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Bose-Einstein Correlations in the Hadronic Decays of the Z^o

DELPHI Collaboration

Abstract

Bose-Einstein correlations between pairs of like sign charged particles produced in e^+e^- annihilations near the Z^0 peak have been studied using data taken with the DELPHI detector at LEP. An enhancement is found in the production of pairs of identical pions of similar momenta, with respect to a reference sample. Under the hypothesis that the pions are emitted by a spherically symmetrical source with Gaussian density, the data indicate a radius of the source of $r = 0.62 \pm 0.04(stat) \pm 0.20(syst)$ fm. The large systematic uncertainty reflects the sensitivity of r to the choice of the reference sample.

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1 Introduction

An enhancement in the production of pairs of pions of the same charge and similar momenta produced in high energy collisions was first observed in antiproton annihilations and attributed to Bose-Einstein statistics appropriate to identical pion pairs [1].

Bose-Einstein correlations between pion pairs can be used to study the space-time structure of the hadronization source [2]. This has been done for hadron-hadron, heavy ion, muon-hadron and e^+e^- collisions (see Ref. [3] for reviews, and Ref. [4] for results of e^+e^- experiments below the Z^0 energy). Measurements at the LEP e^+e^- collider have been presented recently [5,6], and disagree in the estimate of the strength of the correlation.

This letter describes an investigation of Bose-Einstein correlations in hadronic decays of the Z^0 at a centre of mass energy of about 91 GeV, using data collected with the DELPHI detector [7] at LEP in 1991.

2 Analysis

To study the enhanced probability for emission of two identical bosons it is useful to define a correlation function R:

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

where $P(p_1, p_2)$ is the two-particle probability density, subject to Bose-Einstein symmetrization, and $P(p_i)$ is the corresponding single particle quantity for a particle with four-momentum p_i. In practice, $P(p_1)P(p_2)$ is often replaced by a reference 2-particle distribution $P_o(p_1, p_2)$, 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 $G[f(x)] = \int f(x) e^{-i(p_1 - p_2)\cdot x}\, dx$ 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. The effect can be described in the variable Q, defined by $Q^2 = M^2(\pi\pi) - 4m_\pi^2$, where M is the invariant mass of the two pions.

The correlation function is often parametrized by the function:

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

where the parameter r gives the source size and λ measures the strength of the correlation between the pions, being 0 for a completely coherent source and 1 for a completely incoherent one.

An expression slightly different from (1) is often used in the literature to analyze the experimental data:

$$R(Q) \;=\; N(1 + \delta \cdot Q)(1 + \lambda e^{-r^2 Q^2}) \tag{2}$$

where the factor $(1 + \delta \cdot Q)$ is introduced to take into account possible long-range momentum correlations in the form of a slow rise, and N is a normalization factor.

The definition of an appropriate reference sample from which $P_o(p_1, p_2)$ can be obtained is the major problem of this kind of studies. In order to estimate systematic errors in the evaluation of the correlation function, two different reference samples have been used in the present study:

a. Pairs of oppositely charged particles have been taken.
b. An artificial sample of "mixed" particles has been obtained by dividing the event into two halves by a plane perpendicular to the thrust axis. The charged particles from one half were then combined with those from the other, reflecting through the origin the momentum of one particle in the pair.
This method requires a clear 2-jet topology, and thus it was applied only to events with a thrust value $T > 0.95$.

3 Experimental procedure and event selection

The sample of events used in the analysis was collected by the DELPHI detector at the LEP e^+e^- collider during 1991.

A description of the apparatus can be found in Ref. [7]. Features of the apparatus relevant for the analysis of multihadronic final states (with emphasis on the detection of charged particles) are outlined in Ref. [8]. The present analysis relies on the information provided by the central tracking detectors: the Micro Vertex Detector (VD), the Inner Detector (ID), the Time Projection Chamber (TPC), and the Outer Detector (OD).

The central tracking system of DELPHI covers the region between 25^o and 155^o in polar angle θ, with reconstruction efficiency near to 1. The average momentum resolution for the charged particles in hadronic final states is in the range $\Delta p/p \simeq 0.001p$ to $0.01p$ (p in GeV/c), depending on which detectors are included in the track fit.

