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One-Prong τ Decays into Charged Kaons

The ALEPH Collaboration*)

Abstract

From a sample of about 75000 τ decays measured in the ALEPH detector, 1-prong charged kaon decays are identified by the dE/dx measurement in the central detector. The resulting branching ratios for the inclusive and exclusive modes are : $B(\tau \rightarrow \nu_\tau K^- \geq 0\pi^0 \geq 0K^0) = (1.60 \pm 0.07 \pm 0.12)\%$, $B(\tau \rightarrow \nu_\tau K^-) = (0.64 \pm 0.05 \pm 0.05)\%$, $B(\tau \rightarrow \nu_\tau K^- \pi^0) = (0.53 \pm 0.05 \pm 0.07)\%$ and $B(\tau \rightarrow \nu_\tau K^- \pi^0 \pi^0) = (0.04 \pm 0.03 \pm 0.02)\%$. Exclusive modes are corrected for measured K_L^0 production. The rate for $\tau \rightarrow \nu_\tau K^-$ agrees well with the prediction based on $\tau - \mu$ universality.

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1 Introduction

The experimental situation in kaon production in τ decays is still unsatisfactory[1]. Except for K^* production, which has been studied through the ($\tau \rightarrow \nu_\tau K^*$, $K^* \rightarrow K_S^0 \pi^-$, $K_S^0 \rightarrow \pi^+ \pi^-$) decay chain, the rates for the other Cabibbo-suppressed channels are not very well known. In particular, the measurements of the simplest process

$$\tau \rightarrow \nu_\tau K^- \quad (1)$$

which are few and suffer from low statistics[2, 3] do not permit a precise test of the $\tau - \mu$ universality by comparison to the leptonic rate for $K^- \rightarrow \bar{\nu}_\mu \mu^-$.

Beyond the K and K^* channels, additional decay modes with more pions are expected, but they have not yet been investigated experimentally. It is also possible to consider Cabibbo-allowed decays with a pair of kaons: such modes are expected to be at a small level although no reliable theoretical estimate is available. Since some of these final states can involve a charged kaon and a neutral kaon which was often not detected in previous experiments, it is worthwhile to undertake a systematic study of kaon production in τ decays.

Such an investigation of 1-prong τ decays with the ALEPH detector is described in this letter and the accompanying one [4]. Hadronic τ decays are classified according to their π^0 multiplicity (up to two π^0 's) and the charged K fraction is determined using a dE/dx measurement in the central detector (this letter). A complementary search for final states containing K^0 's is performed using hadronic calorimetry, which is sensitive to the K_L^0 component (the following letter). Combining the two analyses allows separation of the various exclusive decay channels and the measurement of the branching ratios for the dominant modes.

In this letter, ALEPH measurements of the 1-prong charged kaon τ -decay rates are presented, i.e.

$$\tau \rightarrow \nu_\tau K^- \geq 0 \text{ neutrals} \quad (2)$$

where the neutrals include π^0 's and K^0 's. The branching fractions for the channels

$$\begin{aligned} \tau &\rightarrow \nu_\tau K^- \\ \tau &\rightarrow \nu_\tau K^- \pi^0 \\ \tau &\rightarrow \nu_\tau K^- \pi^0 \pi^0 \end{aligned} \quad (3)$$

are extracted, after subtracting small contributions from other decay modes ($\tau \rightarrow \nu_\tau K^- K^0$ and $\tau \rightarrow \nu_\tau K^- \pi^0 K^0$) measured with the calorimetric analysis[4].

2 The ALEPH detector and the ionization measurement

A detailed description of the ALEPH detector can be found elsewhere[5]. Charged particle momenta are measured by a magnetic spectrometer consisting of a precision vertex detector (VDET), of a cylindrical drift chamber, the inner tracking chamber (ITC), and of a large time projection chamber (TPC). The 1.5 T axial magnetic field is provided by a superconducting solenoidal coil. The transverse momentum resolution is $\sigma_p/p = 6 \times 10^{-4}$, with p in GeV/c. Photons are measured with an energy resolution $\sigma_E/E = 0.18/\sqrt{E}$, with E in GeV, in the electromagnetic calorimeter (ECAL), a 22 radiation length thick sandwich of lead plates and proportional wire chambers. The fine solid-angle readout segmentation ($1^\circ \times 1^\circ$) is essential for high-energy π^0 reconstruction and the 3-fold longitudinal segmentation allows a check of the electromagnetic nature of the detected showers. The 1.2 m thick iron return yoke of the magnet is interleaved with 23 layers of streamer tubes and acts as a hadronic calorimeter (HCAL).

