EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Inclusive Production of η and η' in Two– and Three–Jet Events from Hadronic Z Decays

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Abstract

The production rates of the pseudoscalar mesons η, η' and π^0 as a function of scaled energy $x = E_{meson}/E_{beam}$ in two– and three–jet events from hadronic Z decays have been measured for every jet and compared to Monte Carlo models. The analysis is based on 2.8 million hadronic events collected with the ALEPH detector at LEP at a center–of–mass energy of $\sqrt{s} = 91.2$ GeV.

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1 Introduction

The fragmentation of quarks and gluons into hadrons, basically a non–perturbative process, can be described at present only by phenomenological models. JETSET [1] and HERWIG [2], the most used models for e^+e^- annihilation, treat the gluon fragmentation similar to quark fragmentation, taking into account the different color charge of quarks and gluons. In a different model for gluon fragmentation [3] only isoscalar particles and glueballs are produced directly; as a consequence, a harder spectrum for isoscalar particles is expected in a gluon jet, particularly at higher momenta, with respect to a quark jet.

In this paper, the isoscalar particles η and η' and the isovector particle π^0 are analysed in two– and three–jet events from hadronic Z decays and compared with the JETSET 7.4 and HERWIG 5.8 predictions. Since the enhancement of isoscalar particles in a gluon jet predicted by [3] is not implemented in the MC models used to compare with the data, it should appear in the spectra of isoscalar particles in a gluon jet as a deviation at high momenta from the MC prediction. No deviation should appear for the isovector particle in a gluon jet.

The η and π^0 production rates in gluon jets and quark jets have also been studied at Z energy by the L3 experiment [4] which has found a harder η momentum spectrum for gluon-enriched jets than that predicted by the MC models, and by the ARGUS experiment [5] at $\sqrt{s} = 10$ GeV, which has not seen any enrichment of isoscalars in gluon jets.

2 Data analysis

2.1 Event selection

For this analysis, data collected with the ALEPH detector [6] at the Z peak (center–of–mass energy $\sqrt{s} = 91.2$ GeV) during the 1992–1995 running of LEP has been used.

After a preselection of hadronic event candidates, done with the standard criteria used in ALEPH [8], the hadronic events were selected by demanding at least 15 energy–flow objects [7] and an invariant mass in excess of 45.6 GeV$/c^2$. To have well–contained events, a further cut on the polar angle of the thrust axis of the event (computed also with energy–flow objects) was imposed, by requiring $30^\circ \le \theta_{thr} \le 150^\circ$. This yielded a sample of 2.8 million hadronic events.

The Monte Carlo events, used to compute the detector effects, were generated using the JETSET parton shower model, with modified charm and bottom decay tables and generation of ISR photons with DYMU3 [9]; these events ('MC sample') were passed through the full ALEPH detector simulation, subject to the same cuts and analysed in the same way as the data.

Jets were built from all charged and neutral objects (energy–flow objects) using the $k_\perp$ (Durham) cluster algorithm, with the E recombination scheme and a jet resolution parameter of $y_{cut} = 0.01$. The polar angle of each jet with respect to the beam axis must be in the range $30^\circ \le \theta_{jet} \le 150^\circ$. From the three–jet event sample, the events which have one or more jets with more than 85% of the visible energy of the jet carried by a single photon were rejected, as possible $q\bar{q}\gamma$ events. The final samples consist of 1.8 million two–jet events and 719,000 three–jet events. The events with more than three jets were not considered in this analysis.

For three–jet events, the jet energies were recomputed from their directions, assuming planar, massless kinematics. Jets are then ordered according to the recomputed energies, jet 1 being the most energetical one. The average $x_{jet} = E_{jet}/E_{beam}$ is 0.93 for the first jet, 0.72 for the second jet and 0.35 for the third jet, well reproduced by the MC sample. By matching reconstructed jets with parton jets in MC events it was found that jet 1 (jet 2) is a quark or antiquark jet in 96% (75%) of the cases and that the third jet originates from a gluon with 71% probability.

2.2 Measurement of the production of η, π^0 and η'

The η and the π^0 mesons have been analysed in the $\gamma\gamma$ decay channel. For two– and three–jet event analysis, both photons from a $(\gamma\gamma)$ combination must belong to the same jet.

