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Bose-Einstein Correlations in W$^+$ W$^-$ events at LEP2

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Abstract

Bose-Einstein correlations (BEC) between particles originating from different Ws in the reaction $e^+e^- \rightarrow W^+W^- \rightarrow q_1\bar{q}_2q_3\bar{q}_4$ have been studied. A total integrated luminosity of 550 pb^{-1}, recorded by the DELPHI detector at centre-of-mass energies ranging from 189–209 GeV was analysed. An indication for inter-W BEC between like-sign particles has been found at the level of three standard deviations of the combined statistical and systematic uncertainties. Half of the effect has also been observed between particles from opposite sign.

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1 Introduction

Correlations between final state particles in high energy collisions have been extensively studied since the Goldhaber et al. experiment [1, 2]. They can be due to phase space, energy-momentum conservation, resonance production, hadronisation mechanisms, or are dynamical in nature.

In the particular case of identical bosons the correlations are enhanced by the Bose-Einstein effect. These Bose-Einstein correlations (BEC) are a consequence of quantum statistics. The net result is that multiplets of identical bosons are produced with smaller energy-momentum differences than non-identical ones.

It was established in the past [3] that, like in light quark Z^0 decays, strong correlations of the BE type are present in the hadronic decay of a W boson as well. In addition, the life-time of a W boson is very short. The average proper life-time of a W, $\langle\tau\rangle$, depends on its mass according to

$$\langle\tau\rangle = \frac{\hbar m}{\sqrt{(m^2 - m_W^2)^2 + (\Gamma_W m^2/m_W)^2}}, \tag{1}$$

where m_W and Γ_W are the nominal W boson mass and width and $1 = \hbar \approx 0.197$ GeV$\cdot$ fm. For a W boson with nominal mass, this reduces to the standard expression, $\tau(m_W) = \hbar/\Gamma_W \approx 0.1$ fm. Compared to the emission source sizes measured in e^+e^- interactions, which are of the order of 0.5 –1 fm, this flight distance is small. Therefore, it is natural to expect a large space-time overlap between the decay products of the W's, thus allowing correlations of the BE type between identical bosons originating from different W's to exist.

Together with colour reconnection [4, 5], the poor understanding of the inter-W BEC effect introduces a large systematic uncertainty in the measurement of the W mass in the channel $e^+e^- \rightarrow W^+W^- \rightarrow q_1\bar{q}_2q_3\bar{q}_4$ [6]. The current statistical uncertainty of the combined LEP measurement in this channel amounts to 36 MeV [7], to be compared with the total systematic uncertainty in this channel of 101 MeV. The effect of possible inter-W BEC amounts to 35 MeV. It is thus clear that a better understanding of the inter-W BEC phenomenon would help in reducing this uncertainty.

In addition to its impact on the W mass measurement, the observation of an inter-W BEC signal would be of interest to the understanding of hadronisation models, describing the non-perturbative QCD aspects of hadron production. At present, it is not clear how inter-W BEC can be understood in the framework of these models. Different BEC models predict very different effects on the W mass measurement [6, 8, 9].

2 Analysis method

The method used to extract a possible inter-W BEC signal is largely based on [10] and [11]. In the case of two stochastically independent hadronically decaying W's, the single and two-particle inclusive densities obey the following relations:

$$\begin{aligned} \rho^{WW}(1) &= \rho^{W^+}(1) + \rho^{W^-}(1), \\ \rho^{WW}(1,2) &= \rho^{W^+}(1,2) + \rho^{W^-}(1,2) + 2\rho^{W^+}(1)\rho^{W^-}(2), \end{aligned} \tag{2}$$

where $\rho^W(1)$ denotes the inclusive single particle density of one W and $\rho^W(1,2)$ the inclusive two-particle density of one W. The densities $\rho^{WW}(1)$ and $\rho^{WW}(1,2)$ then correspond to the single, respectively two-particle inclusive density of a fully hadronic WW event. Equation 2 differs from the sum of two-particle densities for each independent W taken separately by the term $2\rho^{W^+}(1)\rho^{W^-}(2)$. Assuming that the densities for the W^+ and the W^- are the same, Eq. 2 can be re-written as

$$\rho^{WW}(1,2) = 2\rho^{W}(1,2) + 2\rho^{W^+}(1)\rho^{W^-}(2). \tag{3}$$

The terms $\rho^{WW}(1,2)$ and $\rho^{W}(1,2)$ can be measured in, respectively, fully-hadronic and semi-leptonic WW decays. The product of the single particle densities $\rho^{W}(1)\rho^{W}(2)$ is, in practical applications, replaced by a two-particle density $\rho^{WW}_{\rm mix}$, obtained by combining particles from two hadronic W decays taken from different semi-leptonic events. The details of this "mixing" procedure are explained later. Expressed in the variable $Q = \sqrt{-(p_1-p_2)^2}$, Eq. 3 can be re-written as

$$\rho^{WW}(Q) = 2\rho^{W}(Q) + 2\rho^{WW}_{\rm mix}(Q), \tag{4}$$

where $p_{1,2}$ stands for the four-momentum of particles 1 and 2.

Experimentally, the factor 2 in front of $\rho^{W^+}(1)\rho^{W^-}(2)$ is accounted for automatically since two W's from different semi-leptonic events are mixed, irrespective of their electrical charge.

Keeping in mind that Eq. 2 was formulated for independent W decays, one can construct test observables to look for deviations from this assumption. Such deviations will signal that particles from different W decays do correlate. The observables considered are:

$$\Delta\rho(Q) = \rho^{WW}(Q) - 2\rho^{W}(Q) - 2\rho^{WW}_{mix}(Q), \tag{5}$$

$$D(Q) = \frac{\rho^{WW}(Q)}{2\rho^{W}(Q) + 2\rho^{WW}_{mix}(Q)}, \tag{6}$$

Any deviation from zero of $\Delta\rho(Q)$, or any deviation from one of $D(Q)$, indicates the presence of inter-W BEC. Note that the integral of $\Delta\rho(Q)$ over the whole Q range corresponds to the covariance of the charge multiplicity distribution of one W and that of the second W [11]. Therefore it vanishes in the absence of inter-W correlations.

3 Selection of WW events

The total analysed dataset used in this thesis amounts to 549.6 pb^{-1}, collected with the DELPHI detector during the years 1998-2000. A detailed description of the DELPHI detector and its performance is given in [12, 13]. A summary of the total amount of integrated luminosity per energy point is given in Tab. 1. The samples of fully-hadronic and semi-leptonic events required

Year	1998	1999				2000
$\sqrt{s}$ (GeV)	189	192	196	200	202	204-209
$\mathcal{L}$ (pb^{-1})	158	25.9	76.9	84.3	41.1	163.4

Table 1: The integrated luminosities, $\mathcal{L}$, for the various years of LEP2 data-taking, expressed in units of pb^{-1}. The corresponding centre-of-mass energies are also given.

for the WW BEC analysis were selected using neural networks, developed in [14] and [15].

