K2K Experiment and Neutrino Interactions

Makoto Sakuda (Okayama)

20 June, 2008 @ Roma, "La Sapienza” →

Outline

1. K2K Experiment
2. K2K Neutrino Interactions
   - Coherent Pion Production ($CC\pi^+$, $NC\pi^0$)
   - Quasi-elastic Interaction
   - Others (Results shown in Proceedings)
3. Summary

What shall I talk about, while…

- K2K/T2K Rome-Univ Group knows the latest K2K results better than I do.
- Experts like Omar and Paolo are here.

Since I moved from KEK to Okayama University in 2004, I mainly work on SN physics in SK and Neutrino Interactions
- 2nd Part in my talk (if I have time)-

1. SEARCH FOR SUPERNOVA NEUTRINO BURSTS AT SUPER-KAMIOKANDE
M.Ikeda et al.(SK Collab), The Astrophysical Journal, **669**:519-524, **2007**
-First systematic SN search in SK Experiment (Largest SN detector) after 1987A-

2. H. Nakamura, T. Nasu, M. Sakuda, and O. Benhar,
"Inclusive electron spectrum in the region of pion production in electron-nucleus scattering and the effect of the quasi-elastic interaction",
*Phys. Rev. C***76**, 065208, **2007**
--Description of pion production and the effect of Spectral Function S(**p**,E)--

3. O. Benhar, N.Farina, H.Nakamura, M.Sakuda and R.Seki, Electron- and neutrino-nucleus scattering in the impulse approximation regime,
Phys.Rev.D**72**:053005-1-13, **2005**.
--Spectral Function and Final State interactions--

K2K Publication List

*K2K Oscillation Results

1. S.H. Ahn et al., Detection of accelerator-produced neutrinos at a distance of 250km, PLB511, 178–184 (2001)
2. M. H. Ahn et al., Indications of Neutrino Oscillation in a 250 km Long-Baseline Experiment, PRD90, 041801 (2003)
3. E. Aliu et al., Evidence for Muon Neutrino Oscillation in an Accelerator-Based Experiment, PRL 94, 081802 (2005)
4. M. H. Ahn et al., Measurement of neutrino oscillation by the K2K experiment, PRD74, 072003 (2006)

5. M. H. Ahn et al., Search for Electron Neutrino Appearance in a 250 km Long-Baseline Experiment, PRL93, 051801 (2004)
6. S. Yamamoto et al., Improved Search for nm→neOscillation in a Long-Baseline Accelerator Experiment, PRL**96,** 181801 (2006)

*K2K Interaction Results

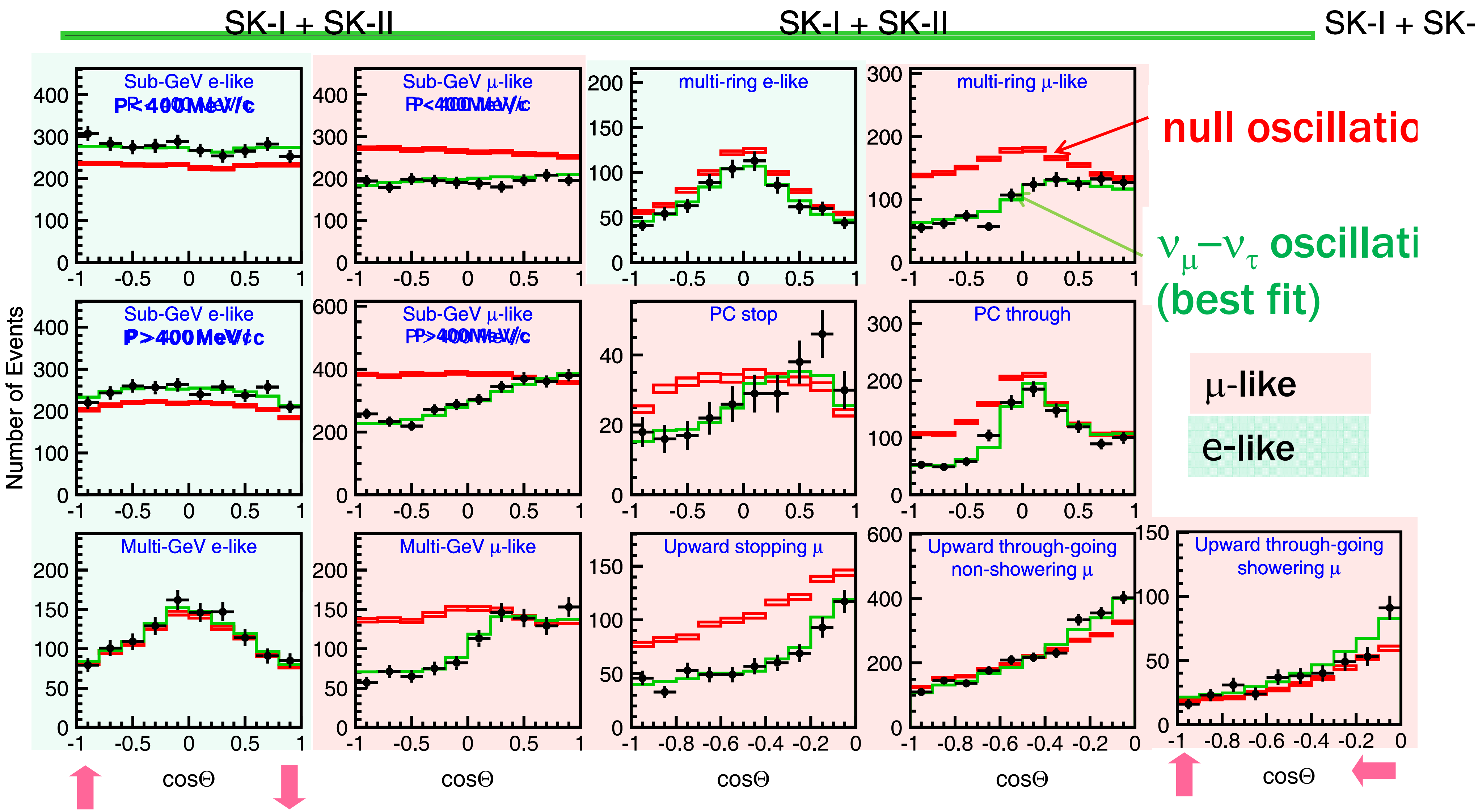
1. M. Hasegawa et al., Search for **Coherent Charged Pion Production** in Neutrino-Carbon Interactions, PRL 95, 252301 (2005)
2. R. Gran et al., Measurement of the **quasielastic axial vector mass** in neutrino interactions on oxygen, PR D**74,** 052002 (2006)
3. S. Nakayama et al., Measurement of single π^0 **production in neutral current neutrino interactions** with water by a 1.3 GeV wide band muonn eutrino beam, PL B**619**, 255–262 (2005)
4. A. Rodriguez et al., Measurement of **single charged pion production in the charged-current interactions** of neutrinos in a 1.3 GeV wide band beam, arXiv:0805.0186v4, May (2008)
5. S. Mine et al., Experimental study of the atmospheric neutrino backgrounds for p→e+π^0 searches in water Cherenkov detectors, PRD**77**, 032003 (2008)

*K2K Preliminary -- Proceedings

6. J. Kameda, Observation of de-excitation gamma rays from nuclei 1kton detector in K2K experiment, NP B**159**, 44–49 (2006).
7. C. Mariani, Neutral pion cross section measurement at K2K, AIP Conf.Proc.**967**, 174-178 (2007).
8. X.Espinal and RSanchez, Measurement of the axial vector mass in neutrino-Carbon interactions at K2K, AIP Conf.Proc.**967**, 174-178 (2007).

Atmospheric ν oscillations (SK-I + SK-II)

First shown at Neutrino1998 -Okumura @NuFact07



All distributions agree with oscillated expectations

How to measure neutrino oscillations

Two neutrino case

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

Flavour eigenstate **Mixing** **Mass eigenstate**

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$$

θ:Mixing angle

$\Delta m^2 = m_2^2 - m_1^2$ (eV^2)

L (km): Distance from source to detector

E (GeV): Neutrino energy

MAX@$\pi/2$

K2K E~0.5GeV

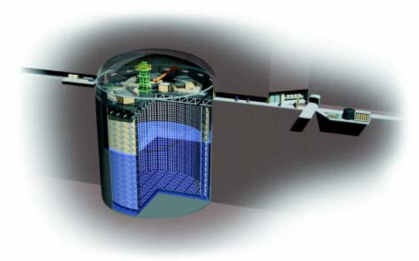
MINOS E~1.5GeV

We compare the neutrino spectrum measured by the near and far detectors and try to measure $P(\nu_\alpha \rightarrow \nu_\beta)$.

$$N_{near}(E_\nu) = F_{near}(E_\nu)\sigma(E_\nu)n_{target}\varepsilon_{near}(E_\nu)$$

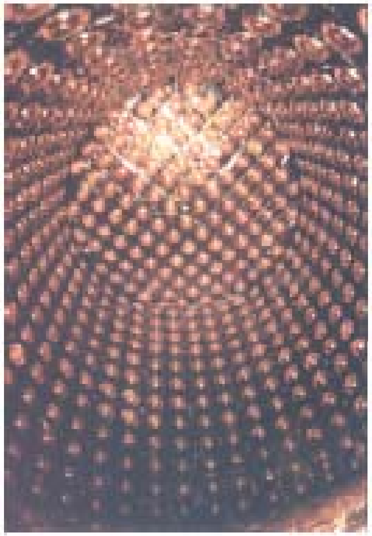
$$N_{far}(E_\nu) = F_{far}(E_\nu)\cdot \underline{P(\nu_\alpha \rightarrow \nu_\beta, E_\nu)}\cdot\sigma(E_\nu)n_{target}\varepsilon_{far}(E_\nu)$$

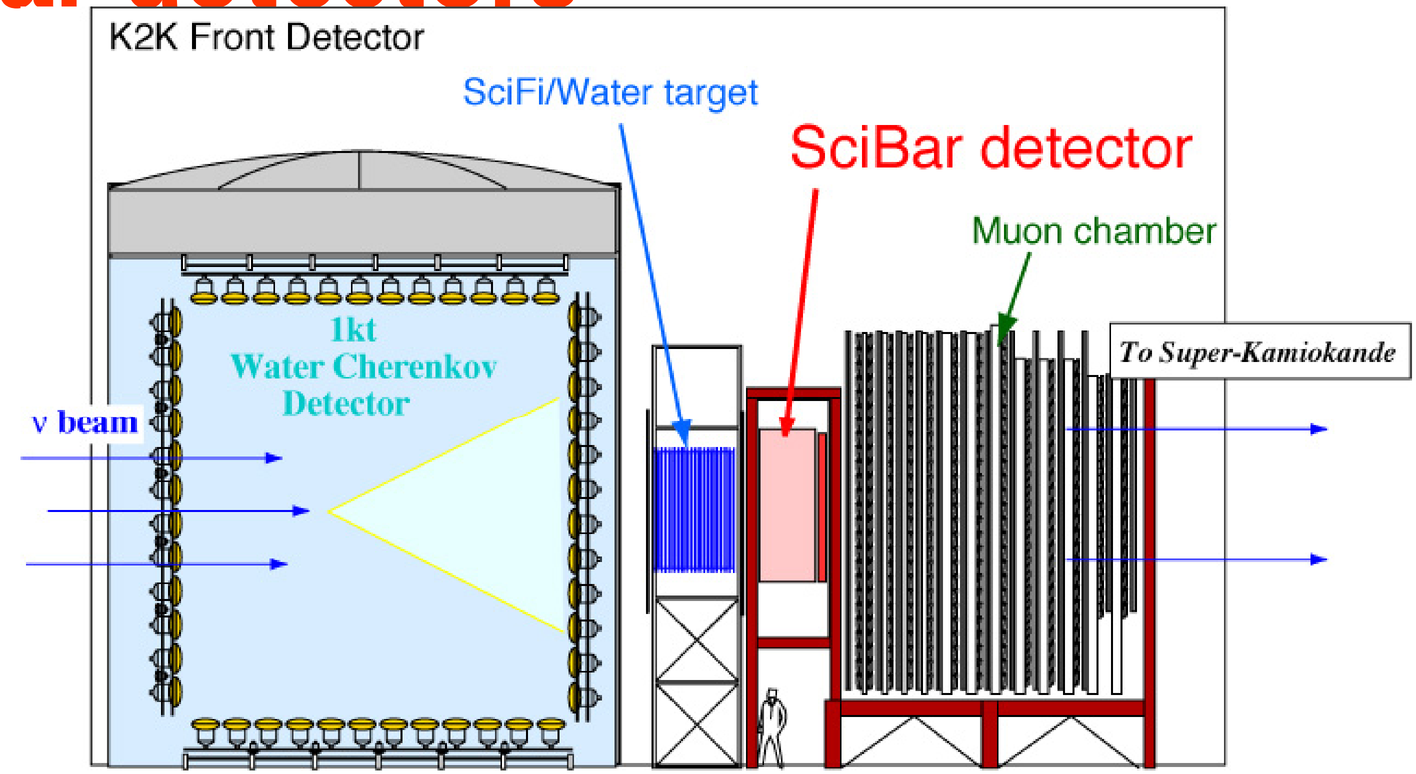
1. K2K: The First Long Baseline Neutrino Experiment, spanning 250km distance from KEK To Kamioka



- Design Concept of K2K Near Detector
  - Since Far Detector (SK) is a Water Cherenkov detector, a small detector of the same type is a “must”.
  - Fine Grain Detector must use water target, not carbon, since we do not know if water and carbon targets would give the same neutrino interactions. –SciFi/Water + Muon Ranger
  - For $\nu_\mu \rightarrow \nu_e$ search, we added LG counters.
  - After the accident (2002), SciBar (Carbon) detector was introduced.

