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# Study of Charged Kaon Production in Three-prong Tau Decays

Preliminary

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**Abstract**

The production of charged kaons in three-prong $\tau$ decays has been studied from data recorded with the DELPHI detector at LEP. The kaons have been identified over a large momentum range using the Barrel Ring Imaging Cherenkov detector. The high granularity electromagnetic calorimeter makes it possible to distinguish the decay modes that include neutral particles. The following branching ratios have been measured:

$$Br(\tau^- \to K^- K^+ \pi^- \nu_\tau) = (0.18 \pm 0.04)\%$$
$$Br(\tau^- \to K^- \pi^+ \pi^- \nu_\tau) = (0.49 \pm 0.08)\%$$
$$Br(\tau^- \to K^- K^+ \pi^- \geq 1\pi^\circ \nu_\tau) = (0.04 \pm 0.02)\%$$
$$Br(\tau^- \to K^- \pi^+ \pi^- \geq 1\pi^\circ \nu_\tau) = (0.14 \pm 0.04)\%$$

Using the large sample of tagged three prong events with kaons, the resonance structure of $(KK\pi)^-$ and $(K\pi\pi)^-$ decays has been investigated. They are dominated by $\tau \to K^* K \nu_\tau$ and $\tau \to K^* \pi \nu_\tau$, respectively.

During recent years there has been a growing interest in measuring the decays of $\tau$ leptons into strange mesons. In this note[1], the measurement of the branching ratios of the decays $\tau^- \to K^- K^+ \pi^- \nu_\tau (neutrals)$ and $\tau^- \to K^- \pi^+ \pi^- \nu_\tau (neutrals)$ is described using a data sample of $Z^0$ events recorded with the DELPHI detector at LEP in 1992, 1993 and 1994. The charged kaons were tagged by the gas Barrel RICH, which provides good kaon and pion separation on a track-by-track basis. The resonances in the decays have been studied.

# 1 Event selection

At LEP energy, a $\tau^+\tau^-$ event consists of two collimated low multiplicity jets in opposite direction. The two hemispheres are separated by the plane perpendicular to the event thrust axis. The thrust axis is calculated using all charged particles with momenta larger than 0.6 GeV/c and a distance of closest approach to the interaction region less than 0.2 cm in the plane perpendicular to the beam and less than 4.5 cm along the beam direction. This requirement rejects most of the charged tracks from interactions and photon conversions in the detector. The remaining tracks from photon conversion are eliminated by means of a dedicated track fitting program tuned to tag such tracks. The sample of 3-prong $\tau$ decays is selected by requiring 3 charged particles on one side and up to 3 charged particles on the other side. This requirement already results in a clean sample of 3-prong $\tau$ decays, since hadronic $Z^\circ$ decays, $Z^\circ \to \mu^+\mu^-$, $Z^\circ \to e^+e^-$, single-prong $\tau$ decays and cosmic rays have completely different topologies.

The event selection is adapted to the kinematical conditions for kaon identification in the RICH. As explained later, a kaon in the fiducial volume of the RICH with momentum between 6 GeV/c and 20 GeV/c can be identified unambiguously. Therefore only events with at least one particle on the 3-prong side meeting this condition, are accepted. The number of hadronic and two photon events is reduced by the minimal momentum requirement of 6 GeV/c. To reduce the background further, the following criteria are applied:

1. The particles in the opposite hemisphere have at least a total momentum of 1 GeV/c.
2. The isolation angle, which is defined as the smallest angle between two particles of opposite hemispheres, is required to be larger than 165°.
3. An event is rejected when neutral particles of more than 5 GeV/c are observed outside a cone of 20° around the thrust axis.
4. An event is rejected when an additional poorly reconstructed track is found in the 3-prong side
5. An event is rejected if two tracks in the 3-prong side have no associated hits in the Vertex Detector and the Inner Detector.

In a first step no effort is made to identify the neutrals in the 3-prong $\tau$ decays. The cuts mentioned above, together with the requirement of good RICH quality, produce a sample of 6171 3-prong $\tau$ decays. From a detailed simulation of the detector and by using JETSET [2] and the KORALZ [3] event generators, the background is found to be 1.3% from single-prong $\tau$ decays and less than 0.2% from hadronic $Z^\circ$ decays.

