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Charged Particle Multiplicity in e^+e^- Annihilations into q$\bar{\text{q}}$ at $\sqrt{s} = 206$ GeV

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Abstract

From the data collected by DELPHI at LEP in the year 2000, the average multiplicity of charged particles and the dispersion of the charged multiplicity distribution, at a luminosity weighted average centre of mass energy of 206 GeV, were measured. When compared to lower energy data, the values measured are consistent with the Koba-Nielsen-Olesen (KNO) scaling hypothesis and with the evolution for the charged multiplicity predicted by QCD. From a distorted gaussian fit to the corrected data distribution of the $\xi_p = -\ln(2p/\sqrt{s})$, the position of its maximum was also determined.

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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 predictions exist for its evolution with energy (see for example [1, 2]). Previous measurements by DELPHI were made at centre-of-mass energies from 70 to 78 GeV [3], equal to the M_W [4], equal to the M_Z [5], at 130 GeV [6], 161 and 172 GeV [7], and at 183, 189 and 200 GeV [4].

The data collected by DELPHI at LEP in year 2000 are at the highest centre-of-mass energies in e^+e^- interactions, up to 208 GeV. In this note, the data recorded using the DELPHI detector [8, 9] were used to compute the average and the dispersion of the charged particle multiplicity distribution at the centre-of-mass energy of 206 GeV. The results have been compared with the predictions from QCD at next-to-leading order. From a fit with a distorted gaussian function to the $\xi_p = -\ln(2p/\sqrt{s})$ distribution, as suggested in [18], the position of its maximum was also determined.

2 Event Selection

The data analysed were collected by DELPHI in year 2000, with all the tracking detectors working properly, and corresponds to a total integrated luminosity of 164 pb^{-1} at centre-of-mass energies $\sqrt{s}$ from 203 to 208 GeV. The results are given for a centre-of-mass energy of 206 GeV, equal to the average of centre of mass energies weigthed by the respective luminosities.

To select hadronic events it was required that the multiplicity for charged particles (with momentum p above 100 MeV/c, relative error on the momentum $\Delta p/p < 1$, polar angle θ with respect to the beam direction between 20 and 160 degrees, a track length of at least 30 cm, and a distance of closest approach to the interaction point less than 4 cm in the plane perpendicular to the beam axis and less than $4/\sin\theta$ cm along the beam axis) was larger than 9, and that the total transverse energy of the charged particles exceeded $0.2\sqrt{s}$. In the calculation of the energies E, all charged particles were assumed to have the pion mass.

The influence of the detector on the analysis was studied with the full DELPHI simulation program, DELSIM [9]. Signal events ($q\bar{q}(\gamma)$) were generated with KK2F [10] for the electroweak part and the fragmentation was followed using the Parton Shower (PS) Pythia Monte Carlo program [11] with parameters tuned to DELPHI data [12]. Background events, dominated by WW and ZZ processes, were generated with WPHACT [13] for the electroweak part, separately for WW (charged currents) and for ZZ (neutral currents), to which was then applied the Parton Shower and fragmentation as implemented in the Pythia Monte Carlo program. For all the data the generated 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.

To check the ability of the simulation to model the efficiency for the reconstruction of charged particles, the calibration sample collected at the Z pole during 2000 was used. From this sample, by integrating the distribution of $\xi_E = -\ln(\frac{2E}{\sqrt{s}})$, where E is the energy of the particle, corrected bin by bin using the simulation, the average charged particle multiplicity in Z hadronic decays was measured. The value was found to be $20.81 \pm 0.02(stat)$, in satisfactory agreement with the world average of 21.07 ± 0.11 [14]. The ratio of the world average value to this measured multiplicity, 1.0125 ± 0.0054, was used as calibration factor to correct the measured multiplicity at high energy.

The sizes of the Monte Carlo simulated samples at high energy were 99266 $q\bar{q}(\gamma)$ events (QQPS), generated with KK2F and later fragmented with Jetset/Pythia tuned to DELPHI data, and 99952 WW events and 99869 ZZ events generated with WPHACT and fragmented with Jetset/Pythia tuned to DELPHI data. For systematic studies, an additional sample of 39186 events were generated with KK2F and fragmented with Ariadne [15] tuned to DELPHI data. An additional one million events were also generated at high energy with KK2F without Initial State Radiation effects, and fragmented with Jetset/Pythia tuned to DELPHI data, to compute the mean charge multiplicity and dispersion at generator level at a centre-of-mass energy of 206 GeV. In this generated sample, particles with lifetimes shorther than 10^{-9}s, like K^0s and Λs, were forced to decay. All the samples were normalized to the absolute luminosity.

