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Charged Particles from the Hadronic Decay of W Bosons and in $e^+e^- \to q\bar{q}$ at 183 GeV

(Preliminary Results for the 1998 Conferences)

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Abstract

Inclusive distributions of charged particles in W decays are experimentally investigated using the statistics collected by the DELPHI experiment at LEP during 1997, at a center-of-mass energy around 183 GeV. The possible effects of interconnections between the hadronic decays of two W are discussed. Measurements of the average charged multiplicity in $q\bar{q}$ events at a center-of-mass energy of 183 GeV and in W decays are also presented.

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1 Introduction

The possible presence of interference due to colour reconnection and Bose-Einstein correlations (see for example [1, 2, 3, 4, 5, 6, 7] and [8, 9] 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 [8] can induce a systematic uncertainty on the W mass measurement in the 4-jet mode comparable with the expected accuracy of the measurement.

Interconnection can happen due to the fact that the 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 exchanges 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 at least 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 such effects can induce shifts of the order of 40 MeV in the W mass [8, 9, 10].

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 [11, 12]; 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 [6] 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 we 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 Ws.

- A qualitative argument shows that the effect of colour reconnection between the decay products of different Ws 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 [5], 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 Ws.

One could be more sensitive to interconnection effects by studying inclusive particle distributions "oriented" by the event axis (like thrust or rapidity). These are anyway difficult to treat experimentally, since it is easy to introduce biases from the selection of $(4q)$ and $(2q)$ events.

- For what is related to BEC, the king of the observables is the two-particle correlation function. BEC could anyway slightly increase the multiplicity for $(4q)$ events in some models [7].

Several models have been proposed to simulate the interconnection effects [9] and some of them have already been included by the most widely used event generators such as PYTHIA, ARIADNE and HERWIG, which have been accurately tuned to Z data. In these models the final state quarks after the parton shower can be rearranged to form colour singlets with probabilities which in some cases can be free parameters (choices of these parameters are directly suggested by the authors by simple considerations). The shift on the W mass in these models is of the order of 50 MeV, but other observables are affected by colour rearrangement. Generally these models suggest a small effect on the total charged multiplicity, of the order of $\pm$1-3% [9], and larger differences are expected when considering special event topologies or restricting to certain phase space regions. The only prediction of an increase of particles in the fully hadronic channel comes from an analysis by Watson and Watson, based on HERWIG [3]. There are also other dedicated models [5] with more extreme W mass and multiplicity shifts (400 MeV and 10%), but some care is needed in these cases, since they might need a tuning of their fragmentation parameters to achieve agreement with Z data.

Previous experimental results are based on the statistics collected by LEP experiments during 1997 (see [13] for a review). A complete Bose-Einstein correlation between pions originating from different Ws in WW $\to 4jets$ events was found to be unlikely. The studies of charged multiplicity and inclusive particle distributions did not indicate at that level of statistics the presence of interconnection effects. DELPHI [14] reported anyway in a momentum analysis an excess of $3.9 \pm 1.6(stat + syst)$ charged particles in the $(4j)$ channel with respect to twice the $(2j)$ for a momentum fraction smaller than 1% of the beam energy, although the published values for the overall charge multiplicity [15] is consistent in the two channels.

This note presents an analysis of charged particles inclusive distributions in the data sample collected by the DELPHI experiment at LEP during 1997, at a center-of-mass energy around 183 GeV. For this energy the WW cross section is about 15.5 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 105 pb. The charged particle multiplicity for the $q\bar{q}$ events at 183 GeV is also measured.

2 Data Sample and Event Preselection

Data corresponding to a total luminosity of 54.0 pb^{-1} collected by DELPHI at centre-of-mass energies around 183 GeV during 1997 were analyzed. A description of the DELPHI detector can be found in [16]; its performance is discussed in [17].

A preselection of hadronic events was made, requiring at least 6 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, a distance of closest approach to the interaction point less than 4 cm in the plane perpendicular to the beam axis and less than 10 cm along the beam axis, and a total energy of the charged particles above 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 $\Delta p/p < 1$, polar angle $20° < \theta < 160°$, a track length of at least 30 cm, 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 [17]. Events were generated with PYTHIA 5.7 and JETSET 7.4 [18], with parameters tuned to fit LEP1 data from DELPHI [19]. The Parton Shower (PS) model was used. 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.

To check the ability of the simulation to model the efficiency for the reconstruction of charged particles, the sample collected at the Z during 1997 was used. From this sample, by integrating the distribution of $\xi_E = -\ln(2E/\sqrt{s})$ corrected bin by bin using the simulation, the average charged particle multiplicity at the Z was measured to be $20.61 \pm 0.04(stat)$, to be compared with the world average of 20.99 ± 0.14 [20]. A scale uncertainty of 1.8% was thus assumed on the measured multiplicities.

3 Analysis of q$\bar{\text{q}}$ Decays

The cross-section for $e^+e^- \rightarrow \text{q}\bar{\text{q}}(\gamma)$ above the Z peak is dominated by radiative $\text{q}\bar{\text{q}}\gamma$ 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 [21] was used. The procedure clusters the particles into two jets using the Durham algorithm [22], 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 using 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 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 160 GeV were used to compute the multiplicity at 183 GeV. A total of 1131 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 [23] was smaller than 0.1. From the simulation it was calculated that the expected background coming from WW decays was 55.4 events. The contamination from double radiative returns to the Z (within 10 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, was $22.01 \pm 0.20(stat)$, to be compared to 22.24 ± 0.09 in the q$\bar{\text{q}}$ PS simulation including detector effects. The dispersion of the multiplicity distribution in the data was $6.27 \pm 0.14(stat)$, to be compared to the dispersion from the q$\bar{\text{q}}$ PS simulation of 6.51 ± 0.06. After correcting for detector effects, the average charged multiplicity was found to be $< n_{ch} >= 26.68 \pm 0.24(stat)$, and the dispersion to be $D = 8.00 \pm 0.18(stat)$. These values again include the products of the decays of particles with lifetime $\tau < 10^{-9}$ s.

The average multiplicity was also computed by integrating the distributions:

- of the rapidity 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);
- of ξ_E,

both corrected bin by bin using the simulation. 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, 0.12, was added in quadrature to the systematic error. The average charged multiplicity of the selected events, including the above corrections, is 26.64 and 26.58 respectively from the y_T 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 0.08 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, 0.03 and 0.12 respectively, were added in quadrature to the systematic error. The effect of the uncertainty on the WW cross-section was found to be negligible.

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, 0.10, was added in quadrature to the systematic error. The systematic errors due to the statistics of the Monte Carlo samples were found to be 0.11 for the multiplicity and 0.07 for the dispersion, and were added in quadrature to the systematic errors. To investigate a possible dependence of the measured multiplicity on the modelling of the detector response in the simulation, the analysis was repeated by using only the tracks with $\theta > 40^\circ$. The values obtained for the multiplicity and the dispersion were 26.73 and 8.13 respectively, and uncertainties of 0.15 and 0.13 were added to the systematic errors.

Finally, for the centre-of-mass energy of 183 GeV, the values

$$< n_{ch} > = 26.58 \pm 0.24(stat) \pm 0.54(syst) \quad (1)$$

$$D = 8.00 \pm 0.18(stat) \pm 0.24(syst) \quad (2)$$

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, plus the scale uncertainty of ± 0.48 for the multiplicity and ± 0.14 for the dispersion.

