Charged-current inclusive distributions from K2K near detectors

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K2K, a long-baseline neutrino-oscillation experiment between KEK PS and Super-Kamiokande (SK), employs two near-site neutrino detectors: a SK-like water Cherenkov detector and a detector complex of a scintillating fiber tracker and a muon range detector. In this talk I describe data of these front detectors in detail. The distributions of muons, a product of charged-current inclusive interactions of neutrinos via nuclei, $\nu_\mu + N \to \mu + X$, are shown in a comparison with our standard Monte Carlo simulation results.

1. K2K NEAR DETECTOR

K2K is the first long-baseline neutrino oscillation experiment in operation[1]. A wide-band neutrino beam is produced by the KEK 12GeV PS. The far detector is Super-Kamiokande (SK), a $50kt$ water Cherenkov neutrino detector in the Kamioka zinc mine, located 250 km west from KEK. Data taking was started in early 1999, and we gradually accumulated data until July 2001. Delivered protons on the target was 5.6×10^{19} in total.

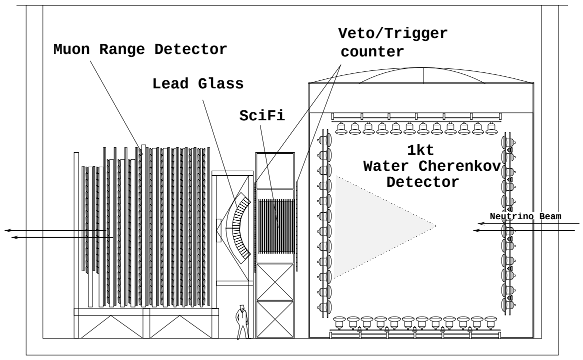

Figure 1. K2K near detector system, $1kt$ (right) and FGD (left, composite of SciFi, VETO, LG, and MRD). The whole setups are in a $24m\phi$ - $16m$ deep well-like hall, so that the neutrino beam, being tilted about -1° towards the direction of Kamioka, will pass through the detector center.

In order to investigate neutrino beam properties at production, we have established a near detector system in KEK. It is located $300m$ downstream from the primary target, after $200m$ of a pion decay pipe and a beam dump. It consists of two independent detectors: a water Cherenkov detector ($1kt$) and a tracking detector with fine granuarity (Fine-Grained Detector, FGD). These near detectors have accumulated data of neutrino-nucleus interactions with significant statistics, whose cross sections are not well determined[2] and are one of the main interests of this workshop.

1.1. Water Cherenkov detector (*1kt*)

$1kt$ is a miniature of SK with a 1/50 volume. It aims to take data which can be directly compared with the SK data by using the same type of detector and by common analysis procedures. Inside of a $8.6m\phi$-8.6m height sylinder, 680 of 20" PMTs are arranged in the same 70cm lynning as the SK. The inner volume is 496 tons of purified water. To choose a single interaction per spill (the event rate in the full volume is 0.2/spill), a flash-ADC records the analog sum of all PMTs. The interaction vertex reconstruction, Cherenkov ring counting, and μ-like / e-like identification of each ring are performed by the same methods as in SK[3].

*On behalf of the K2K collaboration.