The cross section at 206 GeV is dominated by radiative $q\bar{q}(\gamma)$ events; the initial state radiated photons are generally aligned along the beam, and they are not detected. In order to compute the hadronic centre-of-mass energy, $\sqrt{s'}$, the procedure described in [16] was used. The spectrum of the ratio $\sqrt{s'}/\sqrt{s}$ for the events collected is shown in Figure 1, where it is compared with the expectations from the $q\bar{q}(\gamma)$ signal and WW and ZZ background simulations. To remove the radiative return to the Z, it was required that $\sqrt{s'}/\sqrt{s} > 0.9$.

To decrease substantially the contribution from WW events a cut was applied on the narrow jet broadening. The jet broadenings are defined as in [17] to be the ratio between the sum of transverse momenta relative to the thrust axis for charged particles in each of the hemispheres defined by a plane perpendicular to the thrust axis, and twice the sum of absolute momenta for all charged particles. The event narrow jet broadening is the minimum value among the two jet broadenings. Its distribution for the data, compared to the expectations from simulation, is shown in figure 2. It was required for hadronic events that the narrow jet broadening be smaller than 0.065.

3 Analysis and Results

Events with reconstructed hadronic centre-of-mass energy ($\sqrt{s'}/\sqrt{s}$) above 0.9 were used to compute the multiplicity at 206 GeV (they will be referred to as "high energy events" in what follows). A total of 3047 high energy hadronic events were selected in the data, to be compared to the total expected from simulation of 3139.7±18.6 events. From the simulation, it was calculated that the expected background coming from WW and ZZ events is 681.7±4.7 (640.3(WW)+41.4(ZZ)) events.

The distribution of the charged particle multiplicity is compared in Figure 3 to the expected contribution from signal and background simulation.

The distribution of $\xi_E = -\ln(2E/\sqrt{s})$ for the charged particles, corrected bin by bin using the simulation for the effect of the initial state radiation, detector effects, and selection biases is shown in Figure 4(top) for high energy events. The average multiplicity was computed by integrating the corrected data ξ_E distribution up to a value of 6.3. The extrapolation to the region above this cut, where the acceptance is small, was based on the simulation at the generator level.

The average multiplicity of charged particles, obtained from the integration of the data ξ_E distribution after subtraction of the estimated WW and ZZ backgrounds, is $25.36\pm0.20(stat)$. This is to be compared with $25.96\pm0.06(stat)$ in the QQPS simulation including detector effects. The dispersions of the multiplicity distributions are 7.95 ± 0.14 in the data and 7.74 ± 0.04 in the QQPS simulation including detector effects. After correcting the distribution for detector effects, selection biases and initial state radiation, the corrected average charged particle multiplicity ($\langle n_{ch}\rangle$) was found to be $\langle n_{ch}\rangle = 27.69\pm 0.22(stat)$, and the dispersion (D) $D = 8.97\pm0.16(stat)$.

After multiplying by the Z calibration factor the following values were obtained:

$$\langle n\rangle_{206\,\mathrm{GeV}} = 28.03 \pm 0.22(stat) \pm 0.27(syst) \quad (1)$$

$$D_{206\,\mathrm{GeV}} = 8.97 \pm 0.16(stat) \pm 0.13(syst)\,. \quad (2)$$

$$(3)$$

These values include the products of the decays of particles with lifetime $\tau < 10^{-9}$ s. The systematic uncertainties were obtained by adding in quadrature:

1. the propagated uncertainty of the average values in the Z correction factors, ±0.15 for the multiplicity;

2. the effect of the cuts for the reduction of the background and the effect of the uncertainty in the cross-sections of the background. The value of the cut on the narrow jet broadening was varied from 0.045 to 0.085 in steps of 0.010, in order to estimate the systematic uncertainty associated with the procedure of removing the contribution from WW and ZZ events. The new values for the average charged particle multiplicity and the dispersion were stable within these variations, and the spread of the values, 0.05 and 0.08 respectively, were added in quadrature to the systematic uncertainty. The effects of the uncertainties on the WW and ZZ cross-sections, were estimated by varying independently the cross-sections by 2.5% and 15% respectively, and were found to be 0.035 and 0.015 in the multiplicity and 0.022 and 0.001 in the dispersion, and these values were added in quadrature to the systematic uncertainty;