Figure 1 shows the value of the average charged particle multiplicity in $e^+e^- \to q\bar{q}$ events at 183 GeV compared with lower energy points from TASSO [24], HRS [25], and AMY [26], with DELPHI results in $q\bar{q}\gamma$ events at the Z [27], with the world average at the Z [20], and with the averages of the LEP results at 133, 161 and 172 GeV in [28]. A point corresponding to the multiplicity observed by DELPHI in W decays is also included at $\sqrt{s} = M_W$ and is discussed later in this paper. 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 $e^+e^- \to q\bar{q}$ [29]. Similarly, the values at 133, 161, 172 and 183 GeV were lowered by 0.15, 0.12, 0.11 and 0.10 respectively.

The QCD prediction for charged multiplicity has been computed as a function of α_s including the resummation of leading (LLA) and next-to-leading (NLLA) corrections [30, 21]:

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

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 [30] and $\alpha_s(\sqrt{s})$ is the strong coupling constant. The parameter d was introduced [27] to allow for higher order corrections. A fit to data between 20 GeV and 183 GeV, with $\alpha_s(\sqrt{s})$ (expressed at next-to-leading order) and a and d as free parameters, is shown in Figure 1. The results of the fit are: $a = 0.048 \pm 0.003$, $d = 1.27 \pm 0.25$, and $\alpha_s(m_Z) = 0.113 \pm 0.002(stat)$.

The ratio of the average multiplicity to the dispersion measured at 183 GeV, $< n_{ch} > /D = 3.32 \pm 0.11$, is consistent with the average from the measurements at lower centre-of-mass energies (3.15 ± 0.04), as can be seen in Figure 2. This is consistent with KNO scaling [31], and also with the predictions of QCD including 1-loop Higher Order terms (H.O.) [32].

4 Classification of the WW Events and Multiplicity Measurement

About 4/9 of the WW are WW $\to 4jets$ events. At threshold, their topology is 4-jets back-to-back, with no missing energy; the constrained invariant mass of two jet-jet systems equals the W mass. Still at 183 GeV these characteristics allow a clean selection.

About 4/9 of the WW are WW $\to 2jets\, \ell\bar{\nu}$ events. At threshold, their topology is 2-jets back-to-back, 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.

4.1 Fully Hadronic Channel (WW$\to 4j$)

Events with both Ws 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 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, the hadronic centre-of-mass energy was required to 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-jet and 3-jet events of the q$\bar{\rm q}$ 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. Of the three fits obtained by permutation of the jets, the one with the best χ^2 was selected. Events were accepted only if the product of the smallest fitted 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 75% and 74% respectively. The data sample consists of 421 events (387 were expected from the simulation). The expected background was subtracted bin by bin from the observed distributions. The values of $< n_{ch}^{(4q)} >$ before and after the background subtraction were 32.36 and 32.82 respectively.

The final value of $< n_{ch}^{(4q)} >$ was estimated by integrating the ξ_E distribution. To account for inefficiencies due to detector effects and selection criteria, a correction factor was computed, bin by bin, as the ratio 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:

$$< n_{ch}^{(4q)} > \quad = \quad 37.36 \pm 0.54(stat) \pm 0.93(syst)\,, \tag{3}$$

where the systematic error accounts for scale uncertainty (0.68), variation of the selection criteria (0.13), change of the q$\bar{\rm q}$ cross-sections within 5% (0.02), uncertainty on the modelling of the background (0.40), modelling of the detector in the forward region (0.08) and limited statistics in the simulated sample (0.09). The value of $< n_{ch}^{(4q)} >$ was also estimated:

- from the observed multiplicity distribution as 37.78;
- from the integral of the rapidity distribution (with respect to the thrust axis) as 36.91;
- from the integral of the p_T distribution (with respect to the thrust axis) as 37.38.

The maximum difference (0.45) from the reference value was taken as an extra systematic error. The uncertainty on the modelling of the background quoted above is the sum in quadrature of three contributions:

- Uncertainty on the $q\bar{q}$ multiplicity. A relative uncertainty as in Eq. (1) was assumed; this gives a multiplicity error of 0.20.
- Uncertainty on the 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 0.13.

- Uncertainty on the 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 0.32 on the value in Eq. (3).

To investigate a possible dependence of the measured multiplicity on the modelling of the detector response in the forward region, the analysis was repeated by using only the tracks with $\theta > 40°$. The values obtained for the multiplicity and the dispersion were 37.28 ± 0.49 and 8.41 ± 0.39 respectively, and an uncertainties of 0.08 and 0.17 were added to the systematic errors on the multiplicity and the dispersion.

The value in (3) is about 1.4 standard deviations lower than the value previously published by DELPHI [15].

The presence of interference between the jets coming from the different Ws could create subtle effects, such as to make the application of the fit imposing equal 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. No χ^2 cut was imposed in this case. The average multiplicity obtained was again fully consistent (within the statistical error) with the one measured in the standard analysis.

The distribution of the observed charged multiplicity in $(4q)$ is shown in Figure 3a. After correcting for detector effects, the dispersion was found to be:

$$D^{(4q)} = 8.24 \pm 0.38(stat) \pm 0.34(syst)\,, \qquad (4)$$

where the systematic error comes from the variation of the cuts (0.25), modelling of the detector in the forward region (0.19), scale uncertainty (0.15) and from limited Monte Carlo statistics (0.05).

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

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 oppositely charged leptons of the same flavour.

Events were selected by requiring seven or more charged particles, with a total energy (charged plus neutral) above $0.2\sqrt{s}$. 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 $|\cos\theta_{miss}| < 0.94$.

Including 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 either 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_{cut} parameter required by the Durham algorithm to force the event from a 3-jet 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_{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_{cut} was greater than 0.003, and no other charged particle above 1 GeV/c existed in the lepton jet.

All three topologies were then retained for the analysis, giving 225 events in the data sample. The estimated purity was 90%, and the efficiency was 51% (58% in the electron channel, 73% in the muon channel and 23% in the τ channel). A total of 209 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 decay products) to the observed multiplicity, taking as reference the sample generated with one W decaying into hadrons. The values of the observed charged multiplicity before and after the background subtraction were 17.08 and 17.07 respectively.

Finally the following value was obtained for the charged multiplicity for one W decaying hadronically in a WW event with mixed hadronic and leptonic final states by integrating the ξ_E distribution:

$$< n_{ch}^{(2q)} > \quad = \quad 19.48 \pm 0.37(stat) \pm 0.63(syst)\,, \tag{5}$$

where the systematic error accounts for scale uncertainty (0.35), variation of the selection criteria (0.33), variation of the $q\bar{q}(\gamma)$ cross-sections within 5% (negligible), modelling of the detector in the forward region (0.01) and limited statistics in the simulated samples (0.07). The value of $< n_{ch}^{(2q)} >$ was also estimated:

- from the observed multiplicity distribution as 19.20;

- from the integral of the rapidity distribution (with respect to the thrust axis) as 19.08;

- from the integral of the p_T distribution (with respect to the thrust axis) as 19.42.

The maximum difference (0.40) from the reference value was taken as an extra systematic error. To investigate a possible dependence of the measured multiplicity on the modelling of the detector response in the forward region, the analysis was repeated by using only the tracks with $\theta > 40°$. The values obtained for the multiplicity and the dispersion were 19.49 ± 0.39 and 5.94 ± 0.29 respectively, and an uncertainties of 0.01 and 0.18 were added to the systematic errors on the multiplicity and the dispersion.

The value in (5) is about 1.1 standard deviations lower than the value previously published by DELPHI [15].

The distribution of the observed charged multiplicity in $(2q)$ is shown in Figure 3b. After correcting for detector effects, the dispersion was found to be:

$$D^{(2q)} = 5.76 \pm 0.26(stat) \pm 0.42(syst)\,, \tag{6}$$

where the systematic error comes from the variation of the cuts (0.37), modelling of the detector in the forward region (0.18), scale uncertainty (0.10) and from limited Monte Carlo statistics (0.05).

