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Interconnection Effects in Multiparticle Production from WW Events at LEP

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Abstract

Interactions between the products of the hadronic decays of different Ws in WW pair events can occur at several stages: from the colour rearrangement between the quarks coming from the primary branching, to the gluon exchange during the parton cascade, to the mixing of identical pions due to Bose-Einstein correlations. Besides the intrinsic interest of their study related to the understanding of the multiparticle production mechanisms, these phenomena can affect the ultimate accuracy in the W mass measurement by LEP 2. The status of the experimental analysis on interconnection effects between W pairs hadronically decaying is reviewed in this paper.

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Interconnections Effects in Multiparticle Production from WW Events at LEP

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Interactions between the products of the hadronic decays of different Ws in WW pair events can occur at several stages: from the colour rearrangement between the quarks coming from the primary branching, to the gluon exchange during the parton cascade, to the mixing of identical pions due to Bose-Einstein correlations. Besides the intrinsic interest of their study related to the understanding of the multiparticle production mechanisms, these phenomena can affect the ultimate accuracy in the W mass measurement by LEP 2. The status of the experimental analysis on interconnection effects between W pairs hadronically decaying is reviewed in this paper.

1. Introduction

The data collected at LEP are at the highest available centre-of-mass energies in e^+e^- interactions, and a new physics window is opened: the production and decay of W boson pairs.

The possible presence of interference (due to colour reconnection and Bose-Einstein correlations (see for example [1–5] and [6] for a review) in hadronic decays of WW pairs has been discussed on a theoretical basis, in the framework of the measurement of the W mass: this interference [6] can induce a systematic uncertainty on the W mass measurement in the 4-jet mode which is of the order of 40 MeV, i.e., comparable with the expected accuracy of the measurement.

Interconnection can happen due to the fact that the typical lifetime of the W ($\tau_W \simeq \hbar/\Gamma_W \simeq 0.1$ fm/c) is one order of magnitude smaller than the typical hadronization times. The interconnection between the products of the hadronic decays of different Ws in WW pair events can occur at several stages:

1. from colour rearrangement between the quarks coming from the primary branching,
2. due to gluon exchange during the parton cascade,
3. in the mixing of identical pions due to Bose-Einstein correlations.

The first two enter in the category of the QCD

effects. The QCD interference effects can mix up the two colour singlets and produce hadrons that cannot be uniquely assigned to either W. The perturbative effects are suppressed by the need to exchange two gluons and conserve the colour; this creates a suppression $(1/N_C^2 - 1)$, such that the effect is expected to be small (and to induce a possible shift of only about 5 MeV in the W mass). Nonperturbative effects are more difficult to compute, and they need models; typically, according to models, such effects can induce shifts of the order of 40 MeV in the W mass [6,7].

The study of Bose-Einstein Correlations (BEC) is complicated by the fact that a complete description would need the symmetrization of the amplitude for the multiparticle system, which is computationally difficult. One must thus make approximations and build models [8]; care should be taken not to distort the multiplicity distribution by increasing the probability of final states with large multiplicity (the bounds from the precise R_b measurements are in this sense very stringent). The subject became very popular due to the prediction [4] that BEC could shift by 100 MeV the measured W mass.

How to investigate experimentally interconnection effects? 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 I shall often refer to this as to the (4q) mode) with the case in which the other W

decays semileptonically ($(2q)$ mode for brevity). These should be equal in the absence of interference between the products of the hadronic decay of the W s.

- A qualitative argument shows that the effect of colour reconnection between the decay products of different W s could affect the charge multiplicity: close to the WW threshold, the presence of two cross-talking dijets in the fully hadronic WW decay allows the evolving particle system to have a larger kinetic energy than in the case of independent dijets with no cross-talk. In a recently proposed model [3], this correlation could lead to a charge multiplicity for $(4q)$ events that is significantly smaller than twice the multiplicity of $(2q)$ events. In addition, effects of colour reconnection are expected to be considerably enhanced in kinematic regions where there is strong overlap between jets originating from different W s. One could be more sensitive to interconnection effects by studying inclusive particle distribution “oriented” by the event axis (like thrust or rapidity). However, a severe experimental warning is given by the fact that WW events are selected mostly by topological cuts, which could create possible biases between the $(4q)$ and the $(2q)$ in the definition of the axis.
- For what is related to BEC, the queen of the observables is the two-particle correlation function. BEC could anyway slightly increase the multiplicity for $(4q)$ events in some models [5].

