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An Upper Limit for $Br(Z^0 \to ggg)$ from Symmetric 3–jet Z^0 Hadronic Decays

DELPHI Collaboration

Abstract

An upper limit for $BR(Z^0 \to 3g)$ is obtained from a correlation method, which distinguishes statistically between quark and gluon jets by using the difference in their charged particle multiplicity distributions. From the sample of threefold symmetric three–jet events collected by the DELPHI experiment at LEP during 1991-1994, the 95% confidence level upper limit is deduced to be: $BR(Z^0 \to 3g) \leq 1.6 \times 10^{-2}$ for the JADE and $BR(Z^0 \to 3g) \leq 1.5 \times 10^{-2}$ for the DURHAM jet–finder.

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1 Introduction

The Standard Model predicts a very small branching ratio for the decay of the Z^0–boson into three gluons from quark loops [1]:

$$BR^{SM}(Z \to 3g) \simeq 2.0 \times 10^{-6}. \tag{1}$$

Compositeness of the Z–boson would induce new couplings and decay modes and a predicted branching ratio [2]:

$$BR(Z \to 3g) \leq 2.0 \times 10^{-3}, \tag{2}$$

much larger than the standard model expectation.

In this letter an upper limit for $BR(Z \to 3g)$ is determined from a sample of threefold symmetric 3 jet events in which the angles between jets are in the range $120 \pm 20°$. The analysis is based on the difference between the charged particle multiplicity distributions of quark and gluon jets. This difference is exploited by comparing the correlations present between the jet multiplicities in symmetric 3 jet events, in general consisting of two quark jets and one gluon jet, to those in uncorrelated fake events constructed by mixing jets from different real events. This method, generally referred to as the correlation method, has also been applied to the study of the ratio of the mean charged particle multiplicities in gluon and quark jets in symmetric 3 jet events [3].

The data used were collected by the DELPHI experiment at LEP in the years 1991 to 1994 at centre-of-mass energies around 91.2 GeV. They consist of about 4 million hadronic Z^0 decays.

2 The correlation method

The multiplicity correlation function is defined as :

$$C(n_1, n_2, n_3) = \frac{P(n_1, n_2, n_3)}{P_{uncor}(n_1, n_2, n_3)}, \tag{3}$$

where $P(n_1, n_2, n_3)$ is the probability of observing a 3 jet event in which the charged particle multiplicities of the jets are equal to n_1, n_2 and n_3. Jets will always be numbered such that $n_1 \geq n_2 \geq n_3$. $P_{uncor}(n_1, n_2, n_3)$ is the corresponding probability for uncorrelated jets constructed using the mixed event technique: one mixed event was obtained from three different real 3 jet events by selecting one jet at random from each event.

Assuming the multiplicities of the individual jets in a real event to be uncorrelated, the probability $P(n_1, n_2, n_3)$ can be expressed through the multiplicity distributions for gluon jets, $G(n)$, light (not b) quark jets, $Q(n)$, and b–quark jets, $B(n)$, respectively:

$$\begin{aligned} P(n_1, n_2, n_3) = \\ \tfrac{1-\beta}{3}\{(1-R_b)[G(n_1)Q(n_2)Q(n_3) + Q(n_1)G(n_2)Q(n_3) + Q(n_1)Q(n_2)G(n_3)] + \\ +R_b[G(n_1)B(n_2)B(n_3) + B(n_1)G(n_2)B(n_3) + B(n_1)B(n_2)G(n_3)]\} + \\ +\beta G(n_1)G(n_2)G(n_3), \end{aligned} \tag{4}$$

where $\beta = N^{sym}_{ggg}/N^{sym}_{3jet}$ is the fraction of three–gluon events and $1-\beta$ the fraction of $Z \to q\overline{q}g$ events in the symmetric 3 jet event sample, and $R_b = \Gamma_{b\overline{b}}/\Gamma_{had}$ is the $Z \to b\overline{b}$ branching fraction. The particle multiplicity distribution of the gluon jet, $G(n)$, is assumed to be the same in 3–gluon events as in $q\overline{q}g$ events.