5 Analysis of Interconnection Effects from Charged Particle Multiplicity and Inclusive Distributions

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:

$$\frac{< n_{ch}^{(4q)} >}{2 < n_{ch}^{(2q)} >} = 0.96 \pm 0.02(stat) \pm 0.03(syst)\,. \tag{7}$$

In the calculation of the systematic error on the ratio, all the systematic errors were assumed as uncorrelated except for the scale error, for which full correlation was assumed. The same result is obtained when correlations are explicitly computed for:

- modelling of the detector in the forward region;
- change in the $q\bar{q}$ cross section;
- computation of multiplicity using the multiplicity, y and p_T distributions.

The experimental accuracy on this observable is of the same order or larger than the expected effect by most of the models, and thus it does not allow a precise test of interconnection effects. More sensitive observables should be investigated.

By neglecting possible differences in the multiplicity distributions for the $(2q)$ and the $(4q)$ cases, one can average the results to obtain the best determination of the charged particle multiplicity from hadronic decays of the W, and of the dispersion of the distribution. The multiplicity in the $(4q)$ case was divided by a factor of 2, while the dispersion was divided by a factor $\sqrt{2}$. Considering the systematic errors as independent (excluding the scale error), one finally has:

$$< n^{(W)} > \; = \; 18.96 \pm 0.22(stat) \pm 0.43(syst) \tag{8}$$

$$D^{(W)} \; = \; 5.80 \pm 0.19(stat) \pm 0.19(syst)\,. \tag{9}$$

The value of $< n^{(W)} >$ is also plotted in Figure 1 at an energy value corresponding to the W mass; it has been increased by 0.35 units to account for the different proportion of events with a b or a c quark in W hadronic decays than in continuum e^+e^- events [29]. It lies on the same curve as the e^+e^- data. The value of $< n^{(W)} > / D^{(W)}$, plotted in Figure 2, is also consistent with the continuum e^+e^- events.

Inclusive particle distributions can enhance the sensitivity to interconnection effects. In most models (see [9] for a recent review) the depletion in multiplicity in the presence of colour reconnection is expected to take place mostly at small momentum; important distortions of the rapidity y_T with respect to the thrust axis and of the transverse momentum p_T are predicted in [5].

The corrected momentum distribution in the ($4q$) and in the ($2q$) cases is shown in Figure 4. It does not show any significant difference, although there is a small excess in the ($2q$) mode for $p < 2$ GeV/c: $(< n_{ch}^{(4q)} > -2 < n_{ch}^{(2q)} >)_{p<2\,\mathrm{GeV}/c} = -1.3 \pm 0.8(stat + syst)$. Most of the models expect that the difference would be relevant for momenta below ≈1 GeV/c; the observed value is:

$$(< n_{ch}^{(4q)} > -2 < n_{ch}^{(2q)} >)_{p<1\,\mathrm{GeV}/c} = -0.6 \pm 0.6(stat + syst) \tag{10}$$

$$\left.\frac{< n_{ch}^{(4q)} >}{2 < n_{ch}^{(2q)} >}\right|_{p<1\,\mathrm{GeV}/c} = 0.96 \pm 0.04(stat + syst) \tag{11}$$

more than two standard deviations lower than the preliminary value $(< n_{ch}^{(4q)} > -2 < n_{ch}^{(2q)} >)_{x_p<0.01} = 3.9 \pm 1.6(stat + syst)$ presented in [14].

Other inclusive distributions taking into account the orientation of particles could display a larger sensitivity with respect to interconnection effects. Special care should be anyway taken, since the definition of the thrust axis could introduce a bias between ($2q$) and ($4q$) events. To estimate the effect of this bias, the following procedure was used. First the distributions of rapidity and p_T were computed as in the case of the momentum for the ($2q$) and the ($4q$). Then, a set ($4q$)-like events was constructed by mixing pairs of ($2q$) events. For each real ($4q$) event each W was replaced by a W from a ($2q$), flying in the same direction and with the same momentum, and with the two reconstructed jets lying in the same plane. If there would be no bias from the definition of the event axis (or if the Monte Carlo correction could correctly account for the bias), there would be no difference between the y_T and p_T distributions in the mixed sample and twice the ($2q$) sample. This difference has thus been taken as an estimator of the systematic error from the bias, and added in quadrature to the ($4q$) distribution, to twice the ($2q$) distribution, and to their difference.

The distributions of rapidity and transverse momentum with respect to the thrust axis are shown in Figure 5 and 6 respectively. Again, there is no indication of interconnection effects (at this level of statistics) from the standard inclusive distributions.

6 Charge Multiplicity and Momentum Spectrum of W Bosons: an Alternative Analysis

An alternative analysis was performed, cross-checking the results of the previous one. In this analysis, the event selection criteria were optimised in order to reduce the residual contamination from non-WW events.

6.1 Event Selection for Fully Hadronic Final States

Only events where the value of the thrust was less than 0.9 were considered. For each event passing the above criteria, all particles were clustered into jets using the LUCLUS algorithm [18] with the resolution parameter $d_{join} = 6.5$ GeV/c. At least four jets were required, with at least three particles in each jet.

Events from the radiative return to the Z peak were rejected by requiring the effective centre-of-mass energy of the e^+e^- annihilation, estimated as described in Section 3, to be larger than 115 GeV.

Events were then forced into a four-jet configuration. The four-vectors of the jets were used in a kinematic fit, which imposed conservation of energy and momentum and equality of masses of two pairs of jets. Events were used only if at least one of the three possible pairings of jets had a fit probability larger than 2.5%. The final cut to select WW events was the requirement of a fitted mass larger than 75 GeV/c^2 for at least one retained combination.

A total of 189 events were selected; 182 events are expected from the simulation. The purity and efficiency of the selection, estimated using simulated events, were about 91% and 44% respectively. The cut on the fit probability strongly reduces the efficiency of event selection, from 69% to 44%. It was verified with simulated events that the events removed by the cut on the fit probability have practically the same multiplicity distribution as the remaining events.

6.2 Event Selection for Mixed Hadronic and Leptonic Final States

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 six or more charged particles and a missing momentum of more than 10% of the total centre-of-mass energy. Electron and muon tags were applied to the events. In $q\bar{q}(\gamma)$ events, the selected lepton candidates are either leptons produced in heavy quark decays or misidentified hadrons, which generally have rather low momenta and small angles with respect to their quark jets. The momentum of the selected muon, or the energy deposited in the electromagnetic calorimeters by the selected electron, was required to be greater than 20 GeV. The energy not associated to the lepton, but assigned instead to other charged or neutral particles in a cone of 10° around the lepton, is a useful measure of the lepton's isolation; this energy was required to be less than 5 GeV for both muons and electrons. In addition, the isolation angle between the lepton and the nearest charged particle with a momentum greater than 1 GeV/c was required to be larger than 10°. If more than one identified lepton passed these cuts, the one with highest momentum was considered to be the lepton candidate from the W decay. The angle between the lepton and the missing momentum vector was required to be greater than 70°. All the other particles were forced into two jets using the LUCLUS algorithm [18]. Both jets had to contain at least one charged particle.

Further suppression of the radiative $q\bar{q}$ background was achieved by looking for evidence of an ISR (Initial State Radiation) photon. Events were removed if there was a cluster with energy deposition greater than 20 GeV in the electromagnetic calorimeters, not associated with a charged particle. Events with ISR photons at small polar angles, where they would be lost inside the beam pipe, were suppressed by requiring the polar angle of the missing momentum vector to satisfy $|\cos\theta_{miss}| < 0.94$.

