INGRID Analysis Technical Note

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Abstract

In this note we summarize the INGRID analysis results with 2010a data. We measured the neutrino event rate, the beam profile center and these stability for the confirmation and support of 2010a oscillation analysis. We select the neutrino interaction, mainly charged current interaction, at each module and reconstruct the neutrino beam profile. We compare some distributions between data and MC and found good agreement. We get the data/MC ratio for the event rate to be 1.074 ± 0.001(stat.) ± 0.040(syst.). The center of the neutrino beam profile found to be 0.2 ± 1.4(stat.) ± 9.2(syst.) cm for X profile and -6.6 ± 1.5(stat.) ± 10.4(syst.) cm for Y profile. Finally the off-axis angle is measured to be 2.52 degrees with the error of 0.37 mrad.

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Chapter 1

Introduction

INGRID is on-axis near detector which consists of identical 14 modules [1] to monitor the beam stability. Each module has a sandwich structure made of the iron plates and the scintillator trackers. INGRID module consists 11 tracking planes which consists 2 layers. Each layer has 24 scitillator bars and the direction of scitillator is perpendicular each other layer.

We count the number of neutrino interactions, mainly CC interaction, occurred inside the module. Based on the number of selected events for each module, the beam profile is reconstructed. Fig.1.1 shows a typical event in an INGRID module. Detector coordinates are shown in Fig.1.2. INGRID uses a right-handed Cartesian coordinate system in which the z axis is the beam direction and the y axis is the vertical upward direction. With this definition the INGRID module number is decided from horizontal modules.

In this note, we describe the measurements of

(1) neutrino event rate and its stability

(2) neutrino beam center and its stability

(3) neutrino beam direction

for the data taken from January to June 2010 (2010a data set).

This article is organized as follows. Chapter 2 explains the overview of Monte Carlo simulation.Chapter 3 explains the neutrino event selection. Finally the result of the event rate measurement, beam profile measurement and beam direction are shown in Chap. 4, Chap. 5 and Chap. 6, respectively.

[1] Additional two off-center modules and a proton module are installed after 2010a data taking.

Figure 1.1: The typical neutrino event

Figure 1.2: INGRID coordinates and the definition of the number of an INGRID module

Chapter 2

Monte Carlo simulation

Three MC simulation programs are used : JNUBEAM, NEUT and a INGRID dedicated dedetector simulation code (Fig.2.1).

- Neutrino flux prediction : JNUBEAM (version 10d tuned ver. 2)
- Neutrino interaction to materials : NEUT (version 5.0.6.)
- Detector response simulation based on Geant4 [1]

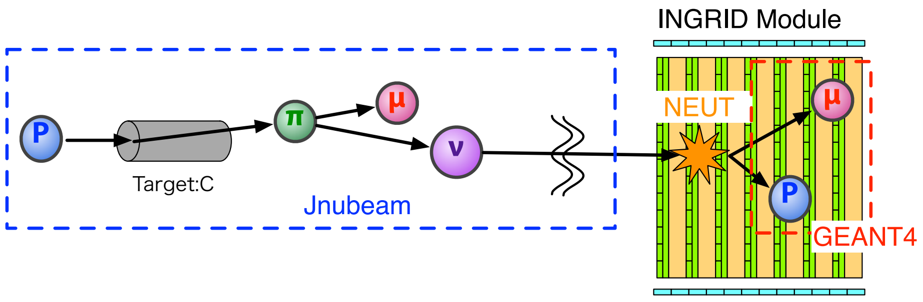

Figure 2.1: INGRID MC overview

Neutrino flux prediction

The neutrino flux at INGRID are predicted by JNUBEAM version 10d. For the detailed description of JNUBEAM, see Ref.[1]. Figure 2.2 shows the neutrino energy spectrum at the INGRID detector location. The estimated integrated neutrino flux at the INGRID center module is 5.94×10^{14} cm^{-2}10^{-21}POT (POT means "# of protons on the target ". The flux at INGRID is dominated by

[1]This INGRID MC is not the software of ND280 software packages

muon neutrinos (95%). Figure 2.3 and 2.4 show the flux energy spectrum at the INGRID center module and horizontal edge module, and the Super-Kamiokande detector, respectively. Because each INGRID module covers the different off-axis angle, the neutrino energy spectrum is slightly different at each module. Table 2.1 shows the average neutrino energy at each module and the average energy is different for about 0.2 GeV between the center module and the edge module.

Table 2.1: Average energy of neutrino flux at each horizontal modules and SK. The module # 3 is center module. The average energy at INGRID is larger than one at SK

module#	0	1	2	3	4	5	6	SK
Average energy[GeV]	1.08	1.20	1.29	1.32	1.29	1.21	1.09	0.61

Neutrino interaction simulation

Neutrino interactions with the iron plate (Fe) in the INGRID detector is simulated by the NEUT program libraries. INGRID modules include the iron targets and the scintillator targets. Currently, all the neutrino interactions at INGRID module are assumed the interactions with iron at the whole of module (the difference of the cross section is neglected). The neutrino interactions with scintillator target is under preparation. The neutrino interaction at support material is neglected. The mass ratio of the support material to INGRID module is about 1 %, its effect should be small. Simulation with correct material is under preparation. For a detailed description of NEUT, see Ref.[2].

Detector response simulation

The detector response to the generated particles from the neutrino interaction is simulated by the simulator based on Geant4. The x and y vertex position of the neutrino interaction is obtained from JNUBEAM flux file. The vertex z is uniformly generated in the iron plate and the scintillator tacker taking into account the mass ratio of iron planes (99.54 ton) to scintillator planes (3.74 ton).

Detector response simulation includes following effects.

- The conversion factor from energy deposit to the number of photon in MC simulation is tuned by adjusting the peak photoelectron (PE) of beam related sand muon. Tthe quenching effect of scintillator, attenuation of photon propagating in the fiber and MPPC response model based on [3] are also included. Figure 2.5 shows the typical PE distribution of the beam related sand muons after these MC tuning. The peak PE is well reproduced.

