DELPHI 97-78 CONF 64
28 July, 1997

Charged Particle Multiplicity in $e^+e^- \to \mathrm{q\bar{q}}$ events at 161 and 172 GeV and from the decay of the W Boson

Preliminary

DELPHI Collaboration

P. Abreu
LIP, IST, FCUL - Av. Elias Garcia, 14-1^o,
P-1000 Lisboa Codex, Portugal
A. De Angelis
CERN, CH-1211 Geneva 23, Switzerland
L. Vitale
Dipartimento di Fisica, Università di Trieste and
INFN, Via A. Valerio 2, I-34127 Trieste, Italy

Abstract

The data collected by DELPHI in 1996 have been used to measure the average charged particle multiplicities and dispersions in $q\bar{q}$ events at centre-of-mass energies of $\sqrt{s}$ = 161 GeV and $\sqrt{s}$ = 172 GeV, and the average charge multiplicity in WW events at $\sqrt{s}$ = 172 GeV. The multiplicities in $q\bar{q}$ events are consistent with the evolution predicted by QCD. The dispersions in the multiplicity distributions are consistent with Koba-Nielsen-Olesen (KNO) scaling. The average multiplicity of charged particles in hadronic W decays has been measured for the first time; its value, $19.23 \pm 0.74(stat + syst)$, is consistent with that expected for an e^+e^- interaction at a centre-of-mass energy equal to the W mass. The charge multiplicity in W decays shows no evidence of effects of colour reconnection between partons from different W's is observed at the present level of statistics.

Paper submitted to the LP'97 Conference
Hamburg, July 28 - August 1st

1 Introduction

The average charged particle multiplicity is one of the basic observables characterizing hadronic final states. It has been extensively studied both theoretically and experimentally, and many results exist at several centre-of-mass energies in $e^+e^- \rightarrow \mathrm{q\bar{q}}$ events [1].

The data collected at LEP in 1996 are at the highest available centre-of-mass energies in e^+e^- interactions, 161 and 172 GeV, and a new physics window is opened: the production and decay of W boson pairs. The cross-section for WW production rises rapidly from about 3 pb at 161 GeV to about 12 pb at 172 GeV. Besides the study of the evolution of charge multiplicity with energy, this channel is important because it allows a comparison of the average charged multiplicity in W hadronic decays when both W's decay in fully hadronic modes with the case in which one of the W's decays semileptonically. These two multiplicities should be equal in the absence of interference between the products of the hadronic decay of the W's.

The presence of interference (due to colour reconnection [2, 3, 4] and Bose-Einstein correlations [5, 6]) in hadronic decays for WW pairs has been recently discussed on a theoretical basis, in the framework of the measurement of the W mass. A first measurement of Bose-Einstein correlations in WW events has shown, within the limited statistics, no evidence for such correlations between pions from different W's [7]. A qualitative argument shows that the effect of colour reconnection between the decay products of different W 's could affect the charge multiplicity. The presence of two cross-talking dijets in the fully hadronic WW decay allows the evolving particle system to pick states with smaller invariant mass than in the case of independent dijets with no cross-talk. In a recently proposed model [4], this correlation could lead to a significantly smaller charged multiplicity for a WW system in which both W's decay hadronically compared to twice the multiplicity of a W whose partner decays semileptonically. 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. The presence of Bose-Einstein correlations could increase in some models [6] the multiplicity in WW events.

In this paper, the data recorded using the DELPHI detector [8, 9] have been used to compute the average and the dispersion of the charge multiplicity distributions in $\mathrm{q\bar{q}}$ events at 161 and 172 GeV and in WW events at 172 GeV. The multiplicity in $\mathrm{q\bar{q}}$ events is compared with the evolution predicted by QCD. The multiplicity in W decays is discussed as a probe for correlations between the W decay products. Since no significant difference is found between the fully hadronic and the mixed hadronic-leptonic decay modes, both are used to extract the first determination of the average charged multiplicity in W decays.

The paper is structured as follows. Section 2 describes the detector, the data sample and the track selection. Section 3 describes the selection and analysis of $\mathrm{q\bar{q}}$ data. Section 4 describes the selection and analysis of WW data. Finally in Section 5 results are discussed and conclusions are drawn.

2 Data Sample and Event preselection

During 1996, DELPHI collected data at centre-of-mass energies around 161 GeV and around 172 GeV with integrated luminosities of 9.96 pb^{-1} and of 10.14 pb^{-1} respectively.

A preselection of hadronic events in both samples was made, requiring a multiplicity of at least 6 for charged particles with momentum p above 400 MeV/c, angle θ with respect to the beam direction between 20° and 160°, a track length of at least 30 cm in the Time Projection Chamber (DELPHI's main tracking detector), a distance of closest approach to the interaction point of less than 4 cm in the plane perpendicular to the beam axis, and of less than 10 cm along the beam axis, and that the total energy of the charged particles exceeded 0.15 times the centre-of-mass energy $\sqrt{s}$. In the calculation of the energies E, all charged particles were assumed to have the pion mass.

Charged particles were then used in the analysis if they had $p > 100$ MeV/c, a relative error on the momentum measurement $\Delta p/p < 1$, $20° < \theta < 160°$, a track length of at least 30 cm in the TPC, and a distance of closest approach to the primary vertex smaller than 3 cm in the plane perpendicular to the beam axis and 6 cm along the beam axis.

The influence of the detector on the analysis was studied with the full DELPHI simulation program, DELSIM [9]. Events were generated with PYTHIA 5.722 and JETSET 7.409 [10], with parameters tuned to fit LEP1 data from DELPHI [11]. The Parton Shower (PS) model was followed. The particles were followed through the detailed geometry of DELPHI giving simulated digitizations in each detector. These data were processed with the same reconstruction and analysis programs as the real data. The sizes of the simulated samples were 20995 $q\bar{q}\gamma$ and 4806 WW events at 161 GeV; 62823 $q\bar{q}\gamma$ and 27546 WW events at 172 GeV. An additional 100,000 events were also generated with JETSET/PYTHIA for each energy and channel without Initial State Radiation effects, to compute the average charged multiplicity and dispersion at generator level. In the WW case two samples were generated, one with two W bosons and the other with only one W with energy equal to half the centre-of-mass energy; for both samples only hadronic W decays were generated.