Only charged particles fulfilling the following criteria were used in this analysis: (a) impact parameter at the primary vertex below 1 cm in radius from the beam axis and below 5 cm along the beam axis; (b) momentum, p, larger than 0.1 GeV/c; (c) measured track length in the TPC above 50 cm; (d) polar angle, θ, between 25^o and 155^o.

All these particles were assumed to be pions.

Hadronic events were then selected by requiring that (α) each of the two hemispheres $cos\theta < 0$ and $cos\theta > 0$ contained a total energy of the charged particles larger than 3 GeV; (β) the total energy of the charged particles seen in both hemispheres together exceeded 15 GeV; (γ) there were at least 5 charged particles with momenta above 0.2 GeV/c; (δ) the polar angle θ of the sphericity axis was in the range $40^o < \theta < 140^o$ (this selection ensures that the retained events are well contained inside the TPC).

A total of 75,576 events satisfying these selections were used in the present analysis. Events due to beam-gas scattering and to $\gamma\gamma$ interactions have been estimated to be less than 0.1% of the sample; background from $\tau^+\tau^-$ events was calculated to be less than 0.2%.

Only events in which the thrust value was larger than 0.95 were used in the part of this analysis based on a "mixed" reference sample. The 34,984 events which passed this selection have a clear back to back two-jet topology, which ensures the correct functioning of the mixing technique.

Particles were paired only if each had a momentum below 5 GeV/c, to avoid the limits of phase space where dynamical correlations are strong. Each particle was required to have a transverse momentum with respect to the beam axis above 250 MeV/c, in order

to exclude tracks curling inside the magnetic field, that was parallel to the beam axis. In addition, tracks were required to give a signal in the VD.

To exclude partially overlapping track pairs with potential problems in reconstruction, pairs were rejected if their opening angle was smaller than 2^o. The cut $Q > 60$ MeV/c was imposed in addition, to reduce possible residual contaminations from photon conversions not correctly reproduced in the simulation, and the influence of correlated pions from η' decays.

The influence of detector effects and selections were studied by means of the detailed detector simulation Monte Carlo program DELSIM [9]. A sample of 75,000 events was generated using the JETSET 7.2 Parton Shower (PS) [10] Monte Carlo with parameters tuned as in [11] (without including any Bose-Einstein symmetrization), followed through the simulation of the detector, and processed through the same reconstruction and analysis chain as the real data.

4 Results

Figure 1 shows the distribution as a function of Q of the numbers of like and unlike pion pairs found. In the unlike pairs, the presence of the pions coming from the decays of K^o_S and ρ^o is evident.

The ratio $R_{+-}(Q) = N_{\pm\pm}(Q)/N_{+-}(Q)$, where $N_{\pm\pm}$ and N_{+-} are the number of like and unlike-charged pairs, is shown in Figure 2, together with the Monte Carlo distribution in which the Bose-Einstein effect was not simulated. The enhancement due to Bose-Einstein correlations is clearly visible in the region $Q < 0.3$ GeV/c. The dips near $Q = 0.4$ GeV/c and $Q = 0.7$ GeV/c in both data and simulation are caused by contributions to the denominator by K^o_S and ρ^o decays.

In principle the bias due to residual correlations in the reference sample can be removed by dividing the ratio obtained from the data by the equivalent ratio from the simulation. This normalized ratio for the unlike charged reference sample is plotted in Figure 3a, with the fit of form (2) superimposed. The results of the fit are $r = 0.83 \pm 0.03$ fm, $\lambda = 0.31 \pm 0.02$ ($\chi 2 = 65/73$ Degrees of Freedom,[†] correlation coefficient $C(r\lambda) = 0.19$). Quantitative results from this correction procedure require a satisfactory model of non Bose-Einstein correlations in the simulation. In order to get an idea of the possible systematic error induced by bad modelling, the same analysis was done with the "mixed" reference sample described above.

First it was verified that:

a. The procedure using unlike-sign pairs as a reference gives completely compatible results in the full event sample as in the subsample of 2-jet events with thrust, T, above 0.95.
b. The results using unlike-sign pairs as reference, in the subsample of 2-jet events defined as in a., were not affected by the requirement that both particles in like and unlike pairs were in the same hemisphere relative to the thrust axis.

