K2K Cross Section Measurements

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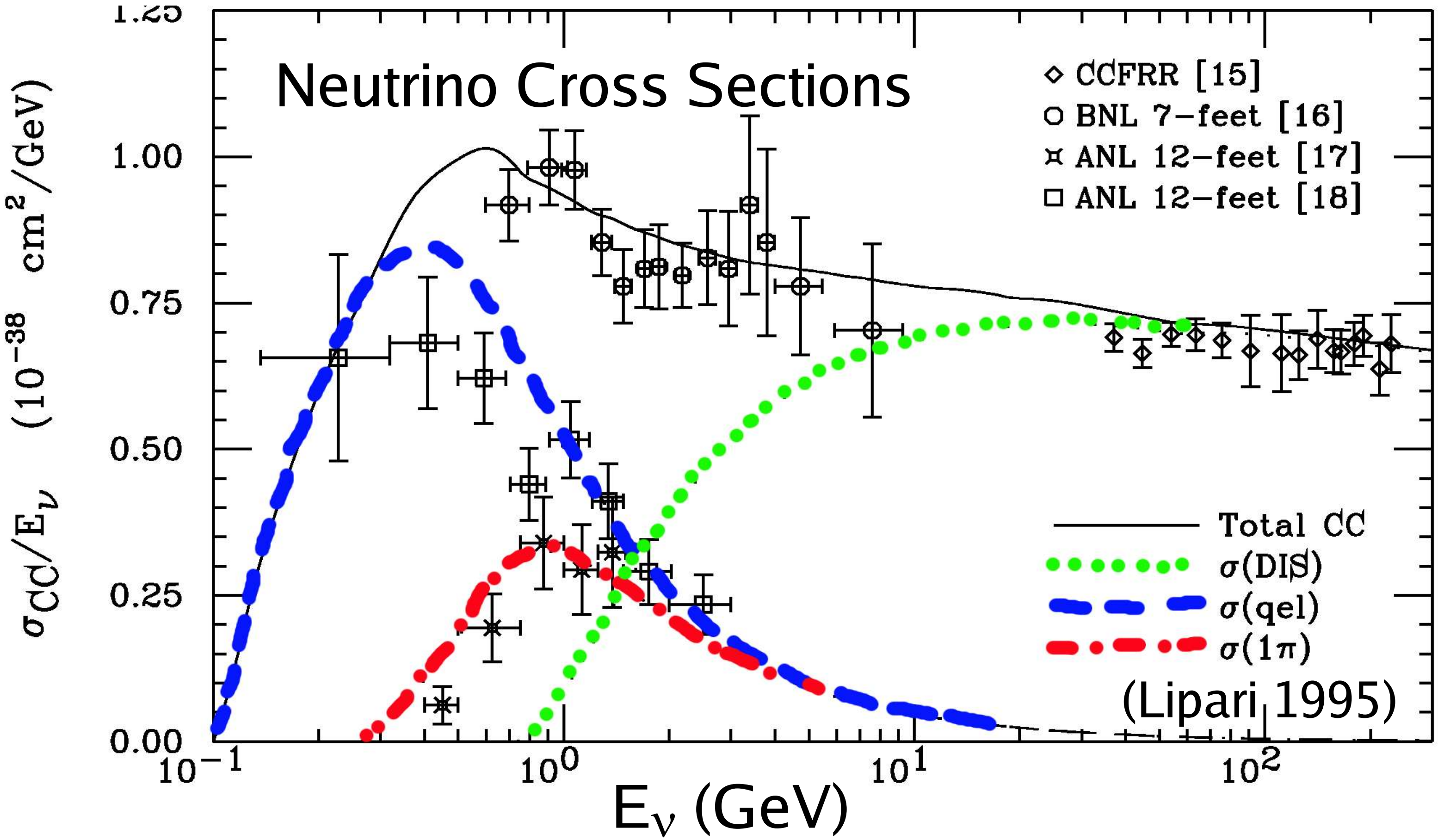
For the K2K collaboration