[1]This note is largely based on the thesis of Wei Hao [1].

# 2 Kaon Identification using the RICH

The Cherenkov angle is calculated for a given particle from the positions where photons hit the detection plane and from the location and direction of the particle track in the radiator. Therefore, good particle tracking is needed. In the barrel region, tracking through the RICH is done by interpolation between the track segment measured in the TPC, located before the RICH and the measurement in the Outer Detector just behind the RICH. About 16% of the tracks are rejected due to the absence of TPC or OD information in tracking. The uncertainty on the momentum is required to be less than 20%.

Two techniques are used for kaon identification with the gas radiator. Below $\sim$9 GeV/c, the kaons are below the threshold for producing Cherenkov photons, while the pions yield a nearly saturated Cherenkov angle and the maximum number of photons. In this momentum range kaons are identified by "Veto Identification", i.e. by requiring that no photo-electrons are associated with the particle. Above the kaon threshold the Cherenkov angle is determined from the detected Cherenkov photons. The kaon is identified by requiring that the measured Cherenkov angle is compatible with the kaon hypothesis but is incompatible with the ($\pi$,$\mu$) hypothesis. This is called "Ring Identification" and allows kaon identification up to 20 GeV/c.

To gain in efficiency both veto and ring identification are applied for particles with a momentum between 8.5 and 10.5 GeV/c.

At $Z^0$ energy, tracks from 3-prong $\tau$ decays are close together. The images of the Cherenkov rings may overlap, so that some of the photons may be attributed to more than one track. To get a good $K/\pi$ separation the photons are selected carefully. Simultaneous fits to all tracks are made to find the ambiguous photons. The effects of the background are taken into account in the angular resolution and noisy tracks are rejected. In the ring identification the following steps are made:

- Fit the ring independently for each track, and resolve part of the ambiguous photons.
- Fit the rings simultaneously for two tracks if there are ambiguous photons.
- The error of the measured Cherenkov angle for each track is corrected.

In this way the resolution function has a Gaussian distribution with a standard deviation of one, as shown in figure 1 (the kaons are on the negative side of the distribution).

Figure 2 shows the measured Cherenkov angle of a track as a function of the particle momentum for multi-prong $\tau$ decays. A $K$ population around the expected line is clearly seen.

A particle is identified as a kaon if the measured Cherenkov angle $\theta_c$ is within $\pm 2.5\sigma_c$ around $\theta_K$ (expected angle in the kaon hypothesis) and is incompatible with $\theta_\pi$ (expected angle in the pion hypothesis), i.e. more than $3\sigma_c$ below $\theta_\pi$. Similarly, a particle is identified as a pion if $\theta_c$ is compatible with $\theta_\pi$ and incompatible with $\theta_K$. The misidentification rate is derived from particles with a momentum between 6.0 and 8.5 GeV/c, where pions produce almost the maximal amount of photons and the kaons produce no photons, by integrating the tail on the negative side of the resolution function of these tracks (incompatible with $\pi$ hypothesis) The misidentification probability is found to be $0.14 \pm 0.06\%$.

For the veto identification the observed number of photo-electrons has to be well understood. The number of observed photons is defined as the number of photons within a $\pm 2.5\sigma_\gamma$ window around $\theta_\pi$. ($\sigma_\gamma$ is the error on the Cherenkov angle for individual photons.) The expected number of photo-electrons is calculated for each track. It depends on the momentum of the track and its polar angle, since the length of radiator passed by a particle increases at low polar angles. Also the details of the RICH geometry (e.g. focusing mirrors) have to be taken into account.

In the veto identification some further cuts are applied to reduce the misidentification rate. The tracks with polar angle between 70° and 110° are rejected because of relatively low photon production and high background. At least two ionization hits must be detected along the track in the drift tube of the RICH to be sure the detector is fully active on a track-by-track basis. Kinematically the minimum momentum of a kaon in a 3-prong decay is 4.0 GeV/c, but near threshold the K production is small while the $\pi$ production reaches a maximum. Therefore, the veto identification is only applied for particles with a momentum between 6.0 and 10.5 GeV/c.