In the data sample used for this analysis, all components of the detector were required to be operational. Furthermore, one of the following trigger conditions was demanded: a minimum ECAL energy of 6 GeV, or a track segment in the ITC pointing to an energy deposit in ECAL of a least 1.2 GeV, or a track segment in the ITC matching the signal of a penetrating particle in HCAL.

Of prime interest for this analysis is the measurement of the ionization deposited by charged particles traversing the TPC gas at atmospheric pressure and sampled up to 330 times on the sense wires of the TPC end-plates. To avoid the large fluctuations caused by δ -rays, a truncated mean is used, leaving aside the 40 % largest values. The resulting resolution is 5.0 % for tracks at a polar angle of 90° , decreasing to 4.0 % near 40° where the track length is maximum and increasing again to 5.3 % down to 20° because of the reduced number of samples.

3 Event selection

The present analysis is based on a data sample corresponding to about one million hadronic Z decays collected by ALEPH in 1991 and 1992. Candidates for the $\tau^+\tau^-$ final states are selected using an off-line filter, designed to reduce backgrounds with specific cuts while preserving $\tau^+\tau^-$ candidates in background-free topologies[6]. This goal is achieved using particle identification to reduce Bhabha, μ -pair and $\gamma\gamma$ -induced lepton pair backgrounds and applying multiplicity cuts to suppress hadronic Z decays.

Within the geometrical acceptance of 84.2 % defined for a reliable analysis, the $\tau^+\tau^-$ filter has an efficiency of 92.8 %, with a background contamination of only 1.6 %, the largest contribution coming from Bhabha events (0.7 %). The one-prong hadronic τ decay sample studied is even cleaner with a non- τ background of 0.1 %.

Decays with only one charged particle originating from the interaction region are selected by requiring a minimum momentum of 2 GeV/c and a positive hadron identification. The latter requirement is based on a likelihood method using ECAL and HCAL information, as described in Ref. 7. In the selected momentum range, hadrons are identified with an efficiency of 98.5 % (0.9 % of them being mis-identified as muons). The electron and muon contaminations in the hadron sample are 0.18 % and 0.22 %, respectively.

Next, photons are identified in ECAL with an energy threshold of 250 MeV and π^0 's are reconstructed with a cut on the $\gamma\gamma$ invariant mass (0.07 - 0.21 GeV/c²). Since high-energy π^0 decays cannot be easily resolved and low-energy photons are lost, single photons with an energy in excess of 4 GeV are also retained as π^0 candidates[8]. Four data samples are defined with respect to the π^0 multiplicity : the global sample, with no requirement on the number of π^0 's, is referred to as 'h inclusive', whereas three sub-samples, 'h', 'h π^0 ', 'h2 π^0 ', are labelled by the observed number of π^0 's. Events with additional photons are excluded from these exclusive samples. The efficiencies of this classification for kaon final states are calculated by Monte Carlo[9] to be 84 %, 56 % and 39 % for the 'h', 'h π^0 ' and 'h2 π^0 ' samples, respectively, while the corresponding purities (fraction of events in a given class originating from the correct π^0 multiplicity) are 98 %, 96 % and 82 %.

The $\tau^+\tau^-$ filter selects a sample of 37778 events, yielding 28481 one-prong hadronic τ candidates after all cuts, of which 28390 have dE/dx information.

