THE DONUT EXPERIMENT: FIRST DIRECT EVIDENCE OF ν_τ

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ABSTRACT

The DONUT experiment was designed to directly observe the charged-current interactions of the tau-neutrino. An 800 GeV proton beam from the Fermilab Tevatron is used to create a prompt neutrino beam, predicted to have a 5% tau neutrino component. Tau neutrino interactions are identified by observing the τ lepton produced in the charged current interaction $\nu_\tau + N \rightarrow \tau + X$. The experiment locates and identifies τ lepton decays using an emulsion target and spectrometer. An overview of the experiment and analysis methods is presented. The results from an analysis of 203 neutrino interactions are also presented. A decay search on these events has found evidence of four tau neutrino interactions with an estimated background of 0.42 events. This number is consistent with the Standard Model expectation.

*DONUT is an acronym standing for Direct Observation of Nu Tau. The DONUT Collaboration is composed of 56 physicists from 13 institutions in the U.S., Japan, Korea and Greece.

1 Introduction

The discovery of the τ lepton in 1975[1] led to the assumption that the ν_τ exists as the Standard Model third generation neutrino. Since then there has been compelling evidence that it participates normally in electroweak interactions.[2,3] Recent results from the Super-K experiment postulate that the observed deficit of ν_μ atmospheric neutrinos is explained by the oscillation of $\nu_\mu \rightarrow \nu_\tau$.[4] However, its interactions with matter have not been directly observed in the same manner as the interactions of ν_e or ν_μ.[5,6]

Observation of a ν_τ interaction is made by observing the τ lepton produced in the charged current interaction $\nu_\tau + N \rightarrow \tau + X$, and the subsequent decay of the τ in an active target. The τ lepton has a $c\tau$ of 0.087 cm and therefore will decay within a distance of $\sim$ 5mm. Eighty-six per cent of the τ decays have only one charged track (a "kink" decay). This implies that a very high spatial resolution on tracks near the vertex is required.

In the early 1980's two proposals to produce and observe ν_τ interactions were approved to run at the Fermilab Tevatron.[7,8] The proposals were expensive and concerns about event yields and detector resolution led to the cancellation of the experiments before they were constructed. Ten years later, as a first step in the development of the Fermilab neutrino oscillation program, the DONUT experiment was proposed and approved.[9]

Nuclear emulsion was chosen as the neutrino interaction target since it provides the very high spatial resolution necessary to resolve τ decays, as well as sufficient mass to produce a reasonable event rate. The ν_τ interaction candidates are recognized by the topology of the tracks associated with the neutrino interaction vertex. The primary characteristics of the decay which can be measured with an emulsion target are the direction of the τ with respect to the incoming neutrino, the decay length of the τ, the angle(s) between the tau and its daughter(s), and the momentum of the daughter(s).

2 The Experimental Setup

2.1 Prompt Neutrino Beam

The primary source of the ν_τ is the leptonic decay of the D_S meson into a τ and $\bar{\nu}_\tau$. The τ subsequently decays yielding another ν_τ. The charmed mesons are produced in the interactions of 800 GeV protons from the Fermilab Tevatron in a tungsten beam dump.

Production of ν_τ from other sources such as charged D decays, secondary interactions of the D_S in the dump, and B meson to τ decay contributes an additional 14% to the total ν_τ flux. The proton intensity was typically 8×10^{12} protons per 20 second spill. The unwanted products of the high energy proton interactions were reduced to tolerable levels by shielding the emulsion with active magnetic shields and passive iron shielding. The large flux of muons that is created in the dump is swept to either side of the emulsion targets by the magnets and the rate of muons in the target area was measured to be 2×10^4 per spill.

Eighty five per cent of all the neutrinos at the emulsion targets originate in the leptonic or semi-leptonic decays of charmed mesons. Thus, the beam consists of approximately equal numbers of ν_μ and ν_e as well as an equal number of ν and $\bar{\nu}$. Neutrinos from π decays are calculated to account for $\sim$23% of the total number of observed interactions. The mean energy of the neutrinos (uninteracted) is estimated to be 54 GeV for ν_e and ν_μ and 56 GeV for ν_τ. The interaction rate of ν_τ relative to the total interaction rate is calculated to be $5 \pm 1\%$. The largest uncertainty in this number originates in an uncertainty of $\pm$20% in the D$_S$ production rate and $\pm$15% in f_{D_S}, which controls the branching ratio of $D_S \to \tau\bar{\nu}_\tau$

2.2 Hybrid Emulsion Spectrometer

Emulsion is an "active" target since it records all the tracks that are produced at the interaction vertex. However, it is passive in the sense that it has no electronic output indicating when an interaction has occurred. It simply integrates all tracks that are produced in it or pass through it during the time in which it is exposed to the beam. In order to untangle interesting interactions from the background, an electronic spectrometer is used to trigger a data acquisition system which records the signals from the particles that emerge from the emulsion targets. The electronic spectrometer in conjunction with the emulsion target is called a hybrid emulsion spectrometer (HES). This technique for detecting rare, short lived particles has been used in a number of previous experiments.[2,10,11]

2.2.1 Electronic Spectrometer

A conventional spectrometer provides the event trigger, tracking to locate the primary vertex, momentum measurement and lepton identification. It consists of a charged particle veto wall, trigger counters, 44 planes of 0.5mm diameter scintillating fiber tracker (SFT), 38 drift chamber planes, an analysis magnet, a lead glass electromagnetic calorimeter and a muon tagging system.

The spectrometer readout was initiated by a fast trigger formed from signals from three planes of scintillator hodoscopes placed in the target region. The trigger logic required that more than one charged track passed through the target region, and no signal from the upstream veto wall. Muons were identified with an array of proportional tubes between 3 walls of iron (from upstream) 0.6 m, 1m, and 1m thick. Electrons were tagged either by a lead glass calorimeter, shower development in the SF, or pair production in the emulsion.

Tracks in the scintillating fibers were linked to those in drift chambers upstream and downstream of the 1.85 m $\times$ 1.45 m aperture magnet with a strength of 0.76 T-m. The detector tracking accuracy increased from downstream to upstream. The drift chambers had a resolution of $\sim$300μm, whereas the resolution of the scintillating fibers was $\sim$100μm. The reconstructed tracks were used to predict the location of an interaction in the emulsion targets to $\sim$1mm accuracy.

A plan view of the experimental apparatus is shown in figure 1.