On average, the photon production per track is 5.5 in 3-prong $\tau$ decays, much smaller than in dimuon events and single-prong $\tau$ decays (7.9 photons per track). To have good $K/\pi$ separation in the veto region, only those particles are selected, which have in the $\pi$ hypothesis an expected photon production higher than 6.2. This makes the probability for observing no photons from a $\pi$ less than 0.2%.

After all cuts only 22% of the particles in the veto region survive. Figure 3 shows the distributions of observed and expected number of photo-electrons. The kaon production is seen at bin zero. A particle is taken as a kaon if the pion probability is less than 0.2%. The misidentification rate is compatible with Poisson statistics for the expected number of photo-electrons.

# 3 Branching Ratios in 3-prong $\tau$ decays to Kaons

After the tracking quality requirements and the RICH quality cuts, the kaon identification efficiency is low, and it is difficult to identify all three particles in a 3-prong $\tau$ decays. Instead, the branching ratios are determined in two steps. First, events are tagged with at least one charged kaon in the final state. Then these event are classified as $K^-K^+\pi^-$ or $K^-\pi^+\pi^-$ using loose particle identification.

The branching ratios of $\tau^- \to K^-K^+\pi^-\nu_\tau(neutrals)$ and $\tau^- \to K^-\pi^+\pi^-\nu_\tau(neutrals)$ were derived from the number of tagged events of these two decays compared with the total number of 3-prong $\tau$ decay events, for which the world average branching ratio was used [4]:

$$Br(\tau^- \to h^-h^+h^-\nu_\tau(neutrals)) = (14.49 \pm 0.23)\%.$$

With this method most of the systematic errors cancel.

The efficiency for tagging $K\pi\pi$ events is equal to the efficiency for kaon identification, and the efficiency of tagging $KK\pi$ events is equal to the sum of the two kaon identification efficiencies minus the product of the two efficiencies. In 3-prong $\tau$ decays, two of the particles have equal charge. Their trajectories are bent in the same direction in the magnetic field. These two tracks are more likely close and parallel to each other. Therefore, their tracking qualities are slightly worse than that of the third one, and their images of Cherenkov rings have more chance to overlap since the position of the ring is only sensitive to the direction of the track. The efficiency to identify these like-charged particles is about 30% lower than that for the oppositely charged particles.

Considering the momentum dependent efficiency of the particle identification, the momentum spectra of $K$ and $\pi$ in 3 prong $\tau$ decays are simulated with the KORALZ program. Assuming equal efficiencies for $\pi$ and $K$ identification, an average efficiency is calculated by folding the efficiency and the $K$ momentum distributions. The efficiencies of identifying the $h^-$ and $h^+$ of $\tau^-$ decay are found to be 19.4% and 24.2% respectively for 1994 data. Therefore the average efficiency to tag $\tau \to KK\pi\nu_\tau(neutrals)$ is $38.9 \pm 1.0\%$ and the efficiency to tag $\tau \to K\pi\pi\nu_\tau(neutrals)$ is $19.4 \pm 0.5\%$. The uncertainty in the efficiency (2.5%) is dominated by the uncertainty of the $K$ spectrum from different $\tau$ decay models.

The result on kaon production is listed in table 1. In total, 92 candidates of $\tau$ decays to kaon(s) are tagged. The number of background events, caused by pions misidentified as kaons, is calculated from the number of misidentified tracks. In our sample 105 identified kaons correspond to 92 events, therefore $7.1 \pm 2.9$ misidentified kaons are equivalent to $6.2 \pm 2.5$ background events.

| | 3-prong events | identified tracks | | tagged as Kaon | | Events with kaons | Background of misidentified kaon |
|---|---|---|---|---|---|---|---|
| | | in veto | in ring | in veto | in ring | | |
| 92 | 1112 | — | 631 | – | 14 | 12 | $1.0 \pm 0.4$ |
| 93 | 931 | 117 | 613 | 4 | 14 | 15 | $1.2 \pm 0.5$ |
| 94 | 4128 | 798 | 2932 | 14 | 59 | 65 | $4.9 \pm 2.0$ |
| total | 6171 | 915 | 4176 | 18 | 87 | 92 | $7.1 \pm 2.9$ |

Table 1: Number of identified kaons and events in 3-prong $\tau$ decay.