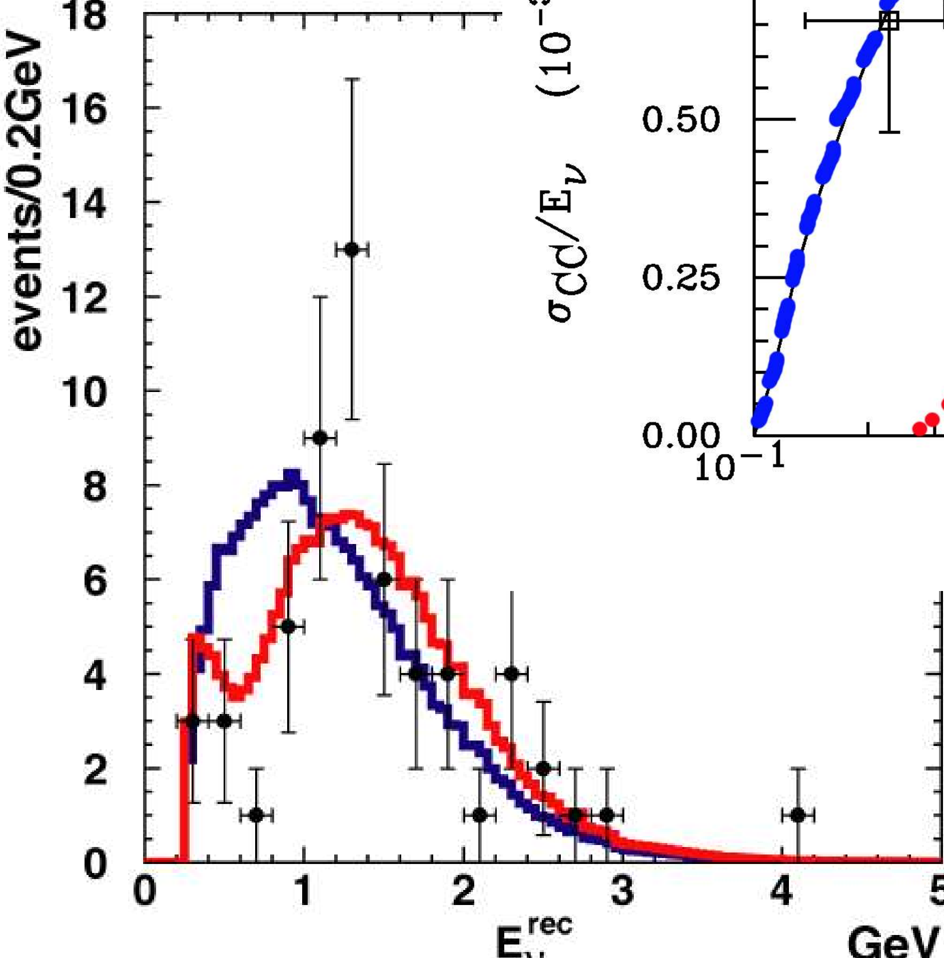
1. NC single π^0/(All CC) in 1KT Cherenkov detector
2. CC-Coherent Pion Production in SciBar detector
3. MA-QE from shape fit to SciFi detector data

(4. Final results from mu-disappearance and e-appearance)

Motivations

Improve knowledge of Cross Sections





K2K oscillation result

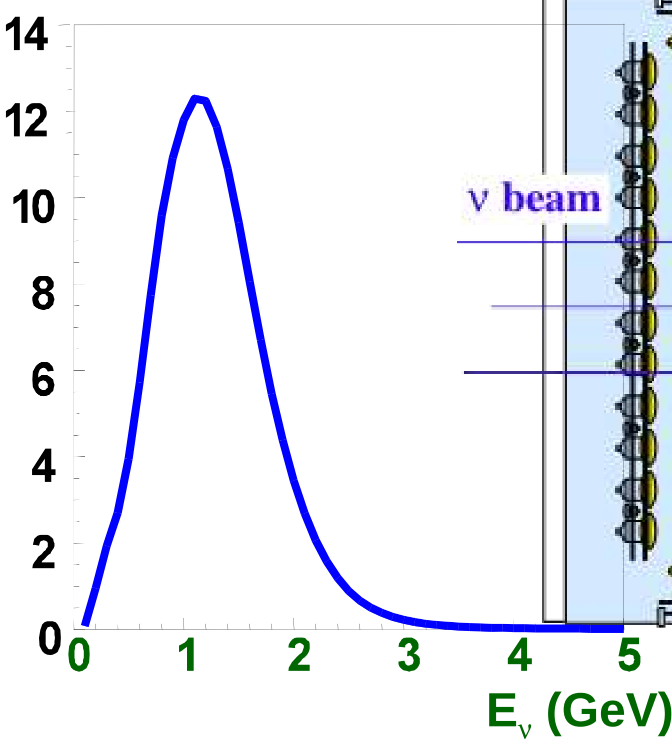
Cross Sections and Nuclear Effects are important for extracting oscillation parameters from nu-mu disappearance nu-e appearance experiments.

