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Study of QCD Coherence in Hadronic Z Decays

The ALEPH Collaboration

Abstract

Two variables are used to investigate QCD coherence phenomena in $e^+e^- \rightarrow Z \rightarrow q\bar{q}$ events: the particle-particle-correlation asymmetry (PPCA) and the energy-multiplicity-multiplicity correlation (EMMC). The former was invented for this study of the Angluar Ordering (AO) phenomenon, an *intrajet* coherence effect predicted by theory to affect the angular distribution of particles within the parton shower of a jet. The latter was designed to study *interjet* coherence predicted to influence the angular distribution of particles between jets (the "string effect") and also to be visible as correlations C(ϕ) of in the azimuthal distributions of particles emitted about the quark direction. A sample of 0.8 million hadronic events registered by ALEPH detector in 1992-93 along with several Monte Carlo generators were used to study both variables for AO. The data favours Monte Carlos with AO included in the parton shower and disfavours those with it not included. The EMMC value for C(ϕ) at $\phi = \pi$ is 0.78±0.02, which lies between the leading-order (C(π)=0.44) and the next-to-leading order (C(π)=0.93) QCD predictions.

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1 Introduction

QCD colour coherence deals with the parton emission in the shower development of high energy jets. The quantum mechanics of the gluon radiation affects the hadronic final states of e^+e^- annhiliation [1]–[5]. In general there is destructive interference among infrared gluons which has consequences for *intrajet* and *interjet* properties. *Intrajet* coherence leads to the angular ordering (AO) of the parton emission; each successive gluon in the shower development is radiated at a smaller angle than its predecessor. Examples of jet properties which manifest this "QCD coherence of the first kind" are the angular ordering, the particle momentum spectra, the two-particle momentum correlations, the particle multiplicity, and the related subject multiplicity. The *interjet* effects are sometimes referred to as "QCD coherence of the second kind": the angular structure of particle flows, when three or more partons are involved in a hard process, lead to the well-known "string effect" seen in the angular distribution of particles between hard partons in three-jet events and to "energy-multiplicity-multiplicity" correlations $C(\phi)$ in the azimuthal distribution of particles emitted about the quark direction [6].

Under the assumption of Local Parton-Hadron Duality (LPHD), which is generally used in such studies [4], the QCD effects which are parton-level predictions should appear in the final-state hadrons measured by the experiment. One thus has two handles for comparison with the data: the theoretical QCD predictions and the Monte Carlo models.

The main subjet of this paper is the study of AO in the parton shower [4] of $e^+e^- \to q\bar{q}$ events. Two variables have been studied, the Particle-Particle-Correlation Asymetery (PPCA), a new observable devised for this investigation[7], and the Energy-Multiplicity-Multiplicity Correlation (EMMC) [6] as parameters with sensitivity to AO. As indicated above, the latter variable is also sensitive to azimuthal correlations $C(\phi)$, which will also be measured.

2 PPCA and EMMC

2.1 PPCA

In order to be sensitive to AO in the hadronic decays of the Z, a parameter had to be found which is a function of the angluar distribution between the particles. This parameter, which will be called the Particle-Particle Correlation (PPC), has been constructed in analogy to the Energy-Energy Correlation [9]. The PPC is a normalized function and can be written as :

$$PPC(\chi) = \frac{1}{N_{Event}} \frac{1}{\Delta\chi} \sum_{1}^{N_{Event}} \sum_{i=1}^{N_{ch}} \sum_{j=1}^{N_{ch}} \frac{\delta(\chi \pm \frac{\Delta\chi}{2} - \chi_{ij})}{N_{ch}^2}, \qquad (1)$$

where N_{Event} is the number of events selected, $\Delta\chi$ is the bin width, N_{ch} is the number of charged tracks in an event, and χ_{ij} is the angle between track i and track j of an event. For $i = j$, $PPC = \frac{1}{\Delta\chi}$, a constant term which has no impact on the results and will be removed for the purpose of this paper in order to allow the use of a linear scale instead of a logarithmic one for the plots.

