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# Measurement of Tau Branching Ratios to Five Charged Hadrons

The OPAL Collaboration

## Abstract

The branching ratios of the decay of the  $\tau$  lepton to five charged hadrons have been measured with the OPAL detector at LEP using data collected between 1991 and 1995 at  $e^+e^-$  centre-of-mass energies close to the  $Z^0$  resonance. The branching ratios are measured to be

$$B(\tau^- \rightarrow 3h^-2h^+\nu_\tau) = (0.091 \pm 0.014 \pm 0.005)\%$$

$$B(\tau^- \rightarrow 3h^-2h^+\pi^0\nu_\tau) = (0.027 \pm 0.018 \pm 0.007)\%$$

where the first error is statistical and the second systematic.

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# The OPAL Collaboration

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## Introduction

Knowledge of the tau lepton properties is becoming increasingly more precise with the large data sets available. Measurements of the decay modes to a single charged particle (1-prong) and three charged particles (3-prong) have been made by numerous experiments with precision surpassing the 1% level [1]. However, only a few measurements of the  $\tau^- \rightarrow 3h^-2h^+\nu_\tau$  and  $\tau^- \rightarrow 3h^-2h^+\pi^0\nu_\tau$ <sup>1</sup> branching ratios (5-prong) have been made [2, 3, 4, 5]. Studies of the 5-prong decay modes are important as they are used in the determination of the mass limit on the tau neutrino (for example, see ref. [6]). Further the branching ratios of tau decays to five and six pions can be compared with the predictions of an isospin model [7, 8].

This paper presents a new measurement of these modes using the data collected between 1991 and 1995 at energies close to the  $Z^0$  resonance, corresponding to an integrated luminosity of  $163 \text{ pb}^{-1}$ , with the OPAL detector at LEP. A description of the OPAL detector can be found in ref. [9]. The performance and particle identification capabilities of the OPAL jet chamber are described in ref. [10]. The tau pair Monte Carlo samples used in this analysis were generated using the KORALZ 4.0 package [11]. The dynamics of the tau decays were simulated with the TAUOLA 2.0 decay library [12]. A total of 830 000 tau pair Monte Carlo events were used in this analysis. In addition, samples of 5000  $\tau^- \rightarrow 3h^-2h^+\nu_\tau$  and 2000  $\tau^- \rightarrow 3h^-2h^+\pi^0\nu_\tau$  Monte Carlo events were also used. Both the  $\tau^- \rightarrow 3h^-2h^+\nu_\tau$  and  $\tau^- \rightarrow 3h^-2h^+\pi^0\nu_\tau$  decays were generated with a uniform phase space distribution. The  $\tau^- \rightarrow 3h^-2h^+2\pi^0\nu_\tau$  decay was not simulated. The Monte Carlo events were then passed through the OPAL detector simulation [13].

## Event selection

The procedure used to select  $Z^0 \rightarrow \tau^+\tau^-$  events is similar to that described in previous OPAL publications (for example, see [14]). The  $\tau^+\tau^-$  events are characterized by a pair of back-to-back, narrow jets with low particle multiplicity. The two tau jets are restricted to the barrel region of the OPAL detector by requiring that the polar angle of the two jets satisfy  $|\cos\theta| < 0.68$  in order to avoid regions of non-uniform calorimeter response. Background from other two fermion events is reduced by a number of requirements. Multihadronic events ( $e^+e^- \rightarrow q\bar{q}$ ) are significantly reduced by requiring fewer than eight tracks and ten electromagnetic clusters per event. Bhabha ( $e^+e^- \rightarrow e^+e^-$ ) and muon pair ( $e^+e^- \rightarrow \mu^+\mu^-$ ) events are removed by rejecting events where the total electromagnetic energy or the scalar sum of the track momenta are close to the centre-of-mass. Two photon ( $e^+e^- \rightarrow (e^+e^-) e^+e^-$  or  $e^+e^- \rightarrow (e^+e^-) \mu^+\mu^-$ ) events are removed by rejecting events in which there is little energy in the electromagnetic calorimeter.