To check the capability of the simulation to model the efficiency for the reconstruction of charged track, the sample of 0.9 pb^{-1} collected at the Z during 1996 was used. From this sample the average charged particle multiplicity at the Z was measured to be $20.98 \pm 0.04(stat)$, well in agreement with the world average of 20.99 ± 0.14 [14]. A "multiplicity scale" uncertainty of 0.7% can thus be assumed.

3 Analysis of $q\bar{q}$ decays

3.1 Charged multiplicity in $q\bar{q}$ events at 161 GeV

The cross-section for $e^+e^- \to q\bar{q}(\gamma)$ above the Z peak is dominated by radiative $q\bar{q}\gamma$ events; the initial state radiated photons (ISR photons) are generally aligned along the beam direction and not detected. In order to compute the hadronic centre-of-mass energy, the procedure described in [12] was used. The procedure clusters the particles into two jets using the Durham algorithm [13], excluding candidate ISR photons. Assuming an ISR photon along the beam pipe if no candidate ISR photon has been detected, the energy of the ISR photon is computed from the jet directions assuming massless kinematics. The effective centre-of-mass energy of the hadronic system, $\sqrt{s'}$, is calculated as the invariant mass of the system recoiling from the ISR photon. The spectrum of the calculated energies for the events collected at 161 GeV is shown in Figure 1 (data and simulation are normalized to the same number of events). The full width at half maximum of the peak corresponding to the radiative return to the Z is about 10 GeV, in agreement with simulation. The contamination from WW pairs was found to be small, and is shown in the same figure.

The method used to obtain the hadronic centre-of-mass energy overestimates the true energy in the case of double hard radiation in the initial state. For instance, if the two ISR photons are emitted back to back, the remaining two jets may also be back to back, but with energy much smaller than the beam energy. Cutting on the total energy measured in the detector reduces the contamination from such events. Events with reconstructed hadronic centre-of-mass energy ($\sqrt{s'}$) above 150 GeV, with total energy seen in the detector above 105 GeV, and with at least 9 charged particles with momentum above 100 MeV/c, were used to compute the multiplicity at 161 GeV. A total of 282 events were selected.

The background from WW events was estimated from the simulation to be 7.9 events. The contamination from double radiative returns to the Z (within 10 GeV of the nominal Z mass) was estimated from the simulation to be around 2%.

The measured average multiplicity of charged particles with $p > 0.1$ GeV/c, after subtraction of the WW background events, is $22.54 \pm 0.40(stat)$, to be compared to $22.75 \pm 0.12(stat)$ in the $\mathrm{q\bar{q}}$ PS simulation including detector effects. The dispersion of the multiplicity distribution in the data is $6.55 \pm 0.28(stat)$, to be compared to $6.63 \pm 0.08(stat)$ in the $\mathrm{q\bar{q}}$ PS simulation. After correcting for detector effects, the average charged multiplicity comes out to be $< n_{ch} >= 25.45 \pm 0.45(stat)$, and the dispersion is $D = 7.80 \pm 0.34(stat)$. The above values include the products of the decays of particles with lifetime $\tau < 10^{-9}$ s, in particular $\mathrm{K^0_S}$ and Λ.

In order to investigate possible sources of error due to the correction procedure, the average multiplicity was also computed by integrating the distributions of rapidity, $y = \frac{1}{2}\ln\frac{E-p_{||}}{E+p_{||}}$, with respect to the thrust axis and of $\xi_E = -\ln(2E/\sqrt{s})$, both distributions having been corrected bin by bin using the simulation. In the calculation of the energies, all particles were again assumed to have the pion mass. The ξ_E distribution was integrated up to a value of 6.3, and the extrapolation to the region above this cut was based on the simulation at generator level.

Half of the value from this extrapolation, 0.04, was added in quadrature to the systematic error. The average charged multiplicity in the selected events, including the above corrections, is 25.19 and 25.46 respectively from the y and ξ_E distribution, consistent with the value, 25.45, obtained from the average observed multiplicity. In the selected events, one is integrating over hadronic energies above 150 GeV. By comparing the multiplicity and the dispersion obtained using JETSET PS at 161 GeV with the average value above 150 GeV from the energy spectrum of the selected events in the simulation, it was found that the values of $< n_{ch} >$ and D differ by 0.21 and 0.10 respectively. These shifts were also added in quadrature to the systematic error. As a central value for the measurement of the charged multiplicity the result of the integration of the ξ_E distribution was taken, since the detection efficiency depends mostly on the momentum of the particle. The maximum shift of this value with respect to the values from the above methods, 0.28, was added in quadrature to the systematic error. The systematic errors due to the statistics of the Monte Carlo samples were found to be 0.1, both for the multiplicity (with ξ_E) and for the dispersion, and were added in quadrature to the systematic errors.

Finally, for the centre-of-mass energy of 161 GeV, the values

$$< n_{ch} > \; = \; 25.46 \pm 0.45(stat) \pm 0.37(syst) \tag{1}$$

$$D \; = \; 7.80 \pm 0.34(stat) \pm 0.14(syst) \tag{2}$$

were obtained for the average charged multiplicity and for the dispersion. The systematic errors were obtained by adding in quadrature the contributions from the sources above and the multiplicity scale error (see section 2).

3.2 Charged multiplicity in $\mathrm{q\bar{q}}$ events at 172 GeV

Events with reconstructed hadronic centre-of-mass energy ($\sqrt{s'}$) above 155 GeV were used to compute the multiplicity at 172 GeV.

A total of 235 hadronic events were selected by requiring that the multiplicity for charged particles (with $p > 100$ MeV/c) was larger than 9, that the total energy of the charged particles exceeded $0.2\sqrt{s}$, and that the narrow jet broadening [15] was smaller than 0.1. The distribution of the narrow jet broadening for the data, compared to the expectations from simulation, is shown in Figure 2. From the simulation it was calculated that the expected background coming from WW events was 4.1±0.1 events. The contamination from double radiative returns to the Z (within 5 GeV of the nominal Z mass) was estimated by simulation to be around 3%.