Then, in analogy with the Energy-Energy Correlation Asymmetry [10], which has fewer systematic uncertainties related to detector effects or to Monte Carlo models, one identifies the Particle-Particle Correlation Asymmetry (PPCA) as the better variable to be senstive to the AO. The formula for PPCA(χ) can be expressed in terms of PPC(χ) as

$$PPCA(\chi) = PPC(180 - \chi) - PPC(\chi). \tag{2}$$

2.2 EMMC

The second variable studied is the energy-multiplicity-multiplicity correlation (EMMC). The EMMC is a correlation function which was proposed [6] in order to study the azimuthal emission of two soft gluons from hard $q\bar{q}$ pairs. In this paper, its sensitivity to the AO of the emitted gluon is studied. The EMMC is constructed as follows. One considers each set of three particles in an event:i, j, k. Particle i is energy-weighted in order to sense the jet direction and particles j and k sense the azimuthal correlation of the soft gluons about the jet direction. The particles j and k are constrained to lie in a certain presudo-rapidity, $\eta = \ln\tan(\theta/2)$ interval and have relative azimuthal angle ϕ about the direction of particle i. If both particles j and k are contained within the region of pseudorapidity $\eta_{min} \leq \eta_{j,k} \leq \eta_{max}$, then an entry is made in the histogram of $\phi = |\phi_j - \phi_k|$ weighted by the energy of particle i, E_i. The EMMC is thus given by

$$\begin{aligned} C_{EMM}(\eta_{min}, \eta_{max}, \phi) \; = \; & \frac{1}{\sigma_{tot}} \int E_i dE_i dE_j dE_k \int_{\eta_{min}}^{\eta_{max}} d\eta_j d\eta_k \\ & \int_0^{2\pi} d\phi_j d\phi_k \delta(\phi - \phi_j + \phi_k) \frac{d\sigma}{dE_i dE_j dE_k d\eta_j d\eta_k d\phi_j d\phi_k} \end{aligned} \tag{3}$$

The weighting by E_i picks out the leading particles associated with the jet axis, and η_{min} and η_{max} are chosen so that particles j and k are associated with soft gluon radiation. For this investigation η_{min}=1.0 and η_{max}=2.0 were used. To obtain a quantity related to the correlation in azimuth of particles j and k, one normalizes to the two-particle energy-mutiplicity correlation squared divided by the total energy flow:

$$C(\phi) = \frac{C_{EMM}(\eta_{min}, \eta_{max}, \phi) C_E}{|C_{EM}(\eta_{min}, \eta_{max})|^2} \tag{4}$$

where

$$C_E = \frac{1}{\sigma} \int E_i dE_i \frac{d\sigma}{dE_i} \tag{5}$$

and

$$C_{EM}(\eta_{min}, \eta_{max}) = \frac{1}{\sigma_{tot}} \int E_i dE_i dE_j \int_{\eta_{min}}^{\eta_{max}} d\eta_j \int_0^{2\pi} d\phi_j \frac{d\sigma}{dE_i dE_j d\eta_j d\phi_j} \tag{6}$$

The function C(ϕ) is then a measure of the enhancement (or suppression) to find two particles at a similar polar angle (between η_{min} and η_{max}) seperated by an azimuthal angle ϕ.

The corresponding quantity can be computed analyticaly in perturbative QCD for the case of emission of two soft gluons from a quark-antiquark "colour-antenna" [6]. Interference effects lead to a suppression in the region $\phi \sim \pi$. To leading order the correlation function C(ϕ) at $\phi = \pi$ for an infinitesimal pseudorapidity interval is $7/16 = 0.44$ and to next-to-leading order is 0.93[8].

3 Event Selection

The ALEPH detector is described elsewhere[11]. This analysis makes use of the ALEPH tracking, which consists of a large time projection chamber (TPC) of 3.6m diameter and 4.4m length with a point-measuring precision of $\sigma_{r\phi} \simeq 200\mu$m and $\sigma_z \simeq 1$mm measured at up to 21 radial positions, an inner tracking drift chamber (ITC) of 0.6m diameter and 2m length with $\sigma_{r\phi} \simeq 150\mu$m measured at 8 points, and a silicon-strip vertex detector (VDET) of 0.2m diameter and length with $\sigma_{r\phi} \simeq \sigma_z \simeq 10\mu$m precision measured in two layers. The detectors are embedded in a 1.5T magnetic field and have a combined momentum-measurement accuracy of $\frac{\delta p_T}{p_T^2} \simeq 0.0006$.

