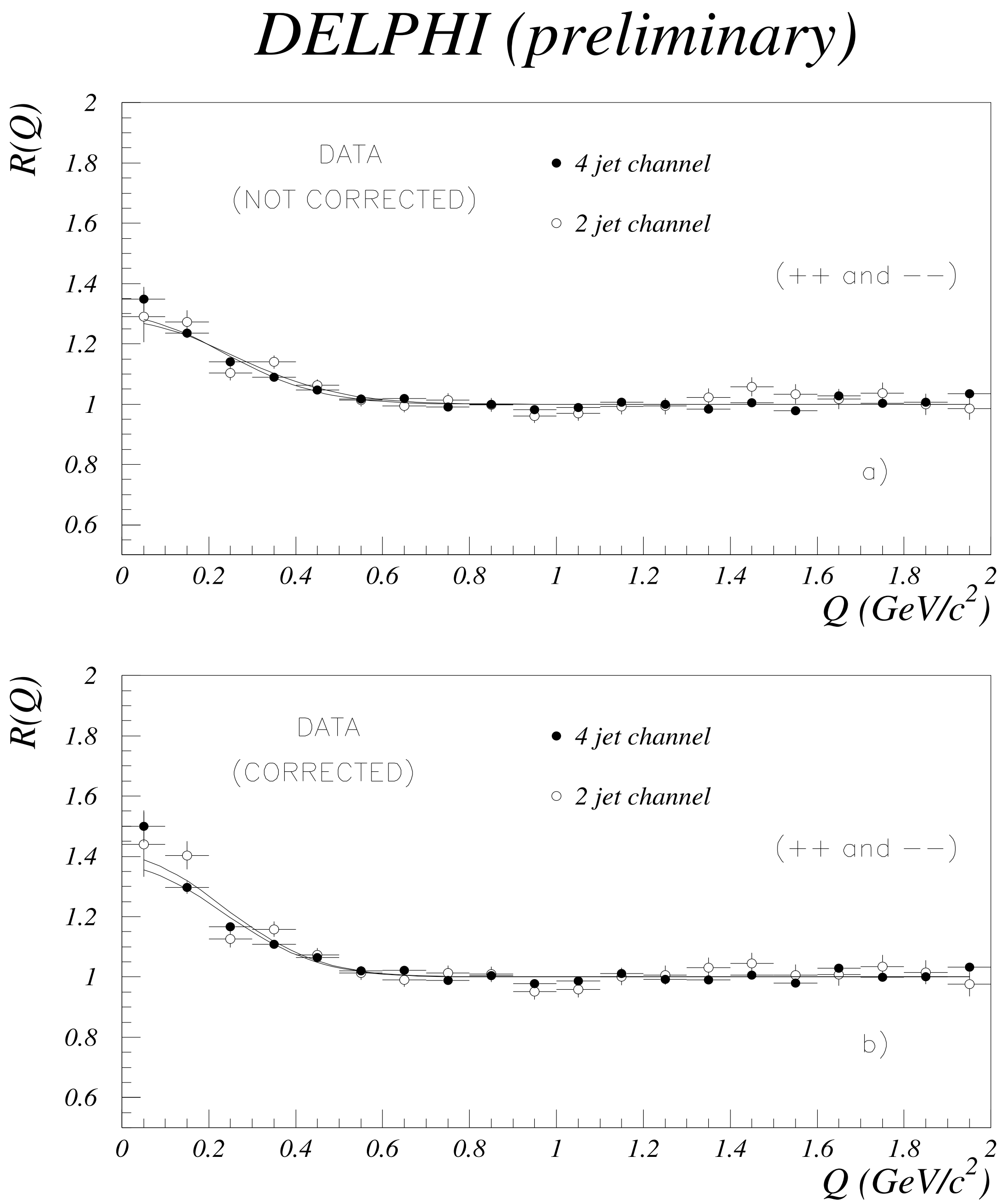

Figure 1: (a) The uncorrected correlation functions $R(Q)$ for like-sign pairs for the mixed decay channel (open circles) and for the fully hadronic decay channel (closed circles). (b) The same as in (a), but after corrections. The curves in the figures are the fit results using expression (5).

