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# Doubt on distinctions between muon and electron events with the Super-Kamiokande detector

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**Abstract.** In the measurement of atmospheric $\nu_e$ and $\nu_\mu$ fluxes, the calculations of the Super Kamiokande (S.K.) group for distinction between muon-like and electron-like events in the water $\check{C}$erenkov detector have assumed a misidentification probability of less than 1 % in sub-GeV and multi-GeV energy ranges. However, their expressions and the calculation method do not include the fluctations due to the stochastic process of the expected number of photoelectron (p.e.) produced by muons and electrons. Our full MC simulation including the fluctuation behaviours show that the total misidentification probability for electron and muon events should be order of $\geq$ 20 % for the sub-GeV region. Even in the multi-GeV region a muon deficit of the order of several % is observed. The misidentified events are mostly of muonic origin.

## 1 Introduction

The S.K. data for the sub-GeV region collected during the period between March 1996 and October 1997 have been analysed independently by the Analysis A amd B groups respectively (Fukuda et al., 1998, 1998), (Kajita, 1998). Further, results for the 33.0 kiloton-year exposure have been reported for the sub-GeV ($E_{vis}$ <1330 MeV) and the multi-GeV ($E_{vis}$ >1330 MeV) data (Fukuda et al., 1998). The latest results for the 70.4 kt-y exposure including the 33.0 kt-y one were presented at the Japanese Physical meeting in Sept. 2000 (Kaneyuki et al., 2000). From these report we compare the respective values/kt-year as shown in Table 1. There are some discrepancies in the two analysis methods A and B for the $\mu$-like and e-like events beyond statistical uncertainties. These cases are marked with an asterisk $*$. These aspects indicate some difficulty in the identification of muon and electron events in the water $\check{C}$erenkov detector. This is our motivation to examine the particle identification method of the S.K. group (Kasuga, 1995), (Kasuge et al., 1996), (Kasuga, 1998).

The only experimental test of the e/$\mu$ identification capability was carried out by some members of the group using the 12-GeV proton syncchrotron at KEK, Japan (Kasuga et al., 1996). For the test, they used a 1000 ton water $\check{C}$erenkov detector, which is a cylindrical volume of 9.6 m in diameter and 9.3 m in height equipped with 380 photomultiplier tubes (PMTs with 50-cm diameter). On the other hand the S.K. detector, which has a fiducial volume of 32,000 metric tons, is a cylindrical volume of 33.8 m in diameter and 36.2 m in height equipped with 11,146 50-cm PMTs. Surrounding the inner detector is the outer detector covering with 1,885 20-cm PMTs, that comprises a 2.6 m to 2.75 m thick layer of water. Then, the question arises whether the large scale diffences between both detectors may lead to an underestimate of the misidentification probability for the large 32,000 ton detector.

## 2 Calculation methode of S.K. group

The S.K. group has performed a MC calculation to make a table concerning a relation, $N_{MC}(\theta, P_{\rm e})$, among the average number of photoelectrons (p.e.), the momentum of electron $P_e$, and the opening angle $\theta$ of $\check{C}$erenkov light. Then, an electron with a given momentum was started at a center of sphere having 16.9m radius as a position of vertex. The $\theta$ was an angle between the particle direction and the circular area which was made by the $\check{C}$erenkov lights (Kasuga, 1998). The relation is based only on the average number of p.e., neglecting the fluctuations from the average. By using the value of $N_{MC}(\theta_j, P_{\rm e\ j})$, the expected p.e. number produced by the electron in the j-th PMT on a surface of the cylindrical volume was calculated with the expression (6.7) in the same paper (Kasuga, 1998). Also a p.e. number distribtuion for muons is given in a similar expression (6.8). The likehood function $L_e$ for e-like event and $L_\mu$ for $\mu$-like event are obtained with the probability function $Prob(N_{exp}, N_{obs})$ for studing the e/$\mu$ identification capability of the events. By