Hadronic events were selected as follows. A charged track was used if it: (1) had at least 4 coordinates in the TPC, (2) had a polar angle $\geq$ 20 degrees, (3) had transverse momentum $p_T \geq 0.2$ GeV, and (4) originated from a cylindrical volume around the interaction point with diameter $\leq$ 2.0 cm and length $\leq$ 10.0 cm. An event was accepted if it had : (1) number of charge tracks ≥ 5, (2) total visible energy of the charged tracks $\geq$ 15 GeV, and (3) polar angle of its thrust axis $\geq$ 35 degrees. About 800000 hadronic events registered in 1992-93 were thus selected for the analysis.

4 Corrections and Systematic errors

4.1 Correction factors

The PPCA(χ) distribution from the data was corrected for detector effects by first correcting the PPC(χ) distribution and then forming the PPCA. The PPC(χ) was corrected bin by bin in the range $0° \leq \chi \leq 180°$ as follows

$$PPC_{corrected}(\chi) = \frac{PPC_{MC-GEN}(\chi)}{PPC_{MC-SIM}(\chi)} \times PPC_{data}(\chi) \qquad (7)$$

where PPC_{MC-GEN} was derived from the Monte Carlo generator hadron level, and PPC_{MC-SIM} was from the Monte Carlo with the fully simulated ALEPH detector. Finally,

$$PPCA_{corrected}(\chi) = PPC_{corrected}(180-\chi) - PPC_{corrected}(\chi). \qquad (8)$$

The corrected EMMC distribution from data was obtained using an expression similar to Eq.(7).

Jetset is the Monte Carlo with full simulation which is available with the highest statistics in ALEPH. It has the colour coherence option enabled and has been used to correct the PPC distribution. The correction factor used was thus

$$CF(\chi) = \frac{PPC_{MC-GEN}(\chi)}{PPC_{MC-SIM}(\chi)} \qquad (9)$$

with MC = Jetset. In order to test that the observations are not dependent on the model used for the correction factor, a pseudo correction factor was studied:

$$CFG(\chi) = \frac{PPC_{MC-GEN}(\chi)}{PPC_{MC-GEN-CUT}(\chi)}, \qquad (10)$$

where $PPC_{MC-GEN-CUT}$ is the distribution at generator hadron level with the same cuts described in Section 3 except for the track cut (1) related to the TPC, which is detector-specific and is essentially covered by the second cut. In this approach, the generator level and thus all Monte Carlo programs can be studied with high statistics. The status of the Monte Carlo programs is summarized in Table 1.

	Tuned to ALEPH data	B-E correlation	Parton level	Coherence	Fragmentation scheme
Jetset 7.3	Yes	On/Off	PS LLA	On/Off	SF
Ariadne 4.03	Yes	On/Off	Colour dipole	On	SF
Nlljet 2.0	Yes	On/Off	PS NLLA	On/Off	SF
Herwig 5.4	Yes	Off	PS LLA	On	CF
Cojet 6.23	No	Off	PS LLA	Off	IF

Table 1: Status of the Monte Carlo programs [12]-[16] used in the study of AO with the ALEPH detector. Symbols are: PS for parton shower, LLA for leading-log approximation, NLLA for next-to-leading-log aproximation [17], SF for string fragmentation [20], CF for cluster fragmentation [21], and IF for indpendent fragmentation [22].

The results for CFG show that in general they are small ($\leq$ 15%) and are model independent except for slight deviations for Cojet Monte Carlo in the region near $\chi = 90°$ for the PPC and near $\phi = 180°$ for the EMMC.

4.2 Systematic errors

The systematic effects studied are summarized here. The corresponding errors were combined in quadrature with the statistical errors.