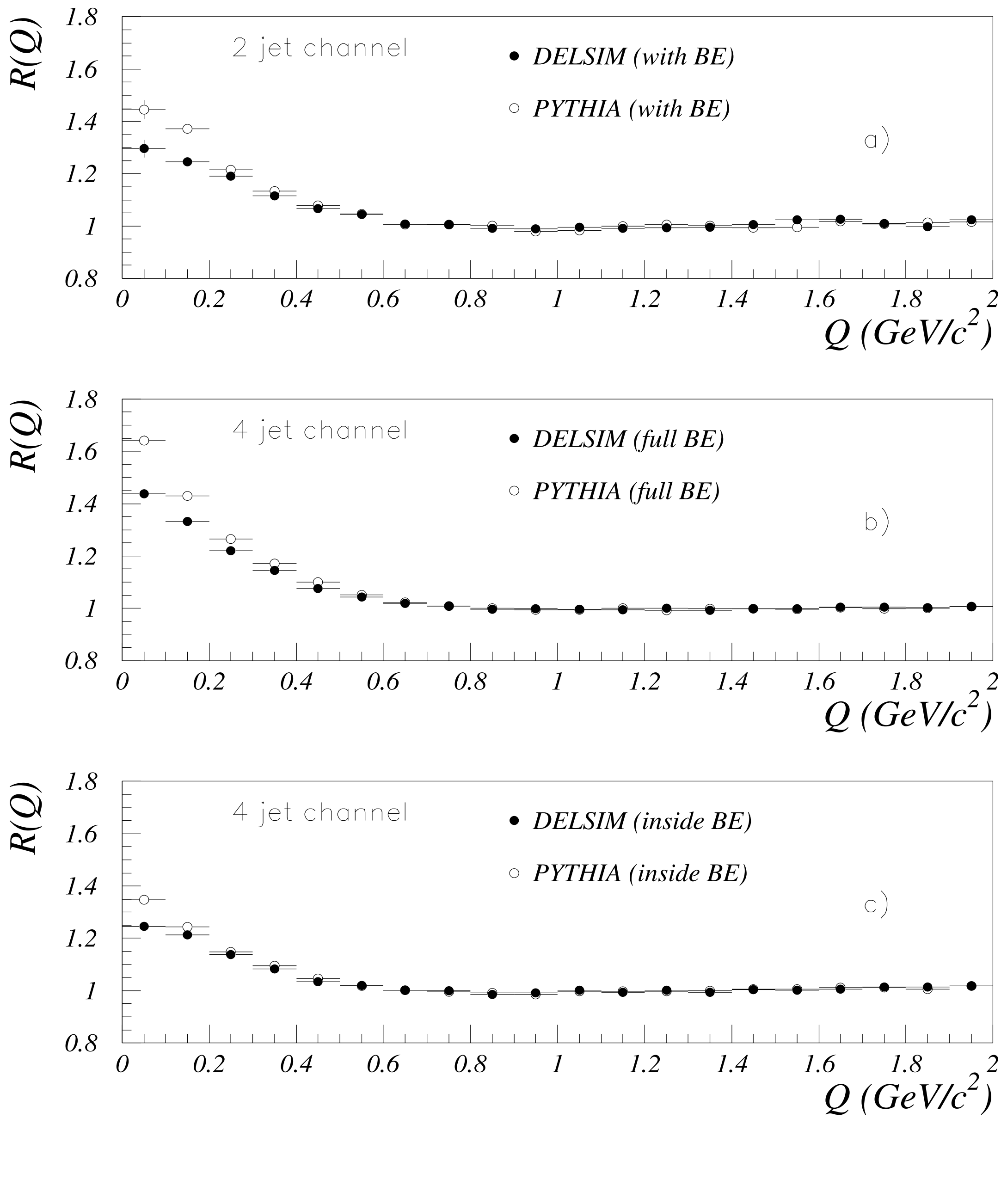

Figure 2: The correlation functions $R(Q)$ for like-sign pairs in WW events obtained using events generated by PYTHIA (open circles) and using the same generated by PYTHIA events which were passed through the full detector simulation and were subject to the same selection criteria as the data (closed circles) for a) the mixed decay channel, b) for the fully hadronic channel with full BEC, c) for the fully hadronic channel with inside Ws BEC.