In the OPAL tau pair selection events are usually required to have between two and six tracks; however, events with up to eight tracks are allowed in the present selection in order to increase the efficiency for  $\tau^- \rightarrow 3h^-2h^+(\pi^0)\nu_\tau$  decays. In addition, tracks are normally required to have at least one hit in the central drift chamber at a radius of less than 75 cm from the beam axis. However, for this analysis this requirement is not imposed in order to avoid rejecting tracks that overlap at small radii. The efficiency for selecting tau pair events is approximately 54% from the Monte Carlo simulation, primarily due to the requirement that the tau jets are in the barrel region of the OPAL detector.

A total of 98347  $\tau^+\tau^-$  candidates were selected from the 1991-1995 data set. The number of  $e^+e^- \rightarrow$

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<sup>1</sup>Charge conjugation is implied throughout this paper. The symbol  $h^-$  is used to indicate either  $\pi^-$  or  $K^-$ .

$e^+e^-$ ,  $e^+e^- \rightarrow \mu^+\mu^-$  and  $e^+e^- \rightarrow (e^+e^-)X$  (where  $X$  is either  $e^+e^-$  or  $\mu^+\mu^-$ ) events in the tau pair sample is unaffected by the modifications in the standard tau pair selection and the background fraction is estimated to be  $(1.24 \pm 0.09)\%$  (see ref. [14]). The  $e^+e^- \rightarrow q\bar{q}$  background, however, is sensitive to the requirement on the number of tracks and was determined to be  $(0.74 \pm 0.05)\%$  in the selected sample. The  $q\bar{q}$  background in the tau pair sample was determined by comparing the data with the expectation of the Monte Carlo simulation [15]. The  $q\bar{q}$  Monte Carlo generator is found to give more low multiplicity  $q\bar{q}$  events than are observed in the data and a correction is made to the  $q\bar{q}$  Monte Carlo. The total fraction of background is estimated to be  $(2.0 \pm 0.1)\%$ .

The  $\tau^- \rightarrow 3h^-2h^+(\pi^0)\nu_\tau$  selection begins by identifying jets with five well-measured tracks where the absolute value of the sum of the charges of the tracks must be equal to unity. Approximately 72% of the  $\tau^- \rightarrow 3h^-2h^+(\pi^0)\nu_\tau$  jets in the tau pair sample are selected with these requirements. A large fraction of this sample are  $\tau^- \rightarrow 3\pi^-(\geq 1\pi^0)\nu_\tau$  decays where one of the photons in the final state undergoes a conversion to an  $e^+e^-$  pair. A neural network algorithm [16] found 70% of the 5-track jets contained a photon conversion and these jets are removed from the sample. The rejection of jets with photon conversions decreases the efficiency for selecting  $\tau^- \rightarrow 3h^-2h^+(\pi^0)\nu_\tau$  jets from 72% to 64%.

The sample of 5-track jets also includes  $\tau^- \rightarrow X^-K_S^0\nu_\tau$  decays where the  $K_S^0$  decays to  $\pi^+\pi^-$  and  $X^-$  is any number of hadrons. The sample also includes jets where a hadron has interacted in a part of the detector creating secondary particles. After the 5-track jets with photon conversions have been removed, approximately 20% of the remaining 5-track jets are found to have a pair of oppositely charged tracks with a secondary vertex in the  $r - \phi$  plane. Details of the secondary vertex algorithm can be found in [17]. The 5-track jets with an identified secondary vertex are rejected and the  $\tau^- \rightarrow 3h^-2h^+(\pi^0)\nu_\tau$  selection efficiency decreases from 64% to 62%.

The residual background is reduced by requiring that each track in the jet has a momentum ( $p$ ) greater than 0.5 GeV (see Fig. 1(a)) and that the invariant mass of the five tracks is less than 3 GeV assuming that the tracks are pions (see Fig. 1(b)). The jet is rejected if the lowest momentum track has  $p < 2$  GeV and  $dE/dx > 9$  keV/cm (see Fig. 1(c)), where  $dE/dx$  is the ionization energy deposited by the track in the OPAL jet chamber. The  $dE/dx$  on a track is only considered to be reliable if there are at least 20 wires out of a possible 159 wires with good  $dE/dx$  measurements. Background from  $e^+e^- \rightarrow q\bar{q}$  events is reduced by limiting the number of clusters in the electromagnetic calorimeter to a maximum of eight clusters in the event (see Fig. 1(d)). These selection criteria reduce the background to approximately 20% of the sample while only slightly decreasing the  $\tau^- \rightarrow 3h^-2h^+(\pi^0)\nu_\tau$  selection efficiency from 62% to 56%.