The photons are reconstructed as neutral clusters in the electromagnetic calorimeter (ECAL); the algorithm used for photon identification is described in detail in [7]. The following supplementary criteria are imposed to the identified photons: the fraction R_1+R_2 of their energy in the first two stacks of the ECAL greater than 0.8, the fraction of their energy in the four central towers of the shower greater than 0.8 (both cuts are used to further reduce the hadronic contamination) and the energy of the photon candidates greater than 1 GeV. In addition, for the η analysis the photon pairs with invariant mass within 40 MeV/c^2 of the π^0 mass were removed and a further cut on photon energy $E_\gamma > 1.75$ GeV was imposed.

The invariant mass m of the $\gamma\gamma$ pairs was obtained in several intervals of the variable $x = E(\gamma\gamma)/E_{beam}$. For each x interval, the η rate was determined by fitting the invariant mass distribution in the corresponding mass region with the sum of a Gaussian (for the signal) and a quartic polynomial (for the background). For π^0, the fit was done with the sum of a distorted Gaussian (for the signal) and a Fermi–like function (for the background) $(f_{bg}(m) = (b_3 + b_4(m - b_1))/(1.0 + \exp((b_1 - m)/b_2)))$. The rate was corrected for acceptance loss, the measured branching ratio and the effect of initial state radiation (ISR).

The η fragmentation function for each jet of the three-jet events was computed in every x bin as:

$$f^{\text{jet i}}(x) = \frac{1}{N^{\text{DATA}}_{\text{3−jet events}}} \frac{N_\eta^{\text{DATA, jet i}}(\text{rec})}{\Delta x} \cdot \frac{N_\eta^{\text{MC, jet i}}(\text{no cuts, no ISR})}{N_\eta^{\text{MC, jet i}}(\text{rec})} \tag{1}$$

where $N^{\text{DATA}}_{\text{3−jet events}}$ is the number of selected three–jet events, $N_\eta^{\text{DATA, jet i}}(\text{rec})$ is the number of reconstructed η particles in jet i in a given x bin for data (similar for MC), Δx is the width of the x bin, and $N_\eta^{\text{MC, jet i}}(\text{no cuts, no ISR})$ is the number of generated η particles in jet i in a given x bin for MC events without any selection criteria and without ISR (normalized to the same number of events as the MC sample with cuts, ISR on and full detector simulation). The same relation was used for π^0. The fragmentation function was also determined for two–jet events (normalized to the number of selected two–jet events) where the two jets were summed before fitting and for hadronic events (i.e. without jet selection) where it was normalized to the number of hadronic events.

The η' analysis has been done in the $\eta' \to \eta\pi^+\pi^-$ decay channel. Photon pairs with invariant mass within 100 MeV/c^2 of the fitted η mass were taken as η candidates; for these pairs, the mass was then constrained to the nominal η mass.

The pions were selected from the energy–flow objects as charged tracks which have at least 5 coordinates in the TPC, originate from a cylindrical region of radius 1 cm and half–length 5 cm centered on the nominal interaction point, have a polar angle in respect to the beam axis in the range $20° \leq \theta \leq 160°$ and a transverse momentum greater than 0.2 GeV/c. The charged tracks identified as electrons or muons (see [7] for details of the identification) were rejected from the pion candidate sample.

For the analysis of two– and three–jet events, all three particle candidates from a $(\eta\pi^+\pi^-)$ combination, must belong to the same jet.

The invariant mass distributions of the $(\eta\pi^+\pi^-)$ combinations were obtained as a function of the scaled energy $x = E(\eta\pi^+\pi^-)/E_{beam}$ and were fitted for every x bin with the sum of a

Gaussian (for the signal) and a cubic polynomial (for the background). The same correction procedure as given in Eqn. (1) was used to obtain the fragmentation function.

The systematic errors were estimated by varying one–by–one the selection cuts, by varying the fit range and, in the case of π^0 and η' , by comparing data and fully–simulated MC samples for those features not covered by the variation of the selection cuts.

The corrected fragmentation functions $f(x)$ of η, π^0 and η' are shown in Figure 1 for two–jet events and in Figures 2–7 for three–jet events. Also shown are the JETSET 7.4 and HERWIG 5.8 model predictions and the differences between model and data values in units of the total error.