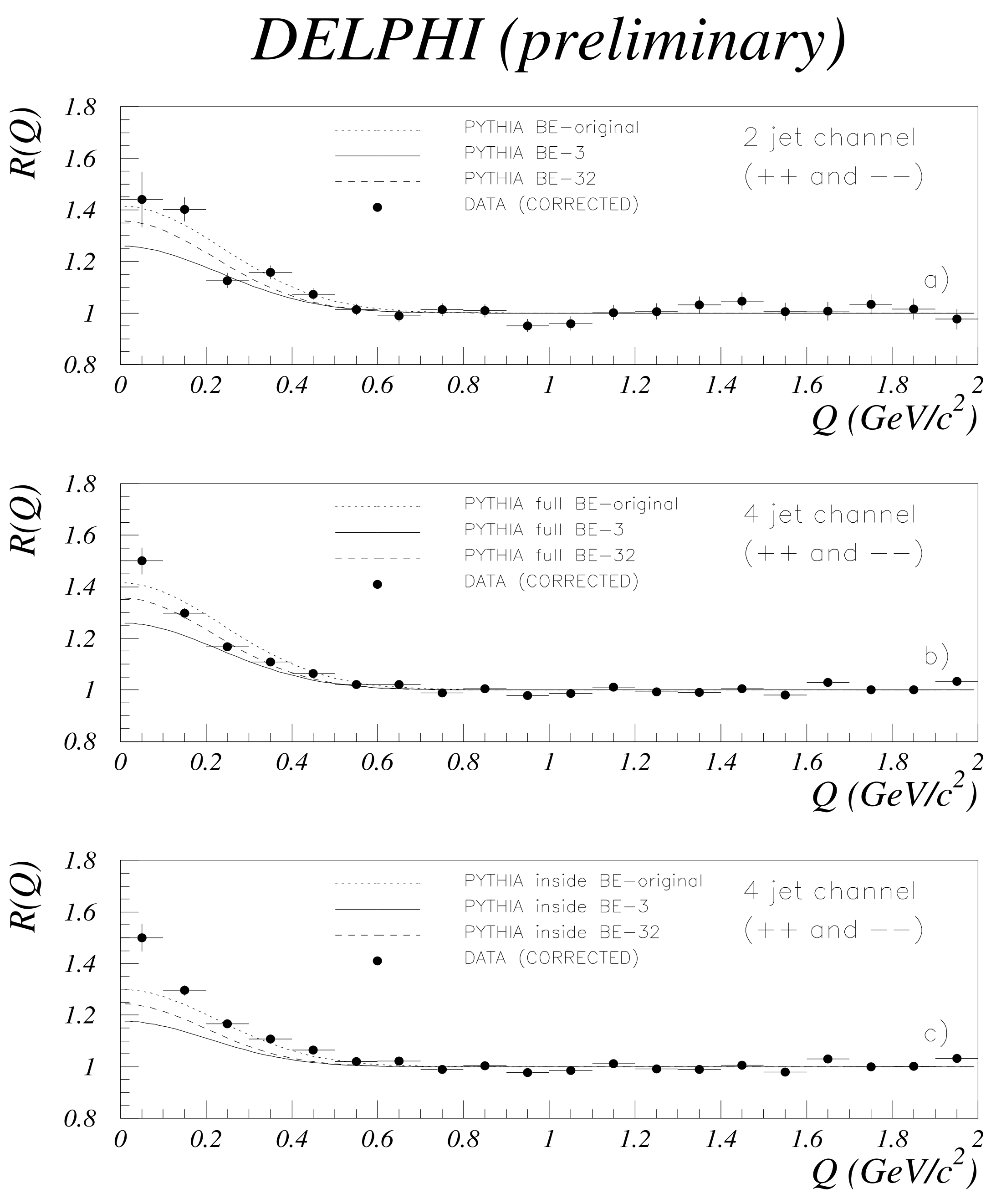

Figure 3: (a) The measured $R(Q)$ for the mixed decay channel (closed circles). The predictions of PYTHIA with BEC according to different versions of LUBOEI are shown by curves. (b) The measured $R(Q)$ for the fully hadronic decay channel (closed circles). The predictions of modifications of PYTHIA with full BEC are shown by curves. (c)The measured $R(Q)$ for fully hadronic decay channel (closed circles). The data points are the same as in (b). The predictions of modifications of PYTHIA with inside Ws BEC are shown by curves.