A total of 152 five-track jets pass the selection. The sample includes a background estimated to be approximately 22 jets from other tau decays (primarily 3-prong decays) and 10 jets from  $q\bar{q}$  events.

## Results

The number of  $\tau^- \rightarrow 3h^-2h^+\nu_\tau$  and  $\tau^- \rightarrow 3h^-2h^+\pi^0\nu_\tau$  decays is determined by performing a binned likelihood fit of the  $E/p$  spectrum, where  $E$  is the sum of all the electromagnetic energy in the jet and  $p$  is the scalar sum of the momentum of the five tracks. The shapes of the  $E/p$  distributions are obtained from high statistics  $\tau^- \rightarrow 3h^-2h^+\nu_\tau$  and  $\tau^- \rightarrow 3h^-2h^+\pi^0\nu_\tau$  Monte Carlo samples. The  $E/p$  distributions for the background are obtained from the tau and  $q\bar{q}$  Monte Carlo samples. The normalization of the

	$\tau^- \rightarrow 3h^-2h^+\nu_\tau$	$\tau^- \rightarrow 3h^-2h^+\pi^0\nu_\tau$
Events	$96.5 \pm 14.4$	$22.6 \pm 14.8$
Tau candidates	196694	196694
Efficiency	$0.584 \pm 0.007$	$0.463 \pm 0.011$
Non-tau background	$0.020 \pm 0.002$	$0.020 \pm 0.002$
Bias factor	$0.941 \pm 0.009$	$0.931 \pm 0.014$
Branching Ratio	$(0.091 \pm 0.014 \pm 0.005)\%$	$(0.027 \pm 0.018 \pm 0.007)\%$

Table 1: The results used to calculate the branching ratios.

$\tau^- \rightarrow 3h^-2h^+\nu_\tau$ ,  $\tau^- \rightarrow 3h^-2h^+\pi^0\nu_\tau$ , tau background and  $q\bar{q}$  background  $E/p$  distributions were allowed to vary in the fit. The uncertainties in the tau and  $q\bar{q}$  backgrounds (discussed below) were included into the likelihood fit. The result of the fit is shown in Fig. 3.

The branching ratios were evaluated using

$$B = \frac{N}{N_\tau(1-f)} \frac{1}{\epsilon} \frac{1}{F_B}$$

where  $N$  is the number of signal events determined from the likelihood fit,  $N_\tau$  is the number of tau candidates,  $f$  is the non-tau background in the tau pair sample, and  $\epsilon$  is the efficiency.

The tau pair selection does not select all tau decay modes with equal probability. The factor  $F_B$ , obtained from Monte Carlo, corrects for the bias introduced by the tau pair selection. In general, these factors are close to unity for most tau decay channels, however, they are slightly less than unity for the  $\tau^- \rightarrow 3h^-2h^+\nu_\tau$  and  $\tau^- \rightarrow 3h^-2h^+\pi^0\nu_\tau$  decay channels (see Table 1) due to the requirement that the tau pair events have less than or equal to eight tracks. Minor variations in the tau pair selection criteria were found to have little impact on the value of  $F_B$ .

The results of this likelihood fit are given in Table 1. The uncertainty of the background (discussed below) was included in the likelihood fit. The normalization factors of the tau and  $q\bar{q}$  backgrounds obtained in the fit were  $0.996 \pm 0.217$  and  $1.004 \pm 0.337$ , respectively. The correlation coefficient between the  $\tau^- \rightarrow 3h^-2h^+\nu_\tau$  and  $\tau^- \rightarrow 3h^-2h^+\pi^0\nu_\tau$  branching ratios is found to be  $-0.60$ . The systematic errors on the branching ratios include uncertainties on the tracking, energy resolution and fit method (see Table 2).