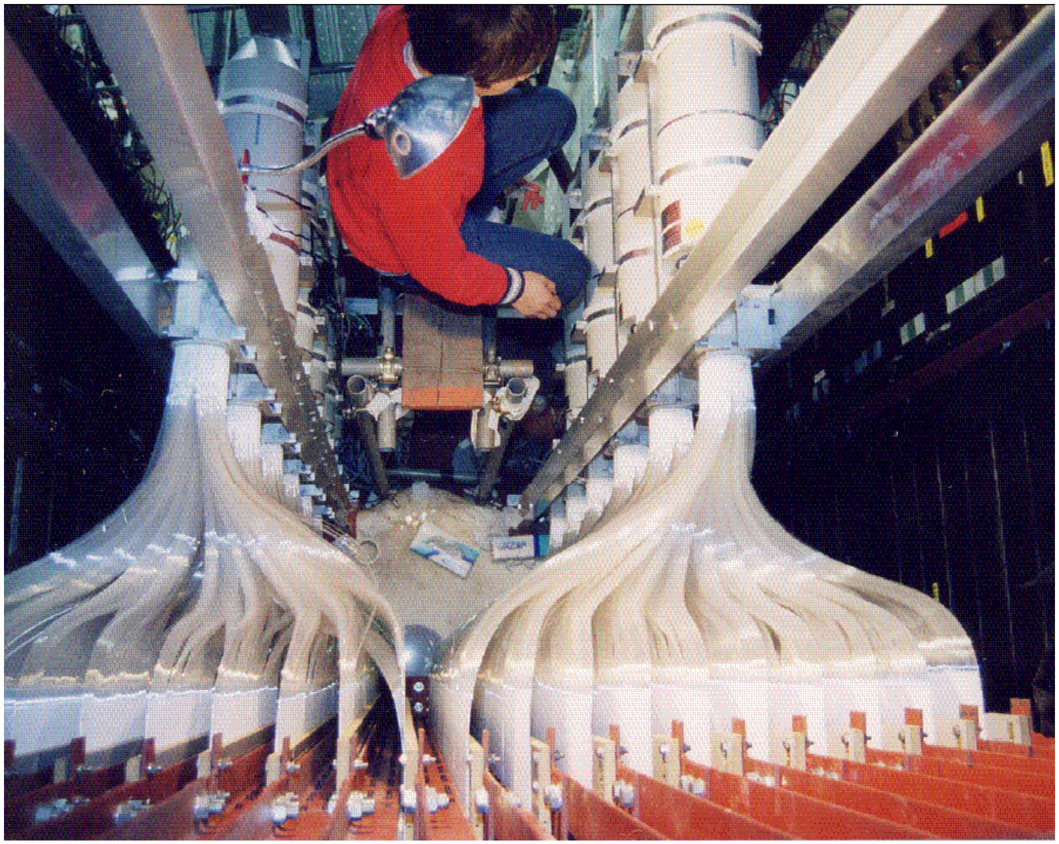
K2K near detectors

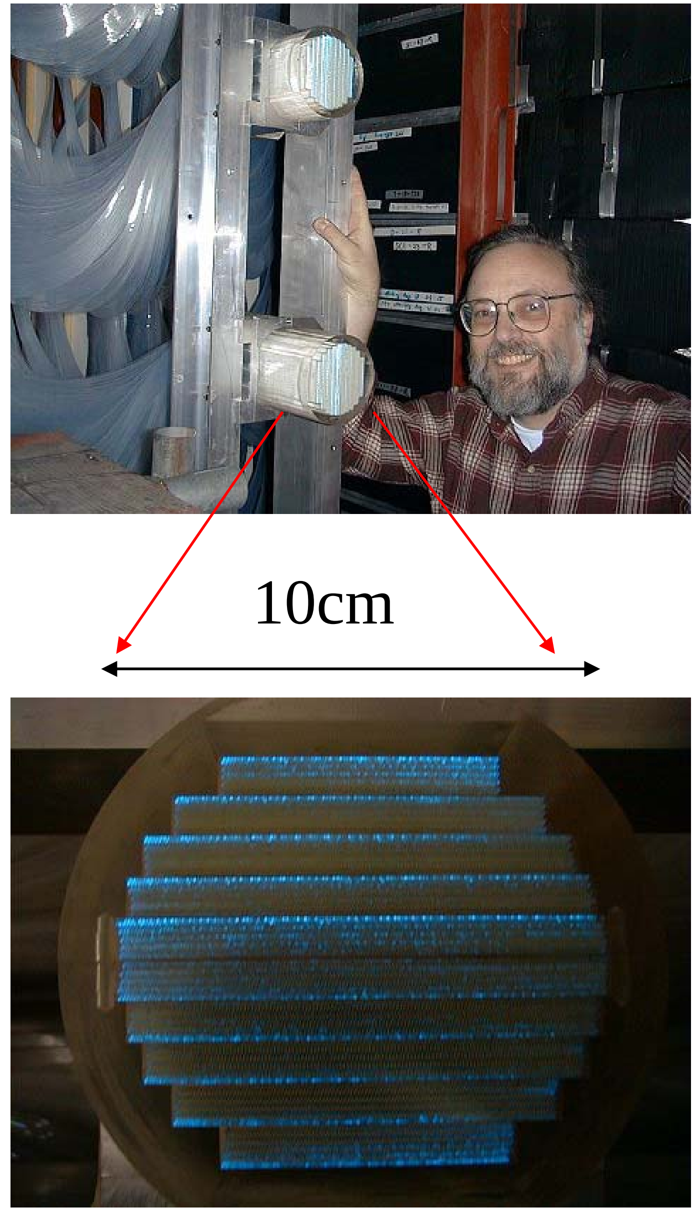




- 1kt Water Čerenkov detector (1kt/water) -680PMTs
- Scintillating Fiber Detector (Scifi/water)
- Lead Glass→Scintillator Bar Detector (SciBar/Carbon) (from 2003)
- Muon Range Detector (MRD)

Scintillating Fiber (SciFi) Detector

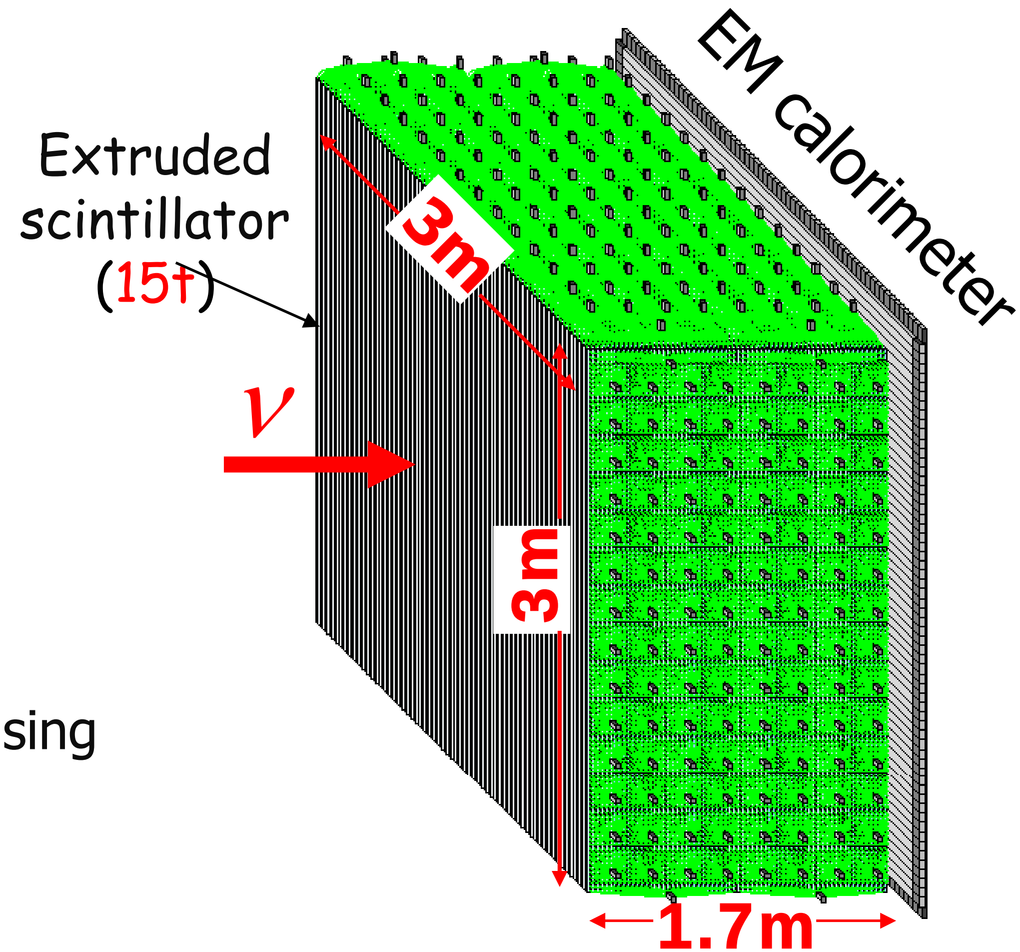




SciBar Detector

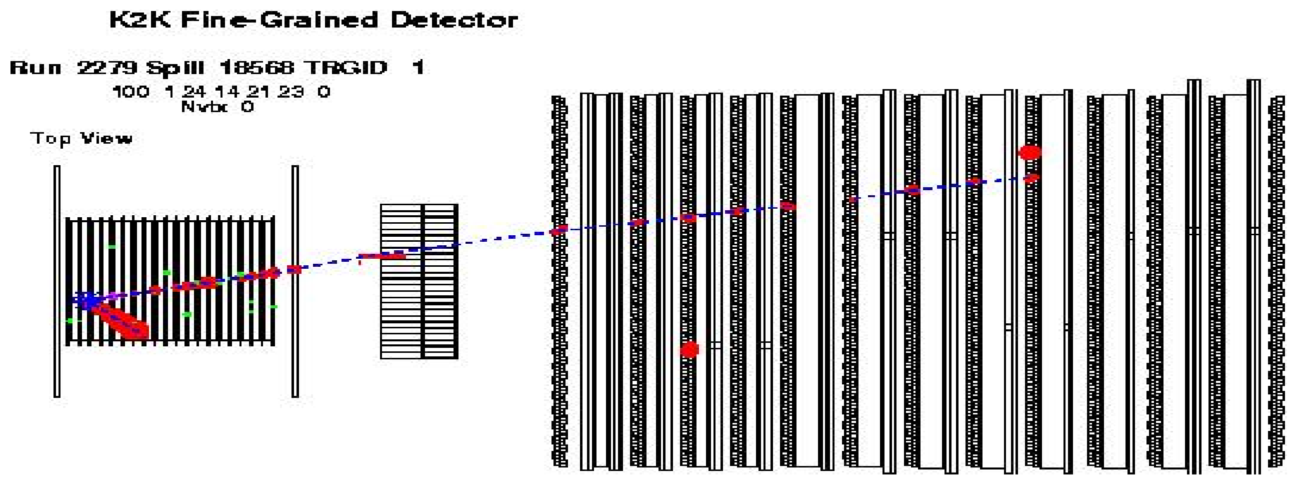
Sanchez@NuFact05

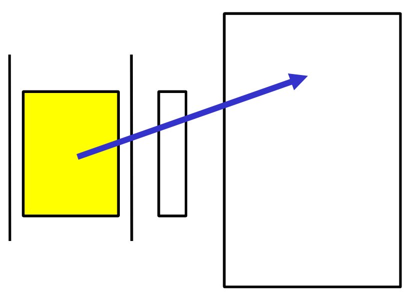
- Extruded **Sci**ntillator **Bar**
- WLS fiber readout.
- Active target.
- 2.5 x 1.3 x 300 cm^3 cell.
- Order of 15000 channels.
- Light yield ~8 p.e./MeV.
- Detect 10 cm track.
- Distinguish protons from π by using dE/dx. Miss ID < 5% (<1GeV/c proton).



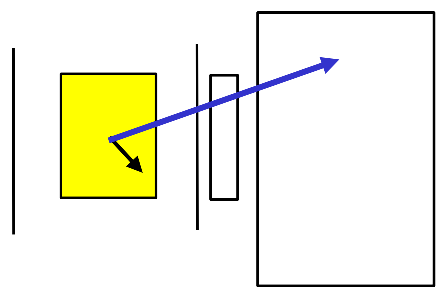
Event Display

We require a muonj track at least.