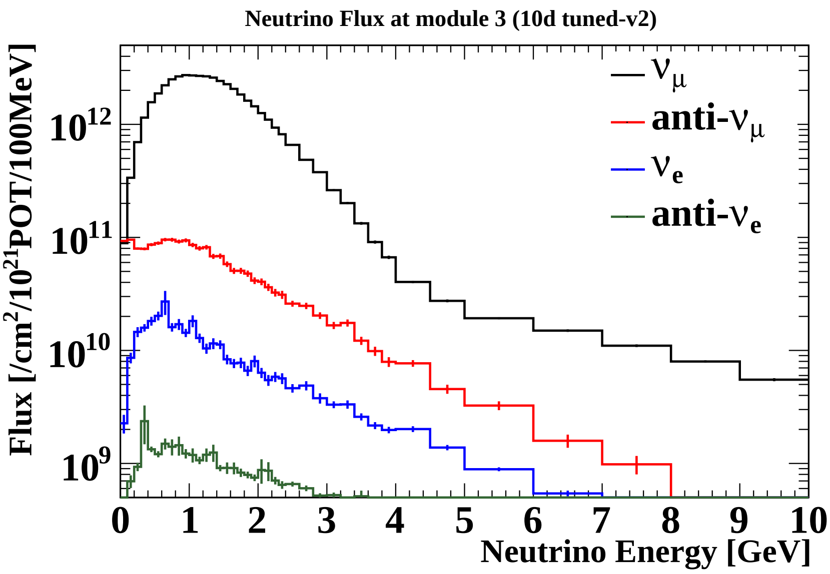

Figure 2.2: Neutrino flux energy spectrum predicted by JNUBEAM at the INGRID center module

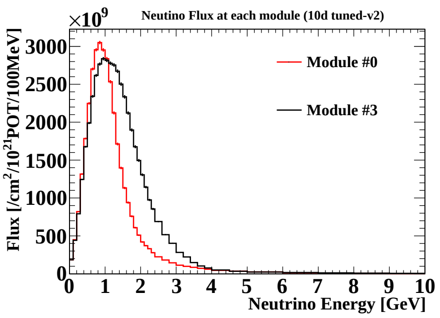

Figure 2.3: Neutrino flux energy spectrum predicted by JNUBEAM at the INGRID center module (#3) and edge module (#0)

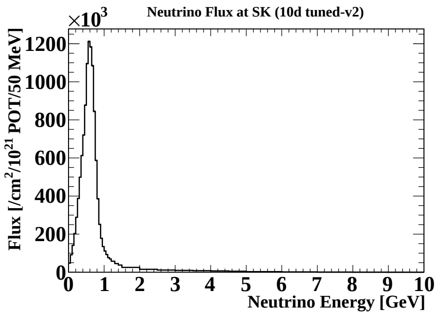

Figure 2.4: Neutrino energy spectrum predicted by jnubeam at the SK detector location

- Although the inefficiency resulted from the photoelectron statistics (light yield is $\sim$ 20 PEs at peak and the TDC threshold is 2.5 PEs) is expected to be less than 0.1%, each channel has 1 $\sim$ 2% inefficiency resulted from the gap between scintillator bars. This is studied by cosmic-ray data. In Fig.2.6, black line shows the tracking inefficiency as a function of the angle with respect to z-axis. Because the particle with small angle has more probability to go through the gap, the inefficiency becomes larger for a smaller angle track. We changed the cross-section of the scintillator bar in MC (from the simple square one to the octagon-shaped one) by reference to the real geometry (Fig.2.7) to reproduce the angular dependence of the inefficiency in data. The blue and red points in Fig.2.6 show the angular dependence of the tracking inefficiency in the MC simulation before and after the tuning, respectively. The angular dependence of the tracking inefficiency is well reproduced in MC.

- Accidental hits by MPPC dark noise result in miss reconstruction of the track and miss identification of the vertex position. As a consequence the selection efficiency is influenced by the MPPC dark noise. In MC, the MPPC noise hits are generated to reproduce the number of PE, timing, and noise rate of data. Figure 2.8 shows the timing distribution for data during the beam-off period and MC. Because the accumulation of the charge due to MPPC noise smaller than TDC threshold is increase with respect to time, the number of hits increase with respect to time. The distribution is well reproduced.

Figure 2.5: PE distribution of beam related sand muon. Left plot is MC simulation and right one is data.

Figure 2.6: Tracking inefficiency as a function of angle of the reconstructed track. Data is cosmic data.

Figure 2.7: Photo of the cross-section of the scintillator bar (left) and the cross-section in MC (right)

Figure 2.8: The timing distribution of MPPC noise. Left is data and Right is MC.

Chapter 3

Neutrino event selection

3.1 Event selection

The events at INGRID include not only neutrino events but also back ground events, for example accidental events due to MPPC noise, cosmic events, and sand muons events. The neutrino events have to be selected in those events. At this time, the long track of charged particle whose vertex is within the fiducial volume of an INGRID module is selected as the neutrino event. The beam data shown in Chap.**??** and the MC simulation corresponded to 100×10^{21} pot are used for analysis. To select neutrino events and reject back ground events, some event selections are applied to the beam data and MC. These selections are as following :

(1) Time clustering

(2) Number of active planes cut

(3) PE/(number of active layers) cut

(4) Tracking

(5) Track matching

(6) Beam timing cut

(7) Upstream VETO cut

(8) Fiducial volume cut

Theres selections are applied to a event at each module and each bunch one by one. The detail of these selections is explained in this section. In this analysis, channels having a ADC signal larger than 2.5 PE are defined as "hit".

Time clustering

Hits are clustered with the following criteria : If there are more than 3 hits within 100 nsec, all the hits within ± 50 nsec from the average time are classified into a cluster. By this clustering, the random MPPC noise hits are expected to be rejected. Other event selections (#2∼#8) are applied to each cluster. In the following, one cluster is called one event.

Number of active layers cut

The planes with at least one coincidence hit in both x and y layers are called active planes. Figure 3.1 shows the distribution of the number of active planes. The event which has more than 2 active planes are select as the signal and the back ground events due to the random MPPC noise are expected to be rejected.