Correction factor

Since the detection efficiency could depends on the charged-track multiplicity, the error in the correction factor CF is estimated by using the difference of the CF for high and low mutiplicity events. Fully simulated events with low mutiplicity are selected by requiring the event at generator level to have between 5 and 15 charged tracks and the same fully simulated event to pass the cuts described in Section 3. For the high mutiplicity events then the number of charged tracks at generator level is required to be $\geq$24. The difference between $CF_{high-multip}$ and $CF_{low-multip}$ is taken to be twice the standard deviation of the systematic error.

Monte Carlo models

The standard deviation of the CFG results for the different Monte Carlos as described in the previous section is taken as systematic error on the final result. Since the CFG is model independent, the results are not biased by using Jetset with AO for correcting the data.

Jetset parameters

The Jetset programs with and without the AO option have parameters tuned to ALEPH data [18]. Four parameters have been changed, one at a time, by plus and minus one standard deviation from its mean value.These parameters are PARJ(21)$\equiv \sigma_{PT}$, PARJ(42)$\equiv$ B fragmentation parameter, PARJ(81)$\equiv M_{min}$, and PARJ(82)$\equiv \Lambda_{LLA}$. The spread of the distribution caused by changing each parameters by $\pm 1\sigma$ is taken to be twice the systematic error for that parameter. The total systematic error due to varying the four parameters is estimated by adding the individual errors in quadrature. The variations of these parameters cause little change in the PPCA and EMMC distributions and do not degrade the ability to differentiate between Jetset with and without AO.

Coherence scheme

The angular ordering in Jetset can be performed in different ways depending on the value of MSTJ(43) one choses. This parameter controls the AO of the parton shower to be local (in the center of mass of the parents), or global (in the overall center of mass of the event). It is found that both PPCA and EMMC are not sensitive to whether the angular ordering is being perfomed localy or globaly.

Bose-Einstein effect

Most of the charged particles in the hadronic decays of Z are pions. Since PPCA and EMMC deal with the angular correlations of these pions plus other charge particles, a study to see whether the Bose-Einstein (B-E) correlation [19] affects these distributions was in order. For this Jetset was used with the B-E option turned ON or OFF and the change in the corresponding distribution PPCA or EMMC was taken to be the one standard deviation systematic error.

Independent fragmentation

The Jetset distributions of PPCA and EMMC with the comparison of string fragmentation and independent fragmentation show that the EMMC variable loses its sensitivity to AO for independent fragmentation, whereas, while the PPCA is affected numerically by the fragmentation scheme, it is still sensitive to the presence or absence of AO. No error was included for independent fragmentation.

5 Results and Conclusions

5.1 Angular Ordering

The data for the PPCA is compared to models with AO in Fig. 1 and to models without AO in Fig. 2.

The values for the difference between ALEPH data and Monte Carlos with AO for the PPCA variable is shown in Fig. 3, and the difference to Monte Carlos without AO in Fig. 4.

The corrected data for the energy-multiplicity-multiplicity variable C(ϕ) is compared to the Monte Carlo generators with AO are plotted in Fig. 5, and in Fig. 6 to the Monte Carlos without AO.

The values for the difference between ALEPH data and Monte Carlos with AO for C(ϕ) is shown in Fig. 7, and the difference to Monte Carlos without AO in Fig. 8 .

The χ^2 deviations of the data from the Monte Carlo distributions are summarized in Table 2. The PPCA (EMMC) distribution has 24 (49) degrees of freedom, and the χ^2 value has been computed taking into account the correlations between the bins. The correlation matrix was estimated by generating 500 samples of 2000 events each.