The JETSET and HERWIG model parameters are tuned [10] on ALEPH event shape and single charged particle distributions and on ALEPH inclusive spectra of various particles (including η and η') in hadronic events. The inclusive spectra in two– or three–jet events presented here were not used for tuning. The η' suppression parameter in JETSET is PARJ(26)=0.275, no η suppression is used (PARJ(25)=1.) and the η–η' mixing angle is set to $-9.7°$. The particle analysed was put stable before jet clustering in the MC calculations, consistent with the requirement of $(\gamma\gamma)$ or $(\eta\pi^+\pi^-)$ combinations to be in the same jet. Jet energies were also recomputed from their directions, assuming planar, massless kinematics.

The multiplicities for the different event types, obtained by integrating the corrected fragmentation function over the accessible x range, are summarized in Tables 1 and 2 for η, Tables 4 and 5 for π^0 and Tables 7 and 8 for η'. Also given are the multiplicities extrapolated to the full x range, using the predictions of the JETSET 7.4 model.

For a quantitative comparison between data and MC models, we give a $\chi^2 = \sum_{x\ bins}(f_{model}(x) - f_{data}(x))^2/(\sigma_{tot}^{data})^2$ for every situation and compare it to the number of degrees of freedom; the values are presented in the Tables 3, 6 and 9 for η, π^0 and η', respectively.

3 Discussion and conclusions

The production of the isoscalar particles η and η' and of the isovector particle π^0 was analysed in two– and three–jet events from hadronic Z decays. The high x region explored here for η and η' is relevant for testing the model of Ref. [3]. As a check, the production of η and η' in hadronic events was updated using almost all the available LEP1 statistics.

In two–jet events, reasonable agreement of the data with the predictions of JETSET is found, apart from the high $x > 0.75$ region where JETSET shows an excess of η particles. This latter region is very sensitive to the values of the fragmentation parameters and a similar discrepancy has been observed [10] for the charged particle distribution in hadronic events. In contrast, HERWIG shows a slightly too steep dependence on x for η and η'.

The measured fragmentation functions of η and η' in hadronic events are in very good agreement with the previous ALEPH results [10].

In three jet events, the η and π^0 data of all three jets are also found to be in good agreement with the JETSET prediction. This is especially true for the third jet which, according to MC calculations, represents the gluon jet in $\sim 71\%$ of the cases. The same also holds for the η', although with much large errors. Hence there is no experimental evidence for enhanced isoscalar meson production in gluon jets with respect to quark jets, within the errors. As in the two–jet case, the HERWIG predictions are slightly too steep in x for η for all three jets. They agree with the data in case of η'.

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Table 1: Measured multiplicity for η in different event types, compared with JETSET and HERWIG predictions. The extrapolation to the full x range is made using JETSET 7.4

Event type	x range	Multiplicity $\pm\Delta_{stat} \pm \Delta_{syst}$	JETSET	HERWIG
hadronic events	0.10 - 1.0	$0.282 \pm 0.006 \pm 0.013$	0.297	0.331
	all	$1.01 \pm 0.02 \pm 0.05$	1.03	0.98
two–jet events	0.10 - 1.0	$0.280 \pm 0.007 \pm 0.019$	0.304	0.342
	all	$0.88 \pm 0.02 \pm 0.06$	0.90	0.88
three–jet events	0.10 - 0.62	$0.277 \pm 0.013 \pm 0.028$	0.283	0.317
	all	$1.20 \pm 0.06 \pm 0.12$	1.20	1.12

Table 2: Measured multiplicity for η in three–jet events, compared with JETSET and HERWIG predictions. The extrapolation to the full x range is made using JETSET 7.4

Jet	x range	Multiplicity $\pm\Delta_{stat} \pm \Delta_{syst}$	JETSET	HERWIG
Jet 1	0.10 - 0.62	$0.123 \pm 0.009 \pm 0.010$	0.138	0.155
	all	$0.417 \pm 0.029 \pm 0.034$	0.432	0.421
Jet 2	0.10 - 0.52	$0.114 \pm 0.009 \pm 0.015$	0.108	0.121
	all	$0.408 \pm 0.031 \pm 0.054$	0.402	0.382
Jet 3	0.10 - 0.32	$0.041 \pm 0.004 \pm 0.003$	0.037	0.041
	all	$0.370 \pm 0.035 \pm 0.031$	0.366	0.320

Table 3: χ^2 for η fragmentation function in different event types, computed for JETSET 7.4 and HERWIG 5.8 predictions. For the rows marked (*), χ^2 was computed without the last x bin.