4 K/ π separation by dE/dx and calibration

The dE/dx measured in the TPC (hereafter called R) is to a very good approximation Gaussian-distributed around the expected value R_i for a given particle type i . In the standard ALEPH analyses using dE/dx, the R_i values are computed using a parametrization of the Bethe-Bloch formula fitted to ALEPH data[10]. The calculations of R_i and its variance σ_i^2 take into account efficiencies and geometrical effects, through the number of samplings and the track sample length, which are both angle-dependent and include the effect of the small dead zones between TPC sectors in the end-plates.

Taking these estimates of R_i and σ_i as a starting point, a finer calibration is performed, taking into account the following facts :

- (i) the standard calibration, obtained mostly from pions in hadronic Z decays corresponding to tracks in general not isolated in the TPC, is not precise enough for the purpose of this analysis where the kaon fraction is expected to be low (a few %).
- (ii) one-prong τ decays offer a unique possibility to achieve a better calibration : in contrast to the Z hadronic sample, tracks are completely isolated and unperturbed by the rest of the event. Furthermore, Z and τ decays into muons (in the range from 2 to 45 GeV/c) can be used with the advantage of the same angular distribution in the detector as for the hadrons under study. For the sample of τ decays into muons, it is important to take into account the small contributions from hadrons mis-identified as muons.

Thus the shape of the R distribution is taken from muons. The distribution $\rho(x_\mu)$ of the quantity

$$x_\mu = \frac{R - R_\mu}{\sigma_\mu} \quad (4)$$

deviates slightly from a pure Gaussian with zero mean and unit variance and a more precise parametrization is obtained from the muon samples. No significant dependence of $\rho(x_\mu)$ on momentum is noticed in the 2-45 GeV/c range. The muon R probability density is therefore given by

$$W_\mu(R) = \frac{\rho(x_\mu)}{\sigma_\mu} \quad (5)$$

with x_μ defined by (4). The densities $W_i(R)$ for the other particle types are obtained from the same ρ distribution and from the calibrated R_i and σ_i .

The K fraction f_K is obtained from the distribution of x_π (defined analogously to (4)) for the hadron sample which is fitted to a sum of π and K contributions, each proportional to $W_{\pi,K}(R)$, respectively. Another approach is to define a kaon estimator for each hadron with ionization R :

$$P_K = \frac{W_K(R)}{W_\pi(R) + W_K(R)} \quad (6)$$

A peak near one in the distribution of this variable signals the presence of kaons.

The K/ π separation is momentum-dependent. The variation of the separation parameter

$$\eta = \frac{R_\pi - R_K}{\sigma_\pi} \quad (7)$$

is given in Figure 1.

5 Fits and systematic uncertainties

To derive the K fraction in each of the data samples, the respective x_π distributions are not only fitted to a linear combination of pion and kaon expected contributions, but also to small components for electrons and muons. This latter contribution does not significantly affect the derived K fraction, but improves the overall description of the ionization loss distribution. The rates for these contaminations are kept fixed, and are given by the Monte Carlo simulation of the particle identification which has been checked with real data. The fits are performed with both unbinned likelihood or binned χ^2 methods : both procedures yield consistent results and statistical errors. The results quoted below are from the χ^2 fits.

The fit results for the inclusive hadron sample are given in Figure 2. A significant contribution from kaons is observed corresponding to a clear peak at one in the P_K distribution. Similar excesses are observed in all hadron samples.

Beyond statistical limitations the main source of uncertainty is the description of the pion dE/dx distribution as a function of momentum. An estimate of the systematic uncertainty involved in this procedure is obtained from fitting a hypothetical K fraction in the muon samples. The distribution of identified muons in τ decays is dominated by real muons with a pion contamination taken from the Monte Carlo simulation of the particle identification. A kaon component is left free in the fit (Fig. 3) which yields a fraction $((0.14 \pm 0.06)\%)$ compatible with the expected kaon mis-identification predicted by the Monte Carlo $((0.11 \pm 0.02)\%)$. Fixing this real kaon contribution at the expected value, fits are performed in different momentum bins of the same muon sample searching for an additional (fake) kaon signal located at $R = R_K + R_\mu - R_\pi$. Such a procedure is sensitive to a local distortion in the reference distribution $\rho(x)$ measured with muons, which would reflect into a fake K signal in the hadron x_π distribution.