PE/(number of active layers) cut

Figure.3.2 shows total PE of all hits in the active layer divided by the number of active layers (PE/(number of active layers)) after the selection with the number of active planes > 2. The events with more than 6.5 PE/(number of active layers) are selected as signal.

Tracking

Next is the explanation of the tracking method. The hits in the most downstream active x and y layer are adopted as a end-point of the track. Looking at the hits in the next upstream plane in order, the hit is selected as the track if the difference of the slope calculated from the straight line is less than 2 channels. The selected hits are fitted to a straight line by a least square method to get the angle of the reconstructed track. In this tracking, the longest track should to be selected. If there are two hits in the most downstream layers, the tracking is processed at each hit, and then select the longer reconstructed track.

Track matching

After reconstruction of the track some badly fitted tracks are rejected by considering the difference of the start point z of a 2-D track in x view and y view. Fig.3.3 shows the distribution of the difference of the start point z of the track between 2-D track in x view and y view. We require the difference smaller than 2 planes. Figure 3.4 shows the angular distribution of the reconstructed track after following track matching selection.

Beam timing cut

To reject background events such as cosmic-ray on beam off timing, the events within ± 100 nsec from the expected timing of each bunch are selected (Fig.3.5).

Figure 3.1: Number of active planes(left:DATA, right:MC normalized by area)

Figure 3.2: PE/(number of active layers) after the selection with the number of active planes > 2 (Left:DATA, Right:MC normalized by area)

Figure 3.3: Difference of the start point z of the track in x view and y view (Left:DATA, Right:MC normalized by area)

Figure 3.4: Angular distribution of the reconstructed track after all selections after the track matching selection (Left:DATA, Right:MC normalized by area)

Figure 3.5: Time residual plot after the track matching selection

Upstream VETO cut & Fiducial volume cut

Two selections are applied to reject the incoming particles produced by the neutrino interaction in upstream materials (for example the wall of the neutrino hall).

First one is the upstream VETO cut. If the VETO plane has a hit at the upstream position extrapolated from the reconstructed track, the event is rejected. Figure 3.6 shows the example of the event rejected at this selection.

After the VETO cut, fiducial volume cut is applied. The fiducial volume is the cubic volume which is defined as $\pm$ 50 cm^2 transverse area from the center of an INGRID module and from 2 to 8-th tracker(Fig.3.7). The position of most upstream hit associated with the reconstructed track is defined as the vertex of the neutrino event. The vertex is required to be within the fiducial volume (Fig.3.8 and 3.9).

Figure 3.6: The event rejected by upstream VETO selection

Figure 3.7: The definition of fiducial volume

Figure 3.8: vertex x after the upstream VETO cut (Left:DATA, Right:MC normalized by area)

Figure 3.9: vertex y after the upstream VETO cut (left:DATA, right:MC normalized by area)

Event selection summary

The number of events and the selection efficiencies at each selection step is summarized in Tab.3.1. We obtained 493813 neutrino event candidates among 2010a data set.

Table 3.1: Summary of the event selection. Data and MC are normalized by POT

	selection	Data	selection eff.	MC	selection eff.
1	# of active planes > 2	1906146		1.97×10^6	
2	PE / active layers > 6.5	1906078	(1.00)	1.97×10^6	(1.00)
3	Tracking	1804786	(0.95)	1.83×10^6	(0.93)
4	Track matching	1749548	(0.97)	1.77×10^6	(0.97)
5	Beam timing	1747181	(0.99)	1.77×10^6	(1.00)
6	Upstream VETO cut	745912	(0.43)	7.34×10^5	(0.42)
7	Vertex in fiducial	493813	(0.66)	4.73×10^5	(0.66)

3.2 Basic distribution

In this section, some distributions of the selected events are showed. In each plot the distribution of MC simulation is normalized by the area of the distribution of data. The data/MC ratio is found to be few percents at each plot.