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| | | Analysis A (25.5 kt-y) | | Analysis B (25.8 kt-y) | |
|---|---|---|---|---|---|
| **sub-GeV** | $\mu$-like | 900 | $(35.3 \pm 1.2)$/kt-y | 1041 | $*\ (40.4 \pm 1.3)$/kt-y |
| | e-like | 983 | $(38.6 \pm 1.2)$/kt-y | 967 | $(37.5 \pm 1.2)$/kt-y |
| | | **$\nu$-98 (33.0 kt-y)** | | **JPS2000 (37.4 kt-y)** | |
| **sub-GeV** | $\mu$-like | 1158 | $(35.1 \pm 1.0)$/kt-y | 1328 | $(35.5 \pm 1.0)$/kt-y |
| | e-like | 1231 | $(37.3 \pm 1.1)$/kt-y | 1300 | $*(34.8 \pm 1.0)$/kt-y |
| **multi-GeV (FC)** | $\mu$-like | 230 | $(7.0 \pm 0.5)$/kt-y | 272 | $(7.3 \pm 0.4)$/kt-y |
| | e-like | 290 | $(8.8 \pm 0.5)$/kt-y | 286 | $*(7.7 \pm 0.5)$/kt-y |
| **multi-GeV (FC + PC)** | $\mu$-like | 531 | $(16.1 \pm 0.7)$/kt-y | 636 | $(17.0 \pm 0.7)$/kt-y |
| | e-like | 290 | $(8.8 \pm 0.5)$/kt-y | 286 | $*(7.6 \pm 0.5)$/kt-y |

**Table 1.** Summary of for sub-GeV and multi-GeV event samples in the Kamiokande and S.K. detectors.

adding informations of the $\check{C}$erenkov opening angles combined with the informations of ring pattern, the method is improved by PID (Particle Identification)-parameters to obtain a less misidentification possibility.

## 3 Our fully simulated MC calculations

The above-mentioned expressions are calculated only by the respective average number p.e. for $\theta_j, P_{\mathrm{e\ j}}$ or $\theta_j, P_{\mu\ \mathrm{j}}$. Of course, it is only natural that there exist many events where each observed p.e. number is deviated from the average owing to the fluctuations. Then the fluctuations are not only caused by Poisson distributions, but also by stochastic process in electromagnetic interactions of electon and muon. Accordingly, it is the another mistake that the S.K. group uses only ionizations and knock-on electron processis for expected p.e. numbers in the muon expression (6.8) (Kasuga, 1998). In the cylindrical fiducial volume, also, different path lengths of $\check{C}$erenkov lights being due to various differet vertex positions contribute to the fluctuations of p.e. number. In view of these reasons, we made a full MC simulations including all such fluctuations for the S.K. cylindrical detector. Then, all necessary quantities (water transparency, vertex position resolution and angular resolution etc.) follow to the values used by the S.K. group. The step size of track length is taken as 0.028 radiation length of water in electron event.

As an appropriate coordinate system we cosider x- and y-axes in a plane and the z-axis, extending perpendicular downward. So the upper circular surface is at z= 0 cm and the lower one at z= 3,400 cm. For a reference, Figs.1 & 2 show the fluctuation pattern obtained by repeating 100 times the calculations of both types of events for 5 GeV/c at z = 200 cm and $\theta = 0^\circ$. Further, the average p.e. numbers in muon cases of Fig.1 give 24,650 at z = 700 cm, 27,330 at z = 1,200 cm, 31, 400 at z = 1,700 cm, $29,100^\star$ at z = 2,000 cm, $18,100^\star$ at z = 2,200 cm and $4,900^\star$ at z = 3,000 cm. Those in electron cases of Fig. 2 are 17,300 at z = 700 cm, 19,550 at z = 1,200 cm, 22,500 at z = 1,700 cm, 25,650 at z = 2,000 cm, 29,700 at z = 2,200 cm and $23,000^\star$ at z = 3,000 cm. The