1 track event

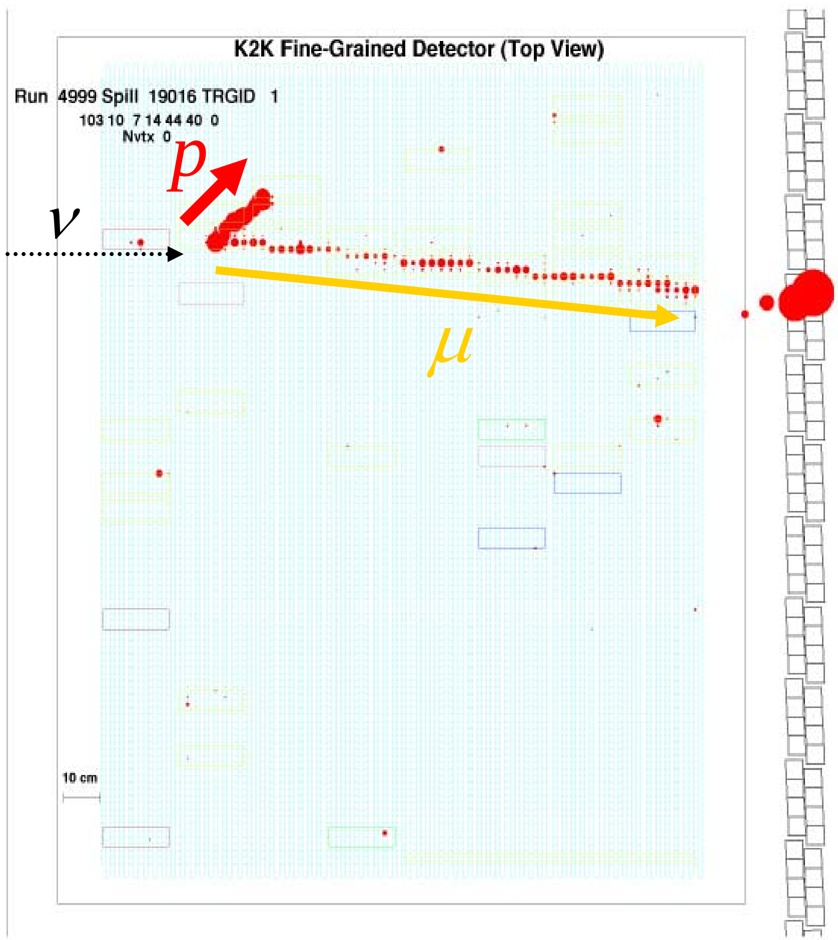


2 track event

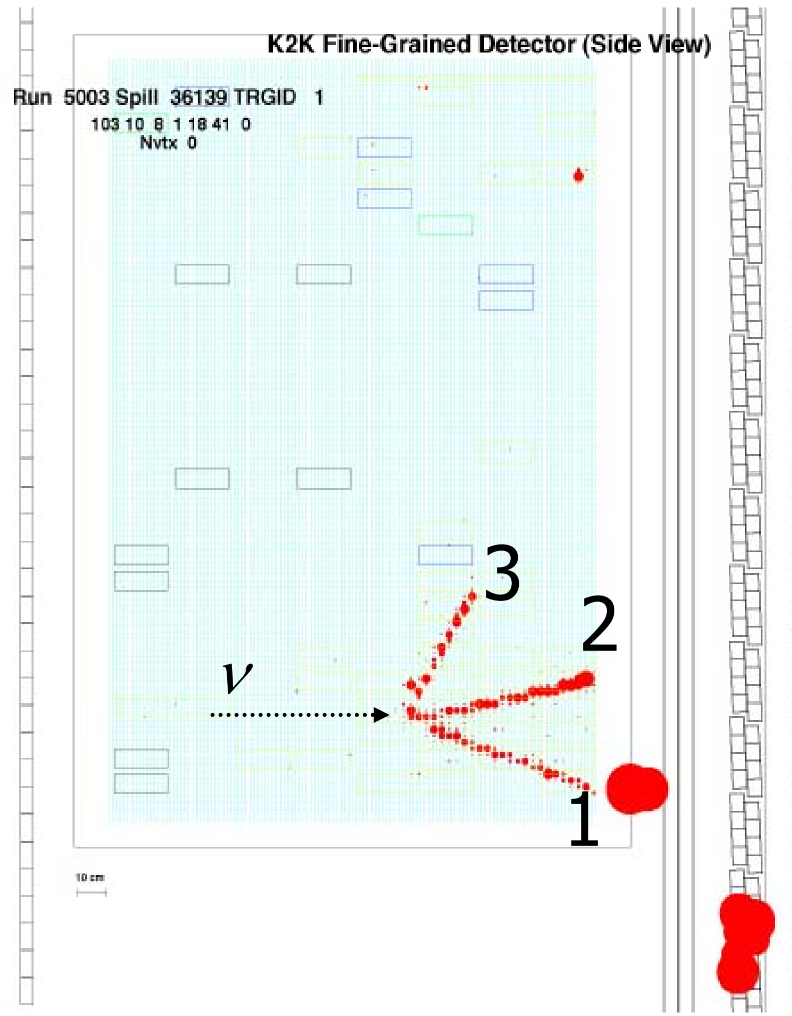
Neutrino interaction in H_2O target (+ 20% Aluminum)

SciBar Event examples

CCQE candidate



CCnQE candidate



Data-taking of K2K (and SK)

Present

1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008

Accident & Partial Reconstruction

Full Reconstruction

Discovery of ν_μ oscillations (SK)

Discovery of solar ν oscillations (SK/SNO)

SK-I

SK-II

SK-III

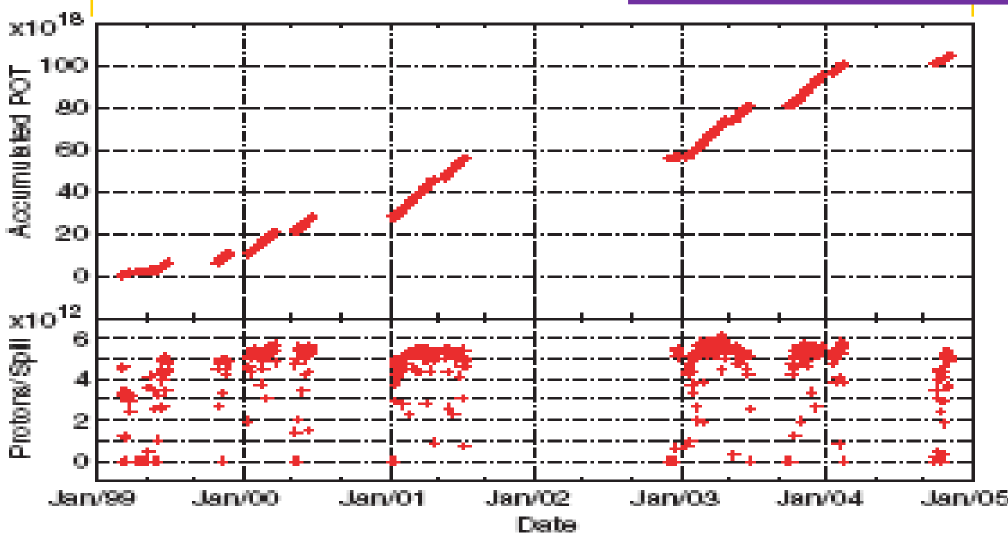
K2K

Confirmation of ν_μ oscillations (K2K)

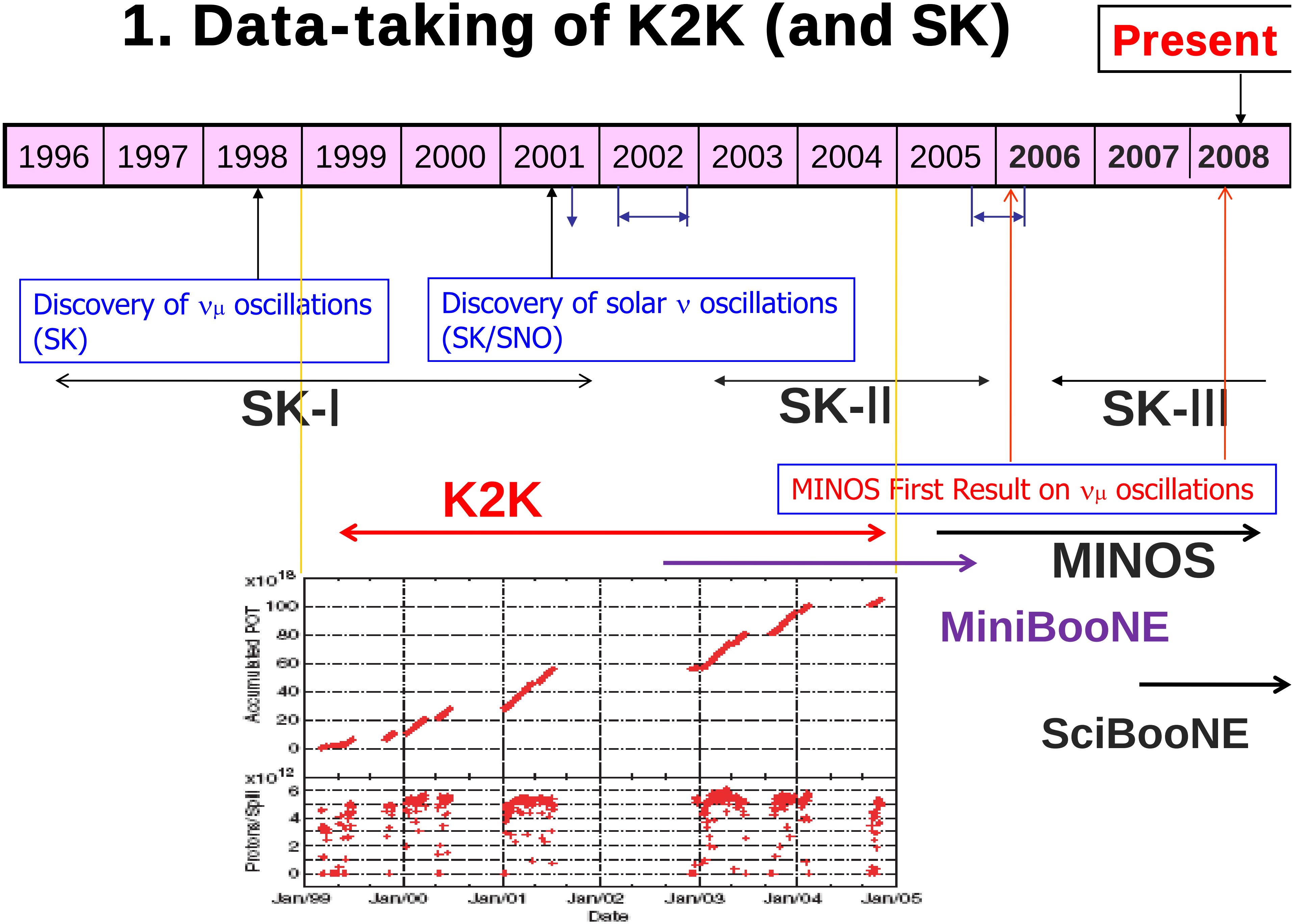
MINOS

MiniBooNE

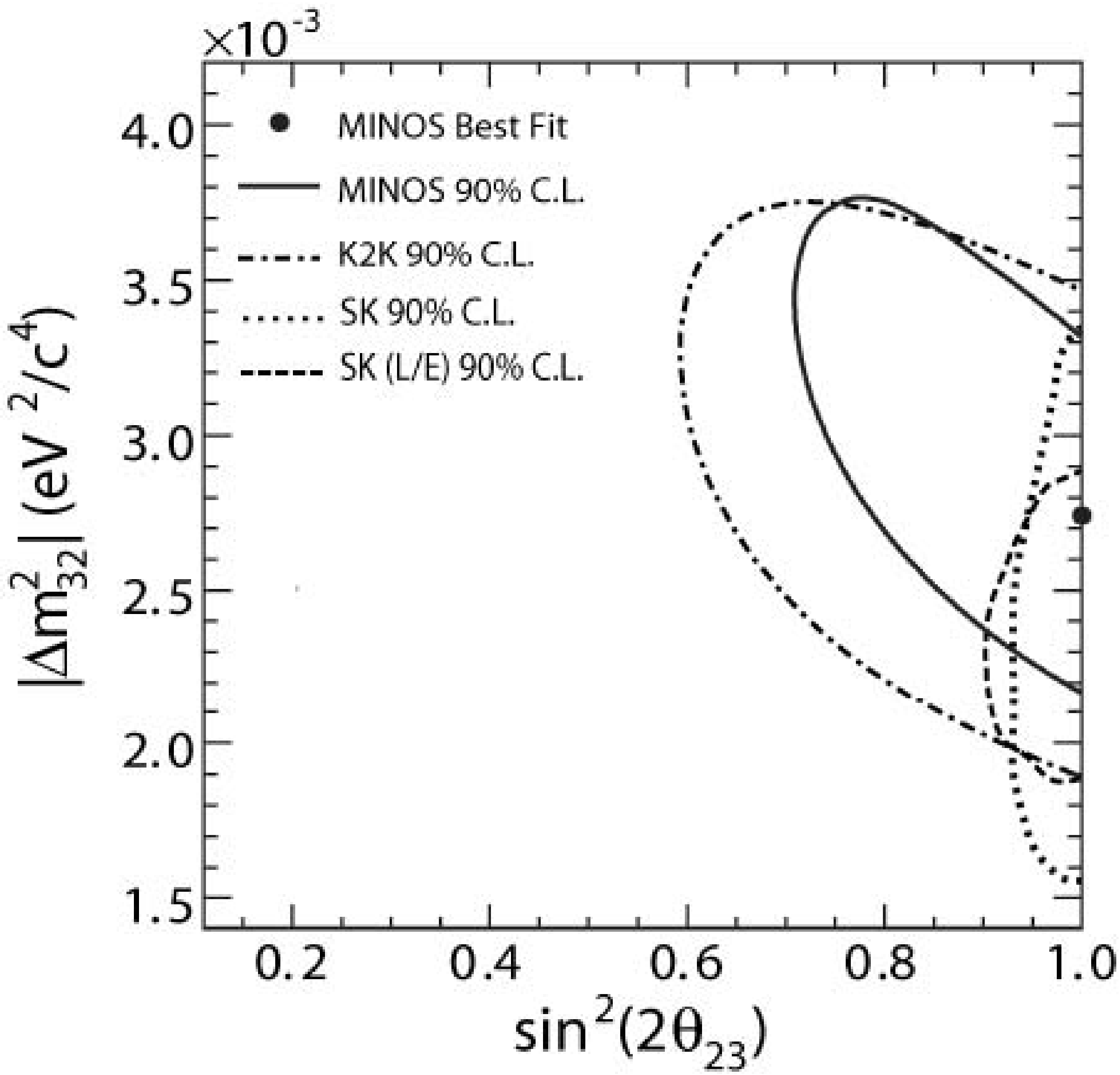
SciBooNE



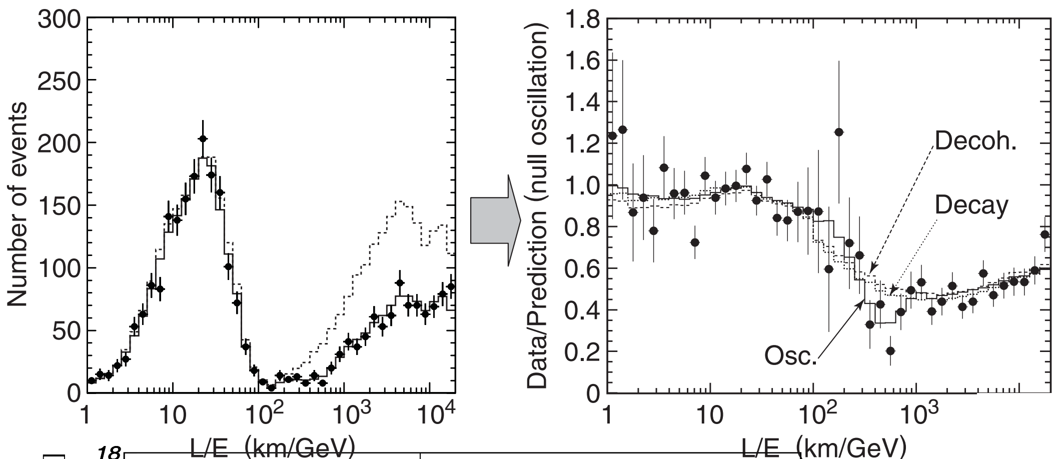
1. Data-taking of K2K (and SK)