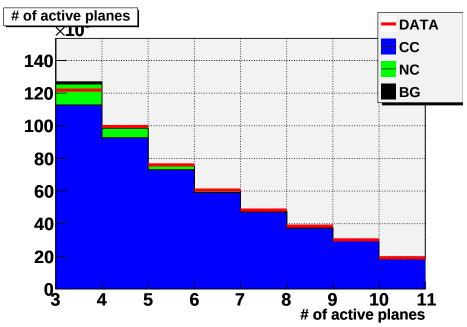

Figure 3.10: number of active planes

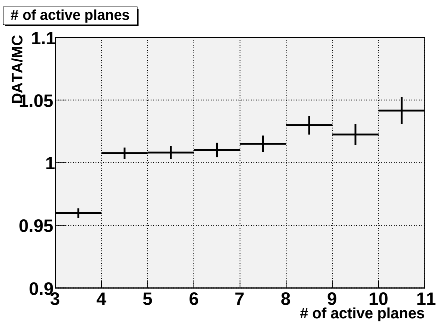

Figure 3.11: DATA/MC

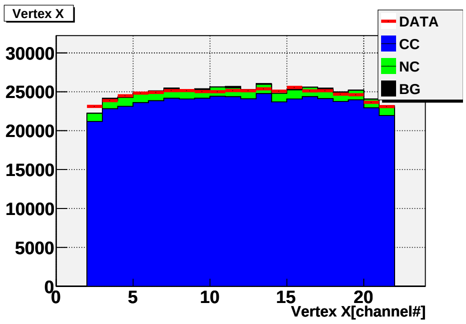

Figure 3.12: Vertex X

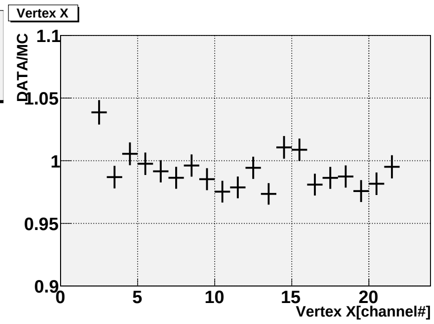

Figure 3.13: DATA/MC

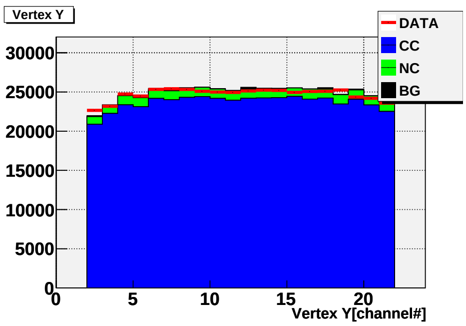

Figure 3.14: Vertex Y

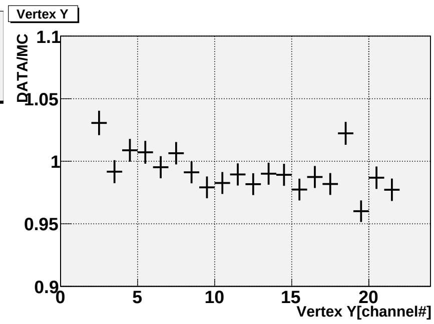

Figure 3.15: DATA/MC

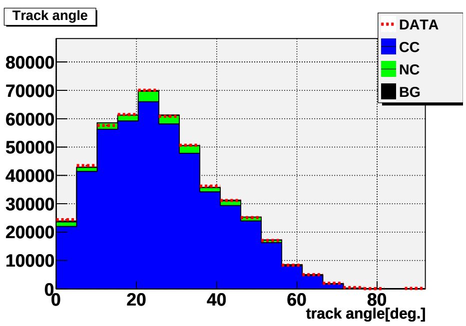

Figure 3.16: Reconstructed track angle

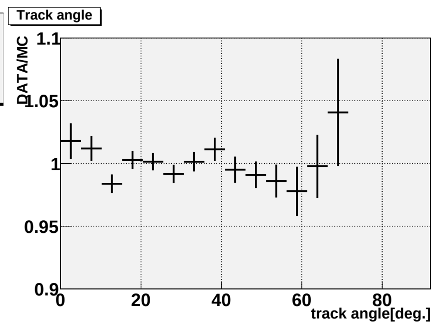

Figure 3.17: DATA/MC

3.3 Vertex resolution of tracking

Vertex resolution is checked by MC simulation to compare the reconstructed value and the MC true information. The results of vertex X, Y and track angle are shown in Fig.3.18, Fig.3.19 and 3.20, respectively. Their r.m.s. for CCQE events are 2.7 cm for X, 2.8 cm for Y and 3.8 degree, respectively.

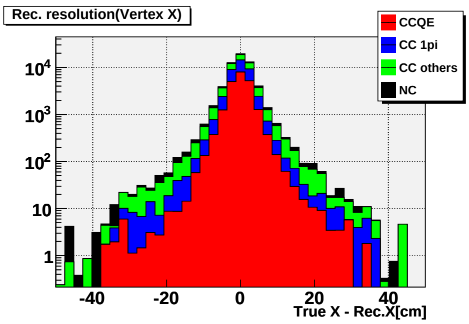

Figure 3.18: Vertex resolution in the X direction

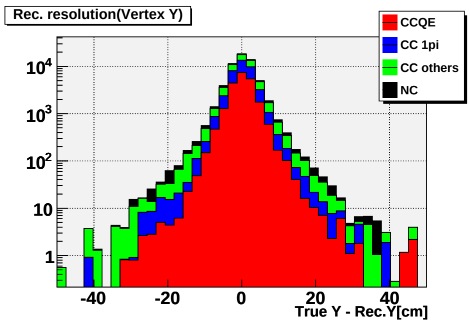

Figure 3.19: Vertex resolution in the Y direction

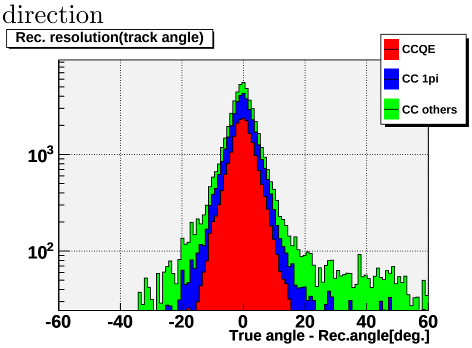

Figure 3.20: Angular resolution of reconstructed track

3.4 Detection efficiency to neutrino interaction events

The event selection efficiency as a function of the true neutrino energy is estimated by MC. The efficiency is showed in Fig.3.21 and 3.22. The definition of this efficiency is the ratio of the number of selected events to that of the events generated inside the fiducial volume. Figure 3.23 shows the selection efficiency for CC interactions as a function of the muon angle. The muon angle dependence to the neutrino energy (Fig.3.24). The acceptance for the muon angle is restricted due to the event selections, especially at large angle. The efficiency for CC interaction depends on the neutrino energy. Figure 3.25 shows the efficiency for the muons with all angle and less than 15 degrees. The selection efficiency for the muon with small angle is almost 100% and the rising edge around 0.3 GeV corresponds to the minimum energy of the muon to penetrate the 2 iron plates and 3 scintillator trackers.

Table 3.2 shows the selection efficiency for each module. Because the energy spectrum of the beam neutrino is slightly different module by module, the selection efficiency is also different.

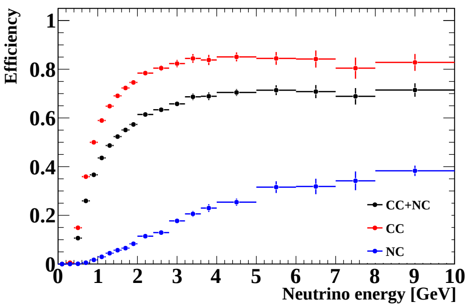

Figure 3.21: Neutrino event selection efficiency

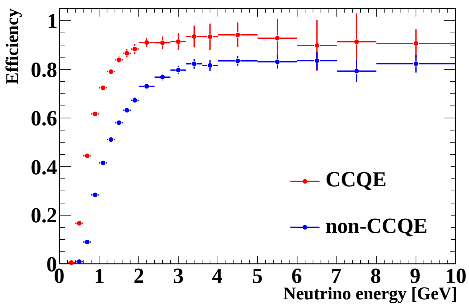

Figure 3.22: Selection efficiency for CCQE and CC others.

module	Efficiency[%]
0	51.7
1	54.0
2	55.1
3	55.1
4	55.0
5	54.2
6	51.2

Table 3.2: Efficiency of each module

Figure 3.23: The selection efficiency for CC interactions as a function of the muon angle.