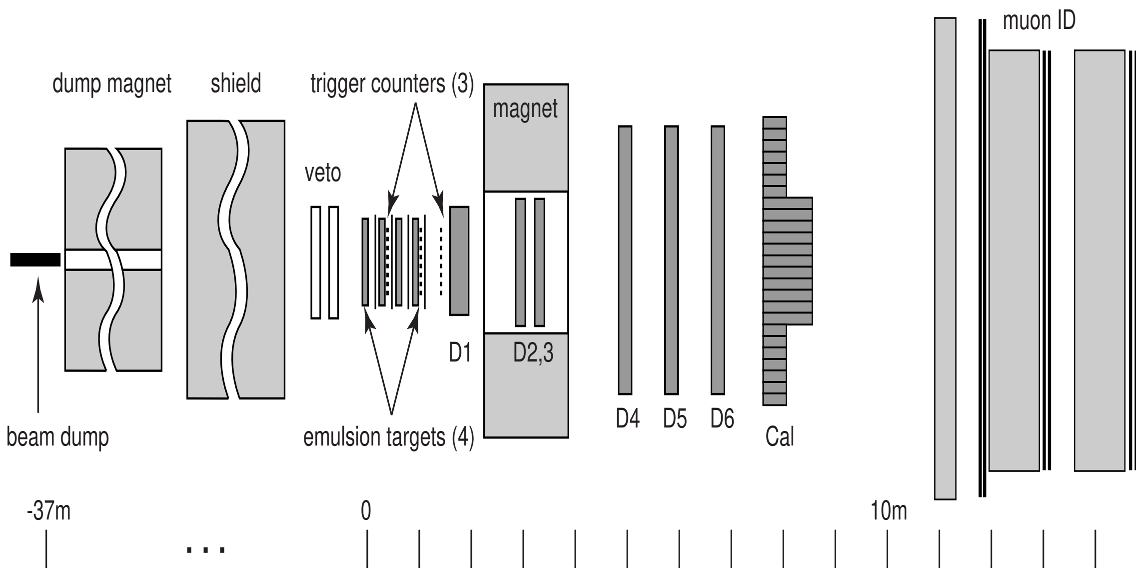

Fig. 1. Experimental beam and spectrometer. At the left, 800 GeV protons were incident on the beam dump, which was 36.5m from the first emulsion target. Muon identification was done by range in the system at the right (downstream).

2.2.2 Emulsion Targets

The target station, located 36 m from the dump, was composed of four emulsion modules placed one behind the other on a precision stand. Each module was made from emulsion sheets, 50 cm×50 cm in area, oriented perpendicular to the ν beam. The emulsion modules and arrangement of SFT planes is illustrated in figure 2.

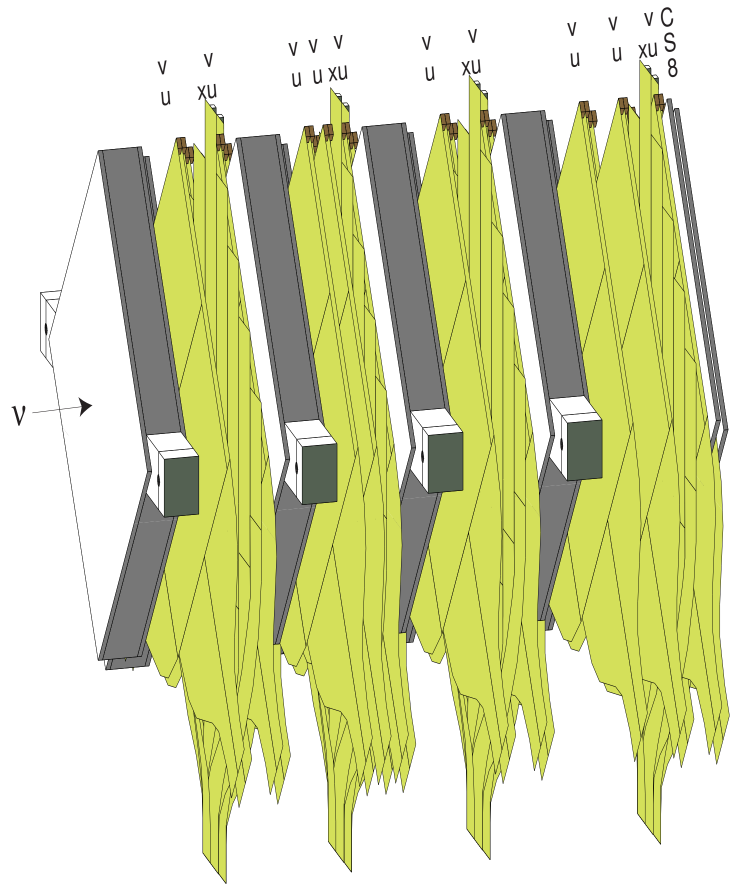

Fig. 2. Emulsion target and scintillating fiber tracker configuration. The fiber planes are arranged in three views, (u,v,x). The six image intensifiers and readout CCD cameras are not shown.

The emulsion used for the DONUT experiment was Fuji ET7C. A typical grain size in this emulsion was 0.07±0.02μm. A minimum ionizing track would then form 29±2 grains per 100μm. Thus, the information capacity of an emulsion detector is staggering. After exposure the DONUT emulsion modules literally held terabytes of data!

Three types of emulsion modules were used as neutrino targets. The first type of emulsion target (called *bulk*) was constructed from 88 sheets with 330μm thick emulsion layers on both sides of a 90 μm thick plastic base. The nuclear emulsion comprised 96% of the total mass (50kg) and had a thickness of 2 radiation lengths and 0.17 interaction lengths. The second type (called *ECC*) had 48 alternating sheets of 1mm thick stainless steel and emulsion. The emulsion sheets had 100 μm emulsion layers on each side of a 200 μm thick plastic base. The mass of the emulsion in the *ECC* target was just 8% of the total (97 kg), so that the neutrino interactions most likely occured in the steel plates. This type of target was 3.0 radiation lengths and 0.29 interaction lengths. The third type (*ECC/bulk*) was a hybrid target, where the downstream part was 50 sheets of bulk-type, and upstream part was a variation of the *ECC* design, such that the thickness of the plastic base was increased to 800 μm. The mass of the emulsion for the *ECC/bulk* target was 44% of the total (67 kg). Each *ECC/bulk* target had a thickness of 2.5 radiation lengths and 0.24 interaction lengths. A schematic drawing of an *ECC* and a *Bulk* sheet are shown in figure 3.

In the course of the experiment a total of seven targets were exposed: five were *ECC/bulk*, two were *ECC*, and one *bulk*.

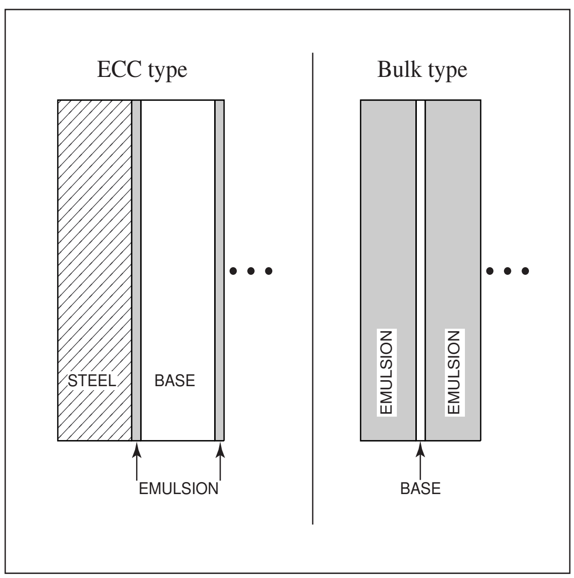

Fig. 3. Two configurations of emulsion sheets used in constructing the target modules

3 The Data Set

Data was taken between April 1997 and September 1997. During that time the emulsion modules were exposed to a total of 4.6×10^{17} protons on target. A total of 6.6×10^{6} triggers were recorded. After live-time correction the effective proton intensity was 3.54×10^{17}. For this number of protons on target the expected number of neutrino interactions of all types is $\sim$1100$\pm$300.