2. Experimental Results

The cross section for WW production at $\sqrt{s} = 161$ GeV being small (about 3 pb) and the data taking at 183 GeV having just started, the experimental results are based on the analysis of the data taken at 172 GeV. For this energy the WW cross section is about 12 pb; the main background is given by $q\bar{q}$ events, with a cross section (for an effective center of mass energy larger than 10% of the maximum annihilation energy) of about 125

pb. The situation will improve with the analysis of the data at 183 GeV. A total integrated luminosity of 50 pb^{-1} per experiment can be expected before end 1997. The WW cross section is about 15 pb; the cross section for $q\bar{q}$ events is about 105 pb.

- About 4/9 of the WW are $WW \rightarrow 4jets$ events. At threshold, their topology is a clear 4-jet back-to-back topology, with no missing energy; the constrained invariant mass of two jet-jet systems equals the W mass. Still at 172 and 183 GeV these characteristics allow a clean selection, such that the typical efficiency is about 85%, for a purity of about 80%.
- About 4/9 of the WW are $WW \rightarrow 2jets \ell\bar{\nu}$ events. At threshold, their topology is a clear 2-jet back-to-back topology, with a lepton and missing energy opposite to it; the constrained invariant mass of the jet-jet system and of the lepton-missing energy system equals the W mass. Still at 172 and 183 GeV, despite of the boost, these characteristics allow a clean selection, such that the typical efficiency is about 80%, for a purity of about 90%.

For a more detailed description of the selection criteria and of the cross section and branching fractions measurements, see [9].

2.1. QCD Effects

Charged multiplicity and momentum spectrum of charged particles in $WW \rightarrow 4jets$ events and $WW \rightarrow 2jets \ell\bar{\nu}$ events have been studied by DELPHI [10,11], OPAL [12] and L3 [13] looking for possible effects of correlations on the $WW \rightarrow 4jets$ events.

In a recent OPAL paper [12], inclusive distributions of charged particles from the decay of the W in WW events are studied. The main conclusions are that:

- The momentum spectrum of charged particles in $WW \rightarrow 4jets$ events and in $WW \rightarrow 2jets \ell\bar{\nu}$ events agree with the expectations from PYTHIA [14], KORALW [15]