Figure 3.24: The neutrino energy VS. the muon angle generated from CC interactions. Black rectangle shows the mean energy at each angular bin.

Figure 3.25: The selection efficiency for CC interactions for the muon with all angle and less than 15 degree

Chapter 4

Event rate measurements

4.1 Data set

We analyze the beam data from January to June, 2010. Data taking period, number of good spills and number of INGRID good spills are summarized in Tab.4.1. Data taking efficiency for entire period is 99.9%, and total number of protons recorded at INGRID is 3.255×10^{19}. The MC simulation corresponds to an equivalent of 100×10^{21} pot.

4.2 Event rate stability

We measured the event rate of the neutrino event candidates and the beam related dirt muon candidates with all fourteen modules. Here the dirt muon candidate is defined as the event rejected at upstream VETO selection or the fiducial volume cut. Figure 4.1 and Fig.4.2 show the daily pot and number of the neutrino event candidates, and number of dirt muon candidates, respectively. Figure 4.3 and Fig.4.4 show daily event rate normalized by pot. We succeeded to measure the daily event rate of neutrino event candidate and dirt muon

MR run #	Period	Good spills	INGRID good spills	Protons at CT05
29	Jan. 23 - Feb. 5	26813	26813	0.32×10^{18}
30	Feb. 24 - Feb. 28	59256	59070	1.12×10^{18}
31	Mar. 19 - Mar. 25	86980	86935	1.97×10^{18}
32	Arp. 14 - May. 1	237350	236647	7.64×10^{18}
33	May. 9 - Jun. 1	350079	350012	1.22×10^{19}
34	Jun. 7 - Jun. 26	246504	246410	9.30×10^{18}
Total		1006982	1005887	3.26×10^{19}

Table 4.1: Summary of data sets

candidate with about 1.7% and 1.1% statistical error each day. The chi-squares calculated from the average rate are 86 and 82 for 76 degrees of freedom. It is concluded that the beam events is stable within statistical error.

4.3 The data/MC ratio

To obtain the number of events in the fiducial volume, we need to do following corrections.

(1) Iron mass

In INGRID most of the neutrino interactions occur in the 9 iron targets of each module. During their fabrication, there was a tolerance on the thickness of those iron planes. This results in iron planes having slightly different volumes, and as a consequence different masses. The maximal variation from design mass is 2.15 % from the given tolerance on thickness. The mass of each iron plane was measured at the end of the fabrication process, so we can deduce correction factors for the expected number of events for each module, by using the fact that 95.2 % of interactions in one module occur in the iron.

(2) Accidental MPPC noise

Another correction on the number of observed events comes from noise hits in the detector. Those noise hits reduce the number of reconstructed events compared to the case when there is no noise. To correct this effect, we use the following procedure:

- Measure noise in data
- Create a noise simulation to reproduce those measurements
- Use Monte Carlo simulation to compare the number of reconstructed events with and without adding noise
- Deduce from the simulation correction factors and systematic errors

Noise is measured in beam data. We measure the rate of noise hits, which are defined as hits occuring in the detector when no particles are actually going through the detector. To find such hits, we look at cycles where beam spills are not coming (INGRID records data on 23 integration cycles, but beam spills only arrive during 6 of them), and perform regular event selection to make sure there is no cosmic particle in the detector. We then measure a noise rate for each channel of the detector, as well as light yield and timing distribution.

Noise is then simulated with a given probability for each channel. Timing for the noise hits is simulated using the distribution measured in data. Light yield is then simulated using a measured light yield distribution for the corresponding timing.