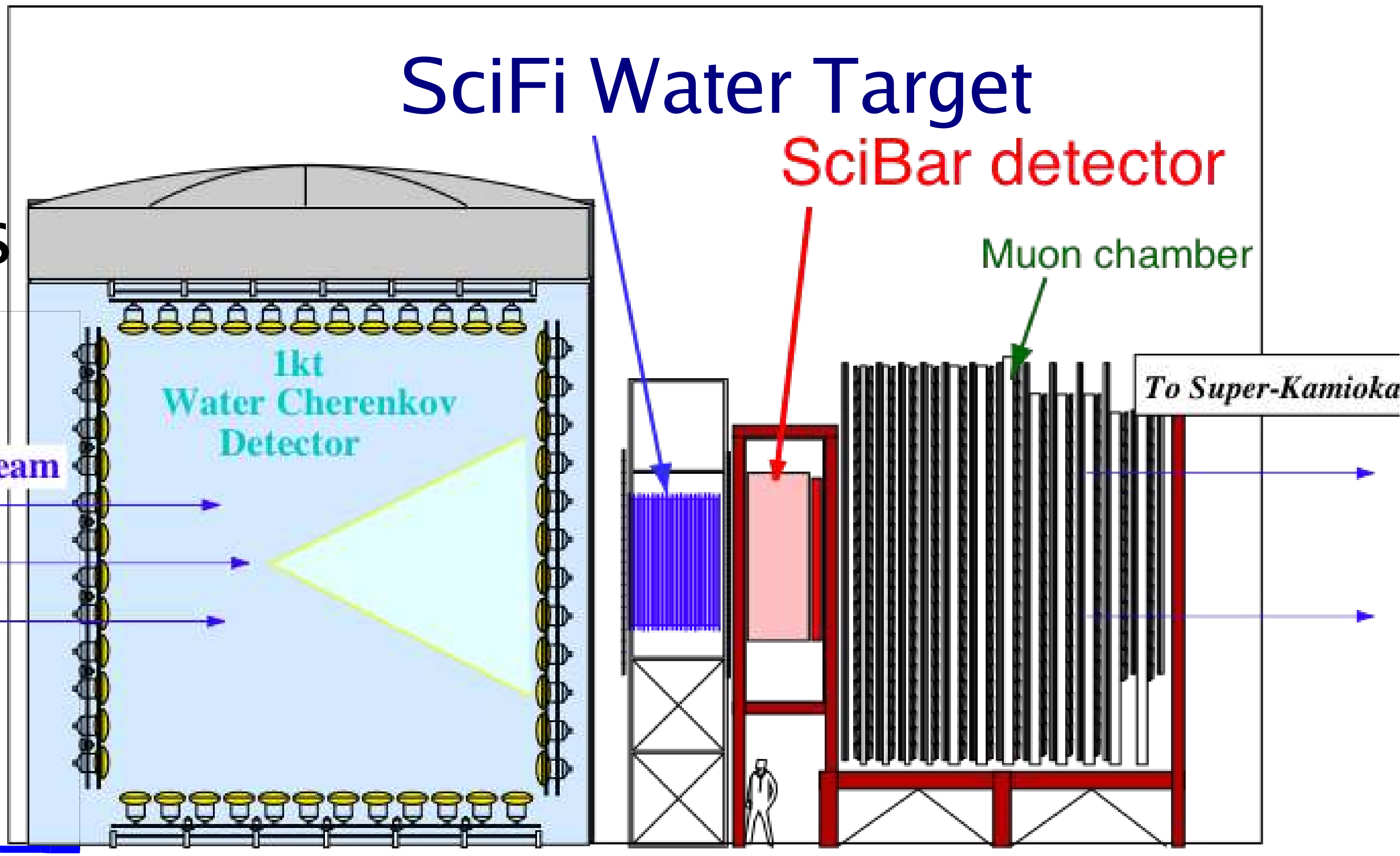
K2K beam and near detectors

98% pure ν_μ beam

target materials: H_2O, HC, Fe

ν_μ energies at the K2K near detectors



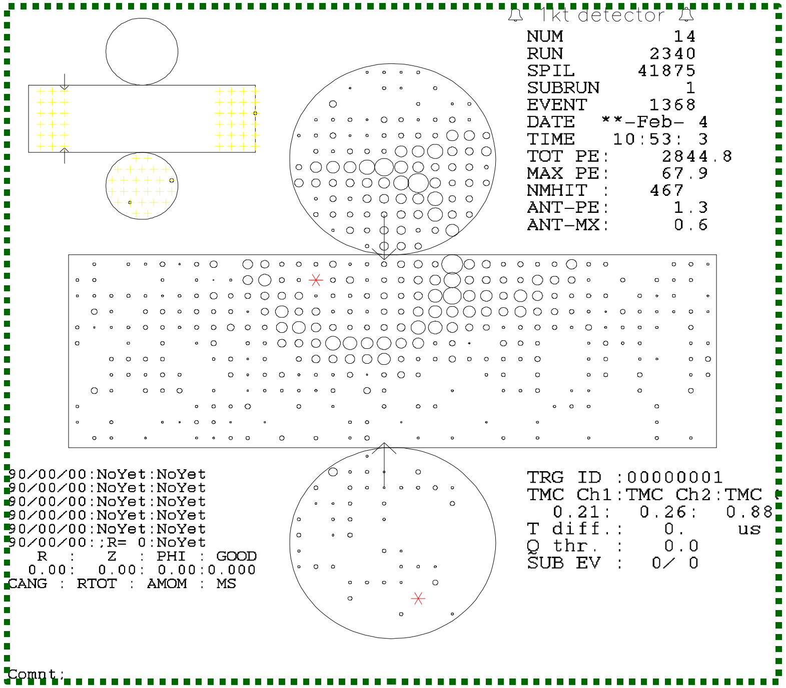