For the **fully-hadronic** event selection, it was demanded that the events fulfill the following requirements: a minimum charge multiplicity, a large effective centre-of-mass energy, $\sqrt{s'}$, large visible energy and a topology of four or more jets.

The final selection was performed using a neural network trained on thirteen event variables. The dominant background contribution comes from the $q\bar{q}(\gamma)$ events. All other backgrounds are negligible. The hadronically decaying ZZ events were taken as signal events in the fully-hadronic selection.

By requiring a neural network output larger than a given value, a desired purity or efficiency can be reached. The whole analysis is repeated for several cuts on the neural network output, selecting samples with an increasing purity, ranging from 83% to 97%. This will allow us to choose an optimal working point. The strength of the Bose-Einstein effect in the $q\bar{q}(\gamma)$ background is not known. Therefore, it has to be modeled using a Monte Carlo model, including BEC. After modeling BEC inside this background sample, it was subtracted from the real data. The systematic uncertainty due to the modeling of the background will, evidently, be smaller when the background fraction is reduced. This can be accomplished by a more stringent selection of fully-hadronic WW events, resulting in a smaller number of selected signal events and, consequently, a reduction of the statistical precision. This cost-benefit exercise was optimised choosing a selection giving the smallest total uncertainty. The optimal working point was found to be at a neural network output value larger than 0.6, corresponding to a selection efficiency and purity of 63% and 92% respectively, with 3252 events selected in total.

The **semi-leptonic** events are selected by requiring two hadronic jets, a well isolated, identified muon or electron or a narrow jet with a low multiplicity (in case of hadronic tau decays) and missing momentum resulting from the neutrino. The missing momentum direction should point away from the beam pipe. Dedicated neural network trainings were used for all lepton flavours. By cutting on a value of 0.4 for the electron and muon output and 0.9 for the tau output, an overall efficiency and purity of respectively 61% and 96% was reached, corresponding to 2567 selected events

The WPHACT [16] generator with the JETSET [17] hadronisation model was used for the simulation of all signal and four-fermion background events. The $q\bar{q}(\gamma)$ background was simulated using the KK2F [18] generator and also hadronized with JETSET. Dedicated Monte Carlo samples inclusing the Bose-Einstein effect were used to test the analysis and to give predictions for a possible inter-W BEC signal. All make use of the BE_{32} variant of the LUBOEI algorithm. For a detailed description of LUBOEI and its possible impact on the W mass, we refer to [19, 6]. In the particular case of fully-hadronic WW events, the LUBOEI predictions where BEC are only present between particles coming from the *same* W is referred to as the BEins model, whereas the BEfull model includes BEC between *different* Ws.

3.1 Track selection

The analysis of two-particle inclusive densities requires a selection of tracks of good quality. In WW events, most of the charged particles are pions. Although no explicit pion identification is made, it is a good approximation to assume that all charged particles in the W hadronic decay products are pions.

The charged tracks used in the inter-W BEC analysis are required to fulfill the following criteria:

- information from the TPC was used to reconstruct the track;

- their momentum is bigger than 0.1 GeV/c;
- the relative error on the measured momentum, $\Delta p/p$ is smaller than unity;
- their impact parameter with respect to the nominal interaction point is less than 0.4 cm in the plane perpendicular to the beam and less than $1/\sin\theta$ cm along the beam;
- the particle is not associated with a reconstructed secondary vertex;
- the particle is not the tagged lepton or does not belong to the leptonic jet in the semi-leptonic selection.

The strict impact parameter cuts are stronger than the standard DELPHI track selection procedure. The cut is, however, justified since it reduces considerably the amount of tracks coming from secondary interactions with the detector material. The total fraction of secondary tracks per event amounts to 5% after this stricter track selection, to be compared with more than 10% in the standard selection.

4 Background subtraction

Depending on the chosen value of the neural network output parameter, the fully hadronic W events can be contaminated by a considerable fraction of high energy $q\bar{q}(\gamma)$ events. Therefore, the density $\rho^{WW}(Q)$ is corrected for this background using the expression

$$\rho^{WW}(Q) = \frac{1}{N_{tot} - N_{q\bar{q}}} \left(\frac{dn_{tot}}{dQ} - \frac{dn_{q\bar{q}}}{dQ} \right), \tag{7}$$

where N_{tot} and $N_{q\bar{q}}$ are the total number of selected events and the number of selected background events, respectively, and n_{tot} and $n_{q\bar{q}}$ the respective number of particle pairs from these events.

The background is subtracted using simulated Monte Carlo events including Bose-Einstein correlations implemented with the LUBOEI BE_{32} algorithm. Due to the fact that the LUBOEI model is tuned using data at the Z^0 peak, we know that the model should describe the inclusive high energy Z^0 data fairly well. It is not known, however, whether it will describe the special subsample of events that are selected by the fully-hadronic WW selection. It would be impossible to select real WW-like $q\bar{q}(\gamma)$ events at high energies due to the high contamination by WW events itself. We therefore selected events at the Z^0 peak which exhibit a clear four-jet structure. It was found that, while an input correlation strength PARJ(92)=1.35 describes the inclusive Z^0 sample quite well, the four-jet subsample is better described by a lower input strength equal to 0.9. Therefore, the background MC with the lower correlation strength of PARJ(92)=0.9 is used as standard for the background subtraction. A systematic uncertainty due to the uncertainty on that parameter is taken into account by performing the analysis subtracting two background samples corresponding to half of the data luminosity with respectively both tunings. The difference between results obtained by the standard and this alternative background subtraction are taken as the systematic error.

5 W Mixing procedure

In this section it is described how ρ^{WW}_{mix} is measured by means of mixing tacks from different events. The main features of a good "mixed" sample should be that it represents a real fully-hadronic sample in all respects, except for inter-W correlations.

The mixed sample is constructed by taking a single hadronically decaying W and combine it with another one. These hadronic W's are taken from semi-leptonic WW decays, $q\bar{q}l\bar{\nu}_l$, of which the $l\bar{\nu}_l$ system is removed. In practice it means that the identified lepton, or leptonic jet, after clustering the event into three jets, is removed from these events, together with any possible remaining neutrals in a cone of 10° around it. The four-momentum of the hadronic W is obtained from a constrained fit, assuming total energy and momentum conservation of the event and where every W is given the nominal W mass of 80.35 GeV/c^2.

All particles from one W system are rotated in such a way that the directions of the momenta of the two W systems are opposite. In order to take into account the detector acceptance, two events are combined only if the W momenta are lying on a double cone of a diabolo shape with a full opening angle of $10°$. This is sketched in Fig. 1.