Event type	JETSET 7.4			HERWIG 5.8		
	χ^2	ndf	χ^2/ndf	χ^2	ndf	χ^2/ndf
Hadronic events	123.	17	7.2	122.	17	7.2
(*)	37.	16	2.3	115.	16	7.2
Two–jet events	104.	9	11.5	107.	9	11.9
(*)	21.	8	2.6	103.	8	12.9
3–jet ev, jet 1	11.7	6	2.0	33.8	6	5.6
3–jet ev, jet 2	5.9	5	1.2	13.9	5	2.8
3–jet ev, jet 3	2.9	3	1.0	6.6	3	2.2

Table 4: Measured multiplicity for π^0 in different event types, compared with JETSET and HERWIG predictions. The extrapolation to the full x range is made using JETSET 7.4

Event type	x range	Multiplicity $\pm\Delta_{stat} \pm \Delta_{syst}$	JETSET	HERWIG
hadronic events	0.06 - 0.62	$2.131 \pm 0.007 \pm 0.079$	2.274	2.192
	all	$9.52 \pm 0.03 \pm 0.35$	9.66	9.58
two–jet events	0.06 - 0.52	$2.156 \pm 0.008 \pm 0.079$	2.313	2.169
	all	$8.39 \pm 0.03 \pm 0.31$	8.54	8.54
three–jet events	0.06 - 0.52	$2.069 \pm 0.011 \pm 0.097$	2.208	2.215
	all	$11.06 \pm 0.06 \pm 0.52$	11.20	11.09

Table 5: Measured multiplicity for π^0 in three–jet events, compared with JETSET and HERWIG predictions. The extrapolation to the full x range is made using JETSET 7.4

Jet	x range	Multiplicity $\pm\Delta_{stat} \pm \Delta_{syst}$	JETSET	HERWIG
Jet 1	0.06 - 0.52	$0.978 \pm 0.008 \pm 0.056$	1.060	1.008
	all	$4.05 \pm 0.04 \pm 0.23$	4.13	4.09
Jet 2	0.06 - 0.52	$0.790 \pm 0.007 \pm 0.030$	0.829	0.834
	all	$3.79 \pm 0.03 \pm 0.14$	3.83	3.75
Jet 3	0.06 - 0.32	$0.301 \pm 0.003 \pm 0.011$	0.318	0.373
	all	$3.21 \pm 0.03 \pm 0.12$	3.23	3.24

Table 6: χ^2 for π^0 fragmentation function in different event types, computed for JETSET 7.4 and HERWIG 5.8 predictions.

Event type	JETSET 7.4			HERWIG 5.8		
	χ^2	ndf	χ^2/ndf	χ^2	ndf	χ^2/ndf
Hadronic events	81.0	12	6.7	77.3	12	6.4
Two–jet events	53.4	7	7.6	38.6	7	5.5
3–jet ev, jet 1	18.3	7	2.6	10.8	7	1.5
3–jet ev, jet 2	48.5	7	6.9	73.2	7	10.5
3–jet ev, jet 3	13.1	5	2.6	151.4	5	30.5

Table 7: Measured multiplicity for η' in different event types, compared with JETSET and HERWIG predictions. The extrapolation to the full x range is made using JETSET 7.4

Event type	x range	Multiplicity $\pm\Delta_{stat} \pm \Delta_{syst}$	JETSET	HERWIG
hadronic events	0.16 - 1.0	0.045 $\pm$ 0.007 $\pm$ 0.008	0.045	0.054
	all	0.155 $\pm$ 0.024 $\pm$ 0.029	0.155	0.131
two–jet events	0.16 - 1.0	0.040 $\pm$ 0.006 $\pm$ 0.009	0.048	0.059
	all	0.130 $\pm$ 0.018 $\pm$ 0.029	0.138	0.124
three–jet events	0.16 - 0.52	0.039 $\pm$ 0.009 $\pm$ 0.014	0.038	0.046
	all	0.181 $\pm$ 0.040 $\pm$ 0.065	0.180	0.142

Table 8: Measured multiplicity for η' in three–jet events, compared with JETSET and HERWIG predictions. The extrapolation to the full x range is made using JETSET 7.4