NC single π^0 in the water Cherenkov detector

$$\nu + N \rightarrow \nu + N + \pi^0$$

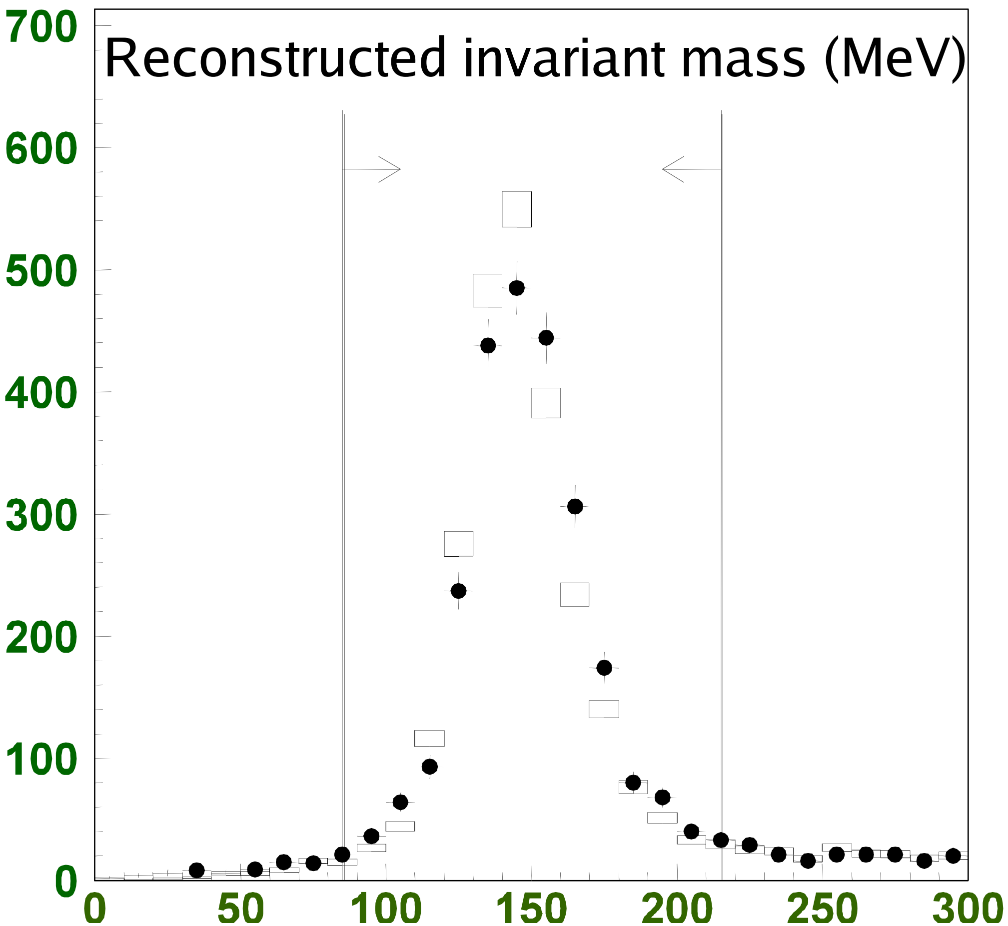
Neutral Current (no muon),

recoil proton below 1 GeV/c threshold (no proton)