The results of this procedure are given in Table 1 : the values are consistent with zero and they are used to bound possible systematic effects through convolution with the momentum distribution of each

hadron sample. The resulting absolute systematic uncertainty on the kaon fraction f_K is estimated to be 0.22 %, almost independent of the data sample.

The calibrations of R and σ can be checked using the hadron sample. A likelihood fit with 3 parameters (K fraction, deviation ΔR from expected mean R_π value and ratio λ of the standard deviation to the expected value σ_π), yields

$$\begin{aligned}\Delta R &= -0.00072 \pm 0.00084 \\ \lambda &= 1.0014 \pm 0.0097\end{aligned}\tag{8}$$

The values are consistent with the calibration based on muons and show that the knowledge of the absolute ionization loss scale is at the 0.1 % level, while the standard deviation is known to about 1 %.

Additional checks are possible :

- (i) Because the large kaon mass cannot be neglected in τ decays, the K fraction is expected to vanish below the kinematic threshold of 3.6 GeV/c (except for a very small contribution from radiative events). In the range 2-3.5 GeV/c, the inclusive sample with $f_K = (0.08 \pm 0.34)\%$ is consistent with the Monte Carlo expectation, $f_K^{MC} = (0.05 \pm 0.03)\%$. This test is less precise than the quoted systematic uncertainty, but it is consistent and completely independent.
- (ii) The $K\pi^0$ channel should be dominated by the $K^*(892)$ resonance, characterized by a smaller Q value compared to the $\rho \rightarrow \pi\pi^0$. A cut on the $K\pi$ mass below 1 GeV/c² isolates most of the K^* events, hence the K sample. Defining r as the ratio of the f_K values above and below the cut, a good agreement is observed between data and Monte Carlo with r values of $(8 \pm 3)\%$ and $(8.6 \pm 1.0)\%$, respectively. If the measured f_K were due to fake kaons r would be consistent with unity. While this test is a factor of two more precise than the quoted systematics, it relies on K^* dominance. So the more conservative estimate is preferred.

Less important contributions to the systematic uncertainty are estimated, such as those related to the selection efficiency of a given channel and its purity. The relative uncertainties for this source vary from 2 to 4 %, depending on the sample. The final values for systematic uncertainties are quoted with the final results in Table 2.

6 Discussion of the results

The K fractions, as obtained by the fits, are given in Table 2. The quality of the fits is good and the resulting statistical power is close to that of an ideal analysis identifying kaons perfectly on an event-by-event basis, the sensitivity being degraded by only a factor of 0.75.

Given the selection procedure, it is possible that additional K^0 's could be present in the same τ hemisphere. Almost all K_S^0 decays to $\pi^+\pi^-$ would have at least one extra track pointing to the interaction vertex and hence the efficiency for keeping these decays is very small. Most K^0 contamination would

therefore come from K_S^0 's decaying into $\pi^0\pi^0$, K_S^0 's not decaying in the TPC and K_L^0 's. These contributions can be estimated with the KORALZ Monte Carlo[9] up to a scale factor, since the decay modes in question are not yet experimentally measured. In addition, some possible decay channels like

$$\tau \rightarrow \nu_\tau K^- K^0 \quad (9)$$

are not yet simulated in KORALZ and are treated separately in a model assuming a spin-one state for the K^-K^0 system ¹.

By performing a dedicated complementary search for K_L^0 candidates in HCAL, these contributions can be evaluated directly from the data. Searching for K_L^0 's rather than K_S^0 's has the advantage of being completely independent of the present analysis using tracks (TPC) and photons (ECAL). The K_L^0 analysis is described separately[4] and studies the decay modes

$$\tau \rightarrow \nu_\tau h^- K^0 \quad (10)$$

and

$$\tau \rightarrow \nu_\tau h^- \pi^0 K^0 \quad (11)$$

Contamination of the present event samples by the K^-K^0 and $K^-\pi^0 K^0$ channels are computed using the Monte Carlo simulation normalized to the measured total rate in the K_L^0 analysis[4]. The corresponding values are used to correct the measured branching ratios into the final states of interest for the present analysis.

