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Topological analysis of the particle production in hadronic Z decays

The ALEPH Collaboration

Abstract

The production of charged particles, K^0_s and Λ in hadronic Z decays is measured with the ALEPH detector at LEP-1 in 2 and 3-jet events. Taking into account the topology of the events, this production is well described in the framework of the QCD Modified Leading Log Approximation assuming Local Parton Hadron Duality.

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1 Introduction

According to QCD, the ratio of the mean multiplicities in gluon and quark jets [1] , $f = n_g/n_q$, is expected to be different from unity. This ratio has been measured by several experiments at LEP-1 by selecting three-jet events with particular angular configurations or quark flavour tagging [1]. Recently, ALEPH has performed an analysis [2] without restricting the three-jet phase space to specific topologies and has shown that n_g^{ch} and n_q^{ch} for jets of constant energies vary according to the topology of the event. It was also demonstrated that f^{ch} can be extracted from the measurement of n_{evt}^{ch} in three-jet events, thus avoiding the use of a jet algorithm to count particle multiplicities in jets.

In the present analysis, using the very high statistics recorded by ALEPH between 1992 and 1995 at $E_{cm} = M_Z$, the method of [2] is applied to charged particles and extended to K_s^0 and Λ's: the production rates of charged particles, K_s^0 or Λ are measured in three-jet events as a function of the event topology. A fit of the mean event multiplicities as a function of the event topology is performed according to the formulae described in [2] and detailed hereafter. The mean quark and gluon jet multiplicities in three-jet events are derived. The same analysis is applied to two-jet events and a global fit (two and three-jet events) is performed. The resulting quark and gluon jet mean multiplicities can be compared to inclusive measurements in hadronic events and to recent measurements obtained by other LEP experiments [3], [4], [5].

2 Data analysis

2.1 Event selection and definitions

The ALEPH detector is described in details elsewhere [6]. A sample of 3.4 million hadronic events is selected according to the criteria described in [8]. Jets are reconstructed by applying the Durham algorithm [9] with y_{cut}^D =0.01 on all (charged and neutral) energy flow objects [7]. Only those events containing two or three jets are kept. The polar angle of each jet in the event must be greater than 30 degrees. In the three-jet event sample, the jet energies are recomputed from their directions assuming planar, massless kinematics. From these recalculated energies, the minimum y_{cut}^D between two jets, y_{min}^D , is determined and the events with y_{min}^D <0.01 are rejected. This selection provides a sample of about 2 millions two-jet events and 800,000 three-jet events.

The same selection is applied to a statistically equivalent sample of $q\overline{q}$ Monte Carlo events simulated with the JETSET-DYMU3 [10], [11] generator tuned to the Aleph data and processed through the detector simulation and the event reconstruction ('MC Rec' sample). A generator level sample ('MC gen') is also produced by applying the same jet algorithm to hadron level Monte Carlo events for which the simulation of ISR is turned off and the decay of particles with a lifetime smaller than 1 nsec is forced.

The topology of a three-jet event is uniquely defined by the energy of one of the jets, E_{jet}, and $\Delta\theta$, the difference of the opening angles to the other two jets ([2]). In a two-jet event E_{jet}= $M_Z/2$ and $\Delta\theta$= 180 degrees.

[1]for simplicity, n^x will refer hereafter to the mean number of 'x' particles per jet (n^x), gluon jet (n_g^x), quark jet (n_q^x) or event (n_{evt}^x)

2.2 Particle counting

The production rates of charged particles, K_s^0 and Λ are measured in the two-jet event and three-jet event samples separately. In the latter, these rates are measured as a function of the event topology (E_{jet}, $\Delta\theta$) with a bin size of (4GeV,20^o).