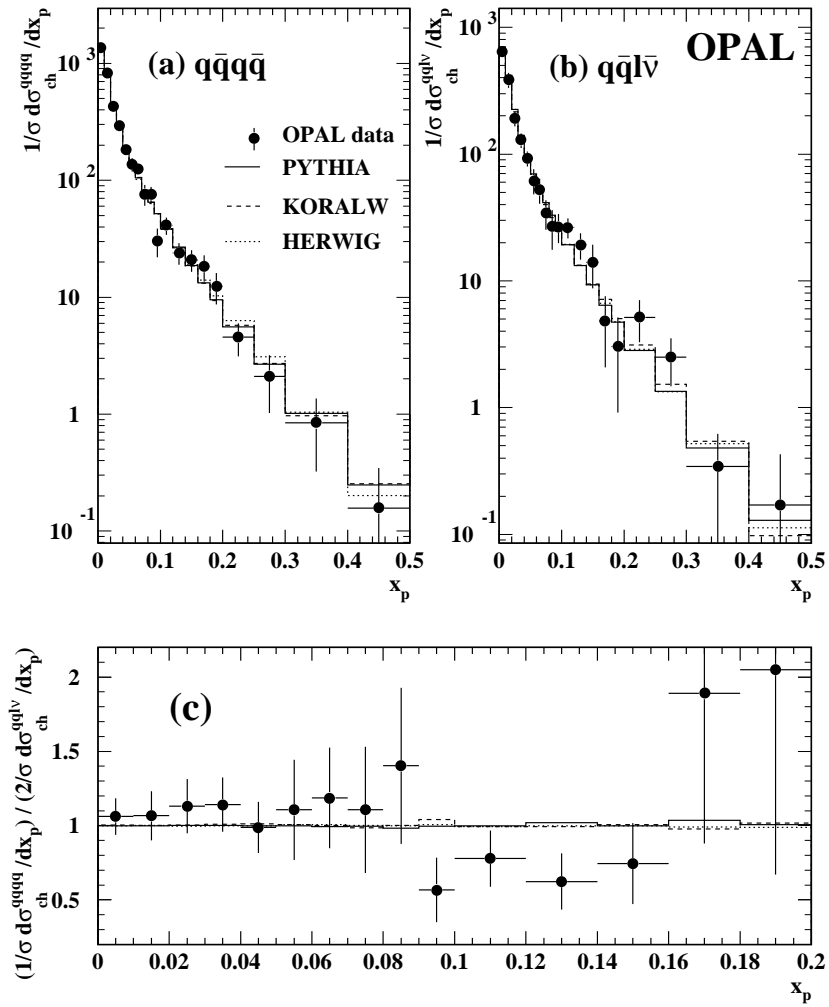


Figure 1. Corrected x_p distributions for (a) $(4q)$ events and (b) $(2q)$ events. The ratio between $(4q)$ and twice $(2q)$ is shown in (c).

and HERWIG [16] (figure 1). No interconnection effects were present in the $WW \rightarrow 4jets$ events simulated using these Monte Carlo programs.

- The mean values of two oriented event shape variables:

$$\begin{aligned} \langle 1 - T \rangle^{(4q)} &= 0.227 \pm 0.036 \pm 0.021 \\ \langle |y| \rangle^{(4q)} &= 1.033 \pm 0.042 \pm 0.025 \end{aligned}$$

in (4q) are also in agreement with the above models without interconnection effects.

- The average momentum fraction $\langle x_p \rangle$ (where $x_p = 2p/\sqrt{s}$) for charged particles in (4q) and in (2q) are also consistent with models, and within 1.5σ between each other:

$$\begin{aligned} \langle x_p \rangle^{(4q)} &= (3.22 \pm 0.13 \pm 0.08) \times 10^{-2} \\ \langle x_p \rangle^{(2q)} &= (3.60 \pm 0.20 \pm 0.11) \times 10^{-2} \\ \langle \Delta x_p \rangle &= (-0.38 \pm 0.25) \times 10^{-2}, \end{aligned}$$

where $\Delta x_p = x_p^{(4q)} - x_p^{(2q)}$.

One could try to increase the sensitivity to interconnection effects by subtracting from the charged momentum distribution in $WW \rightarrow 4jets$ events twice the momentum spectrum in $WW \rightarrow 2jets \ell\bar{\nu}$ events. In a preliminary paper [11], DELPHI observes a $\sim 2\sigma$ effect in the low- x_p region; there is an excess of $3.9 \pm 1.5 \pm 0.7$ charged particles for $x_p < 0.01$ (figure 2a). This result is not confirmed by L3 [13], which observes an excess in the opposite direction (figure 2b) nor by OPAL [12] (figure 1c).

Finally, the measurements of charge multiplicity in (4q) and (2q) are consistent (table 1). One obtains

$$\langle n \rangle^{(4q)} - 2 \langle n \rangle^{(2q)} = 2.5 \pm 1.8(stat+syst). \quad (1)$$

In conclusion, the studies of mean charged multiplicity and inclusive particle distribution do not indicate at the present level of statistics the presence of interconnection effects.

A study which can be very fruitful in the future is the comparison of the momentum spectra for identified hadrons (heavier than pions),

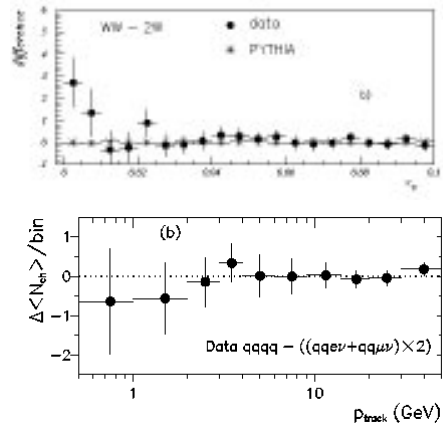


Figure 2. Difference between the x_p distribution for (4q) and twice (2q) as measured by DELPHI (top) and L3 (bottom).