Jet	x range	Multiplicity $\pm\Delta_{stat} \pm \Delta_{syst}$	JETSET	HERWIG
Jet 1	0.16 - 0.52	0.019 $\pm$ 0.006 $\pm$ 0.006	0.020	0.025
	all	0.065 $\pm$ 0.022 $\pm$ 0.022	0.066	0.059
Jet 2	0.16 - 0.52	0.016 $\pm$ 0.006 $\pm$ 0.006	0.015	0.018
	all	0.061 $\pm$ 0.023 $\pm$ 0.023	0.060	0.051
Jet 3	0.16 - 0.34	0.0040 $\pm$ 0.0018 $\pm$ 0.0016	0.0034	0.0030
	all	0.054 $\pm$ 0.025 $\pm$ 0.022	0.053	0.033

Table 9: χ^2 for η' fragmentation function in different event types, computed for JETSET 7.4 and HERWIG 5.8 predictions.

Event type	JETSET 7.4			HERWIG 5.8		
	χ^2	ndf	χ^2/ndf	χ^2	ndf	χ^2/ndf
Hadronic events	17.8	9	1.98	19.6	9	2.18
Two–jet events	11.1	7	1.59	16.3	7	2.33
3–jet ev, jet 1	0.2	3	0.07	1.4	3	0.47
3–jet ev, jet 2	1.0	3	0.33	1.3	3	0.43
3–jet ev, jet 3	0.4	1	0.40	1.1	1	1.10

Figure 1: The fragmentation function for inclusive η, π^0 and η' production in two–jet events compared with the predictions of JETSET 7.4 and HERWIG 5.8. The error bars show the total errors (statistical and systematic errors added in quadrature).