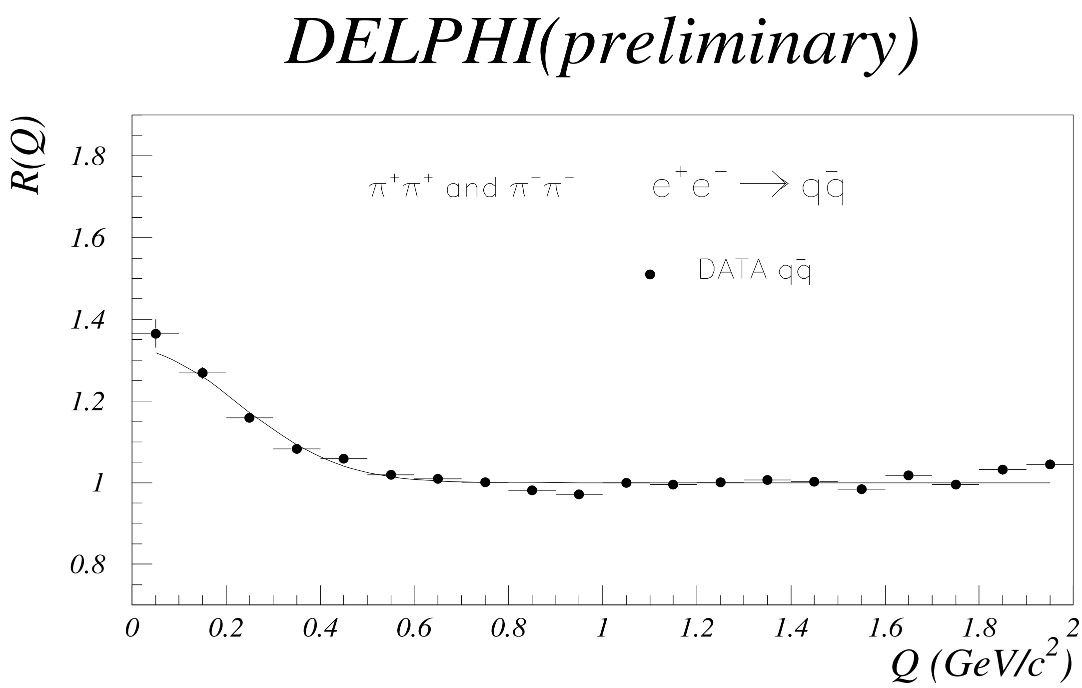

Figure 4: The measured correlation function $R(Q)$ for like-sign pairs in $q\overline{q}(\gamma)$ events. The curve in the figure is the fit result using expression (5).