By construction, jets in the mixed event sample are completely uncorrelated. Therefore:

$$P_{uncor}(n_1, n_2, n_3) = J(n_1)J(n_2)J(n_3), \tag{5}$$

where

$$J(n) = \frac{1-\beta}{3}\{G(n) + 2[(1-R_b)Q(n) + R_b B(n)]\} + \beta G(n). \tag{6}$$

The experimental correlation function $C(n_1, n_2, n_3)$ is determined by dividing the number of measured events with given n_1, n_2 and n_3 by the normalized number of such events from the mixed event sample.

Examples of the measured distribution $P(n_1, n_2, n_3)$ for jets obtained with the JADE jet–finder (y_{min}=0.15), and the distribution $P_{uncor}(n_1, n_2, n_3)$ for the mixed event sample as well as the correlation function $C(n_1, n_2, n_3)$, are shown in Fig.1 as a function of the multiplicity n_3 for $n_1 \geq 12$. The significantly larger width of $P_{uncor}(n_1, n_2, n_3)$ in comparison to $P(n_1, n_2, n_3)$, and consequently the clear deviation of $C(n_1, n_2, n_3)$ from unity, provides evidence for the fact that quark and gluon jets have different charged particle multiplicity distributions.

In the analysis the particle multiplicity distributions of gluon and quark jets, $G(n)$, $B(n)$ and $Q(n)$, are assumed to be described by Negative Binomial Distributions (NBD):

$$P(n|\mu, k) = \frac{(n+k-1)!}{n!(k-1)!}\left(\frac{\mu/k}{1+\mu/k}\right)^n \frac{1}{(1+\mu/k)^k}, \tag{7}$$

where μ is the mean multiplicity and k is the width parameter related to the dispersion of the distribution. The motivation for the choice of the NBD lies in the fact that it describes well the charged particle multiplicity distributions in e^+e^- annihilation as well as those of the individual jets in Z^0 hadronic decays [4]. Additional motivation for the use of the NBD for the parameterization of single jet multiplicity distributions can be found in [5]. To cross–check that the results are not unduly sensitive to this assumption, a Poissonian parameterization (PD) of the shapes of the multiplicity distributions was also tried.

The unknown parameters were determined from a fit of the parametrized correlation function $C(n_1, n_2, n_3)$ as defined by equations 3–6 to the measured one. The parameters corresponding to light quark jets and the difference in mean multiplicity between b-quark and light quark jets were fixed according to the published data [6,7]. The NBD width parameter of b–quark jets, k_b, was obtained from a separate fit to the charged particle multiplicity distribution of the highest energy jet in b–tagged[8] 3 jet events. Therefore the finally fitted parameters are the NBD width parameter for gluon jets, k_g, and the fraction of 3–gluon events, β.

3 Experiment and data selection

A detailed description of the DELPHI detector can be found elsewhere [9]. In this analysis only charged particles were used. Their momenta were measured in the 1.2 T solenoidal magnetic field by the following tracking detectors: the Micro Vertex Detector, the Inner Detector, the Time Projection Chamber (TPC, the principal tracking device of DELPHI), the Outer Detector and the Forward Chambers A and B.

A charged particle was required to satisfy the following criteria :

- momentum, p, greater than 0.2 GeV/c;
- error on $p < p$;

– polar angle, θ, with respect to the beam between 25° and 155°;
– measured track length in the TPC greater than 50 cm;
– impact parameter with respect to the nominal beam crossing point within 5 cm in the transverse xy plane and 10 cm along the beam direction (z-axis).

Hadronic events from Z^0 decays were then selected if

– there were at least 5 charged particles;
– the total energy of charged particles (assuming a pion mass) in each of the two hemispheres defined with respect to the beam direction exceeded 3 GeV;
– the total energy of all charged particles was greater than 15 GeV.