The average multiplicity of charged particles with $p > 0.1$ GeV/c measured in the selected events, after subtraction of the WW background estimated by simulation, is $22.25 \pm 0.44(stat)$, to be compared to $22.04 \pm 0.06(stat)$ in the $\mathrm{q\bar{q}}$ PS simulation including detector effects. The dispersion of the multiplicity distribution in the date is $6.69 \pm 0.31(stat)$, to be compared to the dispersion from the $\mathrm{q\bar{q}}$ PS simulation of $6.39 \pm 0.04(stat)$. After correcting for detector effects, the average charged multiplicity is $< n_{ch} >= 26.60 \pm 0.53(stat)$, and the dispersion is $D = 8.46 \pm 0.40(stat)$. The above values include the products of the decays of particles with lifetime $\tau < 10^{-9}$ s, in particular $\mathrm{K^0_S}$ and Λ.

The average multiplicity was also computed, as already done in Section 3.1, by integrating the distributions of rapidity with respect to the thrust axis and of ξ_E. The ξ_E distribution was integrated up to a value of 6.3, and the extrapolation to the region above this cut was based on the simulation at generator level. Half of the value from that extrapolation, 0.07, was added in quadrature to the systematic error. The average charged multiplicity of the selected events, including the above corrections, is 26.78 and 26.52 respectively from the y and ξ_E distribution, consistent with the value from the average observed multiplicity.

To estimate the systematic error associated with the procedure to remove the contribution from the WW events, the value of the cut on the narrow jet broadening was varied from 0.06 to 0.14 in steps of 0.02. The new values for the average charged multiplicity and the dispersion were stable within these variations, and the highest shifts with respect to the previous results, 0.38 and 0.45 respectively, were added in quadrature to the systematic error. The effect of the uncertainty on the WW cross-section was found to be negligible.

By comparing the multiplicity and the dispersion obtained using JETSET PS at 172 GeV with the average value above 155 GeV from the energy spectrum of the selected events, it was found that the values of $< n_{ch} >$ and D differ by 0.27 and 0.13 respectively. These shifts were added in quadrature to the systematic error. As a central value for the measurement of the charged multiplicity the result of the integration of the ξ_E distribution was taken, since the detection efficiency depends mostly on the momentum of the particle. The maximum shift with respect to the values obtained with the previous methods, 0.26, was added in quadrature to the systematic error. The systematic errors due to the statistics of the Monte Carlo samples were found to be 0.06, both for the multiplicity (with ξ_E) and for the dispersion, and were added in quadrature to the systematic errors. The multiplicity scale error of 0.7% was also accounted for (section 2).

Finally, for the centre-of-mass energy of 172 GeV, the values

$$< n_{ch} > \; = \; 26.52 \pm 0.53(stat) \pm 0.54(syst) \tag{3}$$
$$D \; = \; 8.46 \pm 0.40(stat) \pm 0.47(syst) \tag{4}$$

were obtained for the average charged multiplicity and for the dispersion. The systematic errors were obtained by adding in quadrature the contributions from the sources above.

4 Analysis of WW decays

The analysis of WW decays was performed only on the 172 GeV data, since the sample collected at that energy was significantly larger than that at 161 GeV.

4.1 Fully hadronic channel (WW$\rightarrow$ 4j)

Events with both W's decaying into $q\bar{q}$ are characterized by high multiplicity, large visible energy, and tendency of the particles to be grouped in 4 jets. The events were pre-selected by requiring at least 12 charged particles (with $p > 400$ MeV/c), with a total energy (charged plus neutral) above 20% of the centre-of-mass energy.

The background at 172 GeV is dominated by $q\bar{q}(\gamma)$ events. For these events, the hadronic centre-of-mass energy was computed as described in the previous section. To remove the radiative hadronic events it was then required that the hadronic centre-of-mass energy be above 110 GeV.

The particles in the event were forced to 4 jets using the Durham algorithm, and the events were kept if all jets had charged multiplicity larger than 1. It was also required that the separation between the jets ($y_{\rm cut}$ value) be larger than 0.005. The combination of these two cuts removed most of the remaining semi-leptonic WW decays and the 2 and 3 jet events of the $q\bar{q}$ background.

A four constraint fit was applied, imposing energy and momentum conservation except along the beam line, and the equality of the two dijet masses. Events were accepted only if the product of the fitted minimal jet energy and the smallest angle between the fitted jet directions was greater than 13 GeV·rad.

The purity and the efficiency of the selected data sample were estimated using simulation to be about 68% and 73% respectively. The data sample consists of 58 events, where 57.2 are expected from simulation. The expected background was subtracted bin by bin from the observed distributions. The values of $< n_{ch} >$ before and after the background subtraction were 34.5 and 35.4 respectively.

The final value of $< n_{ch} >$ was estimated by integrating the ξ_E distribution. To account for inefficiencies due to detector effects and selection criteria, a correction factor was computed, to be the ratio bin by bin of the ξ_E distributions at generator level and after full simulation of the DELPHI detector and application of the above cuts. The following final value was obtained:

$$< N_{had}^{(HAD)}(2W) > \; = \; 40.6 \pm 1.7(stat) \pm 1.1(syst)\,, \tag{5}$$

where the systematic error accounts for variation of the selection criteria (0.8), change of the $q\bar{q}$ cross-sections within the error of the measured value [16] (0.04), uncertainty on the modelling of the background (0.64), and limited statistics in the simulated sample (0.08). The value of $< n_{ch} >$ was also estimated from the average multiplicity distribution obtaining $40.3 \pm 1.7(stat)$, and the difference (0.36) from the reference value was taken as an extra systematic error. Related to the uncertainty on the modelling of the background, two sources were considered, one due to the modelling of the 4-jet rate in the simulation, and the other related to the modelling of the multiplicity. The uncertainty on the modelling of the background is the sum in quadrature of three contributions:

- Multiplicity at 172 GeV. A relative uncertainty as in Eq. (3) was assumed; this gives a multiplicity error of 0.43.