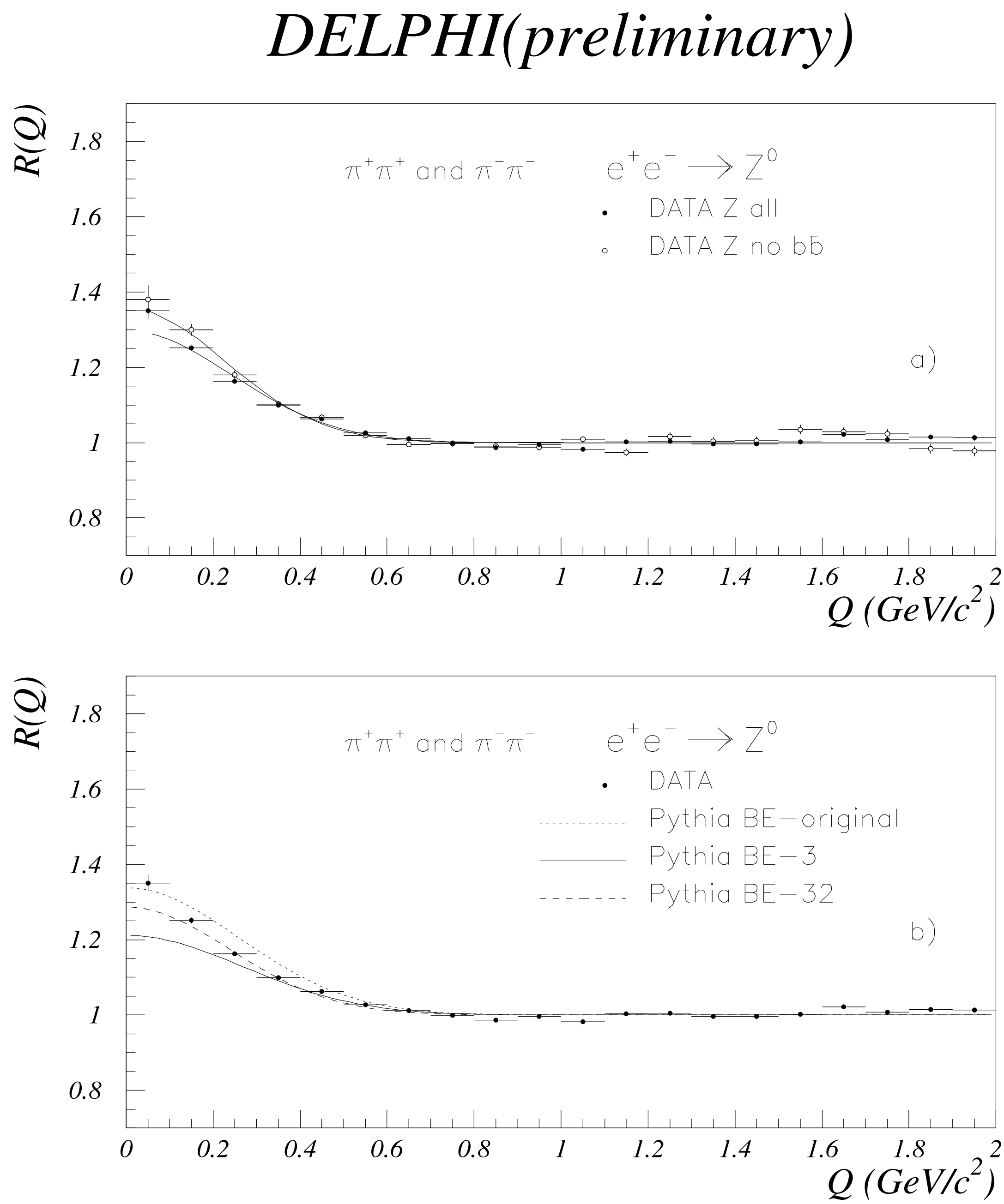

Figure 5: (a) The measured correlation functions $R(Q)$ for like-sign pairs in Z decays (closed circles) and in a Z sample enriched in light flavour decays (open circles). The curves in the figures are the fit results using expression (5). (b) The measured $R(Q)$ in Z decays (closed circles). The data points are the same as in (a). The predictions of PYTHIA with BEC are shown by the curves.