	(4q)	(2q)
L3 preliminary [13]	37.9 ± 0.9	19.4 ± 0.6
DELPHI [10]	$40.6 \pm 1.7 \pm 1.1$	$18.0 \pm 0.9 \pm 0.6$
OPAL [12]	$38.3 \pm 1.1 \pm 0.6$	$18.4 \pm 0.9 \pm 0.4$
Average	38.94 ± 1.07	18.22 ± 0.73

Table 1
Mean charged multiplicities in the (4q) and in the (2q) channels. The L3 value was not used in the calculation of the average, since no systematic error was specified.

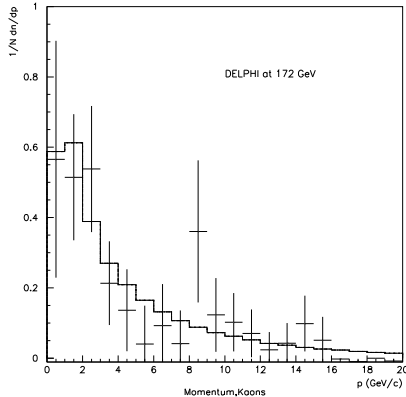


Figure 3. Momentum spectrum of identified K^\pm in $(4q)$ events, compared to the expectation from PYTHIA (solid line).

for which the multiplicity suppression at low x is expected to be stronger than for the inclusive (pion-dominated) spectrum [17]. A preliminary analysis by DELPHI [18], based on the 1996 data, shows agreement with PYTHIA without interconnection effects (figure 3); the errors are completely dominated by statistics.

2.2. Bose-Einstein Correlations

BEC manifest themselves in 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 as a probe. For pairs of particles, it is defined as

$$R(p_1, p_2) = \frac{P(p_1, p_2)}{P_0(p_1, p_2)}, \quad (2)$$

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 $G[f(x)] = \int f(x) e^{-i(p_1 - p_2) \cdot x} dx$ 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. Experimentally, the effect is often described in terms of 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 can then be written as

$$R(Q) = \frac{P(Q)}{P_0(Q)}, \quad (3)$$

which is frequently parametrized by the function

$$R(Q) = 1 + \lambda e^{-r^2 Q^2}. \quad (4)$$

In the above equation, in the hypothesis of a pion source spherically symmetric, the parameter r gives the RMS radius source, and λ is the strength of the correlation between the pions. DELPHI [19] has shown that by taking only primary pions from e^+e^- annihilation λ is consistent with 1, and thus λ can be interpreted as the fraction of interacting pairs. The data from e^+e^- annihilations from PEP energies to LEP show values of r around 0.5 fm; the value of λ strongly depends on the analysis technique, ranging from 0.2 to 1.

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

- Pairs of particles of opposite sign. The drawback of this choice is that many correlated unlike sign pairs come from resonance decays, and the influence of those on the correlation function has to be corrected for by means of a simulation (with possible biases).
- Pairs of particles taken from artificial events constructed by mixing particles from different real events. The mixing technique introduces arbitrariness, and possible biases.