A total of 2,861,000 events satisfied these cuts. The contamination from events due to beam-gas scattering and to $\gamma\gamma$ interactions was estimated to be less than 0.1% and the background from $\tau^+\tau^-$ events to be less than 0.3% of the accepted events [10].

Samples of events with three jets were selected by applying either the JADE jet–finder (with jet resolution parameter y_{min}=0.04 or 0.15) or the DURHAM jet–finder (also known as the $k_\perp$ algorithm, with y_{min}=0.015 or 0.035). These two jet–finders are complementary in the way they assign low energy particles to the jets. The DURHAM jet–finder suppresses soft particles with large angles to the jet axis whereas those particles are often assigned to a jet by the JADE algorithm [11]. The DURHAM jet–finder is well defined in perturbation theory, allowing calculations to incorporate leading terms to all orders [12], and is therefore expected to facilitate comparison between the experimental results and theoretical work.

Each reconstructed jet was required to contain at least 1 charged particle, to have the jet axis lying in the region $|\cos\theta| \leq 0.7$, and to have a visible energy larger than 2 GeV. To eliminate non-planar events, the sum of the angles between the three jets was required to exceed 357°. Threefold symmetric 3 jet events of "Mercedes" type were then selected by projecting the jets into the 3–jet event plane and requiring the angles between them to be in the range 100° to 140°.

The jet selection criteria were tuned and the correlation method was checked by using symmetric 3 jet $e^+e^- \to q\bar{q}g$ events generated by HERWIG 5.4 [13], which provides a direct relation between partons and particles by daughter–mother pointers. The jets were selected by the JADE jet–finder or by using the pointers (referenced below as JADE or HERWIG jets). The correlation method was used to fit the ratio of the mean multiplicity in gluon jets to the mean multiplicity in quark jets, $\xi = \langle n\rangle_g/\langle n\rangle_q$, for fixed values of the parameters k_q and k_g. The correlation method resulted in $\xi = 1.36 \pm 0.06$ for the JADE jets and $\xi = 1.37 \pm 0.06$ for the HERWIG jets. The ξ value calculated directly from the $\langle n\rangle_g/\langle n\rangle_q$ ratio in HERWIG is 1.39. This indicates that the correlation method with the adopted jet selection cuts provides an unbiased estimate of ξ.

The total numbers of symmetric 3 jet events obtained from the data sample using the JADE jet–finder are 11023 at $y_{min} = 0.04$ and 10595 at $y_{min} = 0.15$. The total numbers obtained using the DURHAM algorithm are 9964 at $y_{min} = 0.015$ and 11333 at $y_{min} = 0.035$. The average visible jet energy carried by charged particles is equal to 18.00±0.04 GeV for the DURHAM and 18.15±0.03 GeV for the JADE jet–finder.

In order to correct for the influence of imperfections of the DELPHI detector, the correlation method was applied to the samples of simulated events from the DELPHI detector simulation program DELSIM [10]. In DELSIM, events were generated using the JETSET 7.3 PS program [14] with DELPHI default parameters [15]. Particles were followed through the detector and the resulting simulated digitizations were processed with the same reconstruction programs as the experimental data.

Detector imperfections introduce a systematic difference between $C_J(n_1,n_2,n_3)$ for the events generated by JETSET and $C_D(n_1,n_2,n_3)$ for the events reconstructed after DELSIM (i.e. after the detector simulation). In order to correct for this influence of the detector, the correlation function $C(n_1,n_2,n_3)$ observed for uncorrected data was multiplied by the ratio $K(n_1,n_2,n_3) = C_J(n_1,n_2,n_3)/C_D(n_1,n_2,n_3)$.

In order to take into account the imperfections of the jet finder algorithms, a further correction factor was introduced. It was calculated as a ratio $N(n_1,n_2,n_3) = C_{expected}(n_1,n_2,n_3)/C_{observed}(n_1,n_2,n_3)$ for a normalisation sample of events obtained by generating symmetric $Z^0 \to ggg$ decays using JETSET. This correction is based on the fundamental property that the correlation function should equal unity, i.e. $C_{expected}(n_1,n_2,n_3) = 1$, when the mixed events are constructed from the same numbers of quarks and gluons as real events. The total correction factor $K \cdot N$ is typically between 0.9 and 1.1. An example is shown in Fig. 1b.