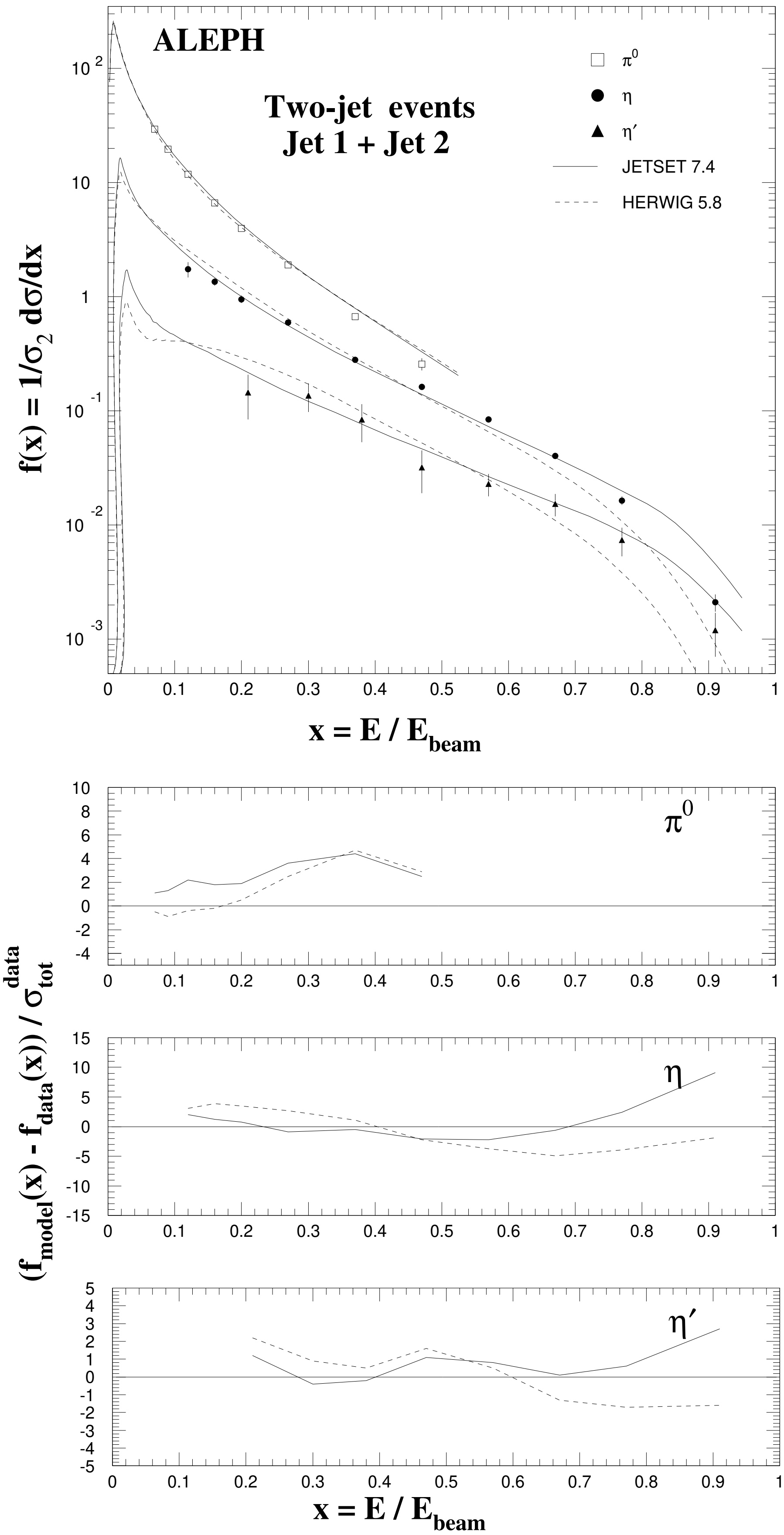


Figure 2: The fragmentation function for inclusive η production in three–jet events compared with the predictions of JETSET 7.4. The error bars show the total errors (statistical and systematic errors added in quadrature).

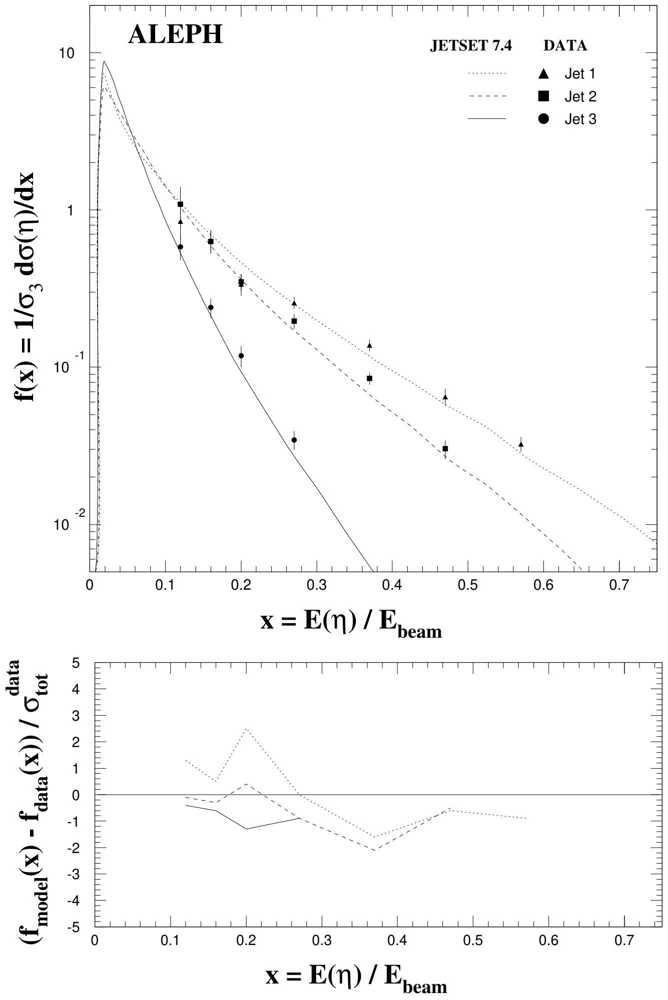


Figure 3: The fragmentation function for inclusive η production in three–jet events compared with the predictions of HERWIG 5.8. The error bars show the total errors (statistical and systematic errors added in quadrature).