- Modelling of the 4-jet rate. The agreement between data and simulation was studied in a sample of 4-jet events at the Z, with y_{cut} ranging from 0.003 to 0.005. The rate of 4-jet events in the simulated sample was found to reproduce the data within 10%. The correction due to background subtraction was correspondingly varied by 10%, which gives an uncertainty of 0.16.

- Multiplicity in 4-jet events. The average multiplicity of 4-jet events selected at the Z for a value of $y_{cut} = 0.005$ is larger by $(2.8 \pm 1.3(stat))\%$ than the corresponding value in the simulation. A shift by 2.8% in the multiplicity for 4-jet events induces a shift of 0.45 on the value in Eq. (5).

The presence of interference between the jets coming from the different W's could create subtle effects, such as to make the application of the fit imposing equal the masses inadequate. For this reason a different four constraint fit was performed, leaving the dijet masses free and imposing energy-momentum conservation. Of the three possible combinations of the four jets into WW pairs, the one with minimum mass difference was selected for the cuts. The average multiplicity obtained in this case was 41.4, again fully consistent with (5).

4.2 Mixed Hadronic and Leptonic Final States (WW$\to 2jl\nu$)

Events in which one W decays into 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 seven or more charged particles, with a total energy (charged plus neutral) above $0.2\sqrt{s}$, and a missing momentum larger than $0.1\sqrt{s}$. Events in the $q\bar{q}\gamma$ final state with ISR photons at small polar angles, which would be lost inside the beam pipe, were suppressed by requiring the polar angle of the missing momentum vector to satisfy $|\cos\theta_{miss}| < 0.94$.

Using the missing momentum as an additional massless neutral particle (the candidate neutrino), the particles in the event were forced to 4 jets using the Durham algorithm. The jet for which the fractional jet energy carried by the highest momentum charged particle was greatest was considered as the "lepton jet". The most energetic charged particle in the lepton jet was considered the lepton candidate, and the event was rejected if its momentum was smaller than 10 GeV/c or greater than 65 GeV/c. The "neutrino jet" was considered the jet clustered around the missing momentum. The event was discarded if the invariant mass of the 2 hadronic jets was smaller than 20 GeV/c^2.

At this point three alternative topologies were considered:

- Muon sample: when the lepton candidate was tagged as a muon and its isolation angle, with respect to other charged particles above 1 GeV/c, was above 10°, the event was accepted if the lepton momentum was greater than 20 GeV/c, or if it was greater than 10 GeV/c and the value of the $y_{\rm cut}$ parameter required by the Durham algorithm to force the event to a 4-jet configuration was greater than 0.003.
- Electron sample: when the lepton candidate had associated electromagnetic energy deposited in the calorimeters larger than 20 GeV, and isolation angle (defined as above) greater than 10 degrees, the event was accepted if the required value of $y_{\rm cut}$ was greater than 0.003.
- Inclusive sample: the events were also accepted if the "lepton" momentum was larger than 20 GeV/c and greater than half of the jet energy, the missing momentum was larger than $0.1\sqrt{s}$, the required value of $y_{\rm cut}$ was greater than 0.003, and no other charged particle above 1 GeV/c existed in the lepton jet.

All the three topologies were then retained for the analysis, consisting of 33 events in the data sample. The estimated purity was 90%, and the efficiency was 54% (being 64% in the electron channel, 81% in the muon channel and 17% in the τ channel). A total of 30.4 events were expected from simulation. A correction was estimated from simulation to account for detector effects and the contribution from the initial lepton (or its decays products) in observed multiplicity, taking as reference the sample generated with one W into hadrons. The values of the observed charge multiplicity before and after the background subtraction were 16.9 and 16.8 respectively.

Finally the following values have been obtained for the charged multiplicity for one W decaying hadronically in WW events with mixed hadronic and leptonic final states:

$$< N_{had}^{(SL)}(W) > \; = \; 18.0 \pm 0.9(stat) \pm 0.6(syst)\,, \tag{6}$$

where the systematic error accounts for the variation of the selection criteria (0.42), variation of the $\mathrm{q\bar{q}}(\gamma)$ cross-sections within the error of the measured value [16] (negligible), limited statistics in the simulated samples (0.06) and the alternative procedure applied to estimate $< N_{had}^{(SL)}(W) >$ by taking the average of the multiplicity distribution (0.43).

5 Discussion

The value of the average charged particle multiplicity at 161 GeV and 172 GeV is displayed in Figure 3 and compared with lower energy points from TASSO [17], HRS [18], AMY [19], and DELPHI in $\mathrm{q\bar{q}}\gamma$ events at the Z [20], with the world average at the Z [14], with the LEP results at 133 GeV [12, 21, 22, 23], and with L3 and OPAL values at 161-172 GeV [24, 25]. The value at the Z has been lowered by 0.20, to account for the different proportion of $b\bar{b}$ and $c\bar{c}$ events at the Z with respect to the continuum $e^+e^- \to \mathrm{q\bar{q}}$ [26]. Similarly, the values at 133, 161 and 172 GeV were lowered by 0.15, 0.12 and 0.11 respectively.

The QCD prediction for charge multiplicity has been computed as a function of α_s including the resummation of leading (LLA) and next-to-leading (NLLA) corrections [27, 12]:

$$n_{ch}(\sqrt{s}) = a\alpha_s(\sqrt{s})^b e^{c/\sqrt{\alpha_s(\sqrt{s})}}\left[1 + d\cdot\sqrt{\alpha_s(\sqrt{s})}\right] ,$$

where s is the squared centre-of-mass energy and a is a parameter (not calculable from perturbation theory) whose value has been fitted from the data. The constants $b = 0.49$ and $c = 2.27$ are predicted by the theory [27] and $\alpha_s(\sqrt{s})$ is the strong coupling constant. The parameter d was introduced [20] to allow for higher order corrections. A fit to data between 20 GeV and $\sqrt{s} = M_Z$ with $\alpha_s(\sqrt{s})$ (expressed at next-to-leading order), and a and d as free parameters, is shown in Figure 3. The results of the fit are: $a = 0.053 \pm 0.006$, $d = 1.11 \pm 0.39$, and $\alpha_s(m_{\rm Z}) = 0.119 \pm 0.003(stat)$. This value of $\alpha_s(m_Z)$ yields $\alpha_s(172\,\mathrm{GeV}) = 0.108 \pm 0.002(stat)$, and the curve describes the data well.