4 Results

The corrected correlation function $C(n_1,n_2,n_3)$ is presented as a function of n_3 in Fig. 2 for the JADE jet–finder with $y_{min} = 0.15$ for several n_1 values. The curves in Fig. 2 are the results of the fit for all values of $5 \le n_1 \le 25$. The numerical results of the fit are presented in Table 1 for the central values of the fixed parameters.

In order to estimate the systematic errors due to the uncertainties in the values of the fixed parameters, the fit was also performed for the central values of these parameters plus or minus one standard deviation. The ratio of the average charged particle multiplicity of gluon jets to the average charged particle multiplicity of quark jets is 1.241±0.029 and 1.369±0.040 for the DURHAM and JADE algorithms respectively [3]. The average value of the difference between the mean charged particle multiplicity in b–quark jets and in light quark jets, δ_{bl}, was 1.34±0.11 [6,7]. The NBD width parameter for quark jets, k_q, is equal to 21.3±9.9 and 10.2±2.8 for the DURHAM and JADE algorithms respectively [3]. The NBD width parameter for b–quark jets, k_b, was determined in the same way from the sample of b–tagged events and found to be equal to 26±6 and 21±4 for the DURHAM and JADE algorithms respectively. The corresponding systematic errors in β are detailed in Table 2.

Further systematic errors were estimated taking into account the variation of the results obtained with different cuts on the highest jet multiplicity n_1 and the uncertainty in the values of the total correction coefficients. The resulting systematic bias in the values of β does not exceed 0.006 and 0.007 for the JADE and DURHAM jet–finders, respectively. Including this error leads to the following final results for β:

$$
\begin{aligned}
\beta &= +0.035 \pm^{0.041}_{0.035}(stat.) \pm^{0.029}_{0.037}(syst.) \quad (JADE, y_{min} = 0.04) \\
\beta &= -0.045 \pm^{0.032}_{0.030}(stat.) \pm^{0.031}_{0.044}(syst.) \quad (JADE, y_{min} = 0.15) \\
\beta &= -0.024 \pm^{0.023}_{0.042}(stat.) \pm^{0.049}_{0.075}(syst.) \quad (DURHAM, y_{min} = 0.015) \\
\beta &= -0.101 \pm^{0.044}_{0.036}(stat.) \pm^{0.051}_{0.082}(syst.) \quad (DURHAM, y_{min} = 0.035).
\end{aligned}
$$

The smaller systematic error for JADE compared to DURHAM may be understood because in the latter case low energy particles at large angles originating from the gluon are frequently assigned to a quark jet, thus diminishing quark/gluon differences in the DURHAM case.

Table 1: Fitted values of the width parameter of the charged particle multiplicity distribution in gluon jets, k_g, and the fraction of 3 gluon events in symmetric 3 jet events, β, and the probability of each fit with parametrisation of multiplicity distributions by Negative Binomial distribution and Poisson distribution (for which $k_q = k_b = k_g = \infty$).

$\langle n\rangle_g/\langle n\rangle_q$	δ_{bl}	k_q	k_b	k_g	β	Prob.
JADE (y_{min}=0.04)						
1.369	1.34	10.2	21	20±11	$+0.035^{+0.041}_{-0.035}$	0.29
1.369	1.34	∞	∞	∞	$+0.135^{+0.037}_{-0.029}$	0.09
JADE (y_{min}=0.15)						
1.369	1.34	10.2	21	28±12	$-0.045^{+0.032}_{-0.030}$	0.14
1.369	1.34	∞	∞	∞	$+0.053^{+0.025}_{-0.020}$	0.01
DURHAM (y_{min}=0.015)						
1.241	1.34	21.3	26	38±29	$-0.024^{+0.023}_{-0.042}$	0.96
1.241	1.34	∞	∞	∞	$+0.002^{+0.054}_{-0.036}$	0.93
DURHAM (y_{min}=0.035)						
1.241	1.34	21.3	26	31±14	$-0.101^{+0.044}_{-0.036}$	0.64
1.241	1.34	∞	∞	∞	$-0.022^{+0.033}_{-0.025}$	0.52