## 3.1 Inclusive Branching ratios

It is important to identify the pion(s) or the second kaon for the separation of the decays $\tau \to KK\pi\nu_\tau(neutrals)$ and $\tau \to K\pi\pi\nu_\tau(neutrals)$. Within the sample of identified 3-prong events where one particle has already been identified as a kaon, the kaon to pion ratio is not small. Thus, the misidentification rate needs not to be as low as in the first step of the analysis, where rare kaons had to be identified in the full sample of 3-prong events. In this second step of the analysis a few methods are combined:

1. Identification of a second kaon (without the stringent tracking and RICH quality cuts).
2. Pion identification. A particle is identified as a pion if:
   - 2a. the momentum of the particle is lower than 3.5 GeV/c.
   - 2b. In the veto region, at least two good photons were observed in the window of the pion hypothesis.
   - 2c. Unambiguously identified pions are present in the ring identification region.
3. Charge combination. Since the two kaons in $KK\pi$ and the two pions in $K\pi\pi$ must have opposite charge, the event is identified as a $KK\pi$ ($K\pi\pi$) if the particle having opposite charge to the $\tau$ is identified as a kaon (pion).

| Events | comments | event type |
|---|---|---|
| 29 | the second kaon has been identified | $KK\pi$ |
| 38 | two opposite charged pions have been identified | $K\pi\pi$ |
| 11 | identified kaon has the opposite charge of the $\tau$ | $KK\pi$ |
| 13 | identified pion has the opposite charge of the $\tau$ | $K\pi\pi$ |
| 1 | 2 identified pions with the same charge | Background |

Table 2: Event classification

| final states | $KK\pi$ | $K\pi\pi$ | 3-prong |
|---|---|---|---|
| Candidates | 23 | 41 | 4182 |
| Misidentification | $4.4 \pm 2.0$ | | |
| Single-prong | $0.2 \pm 0.1$ | | 54 |
| Hadronic $Z^\circ$ decays | $0.4 \pm 0.2$ | | neglected |
| Identified background | 1.0 | | |
| Total background | $4.0 \pm 2.0$ | | 54 |
| signal | 21.6 | 38.4 | 4128 |
| efficiency (%) | 38.9 | 19.4 | |
| Branching ratio/Br(3-prong) (%) | $1.34 \pm 0.28$ | $4.79 \pm 0.74$ | |
| Branching ratio (%) | $0.19 \pm 0.04$ | $0.69 \pm 0.11$ | |

Table 3: Determining the branching ratios and the statistical errors for 1994 data

With these methods, 40 $KK\pi$ candidates and 51 $K\pi\pi$ candidates were identified. One event was identified as background because of a wrong charge combination. The details of these events are listed in Table 2.

Since the uncertainty from other background sources is small compared to the statistical error, it is estimated from Monte Carlo. The background from single-prong $\tau$ decays is calculated from the single-prong $K$ fraction of 2% [5]. With 1.3% single-prong $\tau$ decays in the sample, we expect $0.2 \pm 0.1$ background events in the 1994 data sample. The background in hadronic $Z^\circ$ decays is calculated from the $K$ fraction of 25% [6]. With 0.2% hadronic $Z^\circ$ decays in the sample, we expect $0.4 \pm 0.2$ background events in the 1994 data sample. The 4.9 misidentified kaons correspond to 4.4 background events. In total, 5.0 background events are expected in the 1994 sample of 3-prong $\tau$ decays to kaon(s). Of those one is tagged due to wrong charge combination. The remaining ones are split statistically over the samples of $\tau \to KK\pi\nu_\tau(neutrals)$ and $\tau \to K\pi\pi\nu_\tau(neutrals)$. The uncertainty is taken into account in the systematical error.

From 1992 to 1994, the quality of the RICH data has improved. The consequence is that the efficiencies are slightly changing. The branching ratios are calculated separately for the three years, and the final branching ratios are the weighted averages. Table 3 lists the steps in determining the branching ratios for 1994, and table 4 gives the results for each year with the statistical errors.