For the PPCA distribution Jetset with AO, Ariadne and Herwig, which all have AO implemented different ways, agree well with the data. Jetset without AO and Cojet, which also does not have AO, do not fit the data. Also the study using Jetset showed that it makes little difference whether the AO is implemented locally or globally, and

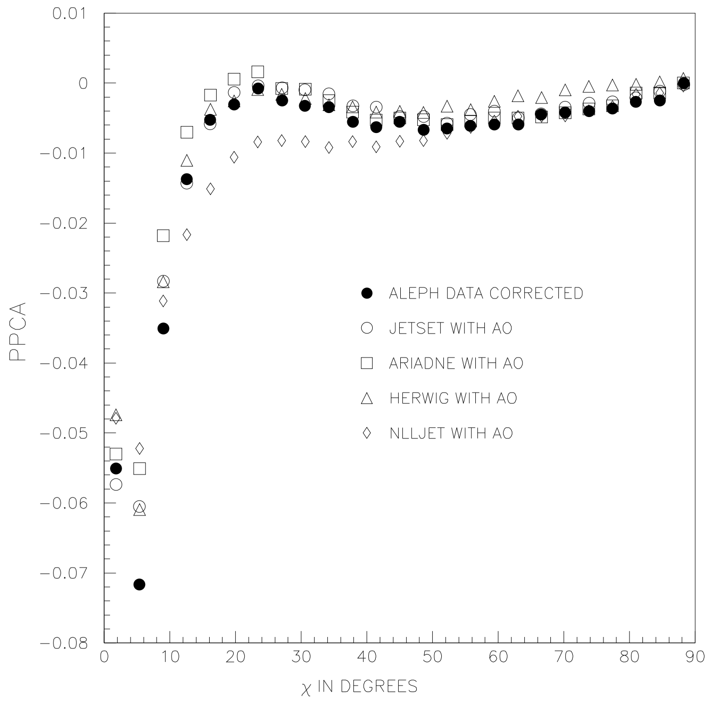

Figure 1: The distribution of $PPCA(\chi)$ for the corrected ALEPH data is compared to Monte Carlo generators with AO. The statistical error bars are smaller than the symbols for the data points.

effects such as Bose-Einstein correlations or the fragmentation scheme used do not have much influence.

In general one can say that the EMMC distribution is less sensitive to AO than the PPCA. But the same conclusions hold as for PPCA, the models with AO describe the data better than those without. The Nlljet Monte Carlo with AO does not describe the data very well, although for PPCA it is better than the models without AO.

5.2 C(ϕ)

The ALEPH data point in the last 3.6^o bin of the C(ϕ) distribution is C($\phi \approx \pi$) = $0.783 \pm 0.001 \pm 0.016$, where the first error is statistical and the second is systematic. Thus the measured value of C(ϕ) at ϕ near π is higher that the lowest order QCD prediction [6] of $7/16 = 0.44$ and smaller than the next-to-leading order prediction [8] of 0.93. One can argue that the missing higher order terms could be the reason for the final discrepancy, if they occur in a series of diminishing corrections of alternating signs. These observations concerning the EMMC are in general agreement with Ref. [23].

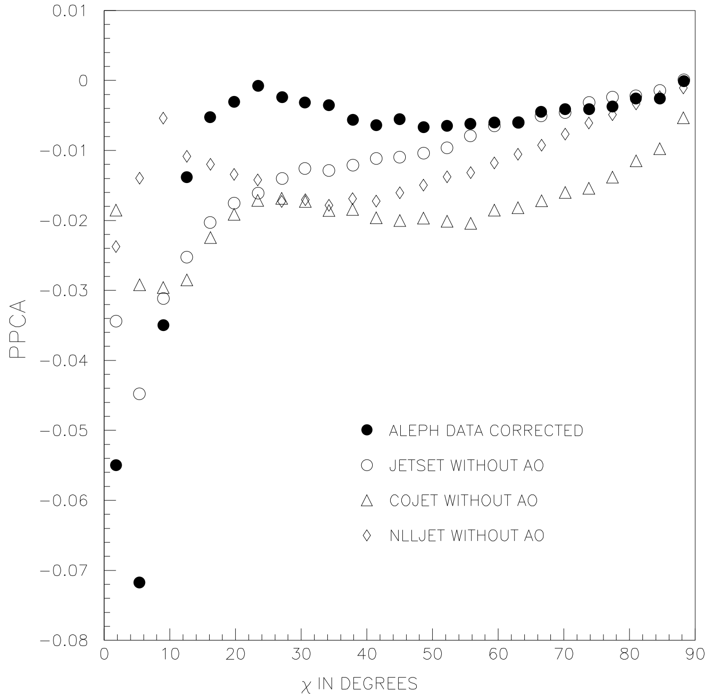

Figure 2: The distribution of $PPCA(\chi)$ for the corrected ALEPH data is compared to Monte Carlo programs without AO. The statistical error bars are smaller that the symbols.