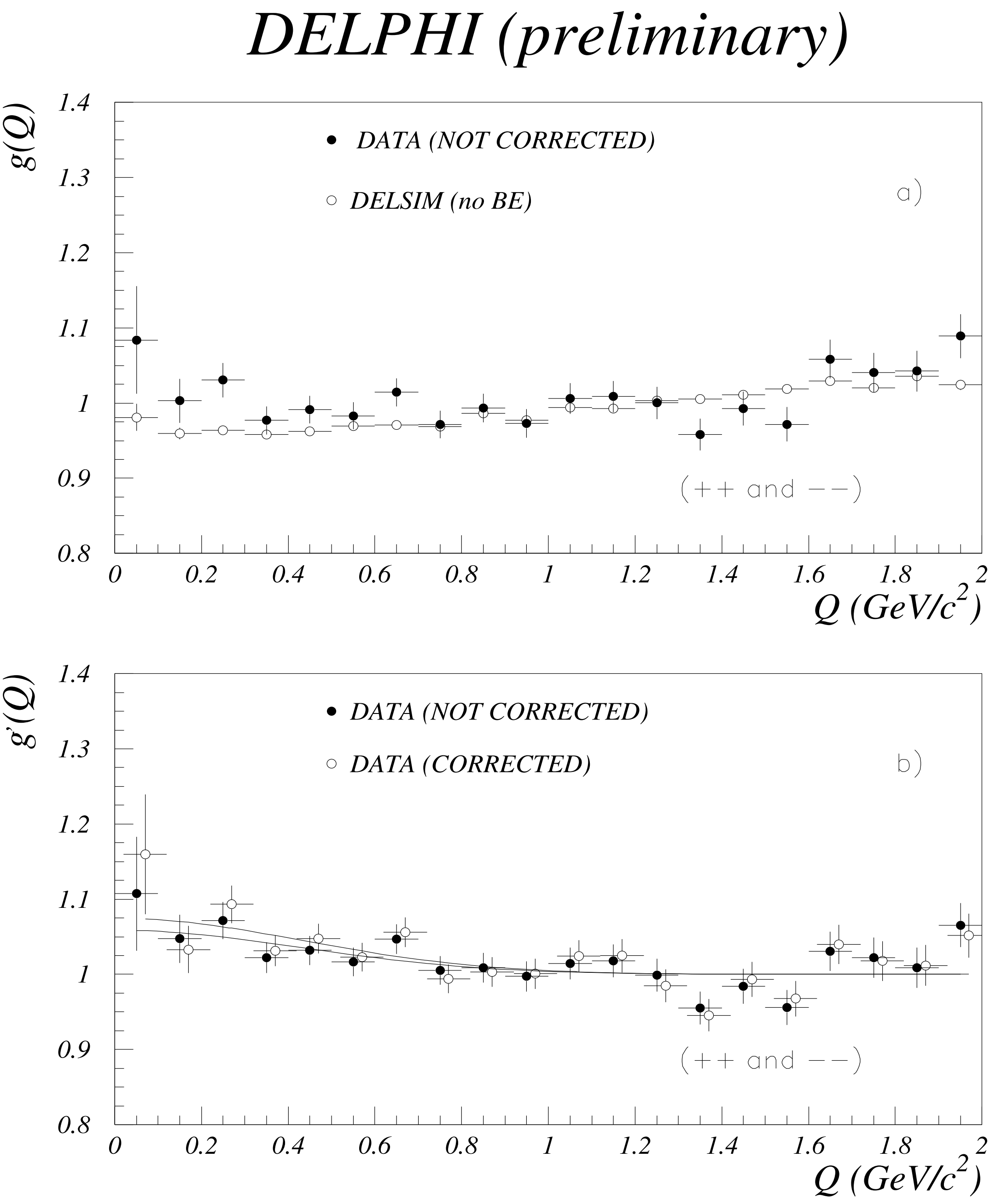

Figure 6: (a) The ratio $g(Q)$ for like-sign pairs for the WW data (closed circles) and for DELSIM without BEC (open circles). (b) the double ratio $g'(Q)$ for the data before and after corrections (closed and open circles, respectively). The curves are fit results using expression (22).