[†]The region from Q =0.4 GeV/c to Q = 0.8 GeV/c (corresponding to K^0 and ρ^0), where the discrepancies between data and simulation are mainly concentrated, was removed from the fit.

Then the "mixing" procedure was used in the subsample of 2-jet events, with the result shown in Figure 3b. The fit to form (2) gives $r = 0.47 \pm 0.03$ fm, $\lambda = 0.24 \pm 0.02$ ($\chi 2 = 98/93\,DF$, $C(r\lambda) = 0.59$). The results of the same technique using a stronger 2-jet selection cut (thrust $T > 0.97$), or by requiring the acollinearity between the axes of the two jets [‡] to be smaller than 3^o, were consistent.

Two cuts described in Section 3 could in principle bias the effect measured, and the stability of the results was checked against dependence on these cuts.

1. The cut on the opening angle of the pairs (2^o) was varied between 1^o and 5^o;
2. The cut on the maximum impact parameter to the primary vertex in the plane perpendicular to the beam (1 cm) was varied between 0.5 cm and 2 cm;

without significant changes in r or λ.

Corrections are often made for two causes that could attenuate the effect of Bose-Einstein correlations seen in Figure 3:

a. Particle identification was not used in this analysis, where all particles were assumed to be pions. The Bose-Einstein effect is thus attenuated by the presence of pairs of particles in which one is not a pion. Particle misidentification can be taken into account by subtracting from both the real density and the reference density distributions the fraction of pairs in which at least one particle is not a pion, as obtained from simulation. This fraction is found to be about 27% in average, smoothly growing from 15% at $Q = 0.06$ GeV/c to 30% at $Q = 1$ GeV/c, and then reaching a plateau.

b. The final state Coulomb interaction modifies the two-pion relative momentum distribution in a different way for like (l) and unlike (u) pairs. The Coulomb effect is usually parametrized in the literature by the Gamow factors [12]

$$W_l(\eta) = \frac{(e^{2\pi\eta} - 1)}{2\pi\eta}, \quad W_u(\eta) = \frac{(1 - e^{-2\pi\eta})}{2\pi\eta}$$

where $\eta = \alpha m_\pi / Q$. Data have been corrected for this final state interaction by weighting each like (unlike) pair with W_l (W_u). Recent calculations [13] suggest that the Gamow factor overestimates the size of the final state Coulomb interaction; however it was decided not to change this correction in order to retain comparability with other results.

Figures 4a and 4b show the same distributions as Figure 3, after corrections for Coulomb effects and non-$\pi\pi$ pairs. The results of the fits in Figures 4a and 4b, in which form (2) is used[§], are $r = 0.82 \pm 0.03$ fm, $\lambda = 0.45 \pm 0.02$ ($\chi 2 = 89/73\,DF$, $C(r\lambda) = 0.38$) and $r = 0.42 \pm 0.04$ fm, $\lambda = 0.35 \pm 0.04$ ($\chi 2 = 155/93\,DF$, $C(r\lambda) = 0.55$) respectively.

The effect of the Coulomb correction is to increase λ by about 20% when the unlike-sign reference sample is used and by about 10% when the mixed reference sample is used. The radius r is only slightly affected by the correction.

The superimposed curves show the results of the fit to these distributions of the expression (2). The results of the fit are presented in Table 1 for the two reference samples,

[‡] The jet axis was defined by the sum of the momenta of the charged tracks.

[§] The region from Q =0.4 GeV/c to Q = 0.8 GeV/c was removed from the fit to figure 4a.

	r (fm)	λ	Ref. sample
(a)	0.83 ± 0.03	0.31 ± 0.02	$+-$
	0.47 ± 0.03	0.24 ± 0.02	mixed
(b)	0.82 ± 0.03	0.45 ± 0.02	$+-$
	0.42 ± 0.04	0.35 ± 0.04	mixed

Table 1: *Results of the fit to the data without* (a) *and with* (b) *Coulomb and non-*$\pi\pi$ *corrections.*

both before (a) and after (b) corrections. The uncertainty resulting from including or removing from the fit the K^o_S and ρ^o regions for R_{+-} is within the statistical error.