Several sources of systematic uncertainties were investigated (Table 5). The largest contribution arises from the estimation of kaon misidentification. In identifying the decay

| | $\tau^- \to K^- K^+ \pi^- \nu_\tau (neutrals)$ | $\tau \to K^- \pi^+ \pi^- \nu_\tau (neutrals)$ |
|---|---|---|
| 1992 | $0.42 \pm 0.15$ | $0.45 \pm 0.23$ |
| 1993 | $0.39 \pm 0.13$ | $0.56 \pm 0.23$ |
| 1994 | $0.19 \pm 0.04$ | $0.69 \pm 0.11$ |
| average | $0.22 \pm 0.04$ | $0.63 \pm 0.09$ |

Table 4: Inclusive branching ratios (%) of $\tau$ decay to charged kaon(s)

| | |
|---|---|
| Background | 3.1 |
| Correlation between the decays | 2.0 |
| $\tau$ selection | 2.0 |
| $K$ identification efficiency | 2.5 |
| $Br(\tau^- \to h^- h^+ h^- \nu_\tau (neutrals))$ | 1.6 |
| Total | 5.1 |

Table 5: Determination of the systematic error (%).

mode loose cuts with a misidentification rate of 2% are used, which leads to a correlation between the two measured branching ratios. In the $\tau$ selection, the rejection of background events is controlled at the level of 2%. The total systematic uncertainty of 5.1% is much smaller than the statistical error.

The resulting branching ratios for the inclusive decays are

$$Br(\tau^- \to K^- K^+ \pi^- \nu_\tau (neutrals)) = (0.22 \pm 0.04 \pm 0.01)\%$$

and

$$Br(\tau^- \to K^- \pi^+ \pi^- \nu_\tau (neutrals)) = (0.63 \pm 0.09 \pm 0.03)\%$$

## 3.2 Exclusive Branching ratios

We checked our $K\pi\pi$ and $KK\pi$ samples for the presence of neutral particles by looking for $\pi^\circ$ candidates in the electromagnetic calorimeter (HPC) within a 20° cone around the event thrust axis. The $\pi^\circ$ decays into two photons. If the energy of the $\pi^\circ$ is sufficiently low (typically below 5 GeV) the two photons produce two separate showers in the calorimeter. For a decay of an energetic $\pi^\circ$ the two photons are too close to each other to be separated. Therefore the following three $\pi^\circ$ signatures are defined:

1. Presence of an electromagnetic shower with an energy above 1.5 GeV and not associated with any charged tracks
2. The invariant mass of two photons is between 0.05 GeV/c$^2$ and 0.225 GeV/c$^2$.
3. The sum of the electromagnetic shower energy in the HPC is above 20 GeV.

Using the MC data of $\tau^- \to a_1^- \nu_\tau \to 3\pi^\pm \nu_\tau$ and $\tau \to \rho' \nu_\tau \to 3\pi^\pm \pi^\circ \nu_\tau$, the efficiency is found to be 76.1% and the misidentification probability is 13.0%.

With this selection we observe a $\pi^\circ$ signal in 10 of the 40 $\tau \to KK\pi\nu_\tau(neutrals)$ candidates and in 14 of the 51 $\tau \to K\pi\pi\nu_\tau(neutrals)$ candidates. This results in the following branching fractions:

$$Br(\tau^- \to K^-K^+\pi^-\nu_\tau) = (0.18 \pm 0.04)\%$$
$$Br(\tau^- \to K^-\pi^+\pi^-\nu_\tau) = (0.49 \pm 0.08)\%$$
$$Br(\tau^- \to K^-K^+\pi^- \geq 1\pi^\circ\nu_\tau) = (0.04 \pm 0.02)\%$$
$$Br(\tau^- \to K^-\pi^+\pi^- \geq 1\pi^\circ\nu_\tau) = (0.14 \pm 0.04)\%$$

Only the statistical errors are given here, the systematic errors are neglected.

# 4 Resonances in the decays

The hadronic decays of the $\tau$ lepton appear to be dominated by coupling of the $W$ boson to $ud$ or $us$ resonant states. The experimental results of $\tau$ decays to $\pi$ and $K$ are in excellent agreement with the theoretical prediction. The $(\pi\pi)^-$ and $(K\pi)^-$ decays are dominated by the $\rho^-$ and $K^{*-}$ vector channels, while the $(\pi\pi\pi)^-$ decay occurs predominantly through $(\rho\pi)^-$ in $s$ wave, consistent with $a_1^-$ axial-vector dominance. However, the resonance structure of $(KK\pi)^-$ and $(K\pi\pi)^-$ decays is still an open question, because of their small branching ratios and the difficulties in identifying and reconstructing the strange mesons. In this section we study the resonant structures using our sample of tagged $(KK\pi)$ and $(K\pi\pi)$ final states.