The final results are given in Table 2. For each channel, the efficiency and the background are computed with the Monte Carlo and the corrections for K^0 production (ΔN_K) are indicated. The latter have a different meaning for the different channels : in the inclusive mode (2) ΔN_K is the loss of events with K_S^0 's decaying to $\pi^+\pi^-$, whereas for the exclusive modes (3) it refers to the background from channels with additional K^0 's.

The total one-prong inclusive K rate

$$B(\tau \rightarrow \nu_\tau K^- \geq 0\pi^0 \geq 0K^0) = (1.60 \pm 0.07 \pm 0.12)\% \quad (12)$$

agrees well with the world average[11], $(1.68 \pm 0.24)\%$. However the treatment of K^0 's is explicit in this analysis.

The improvement in the single K channel is significant with

$$B(\tau \rightarrow \nu_\tau K^-) = (0.64 \pm 0.05 \pm 0.05)\% \quad (13)$$

to be compared to the world average[11], $(0.67 \pm 0.23)\%$, which was not corrected for K^0 production. A test of the Standard Model can be performed in the strange sector of the τ : using the electron branching ratio from Ref. 7, the ratio

$$\frac{B(\tau \rightarrow \nu_\tau K^-)}{B(\tau \rightarrow \nu_\tau e \bar{\nu}_e)} = 0.035 \pm 0.004 \quad (14)$$

can be compared to the value of (0.0393 ± 0.0002) expected from $\tau - \mu$ universality, the measured $K \rightarrow \mu \nu$ decay rate[11] and radiative corrections[12]. Fitting the K fraction in each momentum bin, the K momentum spectrum agrees with the expected distribution including the effect of τ polarisation.

¹A spin-0 state would correspond to a second-class current in τ decay.

The observed branching ratios for the other modes are

$$\begin{aligned} B(\tau \rightarrow \nu_\tau K \pi^0) &= (0.53 \pm 0.05 \pm 0.07)\% \\ B(\tau \rightarrow \nu_\tau K \pi^0 \pi^0) &= (0.04 \pm 0.03 \pm 0.02)\% \end{aligned} \quad (15)$$

The $K^*(892)$ is expected to dominate the $\tau \rightarrow \nu_\tau K \pi$ channel. Previous measurements have studied the mode $K_S^0 \pi^-$, with $K_S^0 \rightarrow \pi^+ \pi^-$. The present result for the $K \pi^0$ mode is consistent with the world average using $K_S^0 \pi^-$, with a comparable uncertainty. The $K \pi^0$ mass distribution, obtained from separate dE/dx fits in each mass bin, is well-described by the K^* resonance (Fig. 4) and other small non- $K \pi^0$ contributions obtained by KORALZ. The fitted mass is 903 ± 8 MeV, in good agreement with the standard value[11], while the fitted resolution of 46 ± 5 MeV matches the Monte Carlo value of 48 ± 2 MeV. The branching ratio for $\tau \rightarrow \nu_\tau K^*$ is given in the following letter[4] taking into account the measurements of the $K \pi^0$ and $K^0 \pi$ final states.

Finally, the sum of the exclusive modes considered here and in Ref. 4 saturates the one-prong inclusive K rate within experimental accuracy, thus ruling out other exclusive channels (with more π^0 's or more K^0 's) at the 0.2 % level :

$$B_{K \text{ incl}} - (B_K + B_{K K^0} + B_{K \pi^0} + B_{K \pi^0 K^0} + B_{K \pi^0 \pi^0}) = (0.05 \pm 0.13)\% \quad (16)$$