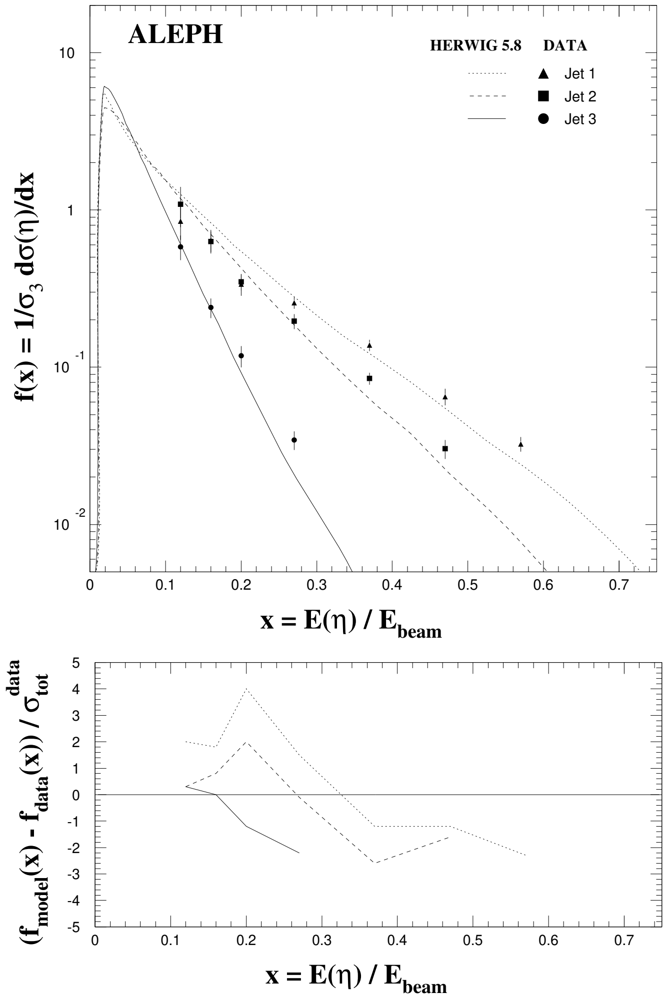
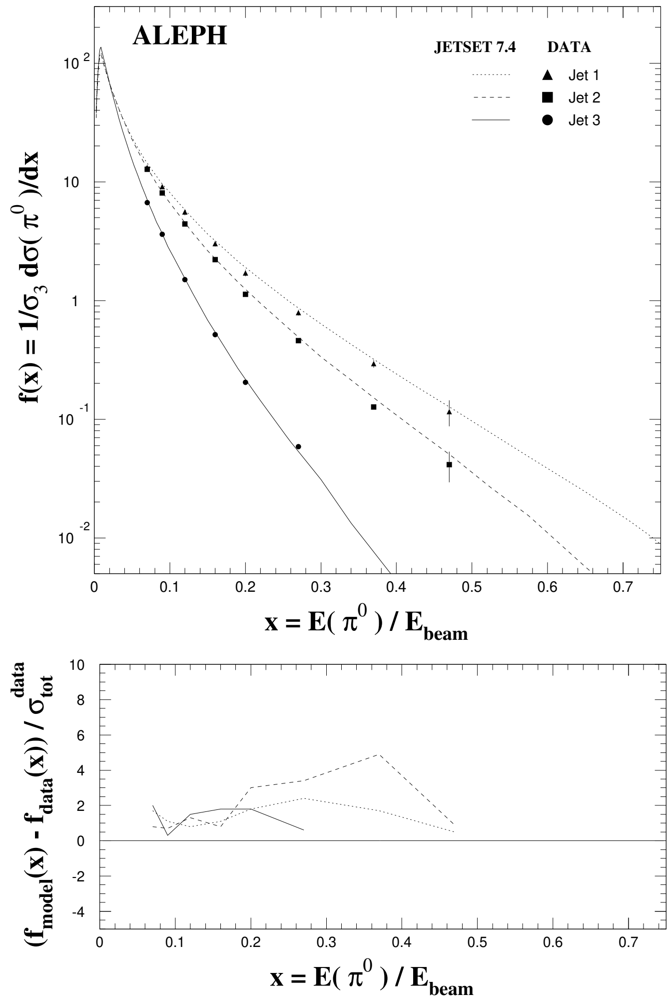


Figure 4: The fragmentation function for inclusive π^0 production in three–jet events compared with the predictions of JETSET 7.4. The error bars show the total errors (statistical and systematic errors added in quadrature).

Figure 5: The fragmentation function for inclusive π^0 production in three–jet events compared with the predictions of HERWIG 5.8. The error bars show the total errors (statistical and systematic errors added in quadrature).