The uncertainty in the tau and  $q\bar{q}$  background includes a statistical component based on the number of data and Monte Carlo events in the background sample and a systematic component based on the modelling of the tau and  $q\bar{q}$  background. The statistical uncertainty is estimated to be 20% and 30% for the tau and  $q\bar{q}$  backgrounds, respectively. The systematic uncertainty is determined using a sample of events in which one of the two jets has four tracks. The composition of this sample (3-prong tau decays with a photon conversion and  $q\bar{q}$  events) is very similar to the background found in the 5-track sample. In Fig. 2(a) the  $E/p$  distribution of the 4-track jets is plotted for events in which the other jet in the event has only one track in order to enhance the tau background. The ratio of the number of 4-track jets in the data versus Monte Carlo simulation is consistent with unity and we estimate the uncertainty on the tau background to be approximately 10% based on the statistical uncertainty of the data and Monte

Carlo samples. In Fig. 2(b), the  $E/p$  distribution is plotted when the other jet in the event has more than one track in order to enhance the  $q\bar{q}$  background. Again, the ratio of the number of 4-track jets in the data versus Monte Carlo simulation is consistent with unity and we estimate the uncertainty on the  $q\bar{q}$  background to be approximately 20%. The combined statistical and systematic uncertainties are found to be 22% and 36% for the tau and  $q\bar{q}$  backgrounds, respectively.

The tracks in 5-prong tau decays are extremely collimated and the results may be sensitive to the modelling of the tracks. This was investigated by studying the distribution of the angle between each track and its nearest neighbour. The data were found to be well-modelled by the Monte Carlo simulation. This comparison was repeated with a Monte Carlo where the track parameters were smeared by  $\pm 20\%$ . The branching ratios were evaluated using these samples and the change in the branching ratios was included as part of the tracking systematic error (see Table 2).

Possible differences in the modelling of the number of reconstructed tracks in the data and Monte Carlo simulation were investigated using the  $dE/dx$  distributions of the tracks. Single tracks in the OPAL detector with momentum greater than 2 GeV should have a maximum  $dE/dx$  of 10 keV/cm. Tracks with  $dE/dx$  substantially above 10 keV/cm are likely due to two charged particles being reconstructed as a single track. The fraction of jets in the 5-track sample where there is at least one track with  $dE/dx > 12$  keV/cm was found to be  $0.020 \pm 0.003$  and  $0.036 \pm 0.002$  in the data and Monte Carlo samples, respectively. Similar results were obtained using the 4-track sample. The difference between the data and Monte Carlo simulation was accounted for by adding a 2% uncertainty to the tracking systematic error (see Table 2).

Additional studies of the modelling of the tracks were made. For example, it is possible for  $\tau^- \rightarrow 3h^-2h^+(\pi^0)\nu_\tau$  jets to appear in the 4-track sample if a track failed one of the track quality requirements, such as the number of hits in the tracking chamber or the impact parameter. Branching ratios obtained using different track quality requirements were almost unchanged and therefore no additional systematic error was added.

A systematic error was added to account for the uncertainty in the modelling of the electromagnetic energy. The uncertainty in the energy scale of the electromagnetic calorimeter between the data and the Monte Carlo sample was determined to be  $\pm 0.5\%$  based on studies using tau 3-prong decays. The uncertainty in the electromagnetic energy for the 5-prong tau decays was assumed to be  $\pm 1\%$ . The change in the branching ratios when the energy was scaled by  $\pm 1\%$  is included in the electromagnetic energy systematic error (see Table 2). In addition, the effect of smearing the electromagnetic energy on the branching ratios was found to be negligible.

The reliability of the likelihood fit was investigated by using the tau Monte Carlo sample to generate a many sets of ‘data’ and subsequently fitting it with the distributions obtained from the high statistic signal Monte Carlo samples. The systematic error quoted on the fit is the result of changing the upper range of the fit (nominally  $E/p = 1.2$ ) between  $E/p = 0.9$  and 1.4.