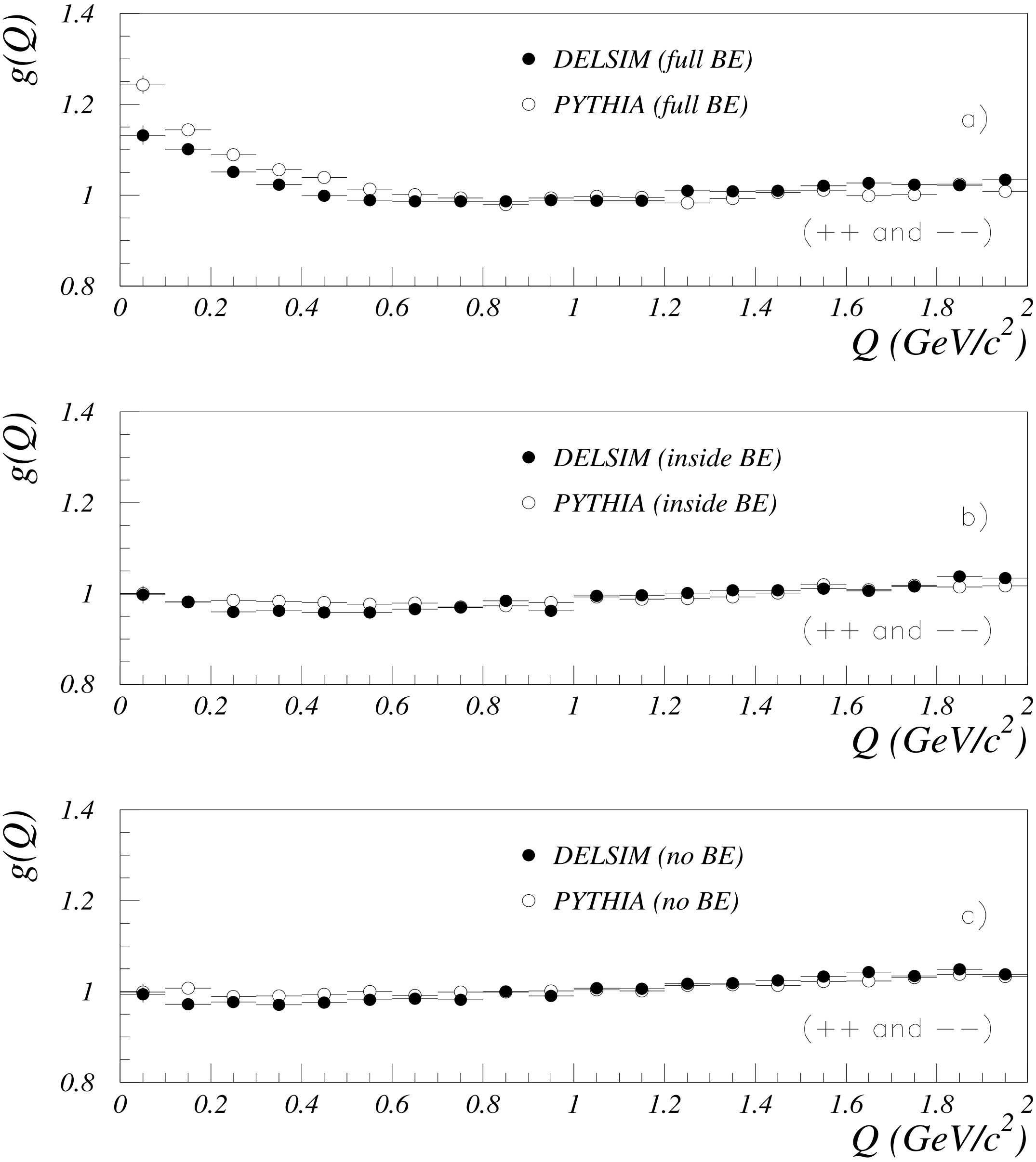

Figure 7: The ratio $g(Q)$ for like-sign pairs in WW events obtained using events generated by PYTHIA (open circles) and using the same generated events which were passed through the full detector simulation and were subject to the same selection criteria as the data (closed circles) for a) full BEC, b) inside Ws BEC, c) no BEC.

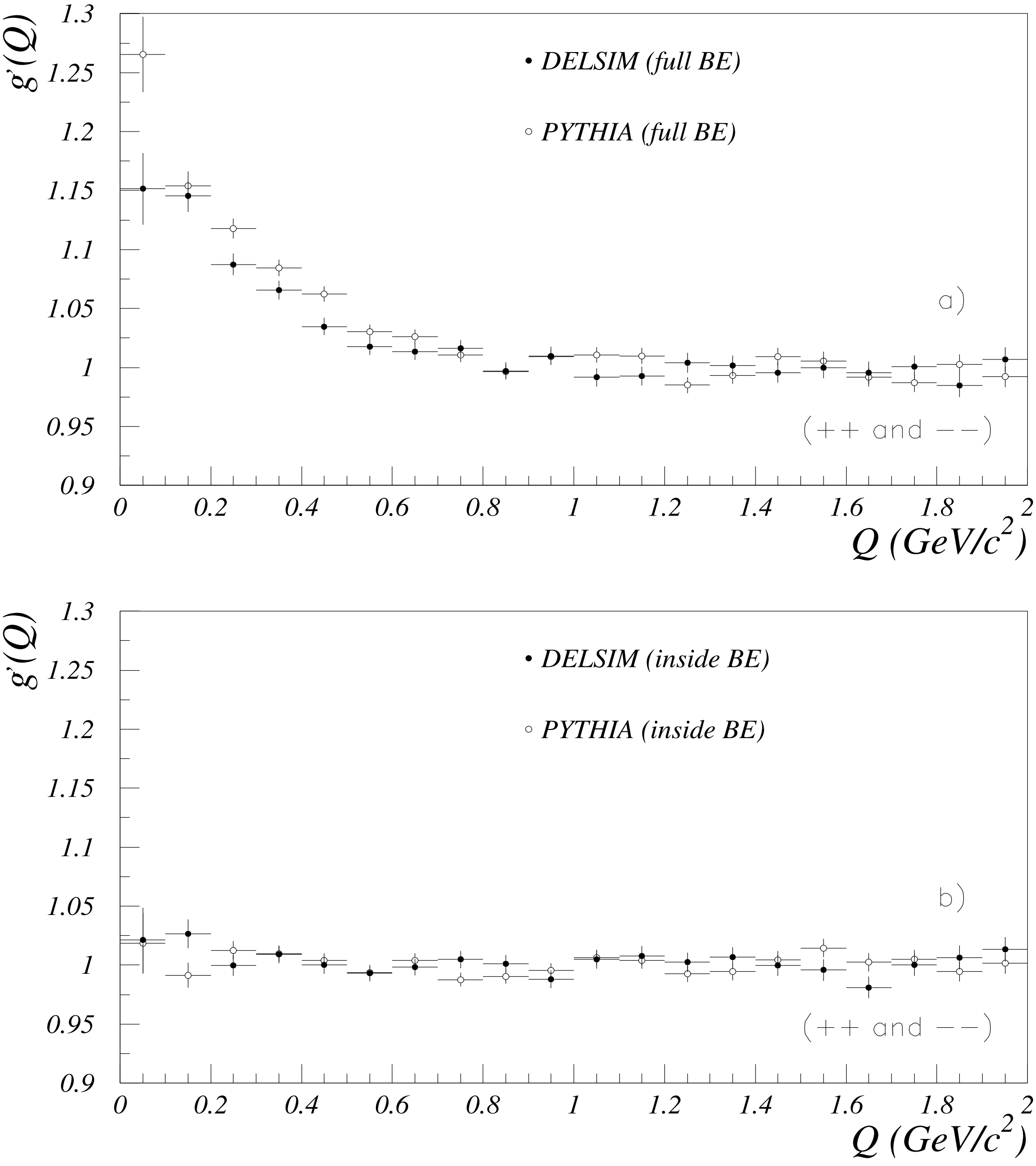

Figure 8: The double ratio $g'(Q)$ for like-sign pairs in WW events obtained using events generated by PYTHIA (open circles) and using the same generated events which were passed through the full detector simulation and were subject to the same selection criteria as the data (closed circles) for a) full BEC and b) inside Ws BEC.