3. the uncertainty on the modelling of the detector response. The analysis was repeated by varying independently the polar angle acceptance of charged particles from 10-170 degrees to 40-140 degrees, the minimum track length required from 15 cm to 80 cm, and the cut on the momentum of the particle from 0.1 to 0.3 GeV/c, both in the high energy samples and in the computation of the Z calibration correction factors. The spreads of the different values obtained for the multiplicities and for the dispersions were found to be respectively 0.17 and 0.08 for the polar angle, 0.03 and 0.03 for the minimum track length, and 0.03 and 0.03 for the cut on the particle's momentum;

4. the systematic uncertainties due to the statistics of the simulated samples, 0.04 for the multiplicity and 0.05 for the dispersion;

5. the uncertainty on the calculation of the efficiency correction factors in the multiplicity. The values of the mean multiplicities, after applying the Z correction factors,

computed as the ratio of the world average value to the measured mean multiplicity using the same method, were also estimated:

- from the observed multiplicity distribution as 27.97;
- from the integral of the rapidity distribution (with respect to the thrust axis), $y_T = \frac{1}{2} \ln \frac{E+p_{||}}{E-p_{||}}$ ($p_{||}$ is the absolute value of the momentum component on the thrust axis) as 27.89.

Half of the differences between the maximum and the minimum values of the multiplicity calculated from the multiplicity distribution and from the integration of the y_T and ξ_E distributions, 0.07, was added in quadrature to the systematic uncertainty;

6. fragmentation model used for the correction factors. To estimate the effect of the fragmentation model, the analysis was repeated using Ariadne for the correction factors instead of Pythia, both in the Z samples and in the high energy samples. The results were found to be compatible and half of the differences in the multiplicity and the dispersion thus obtained with respect to the reference values, 0.09 and 0.02 respectively, were added in quadrature to the systematic uncertainty;

7. uncertainty in the extrapolated multiplicity in the high-ξ_E region. From the difference of predicted values using different fragmentation models for the correction (Pythia versus Ariadne), the difference of extrapolated multiplicities, 0.001, was added in quadrature to the systematic uncertainty;

The distribution of $\xi_p = -\ln(2p/\sqrt{s})$ for the charged particles, corrected via simulation for the effect of the initial state radiation, detector effects, and selection biases is shown in Figure 4(bottom) for high energy events. Superimposed is a fit to the data of a distorted gaussian function as suggested in [18] (5 parameters), in a range around the peak of 15 points from 1.8 to 6.3 in ξ_p, which describes well the data as expected from QCD in Modified Leading Logarithm Approximation [18],with a chi-square per degree of freedom of χ^2/NDF=1.686. From the function with the fitted parameters, the position of the peak was extracted as

$$\xi^*(206\text{GeV}) = 4.21 \pm 0.04(stat) \pm 0.02(syst)\,. \tag{4}$$

The statistical uncertainty was obtained from the covariance matrix on the fitted parameters. In order to estimate the systematic uncertainty, the ξ_p distribution was also obtained after varying the event selection, the charged particle requirements, the background cross-sections and the fragmentation model used in the correction of the data. The overall uncertainty is the quadratic sum of the following contributions:

- 0.005 due to the spread from varying the cut on the narrow jet broadening from 0.045 to 0.085 in steps of 0.010.
- by varying the cross-sections of the background contributions (2.5% in the WW cross-section and conservatively 15% in the ZZ cross-section), the effect in the position of the peak was found to be negligible.

- 0.009 and 0.017 from the spreads obtained after varying independently the polar angle acceptance of charged particles from 10-170 degrees to 40-140 degrees and the minimum track length required from 15 cm to 80 cm.
- 0.015, by changing the signal QQPS fragmentation model from from Pythia to Ariadne. Half of the difference between the reference value and the peak position obtained with correction factors from Ariadne was added in quadrature to the systematic uncertainty.

The value of the average charged particle multiplicity at 206 GeV is displayed in Figure 5 and compared with lower energy points from JADE [19], PLUTO [20], MARK II [21], TASSO [22], HRS [23], and AMY [24], with DELPHI results in $q\bar{q}(\gamma)$ events at the Z [3], with the world average from LEP experiments at $\sqrt{s} = M_Z$ [14], and with the LEP results at high energy [25, 26, 27, 28, 29, 30, 31, 32]. The points from JADE, PLUTO and MARK II do not include the decay products of short lived K^0 and Λ. The value at the Z has been lowered by 0.17, 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^- with pure photon contribution, and correspondingly the values at centre-of-mass energies of 70, 78, 130, 161, 172, 183, 189, 200, and 206 GeV were lowered by 0.17,0.17, 0.15, 0.12, 0.12, 0.12, 0.11, 0.11 and 0.11. The value at $\sqrt{s} = M_W$ was increased by 0.30 for the same reason. To the statistical errors on the charge multiplicities in $q\bar{q}(\gamma)$ events at the Z [3], a systematic uncertainty assumed to be ± 0.50 has been added in quadrature.