The  $\tau^- \rightarrow 3h^-2h^+\nu_\tau$  and  $\tau^- \rightarrow 3h^-2h^+\pi^0\nu_\tau$  branching ratios were determined assuming that the  $\tau^- \rightarrow 3h^-2h^+2\pi^0\nu_\tau$  branching ratio was negligible. The CLEO Collaboration obtained a limit on the  $\tau^- \rightarrow 3h^-2h^+2\pi^0\nu_\tau$  decay of 0.011% [3], suggesting that this decay mode could contribute up to 10% of the inclusive 5-prong branching ratio (based on the CLEO branching ratios). The systematic error due



	$\tau^- \rightarrow 3h^-2h^+\nu_\tau(\%)$	$\tau^- \rightarrow 3h^-2h^+\pi^0\nu_\tau(\%)$
Tracking	0.004	0.006
Electromagnetic energy	0.002	0.001
Fit	0.000	0.003
$\tau^- \rightarrow 3h^-2h^+2\pi^0\nu_\tau$	0.000	0.003
Total	0.005	0.007

Table 2: The systematic uncertainties of the  $\tau^- \rightarrow 3h^-2h^+\nu_\tau$  and  $\tau^- \rightarrow 3h^-2h^+\pi^0\nu_\tau$  branching ratios.

to this assumption is given in Table 2 and was determined by assuming that the efficiency for selecting  $\tau^- \rightarrow 3h^-2h^+2\pi^0\nu_\tau$  decays is approximately 0.3 and that one third of the  $\tau^- \rightarrow 3h^-2h^+\pi^0\nu_\tau$  candidates are  $\tau^- \rightarrow 3h^-2h^+2\pi^0\nu_\tau$  decays.

The inclusive 5-prong branching,  $\tau^- \rightarrow 3h^-2h^+(\geq 0\pi^0)\nu_\tau$ , was determined by applying the same selection procedure used in the exclusive measurement. The inclusive branching ratio was determined using

$$B = \frac{N - N_{q\bar{q}} - N_\tau^{bkgd}}{N_\tau (1 - f) \epsilon F_B}$$

where  $N$  is the number of 5-track jets in the sample (149.0),  $N_{q\bar{q}}$  is the number of background jets from  $q\bar{q}$  events (8.7),  $N_\tau^{bkgd}$  is the number of background jets from tau decays (21.3),  $\epsilon$  is the efficiency for selecting the signal jets (0.556), and  $F_B$  is the bias factor ( $0.94 \pm 0.01$ ). The branching ratio is found to be  $(0.119 \pm 0.013 \pm 0.008)\%$  where the first error is statistical and the second is systematic. The systematic errors are similar to those discussed above. The error on the efficiency includes a statistical component (0.006), a component (0.020) associated with the uncertainty in the ratio between the  $\tau^- \rightarrow 3h^-2h^+\nu_\tau$  and  $\tau^- \rightarrow 3h^-2h^+\pi^0\nu_\tau$  branching ratios quoted here and a component (0.030) for the possible contribution from the  $\tau^- \rightarrow 3h^-2h^+2\pi^0\nu_\tau$  decay (discussed below).

The inclusive branching ratio was calculated assuming that the efficiency for selecting  $\tau^- \rightarrow 3h^-2h^+2\pi^0\nu_\tau$  decays is the same as the efficiency quoted above. However, the efficiency for selecting  $\tau^- \rightarrow 3h^-2h^+\nu_\tau$  and  $\tau^- \rightarrow 3h^-2h^+\pi^0\nu_\tau$  decays was found to 0.58 and 0.46, respectively, so this assumption may not be valid. The difference in the  $\tau^- \rightarrow 3h^-2h^+\nu_\tau$  and  $\tau^- \rightarrow 3h^-2h^+\pi^0\nu_\tau$  efficiencies was found to be due to the requirement that there be five tracks in each candidate jet. The  $\tau^- \rightarrow 3h^-2h^+\pi^0\nu_\tau$  decays contain a  $\pi^0$  that can produce additional tracks by a Dalitz decay or photon conversion. The distribution of the number of electromagnetic clusters was found to have the same shape for the  $\tau^- \rightarrow 3h^-2h^+\nu_\tau$  and  $\tau^- \rightarrow 3h^-2h^+\pi^0\nu_\tau$  so the cut on this quantity is not a concern; this is not unexpected as tau decays are highly collimated and a coarse clustering algorithm is used. The systematic error on our efficiency (0.030) was obtained by assuming that 10% of the inclusive branching ratio is due to  $\tau^- \rightarrow 3h^-2h^+2\pi^0\nu_\tau$  decays (based on the CLEO branching ratios) and that the efficiency for selecting these decays is approximately 0.30.