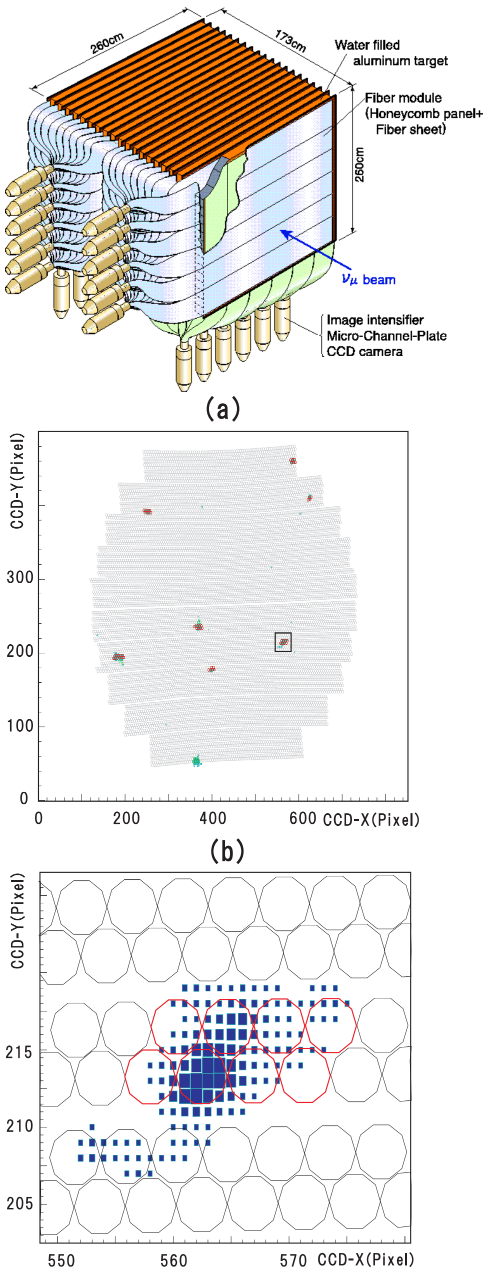

Figure 2. Schematic view of the scintillating fiber tracker (SciFi). (a) A typical CCD image of an IIT from a cosmic-ray event. (b) An expanded view of (a) for a typical SciFi hit. Hit fibers are represented by the red lines. A hit is defined as a cluster of neighboring hit fibers.

1.2. Fine-Grained Detector (FGD)

FGD aims to measure neutrino interactions precisely by using a tracking-type device. It consists of a scintillating fiber tracker (SciFi), plastic scintillator veto counters surounding SciFi, an electromagnetic calorimeter of 600 lead glass blocks (LG) and a muon range detector (MRD).

SciFi[4] is in $2.6m \times 2.6m \times 1.7m$ rectangular shape. It is composed of 19 layers of $6cm$-thick water containers, sandwiched with $20\times(yy\text{-}xx)$ layers of $700\mu m\phi$ scintillating fibers. The full weight of the sensitive volume is $8.6t$. All of the fibers are bundled and attached to 24 image intensifier tubes. CCD pixel images are analyzed for hit and track reconstruction (Fig. 2).

MRD[5] is used to measure the momentum of a muon coming out from SciFi by it's range. It is a sandwitch of 12 iron plates ($10cm\times4$ + $20cm\times8$) with drift chambers, covering a $7.6m\times7.6m$ transverse area of the beam. The total mass is 915 tons. MRD contained events are also important to monitor the neutrino beam stability for the rate and for profile.

2. MONTE CARLO

The Monte Carlo simulation of the K2K experiment takes place in three separate steps: *1.* beam simulation, *2.* neutrino interaction with nuclei, and *3.* detector simulation.

2.1. Beam simulation

The input of the beam simulation is the proton beam emittance measured by two silicon pad ionization chambers between the last beamline magnet and the target horn. π^+, π^- / K^+, K^-, K^0 production in an *Al* target is simulated by the Cho model[6], which is based on empirical formula by Sanford and Wang[7]. Fig.3(a) shows comparisons of the pion production differential cross sections, $d^2\sigma/d\theta_\pi dp_\pi$ in the $\theta_\pi = 0 \sim 12^\circ$ region, between those calculated by the formula and those by experimental data[9]. The π^+s, focused by two horn magnets, decay into μ and ν_μ in 200m of a decay pipe filled with helium gas. This two-body decay process is simulated by GEANT[8] correctly. Contributions from kaons, $K^+ \to \mu\nu_\mu$ etc., are relativelly quite small. As