In the standard picture, the $\tau$ decay to $KK\pi$ occurs through the $\rho'(1700)$ resonance. The dominant decay of the $\rho'(1700)$ leads to four pions, while a small fraction decays into $K^*K$, with the $K^*$ decaying into $K\pi$:

$$\tau \longrightarrow \rho'(1700)\nu_\tau$$
$$\hookrightarrow K^*(892)K$$
$$\hookrightarrow K\pi$$

For the 40 candidates of $\tau \to KK\pi\nu_\tau(\pi^\circ)$, the invariant mass of the opposite charge kaon-pion pairs was reconstructed. Figure 4 shows the distribution of the invariant mass. A clear peak of the $K^*$ resonance is seen, and few events are not within $\pm$ 100 MeV/c$^2$ around the $K^*$ mass, compatible with the expected background. Therefore, the conclusion is that the decay $\tau \to KK\pi(\pi^\circ)\nu_\tau$ is dominated by the $\tau \to K^*K(\pi^\circ)\nu_\tau$ decay.

In the $(K\pi\pi)$ case there are two relevant particles with have the correct quantum numbers, the $K_1(1270)$ and $K_1(1400)$. They are mixtures of the $\bar{s}d$ states in $^3P_1$ and $^1P_1$ quark nonets. The dominant decay chains are:

$$\tau \longrightarrow K_1(1270)\nu_\tau \qquad \tau \longrightarrow K_1(1400)\nu_\tau$$
$$\hookrightarrow \rho(770)K \qquad \hookrightarrow K^*(892)\pi$$
$$\hookrightarrow \pi\pi \qquad \hookrightarrow K\pi$$

The two channels can be distinguished by identifying the $\rho$ or the $K^*$. To suppress the decay $\tau^- \to K^-\pi^+\pi^-(\geq 1\pi^\circ)\nu_\tau$, that may come from other decay processes, events with an identified $\pi^\circ$ are rejected. Figures 5 (a) and (b) show the distribution of invariant masses of oppositely charged kaon-pion and pion-pion pairs from the decay $\tau \to K\pi\pi\nu_\tau$. A peak at the $K^*$ mass is clearly seen, while no obvious signal is visible at the $\rho$ mass.

The number of events outside the $K^*$ resonance is compatible with the expected background. Therefore the conclusion is that the decay $\tau \to K\pi\pi\nu_\tau$ is dominated by the decay $\tau \to K^*\pi\nu_\tau$. However, the $K\pi\pi$ invariant mass distribution (figure 5 (c)) shows a mean at 1.3 GeV, which is nearly 4 standard deviation below the mass of $K_1(1400)$ and compatible with the mass of $K_1(1270)$. Further study is needed.

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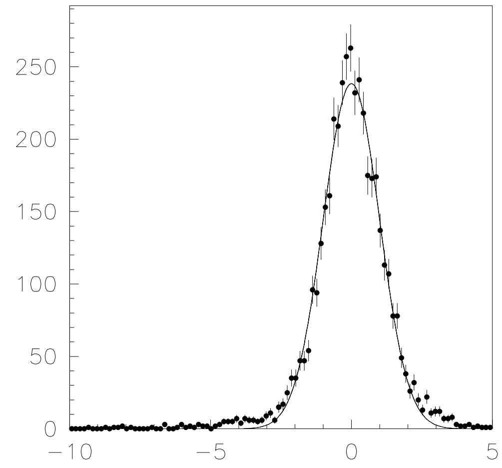


Figure 1: The distribution of the resolution function of the hadrons from 3-prong $\tau$ decay.