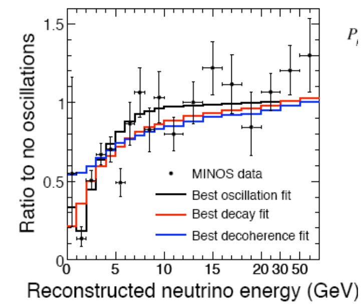


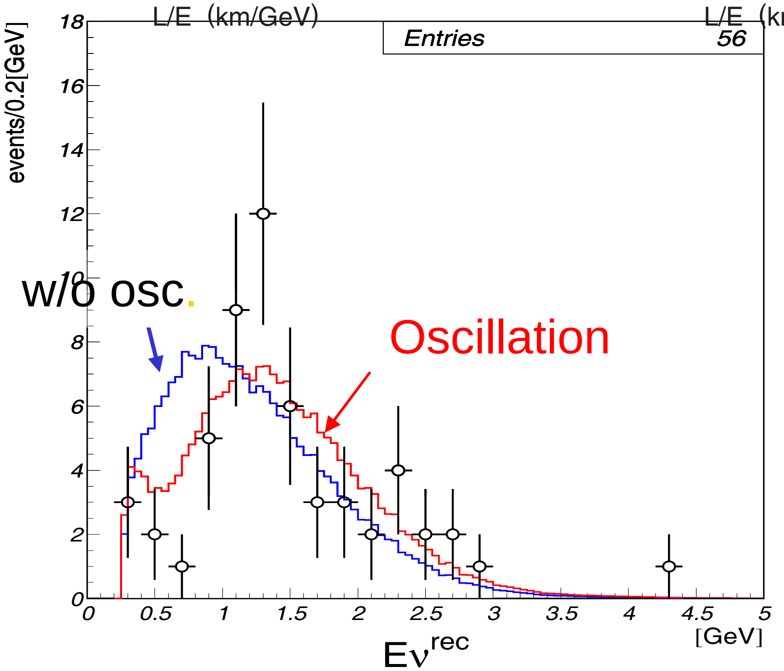
MINOS First Result (2006)

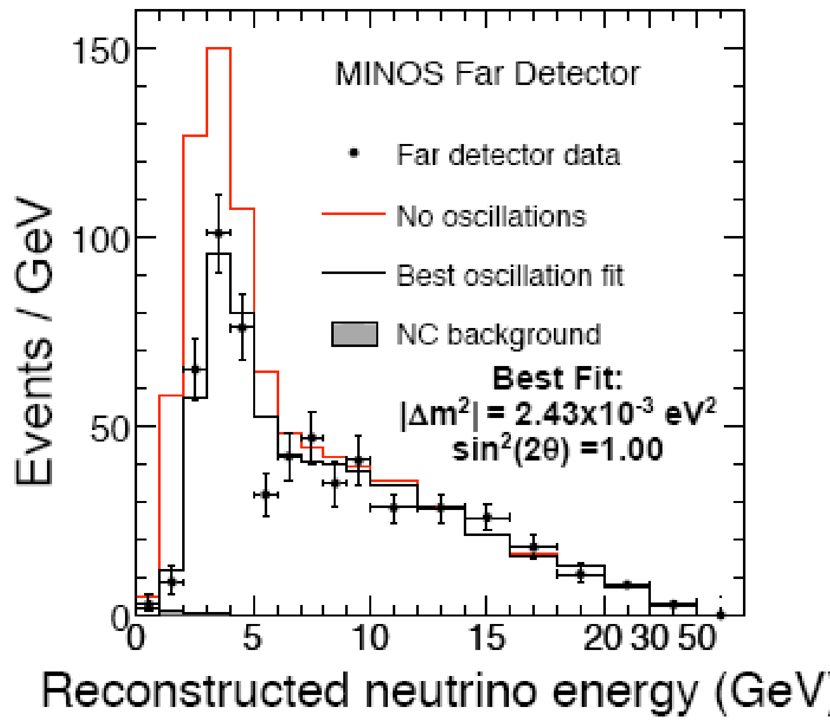


Confirmed by SK L/E analysis (top), K2K (bottom) and MINOS (right)







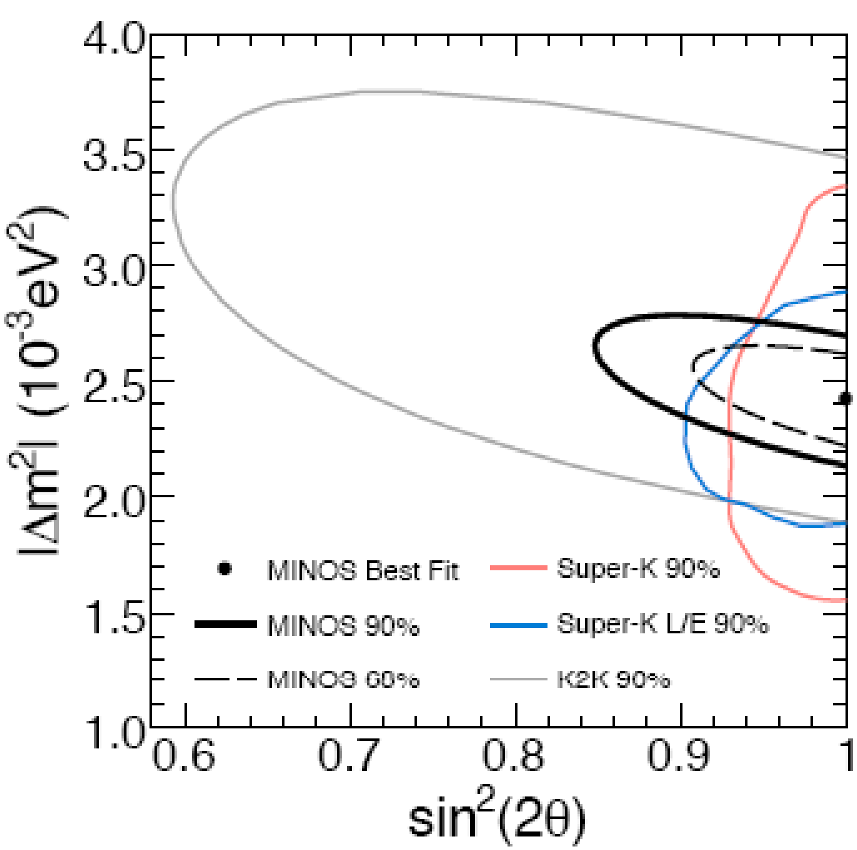


$\nu_\mu - \nu_\tau$ oscillation

-Gallagher @Neutrino08

Allowed Region

H. Gallagher
Tufts University
Neutrino 2008
May 27, 2008



$|\Delta m^2|$ =(2.43±0.13) x 10^{-3} eV^2 (68% C.L.)

$\sin^2(2\theta)$ > 0.90 (90% C.L.)

χ^2/ndof = 90/97

Fit is constrained to the physical region.

Unconstrained:

$|\Delta m|^2$ = 2.33 x 10^{-3} eV^2

$\sin^2(2\theta)$=1.07

$\Delta\chi^2$=-0.6

2. Neutrino Interactions in K2K

- The understanding of the neutrino interactions was essential in understanding the data and detector, especially when the neutrino flux is not precise.

  -Cf. Electron beam experiment

- From 1999 (First data) to 2003 (First K2K Indication paper), we spent a lot of time on comparing Monte Carlo (ν int) and data, and gained confidence with our MC and detector performance, at the level of 20-30%.

Workshop on Neutrino-Nucleus Interactions in the Few-GeV Region (NuInt)

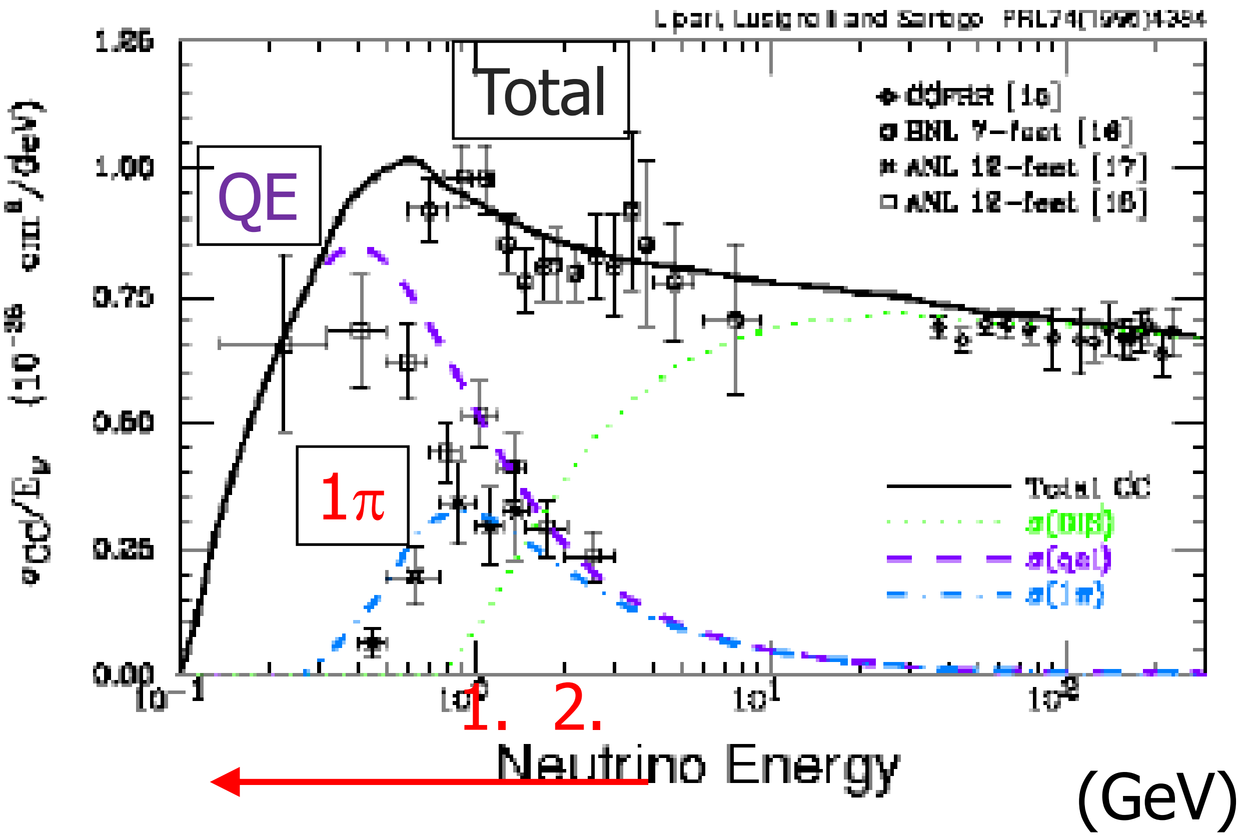
Some of neutrino experimenters (K2K, MINOS and MiniBooNE) and theorists who desparately wanted to understand neutrino interactions started this workshop in 2001, in collaboration with nuclear physicists in electron scattering community.

(1) NuInt01 (KEK, Dec.13-16, 2001)
Nucl.Phys.B(Proc.Suppl.)112, 2002
(2) NuInt02 (UC Irvine , Dec.12-15, 2002)
(3) NuInt04 (Gran Sasso , Mar.17-21, 2004) NPB(Proc.Suppl.)139, 2005
(4) NuInt05 (Okayama , Sep.26-29, 2005) NP(Proc.Suppl.) 159,2006
(5) NuInt07(Fermilab , May30-June3, 2007) AIP Conf.Proc.967

Neutrino Cross Section (by Lipari '90)

- For E_ν< 2 GeV, Quasi-Elastic interaction and Single pion production (Δ production) dominate the cross section.

Old cross section measurements are not precise. ±20-30%.