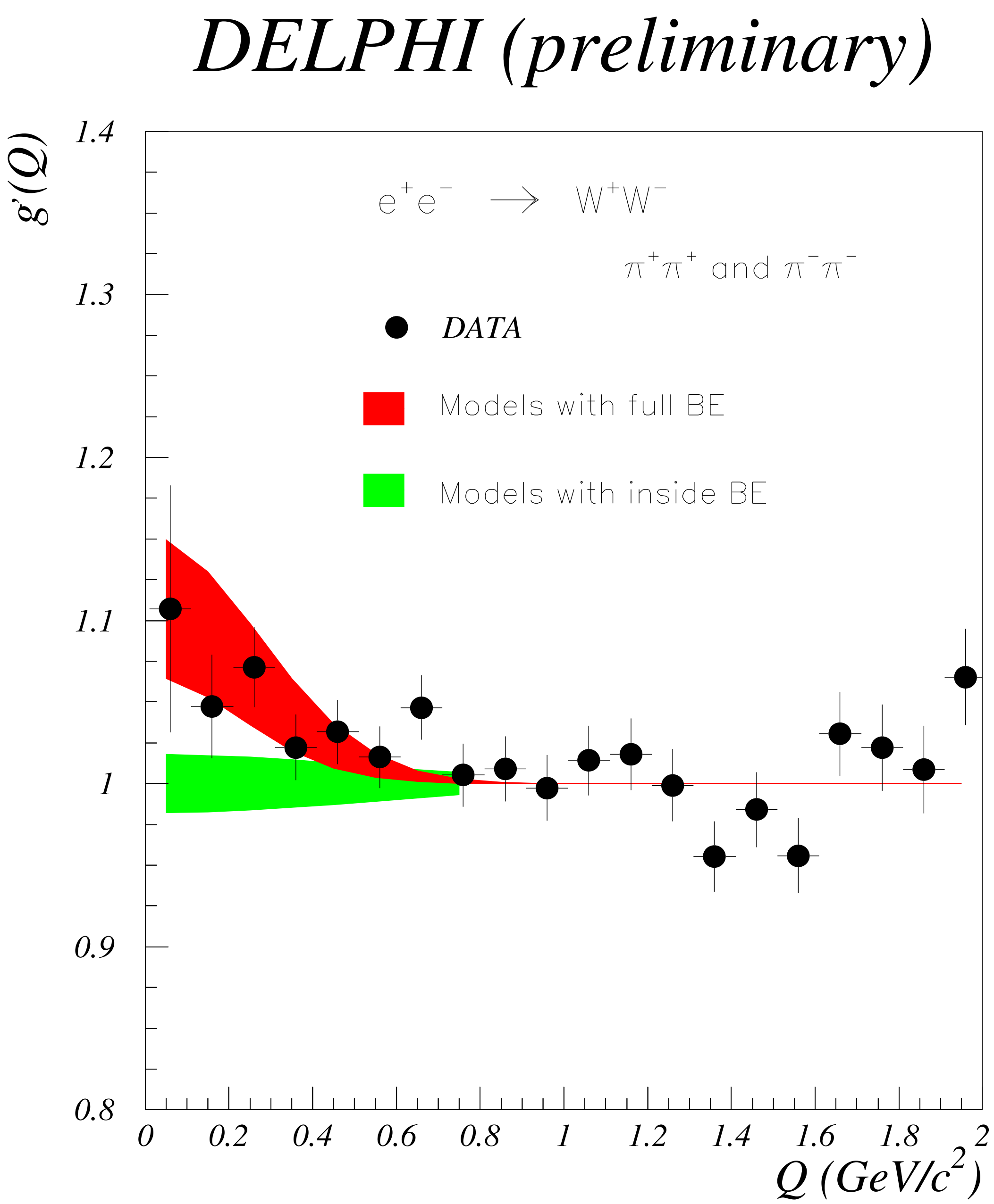

Figure 9: The uncorrected double ratio $g'(Q)$ for the data for like-sign pairs. The data points are the same as in Fig. 5b. The model predictions are shown by the shaded areas (see text).