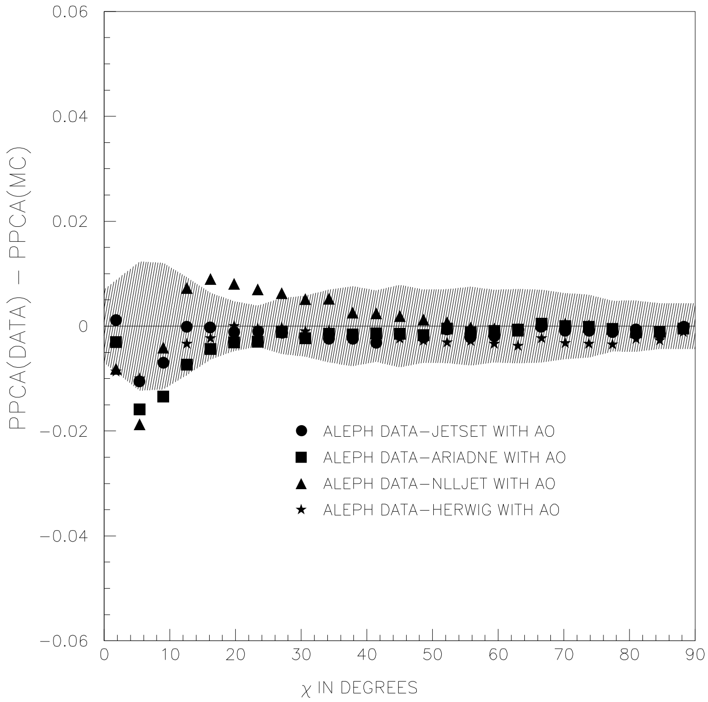

Figure 3: The distributions of $PPCA(\chi)_{data} - PPCA(\chi)_{MCGEN}$ for Monte Carlo programs with AO. The shaded band represents the ± 1 standard deviation for systematic and statistical errors added in quadrature.

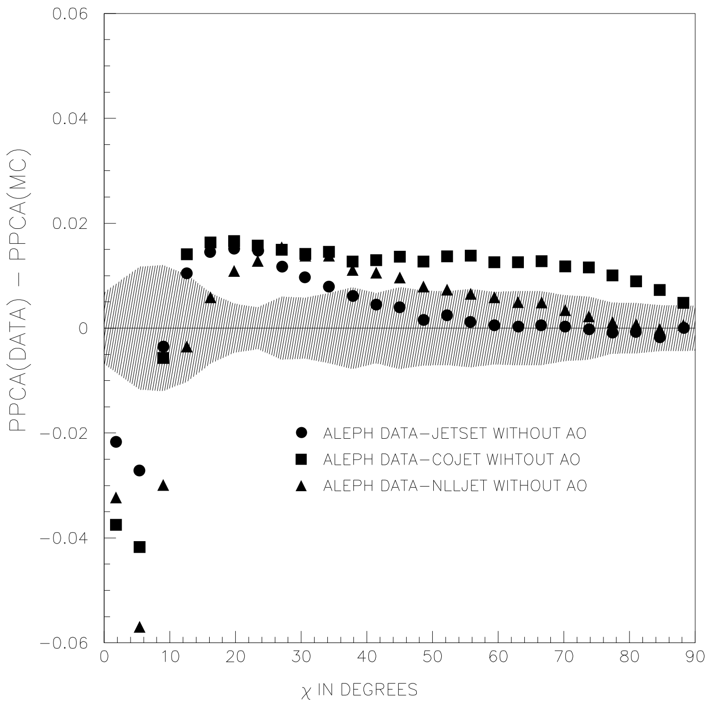

Figure 4: The distributions of $PPCA(\chi)_{data} - PPCA(\chi)_{MCGEN}$ for Monte Carlo programs without AO. The shaded band represents the ± 1 standard deviation for systematic and statistical errors added in quadrature.