Typical π^0 candidate

has two electron-like rings

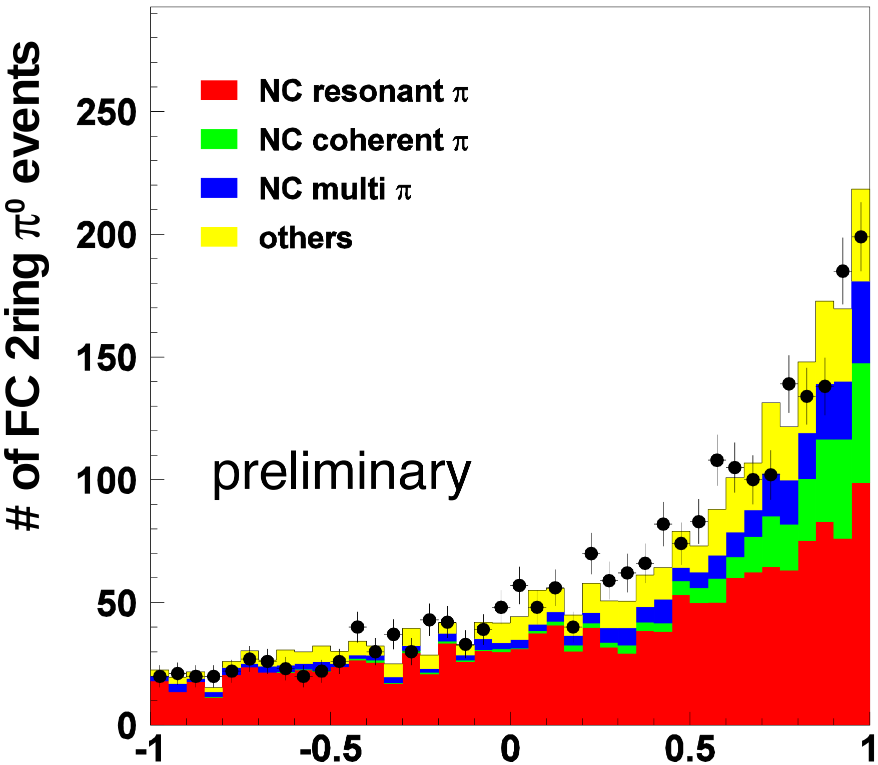


with the right invariant mass

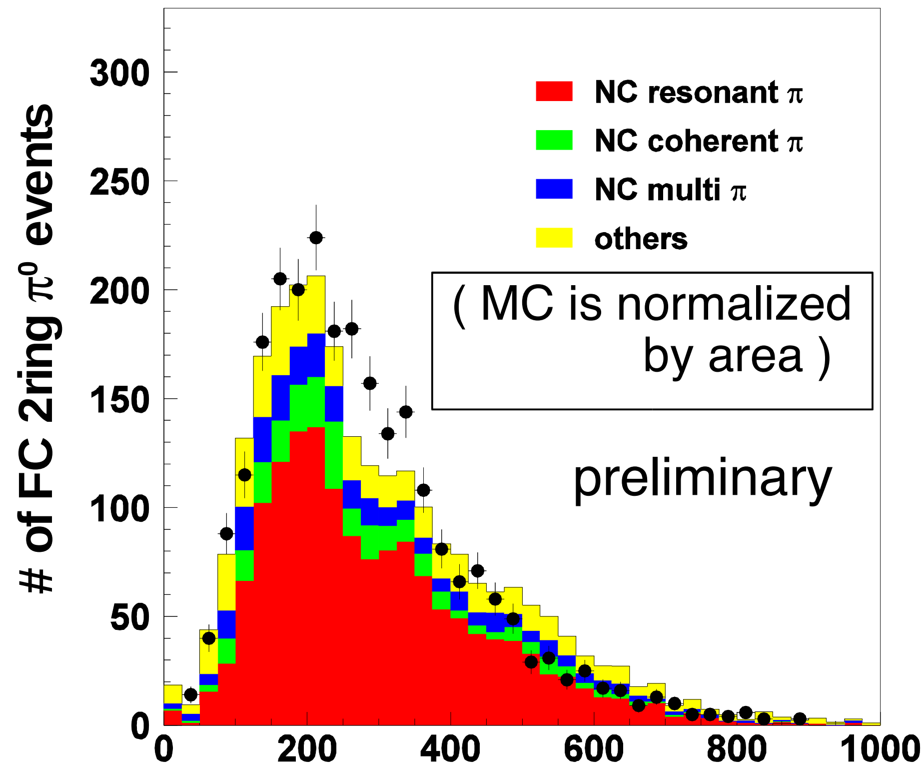
NC single π^0 signal and backgrounds

Signal (70%) is from NC resonant and NC coherent pizero production
AFTER pion-nucleus reinteractions such as charge exchange
(and includes a small amount from non-resonant "DIS" pion production)

Background from multiple (below threshold) pion production
And from Charged Current pion product with muon below threshold



Direction $\cos\theta_\pi$



π^0 momentum (MeV/c)

NC single π^0 fraction result

After efficiency and background corrections

Create ratio with single-ring muon-like events as the reference.

signal in 25 ton fiducial volume
$(3.61 \pm 0.07 \text{ stat} \pm 0.36 \text{ syst}) \times 10^3$

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all muon-like in 25t fiducial volume
$(5.65 \pm 0.03 \text{ stat} \pm 0.26 \text{ syst}) \times 10^4$

$NC1\pi^0/\mu$ ratio at $\langle E\nu \rangle \sim 1.3$ GeV

$= 0.064 \pm 0.001$ stat ± 0.007 syst.

(Prediction from our MC = 0.065)

Major sources of systematic error:

DIS model dependence 5.6% NC/CC cross section 3.2%

Ring counting 5.4% e-like ring particle ID 4.2%

(In mu-like denominator only: vertex reconstruction 4%)