In order to make the combined event balanced in momentum, only rotations in azimuthal angle are performed in combination with an inversion of the z component of the momenta in cases where both W directions point in the same hemisphere. This reflects the azimuthal and left-right symmetry of the detector. The remaining imbalance in polar angle is not compensated for. Due to the presence of ISR photons, true fully hadronic WW events have an imbalance, resulting in a missing momentum spectrum that does not peak at zero. The ISR spectrum is simulated in the mixed events by smearing the W momenta obtained from the constrained fit. This smearing is performed by making a linear combination of the W momenta obtained from the 3C fit with the vector sum of all particles belonging to the W system:

$$\overrightarrow{p}_W = 0.4\overrightarrow{p}_{tracks} + 0.6\overrightarrow{p}_{3Cfit}. \quad (8)$$

It is known that the two track reconstruction efficiency in DELPHI drops drastically for opening angles below 2.5°. Since the mixing procedure does not necessarily reproduce this drop in efficiency all particle pairs having an opening angle below 2.5° are omitted in all two-particle density distributions.

The agreement between real events and mixed events was verified for several event variables and single particle distributions. As an example, Fig. 2 shows the charge multiplicity, missing momentum, the number of natural jets and the reconstructed W mass. In Fig. 3 some single particle distributions are shown. In general a very good agreement was found for both event variables and single particle distributions. It was verified by weighing events that any disagreement between mixed events and real fully-hadronic events was covered by the systematic error assigned to the mixing procedure.

6 The $\Delta\rho(\mathrm{Q})$ and $\mathrm{D}(\mathrm{Q})$ distribution

The two-particle Q distributions for the combined data set are shown in Fig. 4 for both like-sign particle pairs and unlike sign particle pairs. The histograms show the contribution from $q\bar{q}(\gamma)$ background events as they are simulated with the BE$_{32}$ model with an input BE correlation strength of PARJ(92)=0.9.

In both the fully-hadronic and semi-leptonic samples, the number of unlike-sign pairs is higher than the number of like-sign pairs at Q values below 2 GeV/c^2. This is due to the large number of resonance decays with masses in this range. The area around $Q = 0.7$ GeV is dominated by $\pi^+\pi^-$ pairs coming from the ρ resonance which is abundantly present in hadronic decays of the W. Reflections of three-body decays are even present in the like-sign distributions. The two-particle densities of like-sign and unlike-sign pairs for the mixed events coincide, the reason for this being that all pairs in this distribution contain particles from different events.

The statistical bin errors of the two-particle density distributions cannot be estimated using simple Poisson statistics. This can be understood as follows. By taking combinations of n identically charged particles one obtains a total amount of $n(n-1)/2$ entries in the density distributions. Since a particle can contribute several entries in the same bin or in different bins, this introduces bin-to-bin correlations [20]. In addition, the value of n is fluctuating from event to event.

These statistical properties are taken into account by constructing the covariance matrix of all two-particle spectra [21] defined as:

$$V_{j,k} = \frac{N_{ev}}{N_{ev}-1} \sum_{i=1}^{N_{ev}} (h_j^i - H_j/N_{ev})(h_k^i - H_k/N_{ev}), \tag{9}$$

where the h_j^i are the numbers of entries in bin j of event i and $H_j = \sum_i h_j^i$. The expression is nothing more than a long-hand notation of $\langle h_j h_k \rangle - \langle h_j \rangle \langle h_k \rangle$, where $\langle\ \rangle$ denotes the statistical average. Note that the diagonal elements of the covariance matrix are the variances of each bin: $V_{i,i} = \sigma_i^2$. If operations are done on several distributions, i.e. to construct variables like $D(Q)$ and $\Delta\rho(Q)$, the covariance matrices of these quantities are computed using an analytical propagation according to classical statistical methods.

The events in the density $\rho^{mix}(Q)$ are not statistically independent, in addition it will be correlated with $\rho^{2q}(Q)$. This problem is addressed by calculating the covariance matrix of the term $2\rho^{2q}(Q) + \rho^{mix}(Q)$ in one go. Let $H_j(2q) = \sum_{i=1}^{n_{2q}} 2h_j^i(2q)$, $H_j(mix) = \sum_{i=1}^{n_{mix}} h_j^i(mix)$ and $\mathcal{H}_j^i = \sum_{(i)} h_j^{(i)}(mix)$, where the last expression is the sum of the bin entries of all mixed events containing the same 2q event i. The covariance matrix then reads:

$$\begin{aligned} V_{jk}(2\cdot 2q + mix) = \sum_{i=1}^{n_{2q}} &(H_j(2q)/n_{2q} - 2h_j^i(2q) + H_j(mix)n_{2q}(i)/n_{mix} - \mathcal{H}_j^i) \\ &\cdot (H_k(2q)/n_{2q} - 2h_k^i(2q) + H_k(mix)n_{2q}(i)/n_{mix} - \mathcal{H}_k^i), \end{aligned} \tag{10}$$

where $n_{2q}(i)$ represents the number of mixed events containing 2q event i.

Using the normalised two-particle densities, $\rho^{WW}(Q)$, $\rho^{W}(Q)$ and $\rho^{WW}_{\rm mix}(Q)$ one can construct two variables which are sensitive to inter-W Bose-Einstein correlations. The measured $\Delta\rho(Q)$ distribution, using the complete dataset, together with the predictions from the BEins and BEfull model, are given in Fig. 5. The bin errors are taken as the square root of the diagonal elements of the covariance matrix of $\Delta\rho(Q)$.

From this figure, several observations can be made. Firstly, the BEfull model shows a deviation from zero, both in the like-sign and unlike-sign particle pairs.

An enhancement can be observed at Q values below 0.5 GeV/c^2, compensated by a dip in the Q range between 0.5 and 2.5 GeV/c^2. The reason for this dip is understandable for the following reasons. It is known that the total number of charged particles is not affected by any of the LUBOEI models. Therefore, the integral $\int_0^{Q_{\max}} \Delta\rho(Q)dQ$ should be exactly zero. As a consequence, any enhancement at low Q values must be compensated by a depletion at higher Q values.

The measured $D(Q)$ distribution is shown in Fig. 6, together with the BEins and BEfull Monte Carlo predictions. All bin errors are extracted from the covariance matrix of $D(Q)$. A clear enhancement at low values of Q can be observed in Fig. 6 for the like-sign pairs of the BEfull model. A smaller enhancement can, again, be observed in the unlike-sign pairs as well. In both cases, a dip can be observed on the Q region between 0.5 and 2.5 GeV/c^2, for the same reasons as mentioned in the discussion of the $\Delta\rho(Q)$ distribution.

In both the like-sign and unlike-sign distributions, the BEins model shows a flat distribution, compatible with one. The combined data lie in between the two models, showing again an excess situated in a very small Q region, below 0.3 GeV/c^2, both for like-sign pairs and unlike-sign pairs.

6.1 Sensitivity

It should be realised that the number of pion pairs originating from different W's is a relatively small fraction of all pairs. This can be seen in Fig. 7, where the fraction of pairs from different W's, often denoted as $F(Q)$, is shown. It drops to around 20% at very low Q values. It is, therefore, important to try to increase this fraction, especially in the low Q region.