A trigger was selected as an interaction candidate by requiring that a vertex position predicted from SFT tracks be within an emulsion target. In addition, the event trigger timing between two counters was required to be within 10ns, and show no evidence of nearby showering from muon interactions. Remaining events with a visible energy more than 2 GeV and a vertex in the emulsion volume were classified as neutrino interaction candidates. The number of interaction vertices predicted with the spectrometer is 901, and after all fiducial cuts are made this is reduced to 699 events. In 451 of the 699, the primary vertex location was attempted and 264 were found. As of the Spring 2000, 203 events were selected for a complete systematic decay search for tau kinks. The selection of the data set is summarized in Table 1.

Selection	Number of Events
Triggers	6.6 $\times 10^{6}$
Predicted vertices from spectrometer	901
Vertices in fiducial volume	699
Digited emulsion data taken	511
Vertex location attempted	451
Vertex located	264
Sytematic decay search	203

Table 1. The Data Set (Spring/Summer 2000)

The distribution of vertices as a function of z is shown in figure 4. The distribution across the face of the targets is shown in figure 5. A typical ν_μ charged current event is shown in figure 6 and a typical ν_e charged current interaction is shown in figure 7.

In the set of 203 events, there are 71 events with an identified muon from the primary vertex. After correcting for the acceptance and the efficiency of the muon detectors, the number of ν_μ charged current interactions is 86 ± 12. The measured energy distribution in the calorimeter is used to separate the ν_e charged current events from ν_μ

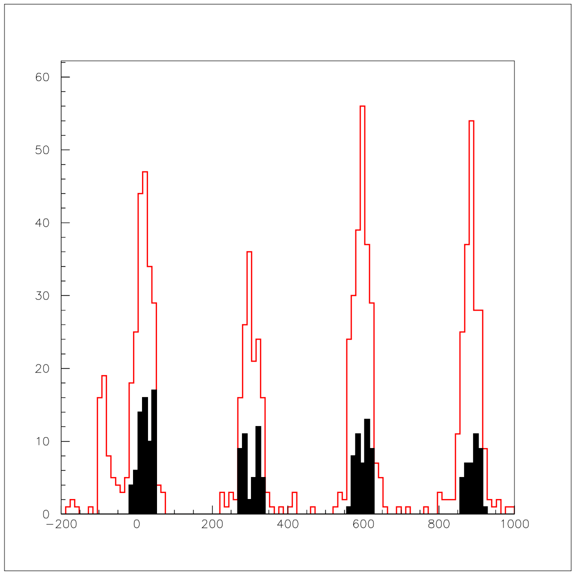

Fig. 4. Distribution of predicted (line) and located vertices (fill). The spike upstream of the first module is produced by neutrino interactions occurring in the upstream veto wall and a lead sheet surrounding the emulsion targets.

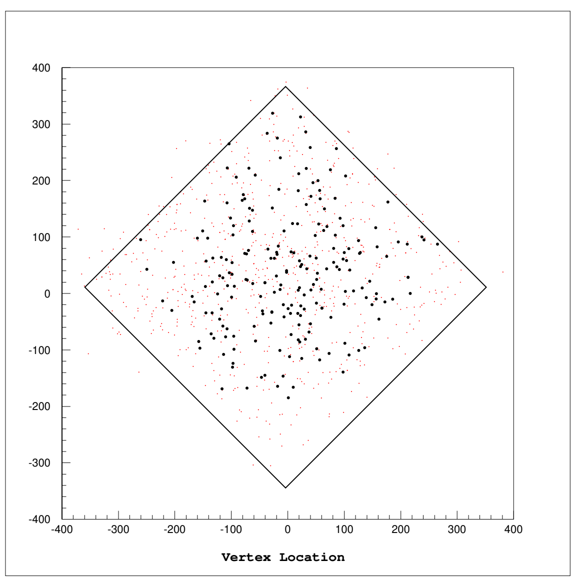

Fig. 5. Distribution of predicted (light) and located vertices (dark).

and neutral current interactions containing electrons. The result obtained is 61 ± 14 ν_e charged current interactions. From the ν_μ charged current event spectrum, an estimated 23% of the total number of interactions were ν_μ interactions from π and K decays in the dump, rather than from charm decays. Since the ν_τ rate is predicted to be ~5% of the total number of interactions, 10±3 ν_τ interactions (before kink finding efficiency) are expected in the "203" data set.

4 Emulsion Analysis

Following the DONUT data-taking phase the emulsion sheets were shipped back to Japan for development and analysis. The use of automated scanning stations, pioneered at Nagoya University, has brought emulsion analysis into the digital era. The data recorded in the emulsion is extracted and summarized on standard mass storage media with speeds and efficiency that exceed human scanners by three orders of magnitude.[13] Nevertheless, it took more than 18 months to process calibrate all of the sheets. This processing was done in parallel with the trigger selection from the electronic data, which was done in the U.S. Scanning of the emulsion is done for three different phases of the analysis, event location, decay search and momentum measurement.

4.1 Event Location

Prior to this experiment, the standard technique for locating a vertex in the emulsion was to reconstruct a high momentum track in the electronic spectrometer and follow this track into the emulsion modules until it ends, presumably at the interaction vertex from which it originated. This method, called "Scan Back", also used in the CHORUS experiment,[11] is appropriate for less than 50% of the data in DONUT. Because the DONUT emulsion targets are very thick (~6cm), this method of following tracks from the spectrometer is less reliable for vertices in the upstream part of the target.