The four-fermion neutral current background was reduced by applying additional cuts to events in which a second lepton of the same flavour as the first was detected. Such events were rejected if the energy in a cone of 10° around the second lepton direction was greater than 5 GeV.

If no lepton was identified, the most energetic particle which formed an angle greater than 25° with all other charged particles was considered as a lepton candidate. In this case the lepton was required to have a momentum greater than 20 GeV/c, as before, but tighter cuts were applied to the amount of missing momentum (greater than 20 GeV/c) and to its polar angle ($|\cos\theta_{miss}| < 0.85$).

A kinematical fit was performed on the selected events. The four-vectors of the two jets and of the lepton were used in the fit, which imposed conservation of energy and momentum and equality of the masses of the two-jet system and the lepton-neutrino system, attributing the missing momentum of the event to the undetected neutrino. Events were used only if the fit probability was larger than 0.1%. The final cut was that the fitted mass of the two-jet system had to be larger than 65 GeV.

A total of 175 events were selected. The purity and efficiency of the selection, estimated using simulated events, were about 96% and 48%, respectively. A total of 180 events is expected from simulation.

6.3 Results

Charged particles were used in the analysis if they had a momentum $p > 100$ MeV/c, error on the momentum measurement less than 100%, polar angle θ between 30° and 150°, track length greater than 50 cm, and impact parameters with respect to the nominal interaction point less than 4 cm. The energetic isolated charged track of the mixed decay channel was not included in the following analysis.

Figure 7 shows the charged particle multiplicity distributions for the fully hadronic decay (a) and for the mixed decay (b) channels of $e^+e^-\to W^+W^-$ events. The shaded areas represent the background contributions, the histograms are the sum of the expected signal and background.

To take into account inefficiencies due to detector effects and selection criteria, correction factors were calculated as the ratio of average multiplicities of generated WW events to average multiplicities after full simulation of the DELPHI detector. The corrected values of the average charge multiplicities for hadronic W decays in the fully hadronic and mixed decay channels obtained in the present analysis are:

$$< n_{ch}^{(4q)} > \;=\; 37.7 \pm 0.6(stat) \pm 1.1(syst) \qquad (12)$$

$$< n_{ch}^{(2q)} > \;=\; 19.5 \pm 0.5(stat) \pm 0.6(syst)\,. \qquad (13)$$

The systematic errors in (12) and (13) are the sum in quadrature of the following contributions:

- Due to variations of the selection criteria, ±0.70 and ±0.55 respectively.
- Due to background events: the selected fully hadronically decaying WW candidate events contain about 9% background and the selected mixed decaying WW candidates about 4%. The systematic errors due to this source were estimated as ±0.78 and ±0.31, respectively.

- The systematic errors due to limited Monte-Carlo statistics were ± 0.16 and ± 0.10 respectively.

The above results are consistent with with those presented in Section 5.

The dependence of the charged particle multiplicities on momentum of the particles was obtained using the same procedure as for the calculation of the total average multiplicities, repeated in each momentum interval. The momentum distributions, corrected for detector effects and kinematical cuts, were obtained by bin by bin multiplication of the uncorrected distributions with the ratio of the generated distributions to the distributions after full detector simulation. The distributions were normalized to the number of events and the distribution for the mixed decay WW channel was multiplied by a factor of two.

The corrected x_p distributions of charged particles for fully hadronic and mixed decay WW channels, where $x_p \equiv 2p/\sqrt{s}$, are shown in Figure 8. No difference between momentum distributions for fully hadronic and twice mixed WW channels was obtained. In Figure 8b the ratio of the x_p distributions at 183 GeV is shown as closed circles. The same ratio at centre-of-mass energy of 172 GeV is shown as open squares. The distributions for events generated by PYTHIA are also shown (histogram in Figure 8a and stars in Figure 8b). The ratio between the distributions for fully hadronic and twice the mixed decay channel for events generated by PYTHIA (stars in Figure 8a), where both Ws decay independently, is consistent with one in all momentum regions.

7 Conclusions

In this note we presented the measurement of the charged particle multiplicity and its dispersion in $e^+e^- \to q\bar{q}$ events and in the WW decays at 183 GeV.

The final results for $q\bar{q}$ events are:

$$< n_{ch} > \; = \; 26.58 \pm 0.24(stat) \pm 0.54(syst) \quad (14)$$

$$D \; = \; 8.00 \pm 0.18(stat) \pm 0.24(syst)\,. \quad (15)$$

The value (14) is consistent with the QCD prediction on the multiplicity evolution and the ratio of the multiplicity (14) and the dispersion (15) scales according to KNO expectations.

For WW events the measured multiplicities are:

$$< n_{ch}^{(4q)} > \; = \; 37.36 \pm 0.54(stat) \pm 0.93(syst) \quad (16)$$

$$< n_{ch}^{(2q)} > \; = \; 19.48 \pm 0.37(stat) \pm 0.63(syst) \quad (17)$$

in fully hadronic (16) and mixed hadronic and leptonic final states (17). The numbers (16) and (17) can be compared with the average multiplicities of 38.10 and 19.05 predicted using WW events generated by PYTHIA (where both Ws decay independently), with parameters tuned to the DELPHI data at LEP1.

The charged multiplicity from WW systems in which both Ws decay hadronically is thus consistent with twice that from a W whose partner decays semileptonically:

$$\frac{< n_{ch}^{(4q)} >}{2 < n_{ch}^{(2q)} >} = 0.96 \pm 0.02(stat) \pm 0.03(syst) \; ; \quad (18)$$

thus, from the multiplicity of charged particles there is no evidence of interconnection effects in fully hadronic WW decays at this level of precision. The study of inclusive distributions like momentum, rapidity and transverse momentum (with respect to the thrust axis), which should display an higher sensitivity on interconnection effects, leads to the same conclusion. In particular, the charged particle multiplicities are also consistent in the low momentum ($p < 1$ GeV/c) region.

Averaging (16) and (17) we finally obtain:

$$< n^{(W)} > \; = \; 18.96 \pm 0.22(stat) \pm 0.43(syst) \quad (19)$$

$$D^{(W)} \; = \; 5.80 \pm 0.19(stat) \pm 0.19(syst)\,. \quad (20)$$

The value (19) is consistent with the QCD evolution for and energy corresponding to the W mass. The ratio $< n^{(W)} > / D^{(W)}$ is also consistent with the continuum e^+e^- events.