Charged particles are detected in the tracking system of ALEPH and reconstructed with an average 98% efficiency. The associated background is very small and has been neglected. K_s^0 and Λ[2] are reconstructed from their decays into charged particles [3] , $\pi^+\pi^-$ and π^-p respectively. All the V^0's reconstructed by the standard ALEPH algorithm [12] are considered. The three following cuts are applied to each V^0 in order to reduce the combinatorial background:

- Flight $>$ 0.4 cm (2.0 cm) for K_s^0 (Λ)
- $\frac{\tau}{\tau_0}$ >0.2
- 2T $<$ 0.4 cm for K_s^0 and $-2\sigma_p < \left(\frac{dE}{dx}\right)_p < +2\sigma_p$ for Λ

where Flight is the distance between the main vertex and the V^0 vertex, $\frac{\tau}{\tau_0}$ is the ratio of the measured lifetime to the proper lifetime, 2T is the two tracks separation at the V^0 vertex, $\left(\frac{dE}{dx}\right)_p$ is the measured ionization of the 'proton' track and σ_p is the expected ionization for a true proton.
The rate of K_s^0 (Λ) is measured by fitting the $\pi^+\pi^-$ (π^-p) invariant mass spectrum with a double gaussian with fixed width for the signal and a polynomial (exponential) function for the background. In the signal region ($\pm 3\sigma$ around the nominal mass), all the entries in the spectrum are summed and the fitted background is subtracted to give the measured signal. An example of the extraction of the signal in one single (E_{jet}, $\Delta\theta$) bin of the three-jet data is shown in Figure 1.

2.3 Corrections and experimental systematics

Corrections for detector/reconstruction inefficiencies and impurities are obtained by applying the same analysis to the 'MC Rec' sample and comparing to the 'MC Gen' values. The following efficiency (ϵ) and purity (P) corrections are obtained:

- $\epsilon(K_s^0)$ = 52% (2jets) – 53% (3jets), $P(K_s^0)$ = 52% (2jets) – 55% (3jets)
- $\epsilon(\Lambda)$ = 39% (2jets) – 44% (3jets), $P(\Lambda)$ = 30% (2jets) – 38% (3jets)

The statistical error on the efficiency and purity corrections is negligible for the two-jet events and is 1% (3%) for K_s^0 (Λ) for the three-jet events. The variations of these corrections as a function of the event topology in the three-jet events is small (5% at most). These corrections are applied bin by bin to the data for each type of particle (as mentionned above the purity for charged tracks is assumed to be 100%).

The dominant systematic error on the above corrections is related to purity determinations and due to the fitting of the mass spectra since the fits are performed, for obvious statistical reasons, on momentum integrated distributions. This effect has been studied with the 'MC Rec' sample and found to correspond to an average 3% systematic error for K_s^0 and 6% for Λ. This error is computed in each topology bin and added in quadrature to the statistical error. No experimental systematic errors are assigned to the charged tracks measurements.

[2]for simplicity Λ refers hereafter to both Λ and $\overline{\Lambda}$

[3]in the following, all K_s^0 and Λ results refer to their decays into charged particles only

3 Results

3.1 Multiplicity formulae

The corrected mean multiplicities are fitted according to the following definitions. The mean event multiplicity is regarded as the sum of the mean multiplicities of each parton jet:

$$\mathrm{n_{evt}} = \mathrm{n_q} + \mathrm{n_{\overline{q}}} + \mathrm{n_g}$$

The quark (anti-quark) mean multiplicity depends on the jet energy scale $\mathrm{Q_q}$ ($\mathrm{Q_{\overline{q}}}$) and is assumed to be described by the following function derived from Local Parton-Hadron Duality applied to a MLLA calculation [13]:

$$\mathcal{N}(\mathrm{Q}) = \mathrm{K}\alpha_\mathrm{s}^\mathrm{b} \exp\left(\frac{\mathrm{c}}{\sqrt{\alpha_\mathrm{s}}}\right)$$

where α_s, the strong coupling constant, is a function of Q and of an effective renormalization scale λ: $\alpha_s \equiv \alpha_s(Q, \lambda)$. The mean gluon jet multiplicity is written: $\mathrm{n_g} = \mathrm{f}\,\mathcal{N}(Q)$; f is the ratio of the gluon/quark mean multiplicities. The total mean event multiplicity can then be written[2]:

$$\mathrm{n_{evt}} = \sum_{\mathrm{perms}} \mathcal{P}_{1=\mathrm{g}} \left\{ \mathrm{f}\mathcal{N}(\overline{\mathrm{Q}}_1) + \mathcal{N}(\mathrm{Q}_{21}) + \mathcal{N}(\mathrm{Q}_{31}) \right\}$$