A new method of event location, called the "Net Scan" technique[14] was developed for this experiment. A "location" scan volume of 5mm×5mm×20mm is defined around the vertex position which has been predicted by the tracks reconstructed in the fiber tracker. All track segments in each emulsion layer are reconstructed using a dedicated automatic emulsion read-out system. Track segment positions and angles are measured by locating emulsion grains in 16 depths in the top 100μm of emulsion. Space tracks in the entire scan volume are reconstructed by linking segments in each layer. A typical

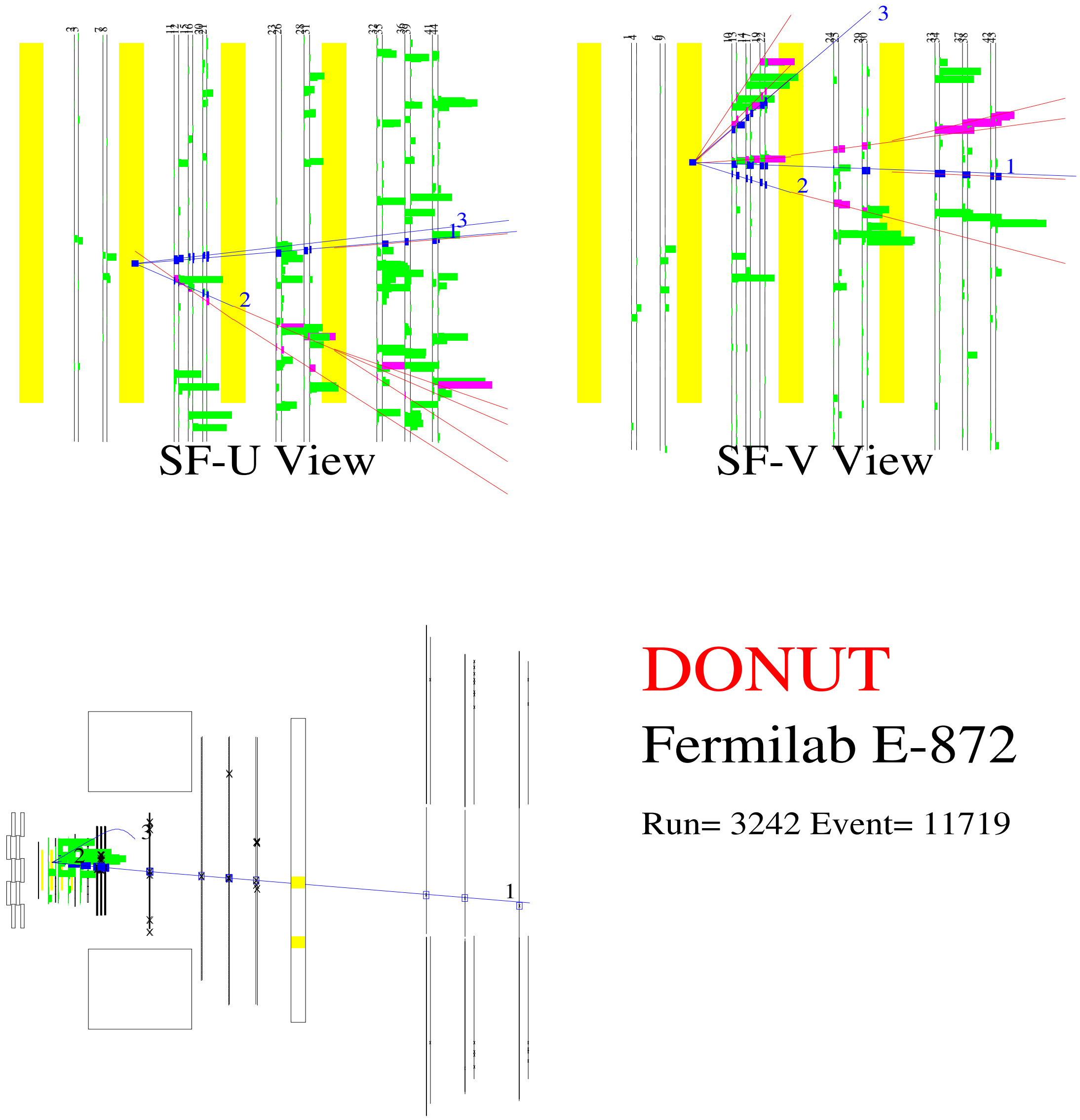

Fig. 6. A typical ν_μ charged current interaction.

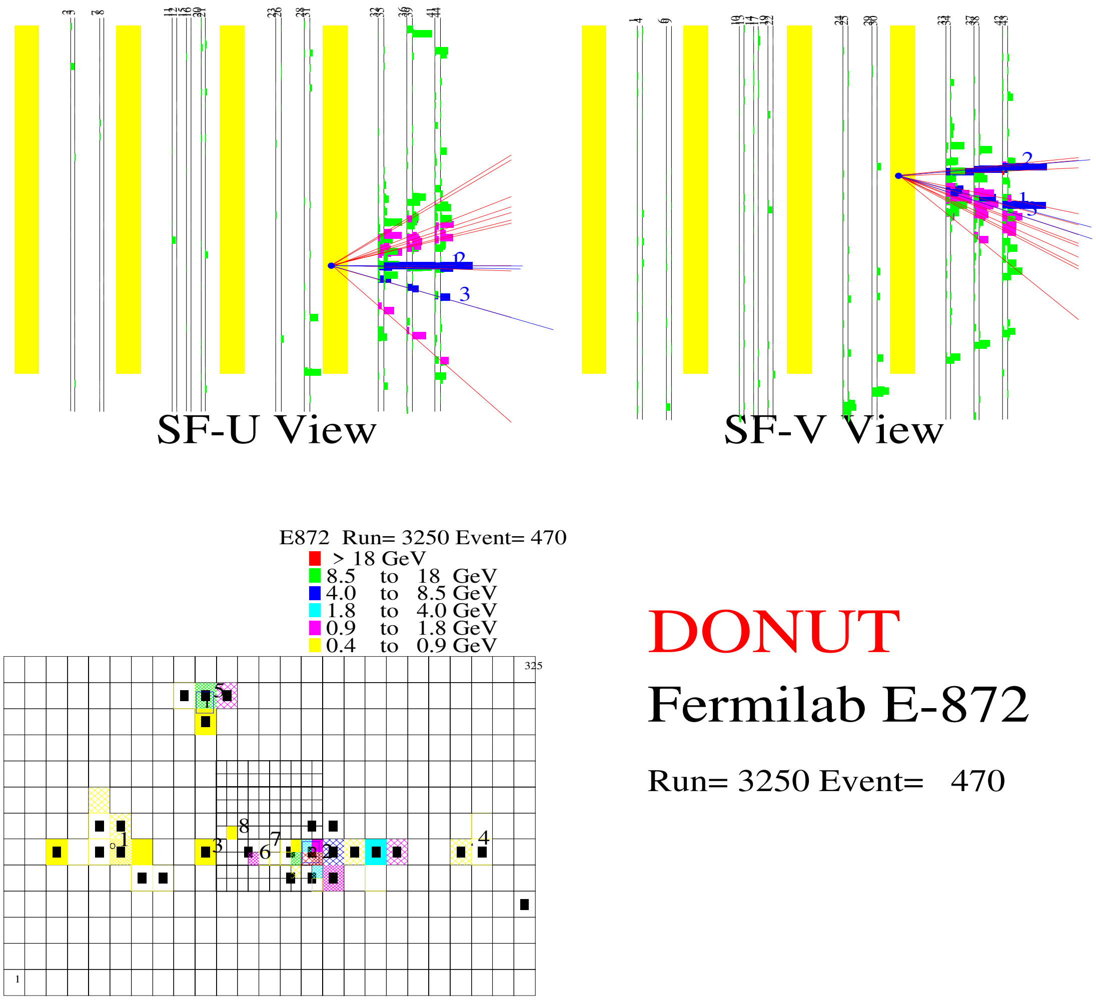

Fig. 7. A typical ν_e charged current interaction.

scan volume will contain $\sim 10^5$ tracks. This number is easily reduced by removing all one and two segment "tracks" and all tracks which traverse the entire scan volume. The number of remaining tracks is $\sim 10^3$. Candidate interaction vertices have 3 or more space tracks that start in the same layer or in an adjacent layer and have an impact parameter less than 10μm. True interaction vertices are confirmed by matching emulsion tracks to the SFT.