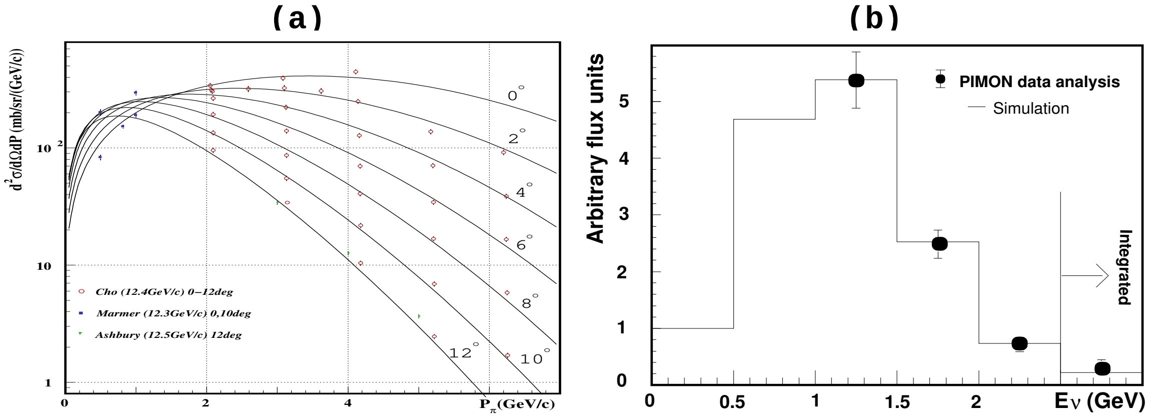

Figure 3. (a) Pion production differential crosssection. The dots are the experimental data[9] and the solid lines are by a compilation fit using mainly Cho *et al.*[6]. (b) Expected neutrino flux at KEK near site detectors. The solid histogram is by a beam simulation and the data points are by a pion beam monitor (PIMON) analysis, normalized by the area above 1 GeV.

a result, we expect an ~98% pure wide-band ν_μ beam with an average energy of E_ν= 1.3 GeV.

We have a gas Cherenkov monitor of pions (PIMON) just after the second horn, which can validate the simulation[10]. It uses a freon gas vessel with a pie-shaped spherical mirror inside. The pressure is controlled so as to change the refractive index, *i.e.* the momentum threshold to pions. Cherenkov light reflected by the mirror is focused onto multi-anode PMTs. By analyzing the Cherenkov ring images with various refractive indices, we can obtain accumulated distributions of the momentum and angle with respect to a beam of produced pions. The neutrino flux is deduced from pion decay kinematics.

Fig.3(b) shows the expected neutrino flux at the front detector site, where the histogram is produced by the beam MC results and dots are by a PIMON analysis. To avoid background from primary 12 GeV protons, the PIMON sensitivity is limited to p_π greater than 2 GeV/c. It corresponds to a 1 GeV threshold on the neutrino energy. In the 1.0 GeV $< E_\nu <$ 2.0 GeV region, the errors are estimated to be $\sim \pm 10\%$.

2.2. Simulation for neutrino interactions

For a simulation of neutrino interactions via nuclei, K2K employs the simulation code NEUT, which has been used for SK atmospheric neutrino analysis. The code was originally developped for the old Kamiokande experiment to simulate the atmospheric neutrino *background* for the nucleon decay signal[11],[2] and as of its nature it treats the neutrino interactions, and also the final-state interactions of the produced hadrons inside of ^{16}O nuclei.

Because details about NEUT will be given in the MC session of the current workshop[13], I describe minimum information here. Limiting the story to the charged current interactions, the following four types of interactions are taken into account in the code.

Quasi elastic scattering (CCQE) $\nu + n \rightarrow \mu^- + p$. We treat it by following the notation by Smith[14]. The q^2 dependence ($q \equiv p_\nu - p_\mu$; 4-momentum transfer) of the cross section can be expressed by a hadronic current, which is described by the vector and axial vector form

[2] $1kt$ data provides good opportunity to study proton decay background[12].

factors. The ep collision experiments determine the vector form factor in the form $1/(1-\frac{q^2}{M_V^2})^2$ with $M_V = 0.84$GeV. The axial vector form factor is in the form $-1.23/(1-\frac{q^2}{M_A^2})^2$, where the axial vector mass (M_A) is to be determined by experiments. Currently, we use M_A=1.01 GeV/c^2[15], based on experiments[16,17].