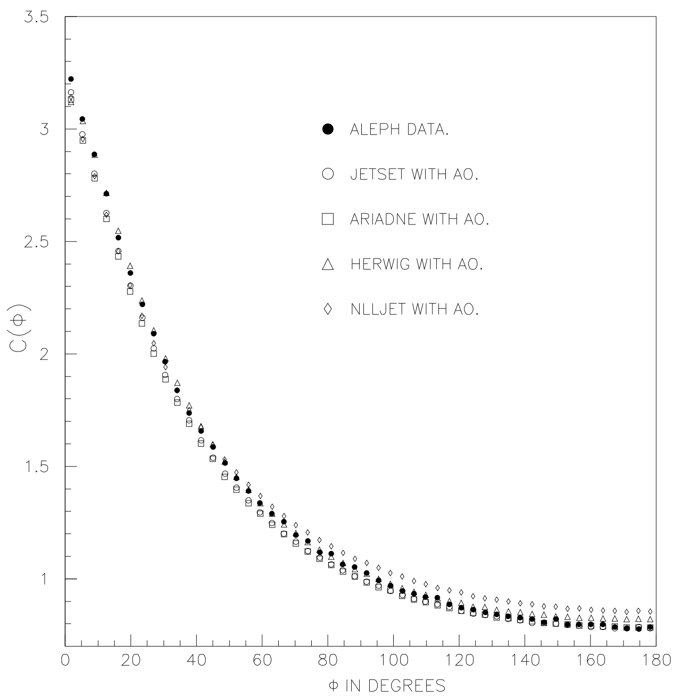

Figure 5: The distribution of $C(\phi)$ for data is compared to those of Monte Carlo programs with AO. The statistical error bars are smaller than the symbols.

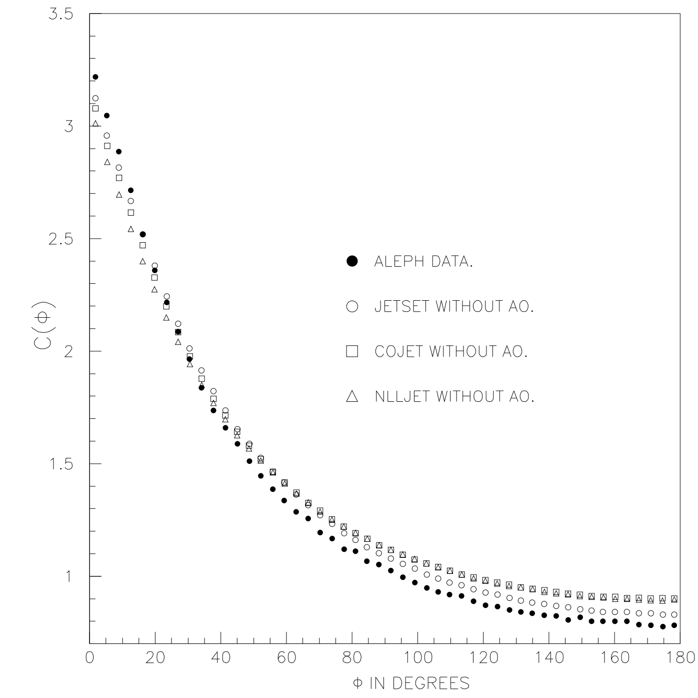

Figure 6: The distribution of $C(\phi)$ for data is compared to those of Monte Carlo programs without AO. The statistical error bars are smaller than the symbols.