The ratios of the average multiplicity to the dispersion, $< N_{\rm ch} > /D$, measured at 161 GeV and 172 GeV, are consistent with the average from the measurements at lower centre-of-mass energies (3.12 ± 0.05), as can be seen in Figure 4. This is coherent with KNO scaling [28], and also consistent with the predictions of QCD including 1-loop Higher Order terms (H.O.) [29].

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

$$\frac{2 < N_{had}^{(SL)}(W) >}{< N_{had}^{(had)}(2W) >} = 0.89 \pm 0.06(stat) \pm 0.04(syst)\,. \tag{7}$$

The ratio above is three standard deviations smaller than the ratio (1.11) obtained by applying our selection efficiency to the prediction in [4] in case of complete colour reconnection, folded around 90 degrees to account for the impossibility to tag the quarks.

A possible dependence of the charged multiplicity in WW fully hadronic events on the minimum angle between two jets was checked by dividing the sample into two sub-samples according to the minimum interjet angle θ_j in the event, (a) $\theta_j < 60^\circ$ and (b) $\theta_j > 60^\circ$. The distribution of the angle θ_j for data and simulation is shown in Figure 5. The average multiplicities measured (including corrections for detector effects) were consistent: $42.9 \pm 2.5(stat)$ in sample (a) and $38.6 \pm 2.3(stat)$ in sample (b). The ratio r of the average multiplicities in sample (b) to sample (a) is

$$r = 0.90 \pm 0.07(stat) \pm 0.03(syst) \tag{8}$$

where the systematic error accounts for the different background correction in the two regions (the result was $0.95 \pm 0.06(stat)$ before background subtraction). This ratio obtained by applying the prediction in [4] to the observed θ_j distribution is 1.08, which is larger than the measurement by 2.3 standard deviations.

At the present level of statistics, the study of charge multiplicity in W decays shows no evidence of colour reconnection effects.

In the hypothesis (consistent with this analysis) that the charged multiplicity in a W decay is independent of the decay mode of the other W, the measurements can be averaged to obtain the best determination of the charged particle multiplicity from hadronic decays of the W. Considering the systematic errors as independent:

$$< N(W) >= 19.23 \pm 0.74(stat + syst)\,, \tag{9}$$

where the error is the sum in quadrature of the statistical and of the systematic contributions. The value of $N(W)$ is also plotted in Figure 3 at an energy value corresponding to the W mass; 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 with respect to the continuum e^+e^- [26]. It lies on the same curve as the e^+e^- data. This supports the point of view (see for example [30]) that the dependence of the average charged multiplicity on the centre-of-mass energy is predominantly determined by the energy available for the particle production and by phase space properties, but not so much by the details of the production mechanism.

Acknowledgements

We are greatly indebted to our technical collaborators and to the funding agencies for their support in building and operating the DELPHI detector. Very special thanks are due to the members of the CERN-SL Division for the excellent performance of the LEP collider. Thanks to Jorge Dias de Deus, to Alberto Giovannini and to Valery Khoze for comments on the manuscript.

References

[1] For a review see for example G.D. Lafferty et al., J. Phys. **G21** (1995) A1.

[2] T. Sjöstrand and V.A. Khoze, Z. Phys. **C62** (1994) 281.

[3] B.R. Webber, in "QCD Event Generators", in "Physics at LEP2", CERN Yellow Report 96-01.

[4] J. Ellis and K. Geiger, "Signatures of Parton Exogamy in $e^+e^- \to W^+W^- \to$ *hadrons*", CERN-TH/97-46.

[5] L. Lönnblad and T. Sjöstrand, Phys. Lett. **B351** (1995) 293.

[6] V. Kartvelishvili, R. Kvatadze and R. Moller, "Estimating the effects of Bose-Einstein correlations on the W mass measurement at LEP 2", Manchester Preprint MC-TH-97/04.

[7] DELPHI Coll., P. Abreu et al., Phys. Lett. **B401** (1997) 181.

[8] DELPHI Coll., P. Abreu et al., Nucl. Instr. Meth. **A303** (1991) 233.

[9] DELPHI Coll., P. Abreu et al., Nucl. Instr. Meth. **A378** (1996) 57.

[10] T. Sjöstrand, Comp. Phys. Comm. **82** (1994) 74.

[11] DELPHI Coll., P. Abreu et al., Z. Phys. **C77** (1996) 11.

[12] DELPHI Coll., P. Abreu et al., Phys. Lett. **B372** (1996) 172.

[13] S. Bethke et al., Nucl. Phys. **B370** (1992) 310.

[14] R.M. Barnett et al., Phys. Rev. **D54** (1996) 1.

[15] Yu.L. Dokshitzer, Phys. Lett. **B305** (1993) 295;
P. Nason and B.R. Webber, in "Physics at LEP2", CERN Yellow Report 96-01.

[16] A. Behrmann et al., "Delphi results on the measurement of fermion pair production for Z peak and higher energies at LEP for the winter 1997 Conferences", DELPHI Note 97-31 PHYS 684.

[17] TASSO Coll., W. Braunschweig et al., Z. Phys. **C45** (1989) 193.

[18] HRS Coll., M. Derrick et al., Phys. Rev. **D34** (1987) 3304.

[19] AMY Coll., H. Zheng et al., Phys. Rev. **D42** (1990) 737.

[20] DELPHI Coll., P. Abreu et al., Z. Phys. **C70** (1996) 179.

[21] ALEPH Coll., D. Buskulic et al., Z. Phys. **C73** (1997) 409.

[22] L3 Coll., M. Acciarri et al., Phys. Lett. **B371** (1996) 137.

[23] OPAL Coll., G. Alexander et al., Z. Phys.**C72** (1996) 191.