1 π production through baryon resonances (CC1π) $\nu+N\to\mu^-+N^*\to\mu^-+N'+\pi$; $W\leq 2.0$ GeV. We adopt the Rein & Sehgal calculation[18]: Based on FKR's relativistic quark model[19], 18 baryon resonant states with mass below 2 GeV/c^2 are taken into account as N^* with interferences among them. Here, the vector and axial form factors also appear in the resonance transition matrix elements. We use the same M_V and M_A values as those for CCQE.

Multi π production (CC$m\pi$) $\nu+N\to\mu^-+N'+m\pi$; $W > 1.4$ GeV. The cross section is calculated under the assumption of Bjorken scaling with the form factors[20] calculated by the parton distribution functions[21]. In the $W \leq 2.0$ GeV region, the pion multiplicity is determined based on experiments[22,23]

Coherent π production $\nu+{}^{16}O\to\mu^-+{}^{16}O+\pi^+$. We treat this based on the Rein & Sehgal model[24].

As for the ^{16}O target, Fermi motion of the nucleon, nuclear potential, and the Pauli blocking effect for the final state nucleon are simulated. For the produced pions, interactions inside of the nuclei are simulated by the Fermi-gas model.

Recently, we have implemented re-scattering of recoil protons inside of the nuclei, whose contribution is found to play an essential role for the SciFi observation[25].

2.3. Detector simulation

Tracking of the outgoing particles produced by the neutrino interactions is done by GEANT[8]-CALOR[26].

3. COMPARISON OF DATA AND MONTE CARLO DISTRIBUTIONS

Here, I present the distributions of the muon momentum (p_μ) and angle with respect to the beam direction (θ_μ) obtained by the front detectors. I also show the q^2 distributions assuming CCQE kinematics. There are three kinds of event categories, *i.e.* (a) 1*kt* FC 1Rμ-like events, (b) SciFi-MRD events, and (c) MRD-contained events.

3.1. Event selection criteria and statistics

The event selection criteria for each event category are as follows, respectively:

(a) *1kt* FC 1Rμ-like event

- Events with >1000$p.e.$ ($\sim$ 100 MeV) single peak in the Flash-ADC(FADC) are chosen. It is used to extract a single interaction in a spill.
- The reconstructed vertex is inside of a cylindrical volume along the beam, $-2m < z < 0m$, $r < 2m$ (fiducial volume mass=25t). By these two cuts, the efficiency for those events which have an interaction vertex in the fiducial volume is *eff*=75%.
- The total light yield of all PMTs should be in the range of 2000$\sim$16000$p.e.$.
- The maximum response of the inner PMTs is less than 200 $p.e.$. It is used to extract fully contained (FC) events, with it's track endpoint inside of the inner detector (FC/Fid.all=75%).
- At last, events with a μ-like single ring pattern are chosen (FC1Rμ-like/FC=47%).

The 1*kt* has 4π acceptance, and has sensitivity to the low muon momentum region (p_μ <1 GeV). In a strict sense, the events are not CC-*inclusive* due to the requirement of a single ring (this is to avoid complexity to treat multi ring systematics). However, it is to be noted that in our relevant energy region a recoil proton track is usually not seen / reconstructed due to the Cherenkov threshold ($p_{thr.}$ $\sim$1.1 GeV/c), and

Table 1
Event rate summary at the near detectors for each event category (November 1999 - July 2001).

	target material	fiducial mass(t)	live time $p.o.t.(\times 10^{19})$	Number of Events
(a) *1kt* FC1Rμ-like	H_2O	25	4.292	36,056
(b) SciFi-MRD	H_2O	5.9	3.970	8,340
(c) MRD-contained	Fe	73	4.192	124,944

Detail of the event selection for each detector is given in the main text.

thus the CCQE interaction is usually identified as a single ring event.