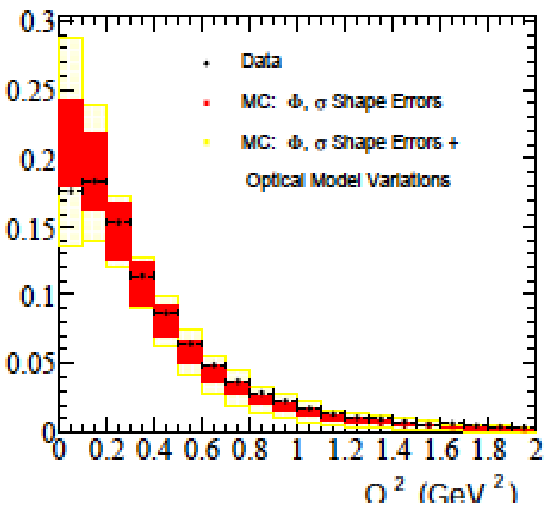
2. K2K Neutrino Interactions

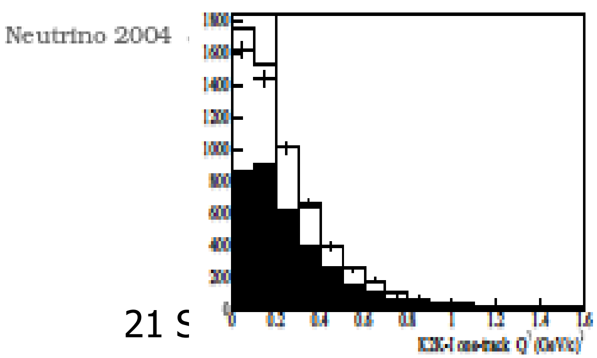
MiniBOONE and K2K Q^2 deficit (as of Mar.2005)
-Similar plots first reported by K2K at NuInt01-

- Nuclear Effect or unknown cross sections (QE,1π, coherent)??

→Later explained by K2K (Coherent π, '05) and MiniBooNE (QE, '08)

MiniBOONE QE sample





K2K Inelastic sample

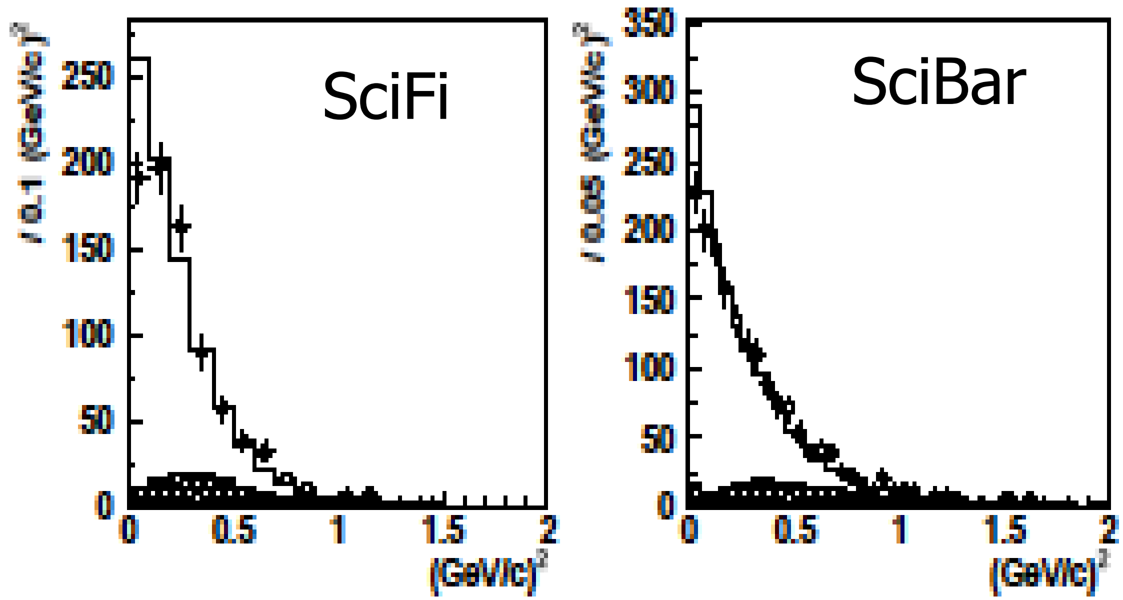
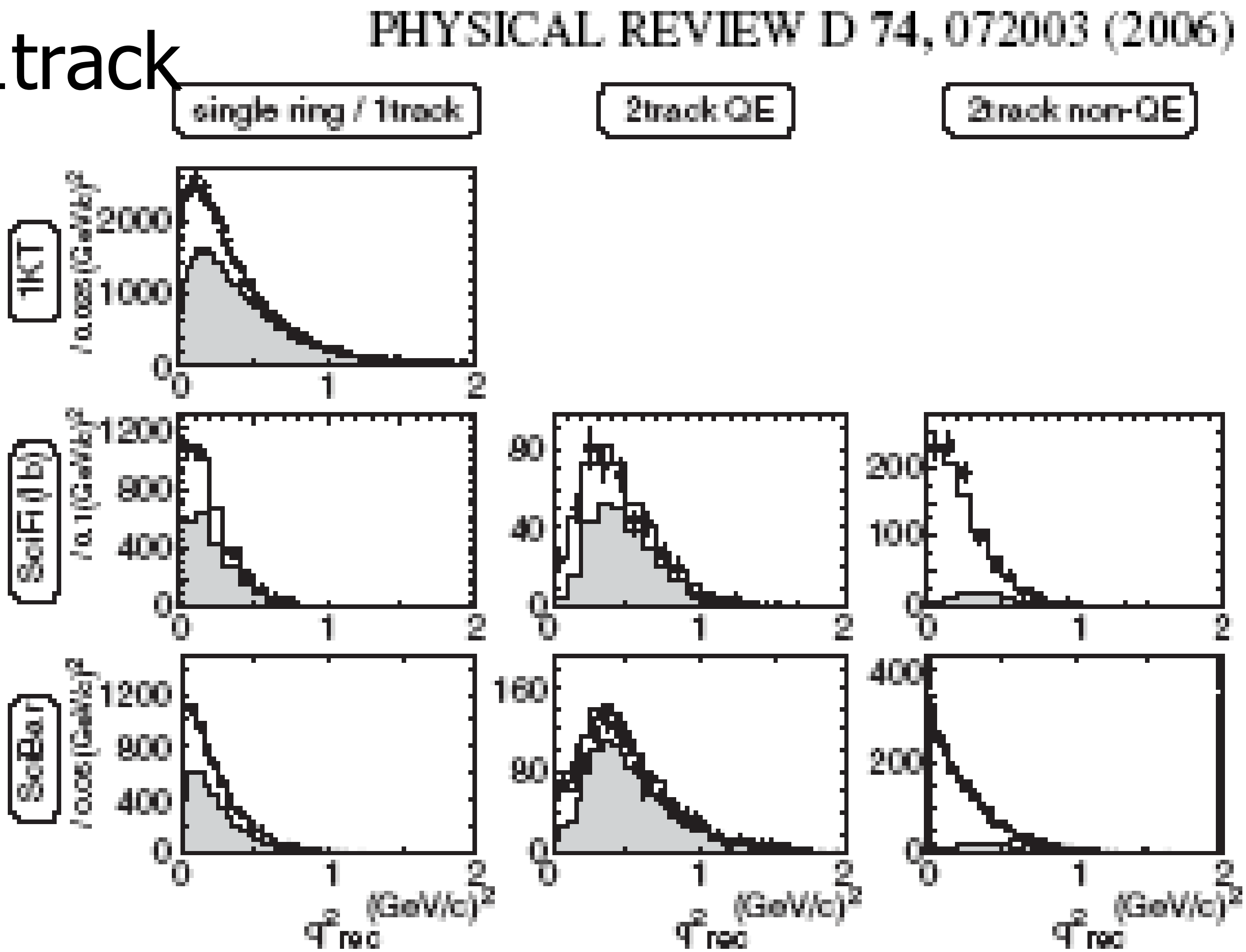


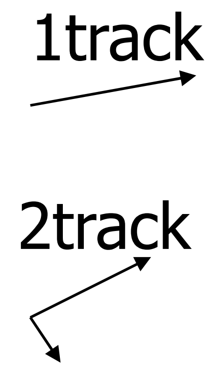
FIG. 1: Reconstructed q^2 distributions for 2-track nonQE-enhanced samples of SciFi (left) and SciBar (right). Open circles with error bars are data. solid lines are MC predictions.

- Data Sample

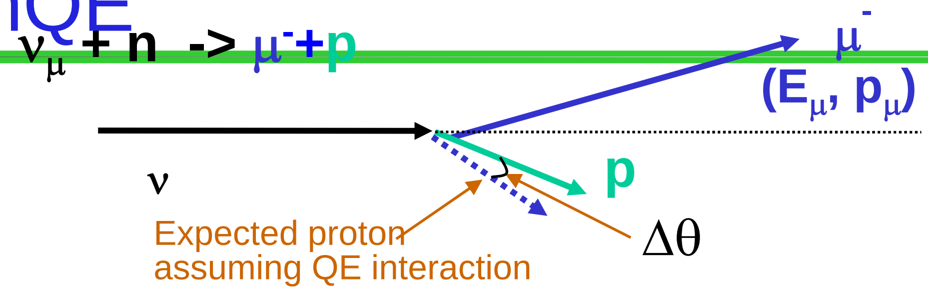
Data in 3 subsamples: 1 track, 2track QE-like, 2track nonQE-like

1track



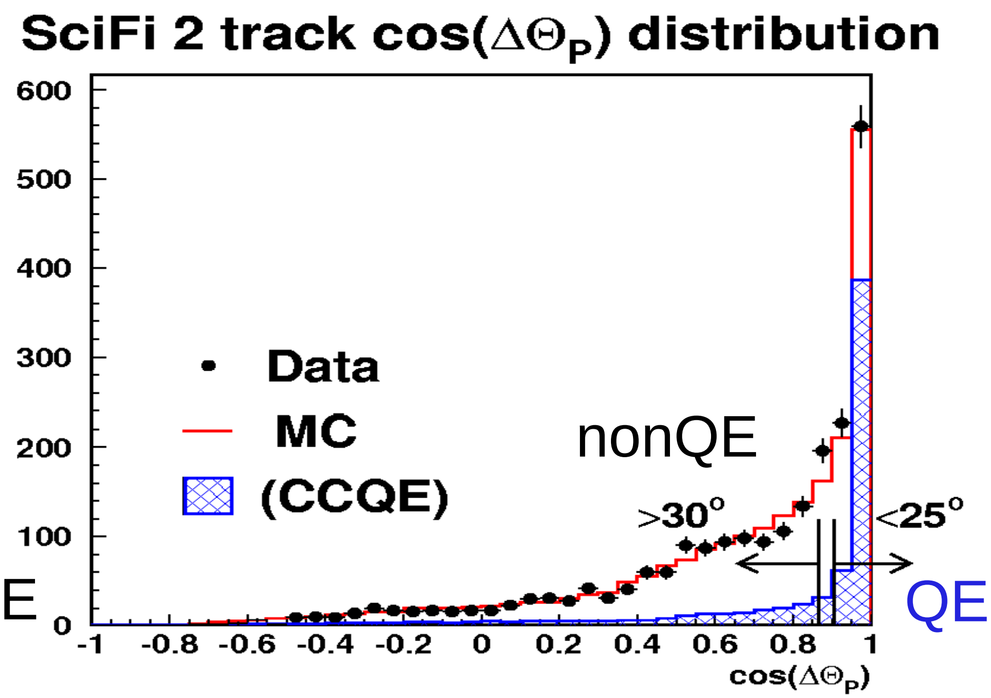


Δθ distribution of 2 track events: how to separate QE and nonQE



Separate events
into three subsamples:

1-track (no proton) 60% QE
2-track QE enhanced 60% QE
2-track nQE 85% nonQE, 15% QE



- Results
  - CC Coherent pion production
  - NC pion production
  - Quasi-elastic interaction
  - NC with gamma rays

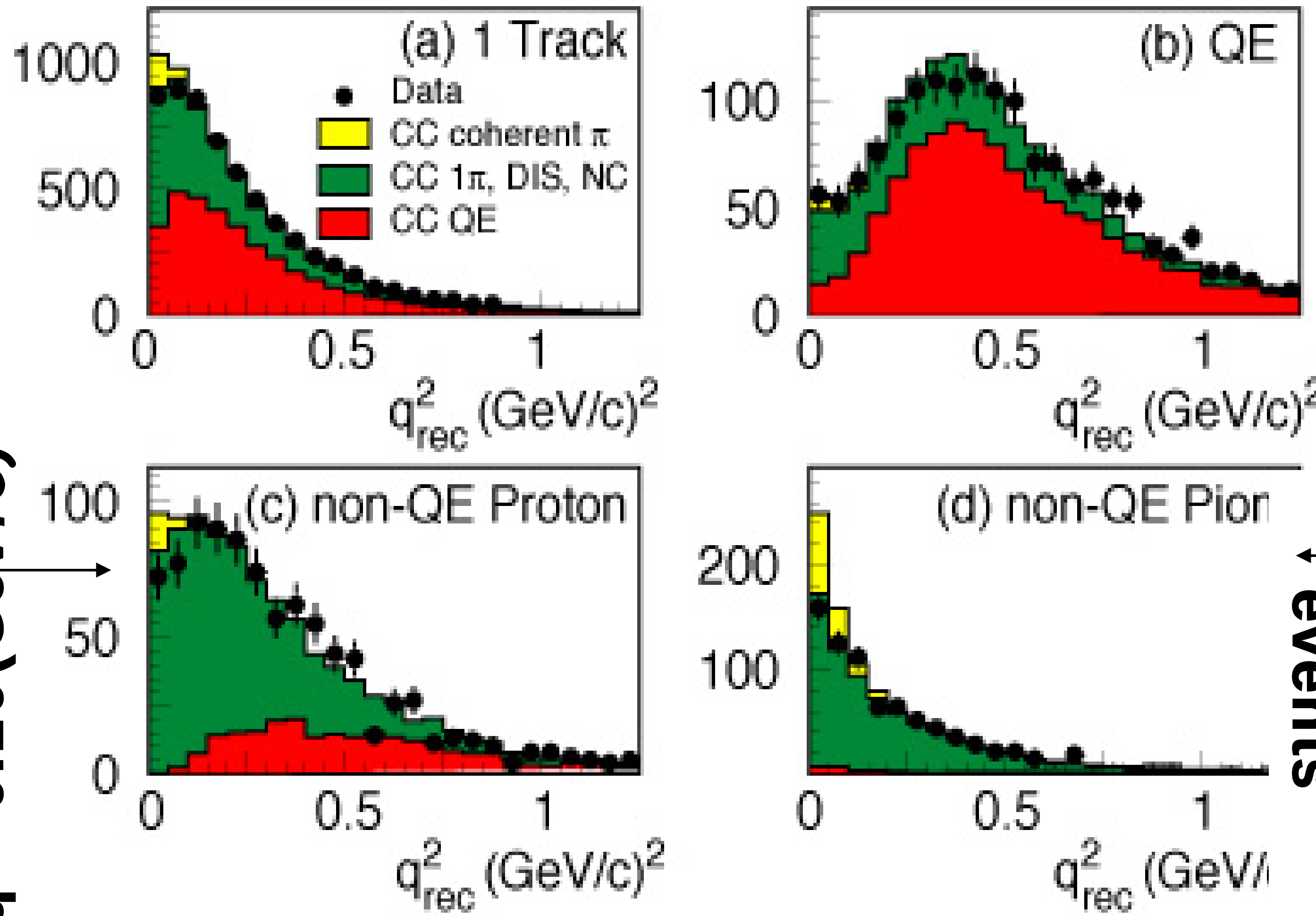
1) Coherent Charged Pion Production

Sanchez@NuFact05

1. M. Hasegawa et al., Search for Coherent Charged Pion Production in Neutrino-Carbon Interactions, PRL95, 252301(2005)

Selected samples (SciBar, Dec.‘05)