[24] L3 Coll., “QCD Studies and Determination of $\alpha_s$in e^+e^-collisions at $\sqrt{s} = 161$ GeV and 172 GeV”, CERN-PPE/97–42, submitted to Phys. Lett. **B**.

[25] OPAL Coll., K. Ackerstaff et al., “QCD Studies with e+e- Annihilation Data at 161 GeV”, CERN-PPE/97–15, submitted to Z. Phys. **C**.

[26] A. De Angelis, “Light Quark Hadrons in Hadronic Z Decays”, CERN–PPE/95–135, in Proc. EPS-HEP Conference, Bruxelles 1995.

[27] B.R. Webber, Phys. Lett. **B143** (1984) 501 and references therein.

[28] Z. Koba et al., Nucl. Phys. **B40** (1972) 317.

[29] B. R. Webber, “QCD Cascade Approach to Jet Fragmentation”, in *Proc. XV Int. Symp. on Multiparticle Dynamics*, Lund 1984, Eds. G. Gustafson and C. Peterson (World Scientific, Singapore, 1984).

[30] P. Chliapnikov and V. Uvarov, Phys. Lett. **B251** (1990) 192.

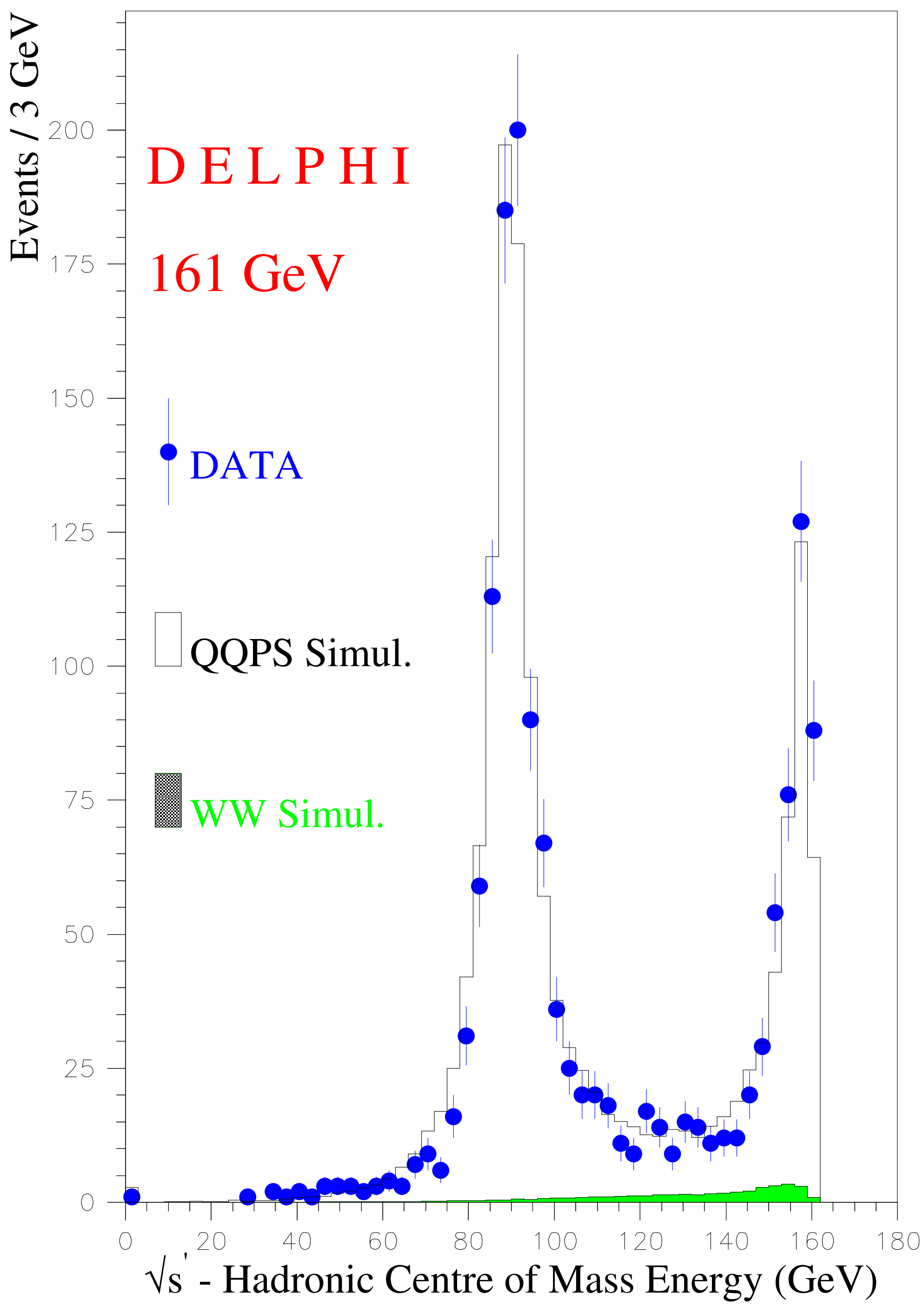

Figure 1: Distribution of the reconstructed hadronic centre-of-mass energy in $e^+e^- \to q\bar{q}$ events at 161 GeV, for data (points) and simulation (solid line). The hatched area represents the contribution from WW events.