(b) SciFi-MRD event

- A vertex with track(s) with a length ≥ 3 SciFi layers is reconstructed. The fiducial volume is defined as a rectangle with Δx and $\Delta y \leq 1.1m$, covering the 1^{st} to 17^{th} water containers (fiducial mass= 5.9 t).
- A SciFi track should match to a hit of the downstream veto/trigger counters: This guarantees that the interaction is in a beam spill.
- The track also should match to a LG cluster, and to a MRD track and/or hit cells.

The last condition guarantees that the track passes the LG cells, and is thus a muon. At the same time, the cut limits the p_μ sensitivity in the range greater than $\sim$ 500MeV/c. In order to get the CC-*inclusive* distribution, we do not apply the number of track cuts at all. With all of these cuts, the *net* efficiency in the fiducial volume is $\sim$45% for the CCQE interactions and $\sim$31% for the CC-*inclusive* interactions.

(c) MRD-contained event

- The track should pass $\geq$2 iron layers. This guarantees that the track is a muon.
- The vertex, *i.e.* track start point, should be in the $1^{st}\sim 3^{rd}$ iron layer within Δx, $\Delta y \leq 3m$ (fiducial volume mass = $73t$).[3]

[3]This fiducial volume definition is to enhance efficiency of MRD contained events. A larger fiducial volume, the $1^{st}\sim 9^{th}$ layer with mass $329t$, is also used to measure beam profile and it's stability.

The MRD events provide the neutrino inetarctions with iron. With these cuts, outgoing hadrons are usually not reconstructed, and CC-*inclusive* events are thus identified as events with a single muon track.

The fiducial mass, live time $P.O.T.$, and observed number of events of each event category during November 1999 $\sim$ July 2001 data taking period are summarized in Table.1. To avoid complexity, hereafter I call (a) $1kt$ events, (b) SciFi events, and (c) MRD events, respectively.

3.2. P_μ and θ_μ distributions

Plots presented hereafter are not corrected by efficiencies. The Monte Carlo distribution is overlayed by entry normalization.

As a systematic error source, we take the energy scale uncertainty into account in a very simple way: We shift the distribution in the x-axis direction by a factor of δ_e, $p_\mu \to p_\mu \times (1 \pm \delta_e)$, and recognize the difference of each bin from the original one as the error we want. δ_e, the scale uncertainty, is set to be 5%, 3%, and 3% for $1kt$, SciFi, and MRD, respectively. Note that the errors coming from the Monte Carlo simulation (*ex.* errors coming from neutrino flux estimation), are *not* taken into account.

Fig. 4 shows the p_μ distributions for each event category. (a) $1kt$ shows good agreement between the data and MC. As I described, high p_μ cutoff is by the FC requirement. For (b) the SciFi and (c) the MRD data distributions, the low momentum cutoff is caused by (b) matching to the MRD track/hit, and (c) the track length cut, respectively.

The energy scale error for MRD(3%) is obtained by taking the weight precision (1%) and