## Summary

The branching ratios of the decay of the  $\tau$  lepton to five charged particles are found to be

$$B(\tau^- \rightarrow 3h^- 2h^+ \nu_\tau) = (0.091 \pm 0.014 \pm 0.005)\%$$

$$B(\tau^- \rightarrow 3h^- 2h^+ \pi^0 \nu_\tau) = (0.027 \pm 0.018 \pm 0.007)\%$$

where the first error is statistical and the second systematic. These results are in good agreement with previous measurements [2, 3, 4, 5]. These results when combined with other measurements of tau decays to five pions are found to be consistent with the prediction of an isospin model [7, 8].

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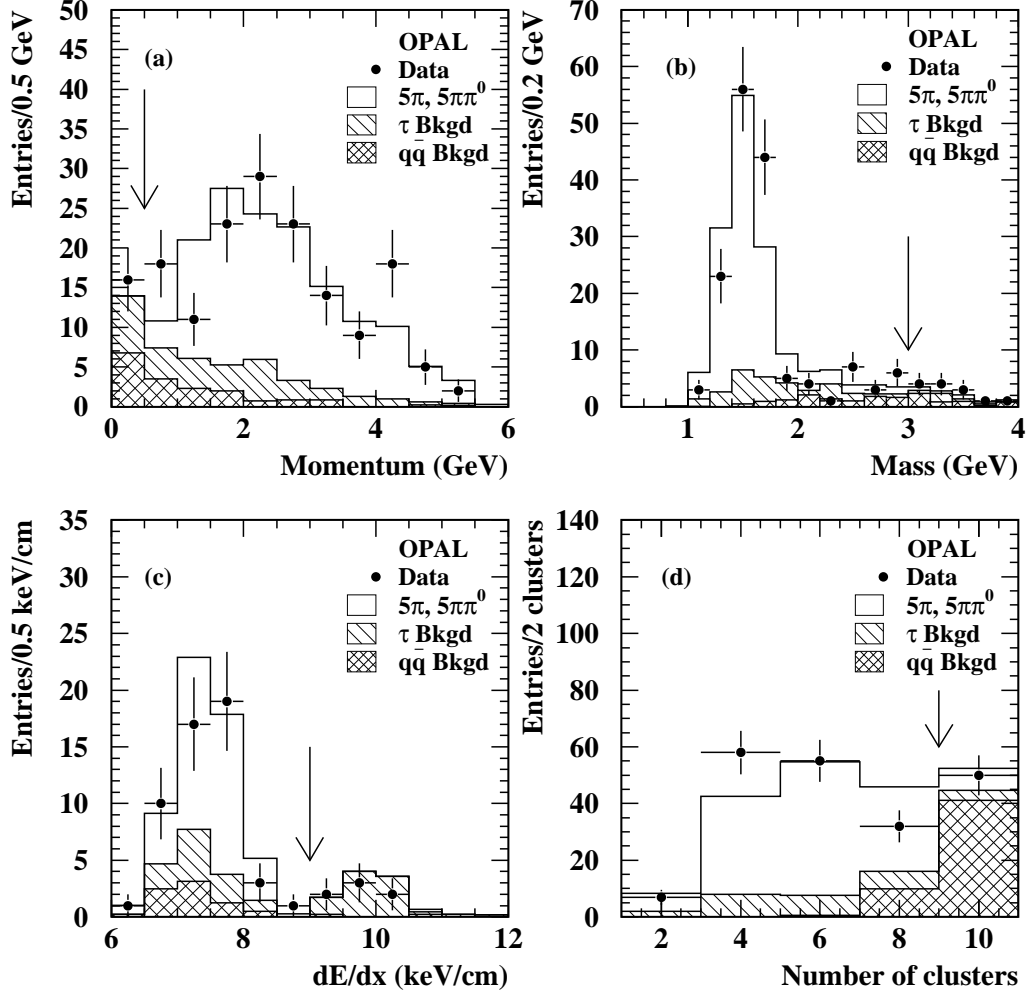