The QCD prediction for the charged particle multiplicity has been computed as a function of α_s including the resummation of leading (LLA) and next-to-leading (NLLA) corrections [2]:

$$\langle n \rangle(\sqrt{s}) = a[\alpha_s(\sqrt{s})]^b e^{c/\sqrt{\alpha_s(\sqrt{s})}} \left[1 + O(\sqrt{\alpha_s(\sqrt{s})})\right] , \tag{5}$$

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 theory [2] and $\alpha_s(\sqrt{s})$ is the strong coupling constant, with the value at $\sqrt{s} = M_Z$ taken from [14] to be $\alpha_s(M_Z) = 0.1181 \pm 0.002$. The fitted curve to the data between 14 GeV and 206 GeV, excluding the results from JADE, PLUTO and MARK II, is plotted in Figure 5, corresponding to $a = 0.043 \pm 0.001$ and $\chi^2/NDF = 0.578$, and shows the consistency of the data values with the QCD prediction on the evolution of the multiplicity with centre-of-mass energy.

The ratios of the average multiplicity to the dispersion measured at 206 GeV, $\langle n \rangle / D = 3.12 \pm 0.06(stat) \pm 0.06(syst)$, are consistent with the weighted average from the measurements at centre-of-mass energies of 14-200 GeV ($3.15 \pm 0.03(stat \oplus syst)$), as can be seen in Figure 6 and expected from Koba-Nielsen-Olesen scaling [33]. The ratio measured is also consistent with the predictions of QCD including 1-loop Higher Order terms (H.O.) [34].

4 Summary

By analysing the data collected in 2000 with the DELPHI detector, for an integrated luminosity of 164 pb^{-1}, the average charged particle multiplicity and the dispersion of the charged particle multiplicity distribution were measured as:

$$\langle n \rangle_{206\,\mathrm{GeV}} = 28.03 \pm 0.22(stat) \pm 0.27(syst)$$
$$D_{206\,\mathrm{GeV}} = 8.97 \pm 0.16(stat) \pm 0.13(syst)\,,$$

in agreement with the expected energy evolution predicted by QCD, and with the Koba-Nielsen-Olesen hypothesis. The position of the peak of the $\xi = -\ln(\frac{2p}{\sqrt{s}})$ distribution was also extracted from the corrected data distribution, using a fitted distorted gaussian function, to be:

$$\xi^*(206\mathrm{GeV}) = 4.21 \pm 0.04(stat) \pm 0.02(syst)\,.$$

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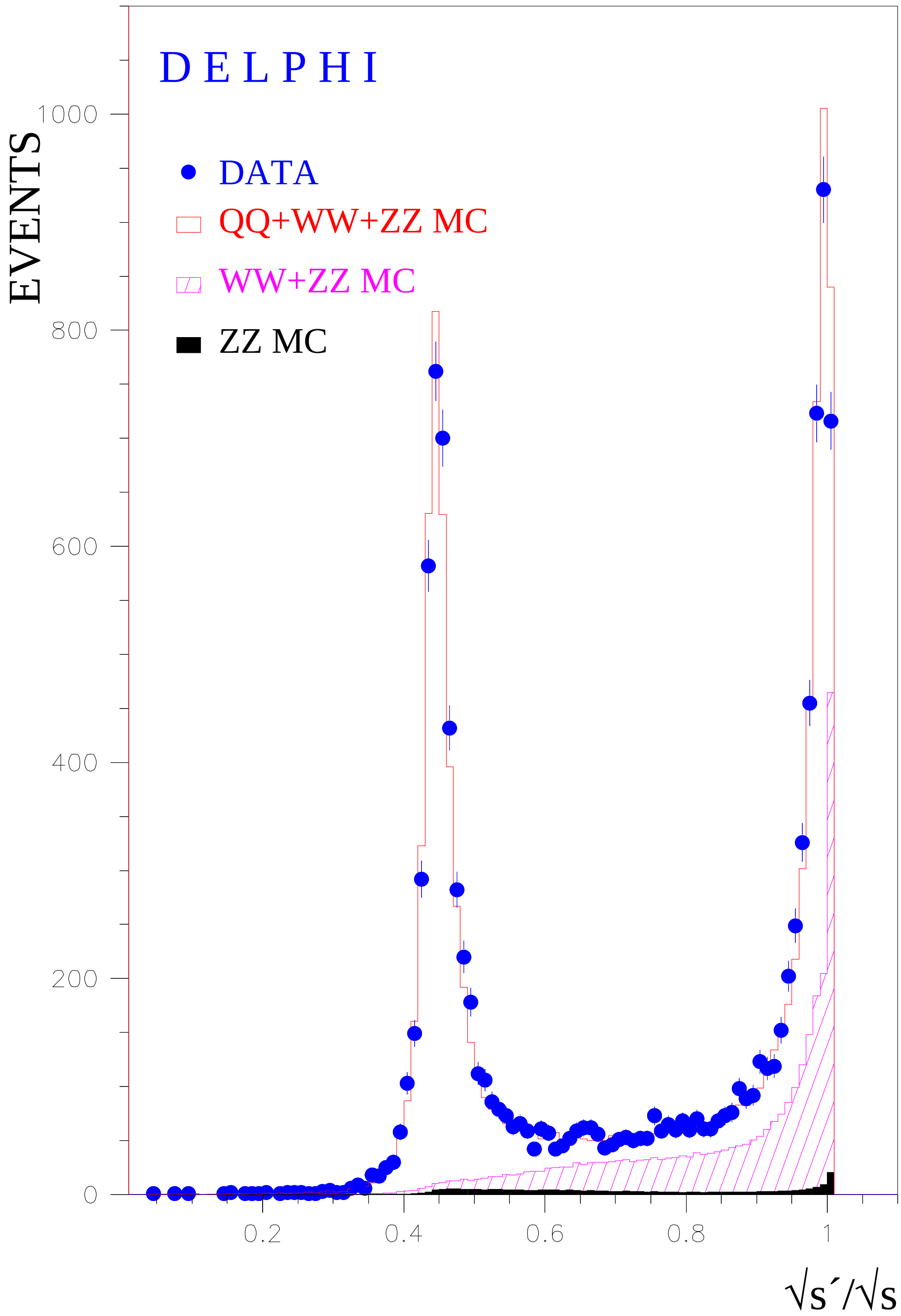

Figure 1: Distribution of the reconstructed hadronic energy; the simulations for QQ(PS)+WW+ZZ, WW+ZZ and ZZ only are superimposed.