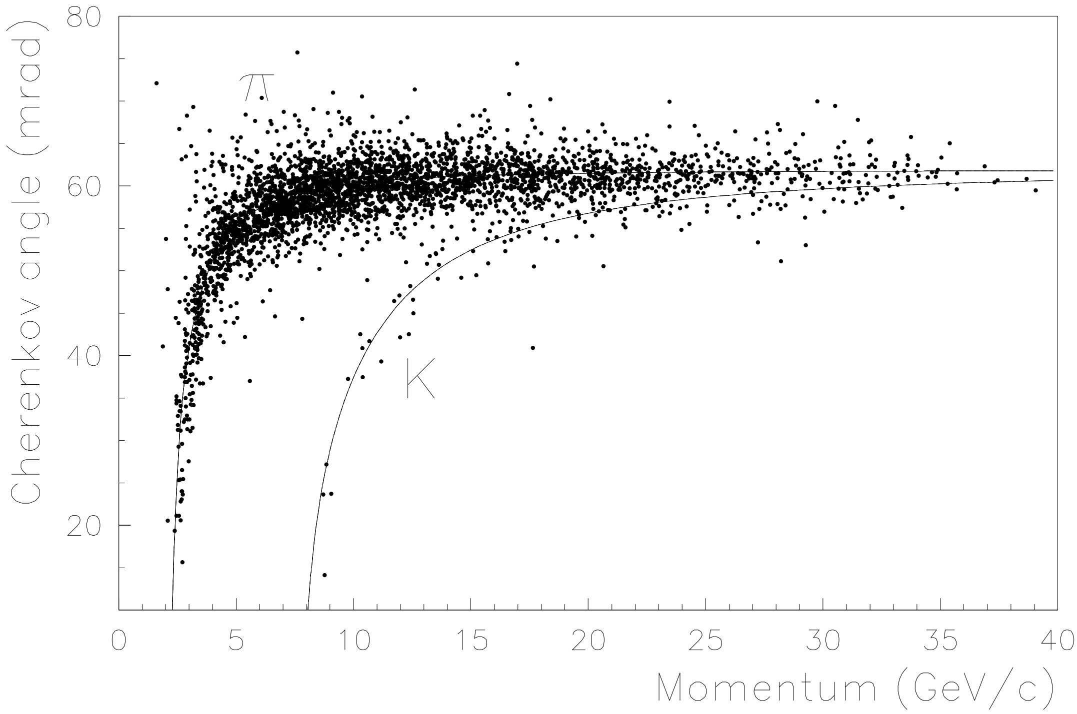


Figure 2: Cherenkov angle as a function of momentum for 3-prong $\tau$ decays (Only the tracks with $\sigma_c$ smaller than 3 mrad are shown).

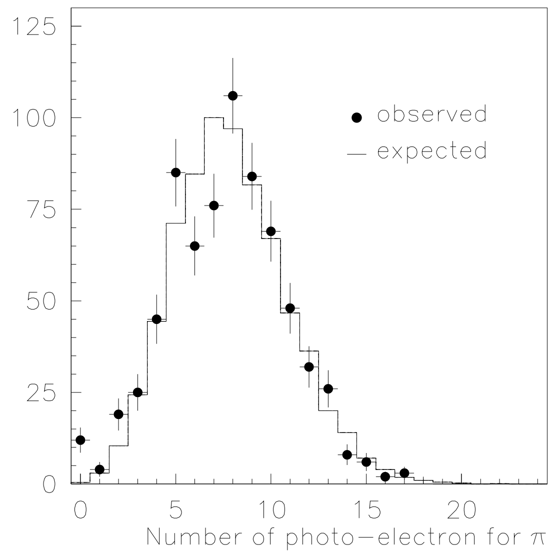


Figure 3: photo-electron production

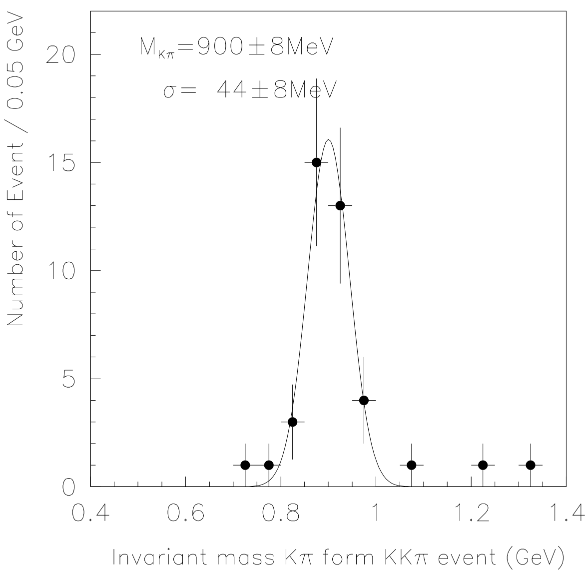


Figure 4: $K^{*}$ signal in $\tau \to K^{-}K^{+}\pi^{-}(\pi^{\circ})\nu_{\tau}$.