Besides Q itself, two more variables are found to be sensitive to whether a pair of tracks is coming from different W's or from the same W. These variables are the Lorentz γ factor of the pair, assuming the pair to be massless:

$$\gamma = \frac{|\overrightarrow{p_1}| + |\overrightarrow{p_2}|}{\sqrt{(|\overrightarrow{p_1}| + |\overrightarrow{p_2}|)^2 - |\overrightarrow{p_1} + \overrightarrow{p_2}|^2}}, \tag{11}$$

and the opening angle θ^*, being the angle between one of the two particles in the rest frame of the system and the system's flight direction in the lab frame, where

$$\cos\theta^* = \frac{||\overrightarrow{p_1}| - |\overrightarrow{p_2}||}{|\overrightarrow{p_1} + \overrightarrow{p_2}|}, \tag{12}$$

with $\overrightarrow{p_1}$ and $\overrightarrow{p_2}$ the three-momenta of the two particles.

For each individual pair, the "purity" $p(Q, \gamma, \cos\theta^*)$ can be computed and parametrized. As such, each individual pair of tracks can be estimated to have a purity $p(Q, \gamma, \theta^*)$. The sensitivity to the inter-W BEC effect will be proportional to this purity. However, the statistical error also depends significantly on whether a pair is coming from the same W event or from two mixed events.

The contribution to the total variance of D(Q) for pairs coming from the same W (taken from the semi-leptonic events) is estimated to be 97.7%, while mixed pairs gave only a variance of 38.6%. The total amount of information coming from a given pair is then proportional to $p/(0.386p + 0.977(1-p))$. When all particle pairs are weighted with their information content, one obtains the full curve for $F(Q)$ in Fig. 7.

7 Results

In order to quantify the excess at low Q values in the data, a fit to the $D(Q)$ distribution is performed using the following expression

$$D(Q) = N(1 + \Lambda e^{-RQ})(1 + \delta Q), \tag{13}$$

where the parameter R is fixed to the value obtained from a fit to the BEfull sample. The reason why the R parameter is kept fixed is the strong correlation with the Λ parameter itself (69%). Moreover, fits performed on the BEins model which result in nearly flat distributions, become unreliable if R is left free. Since $D(Q)$ is not a genuine correlation function one should be wary of giving a physical meaning to the parameters of Eq. 13. The value of Λ and its error will quantify the significance of the excess and R is only an indirect measure of the overlap region between the two W's. The normalisation parameter N and the slope δ are sensitive to multiplicity differences and possible imperfections in the mixing. The results of the fits to the combined data and the two BE scenarios (BEfull, BEins) are shown in Tab. 2. The results of the fits are shown in Fig. 8. In addition a fit with a free R parameter was performed to the combined data. The numerical values of the fitted parameters are shown in Tab. 2. In Fig. 9, the one, two and three sigma contours of the fitted Λ and R parameters are shown. The strong correlation between the two can easily be observed.

8 Systematic uncertainties

The measurement of inter-W Bose-Einstein correlations by means of the $D(Q)$ distribution proves to be intricate from a statistical point of view. However, due to the fact that, in this analysis data are directly compared with data, it has only limited systematic uncertainties.

The total systematic uncertainty on the measured Λ value is the sum in quadrature of the contributions listed in Tab. 3 for both like-sign and unlike-sign particle pairs. The individual contributions can be attributed to the following sources:

- As already mentioned in previous sections, 8% of total selected fully-hadronic events consists of $q\bar{q}(\gamma)$ background events. It is not precisely known how strong the Bose-Einstein correlations in these events are. It was found that the BE_{32} model with an input parameter strength of PARJ(92)=0.9 gives a good description of Z^0 events having a clear four-jet topology at 91.2 GeV. An alternative sample of background events was created, having an equal mixture of simulated events with PARJ(92)=0.9 and PARJ(92)=1.35. The latter input strength describes better the inclusive Z^0 sample. Both background samples were subtracted from the data and the absolute difference in the final result was taken as a systematic uncertainty due to the lack of knowledge about BEC in $q\bar{q}(\gamma)$ events.

- Secondly, the selection of the data and the way in which the mixed reference sample was created can introduce distortions in the two-particle densities. This would result in a non-zero value of Λ, measured in Monte Carlo samples without inter-W BEC. Since it is not known which fragmentation model gives the best description of two-particle densities in the absence of BEC, all available fragmentation models were used. The largest absolute value of the measured Λ for these models was taken as a measure for the influence of selection procedures and mixing method on our measurement.

- Fixing the R parameter to a value obtained from the BEfull model, neglects the correlations between Λ and R and reduces the statistical error on Λ. In order to take this correlation into account, the R parameter was varied within one standard deviation of its value, measured for the BEfull model. The resulting difference in the Λ value, measured from the data was taken as a systematic uncertainty due to neglection of the statistical correlations between Λ and R.

- A last systematic uncertainty was attributed to the Colour Reconnection (CR) effect. This effect could have, in addition to inter-W BEC drastic consequences for the W mass measurement in the fully hadronic channel [4, 5]. As in BEC, it violates the assumption that the two produced W bosons decay independently of each other.

  Colour reconnection occurs when independent colour singlets interact strongly before hadron formation. In fully hadronic W decays it recombines partons from different parton showers. After fragmentation, the resulting hadrons carry therefore a mixture of energy-momentum of both original showers [22].

  The colour reconnection effect has been modeled in various ways [4, 5, 9]. Only the extreme models [4], where reconnection occurs in all events has been ruled out by the LEP experiments [7], however the absence of colour reconnection is also disfavoured.

  For this reason, three possible models of colour reconnection, implemented in JETSET, ARIADNE and HERWIG, were used to estimate their influence on our measurement. The maximum difference in Λ between the CR samples and their equivalent models without CR implementation was taken as systematic uncertainty due to the colour reconnection effect. In our case the HERWIG implementation of CR yields the largest value.

9 Influence of inter-W BEC on the reconstructed W mass

Despite the lack of final results from all LEP collaborations, regular LEP wide combinations of the available results are made [7]. This is done, using a χ^2 combination of the observed fraction of the BEfull model, defined as

$$\Lambda_{frac} = \frac{\text{data} - \text{model(noBE)}}{\text{model(BEfull)} - \text{model(noBE)}}. \tag{14}$$

The obtained result and its total error is translated into a W mass shift by

$$\Delta M_W = (\Lambda_{frac} + \sigma(\Lambda_{frac})) \times [M_W(BEfull) - M_W(noBE)]. \tag{15}$$

The latest combination [7], including only the ALEPH and L3 published results, quotes a value of $\Lambda_{frac} = 0.03 \pm 0.18$, resulting in a W mass uncertainty due to BEC of 7 MeV/c^2 (1 σ limit).

Within DELPHI, the shift due to inter-W BEC is estimated using the LUBOEI BEfull model, using at input parameters λ and r the values tuned on inclusive Z^0 data (PARJ(92)=1.35, PARJ(93)=0.6 fm). The difference between the reconstructed W mass in the fully-hadronic channel for the BEfull model and the BEins model is shown in Fig. 10 as function of the centre-of-mass energy for different W mass estimators. The dependence on the centre-of-mass energy is flat, resulting in a general negative W mass shift of 40 MeV/c^2.