This powerful method of vertex location is only possible because of the speed of the present generation of scanning stations. Nevertheless, until March 1999 it required more than 10 hours to process one event in this way. Today at Nagoya University the next generation of scanning machines are now on-line and have proven speed increases if 8 to 10 over the previous generation.

4.2 Decay Search

Emulsion plates for located events are rescanned by the automated optical system with a scan volume defined by a transverse area of 2.6mm$\times$2.6mm centered on the located vertex with a longitudinal dimension of 20 emulsion planes downstream and 2 planes upstream of the vertex. Tracks in the volume were aligned in both position and angle by using the straight through tracks previously identified. After this fine alignment 203 events satisfied the criteria that the track resolution was better than 0.6μm. The efficiency for linking tracks is shown in figure 8. The distribution of the position resolution of each emulsion plate is shown in figure 9. This fine resolution then allows for a precision of $\sim$1μm in the vertex finding accuracy, shown in figure 10.

4.3 Event Classification

Special scan data was taken for electron identification and to extend the accuracy of measuring a charged particle's momentum using its trajectory through the emulsion due to multiple scattering.

5 Decay (Kink) Search

The kink decay search is divided into two separate analysis. One is for long *(L)* decays where the kink is outside of the plate in which the interaction occurred. For a long decay, illustrated in figure 11, the parent track is recorded in the emulsion data explic-

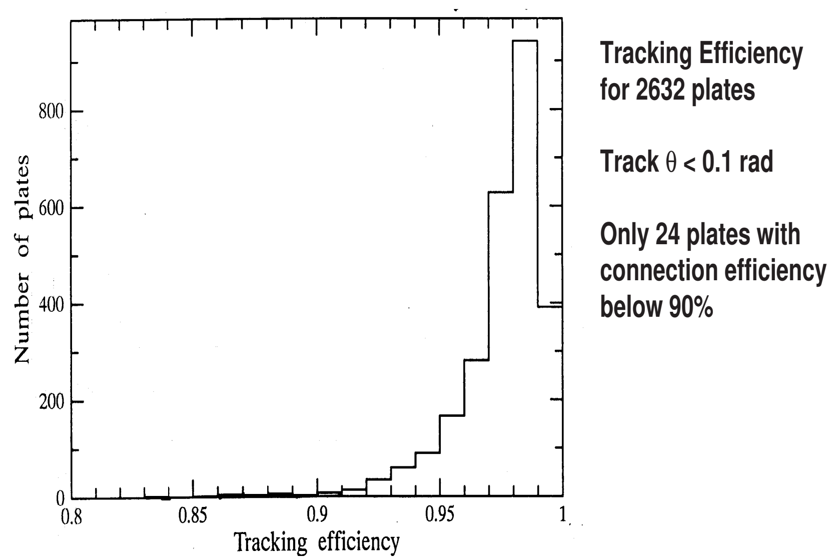

Fig. 8. Emulsion plate tracking efficiency. Note that for a total of 2632 plates scanned and aligned, only 24 plates had a connection efficiency of $< 90\%$.

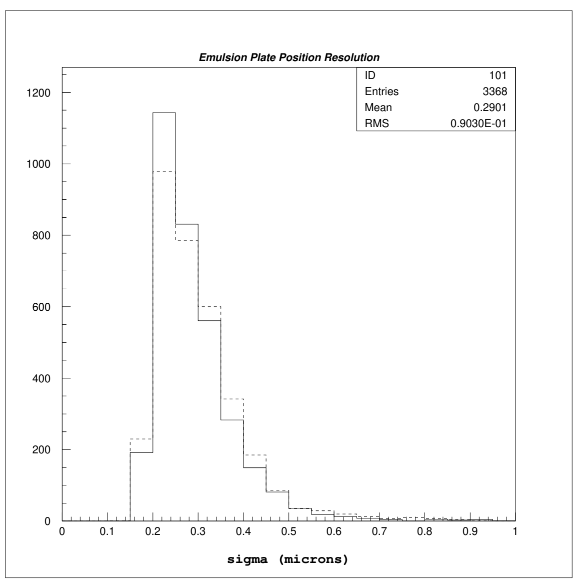

Fig. 9. Emulsion position resolution, determined by calculating the plate to plate residuals using through going muon tracks.

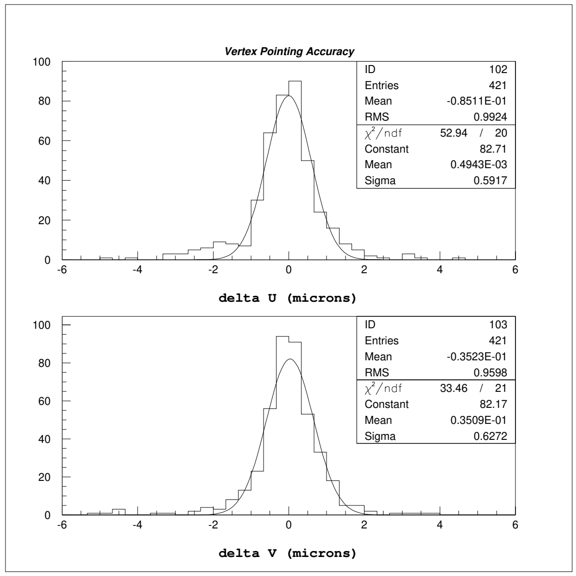

Fig. 10. Vertex pointing accuracy

itly. Additionally, if the kink is from a τ decay there will be no electron or muon from the primary vertex. For the target configurations used in DONUT, about 75% of all τ decays are expected to be long.

The second analysis is for short *(S)* decays in which the kink is in the same plate as the primary vertex, which for ECC-type modules means tha τ decay would be within steel and the event would have to be identified as a τ based on the impact parameter and minimum transverse momentum (p_T) of the daughter track. Only the results of the long decay search are presented here.

The following selection criteria were used to select kink candidates:

- At least one segment of the parent track is identified in the emulsion data.
- The daughter angle with respect to the parent track was >10 mrad and < 400 mrad.
- The impact parameter of the daughter to the parent track was < 5μm.
- The impact parameter of the parent track to the interaction vertex was < 10 μm.
- The impact parameter of the daughter track to the primary vertex was < 500μm.