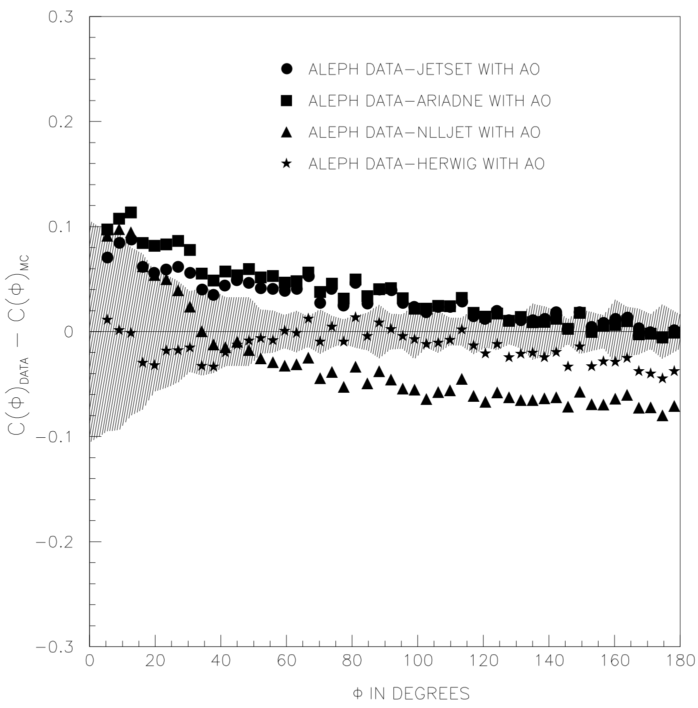

Figure 7: The distributions of $C(\phi)_{data} - EMMC(\phi)_{MCGEN}$ for Monte Carlo programs with AO. The shaded band represents the ± 1 standard deviation for systematic and statistical errors added in quadrature.

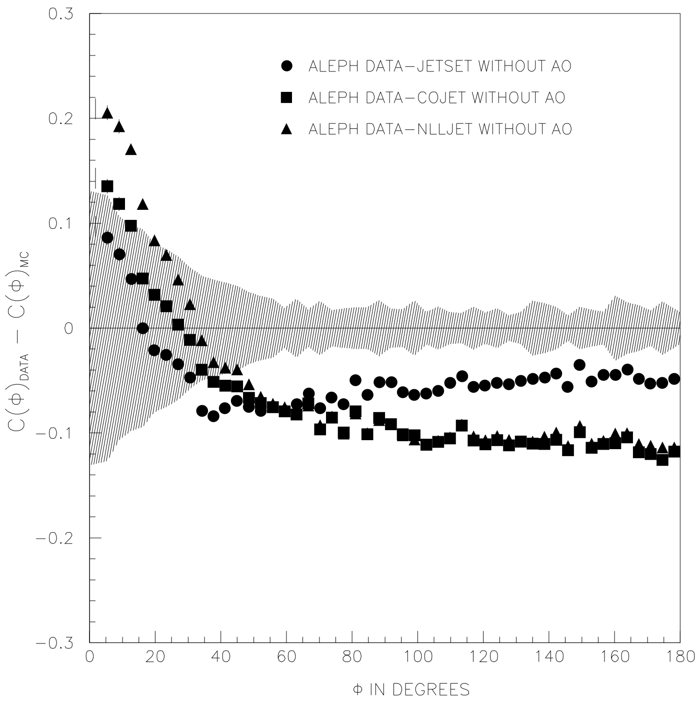

Figure 8: The distributions of $C(\phi)_{data} - C(\phi)_{MCGEN}$ for Monte Carlo programs without AO. The shaded band represents the ±1 standard deviation for systematic and statistical errors added in quadrature.

Model	EMMC	PPCA
	χ^2	
Jetset AO	31.9	2.3
Ariadne AO	38.5	6.1
Herwig AO	30.9	5.2
Nlljet AO	127.0	11.4
Jetset NOAO	93.5	40.4
Cojet NOAO	333.2	102.0
Nlljet NOAO	326.5	70.1

Table 2: The values of χ^2 when comparing the Monte Carlo programs ,at generated level, to the corrected data. The first column is for EMMC and based on 49 degrees of freedom, while the second column is for PPCA and based on 24 degrees of freedom. AO (NOAO) means with (without) Angular Ordering.

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