The observation of a smaller R parameter in the data indicates that fewer particle pairs participate in the inter-W BE effect than expected from the LUBOEI model. This will likely reduce the shift on the reconstructed W mass even more.

10 Conclusion

In this paper, we presented studies of inter-W Bose-Einstein correlations, based on an analysis of 550 pb^{-1} of LEP2 data with centre-of-mass energies ranging from 189 - 209 GeV. An event mixing method is used to construct a reference sample based on data, which allows to extract a signal sensitive to inter-W Bose-Einstein correlations. The analysis is optimized as function of the purity of the fully-hadronic event sample. The sensitivity to inter-W BEC is increased by giving weights to pairs, according to their probability to come from different W's. The mixing method, including the pair weights is highly model independent, since data are compared directly with data. As a consequence, many systematic uncertainties due to detector acceptance and resolution, selection procedures and corrections are eliminated. The remaining systematic uncertainties are dominated by the modeling of the background shape, the mixing procedure itself and the possible presence of colour reconnection effects.

A non-zero value of Λ was found when fitting the $D(Q)$ distribution for like-sign pairs, giving an indication for inter-W Bose-Einstein correlations, at the level of 2.9 standard deviations. The final result is

$$\Lambda = 0.241 \pm 0.075(\mathrm{stat}) \pm 0.038(\mathrm{syst}). \qquad (16)$$

A significant signal was also found in unlike-sign pairs, in accordance with the predictions of LUBOEI. From a comparison of the statistical uncertainty on the measured Λ value with the total systematic uncertainty we conclude that the inter-W BEC measurement is mainly statistically limited. This is due to the small fraction of particle pairs at small Q which come from different W's. Using the LUBOEI BE_{32} model, the influence on the W mass was investigated, using the fraction of the strength of the effect taken from the model. A negative shift in m_W of 36.1 Mev/c^2 was deduced. However, the inter-W effect seems to be situated in a very small Q region, corresponding to a relatively large value of R. The two-particle densities are poorly populated in this region. This is however good news for the impact on the W mass measurement, since it means that in practice, very few particles contribute to the inter-W Bose-Einstein effect. The reconstructed W mass is therefore probably less affected by this smaller number of particles.

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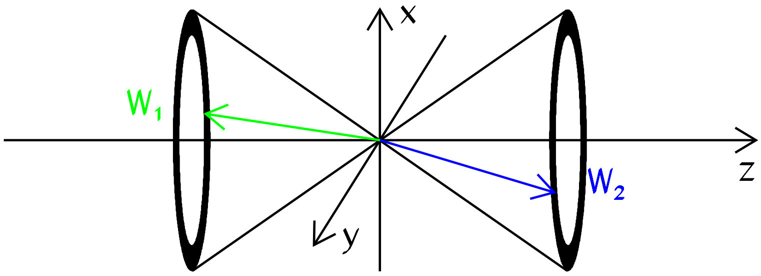

Figure 1: The surface on which different single W systems can be combined into a fully hadronic mixed event.

sample/parameter	Λ	$R(fm)$	δ	N	χ^2/Ndf
R fixed to R(BEfull)					
data (±,±)	0.241 ± 0.075 ± 0.038	0.994	0.0044 ± 0.0078	0.980 ± 0.029	89.2
data (+,-)	0.123 ± 0.050 ± 0.042	0.471	0.0112 ± 0.0082	0.965 ± 0.029	93.0
R free					
data (±,±)	0.38 ± 0.16 ± 0.038	1.63 ± 0.53	0.0027 ± 0.0077	0.987 ± 0.029	87.5
data (+,-)	0.131 ± 0.059 ± 0.045	0.58 ± 0.36	0.0101 ± 0.0086	0.970 ± 0.036	92.8
BEfull (±, ±)	0.360 ± 0.012	0.994 ± 0.030	0.00375 ± 0.00094	0.9747 ± 0.0035	218.7
BEfull (+,-)	0.0785 ± 0.0057	0.471 ± 0.045	0.0030 ± 0.0010	0.9792 ± 0.0039	119.0

Table 2: Fit results to like-sign and unlike-sign D(Q) with R fixed and R free. The second error on the data Λ values corresponds to the systematic error.

syst source	contribution to $\Lambda(\pm,\pm)$	contribution to $\Lambda(+,-)$
background BE model	0.017	0.005
cuts & mixing	0.023	0.028
Colour Reconnection (HER)	0.020	0.030
Variation of R	0.014	0.005
Total syst.	0.038	0.042

Table 3: A breakdown of the systematic errors for the Λ measurement with fixed R, for like-sign and unlike-sign particle pairs.