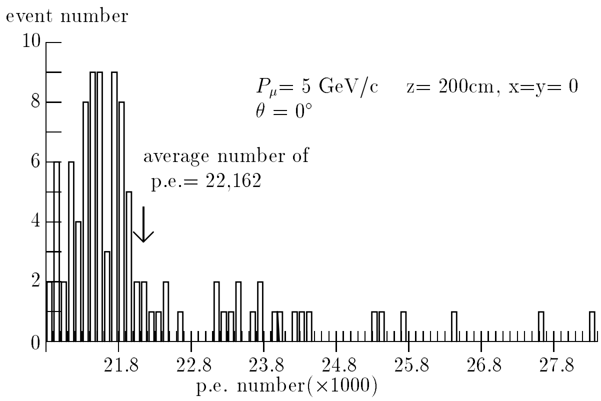


**Fig. 1.** Fluctuation beheviour of p.e. numbers for muons.

values with $\star$ show decreasing p.e. numbers to be affected by muon (electron) passing through the fiducial volume. The S.K. group uses only one value of the average p.e. number. The average values must depend on the z-value (also, on x-, y-values and $\theta$ value). However, we can not compare our average values shown in both the figures with their average ones, because they do not show such z- and $\theta$-dependent behaviours of the average values in their all papers. If forced to compare them with a relation of total number of p.e. and momentum of both events for sub-GeV region shown in Fig. 6.12 (Kasuga, 1998), the case of electron is consistent with ours between z = 1,700 cm and z = 2,200 cm, but the muon case does not consistent in those of any z value (althogh the slope is close to ours of z =2,200 cm).

We inspected $L_\mu - L_e$ distribtuions with different momenta at various z-values of starting vertex positions, keeping x = y = 0. Their calculated results are summarized with the resultant misidentification rate for electrons and muons in Table 2. The % values in the marginal notes mean ,as instance for muon, ((a number of muons mis-judged as electrons) - (a number of electrons mis-judged as muons))/number of muon eveents.

| Z(cm) | 100e/225$\mu$ | 200e/310$\mu$ | 300e/400$\mu$ | 400e/500$\mu$ | 500e/560$\mu$ |
|---|---|---|---|---|---|
| **200** | × | × | × | ◁ | ◁ |
| **700** | × | × | × | × | × |
| **1200** | ◯* | × | × | × | × |
| **1700** | ◯* | × | ◁ | △ | △ |
| **2200** | ◯* | ∘ | △ | △ | △ |
| **2700** | × | ∘ | △ | × | ◁ |
| **3000** | ◁ | △ | ◁ | × | × |
| **Z(cm)** | 600e/650$\mu$ | 800e/820$\mu$ | 1000e/1000$\mu$ | 2000e/2000$\mu$ | 3000e/3000$\mu$ |
| **200** | ◁ | ∘ | ∘ | ◯ | ◯ |
| **700** | × | ◯ | ∘ | ◯ | ◯ |
| **1200** | ◁ | ◯ | ∘ | ◯ | ◯ |
| **1700** | ∘ | ∘ | ∘ | ◯ | ◯ |
| **2200** | △ | ∘ | ∘ | ◯ | ◯ |
| **2700** | △ | △ | △ | ∘ | ∘ |
| **3000** | × | × | × | × | ◁ |

**the resultant mis-identification rate for muons;**
◯: 0 ∼ 5 %, ∘: 6 ∼ 20 %, △: 21 ∼ 60 %, ◁: 61 ∼ 95 %
×: 96 ∼ 100 %,
*: means $L\mu - L_e$ distribution with the opposite signs (plus and minus).