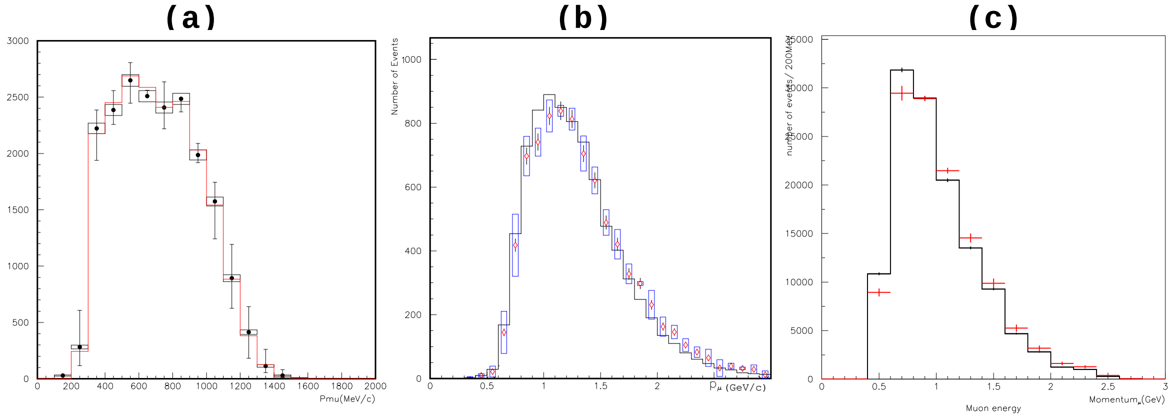

Figure 4. Muon momentum distributions for (a) 1kt, (b) SciFi, and (c) MRD. The solid line histogram is the Monte Carlo distribution overlayed by entry normalization. The errors shown here are (a) the statistical error (*box*) and ±5% of the energy scale error (*bar*), (b) the statistical error (*bar*) and ±3% of the energy scale error (*box*), and (c) combined error of statistical and ±3% energy scale. In (c) the MC statistical errors are also given.

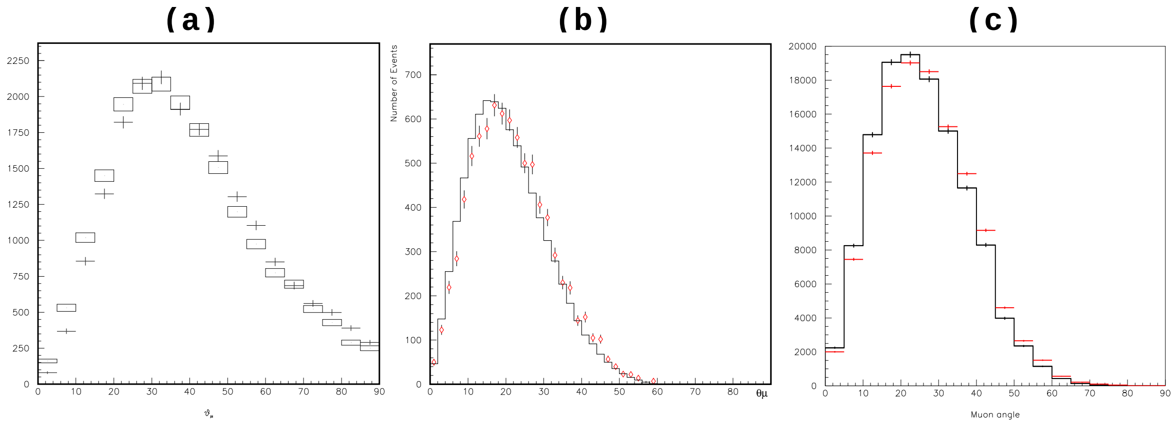

Figure 5. Distributions of the muon angle with respect to the beam direction for (a) 1kt, (b)SciFi, and (c) MRD. The Monte Carlo distributions are overlayed by the entry normalization (solid line histogram). The errors shown here are only statistical. In (a) both data and MC have errors, as shown by bars and boxes, respectively. In (c) MC statistical errors are also given by bars on the histogram.