7 Summary

Using dE/dx measurements in the ALEPH TPC, K- π separation at more than 2 standard deviations is possible over almost the full momentum range. The inclusive rate of one-prong τ decays with a charged kaon is measured. Using a classification of final states with π^0 reconstruction and a complementary calorimetric method of K_L^0 detection[4], several exclusive decay modes are identified and measured for the first time:

$$\begin{aligned} B(\tau \rightarrow \nu_\tau K^- \geq 0 \pi^0 \geq K^0) &= (1.60 \pm 0.07 \pm 0.12)\% \\ B(\tau \rightarrow \nu_\tau K^-) &= (0.64 \pm 0.05 \pm 0.05)\% \\ B(\tau \rightarrow \nu_\tau K^- \pi^0) &= (0.53 \pm 0.05 \pm 0.07)\% \\ B(\tau \rightarrow \nu_\tau K^- \pi^0 \pi^0) &= (0.04 \pm 0.03 \pm 0.02)\% \end{aligned} \quad (17)$$

These results agree with previous measurements when available [2, 3, 13, 14], but are significantly more precise.

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muon source	momentum range (GeV/c)	f_K (%)
$\tau \rightarrow \nu_\tau \mu \bar{\nu}_\mu$	2 – 5	0.10 ± 0.39
	5 – 10	-0.29 ± 0.21
	10 – 20	0.14 ± 0.17
	20 – 45	0.02 ± 0.22
$Z^0 \rightarrow \mu^+ \mu^-$	45.6	0.07 ± 0.08

Table 1: Fake K fractions f_K used to estimate global systematic uncertainties: in the case of muons from τ decays, the mis-identification of kaons as muons is taken into account in the fit and is not counted as a signal.

sample	'h inclusive'	'h'	'h π^0 '	'h 2 π^0 '
decays	28390	6764	11503	2788
$f_K(\%)$	3.17 ± 0.14	5.85 ± 0.41	2.09 ± 0.19	0.90 ± 0.30
χ^2/DF	1.3	1.0	1.1	0.9
N_K	900 ± 40	396 ± 28	240 ± 22	25 ± 8
channel	$\nu_\tau K \geq 0\pi^0 \geq 0K^0$	$\nu_\tau K$	$\nu_\tau K \pi^0$	$\nu_\tau K \pi^0 \pi^0$
correction ΔN_K	$+ 67 \pm 24$	$- 60 \pm 22$	$- 20 \pm 8$	$- 14 \pm 4$
efficiency (%)	63.8	55.6	44.0	30.3
$B_K(\%)$	$1.60 \pm 0.07 \pm 0.12$	$0.64 \pm 0.05 \pm 0.05$	$0.53 \pm 0.05 \pm 0.07$	$0.04 \pm 0.03 \pm 0.02$

Table 2: Results from the dE/dx fit and final branching fractions for inclusive and exclusive final states with statistical and systematic uncertainties, respectively.

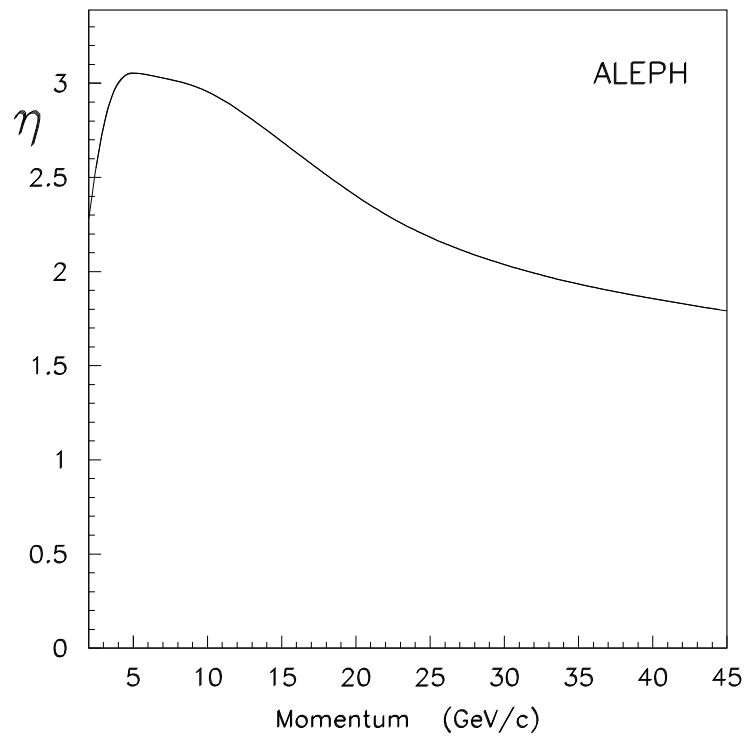


Figure 1: K- π separation parameter η as a function of momentum.