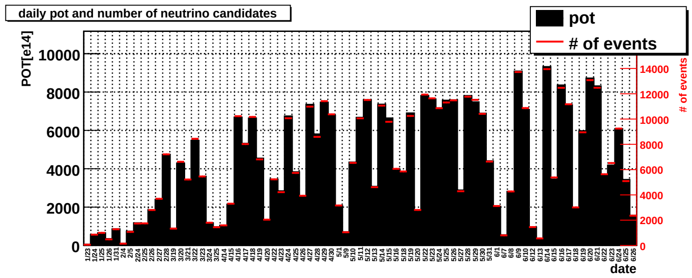

Figure 4.1: daily pot and number of neutrino event candidates

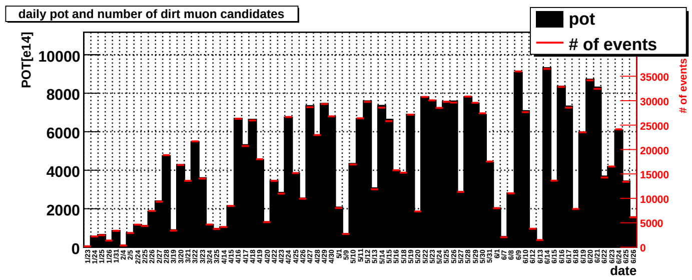

Figure 4.2: daily pot and number of dirt muon candidates

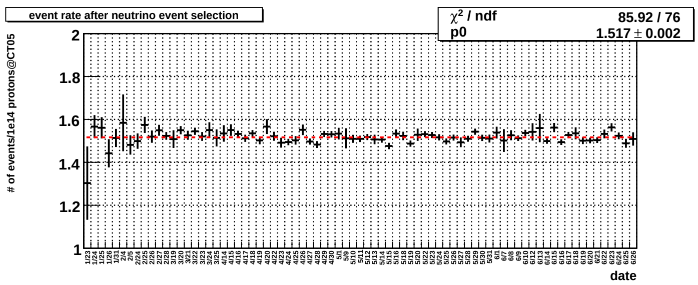

Figure 4.3: daily event rate of neutrino event candidate

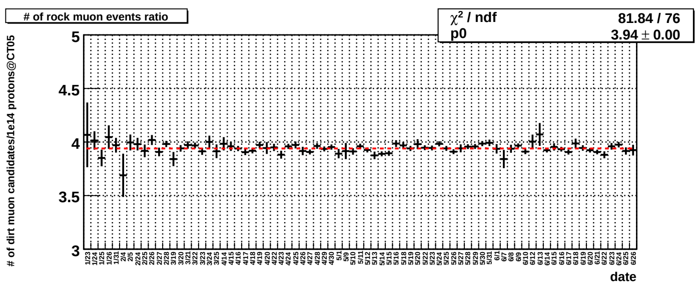

Figure 4.4: daily event rate of dirt muon candidate

Monte Carlo simulation is then used to measure the variation of number of reconstructed events due to noise. We first reconstruct events on Monte Carlo files which do not include noise hits, then add noise hits to those files and perform reconstruction again. We then compare the number of reconstructed events in each case. The simulation is using jnubeam 10c.

From this simulation we have for each module a noise rate and the variation of number of reconstructed events due to noise. There is a linear relation between them as can be seen on Fig.4.5. We will use this linear relation to make corrections on the number of observed events. This relation is:

$$\text{Variation of number of events [\%]} = -0.9585 * < \text{noise rate} >$$

Those corrections are made for each module, and each subset of events we are considering. In each case we measure the noise rate, and then from the linear relation deduce the variation of number of reconstructed events which should be used as a correction factor.

Figure 4.5: Variation of number of reconstructed events as a function of noise rate

(3) Beam related background

We estimated the contamination fraction of beam related background with background MC in which the neutrino flux and the neutrino interaction is generated in upstream dirt (10 x 10 x 5 m^3).

Almost all contaminations come from short track induced neutron ($\sim$ 50%) or gamma ($\sim$ 40%) and dirt muon ($\sim$ 10%) which is not detected accidentally due to scintillator inefficiency.

In background MC, number of generated interactions is normalized so that the number of rejected events at upstream VETO selection, which consists dirt muon mainly, is equal to DATA. The difference from POT expectation is 35% and it is considered as systematic error. Finally contamination fraction is estimated to be 0.4% and it is applied as one of the correction factor.

The correction factors are summarized in Tab.4.2 run by run and module by module. In this table the corrected number of selected events ($\mathrm{N}^{\mathrm{cor.}}$) is calculated with $\mathrm{N}^{\mathrm{cor.}} = \mathrm{N}^{\mathrm{sel.}} \times \frac{1}{1+\mathrm{C}}$, where $\mathrm{N}^{\mathrm{sel.}}$ is the number of selected events and C is the correction factor. The final result is summarized in Table 4.3. Finally we obtain DATA/MC to be 1.074 ± 0.001 (stat.).

	module	29,30	31	32	33	33	34
number of selected events	0	1054	1548	5956	4119	5425	6962
	1	1526	2033	7827	5432	7122	9520
	2	1875	2476	9360	6492	8555	11622
	3	1882	2570	10133	6795	9078	12191
	4	1831	2459	9627	6636	8683	11651
	5	1524	2176	7876	5421	7217	9588
	6	1058	1585	5837	4172	5421	7285
	7	1229	1717	6636	4509	5826	8100
	8	1588	2187	8351	5819	7620	10270
	9	1884	2562	9770	6632	8766	11946
	10	1949	2681	10305	6987	9373	12473
	11	1908	2520	9771	6713	8897	11871
	12	1561	2133	8146	5512	7193	9822
	13	1218	1659	6263	4327	5815	7734
correction factor	0	-3.3	-3.3	-4.3	-4.0	-3.9	-3.9
	1	-2.6	-2.6	-2.6	-2.4	-2.4	-2.4
	2	-2.0	-2.0	-2.0	-1.7	-1.7	-1.7
	3	-2.3	-2.3	-2.3	-2.0	-1.9	-1.9
	4	-1.8	-1.8	-1.8	-1.6	-1.5	-1.5
	5	-1.9	-1.9	-1.9	-1.6	-1.5	-1.4
	6	-2.3	-2.3	-2.8	-2.5	-2.4	-2.3
	7	-2.7	-2.7	-2.5	-3.5	-3.3	-3.1
	8	-2.2	-2.2	-2.0	-3.0	-2.8	-2.6
	9	-2.1	-2.1	-2.7	-4.1	-3.8	-3.6
	10	-4.2	-4.2	-4.1	-5.4	-5.2	-5.0
	11	-1.9	-1.9	-1.8	-2.9	-2.7	-2.6
	12	-4.9	-4.9	-4.7	-6.2	-6.0	-5.9
	13	-2.5	-2.5	-2.5	-3.4	-3.2	-3.0
corrected number of selected events	0	1090	1601	6224	4292	5647	7242
	1	1567	2087	8037	5565	7298	9756
	2	1913	2526	9551	6606	8703	11822
	3	1927	2632	10374	6934	9255	12422
	4	1865	2504	9804	6741	8817	11825
	5	1553	2218	8028	5509	7328	9697
	6	1083	1622	6002	4278	5552	7453
	7	1263	1765	6803	4674	6024	8360
	8	1624	2237	8520	6001	7838	10545
	9	1925	2617	10040	6912	9110	12391
	10	2035	2800	10742	7385	9883	13130
	11	1945	2569	9951	6914	9143	12183
	12	1641	2242	8550	5878	7653	10435
	13	1250	1702	6421	4478	6005	7976

Table 4.2: Correction factors

Number of selected events	493813
Corrected number of events	508511
Number of selected events in MC	4.733e5

Table 4.3: Number of events before and after corrections

4.4 Systematic error of event rate

Table 4.4 shows the systematic errors.