where $\mathcal{P}_{\mathrm{i=g}}$, the probability that jet i is the gluon jet, is computed from the jet energies [14]. $\overline{\mathrm{Q}}_1 = \sqrt{\mathrm{Q}_{12}\mathrm{Q}_{13}}$ is the energy scale for the gluon jet and $\mathrm{Q}_{21}(\mathrm{Q}_{31})$ is the corresponding one for the quark (antiquark) jet. It has been established [2] that the quark and gluon mean multiplicities in three-jet events are topology dependent. This topology dependence of the mean multiplicities is taken into account by defining new energy scales: $\mathrm{Q_{ij}} = \mathrm{E_i} \sin\left(\frac{\theta_{\mathrm{ij}}}{2}\right)$ where θ_{ij} is the angle between jet i and jet j. With these new energy scales, the values of K, f and λ can be obtained from a fit of the total mean event multiplicity measured in each ($\mathrm{E_{jet}}$,$\Delta\theta$) three-jet event topology.

3.2 Two and three-jet event data

The results of the three parameter (K, f, λ) fit performed on the corrected charged particles data are: $\mathrm{K^{ch}} = 0.0342 \pm 0.0013$, $\lambda^{\mathrm{ch}} = 86 \pm 6\mathrm{MeV}$, $\mathrm{f^{ch}} = 1.52 \pm 0.09$. The errors are the statistical errors of the fit. The χ^2/NdF of the fit is 0.7. These results are in perfect agreement with our previous results [2] and benefit from a factor of two increase in statistics.

However a sizeable fraction of the above quoted errors is due to the correlation between the three fitted parameters. It is possible to reduce this effect by redefining the jet energy scales such that λ corresponds to λ_{QCD} and can be fixed to its current world average for five active flavours (208 MeV). This is done by rescaling the quark and gluon jet energy scales: $\mathrm{Q_{ij}^{new}} = 2 \times \mathrm{Q_{ij}^{old}}$.

Then the fits of the mean event multiplicities (charged particles, $\mathrm{K_s^0}$ and Λ) are performed on the two-jet and three-jet event samples together. The two-jet event sample is viewed as a single topology point with $\mathrm{E_{jet}}$= 45.6 GeV, $\Delta\theta$= 180^o and $\mathrm{n_{evt}} = \mathrm{n_q} + \mathrm{n_{\overline{q}}}$. The new definition of jet energy scales, $\mathrm{Q^{new}}$, is used and λ is identified to λ_{QCD} = 208 MeV. The results of the fits [4] are displayed on the table below:

	K	f
$\mathrm{n_{evt}^{ch}}$	0.0354 ± 0.0001	1.87 ± 0.01
$\mathrm{n_{evt}^{K_s^0}}$	0.00121 ± 0.00001	1.94 ± 0.02
$\mathrm{n_{evt}^{\Lambda}}$	0.00043 ± 0.00001	2.13 ± 0.06

[4] the results obtained for charged particles are not directly comparable to the previous results obtained with the three-jet event sample alone since the definition of the jet energy scale has changed

The χ^2/NdF of the fits, shown in Figure 2, 3 and 4, are 1.0, 1.6 and 0.5 respectively. The statistical errors of the fits have been strongly reduced by fixing one of the parameters ($\lambda = \lambda_{\mathrm{QCD}}$). If this parameter is released and included in the fits, its fitted value is always compatible with $\lambda_{\mathrm{QCD}} = 208$ MeV. When only the three-jet event data are fitted, the value of K is 10% higher and the value of f, strongly anti-correlated to K, is 20% lower. This shows the effect of excluding the two-jet events (which have a high statistical weight) in the fit.

3.3 Global systematic errors

The experimental systematics have been described above. Two other sources of systematics are studied here. First, the errors associated with the fitting procedure are investigated: the fit region used for the three-jet event sample is varied; also the numerical integration of the fitted theoretical function over each (E_{jet},$\Delta\theta$) bin of the three-jet event sample is replaced by a simple average. Within statistical errors of the fit, the results are insensitive to these changes.