Figure 1: (a) the momentum of the lowest momentum track in the jet, (b) the mass of the five tracks, (c) the energy loss ( $dE/dx$ ) in the central drift chamber for tracks with  $p < 2$  GeV and (d) the number of clusters in the event. The figures are for jets selected as  $\tau^- \rightarrow 3h^-2h^+(\pi^0)\nu_\tau$  candidates. All  $\tau^- \rightarrow 3h^-2h^+(\pi^0)\nu_\tau$  selection criteria are applied and the arrows indicate the cut locations. In all plots the world average branching ratios [1] are used except for the  $\tau^- \rightarrow 3h^-2h^+\nu_\tau$  and  $\tau^- \rightarrow 3h^-2h^+\pi^0\nu_\tau$  decay modes where the branching ratios obtained in this work are used.

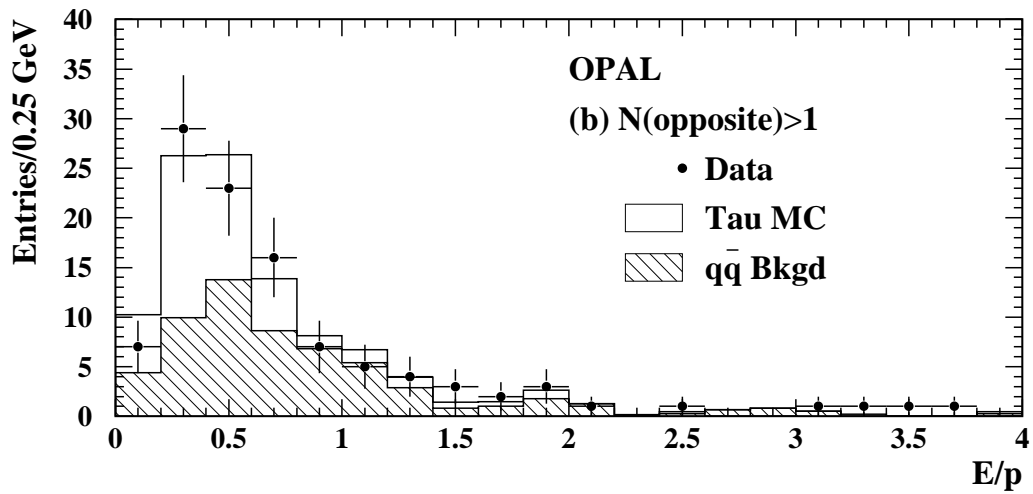
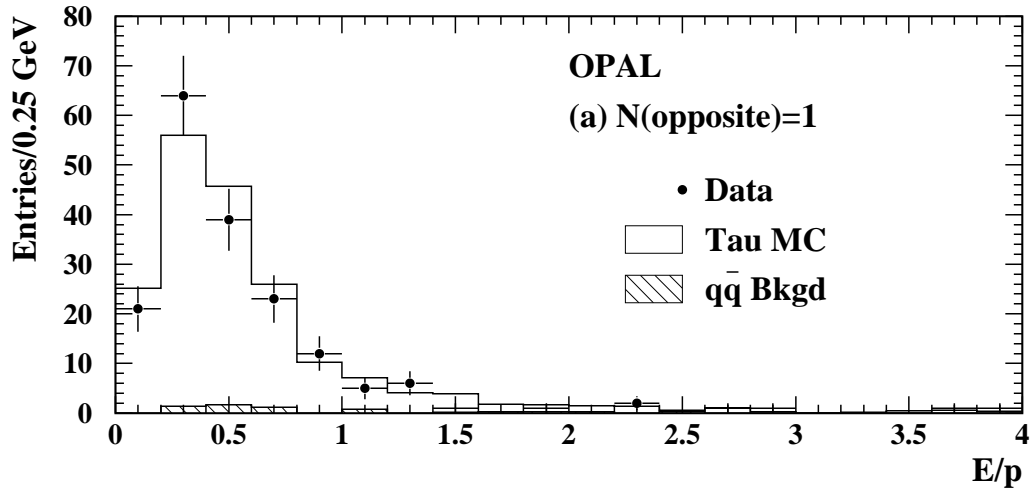


Figure 2: The  $E/p$  spectrum for jets with four tracks is shown. In plot (a) there is a jet on the opposite side with only one track. In plot (b) there is a jet on the opposite side with more than one track.