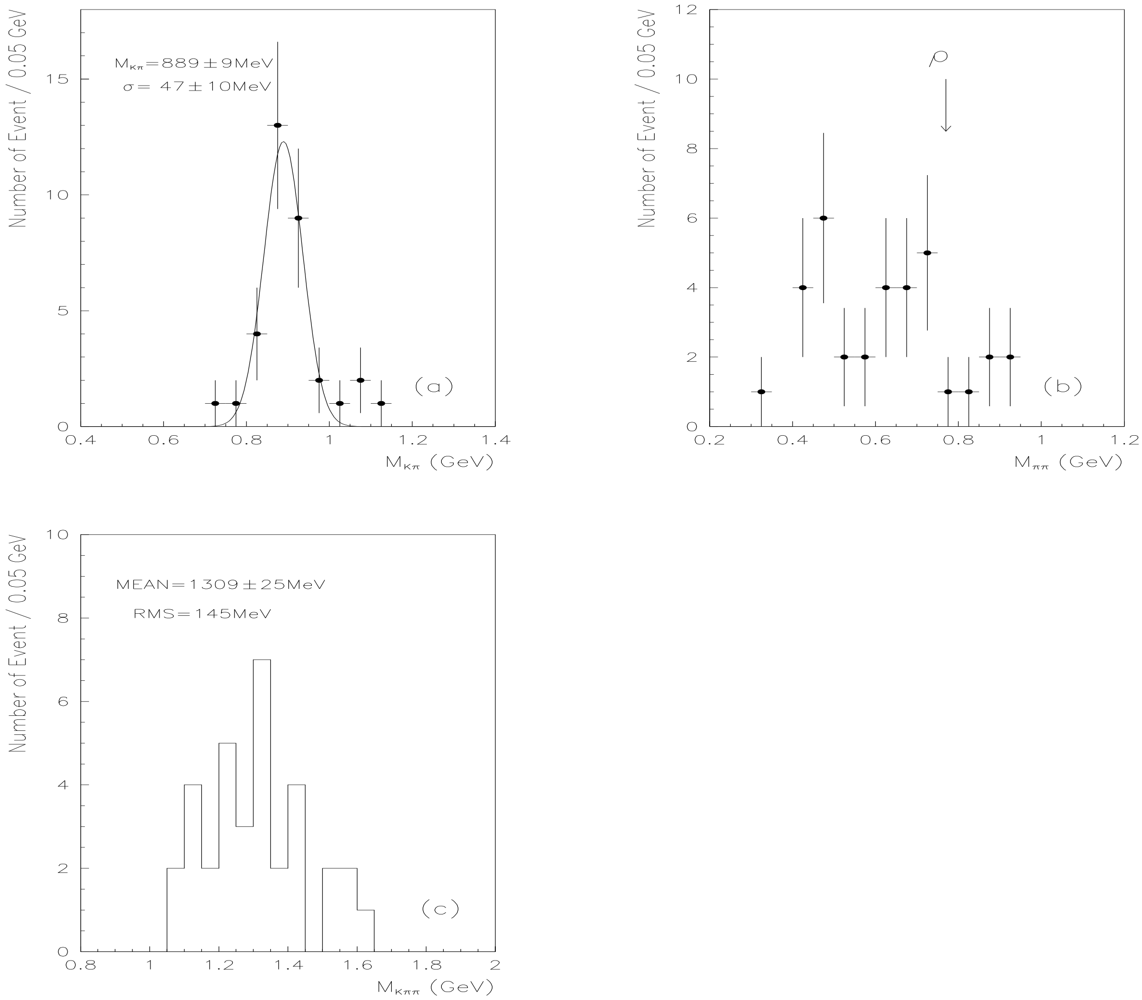


Figure 5: Invariant mass (GeV) of (a) $K\pi$ from $K\pi\pi$ (b) $\pi\pi$ from $K\pi\pi$ (c) $K\pi\pi$