The results from the two different reference samples are inconsistent, as already observed in [6]. This is interpreted as a consequence of the presence of correlations that the simulation fails to model precisely. Many different causes can contribute to this:

- The presence of resonances not correctly parametrized in the simulation[¶].
- A particle from a secondary source, such as a long lived hadron decay, may not contribute to the observed Bose-Einstein correlation. The data have not been corrected for this effect.
- Final state strong interactions are not taken into account. Calculations based on a simplified model [15] suggest anyway that the strong final state interactions in multipion production largely cancel.

The results obtained from the corrected distributions (including Coulomb corrections) using the two reference samples have been averaged and the systematic uncertainty from the choice of the reference sample has been taken to be one half of the difference between the two separate results. This gives:

$$r = 0.62 \pm 0.04\,(stat) \pm 0.20\,(syst)\,fm \quad (3)$$

$$\lambda = 0.40 \pm 0.03\,(stat) \pm 0.05\,(syst)\,. \quad (4)$$

5 Conclusions

Bose-Einstein correlations between like-sign pions produced in the decay of the Z^0 have been studied with the DELPHI detector at LEP, using a sample of about 76,000 selected hadronic events. The results show a Bose-Einstein enhancement which can be parametrized by the expression $R(Q) = 1 + \lambda e^{-r^2Q^2}$, where $\lambda = 0.40 \pm 0.03(stat) \pm 0.05(syst)$ and $r = 0.62 \pm 0.04(stat) \pm 0.20(syst)$ fm. The large systematic errors come mainly from an inconsistency between the results obtained with two different reference samples.

[¶] In particular, the η' decay chain $\eta' \to \eta\pi^+\pi^-$, $\eta \to \pi^+\pi^-\pi^o$ affects the same region of small relative momenta as the Bose-Einstein effect [14], and was a-priori indicated as a possible source of major systematics. By using kinematic methods in order to reject these contaminating pairs, it was concluded that the η' in the data sample does not influence the correlation function significantly.

The full event sample and a subsample of 2-jet events display the same effect when using pairs of opposite sign particles as a reference. This supports the conclusion [16] that the enhancement does not depend on the event topology.

The DELPHI results are comparable with those obtained at lower energy e^+e^- experiments [4]. The measurement of the radius of the interaction region agrees with the recent measurements from the OPAL [5] and ALEPH [6] experiments at LEP. The strength of the effect measured is somehow lower than that published by ALEPH, and considerably lower than that published by OPAL.

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Figure Captions

1. Pairs of like-sign (circles) and unlike-sign (asterisks) tracks, as a function of the 4-momentum difference Q.
2. Ratio R_{+-} between like and unlike sign pairs, for data (circles) and Monte Carlo (asterisks), as a function of the 4-momentum difference Q.
3. Ratios (a) $R_{+-,data}/R_{+-,MC}$ and (b) $R_{mix,data}/R_{mix,MC}$ (see text) as a function of Q. The best fit to (2) is superimposed as a solid line.
4. Same as Figure 3, after corrections for Coulomb effects and non-$\pi\pi$ pairs.