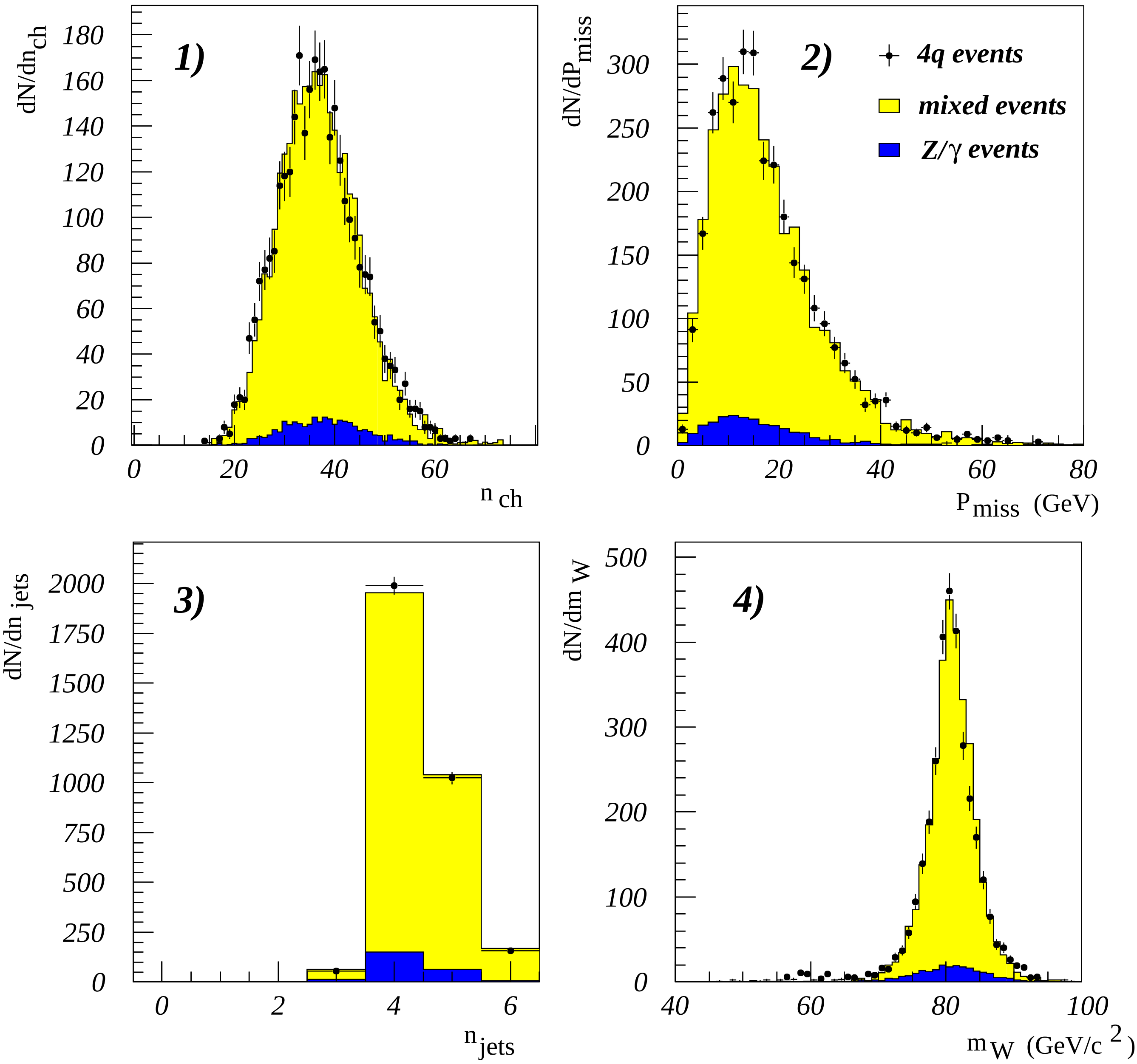

Figure 2: A comparison between real data mixed events (light shaded histogram) and fully-hadronic events (points) for (1) the number of charged particles , (2) the amount of missing momentum, (3) the number of natural jets, clustered with LUCLUS (4) the reconstructed W mass using a 5C fit. The dark shaded histogram shows the contribution from the $q\bar{q}(\gamma)$ background.

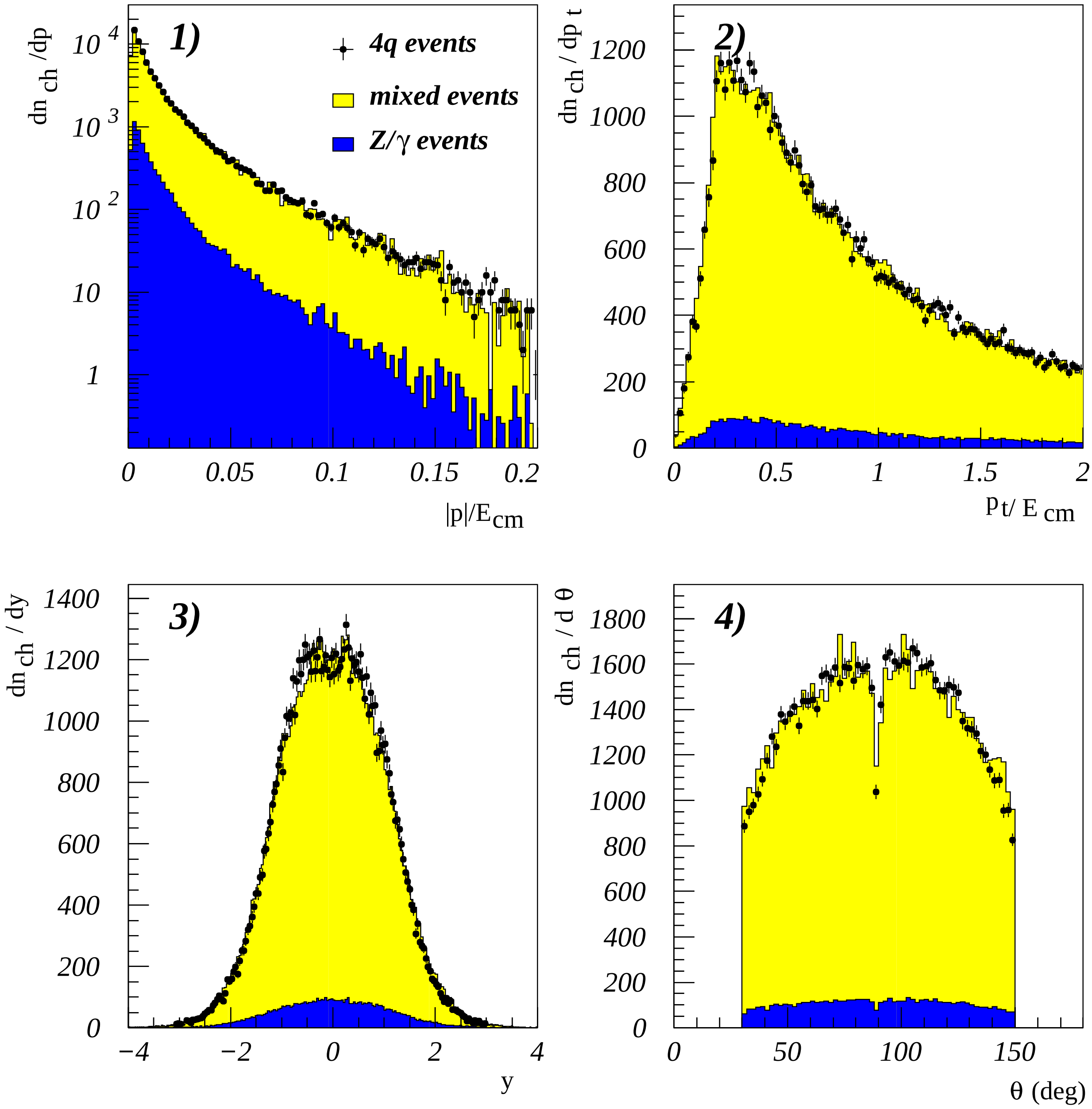

Figure 3: A comparison between real data mixed events (light shaded histogram) and fully-hadronic events (points) for (1) the momenta of all charged particles , (2) their transverse momentum w.r.t the W momentum, (3) the rapidity w.r.t. the W momentum and (4) the polar angle w.r.t. the z axis. The dark shaded histogram shows the contribution from the $q\bar{q}(\gamma)$ background.