The absolute values of K and f are sensitive to the respective fraction of two and three-jet events. This fraction is determined by the value of the resolution parameter $y^{\mathrm{D}}_{\mathrm{cut}}$ of the jet algorithm. The effect of varying this parameter has been studied with Monte Carlo events: K and f have been fitted for several values of $y^{\mathrm{D}}_{\mathrm{cut}}$ (0.005, 0.02), corresponding to a variation of the two-jet event rate from about 50 to 80%. The influence of the jet algorithm has also been tested by replacing the Durham algorithm by Jade [9] ($y^{\mathrm{J}}_{\mathrm{cut}}$ =0.04). Finally, K and f have also been determined, for charged particles only, from a Monte Carlo sample generated with HERWIG [15]. The dominant systematic effect is due to the change of $y^{\mathrm{D}}_{\mathrm{cut}}$. It adds an average 5% systematic error which is the dominating error. The final results with total errors and Monte Carlo expectations are given in the table below. The total error is represented on Figure 2, 3 and 4 by the hatched area.

	K (data)	K (MC)	f (data)	f (MC)
$n^{\mathrm{ch}}_{\mathrm{evt}}$	0.0354 ± 0.0015	0.0353	1.87 ± 0.09	1.88
$n^{K^0_s}_{\mathrm{evt}}$	0.00121 ± 0.00004	0.00123	1.94 ± 0.15	1.78
$n^{\Lambda}_{\mathrm{evt}}$	0.00043 ± 0.00002	0.00041	2.13 ± 0.10	2.01

4 Discussion and conclusions

The sensitivity of K and f to the relative contributions of two and three-jet events can be reduced for K^0_s and Λ results by normalizing K and f to the results obtained with charged particles:

- $K^{K^0_s}/\ K^{\mathrm{ch}} = 0.0342 \pm 0.0018$, $K^{\Lambda}/\ K^{\mathrm{ch}} = 0.0121 \pm 0.0008$
- $f^{K^0_s}/\ f^{\mathrm{ch}} = 1.04 \pm 0.09$, $f^{\Lambda}/\ f^{\mathrm{ch}} = 1.14 \pm 0.08$

The K ratios, assuming that the f ratios are close to 1, can be compared to the mean hadron multiplicities measured in hadronic events at $E_{\mathrm{cm}} = M_Z$ [16]: $n^{K^0_s}_{\mathrm{evt}}/\ n^{\mathrm{ch}}_{\mathrm{evt}} = 0.0330 \pm 0.0006$ and $n^{\Lambda}_{\mathrm{evt}}/\ n^{\mathrm{ch}}_{\mathrm{evt}} = 0.0112 \pm 0.0004$. The agreement is good which indicates that the present description of quark jet mean multiplicities has satisfactoryly been extended from charged particles to other types of particles. Within errors, the values obtained for $f^{K^0_s}$ and f^{Λ} are compatible with f^{ch}. When normalized to f^{ch}, $f^{K^0_s}$ and f^{Λ} can be compared to recent measurements performed with very different techniques by other LEP experiments: the present analysis shows a good agreement between data and string-based fragmentation models as already observed ([3],[4]).

A crude consistency check of the absolute normalization of K and f is performed by extrapolating the above results to mean multiplicities measured in hadronic events in LEP-1/SLC and LEP-2 results. This is done as follows: the mean multiplicities measured in hadronic events are assumed to come only from two and three-jet events with a respective rate of 65 and 35%; for three-jet events a single averaged event topology is used by determining the mean values of the jet energies and angles from simulated events and assuming that the jet with the lowest energy is the gluon jet. The above formulae with the fitted values of K and f are then used to compute the total mean multiplicities. With these assumptions, the mean multiplicities in LEP-1 hadronic events are found (n^{ch}_{evt}=20.0±0.9, $n^{K^0_s}_{evt}$= 0.688±0.022, n^{Λ}_{evt}= 0.248±0.012) in excellent agreement with the world averages measured at $E_{cm} = M_Z$ [16]. The calculation can be extended to hadronic events produced at LEP-2 (E_{cm} = 133, 161 and 172 GeV). The mean charged particle multiplicities computed from K^{ch} and f^{ch} are: n^{ch}_{evt}=23.5±0.9 (133GeV), 25.5±1.0 (161GeV) and 26.2±1.0 (172GeV) again in perfect agreement with direct measurements [17].

The formalism developped in [2] to describe quark and gluon jet mean charged particle multiplicities in three-jet events is extended to other types of particles (K^0_s , Λ) and to other hadronic configurations (both two and three-jet events). The ratio of the gluon/quark mean multiplicities is found almost constant for charged particle, K^0_s and Λ (1.9-2.1) and higher than previously published data (for charged particles) as the present analysis includes two-jet events. The mean quark and gluon jet multiplicities for charged particles, K^0_s and Λ are found in good agreement with Monte Carlo predictions and coherent with results from measurements performed on hadronic e^+e^-annihilations at $E_{cm} = M_Z$.