-PID further separates nonQE into two subsamples-



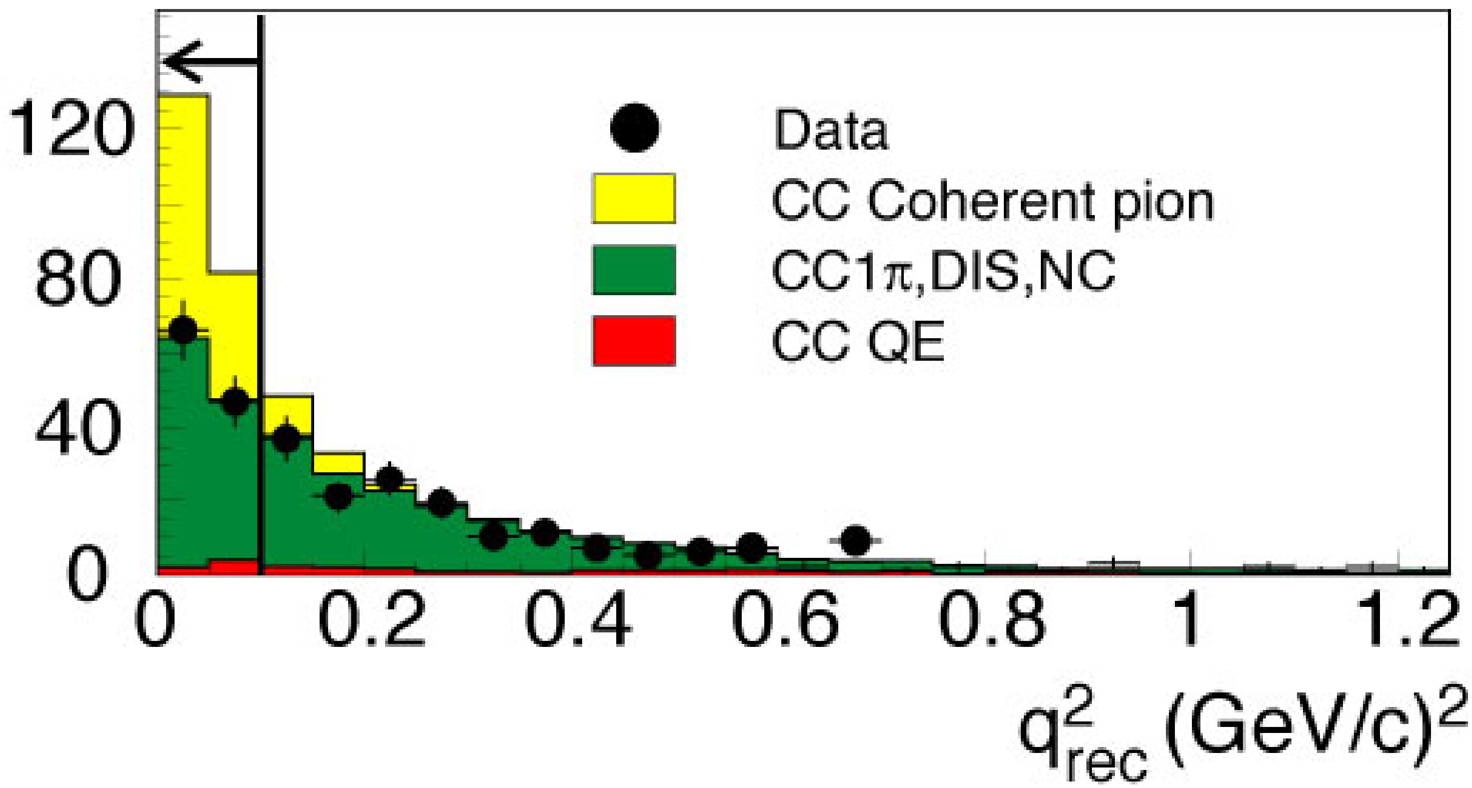
Deficit of events $q^2<0.10(\mathrm{Gev}/c)^2$

No evidence for Coherent events

χ^2/d.o.f = 73.2 / 80 for $q^2 > 0.10$ (Gev/c)^2

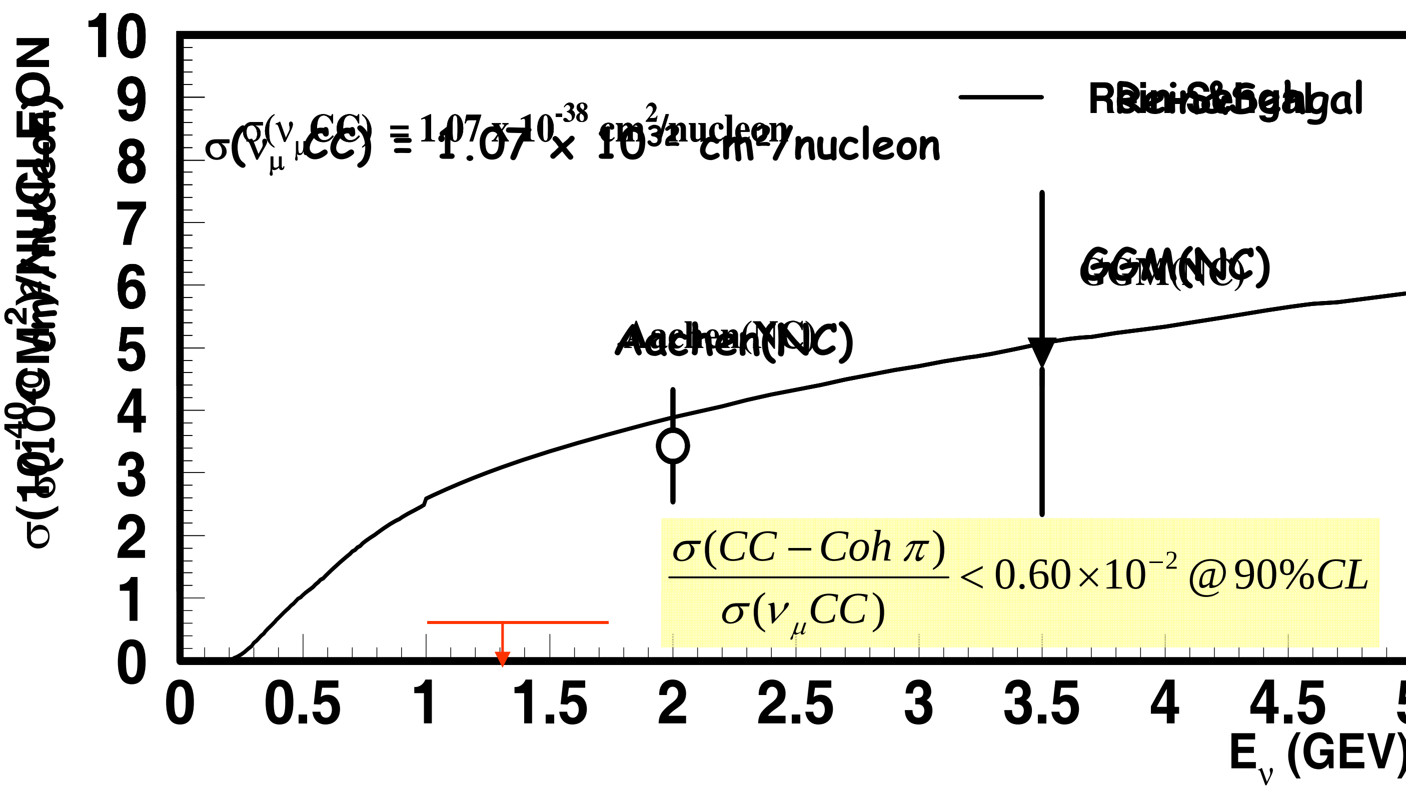
Final coherent enriched sample

cut @ q^2=0.10 $(Gev/c)^2$



Coherent pion production

- The first experimental measurement of CC coherent π production by ν_μ with a mean energy of 1.3 GeV.
- No evidence for this channel has been found and an upper limit on the cross-section has been derived:
  - $\sigma(CC\text{-}Coh)/\sigma(CC) < 0.6\ 10^{-2}$ @ 90 % C.L.



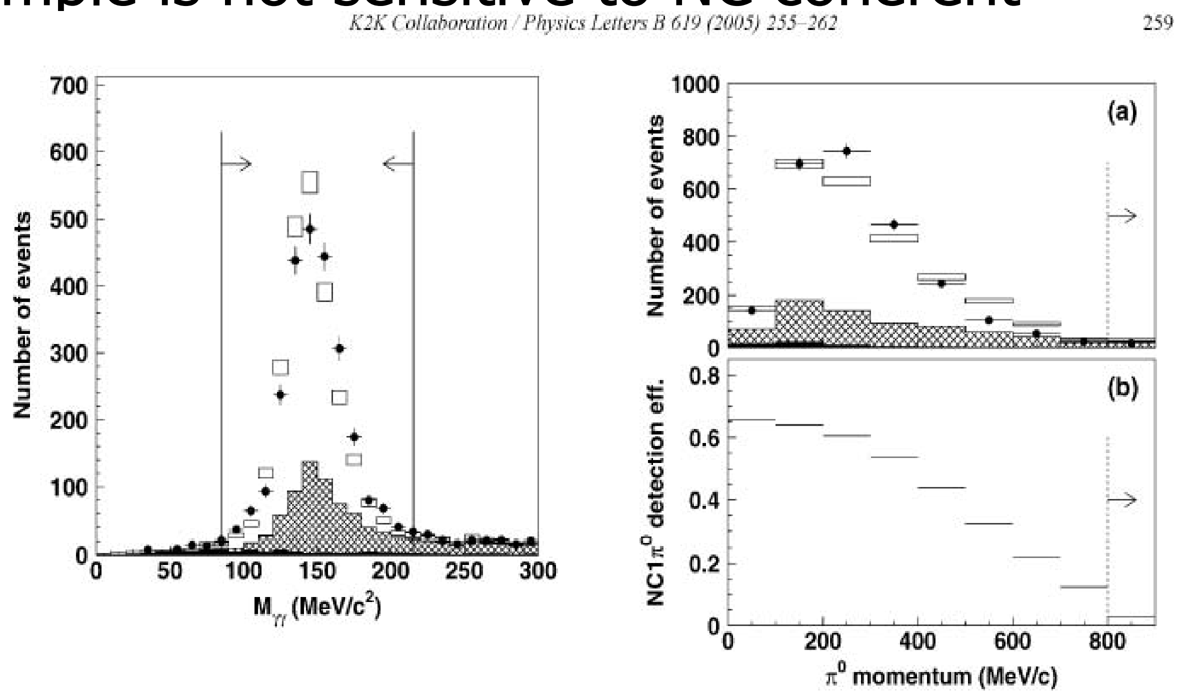
2) NC($1\pi^0$) Production at $<E_\nu>$=1.3 GeV

- S. Nakayama et al., Measurement of single π^0 production in neutral current neutrino interactions with water by a 1.3 GeV wide-band muon-neutrino beam, PL B**619**, 255–262 (2005)

- $\sigma(NC1\pi^0)/\sigma(\nu_\mu CC\ total)$ =0.064 ± 0.001*(stat.)* ± 0.007*(sys.),* in good agreement with MC prediction 0.065.

Note: This NC1π^0 is dominated by resonance production.

Res:Coh=5:1. This sample is not sensitive to NC coherent production.



*Recent update on NC($1\pi^0$) by MiniBooNE

- MiniBooNE reported:

Fcoh =xcoh/(xcoh + xres) × 100%

= (19.5±1.1(stat)%.

Fcoh(Rein-Sehgal)=30%

- BRS08 (next page) explains the reduction of 15-20% for ν_μ CC. This effect is absent in NC pion production.