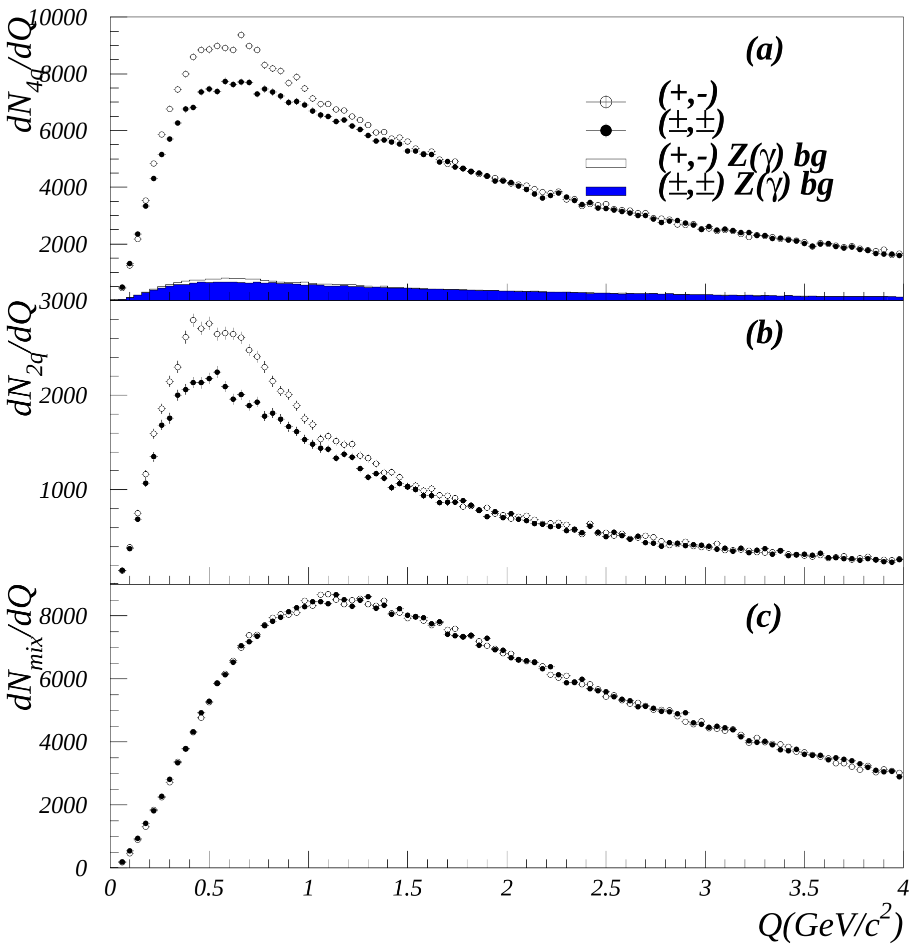

Figure 4: The two-particle distributions in the variable Q for like-sign and unlike-sign particle pairs. The contribution of the $q\bar{q}(\gamma)$ background to the fully hadronic WW decay channel is shown by the shaded histogram. Figure (a) shows the like-sign and unlike-sign densities for fully hadronic events, $N_{4q}\rho^{WW}(Q)$. Figure (b) shows the densities for semi-leptonic events, $N_{2q}\rho^{W}(Q)$, and Fig. (c) shows the densities for mixed events, $N_{\rm mix}\rho^{WW}_{\rm mix}(Q)$.

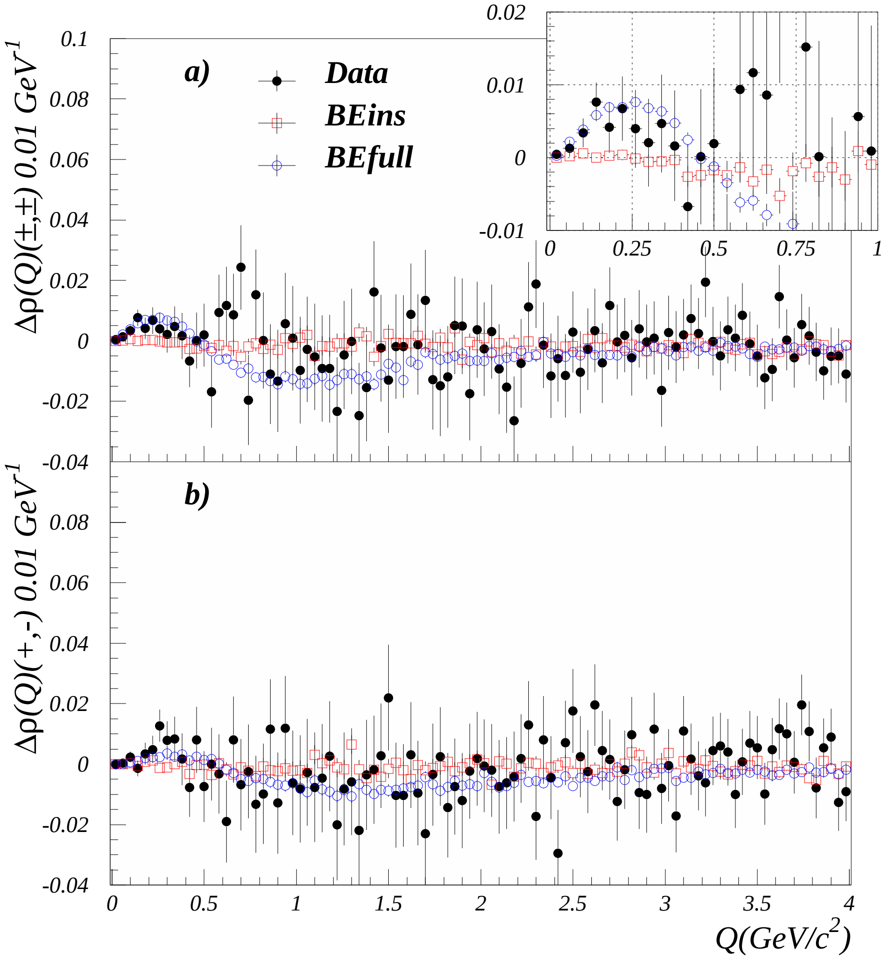

Figure 5: The $\Delta\rho(Q)$ distribution for like-sign particle pairs a). The MC predictions for the BEins and BEfull model are superimposed. In b) the same is shown for unlike-sign particle pairs. The inset shows a zoom in the region $0. < Q < 1.$ for the like-sign distributions.