The branching fraction $BR(Z^0 \to ggg)$ is calculated from β using the following formula:

$$BR(Z^0 \to 3g) = \beta \cdot BR(Z^0 \to hadr) \cdot \frac{N^{sym}_{3jet}}{N_{hadr}} \cdot \frac{N_\Upsilon}{N^{sym}_\Upsilon}, \tag{8}$$

where N^{sym}_{3jet}/N_{hadr} is the fraction of symmetric 3 jet events in the hadronic event sample and $N^{sym}_\Upsilon/N_\Upsilon$ is the fraction of symmetric decays in an Υ–like 1^{--} quarkonium state to three gluons. The latter ratio was calculated using JETSET 7.3. The mass of the pseudo-onium was chosen to be equal to the Z mass. Due to the identical helicity structure of $Z^0 \to ggg$ and $\Upsilon \to ggg$ decays, the angular distributions for jets from the two sources are expected to be identical. Thus N^{sym}_{ggg}/N_{ggg} should equal $N^{sym}_\Upsilon/N_\Upsilon$. The numerical value of the factor relating $BR(Z \to 3g)$ to β in eq.(8) was found from simulation to be 0.120 at y_{min}=0.04 and 0.0875 at y_{min}=0.15 for the JADE sample, 0.129 at y_{min}=0.015 and 0.115 at y_{min}=0.035 for the DURHAM sample.

To calculate the 95% confidence level upper limits on the branching fraction $BR(Z^0 \to ggg)$, the systematic errors were added in quadrature to the statistical errors and unphysical negative values of β were forced up to have $\beta = 0$. The calculation gave:

$$UL\{BR(Z \to 3g)\} = 0.016 \quad (JADE,\ y_{min} = 0.04)$$

$$UL\{BR(Z \to 3g)\} = 0.008 \quad (JADE,\ y_{min} = 0.15)$$

$$UL\{BR(Z \to 3g)\} = 0.014 \quad (DURHAM,\ y_{min} = 0.015)$$

$$UL\{BR(Z \to 3g)\} = 0.015 \quad (DURHAM,\ y_{min} = 0.035).$$

Table 2: Contributions to the systematic error in β from the uncertainties in the parameters fixed in the fits.

Parameter value $\pm$ error	JADE $y_{min} = 0.04$	$y_{min} = 0.15$
$\langle n_g \rangle / \langle n_q \rangle = 1.369 \pm 0.040$	$^{+0.023}_{-0.029}$	$^{+0.025}_{-0.035}$
$\delta_{bl} = 1.34 \mp 0.11$	$^{+0.009}_{-0.002}$	$^{+0.007}_{-0.001}$
$k_q = 10.2 \pm 2.8$	$^{+0.014}_{-0.022}$	$^{+0.016}_{-0.027}$
$k_b = 21 \pm 4$	$^{+0.003}_{-0.003}$	$^{+0.003}_{-0.005}$
Total	$^{+0.029}_{-0.037}$	$^{+0.031}_{-0.044}$
Parameter value $\pm$ error	DURHAM $y_{min} = 0.015$	$y_{min} = 0.035$
$\langle n_g \rangle / \langle n_q \rangle = 1.241 \pm 0.029$	$^{+0.041}_{-0.056}$	$^{+0.044}_{-0.060}$
$\delta_{bl} = 1.34 \mp 0.11$	$^{+0.018}_{-0.003}$	$^{+0.016}_{-0.001}$
$k_q = 21.3 \pm 9.9$	$^{+0.018}_{-0.049}$	$^{+0.019}_{-0.055}$
$k_b = 26 \pm 6$	$^{+0.003}_{-0.003}$	$^{+0.006}_{-0.007}$
Total	$^{+0.048}_{-0.075}$	$^{+0.051}_{-0.082}$