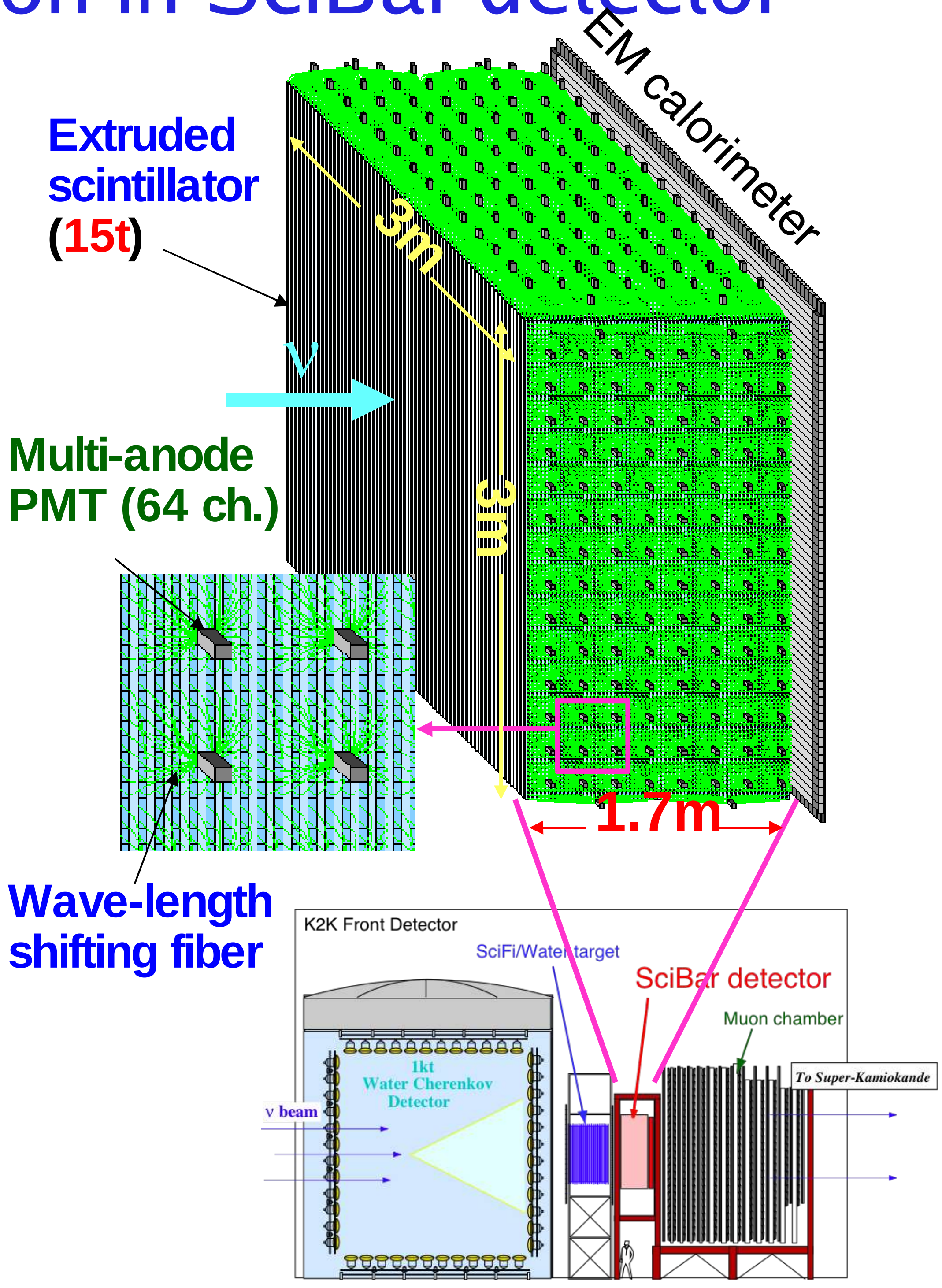
S. Nakayama, et al., Phys. Lett. B 619 (2005)

CC coherent pion in SciBar detector

Fully active scintillator detector (neutrino target HC)

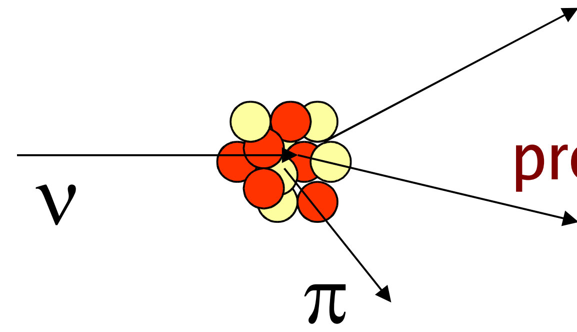
Low thresholds for protons and pions

and proton vs pion particle ID via dE/dx

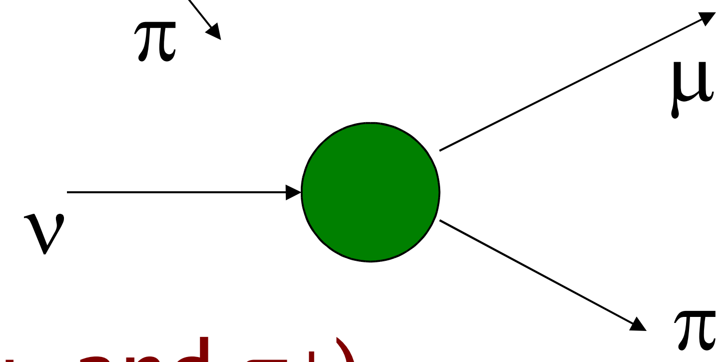


CC coherent pion selection

Resonant pion production
is scattering from nucleon



Coherent pion scatters
from entire nucleus.