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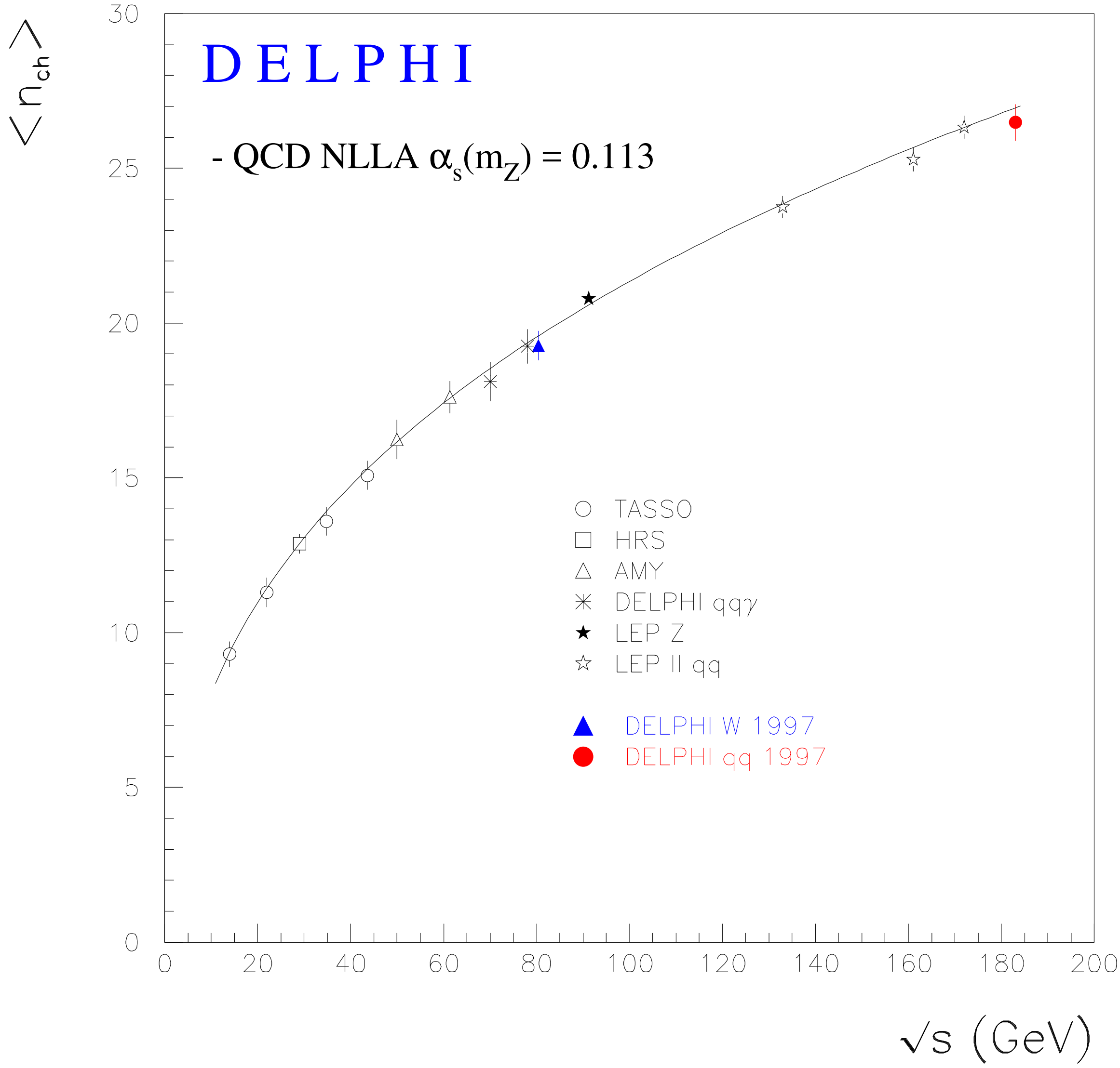

Figure 1: Measured average charged multiplicity in $e^+e^- \to q\bar{q}$ events as a function of centre-of-mass energy $\sqrt{s}$. DELPHI high energy results are compared with other experimental results and with a fit to a prediction from QCD in Next to Leading Order. The average charged multiplicity in W decays is also shown at an energy corresponding to the W mass. The measurements have been corrected for the different proportions of $b\bar{b}$ and $c\bar{c}$ events at the various energies.

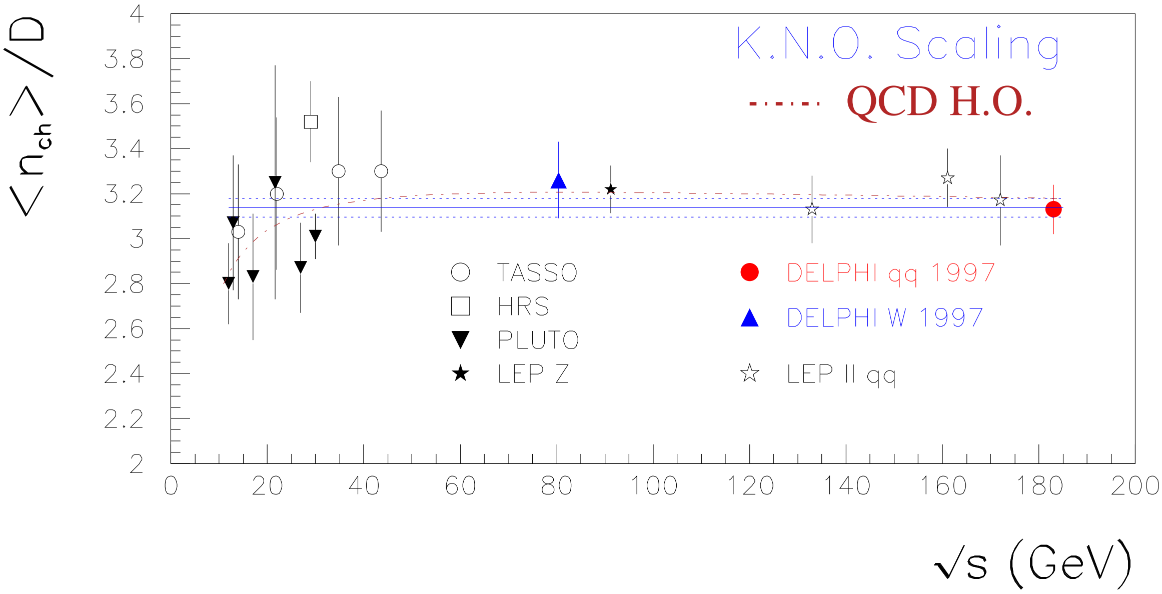

Figure 2: Ratio of the average charged multiplicity to the dispersion in $e^+e^- \rightarrow q\bar{q}$ events at 183 GeV, compared with lower energy measurements. The ratio in W decays is also shown at an energy corresponding to the W mass. The straight solid and dotted lines represent the weighted average of the data points and its error. The dashed line represents the prediction from QCD (see text).