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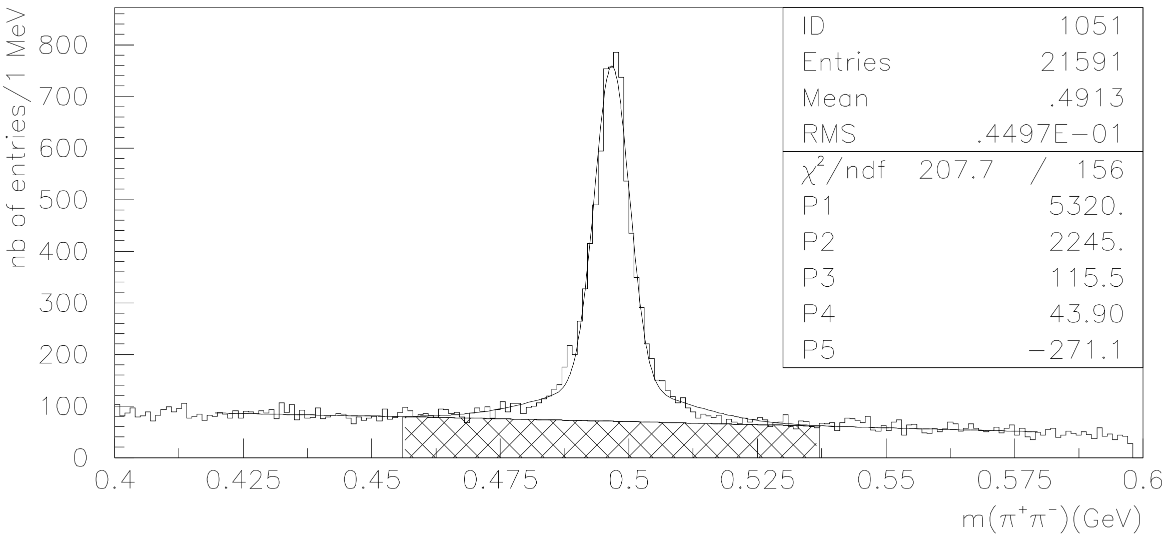

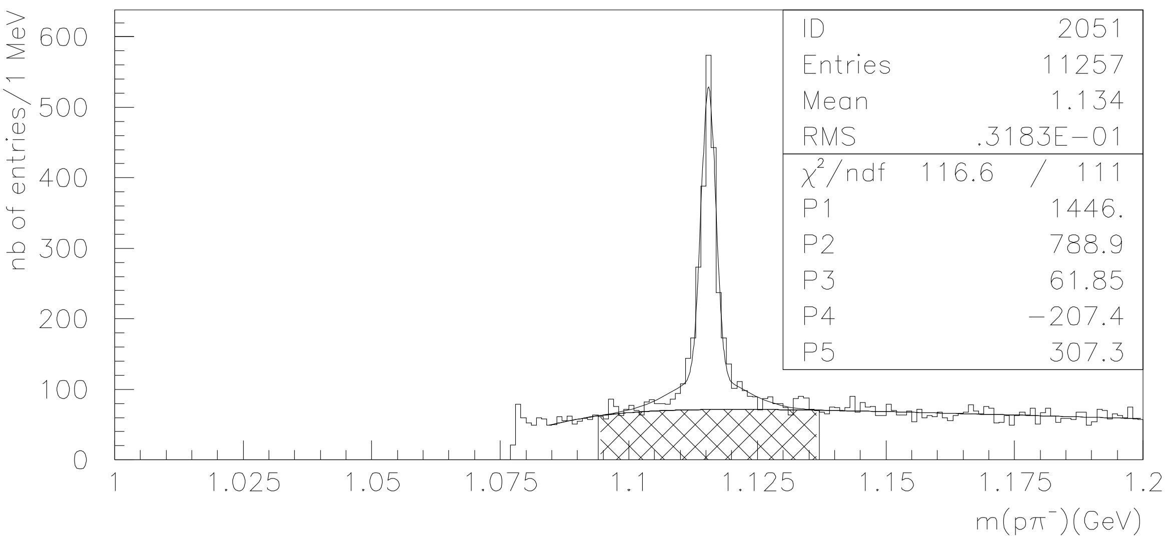

Figure 1: Example of the fit of the K^0_s (top plot) and Λ (bottom plot) signals for the (E_{jet}= (16,20) GeV, $\Delta\theta$= (0,20) degrees) bin of the three-jet event sample.
The solid histogram is the data, the solid line is the fitted signal+background, the hatched histogram is the fitted background ($\pm 3\sigma$).