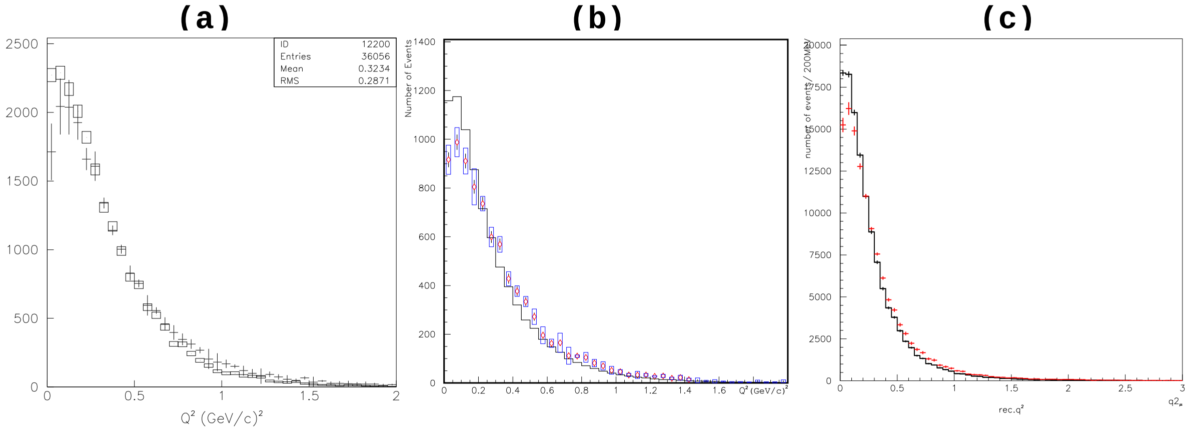

Figure 6. q^2 distributions observed by (a) *1kt*, (b) SciFi and (c) MRD. The errors shown here are (a) the combined error of statistical and $\pm 5\%$ of the energy scale for data (*bar*) and statistical error (*box*) for MC, (b) statistical error (*box*) and $\pm 3\%$ of energy scale error (*bar*), and (c) combined error of statistcal and $\pm 3\%$ energy scale for data and statistical error for MC.

range table error (1.7%) additively. We use the same value for SciFi, because a muon loses it's energy mainly in MRD. The energy offset possibly caused by the energy loss estimation in the LG cell is being studied.[4]

Fig. 5 shows the θ_μ distributions for each event category. The errors shown here are only statistical ones. The angular resolution of each detector is expected to be relatively small ($3°$, $3°$, and $1°$, respectively), and we can hardly imagine other systematic error sources. In all of plots we can commonly find a tendency that data shift towards higher than MC, and there is a disagreement in the small-angle region.

3.3. q^2 distributions

Fig. 6 shows the q^2 distributions:

$$-q^2 = -2E_\nu(E_\mu - p_\mu cos\theta_\mu) + m_\mu^2.$$

Since we do not know the incoming neutrino energy, E_ν, we substitute it by the reconstructed neutrino energy with the assumption of 2-body CCQE kinematics. It only depends on the muon momentum and angle as follows[2]:

$$E_\nu = \frac{(m_N + B)E_\mu - (2m_N B + B^2 + m_\mu^2)/2}{m_N + B - E_\mu + p_\mu cos\theta_\mu}.$$

Here, B is the nuclear binding energy of the target nuclei, which is about -30MeV for oxygen.[5] The energy scale error described in the p_μ section is also taken into account.

In all of these plots, we can admit a tendency that the data distribution looks *harder* than that of MC. Especially in the low-q^2 region, the disagreement seems to be significant.

Because our observable is the neutrino flux times the cross section, it is either due to the error on the flux estimation, or to the error on the neutrino interaction models. Meanwhile, one can anticipate that, in the q^2 distribution, the interaction models play essential roles, and the neutrino flux may have less effect than those.

4. SUMMARY

A comparison of the data and MC has been made by the near detector system of the K2K ex-

[4] A KEK PS beamtest to measure dE/dx in the LG and Fe block has proved these errors are reasonable.

[5] It is the value applied for SciFi plots. For $1kt$ and MRD B is currently set to *zero*.

periment for p_μ, θ_μ and q^2 charged-current inclusive distributions. Agreement between the data and MC is reasonably good for all three detector observations, which guarantees that there are no large systematic errors in our simulation models. Meanwhile, we have observed a small, but significant, discrepancy for the low-q^2 (small scattering angle) region. This tendency seems to be common for all detectors.

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