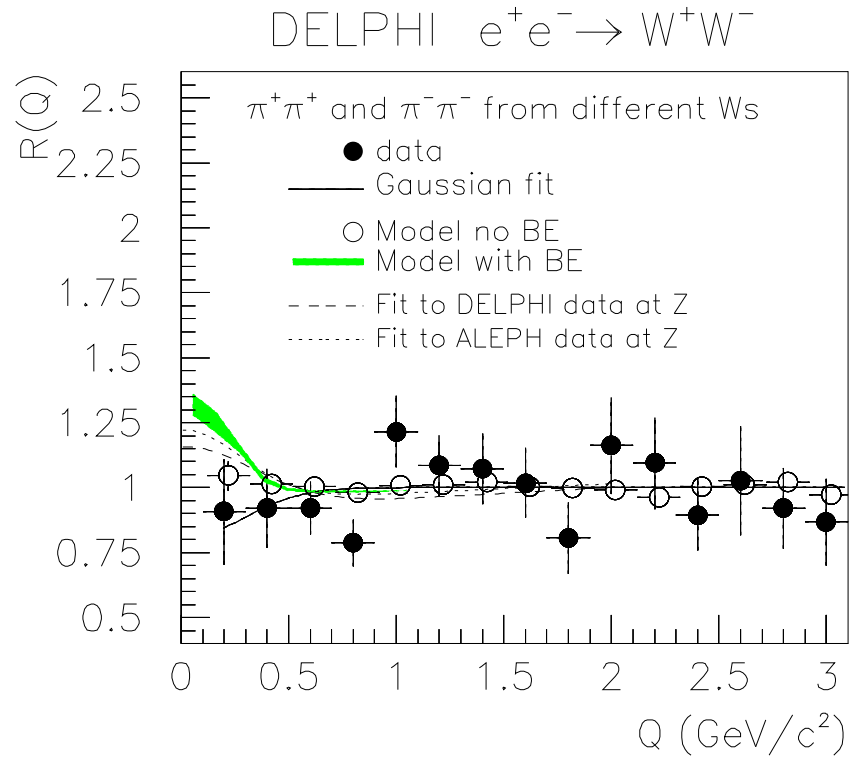


Figure 4. The correlation function $R(Q)$ for like-sign particles arising from different W s for data (closed circles) and simulated events without Bose-Einstein symmetrization (open circles). The shaded area represents the model prediction for events with Bose-Einstein symmetrization (see text). The solid curve shows the result of the fit using equation (4). The dashed and dotted curves are results of fits to $R(Q)$ distributions for like-sign particles measured in Z decays.

- Monte Carlo events simulated without BEC.

Four analyses are proposed for detecting BEC between like-sign pions from different Ws. DELPHI presented two analyses on the subject, one published [20] and one preliminary [11]. ALEPH presented also two analyses [21]. All are based on the sample of 10 pb^{-1} collected at $\sqrt{s} = 172 \text{ GeV}$.

1. DELPHI [20] proposes a technique which uses the unlike-sign reference sample without need of the simulation for correcting for the effect of resonances (provided the colour reconnection effects are not large).

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

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

$$R(Q) = \frac{P_{++}^{(4q)}(Q) - 2P_{++}^{(2q)}(Q)}{P_{+-}^{(4q)}(Q) - 2P_{+-}^{(2q)}(Q)} \quad (5)$$

is shown in figure 4.

Since no enhancement of the correlation function is observed at low Q values, the parameter r is not well defined. The fit to the correlation function with expression (4) was therefore performed with a fixed

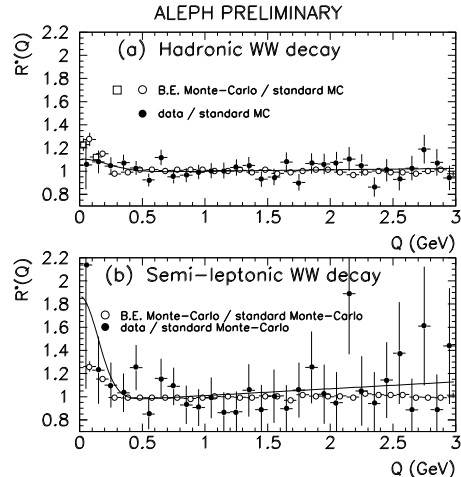


Figure 5. Ratio of both data (full circles) and Monte Carlo with BEC (open circles) to the Monte Carlo without BEC for the hadronic and semi-leptonic W decays. The open squares in (a) show the Monte Carlo with BEC in each W decay only. The solid line shows the result of the fit to the data.

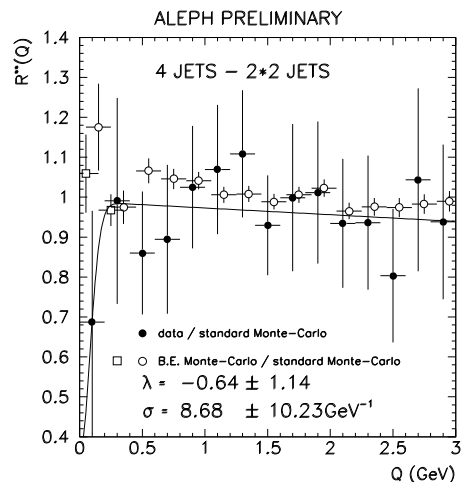


Figure 6. The ratio of the data (full circles) and of the Monte Carlo with BEC (open circles) to the Monte Carlo without BEC for pion pairs from different W. Open squares as in the previous figure.