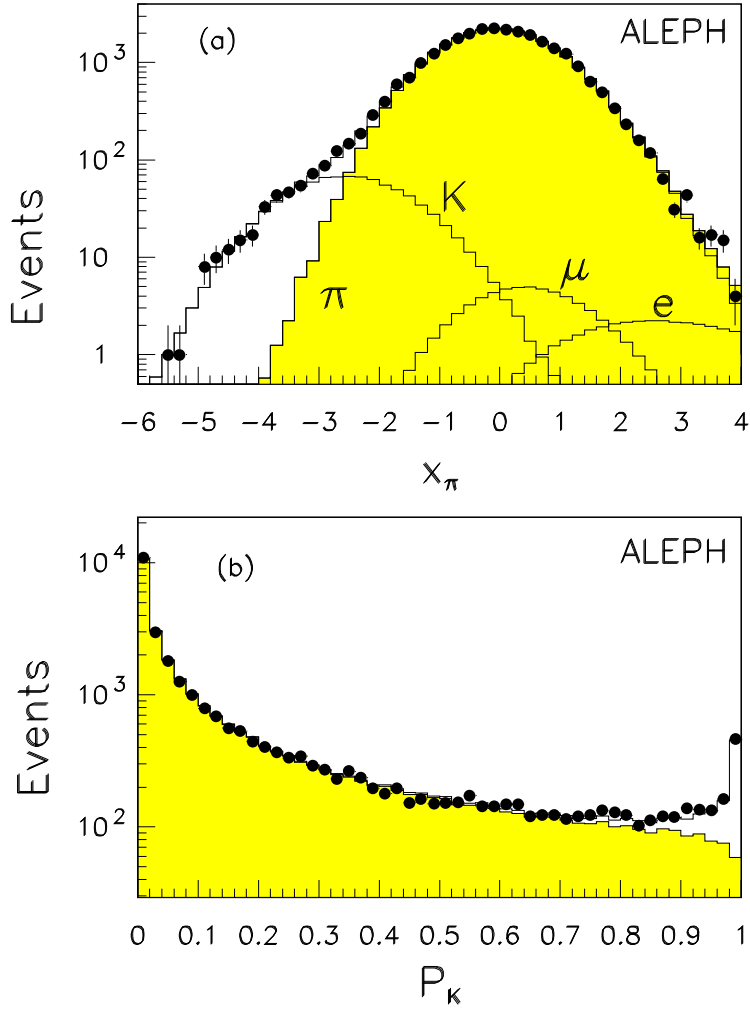


Figure 2: (a) Fit to the x_π distribution in 1-prong inclusive hadronic τ decays with the dominant π contribution, the μ and e contaminations and the fitted K component.(b) Distribution of the estimator P_K for the same sample. The shaded histograms correspond to the sum of all 'background' π , μ , e contributions, the K signal being added for the full histogram.