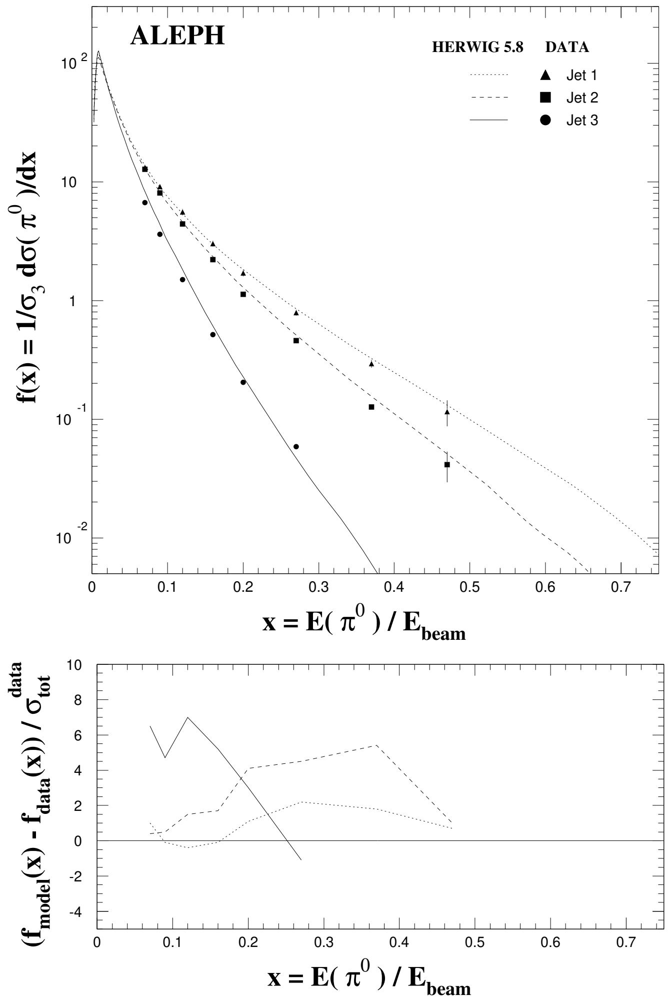


Figure 6: The fragmentation function for inclusive η' production in three–jet events compared with the predictions of JETSET 7.4 (all errors shown are statistical only; the deviation from the model is computed with the total error).

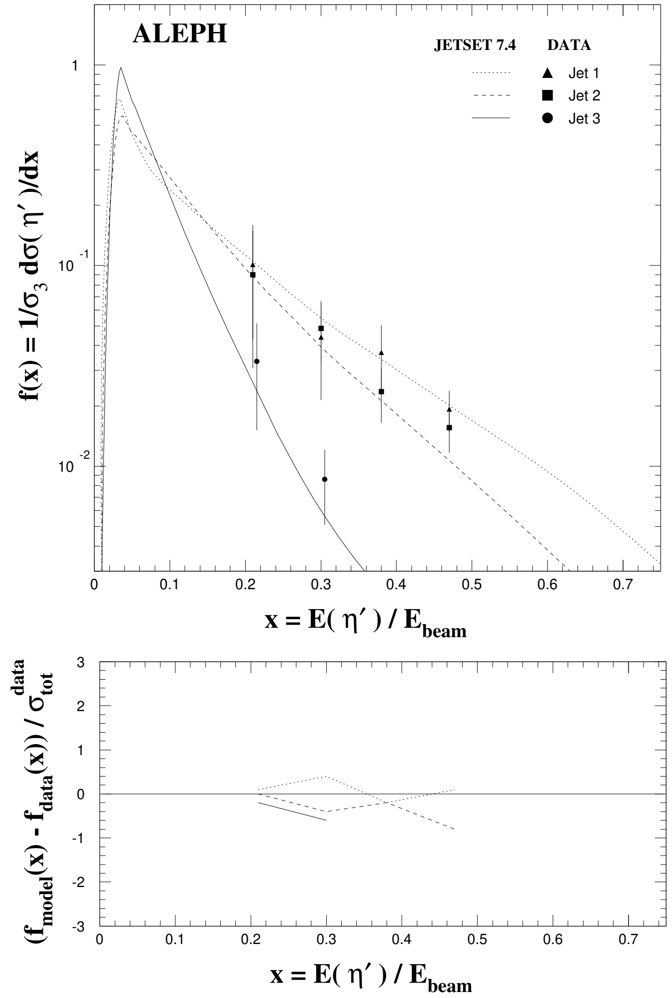


Figure 7: The fragmentation function for inclusive η' production in three–jet events compared with the predictions of HERWIG 5.8 (all errors shown are statistical only; the deviation from the model is computed with the total error).