Figure 1

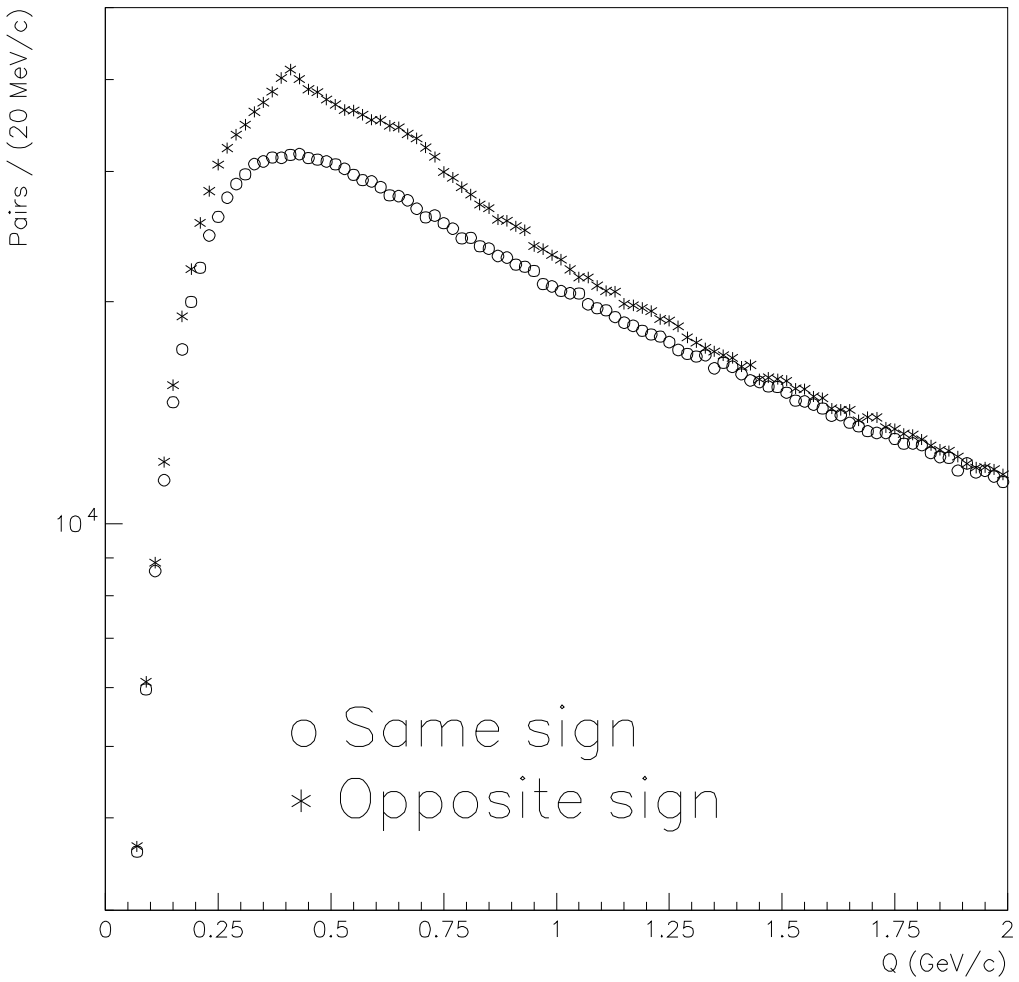

Pairs / (20 MeV/c)
10^4
o Same sign
* Opposite sign
0
0.25
0.5
0.75
1
1.25
1.5
1.75
2
Q (GeV/c)