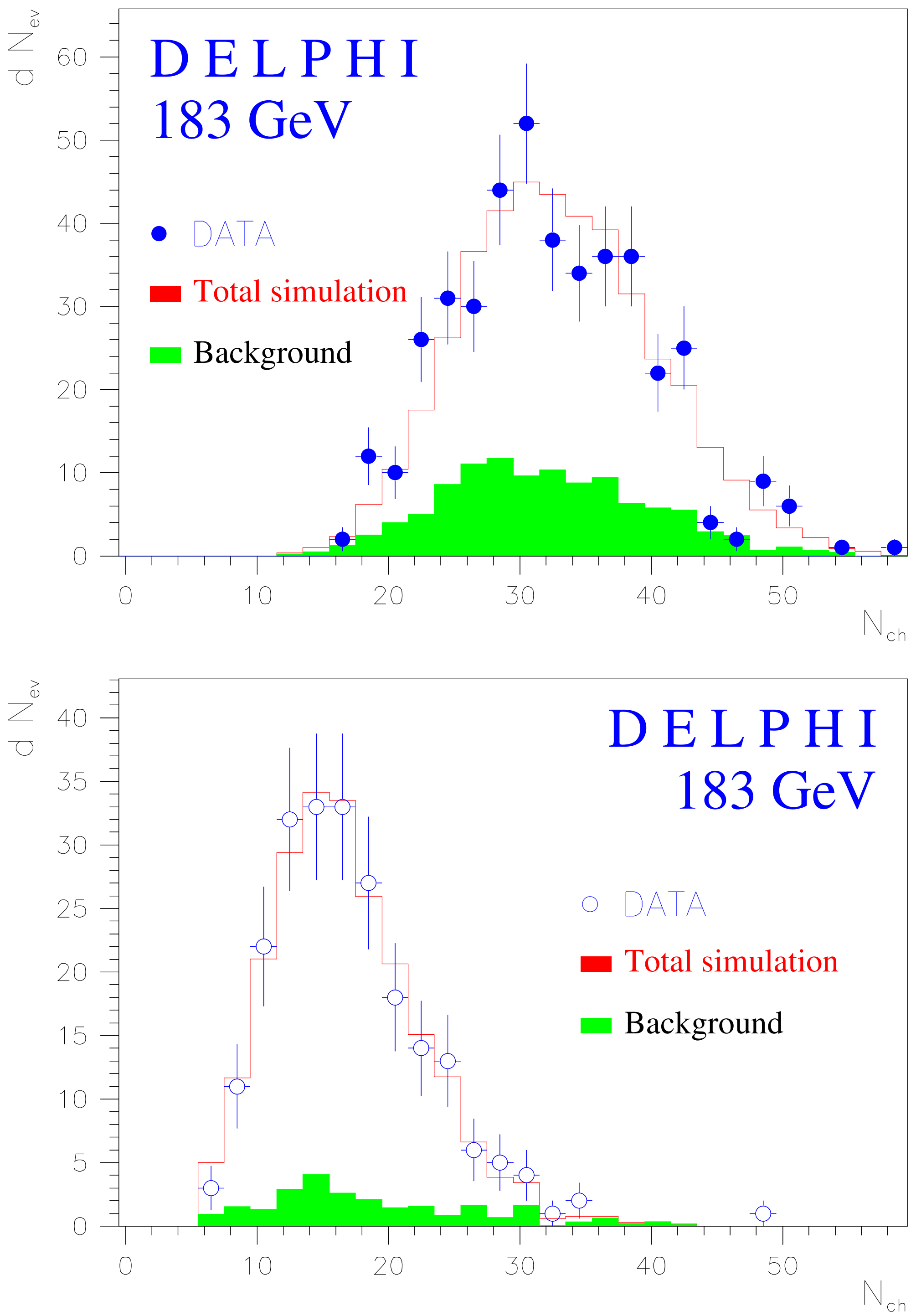

Figure 3: Charged particle multiplicity distribution for (a) the $(4q)$ events and (b) the $(2q)$ events. The shaded areas represent the background contribution; the histograms are the sum of the expected signal and background.

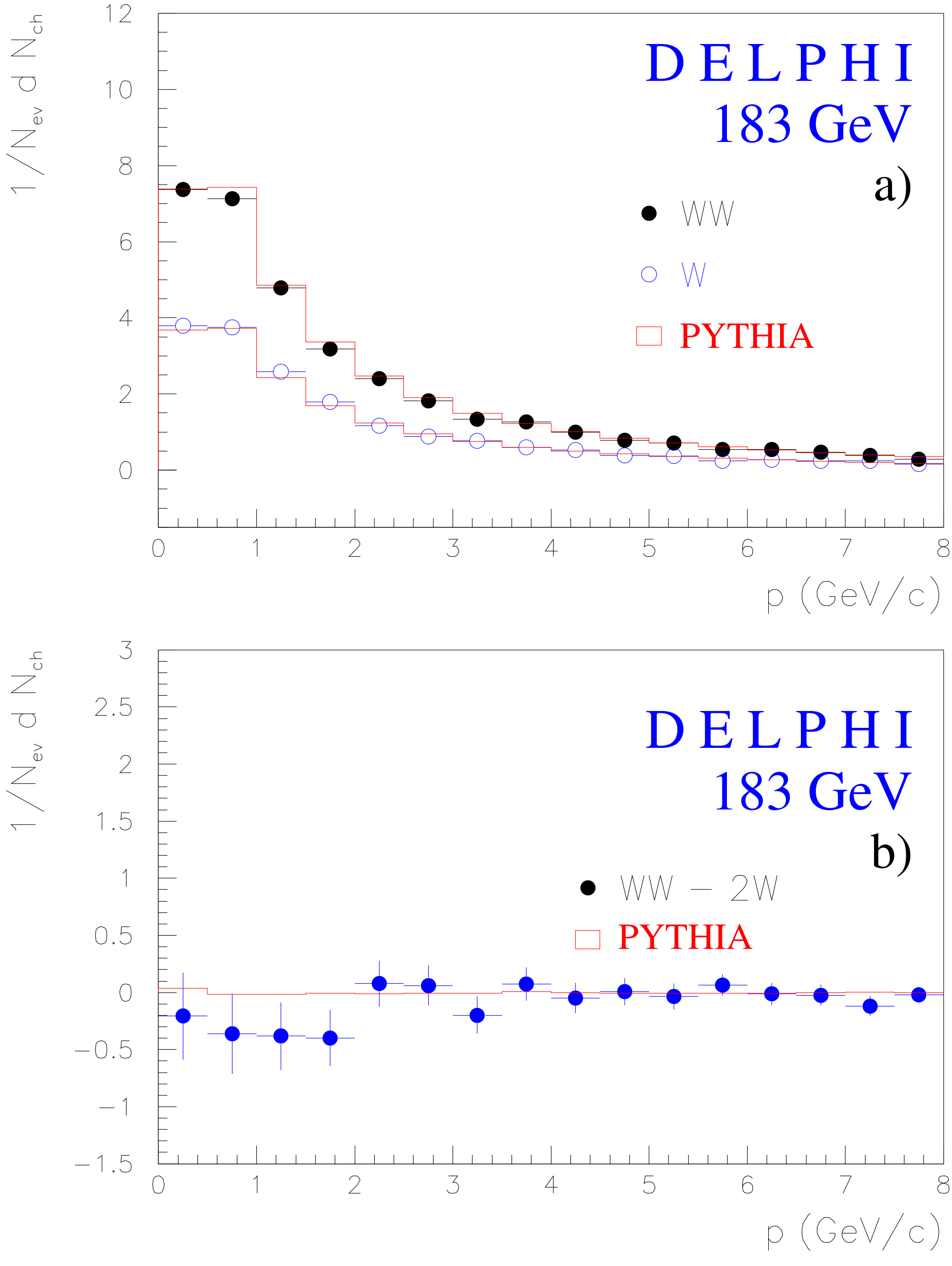

Figure 4: (a) Corrected momentum distributions for $(4q)$ events (closed circles) and $(2q)$ events (open circles), compared to simulation without colour reconnection. The difference between $(4q)$ and twice $(2q)$ is shown in (b).