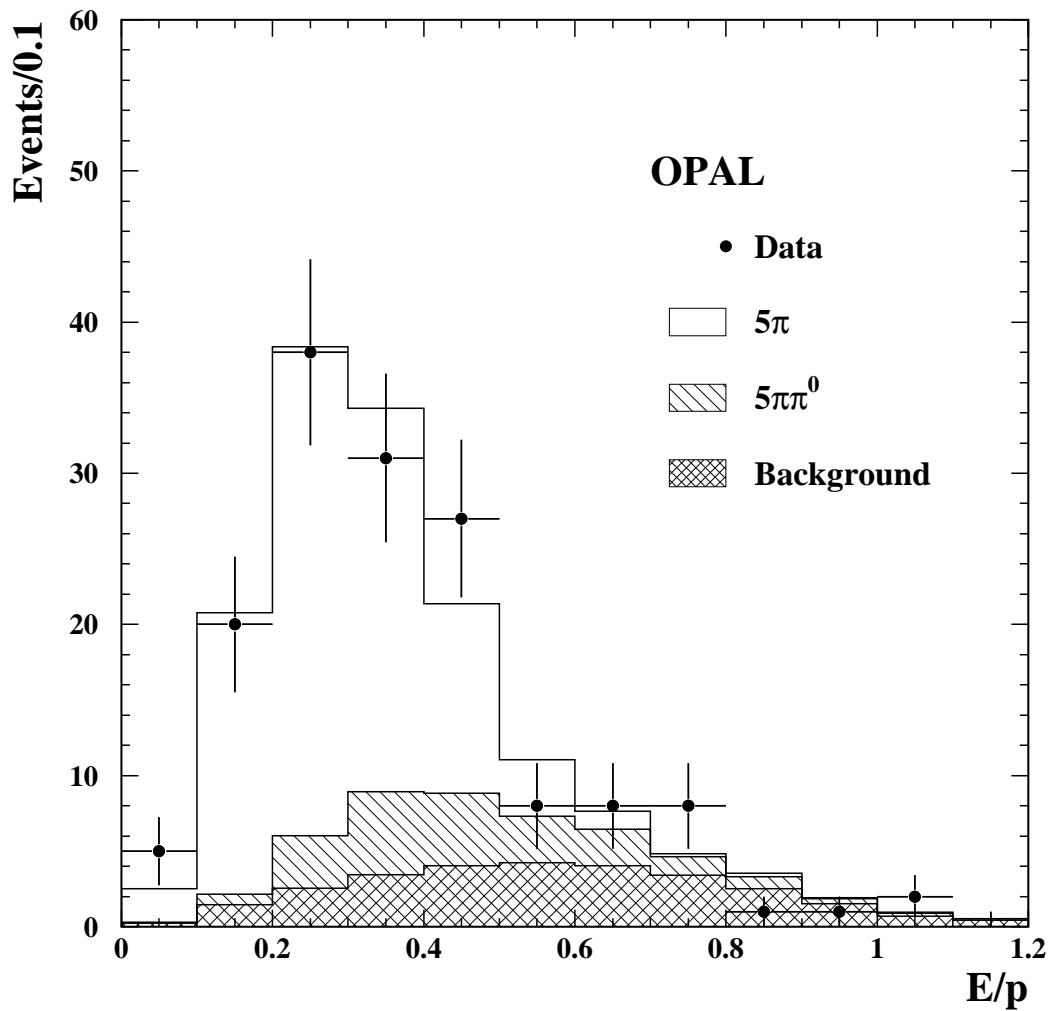


Figure 3: The  $E/p$  spectrum for  $\tau^- \rightarrow 3h^-2h^+(\pi^0)\nu_\tau$  jets is shown. The histograms are the result of the fit to the data.