Figure 2

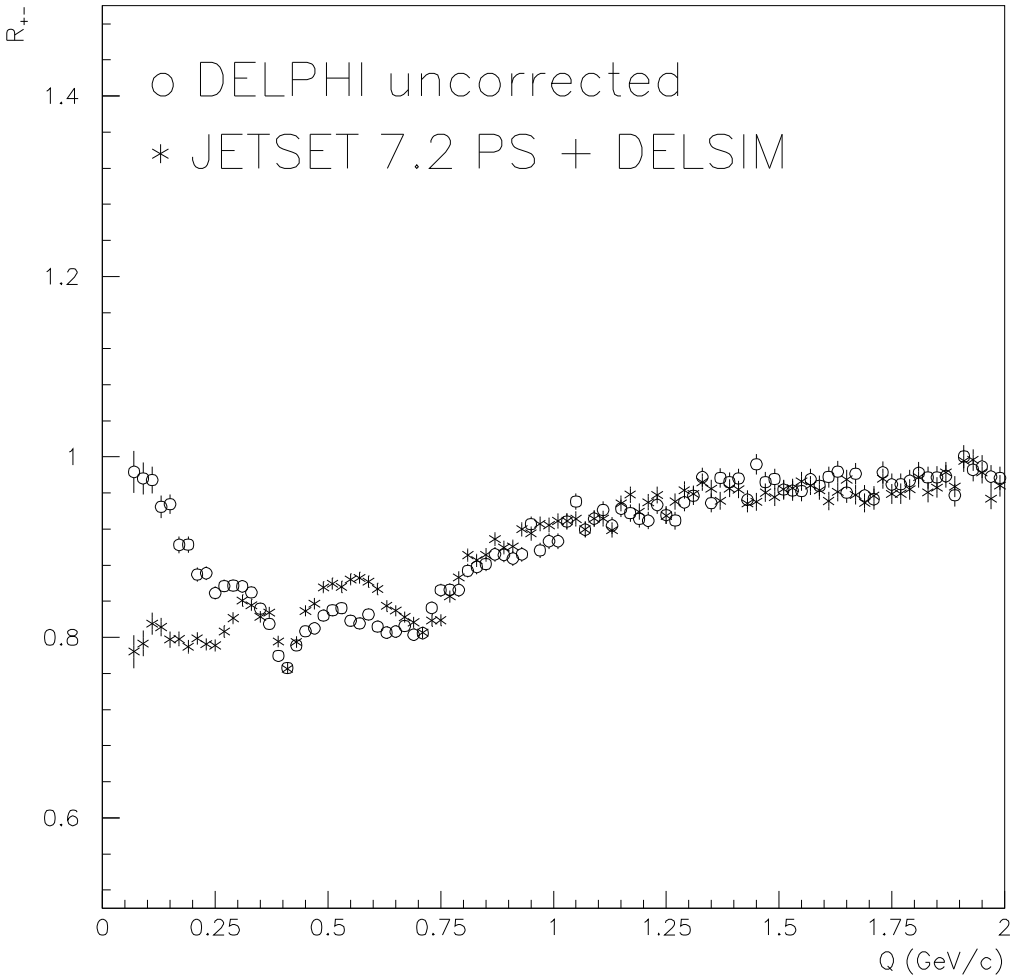

R+-
o DELPHI uncorrected
* JETSET 7.2 PS + DELSIM
1.4
1.2
1
0.8
0.6
0
0.25
0.5
0.75
1
1.25
1.5
1.75
2
Q (GeV/c)