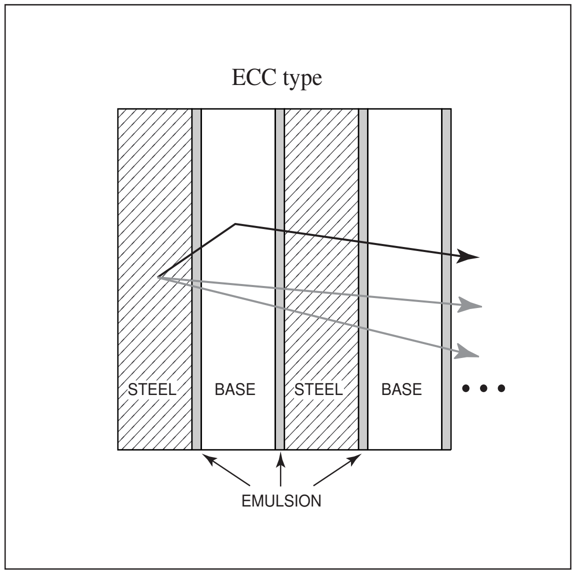

Fig. 11. Long decay topology

Cut	Kinks	$\%\tau$ remaining
none	7642	100
$0.01 <$ kink angle < 0.250	450	78
Parent angle < 0.200 rad	280	90
IP(Parent) $< 5\ \mu$m	142	> 99
IP(kink) $< 5\ \mu$m	65	> 99

Table 2. Kink selection in 680 primary tracks (from 203 interactions). Note that the $\%\tau$ remaining are not cumulative cuts.

6 Potential Backgrounds

Kinked tracks may be classified in the following categories: (1) random association of background tracks, (2) re-scattering, (3) charm decays in charged current interactions, and (4) τ decays.

The following selection criteria, which retained 50% of simulated τ events, were used to identify tau decay candidates from the kink candidates:

• Only one daughter track was associated with a parent track.
• The parent track was $<$ 5mm long.
• The daughter track momentum was $>$ 1 GeV/c.
• The transverse momentum of the decay was $>$ 250 MeV/c.
• None of the tracks originating at the primary interaction vertex was identified as a muon or electron.

6.1 Random Tracks

To determine the probability that an observed kink actually resulted from the mislinking of random background tracks, for each event the impact parameter of each track starting within one plate of the primary vertex was calculated. The distribution of these impact parameters is shown in figure 12. It can be seen that, with the exception of tracks known to be associated with the primary vertex, the shape of the distribution is characteristic of an uncorrelated, uniform distribution. On average there are 40 long tracks/mm^2/event which start near a random point in any layer. The fraction of primary tracks which stop within 5mm of the primary vertex is 0.14. The probability that the random track will be within 5μm of a stopping vertex track is 0.1. Requiring that the "daughter" matches in the SFT system reduces this background by a factor of five, to a negligible level, and it is not included in the final background number.

6.2 Charm Decays

Charged charm decays with a kink topology are a background if the lepton from the primary interaction is not identified. Charm is expected to be produced in 8.1% of the charged current ν_e and ν_μ events. The background is estimated by applying the branching ratios for charged charm and the one-prong kink topology, as well as the

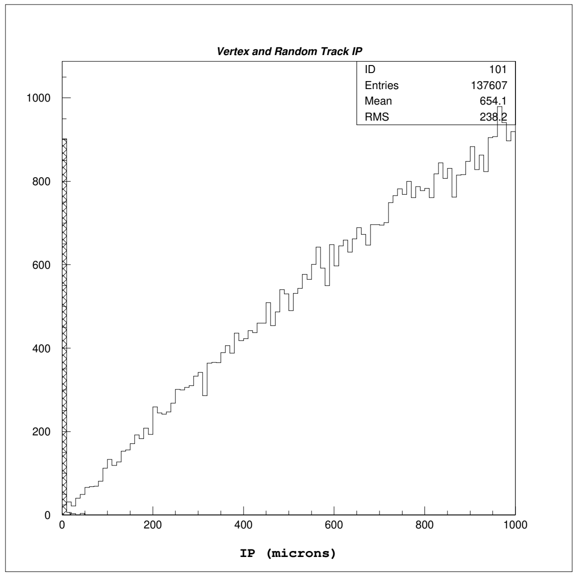

Fig. 12. Distribution of random track impact parameters. Tracks coming from the primary vertex were tagged independently.

cut efficiencies for “long decay”, p_T, and lepton identification inefficiency. These cuts are summarized in Table 3. 2.4 charged charm events with correct lepton identification are expected, and 2 events are found. One of these charm events has a kink topology, consistent with the expectation of 0.9±0.2 events.

However, the charm signal events would constitute a background to the τ sample if and only if the primary lepton is not identified. To estimate this potential background in the DONUT experiment, the muon identification efficiency was estimated to be 79% (82% acceptance $\times$ 96% efficiency). The electron efficiency was estimated (conservatively) to be 75%, giving a total lepton identification *inefficiency* of 23%. This leads to 0.21 ± 0.04 background charm events.

6.3 Interactions

A τ decay may be faked by re-scattering of a primary track in a) a neutral current event, or b) a charged current event where the lepton is not identified. The probability of re-scattering decreases rapidly with transverse momentum (p_T), in contrast to τ decays in which p_T peaks near 0.4 GeV/c. The re-scattering background is estimated by GEANT simulation of both of these processes. We find that the background due to re-scattering with a cut on $p_T \geq 250$ MeV/c is 0.2 ± 0.06 event, with a τ selection efficiency of 56%.

		no. of CC interactions
assume $\nu_\mu \sim \nu_e$		168±18
charm production	0.081±0.008	13±1.3
charged charm	0.47±0.05	6.4 ±0.9
"Long" decay and $<$ 5mm	0.66±0.06	4.2±0.7
kink detection ϵ	0.56±0.06	2.4±0.5
charm $\rightarrow$ kink (C1)	0.38±0.02	0.9±0.2

Table 3. Summary of charm background estimation.

The comparison of signal and background p_T is shown in figure 13.

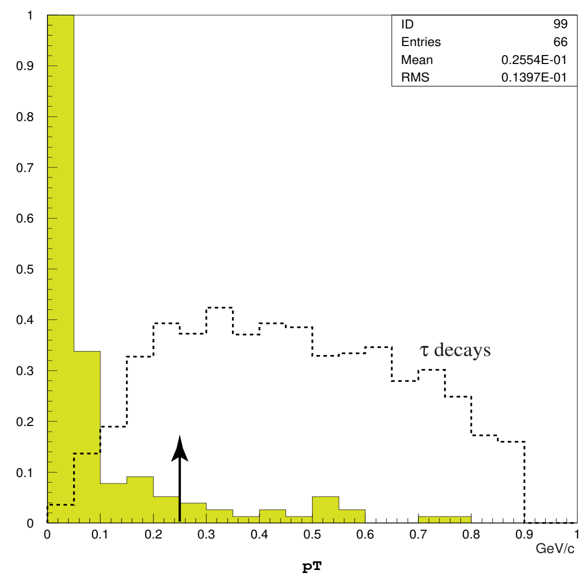

Fig. 13. Distribution of p_T for scattering background and τ decays.