**Table 2.** Ł$_\mu - L_e$ distribution between electrons and muons in sub-GeV and some of multi-GeV.

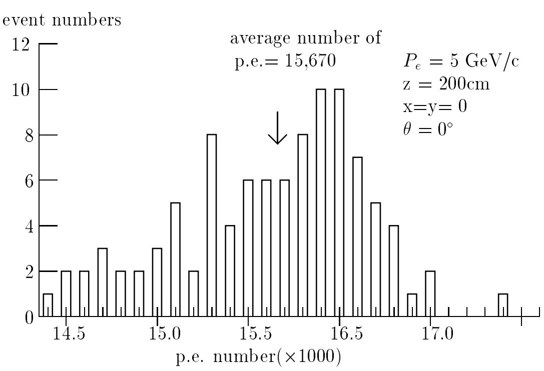


**Fig. 2.** Fluctuation behaviour of p.e. numbers for electron.

3.1 Distributions with PID parameter

For the sub-GeV/c range, we obtained PID paraameters as shown in Table 3 for cases of starting positions from z = 200 cm to 1,400 cm and from z = 200 cm to 3,000 cm for electron (muon) events with various directions of incidence $\theta = 0 \sim 30°$ and y = 0 ∼ 10 m (x = 0 cm). The number of events were 9,240 for electronns and 14,910 for muons taking into account the given intesities from the $\nu_e$ ($\nu_\mu$) energy spectra. In the table, e $\rightarrow \mu$ means that the number of electrons is mis-judged as muons and $\mu \rightarrow$ e means the opposite. The total misidetification in distinguishing between electron and muon events started at z = 200 cm ∼ 3,000 cm is $>$ 20 % for the sub-GeV/c range. For the multi-GeV region, as shwn in Table 4, the event numbers were 1,897 for electrons and 2,380 for muons related to both neutrino fluxes. We arrrve at the conclusion that even for events in the multi-GeV region the misidentification probability is $\geq$ several %, mainly by misidentifying muons as electrons, thereby increasing the $\nu_\mu$ deficit.

In the point at issue, (1) the calculation methode of S.K. group uses only the average number of p.e., neglecting the fluctuations. (2) They do not care that the fluctuation behaviours are caused by stochastic process of electrocmagenetic interactions. (3) They use only ionizations and knock-on processis for expected p.e. numbers of muons. In multi-GeV region, the stochastic process of pair productions and bremsstrahlung become important.

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| Sub-GeV region | z= 200 ∼ 1400 cm | | z= 200 ∼ 3000 cm | | z= 200 ∼ 1400 cm | | z= 200 ∼ 3000 cm | |
|---|---|---|---|---|---|---|---|---|
| | e | $\mu$ | e | $\mu$ | e | $\mu$ | e | $\mu$ |
| | 1) x= 0, y= 0 cm | | | | 2) x= 0, y= 50 cm | | | |
| event number | 4,312 | 6,958 | 9,240 | 14,910 | 4,312 | 6,958 | 9,240 | 14,910 |
| e$\to \mu$, $\mu \to e$ | 1 | 641 | 143 | 1,202 | 78 | 3,153 | 611 | 4,154 |
| increase % | 14.8 % | -9.2 % | 11.5 % | -7.1 % | 71.3 % | -44.2 % | 38.3 % | -23.8 % |
| | 3) x= 0, y= 100 cm | | | | 4) x= 0, y= 250 cm | | | |
| event number | 4,312 | 6,958 | 9,240 | 14,910 | 4,312 | 6,958 | 9,240 | 14,910 |
| e$\to \mu$, $\mu \to e$ | 75 | 3,334 | 672 | 4,411 | 98 | 3,479 | 798 | 4,615 |
| increase % | 75.6 % | -46.8 % | 40.5 % | -25.1 % | 78.4 % | -48.6 % | 41.4 % | -25.6 % |
| | 5) x= 0, y= 500 cm | | | | 6) x= 0, y= 750 cm | | | |
| event number | 4,312 | 6,958 | 9,240 | 14,910 | 4,312 | 6,958 | 9,240 | 14,910 |
| e$\to \mu$, $\mu \to e$ | 140 | 3,541 | 846 | 3,924 | 106 | 3,485 | 688 | 4,735 |
| increase % | 78.9 % | -48.9 % | 33.3 % | -20.6 % | 78.4 % | -48.6 % | 43.8 % | -27.1 % |
| | 7) x= 0, y= 10 m | | | | 8) x= y= 0 cm, $\theta = 10°$ | | | |
| event number | 4,312 | 6,958 | 9,240 | 14,910 | 4,312 | 6,958 | 9,240 | 14,910 |
| e$\to \mu$, $\mu \to e$ | 25 | 3,307 | 596 | 4,570 | 6 | 3,995 | 211 | 5,694 |
| increase % | 76.1 % | -47.2 % | 43.0 % | -26.7 % | 92.5 % | -60.2 % | 59.3 % | -36.8% |
| | 9) x=y= 0 cm, $\theta = 20°$ | | | | 10) x= y= 0 cm, $\theta = 30°$ | | | |
| event number | 4,312 | 6,958 | 9,240 | 14,910 | 4,312 | 6,958 | 9,240 | 14,910 |
| e$\to \mu$, $\mu \to e$ | 25 | 3,307 | 596 | 4,570 | 6 | 3,995 | 211 | 5,694 |
| increase % | 97.3 % | -60.3 % | 67.6 % | -41.9 % | 98.0 % | -60.7 % | 72.9 % | -45.2% |