value of $r=0.5$ fm, as measured in Z decays. The fit (shown by the solid line) yielded the value:

$$\lambda = -0.20 \pm 0.22(stat) \pm 0.08(syst). \quad (6)$$

At the present level of statistics, no evidence is observed for Bose-Einstein correlations between pions from different Ws. If the effect were present, it would be visible (shaded area in the figure); data do not show it at 2σ . Figure 4 also shows $R(Q)$ distributions predicted using WW events generated by PYTHIA with the LUBOEI routine [14]. When no Bose-Einstein effects are included, the correlation function $R(Q)$ is found to be equal to one within errors in the whole Q -region presented, in good agreement with the data (open circles).

2. Another DELPHI analysis [11] studies the correlation function between same-sign pions in $(4q)$ and in $(2q)$ events, using a reference sample from event mixing. If the pions from different Ws were completely correlated, $R(Q)$ would be the same in $(2q)$ and in $(4q)$; otherwise, it would be larger in $(2q)$ (since the pairs of uncorrelated pions in $(4q)$ would dilute the effect).

Within the limited statistics, the data disfavor the complete correlation scenario.

3. A first ALEPH analysis [21] starts from the tuning of the simulation to reproduce the two-particle correlation in the data (about 1 pb^{-1}) taken at the Z in 1996 for calibration purposes. This is done by introducing in the simulation BEC according to the technique described in [22]. Three two-particle correlation functions $P(Q)$ can then be constructed from Monte Carlo in $(4q)$:

- A sample $P_0(Q)$ without BEC;
- A sample $P^{(1)}(Q)$ with BEC between all pion pairs;
- A sample $P^{(1/2)}(Q)$ with BEC only between π from the same W.

The last two coincide in $(2q)$ events. The experimental results are shown in figure 5; the function $P^{(1/2)}(Q)/P_0(Q)$ (open squares) provides the best approximation of the experimental result $P(Q)/P_0(Q)$ (closed circles). The data favour the hypothesis of no cross-talk between pions from different Ws.

4. Finally, a second ALEPH analysis [21] is similar to the DELPHI analysis described at item 1. A correlation function defined as in Eq. 5 is computed, and then normalized to the same function from the simulation without BEC to remove possible residual biases. The results are shown in figure 6; again, the data disfavor the hypothesis of BEC between π from different Ws.

The general conclusion on BEC is that two experiments disfavor (one at the 2σ level, the other at the 1σ level) the hypothesis of complete BEC between pions from different Ws.

3. Conclusions

At the present level of statistics there is no evidence for Bose-Einstein correlations between pions originating from different Ws in $WW \rightarrow 4jets$ events. A complete Bose-Einstein correlations between such pions is unlikely.

From the results obtained on hadronic W decays, we observe that the charged multiplicity from WW systems in which both Ws decay hadronically is consistent with twice that from a W whose partner decays semileptonically:

$$\frac{2 \langle n \rangle^{(2q)}}{\langle n \rangle^{(4q)}} = 0.936 \pm 0.045. \quad (7)$$

As discussed in [10,12], this is one of the facts ruling out the model [3], which predicts a 10% excess in multiplicity for the $(2q)$ channel. However, at this level of statistics only such extreme colour reconnection models can be probed.

The studies of charged multiplicity and inclusive particle distributions do not indicate at the present level of statistics the presence of interconnection effects. One can average the $(4q)$ and the