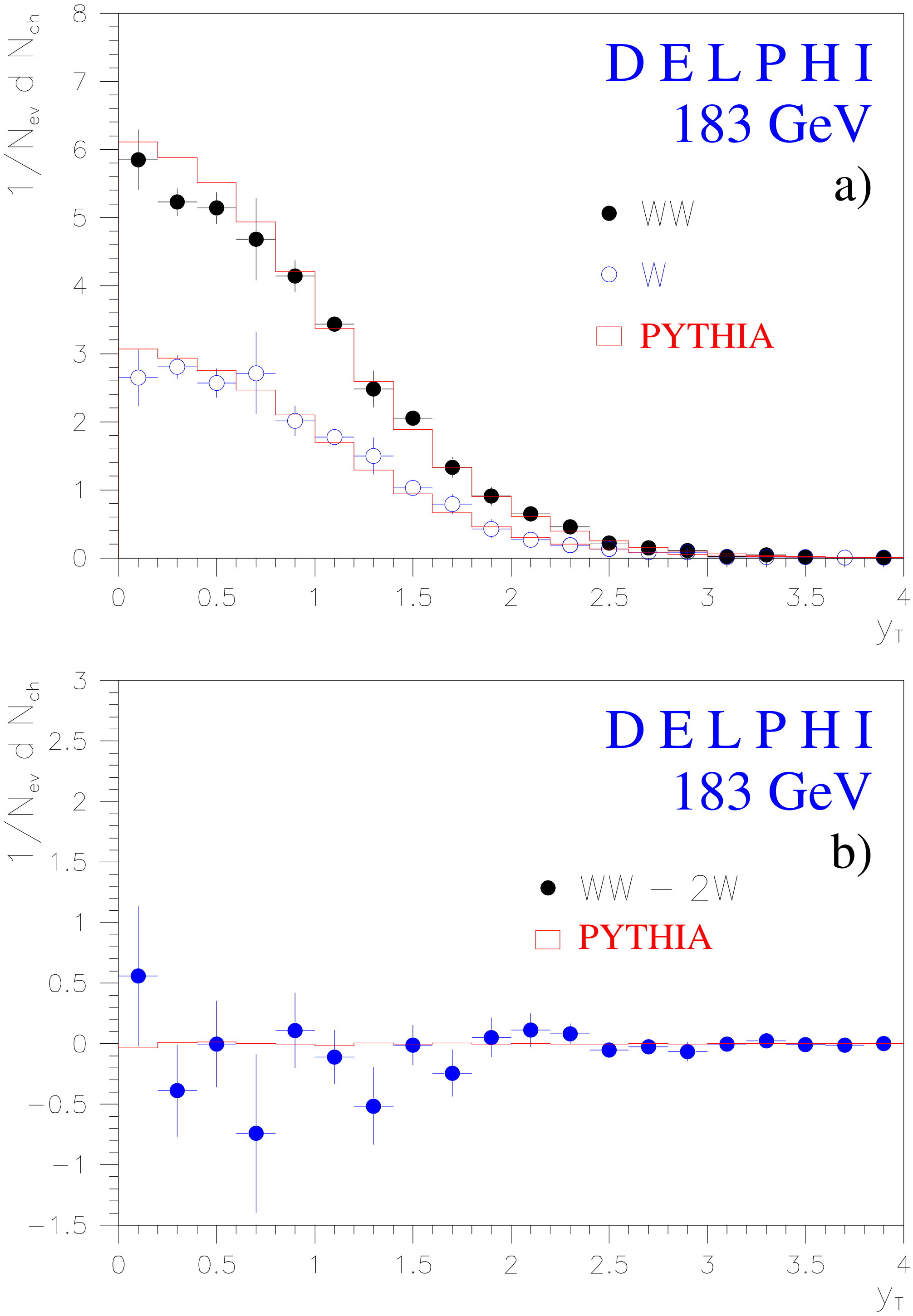

Figure 5: (a) Corrected rapidity distributions for $(4q)$ events (closed circles) and the $(2q)$ events (open circles), compared to simulation without colour reconnection. The difference between $(4q)$ and twice $(2q)$ is shown in (b).

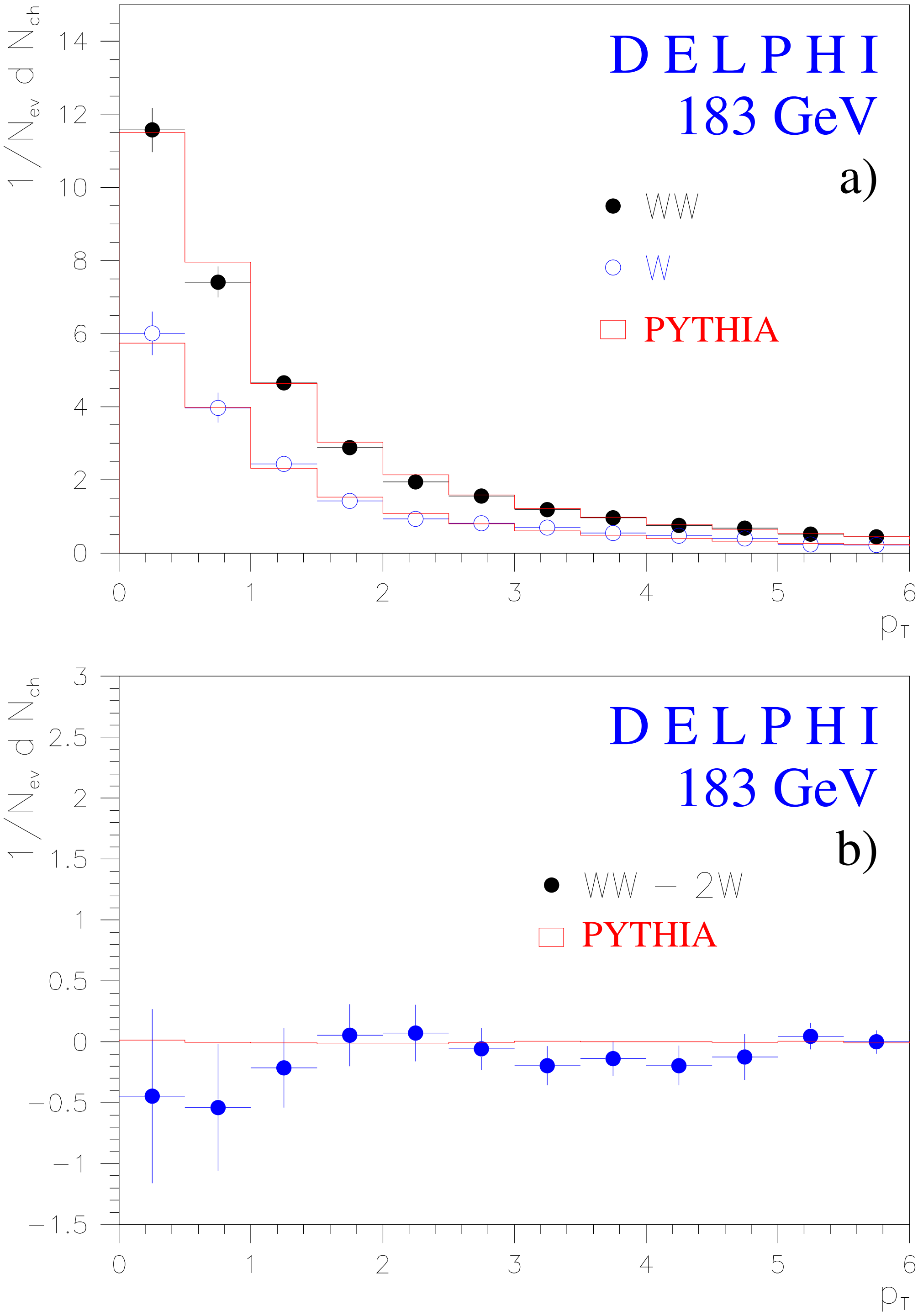

Figure 6: (a) Corrected p_T distributions for $(4q)$ events (closed circles) and the $(2q)$ events (open circles), compared to simulation without colour reconnection. The difference between $(4q)$ and twice $(2q)$ is shown in (b).