For all kinks where it was possible to make a determination of the daughter momentum, the p_T was calculated. The distribution is shown in figure 14.

7 The Large p_T Events

Five events are well separated from a low p_T re-scattering background. One of these events has a clearly identified electron from the primary vertex, and is classified as the previously mentioned single-prong charm event. Each of the other four events are described and illustrated.

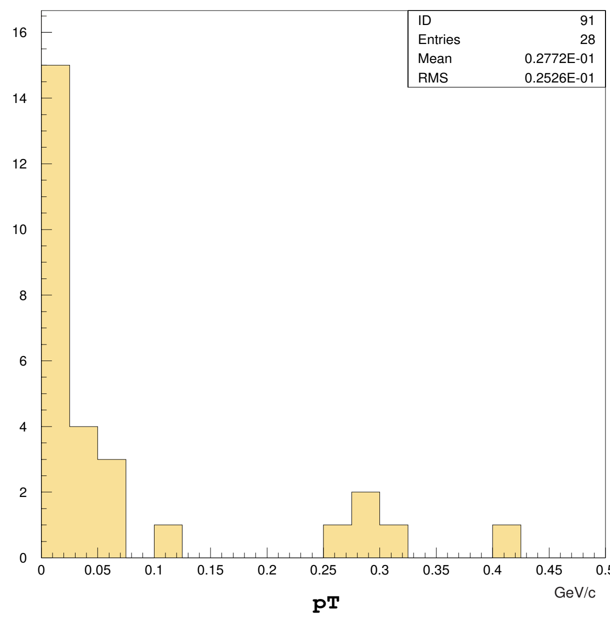

Fig. 14. P_T of kinks

7.1 Event 3333-17665

See figure 15. The track closest to the beam direction has a 13 milliradian kink, 0.54 mm from the primary vertex. The decay is located in the 800 μm thick plastic base. The daughter is identified as an electron. The momentum of the electron was measured to be 21^{+14}_{-6} GeV/c by multiple scattering measurement. Because of the continuous energy loss of the electron, this value must be considered as a lower limit. The corresponding decay p_T limit is $\geq 0.27^{+0.19}_{-0.08}$ GeV/c.

7.2 Event 3263-25102

See figure 16. One track has a 130 milliradian kink, 1.8 mm from the primary vertex. The decay is located in the steel plate. The daughter momentum is estimated to be $1.9^{+1.6}_{-0.6}$ GeV/c. The corresponding p_T is $0.25^{+0.21}_{-0.08}$ GeV/c.

7.3 Event 3039-01910

See figure 17. One track, isolated from the others, has a 90 milliradian kink angle, 0.28 mm from the primary vertex. This track is isolated from the other charged tracks and is emitted opposite to the other tracks in the plane perpendicular to the beam. The decay is located in the plastic base (200 μm thickness). The daughter momentum was measured to be $4.6^{+1.6}_{-0.9}$ GeV/c. The estimated decay p_T is $0.41^{+0.14}_{-0.08}$ GeV/c. The daughter track was identified as a hadron since a secondary interaction is seen after 1.5 cm.

7.4 Event 3024-30175: $\tau \to e + \nu_\tau + \nu_e$.

See figure 18. This event has three tracks from the primary vertex. One track has a 93 mrad kink 4.5 mm from the primary vertex in the plastic substrate. No other tracks including nuclear evaporation tracks from this kink vertex are found. The kink daughter track was identified as an electron, because an electron pair accompanying this track was found in the emulsion, and a shower is observed in the SFT. The energy was estimated by measuring the multiple scattering of the daughter particle and by the shower development in the SFT. The former method gives $3.3^{+3.7}_{-1.2}$ GeV/c, but this value should be considered as a lower limit, as the electron loses energy continuously in the target. The latter method gives a value of 6.5 ± 2.5 GeV.

8 Conclusion and Future Analysis

The decay search for kinks from tau decays has been completed on 203 neutrino interactions using the emulsion data. For the long decay search method, four tau candidates are found. Each of these four events have a track that meets all the criteria for tau decays, with no evidence of another lepton from the primary vertex. The daughter impact parameter to the primary vertex and the kink p_T for the signal events are shown in comparison to the expected distributions for τ events in figure 19. The expected number of τ events in the 203 set, summarized in Table 4 is 4.1$\pm$1.4

The total background is estimated to be 0.42 ± 0.15 events. Kinks are found in the plastic emulsion substrate in three of the four events, however we expect the 0.2 scattering background to be dominated by kinks in the steel plates. Two events are identified as $\tau \to e\nu_\tau\nu_e$ decays and have negligible level of background from scattering. The probability that the four events are from backgound sources is 8×10^{-4}, and we conclude that tau neutrino charged current interactions have been observed.

The results which have been presented represent the analysis of one-third of the neutrino interactions which occurred in the emulsion targets. The collaboration plans to continue the process of event location and the subsequent decay search. It appears feasible to double the number of located interactions.