Item	Error[%]
Iron mass	0.1
Accidental MPPC noise	0.7
Beam related background	0.2
Fiducial selection	1.1
Hit efficiency	1.8
Tracking efficiency	1.4
Track matching selection	2.7
Not beam-related background	<0.1
p.e./active layer selection	<0.1
Beam timing selection	<0.1
Total	3.7

Table 4.4: Systematic error table

Iron mass

Before construction of INGRID the mass of each iron plate was measured with a precision of 1 kg, which corresponds to 0.13 % of the mass of one iron plate. We will use this figure as the systematic error on this correction factor. We might need to increase this systematic error in the future, as the correction factors are calculated using the mass of the whole iron plate, when we actually use a fiducial cut in analysis, only interactions in the central part of the iron plates are kept.

Accidental MPPC noise

The effect of MPPC noise is studied with MC as discussed at previous chapter. Two sources of systematic errors are considered. First one comes from the error on the linear fit. To get this systematic error, we multiply the fit error by the maximal measured noise rate. Second one comes from the measurement of noise. Correction factors are calculated using the average noise rate measured on one period. But this noise rate fluctuates in time (probably due to temperature variations). So we measure the maximal difference between average noise rate and noise rate measured at different times during one period, and using the linear relation between noise rate and variation of number of events we get the systematic error. The quadratic sum of these two errors is 0.7 %.

Beam-related background

We estimated the contamination fraction of beam related background with wall neutrino Monte Carlo. The fraction is estimated to be 0.4% , in which the number of interactions of background is normalized to compare the number of dirt muon in DATA and MC. There is a 35% difference from POT expectation, which is considered as one of the source of the systematic error. We considered 20% neutrino flux uncertainty and 20% cross section uncertainty as other sources of the systematic error. Finally 0.2% ($=\sqrt{0.35^2 + 0.2^2 + 0.2^2}$) is applied as the systematic error.

Fiducial selection

To estimate the uncertainty of fiducial selection and the effect of non uniformity of iron plate, we divided fiducial in several horizontal slices and checked the difference between DATA and MC. Table 4.5 shows the result. The maximum absolute value, 1.1%, is applied as systematic error.

selection	DATA	MC	$\vert$DATA - MC$\vert$
<50 cm from center(nominal selection)	100.0	100.0	0.0
<25 cm	25.6	25.2	0.4
25 $\sim$ 40 cm	39.9	39.3	0.6
40 $\sim$ 50 cm	34.4	35.5	1.1
Systematic error (Maximum absolute)			1.1

Table 4.5: DATA-MC for several sub fiducial volume

Hit efficiency

We estimated the relation between hit efficiency and number of selected events with MC. Fig. 4.6 shows the result from which the systematic error of hit efficiency is estimated to be 1.8% because hit efficiency has 1.1% uncertainty. [1]

Track matching selection

In the neutrino event selection, after reconstruction of XZ track and YZ track we require track start point matching. To estimate the uncertainty of the selection, we changed the tolerance for the matching and checked the difference of the

[1] 0.5% of the measurement error of hit efficiency, 1.0% of the tuning of hit efficiency in MC

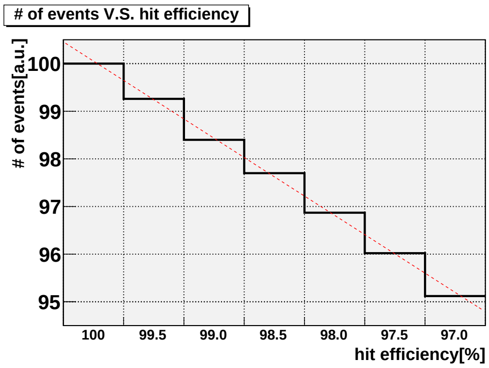

Figure 4.6: hit efficiency V.S. number of selected events

number of selected events between DATA and MC. Table 4.6 shows the result. The maximum absolute value, 2.7%, is applied as systematic error.

Vertex Z of XZ track - Vertex Z of YZ track	DATA	MC	|DATA - MC|
-1, 0, +1 (nominal selection)	100.0	100.0	0.0
0	83.0	85.7	2.7
-2, -1, 0, +1, +2	104.0	103.0	1.0
Systematic error (Maximum)			2.7

Table 4.6: DATA-MC for several tolerance of track matching.

Tracking efficiency

To check the difference of the tracking efficiency between DATA and MC, the tracking efficiency is compared with several sub-sample selected by number of active planes. Table 4.7 shows the result. The maximum absolute value, 1.4%, is applied as systematic error.

Not beam-related background

The off-bunch data (cycle 17 $\sim$ 22 where as on-bunch cycle is 4 $\sim$ 9) are analyzed with same procedure and only 93 events are selected whereas the number of signal is 493813. It is negligible.

PE/active layer selection

To estimate the uncertainty of PE/active layer selection, we changed the cut value and checked the difference of number of selected events from one with

number of active planes	DATA	MC	$\lvert$DATA - MC$\rvert$
3	87.6	86.9	0.7
4	93.2	91.8	1.4
5	94.7	94.3	0.5
6	95.6	96.2	0.6
7	96.2	96.6	0.4
8	96.7	96.8	0.1
9	98.7	97.9	0.8
10	99.1	99.0	0.1
Systematic error (Maximum)			1.4

Table 4.7: The tracking efficiency of DATA and MC with several sub sample

nominal cut. The result is the difference is less than 0.01% and its uncertainty is negligible.

beam timing selection

To estimate the uncertainty from neutrino beam timing, we changed the cut value and checked the difference of number of events from nominal cut. The difference is less than 0.01% and it is negligible.

Chapter 5

Measurements of beam profile

We measured the beam profile on a monthly basis, which corresponds to MR run number. Fig.5.1 shows horizontal and vertical beam profile with RUN 32 data. We fit the profile with gaussian function with least square method and fitted center and sigma are applied as beam center and beam width, respectively.