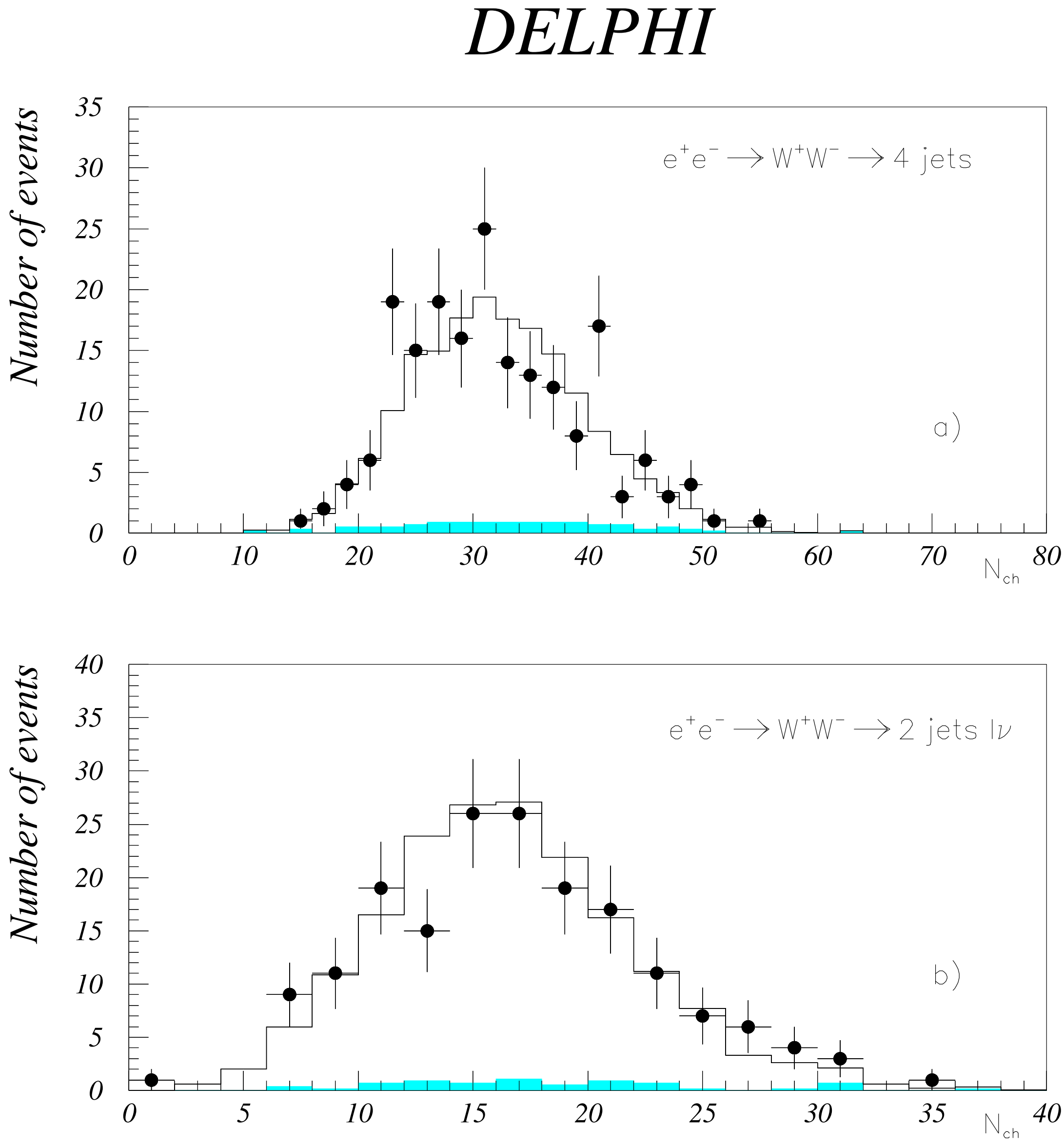

Figure 7: Charged particle multiplicity distributions for (a) fully hadronic (4-jet) final states and (b) mixed hadronic and leptonic (jet-jet-lepton-neutrino) final states in the alternative analysis. The shaded areas represent the background contributions. The histograms are the sum of the expected signal and background.

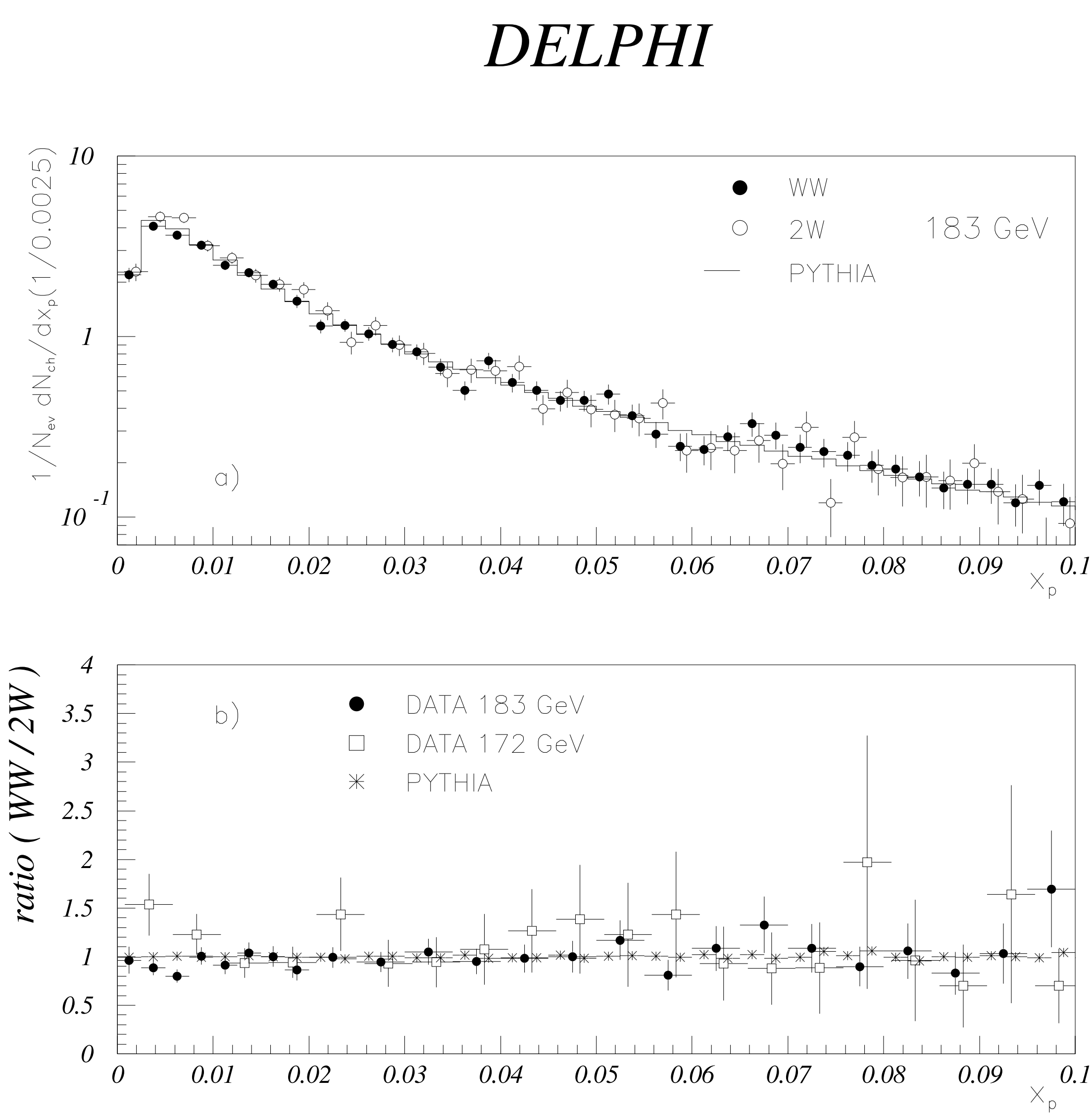

Figure 8: (a) The corrected x_p distributions for charged particles from hadronic W-decays for fully hadronic final states (closed circles) and twice the mixed hadronic and leptonic final states (open circles) in the alternative analysis. The distributions are normalized to the number of events. The predicted distribution obtained by using events generated with PYTHIA is shown by the histogram. (b) The ratio between the distributions in Fig. 3a (closed circles). The same ratio obtained at 172 GeV shown by open squares. The predicted ratio obtained by using events generated with PYTHIA is shown by stars.