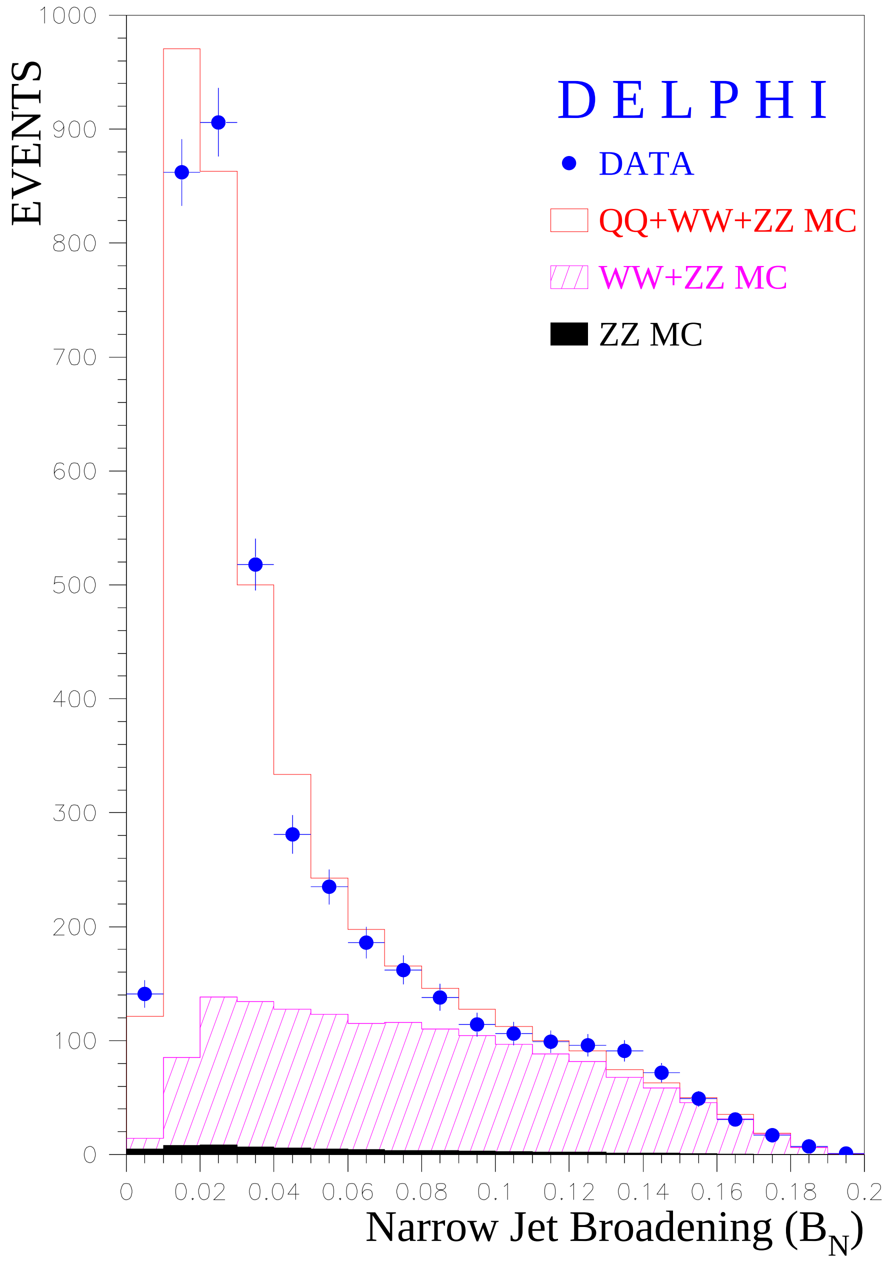

Figure 2: Comparison of the Event Narrow Jet Broadening B_N, defined in the text, between data and the expectations from simulation.

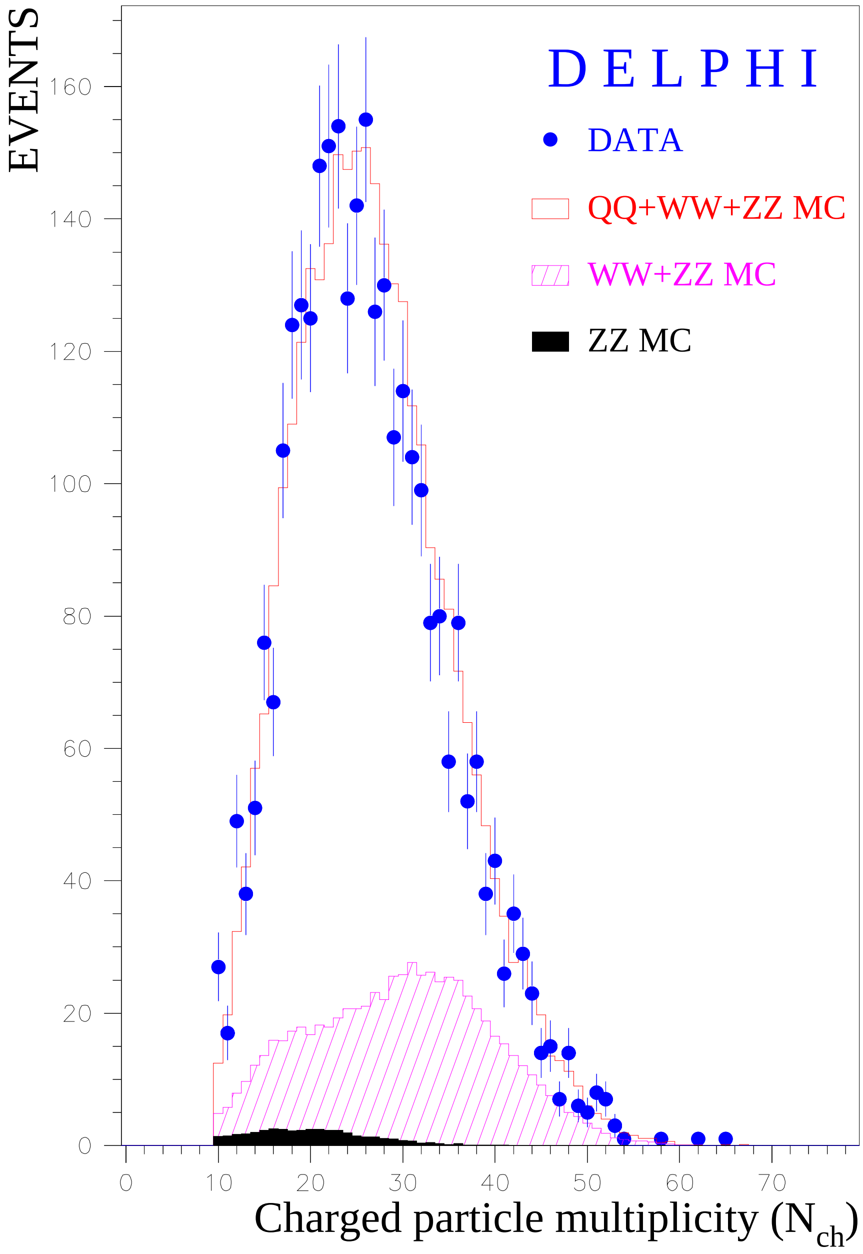

Figure 3: Distribution of the multiplicity of charged particles at 206 GeV for the data compared to the simulated signal and backgrounds.