The cross-check of using the Poissonian parametrisation of the multiplicity distributions gave similar estimates of the upper limit, namely 0.026, 0.0099, 0.017, and 0.011 respectively. A data sample from which b–tagged events are removed has been analysed by using a similar method. This sample was obtained by cutting on a b-probability deduced from the measured impact parameters with respect to the interaction point [8]. The cut applied removed 80% of the $b\overline{b}$–events. However, because of the reduced statistics of the b–depleted sample, the limit was not improved.

5 Summary

By using a correlation method based on the difference between the particle multiplicity distributions of quark and gluon jets, an upper limit at 95% confidence level for the $Z^0 \to ggg$ branching ratio has been established:

$$BR(Z \to 3g) \leq 1.6 \times 10^{-2}$$

for the JADE and

$$BR(Z \to 3g) \leq 1.5 \times 10^{-2}$$

for the DURHAM jet–finder. At the present level of statistics, no signal of the decay $Z^0 \to ggg$ is observed.

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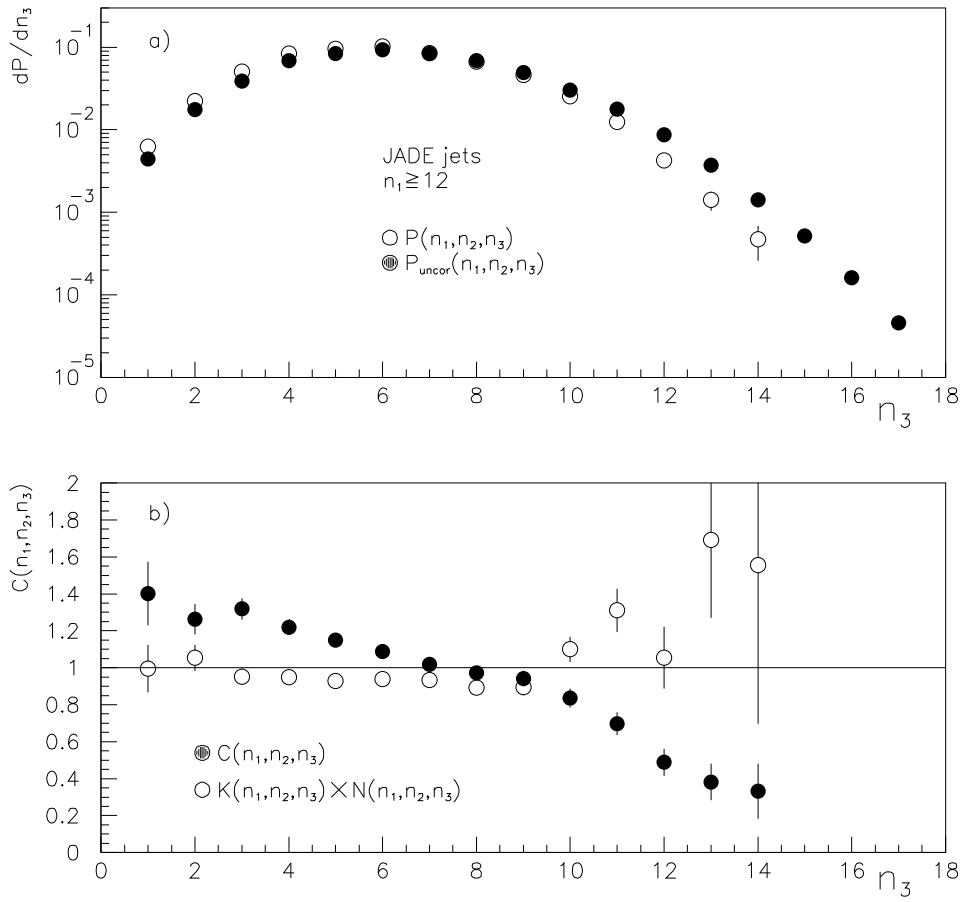