Berger-Sehgal 08 (BRS08)-Sehgal@NuInt07

predicts the reduction of 15-20% for ν_μ CC.

$$C_{\mathrm{Adler}} = \left(1 - \frac{1}{2}\frac{Q^2_{\mathrm{min}}}{Q^2 + m_\pi^2}\right)^2 + \frac{1}{4}y\frac{Q^2_{\mathrm{min}}(Q^2 - Q^2_{\mathrm{min}})}{(Q^2 + m_\pi^2)^2}.$$

TABLE I. Integrated cross section for incoherent and coherent neutrino reactions in units of 10^{-38} cm^2. The index $Q^2 < 0.1$ indicates integration of $d\sigma/dQ^2$ between $Q^2 = 0$ and $Q^2 = 0.1$ GeV^2. The coherent cross section per *nucleus* has been calculated for ^{12}C. The line labeled "RSC" refers to the coherent Rein-Sehgal model as calculated from (27). The line labeled "RSA" includes the Adler screening factor (28).

	Incoherent scattering					Coherent scattering			
	$E = 0.7$ GeV		$E = 1.3$ GeV			$E = 0.7$ GeV		$E = 1.3$ GeV	
	σ	$\sigma_{Q^2<0.1}$	σ	$\sigma_{Q^2<0.1}$		σ	$\sigma_{Q^2<0.1}$	σ	$\sigma_{Q^2<0.1}$
RS	0.227	0.049	0.504	0.073	RSC	0.717	0.568	1.889	1.258
BRS	0.194	0.042	0.483	0.067	RSA	0.609	0.477	1.701	1.117

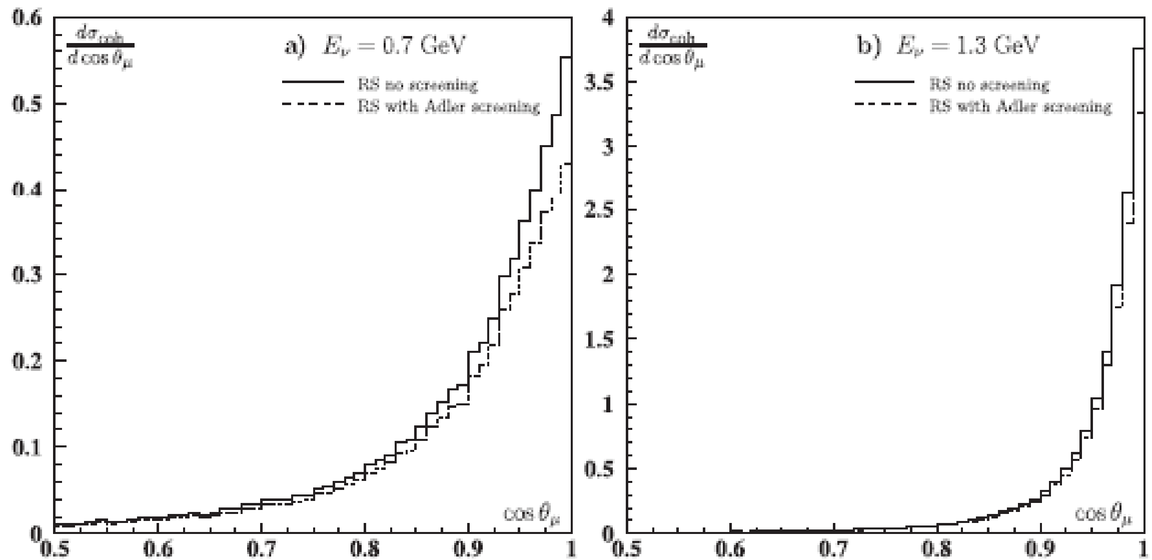
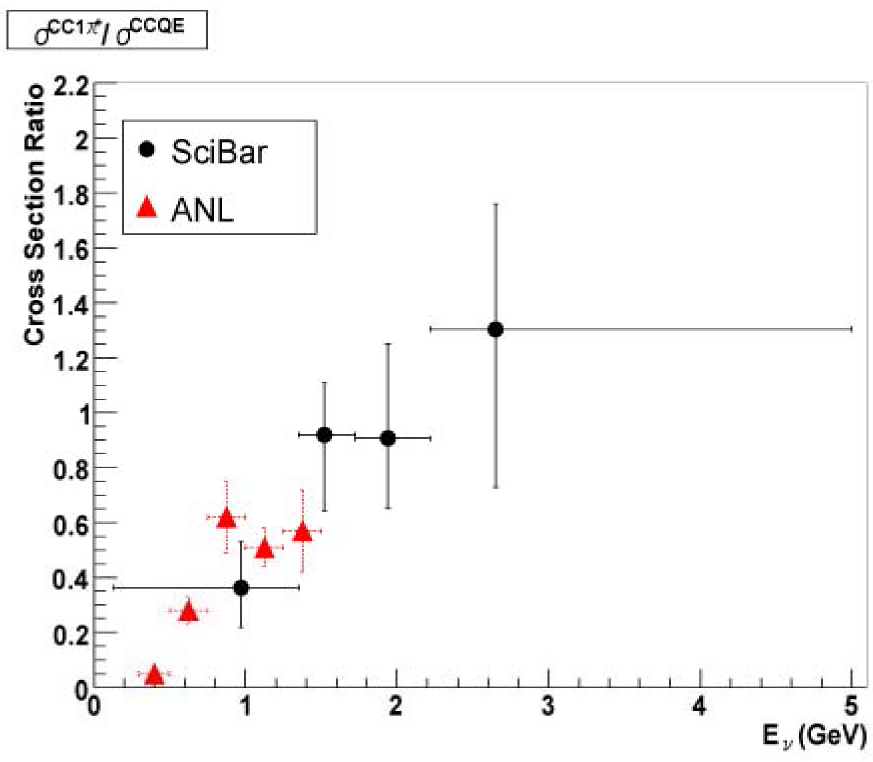


FIG. 3. Differential cross section per nucleon $d\sigma/d\cos\theta_\mu$ in units of 10^{-38} cm^2 for the reaction $\nu_\mu + {}^{12}C \to \mu^- + \pi^+ + {}^{12}C$. The solid line represents the coherent Rein-Sehgal model as calculated from (27). The dashed line includes the Adler screening factor (28). (a) $E_\nu = 0.7$ GeV. (b) $E_\nu = 1.3$ GeV.

CC1π^+

4. A. Rodriguez et al., Measurement of single charged pion production in the charged-current interactions of neutrinos in a 1.3 GeV wide band beam, arXiv:0805.0186, May (2008)



3) Quasi-Elastic Interaction

- R. Gran et al., Measurement of the quasielastic axial vector mass in neutrino interactions on oxygen, PR D**74,** 052002 (2006)

M_A analysis with K2K SciFi detector data

- Previous M_A analyses generally used
  - •Dipole form for vector form factors
  - •Q^2>0.2 $(GeV/c)^2$ to avoid the nulcear effect
    - - Fermi-Gas model for nucleus (Deuteron wave function calculation for deuteron data) shows it.

- In this analysis, we studied carefully the following effects:
  - Effect of the new vector form factor measurements
  - Effect of the energy scale (detector dep.) 1%→~M_A±0.05. This may have been overlooked before.
  - Effect of background shape (1π) from data
  - Proton rescattering
    - –This is relevant to our QE/nQE separation
  - Flux uncertainty and event migration

1. Quasi-elastic cross section $\nu_\mu\, n \rightarrow \mu^- p$ and form factors

$$\frac{d\sigma}{dQ^2} = \frac{M^2 G_F^2 \cos^2\theta_c}{8\pi E_\nu^2}[A(Q^2) - B(Q^2)(s-u) + C(Q^2)(s-u)^2]$$

Form Factors F^1_V, F^2_V, and F_A and $(s-u)=4ME_\nu - Q^2 - M_\mu^2$

$$A = Q^2/4M^2\,[(4 + Q^2/M^2)|F_A|^2 - (4 - Q^2/M^2)|F^V_1|^2 + Q^2/M^2(1-Q^2/4M^2)|\xi F^V_2|^2 + 4Q^2/M^2\xi \mathrm{Re} F^{V*}_1 F^V_2 - m^2/4M^2(|F^V_1 + F^V_2|^2 + |F^V_1 + 2F_p|^2 - 4(1+\tau)|F_p|^2]$$

$$B = -Q^2/M^2 \mathrm{Re} F^*_A (F^V_1 + \xi F^V_2),$$

$$C = 1/4(|F_A|^2 + |F^V_1|^2 + Q^2/4M^2|\xi F^V_2|^2).$$

Historically, we used

- Vector Form factors

  $G_E^p = D$, $G_M^p = \mu_p D$, $G_M^n = \mu_n D$, $G_E^n = -\mu_n \tau/(1+\lambda\tau)D$,

  $D = 1/(1+Q^2/M_V^2)^2$, $M_V = 0.843$ (GeV/c^2)

  $\mu_p = 2.792847$, $\mu_n = -1.913043$, $\lambda = 5.6$, $\tau = Q^2/4M^2$

- Axial-vector form factor F_A

  $F_A(Q^2) = -1.2617/(1+Q^2/M_A^2)^2$

Nucleon Form Factors

- Electromagnetic current (J_a^{em}) and weak hadronic charged current ($J_a^{CC}=V_a^{1+i2}-A_a^{1+i2}$) is written in terms of form factors:

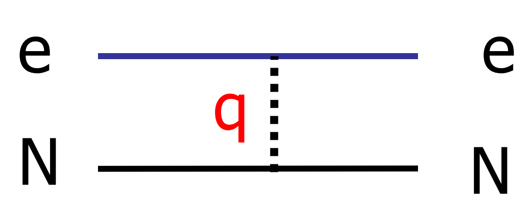
$$< N(p')|J_\alpha^{em}|N(p)>= \bar{u}(p')\left[\gamma_\alpha F_1^N(Q^2) + \frac{i}{2M}\sigma_{\alpha\beta}q^\beta F_2^N(Q^2)\right]u(p),$$

$$< p(p')|V_\alpha^{1+i2}|n(p)>= \bar{u}(p')\left[\gamma_\alpha F_1^V(Q^2) + \frac{i}{2M}\sigma_{\alpha\beta}q^\beta F_2^V(Q^2)\right]u(p),$$

$$< p(p')|A_\alpha^{1+i2}|n(p)>= \bar{u}(p')\left[\gamma_\alpha\gamma_5 F_A(Q^2) + q_\alpha F_p(Q^2)\right]u(p),$$

$$G_E^N(Q^2) = F_1^N(Q^2) - \tau F_2^N(Q^2)$$

$$G_M^N(Q^2) = F_1^N(Q^2) + F_2^N(Q^2) \qquad with \quad \tau = \frac{Q^2}{4M^2}$$

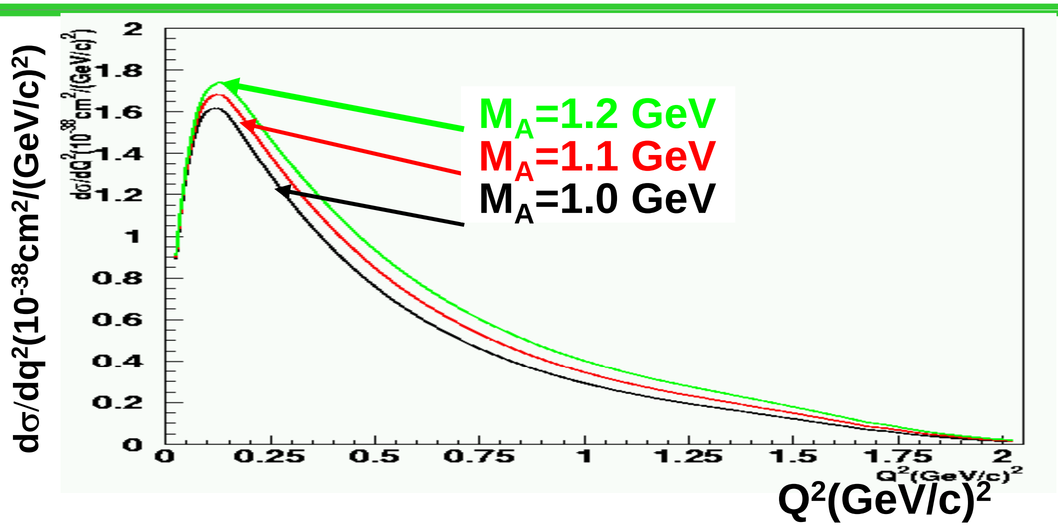


$$G_{E,M}^{V(}(Q^2) = \frac{1}{2}\left[G_{E,M}^p(Q^2) - G_{E,M}^n(Q^2)\right]$$

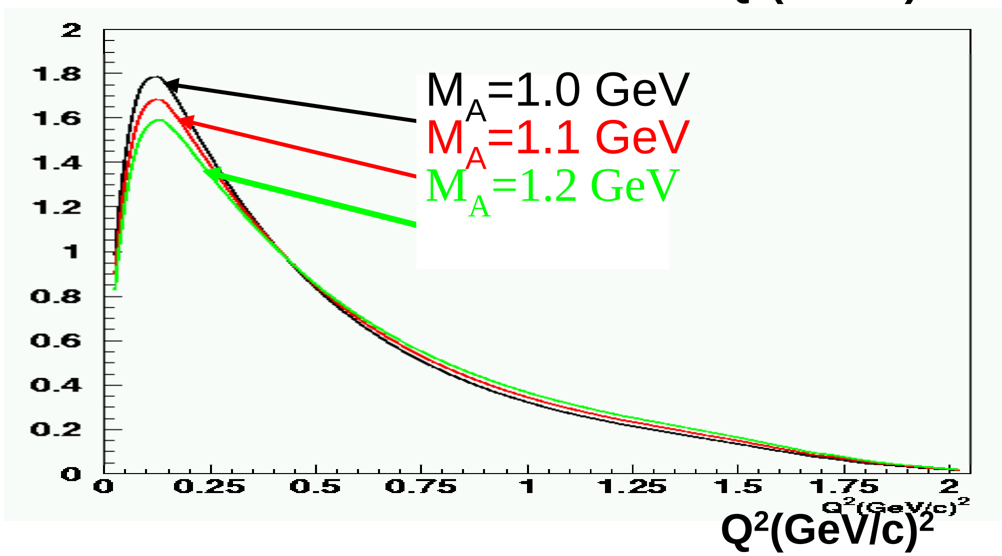
$$F_1^V(Q^2) = \frac{G_E^V(Q^2) + \tau G_M^V(Q^2)}{1+\tau} \quad and \quad F_2^V(Q^2) = \frac{G_M^V(Q^2) - G_E^V(Q^2)}{1+\tau}$$