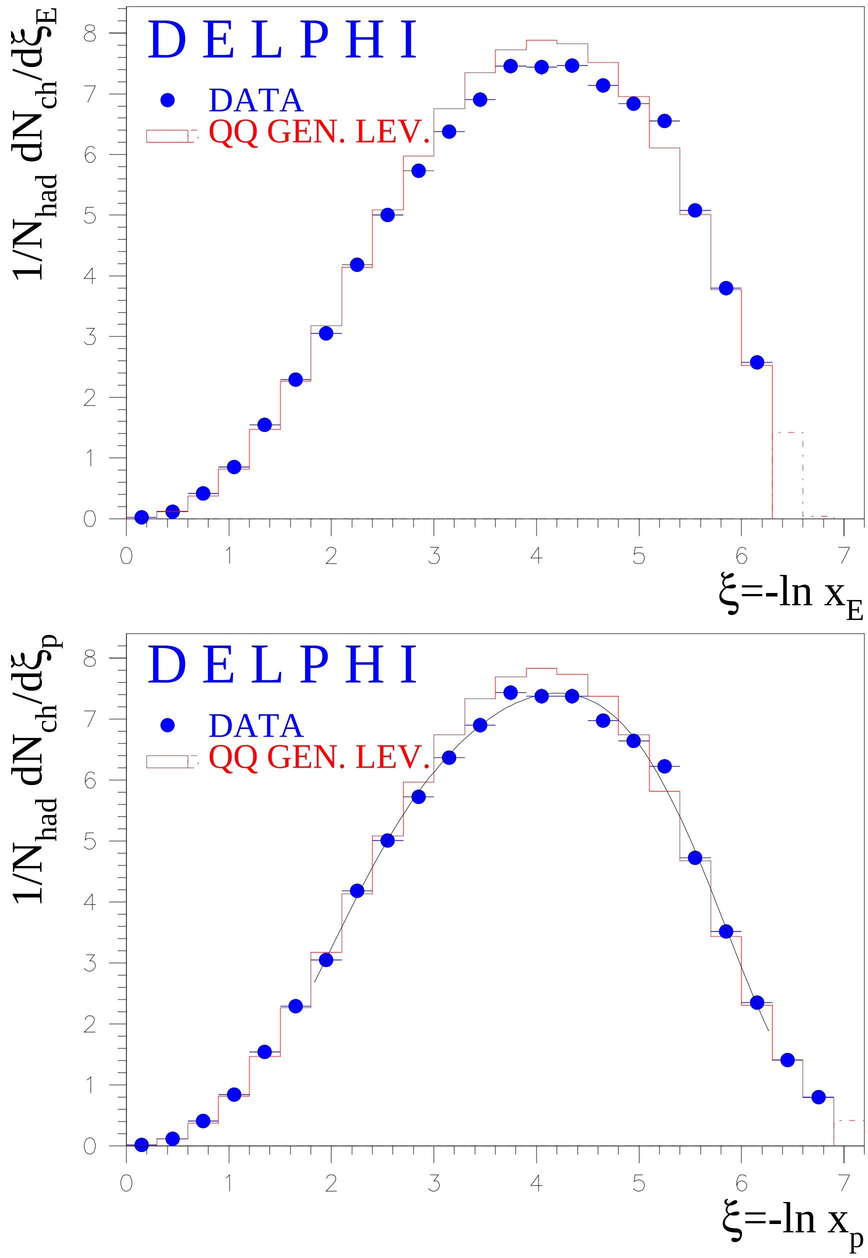

Figure 4: Distribution of $\xi_E = -\ln(2E/\sqrt{s})$ for charged particles at 206 GeV, normalised to the number of events and corrected for detector effects, selection biases and initial state radiation, compared to the simulation at generator level (top) and the equivalent distribution for $\xi_p = -\ln(2p/\sqrt{s})$ (bottom). The fit to ξ_p from which ξ^* is extracted is also shown in the bottom plot. The dotted lines in both plots represent the extrapolated region from the simulation at generator level.