Figure 3

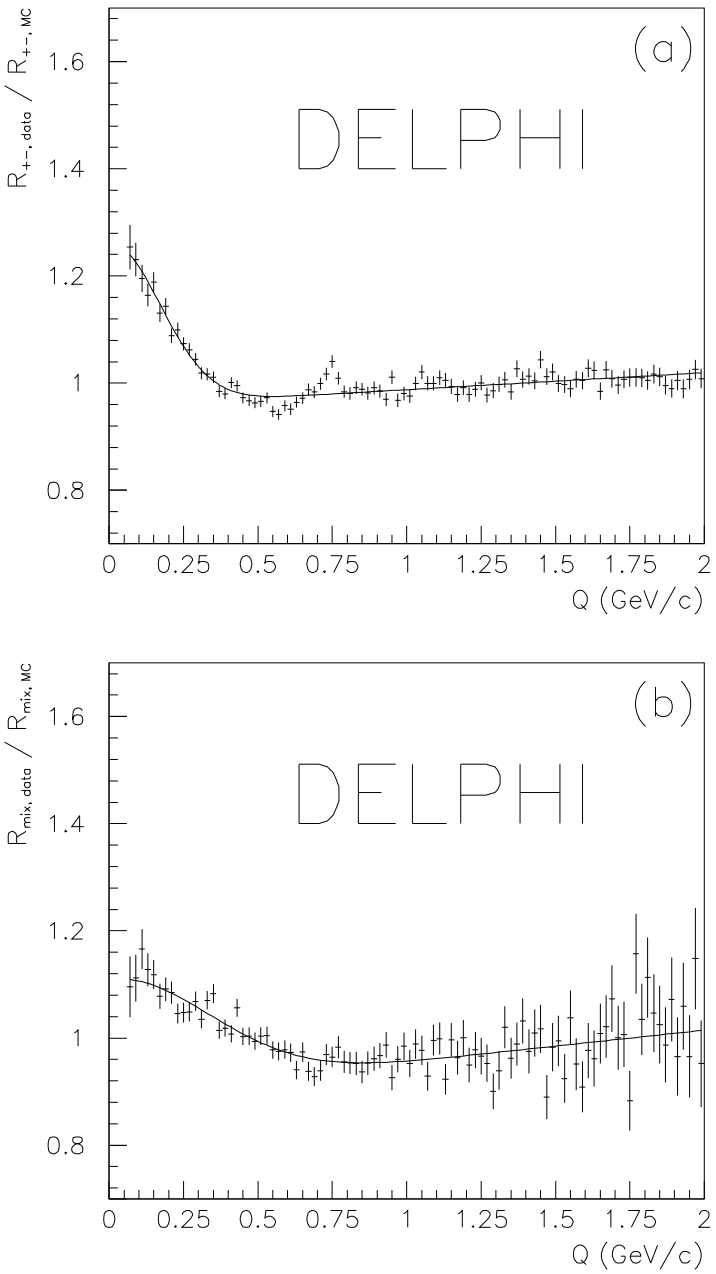
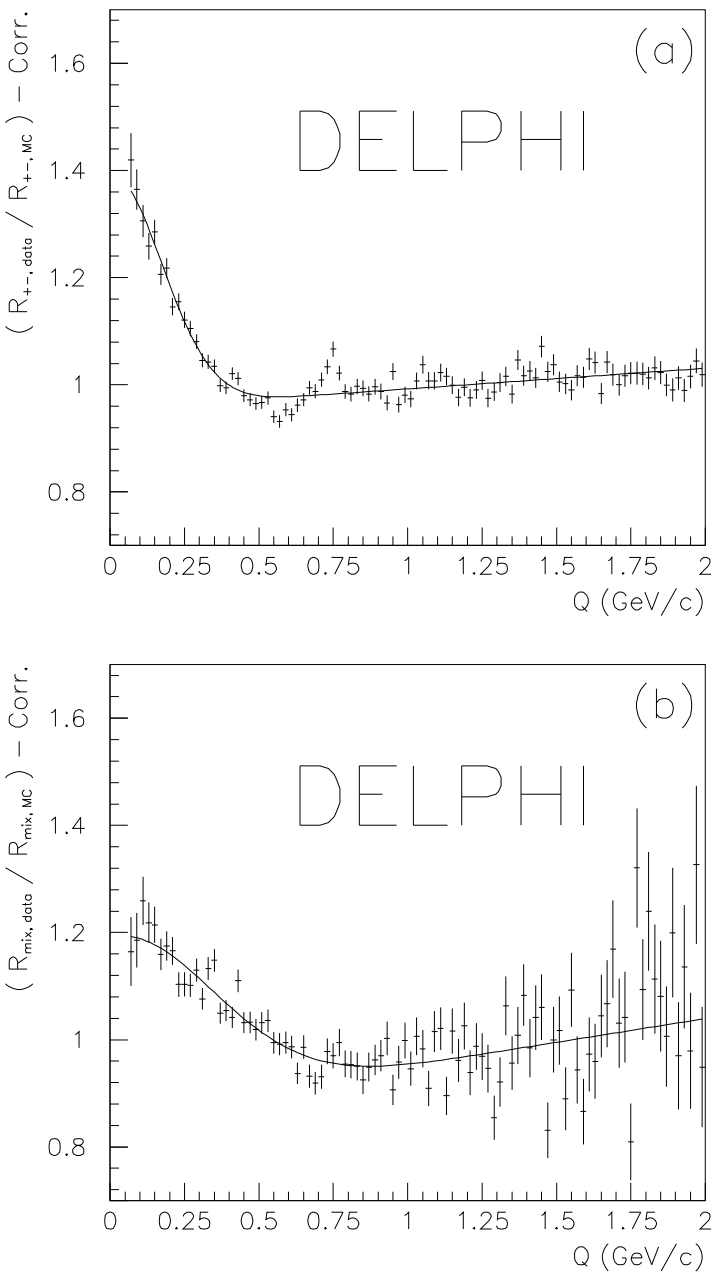

(a)
DELPHI
$R_{+-,\,data}\ /\ R_{+-,\,MC}$
1.6
1.4
1.2
1
0.8
0
0.25
0.5
0.75
1
1.25
1.5
1.75
2
Q (GeV/c)
(b)
DELPHI
$R_{mix,\,data}\ /\ R_{mix,\,MC}$
1.6
1.4
1.2
1
0.8
0
0.25
0.5
0.75
1
1.25
1.5
1.75
2
Q (GeV/c)

Figure 4


(a)
DELPHI
(R+−, data / R+−, MC) − Corr.
1.6
1.4
1.2
1
0.8
0
0.25
0.5
0.75
1
1.25
1.5
1.75
2
Q (GeV/c)
(b)
DELPHI
(Rmix, data / Rmix, MC) − Corr.
1.6
1.4
1.2
1
0.8
0
0.25
0.5
0.75
1
1.25
1.5
1.75
2
Q (GeV/c)