$d\sigma_{QE}/dQ^2$ distribution at E_ν = 1.3 GeV

Absolute
Cross-section
(includes normalization)



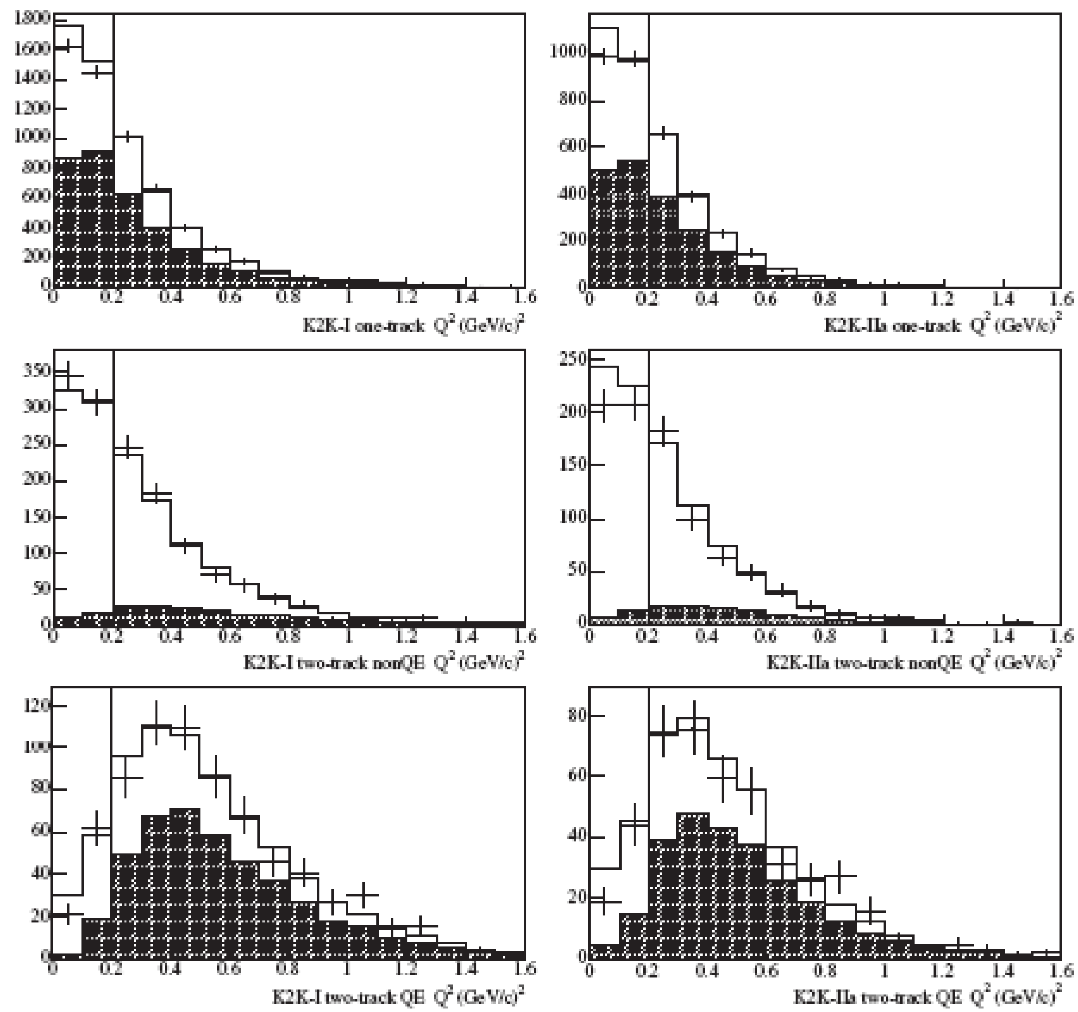
Shape only



Reconstructed Q^2 distribution in SciFi detector

	K2K-I		K2K-IIa	
	$Q^2>0.0$	$Q^2>0.2$	$Q^2>0.0$	$Q^2>0.2$
1 track	5933	2864	3623	1659
2 track QE	740	657	451	388
2 track non-QE	1441	789	893	478
Total	8114	4310	4967	2525

R. GRAN *et al.* PHYSICAL REVIEW D 74, 052002 (2006)



Summary on MA

- QE – SciFi (Water) and SciBar (Carbon)

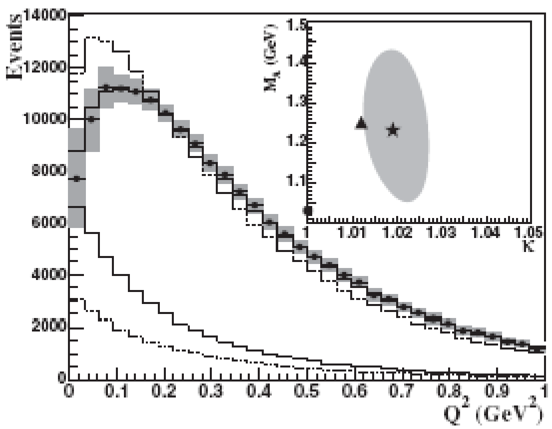
  Using Dipole form factor with axial vector mass,
  - MA=1.20±0.12(sys) $(GeV/c^2)^2$ (Water)

  Vector form factor (Bosted)
  - MA=1.144± 0.077(fit)+0.078-0.072(sys) (Carbon)

  Vector form factor (BBA)

- MiniBooNE:MA=1.23+-0.20 GeV, with a Pauli suppression parameter,κ=1.019+-0.011.
- New measurements higher than the old values.
- Message from here is:
  - If the accurate neutrino cross section is measured in 5-10 years, there is no need for MA in the future. We parameterize axial form factors in the same way as vector form factors to achieve the accuracy of a few %.

MiniBooNE 2008



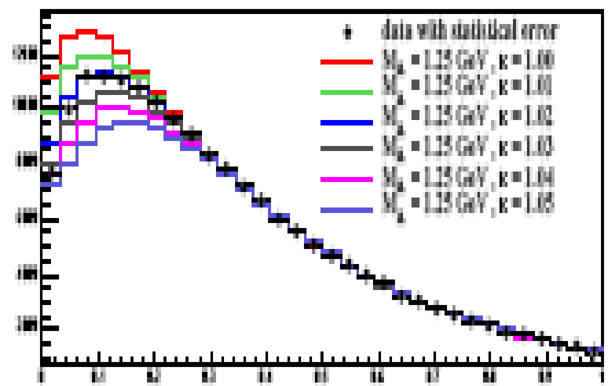
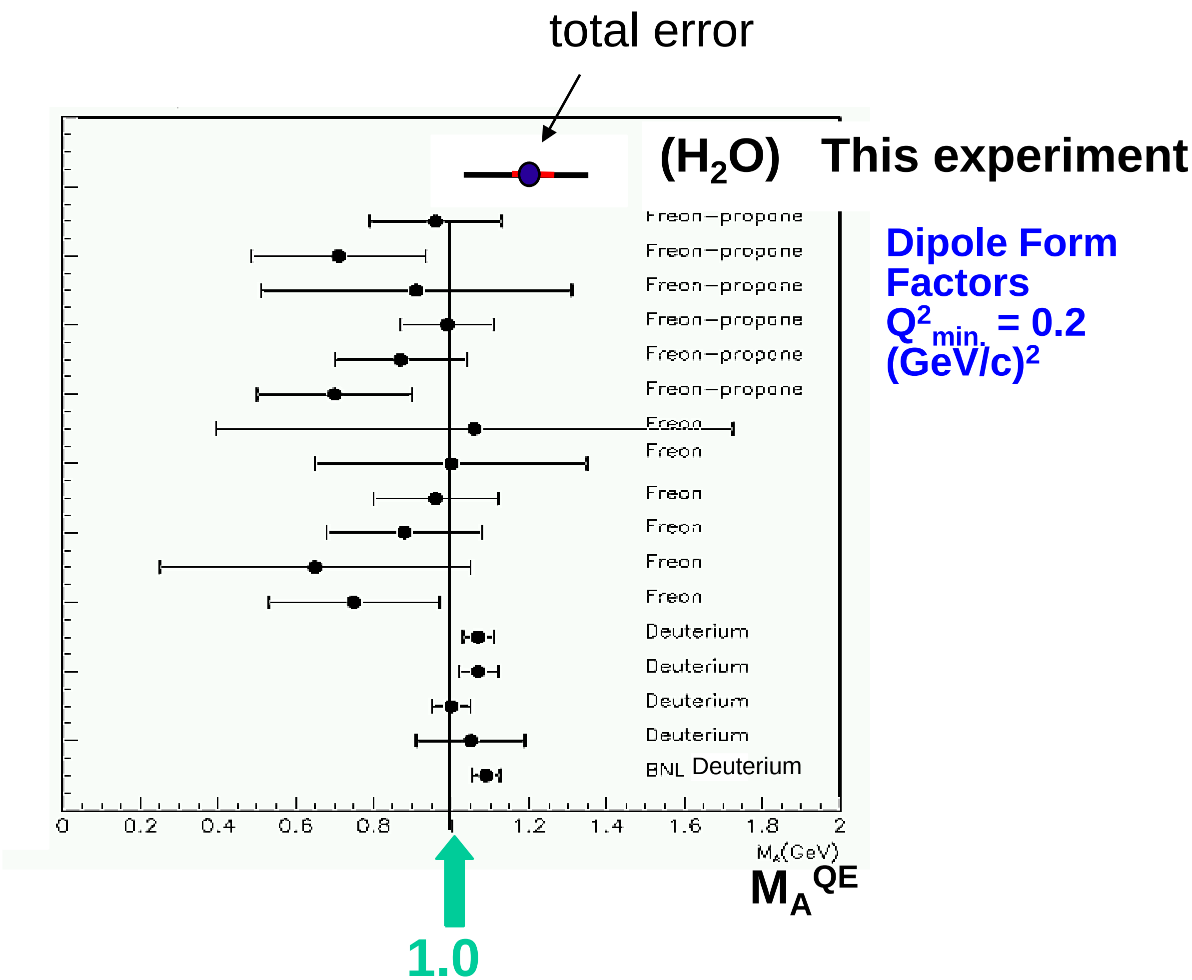


FIG. 2. Reconstructed Q^2 for ν_μ CCQE events including systematic errors. The simulation, before (dashed curve) and after (solid curve) the fit, is normalized to data. The dotted curve (dot-dashed curve) shows backgrounds that are not CCQE (not "CCQE-like"). The inset shows the 1σ C.L. contour for the best-fit parameters (star), along with the starting values (circle), and fit results after varying the background shape (triangle).

Comparison of MA obtained by other experiments

MA=1.20 +/- 0.12 (GeV)^2

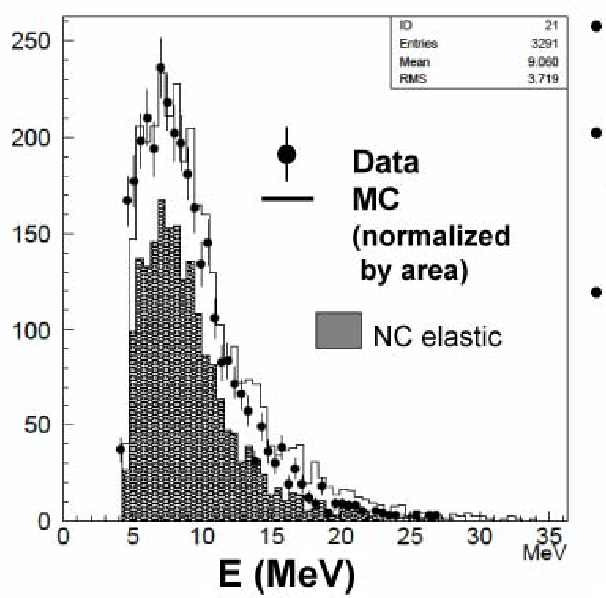


Dipole Form Factors
$Q^2_{min.}$ = 0.2 (GeV/c)^2

NC (6 MeVγ)
-Very important tool to measure neutrino flux

- J. Kameda, Observation of de-excitation gamma rays from nuclei in 1kton detector in K2K experiment, NP B**159**, 44–49 (2006).

About 40% of the neutrino interaction off a nucleon (p or n) in oxygen is expected to be accompanied by about 6MeV gamma rays.



- Observed interaction = 6504.1 events
- MC prediction = 5273 event
- Data/MC prediction = 6504.1/5273 = 1.23 +- 0.04(stat.) +- 0.06 (syst.) (1kton detector systematic error only)

First observation of gamma rays from de-excitation of nuclei induced by neutrino interactions.

Summary

- K2K has confirmed the neutrino oscillations
in 2004, discovered by SK in 1998.
- K2K has initiated the analysis of neutrino interactions.
  - CC coherent pion production
  - NC $1\pi0$ production
  - Quasi-elastic interaction
  - Some more are coming.
- A Q2 deficit has been explained partly by
 1) K2K CC coherent pion production
 2) K2K and MiniBooNE QE analysis

- Personal view: To achieve a few % accuracy in the calculation, this is not enough.
  - BRS predicts a similar reduction in incoherent production.
  - S(p,E) Spectral Function effect is significant.
  - Low Q2 region is still very important. The cross section dominates there.