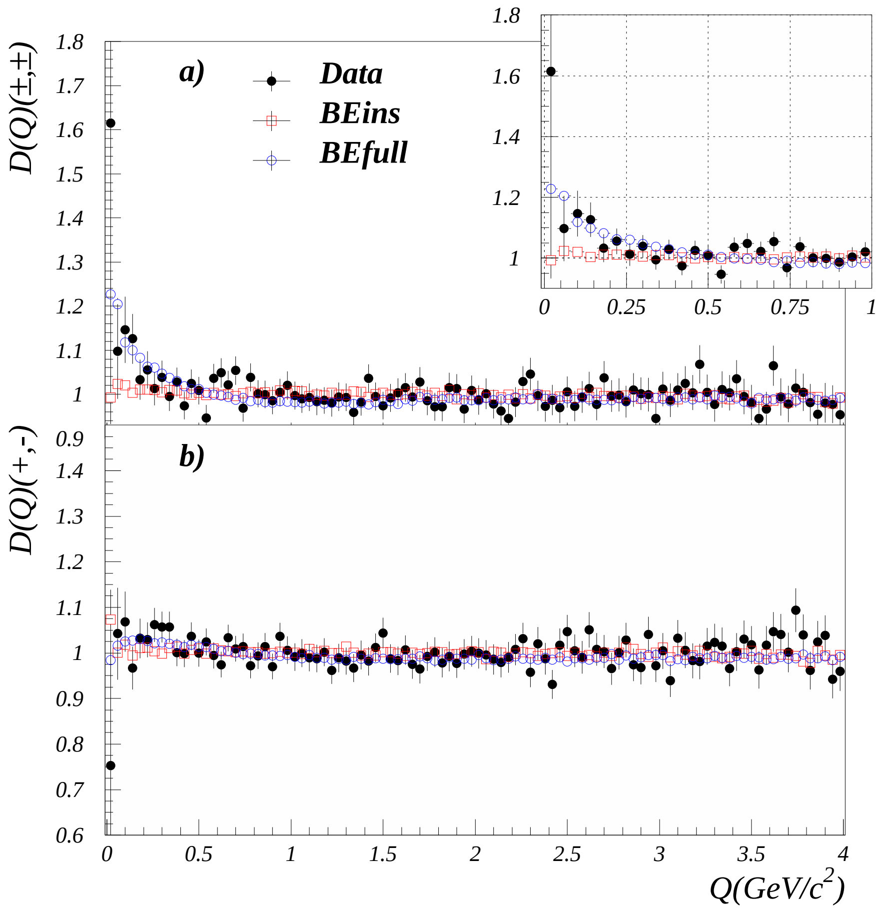

Figure 6: The $D(Q)$ distribution for like-sign particle pairs a). The solid dots represent the combined dataset. In addition, the predictions from a WPHACT Monte Carlo simulation of the BEins model (open squares) and the BEfull model (open dots) is shown. In b) the same distributions are shown for unlike-sign particle pairs. The inset shows a zoom in the region $0. < Q < 1.$ for the like-sign distributions.

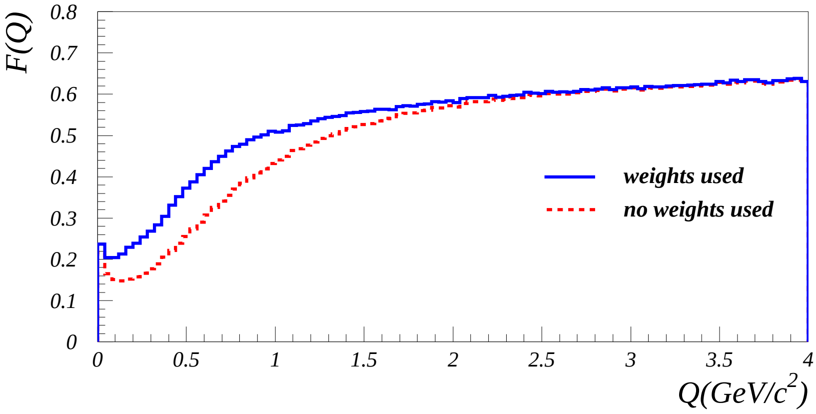

Figure 7: The fraction of pairs coming from different W's, $F(Q)$, obtained for a BEins MC sample without pair weights (dashed line) and using pair weights (full line).

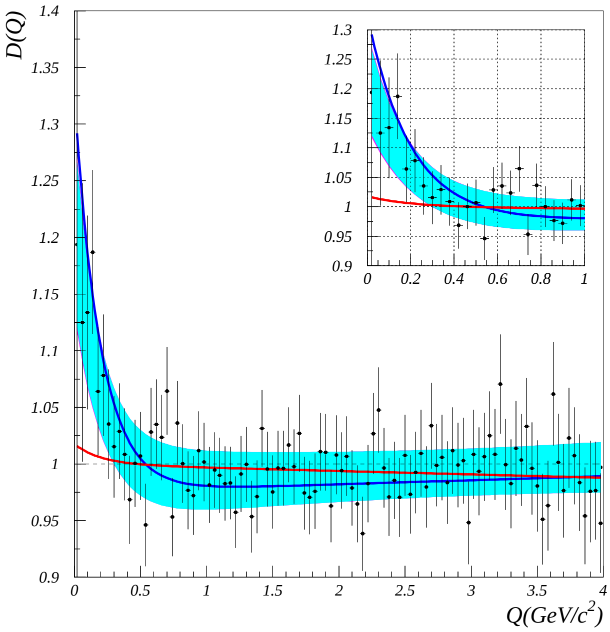

Figure 8: The $D(Q)$ distribution for the combined data set. The band indicates the fit result with the R parameter fixed to the one obtained from the BEfull model. The shape of the band includes the correlation between the remaining free fit parameters. In addition the fit to the BEfull and BEins model are shown by the full lines. The inset is a zoom in the Q region below 1.GeV/c^2.

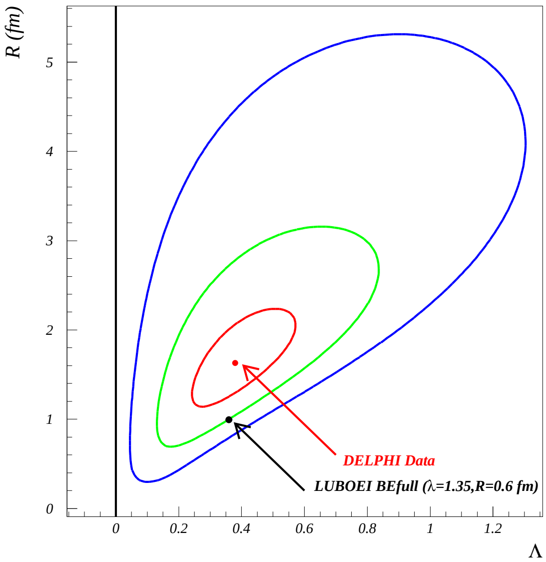

Figure 9: The one, two and three σ contours for a fit to the combined data set, leaving the R parameter free. The fit result obtained from the BEfull model is indicated for comparison (the statistical errors on this measurement are smaller than the size of the dot).

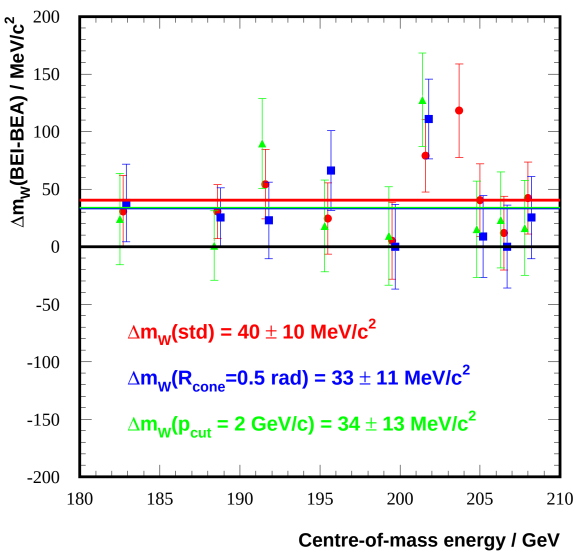

Figure 10: The difference in reconstructed W mass between the BEfull and BEins model, using the DELPHI W mass analysis in the fully-hadronic channel.