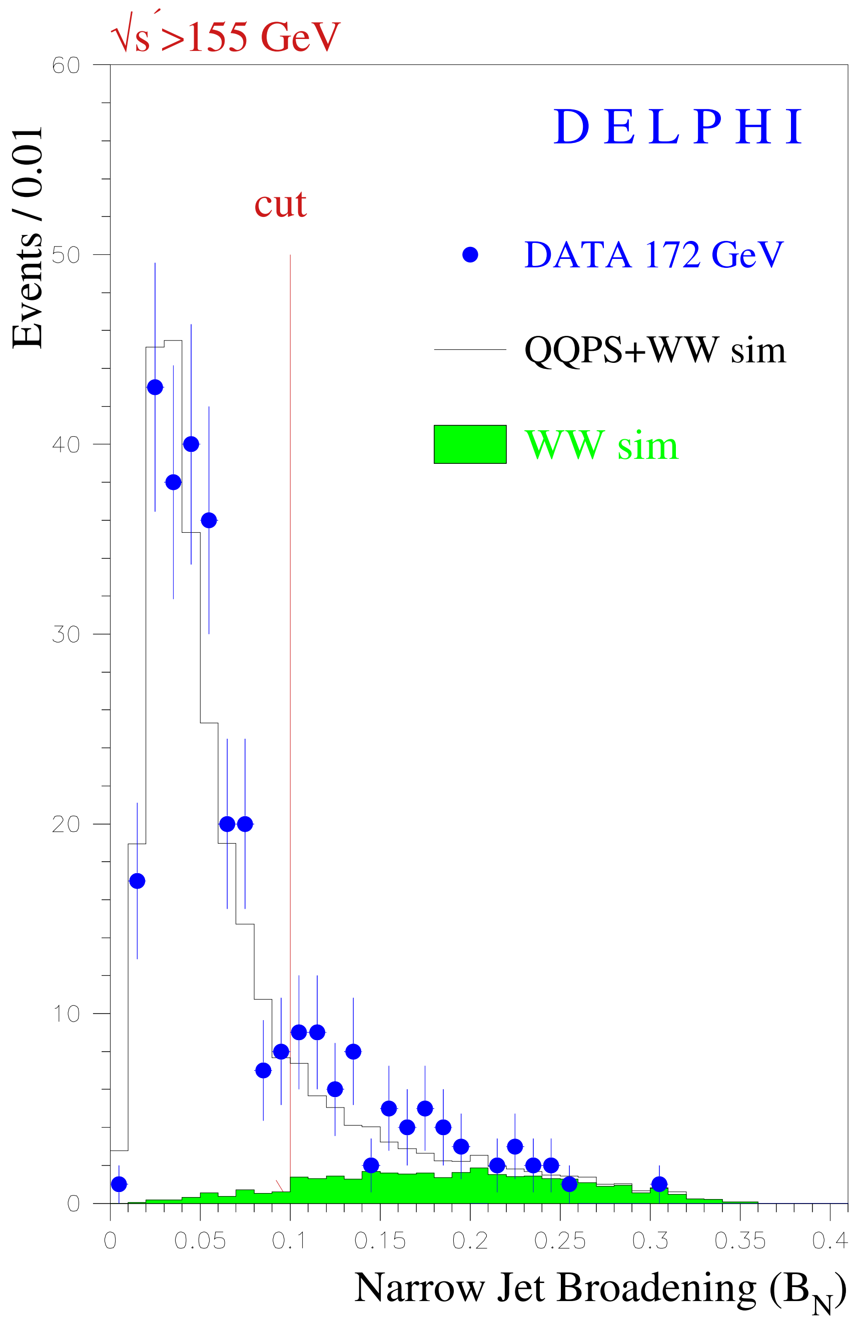

Figure 2: Narrow Jet Broadening distribution, as defined in [15], for the selected events of data compared with the expected simulation.

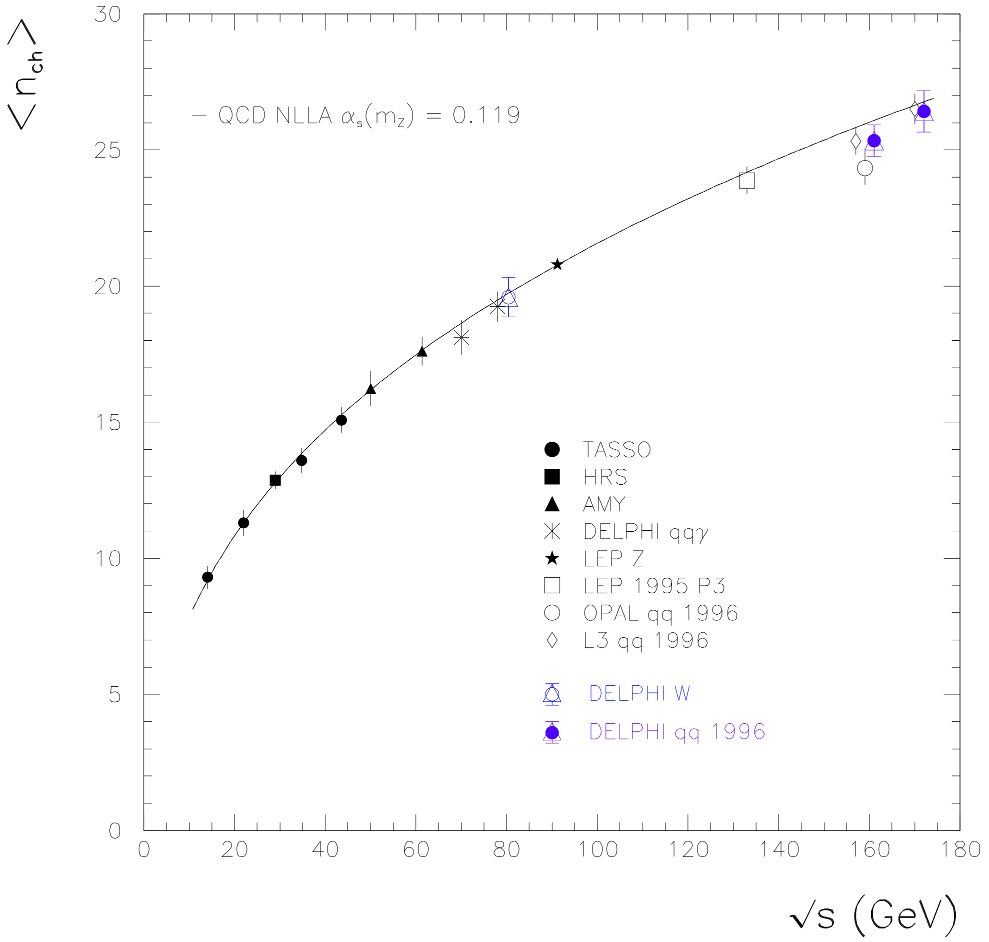

Figure 3: Measured average charged multiplicity in $e^+e^- \to q\bar{q}$ events as a function of centre-of-mass energy $\sqrt{s}$. DELPHI high energy results are compared with other experimental results and with a fit to a prediction from QCD in Next to Leading Order. The average charged multiplicity in W decays is also shown at an energy corresponding to the W mass.