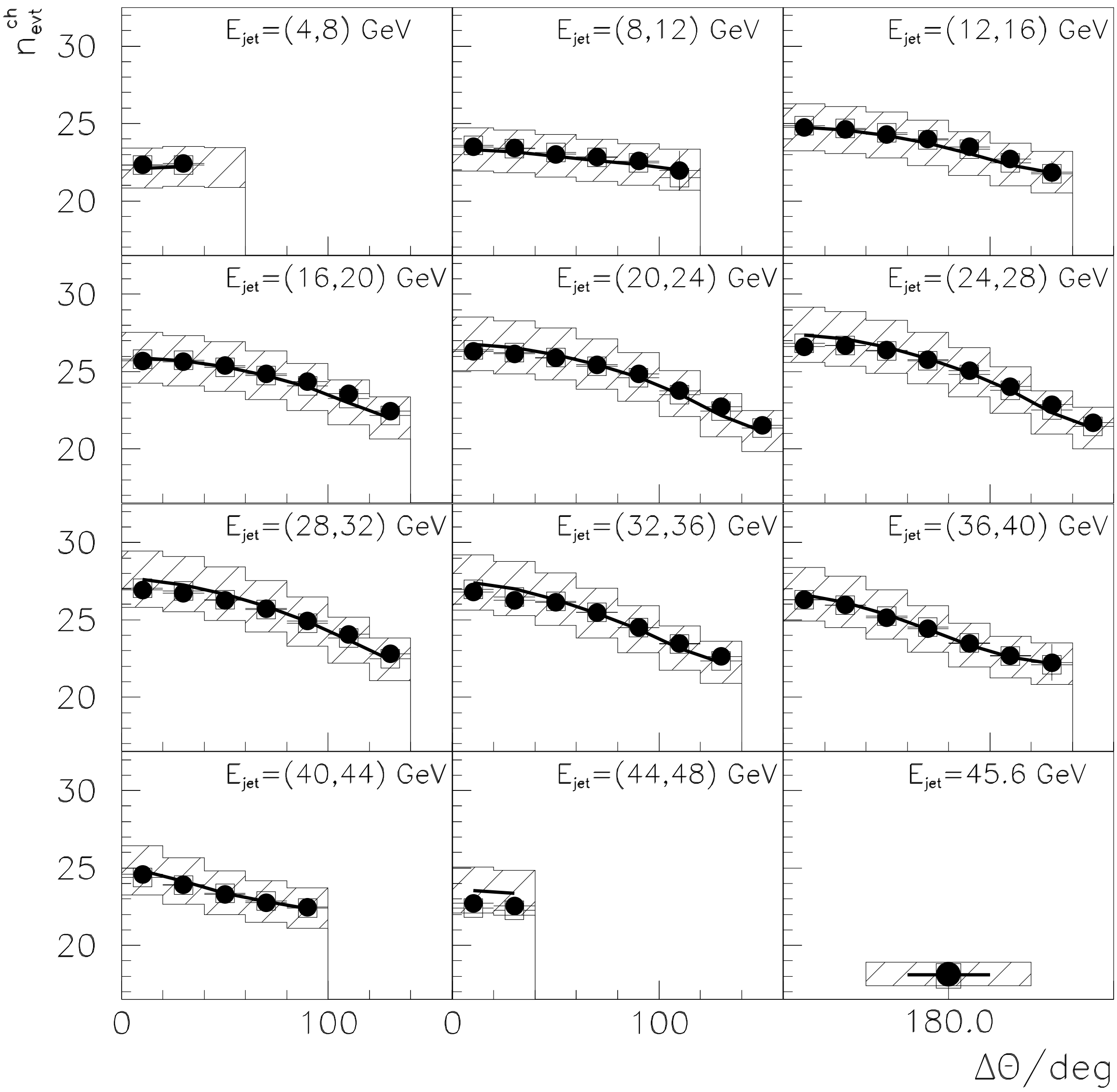

Figure 2: Topological fit of n^{ch}_{evt}: each histogram represents the values of n^{ch}_{evt} for a fixed E_{jet} interval as a function of $\Delta\theta$. The black circles are the data, the open squares are the Monte Carlo, the solid line is the best topological fit, the hatched area is the total error (see text). The bottom right histogram shows the two-jet event bin: E_{jet}= 45.6 GeV, $\Delta\theta$= 180 degrees (the horizontal widths are artificial).