**Table 3.** Summarized PID results for distributions between electron and muon events in the sub-GeV.

| Multi-GeV region | z= 200 ∼ 1400 cm | | z= 200 ∼ 2900 cm | | z= 200 ∼ 1400 cm | | z= 200 ∼ 2900 cm | |
|---|---|---|---|---|---|---|---|---|
| | e | $\mu$ | e | $\mu$ | e | $\mu$ | e | $\mu$ |
| | 1) x= 0, y= 0 cm | | | | 2) x= 0, y= 100 cm | | | |
| event number | 949 | 1,190 | 1,897 | 2,378 | 949 | 1,190 | 1,897 | 2,378 |
| e$\to \mu$, $\mu \to e$ | 5 | 18 | 95 | 167 | 23 | 37 | 88 | 188 |
| increase % | +1.4% | -1.1% | +3.8% | -3.0% | +1.5% | -1.2% | +5.3% | -4.2% |
| | 3) x= 0, y= 250 cm | | | | 4) x= 0, y= 500 cm | | | |
| event number | 949 | 1,190 | 1,897 | 2,378 | 949 | 1,190 | 1,897 | 2,378 |
| e$\to \mu$, $\mu \to e$ | 4 | 41 | 81 | 73 | 14 | 57 | 88 | 236 |
| increase % | +3.8% | -3.0% | -0.4% | +0.3% | +4.1% | -3.3% | +7.8% | -6.2% |
| | 5) x= 0, y= 750 cm | | | | 6) x=y= 0 cm, $\theta = 10°$ | | | |
| event number | 949 | 1,190 | 1,897 | 2,378 | 949 | 1,190 | 1,897 | 2,378 |
| e$\to \mu$, $\mu \to e$ | 18 | 118 | 102 | 309 | 7 | 13 | 84 | 58 |
| increase % | +10.0 % | -8.0 % | +10.9 % | -8.7 % | +0.4 % | -0.3 % | -1.4 % | +1.1 % |
| | 7) x=y= 0 cm, $\theta = 20°$ | | | | 8) x= y= 0 cm, $\theta = 30°$ | | | |
| event number | 949 | 1,190 | 1,897 | 2,378 | 949 | 1,190 | 1897 | 2378 |
| e$\to \mu$, $\mu \to e$ | 31 | 14 | 148 | 38 | 5 | 41 | 81 | 73 |
| increase % | +1.8 % | -1.4 % | -5.8% | +4.6% | +3.8% | -3.0% | -0.4 % | +0.3% |

**Table 4.** Summarized PID results for distributions between electron and muon events in the multi-GeV.