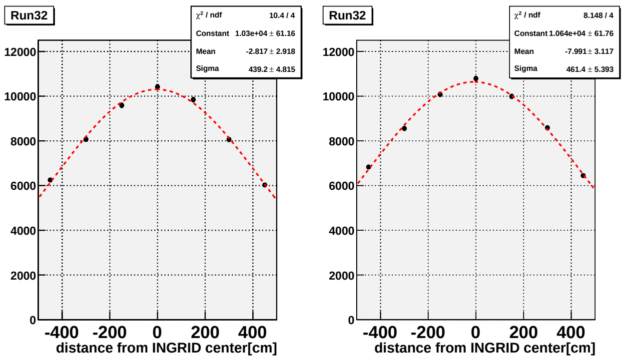

Figure 5.1: Horizontal profile(left) and vertical profile(right)

5.1 Stability of beam center

Figure 5.4 shows the monthly x center and Fig.5.5 show the monthly beam y center. We succeeded to measure the profile center with about 4.2 cm statistical error for each month. The chi-square calculated from the average rate are 4.1 for 5 degrees of freedom for x beam centers and 3.8 for 5 degrees of freedom for y beam centers. It is concluded that the beam center is stable within statistical error.

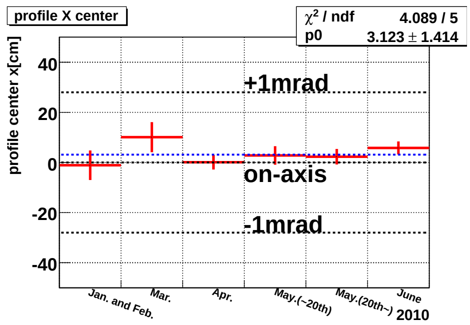

Figure 5.2: Horizontal profile center.

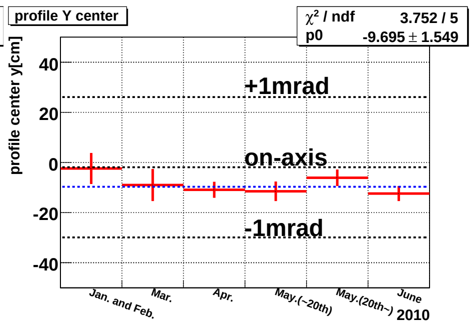

Figure 5.3: Vertical profile center

5.2 The systematic error of beam center

We estimated the systematic error using the toy profile MC simulation in which the number of events at each module is varied with 3.7% from original profile made by all the beam data. 100'000 profiles are generated and the beam center is measured with same method as the data analysis. Figure 5.4 and Fig.5.5 show the x center distribution and y center distribution, respectively. The RMS is applied as the systematic error. The result shows 9.2 cm for x center and 10.4 cm for y center.

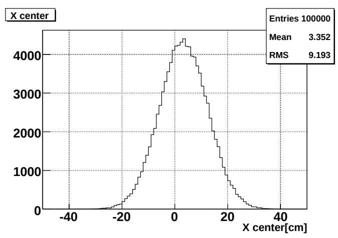

Figure 5.4: Fitted Horizontal center with 100'000 profiles

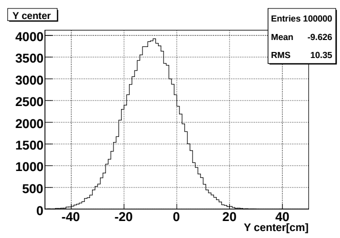

Figure 5.5: Fitted Vertical center with 100'000 profiles

Chapter 6

Measurement of beam direction

The beam direction is measured as a direction from the proton beam target to the beam center measurements summarized in Tab.6.1. Table 6.2 shows the result of survey of the positions of proton beam target, the center of INGRID horizontal modules and vertical modules (based on the result put on [4]). With these measurements we calculate the beam direction and result is shown in Tab. 6.3; Depression angle is 3.651 ± 0.0216 degrees and direction angle is 270.475 $\pm$ 0.0190. Table 6.3 shows also the result of survey of the angle between the target and the SK detector. Finally the off-axis angle is obtained to be 2.519 ± 0.021 degrees (43.96 ± 0.37 mrad).

Table 6.1: Summary of beam center measurements

	X center	Y center
Measurement	+0.2 ± 9.3	-6.6 ± 10.5

Table 6.2: The position with the NEUT coordinate system

	X[m]	Y[m]	Z[m]
Target	0	0.30603	-4.62
INGRID H center	-0.000863	-17.55557	277.36844
INGRID V center	-0.038371	-17.38257	273.35956

Table 6.3: Direction from the proton beam target and SK

	Depression[degree]	Direction[degree]	Angle from SK[degree]
SK	1.260	270.475	-
INGRID center	3.637	269.681	2.506
INGRID measurement	3.651 ± 0.0216	270.475 ± 0.0190	2.519 ± 0.0213 (43.96±0.37 mrad)

Chapter 7

Conclusion

In this note we have presented the measurement of the neutrino event rate, profile center in INGRID during and beam direction with 2010a data. We selected the neutrino interactions to reconstruct the long track started within fiducial volume. The results have been compared to MC and found good agreement with DATA. Finally DATA/MC of the event rate and beam profile centers have been evaluated with an associated systematic error:

$$
\begin{aligned}
\mathrm{R}_{\mathrm{DATA/MC}} &= 1.074 \pm 0.001(\mathrm{stat.}) \pm 0.040(\mathrm{syst.}) \\
\mathrm{Xcenter} &= +0.2 \pm 1.4(\mathrm{stat}) \pm 9.2(\mathrm{syst.})\mathrm{cm} \\
\mathrm{Ycenter} &= -6.6 \pm 1.5(\mathrm{stat.}) \pm 10.4(\mathrm{syst})\mathrm{cm} \\
\mathrm{offaxis\ angle} &= 2.519 \pm 0.021\mathrm{degrees} \\
&= 43.96 \pm 0.37\mathrm{mrad}
\end{aligned}
$$

Bibliography

[1] will be put the name of jnubeam tech. note

[2] will be put the name of NEUT doc.

[3] the report by Calibration group of ND280 working group put on http://www.t2k.org/nd280/calib/Meetings/Jan10Workshop/MPPClinearity/at_download/filet2k.org).

[4] http://www.t2k.org/beam/NuFlux/GeometryInformation