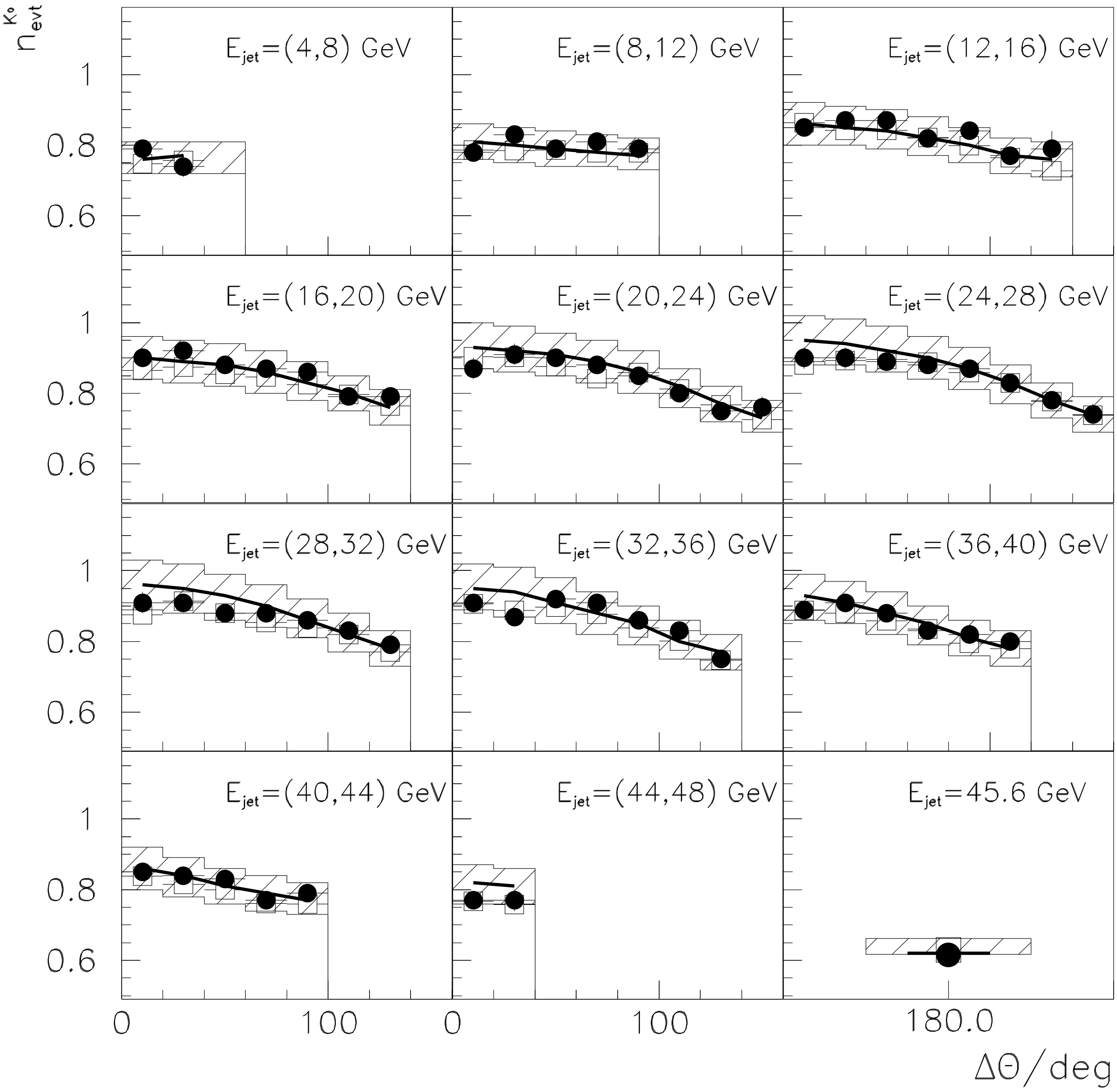

Figure 3: Topological fit of $n_{evt}^{K_s^0}$: same as for Figure 1.