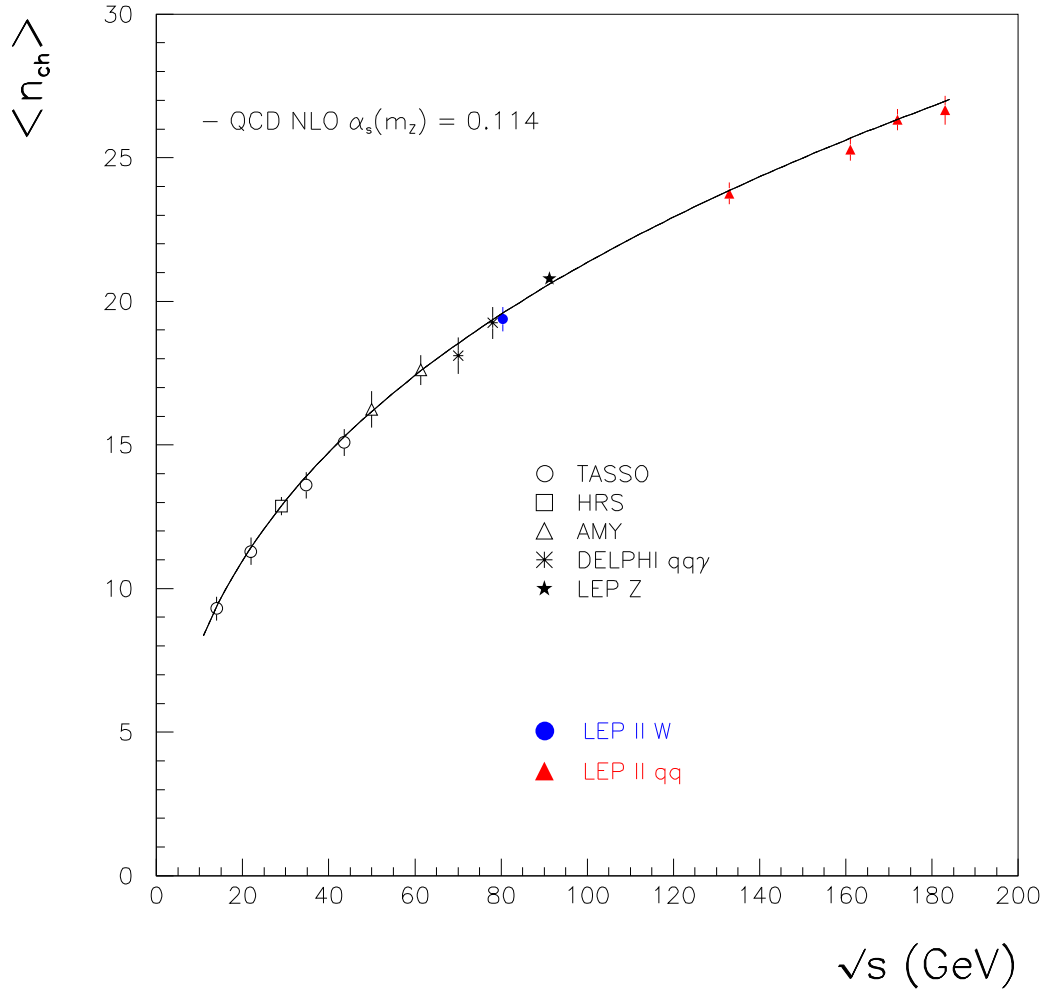


Figure 7. Measured charged multiplicity in $e^+e^- \rightarrow q\bar{q}$ events as a function of centre-of-mass energy \sqrt{s} . The LEP II results on the W are compared with other experimental results and with a fit to a prediction from QCD in Next to Leading Order. The measurements have been corrected for the different proportions of $b\bar{b}$ and $c\bar{c}$ events at the various energies.

($2q$) events to obtain the best value of the mean charged multiplicity in W hadronic decays:

$$\langle n_W \rangle = 19.03 \pm 0.43(\text{stat} + \text{syst}). \quad (8)$$

The value of $\langle n_W \rangle$ is also plotted in Figure 7 at an energy value corresponding to the W mass, together with a recent compilation of e^+e^- data at different centre-of-mass energies [23]; it has been increased by 0.35 units to account for the different proportion of $b\bar{b}$ and $c\bar{c}$ events in W decays than in continuum e^+e^- events [24]. It lies on the same curve as the e^+e^- data, consistent with the prediction from QCD including NLO corrections [25].

It should be underlined that analyses based on a WW statistics larger by one order of magnitude will be possible in one year from now, and important news, which could affect our understanding of multiparticle production mechanisms and of the ultimate accuracy on the W mass measurement, can be expected very soon.

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