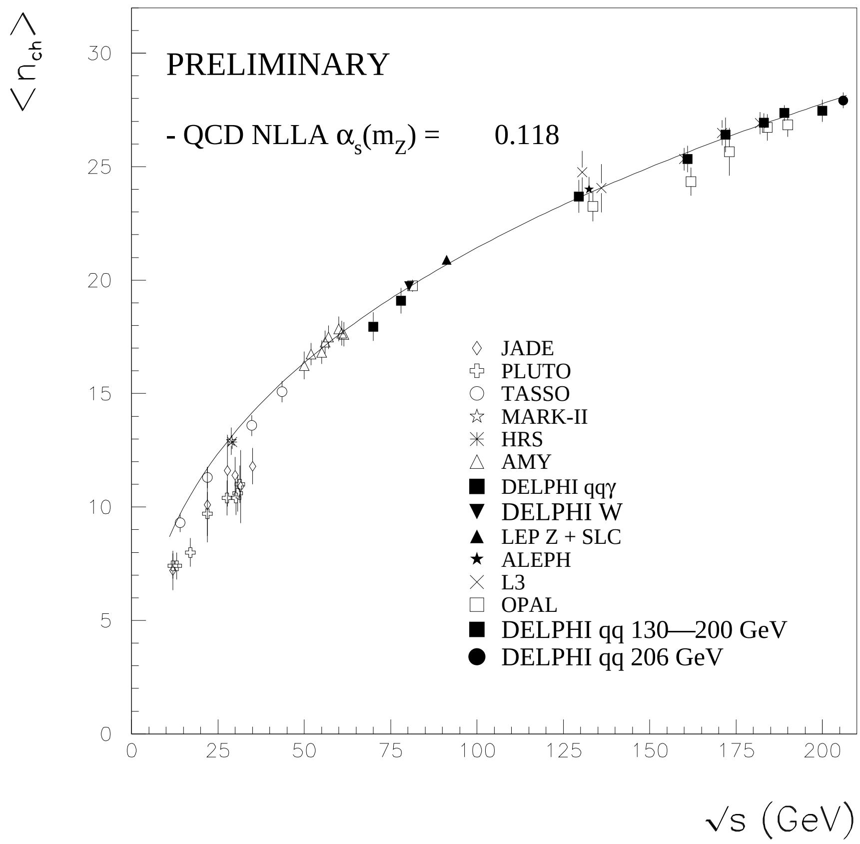

Figure 5: Measured multiplicity at 206 GeV, compared with lower energy measurements and with a fit to a prediction from QCD in Next to Leading Logarithm Approximation.

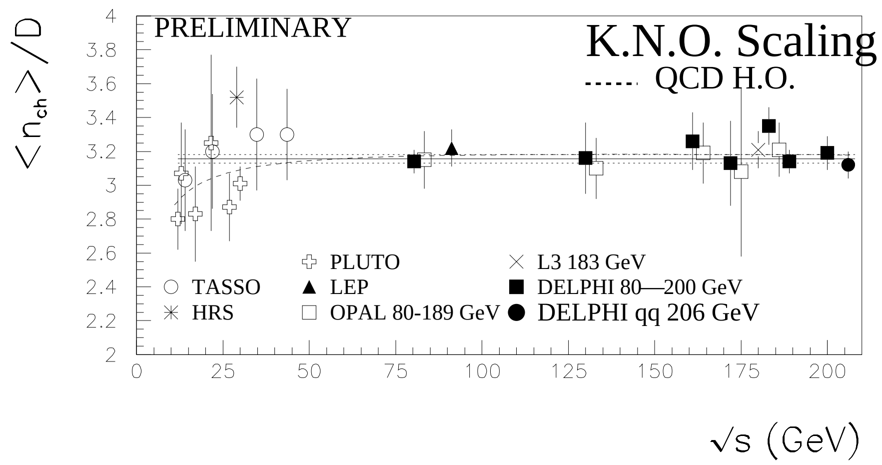

Figure 6: Ratio of the average charged particle multiplicity to the dispersion in $e^+e^- \to q\bar{q}$ events at 206 GeV, compared with lower energy measurements. The error bars represent the sum in quadrature of the statistical and the systematic uncertainties. Some points are slightly shifted on the abscissa for clarity. The ratio in W decays is also shown at an energy corresponding to the W mass. The straight solid and dotted lines represent the weighted average of the data points and its error. The dashed line represents the prediction from QCD including Higher Order corrections (see text).