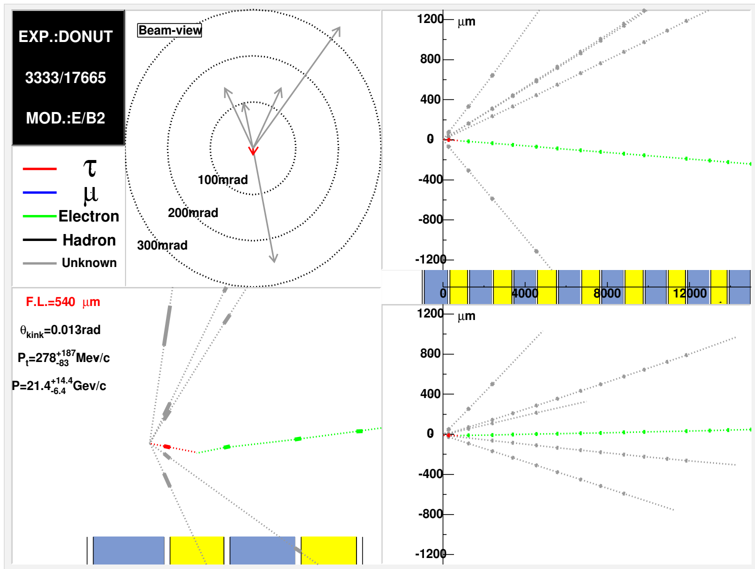

Fig. 15. Event 3333-17665: $\tau \rightarrow e + \nu_\tau + \nu_e$

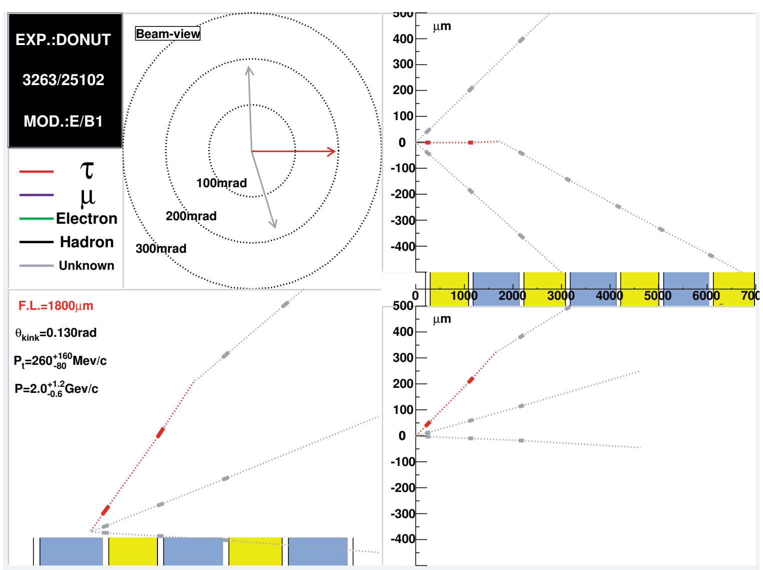

Fig. 16. Event 3263-25102: $\tau \rightarrow h + \nu_\tau + X$

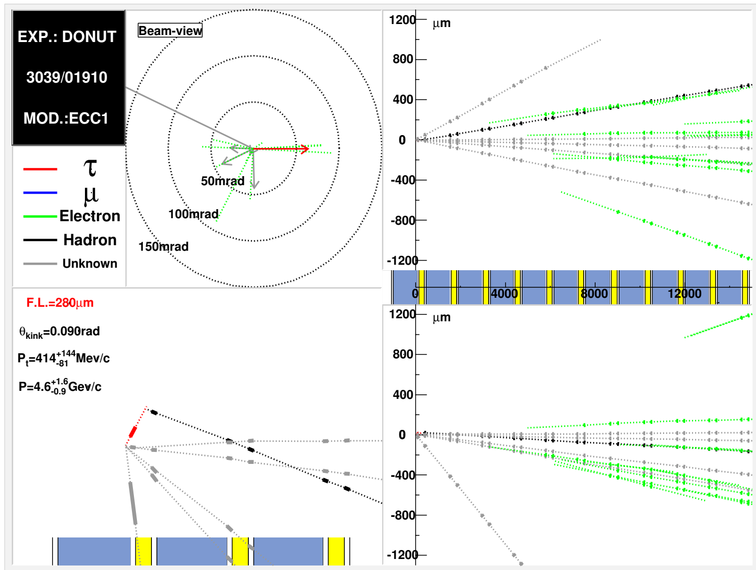

Fig. 17. Event 3039-01910: $\tau \to h + \nu_\tau + X$

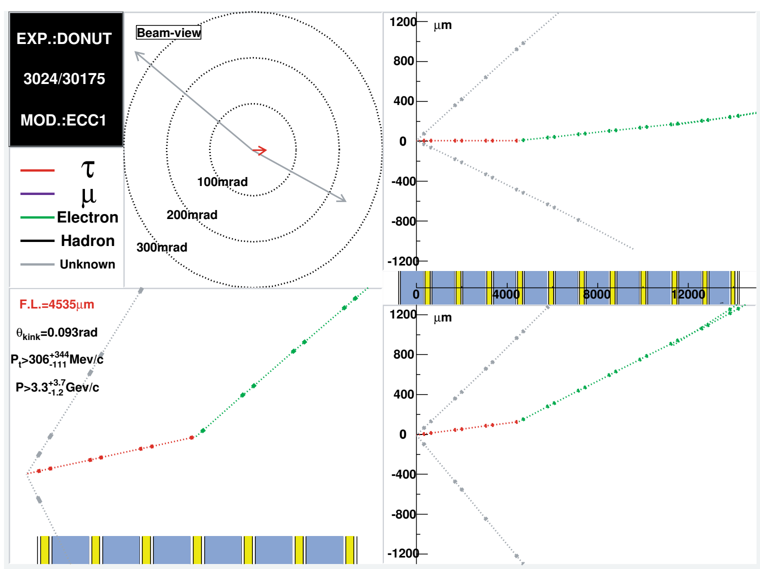

Fig. 18. Event 3024-30175: $\tau \to e + \nu_\tau + \nu_e$.

Number of interactions	203
fraction from ν_τ	0.048
C1 decay	0.86
Long decay	0.76
τ kink finding efficiency	0.65
Expected number of τs	4.1 ± 1.4

Table 4. Expected number of τ events in the 203 set

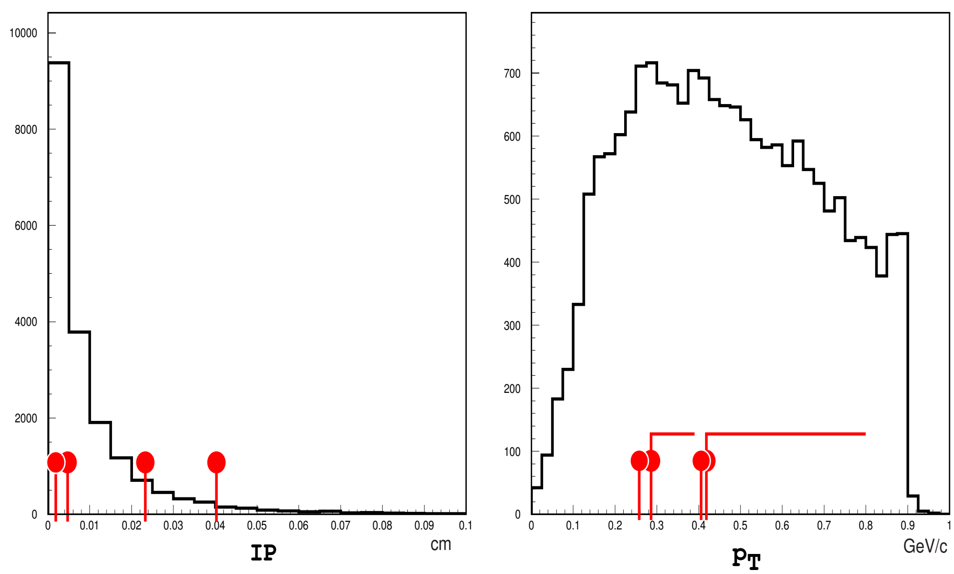

Fig. 19. Impact Parameter (IP) and p_T for tau candidates, compared to expected distributions. The data point for the p_T measurement uses the daughter momentum as determined from multiple scattering in the emulsion. The line indicates the corresponding measurement determined by the energy deposited in the SFT.

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