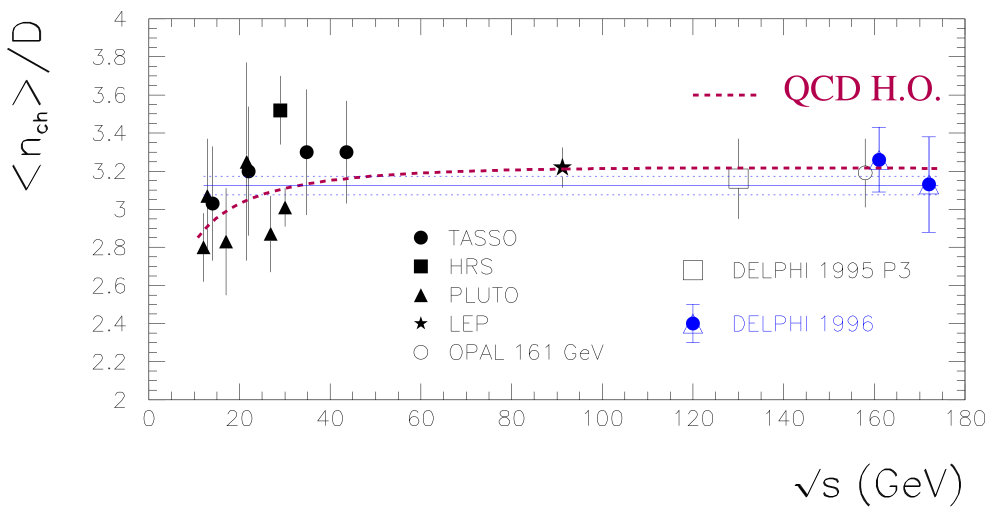

Figure 4: Ratio of the average charged multiplicity to the dispersion in $e^+e^- \to q\bar{q}$ at 161 GeV and 172 GeV, compared with lower energy measurements. The straight solid and dotted lines represent the weighted average and errors of the data points. The dashed line represents the prediction from QCD (see text).

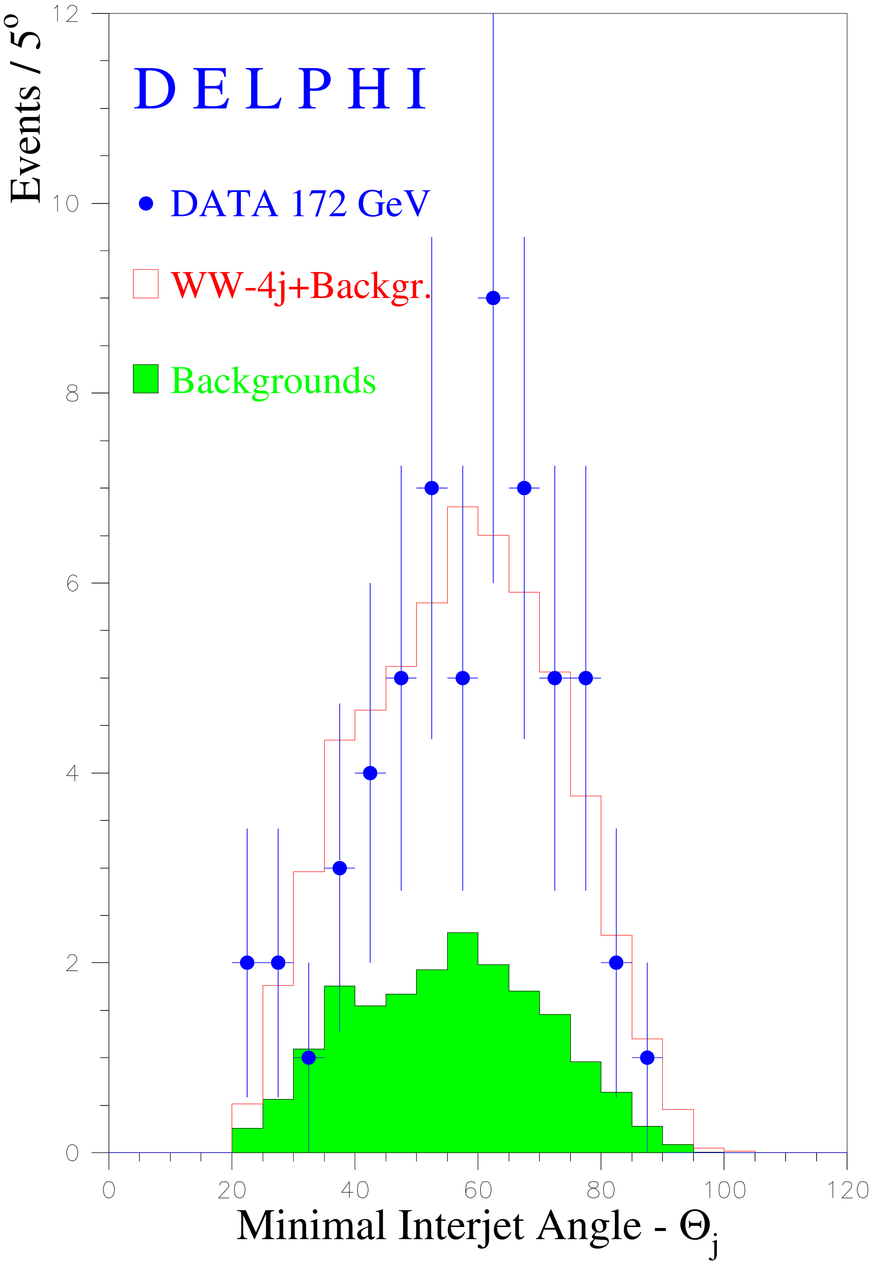

Figure 5: Distribution of θ_j, the minimal angle between the fitted jet directions in $e^+e^- \to$ WW, for events in which both W's decay hadronically. The data (points) are compared with the simulation.