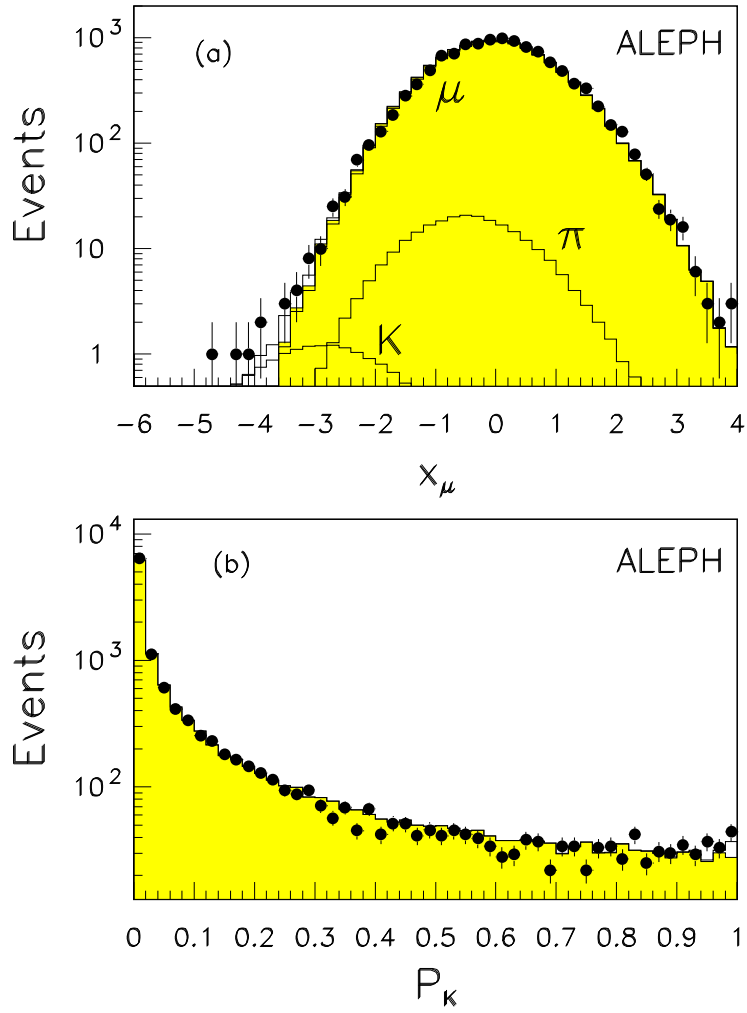


Figure 3: (a) Fit to the x_μ distribution in $\tau \rightarrow \nu_\tau \mu \bar{\nu}_\mu$ events with π and K contaminations from mis-identification. (b) Distribution of the estimator P_K for the same sample. The shaded histograms correspond to the sum of all 'background' π , μ contributions, the K signal being added for the full histogram.

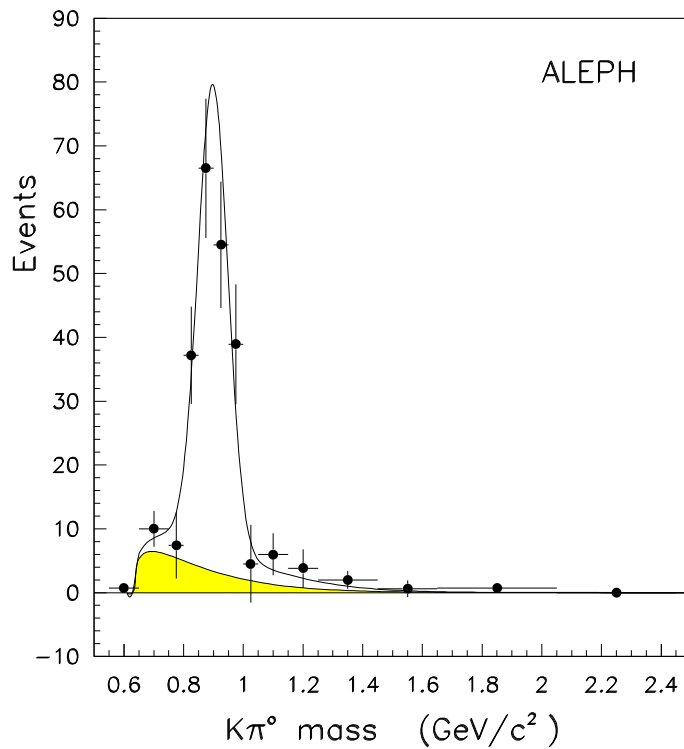


Figure 4: Invariant mass distribution of the $K\pi^0$ final state, as obtained from a dE/dx fit in each mass bin ; the Monte Carlo distributions (solid lines) are given for the $\tau \rightarrow \nu_\tau K\pi^0$ mode and other smaller modes which feed into the selected sample (shaded).