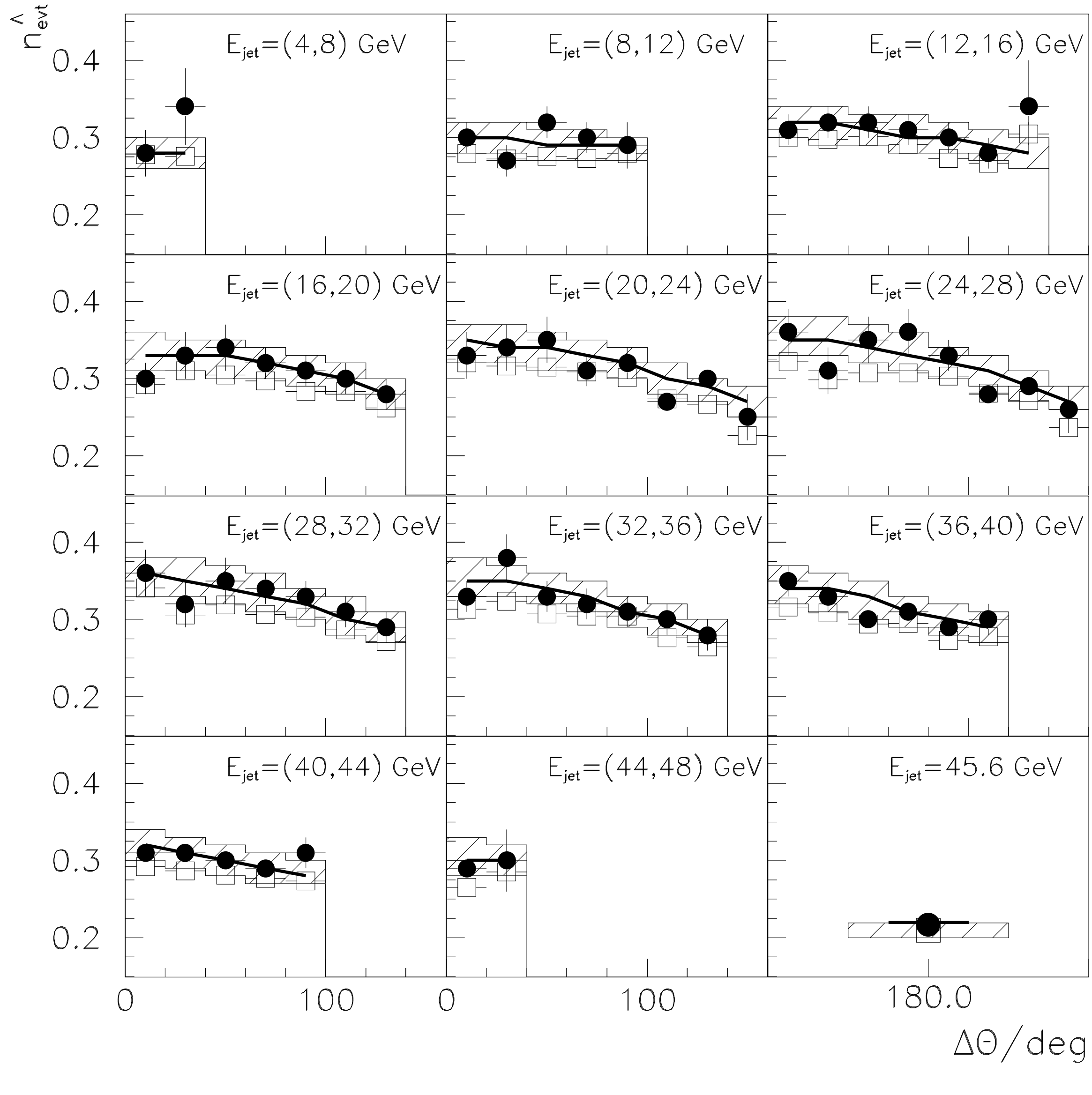

Figure 4: Topological fit of n^{Λ}_{evt}: same as for Figure 1.