Figure 1: a) Measured distribution $P(n_1, n_2, n_3)$ obtained with the JADE jet–finder with y_{min}=0.15 displayed as a function of the lowest multiplicity n_3 for values of the highest multiplicity n_1 above 11 and $n_1 \geq n_2 \geq n_3$, together with the corresponding distribution $P_{uncor}(n_1, n_2, n_3)$ for the mixed event sample. b) The correlation function $C(n_1, n_2, n_3)$, defined as the ratio of these two distributions, and total correction factor again as a function of the multiplicity n_3 for $n_1 \geq 12$.

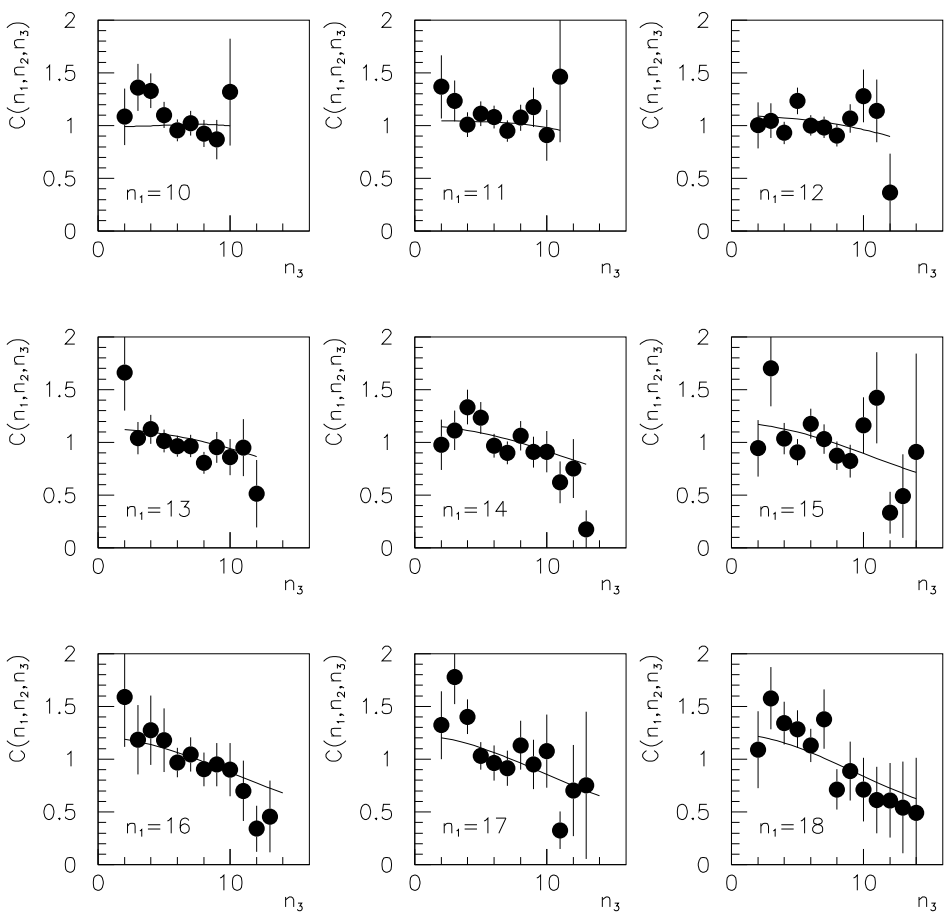

Figure 2: The corrected correlation function $C(n_1, n_2, n_3)$ as a function of the smallest jet multiplicity n_3 for different values of the largest jet multiplicity n_1. Symmetric 3–jet events are selected from the sample of DELPHI data by using the JADE jet–finder with y_{min} equal to 0.15. The curves are the result of the fit.