No recoil nucleon (see only μ^- and π^+)
Very low momentum transfer (low Q^2, low angle).

Several recent experiments see disagreement between data and expectation in very low Q^2 region.

Does CC coherent pion contribute to disagreement?

Reconstruct Q^2 from the muon in CC samples

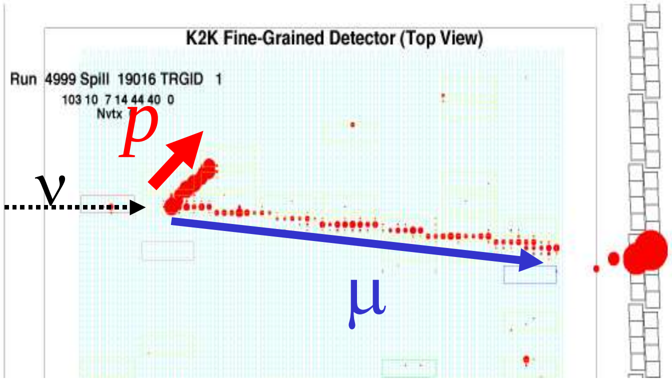
1. Assume CCQE kinematics,
get E_ν and Q^2 from p_μ and θ_μ
get the "wrong answer" (too low)
for non quasi-elastic events
but this treat data and MC same

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

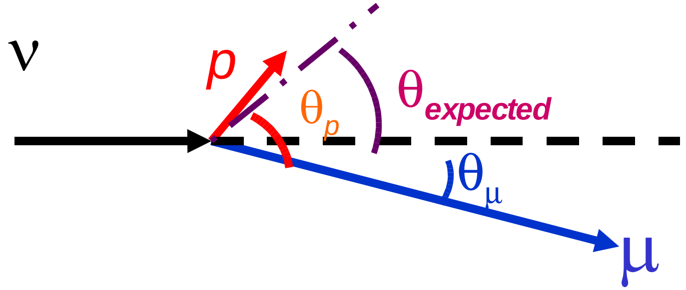
$$Q^2 = -2E_\nu (E_\mu - p_\mu \cos\theta_\mu) + m_\mu^2$$

2. Still using CCQE kinematics
Divide into QE enhanced
and nonQE enhanced subsamples

CCQE candidate in SciBar



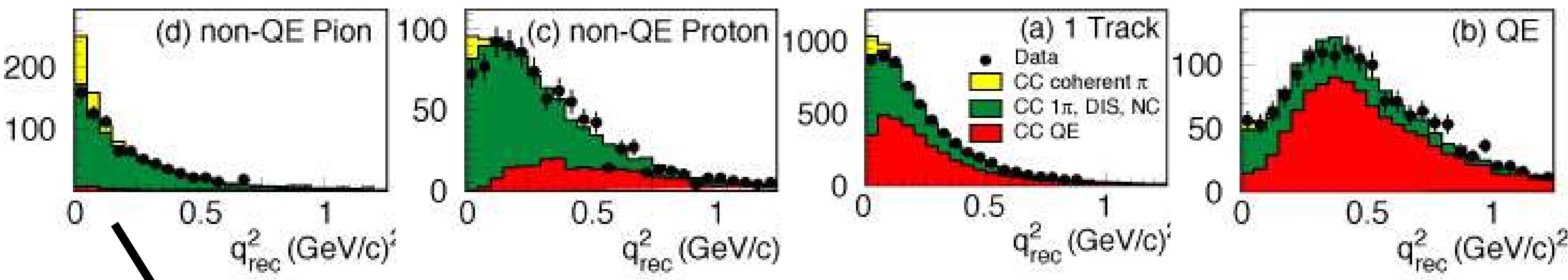
3. Apply SciBar PID ability
to the non muon track to
separate protons and pions



CC coherent pion results

Reconstructed Q^2 for four sub-samples

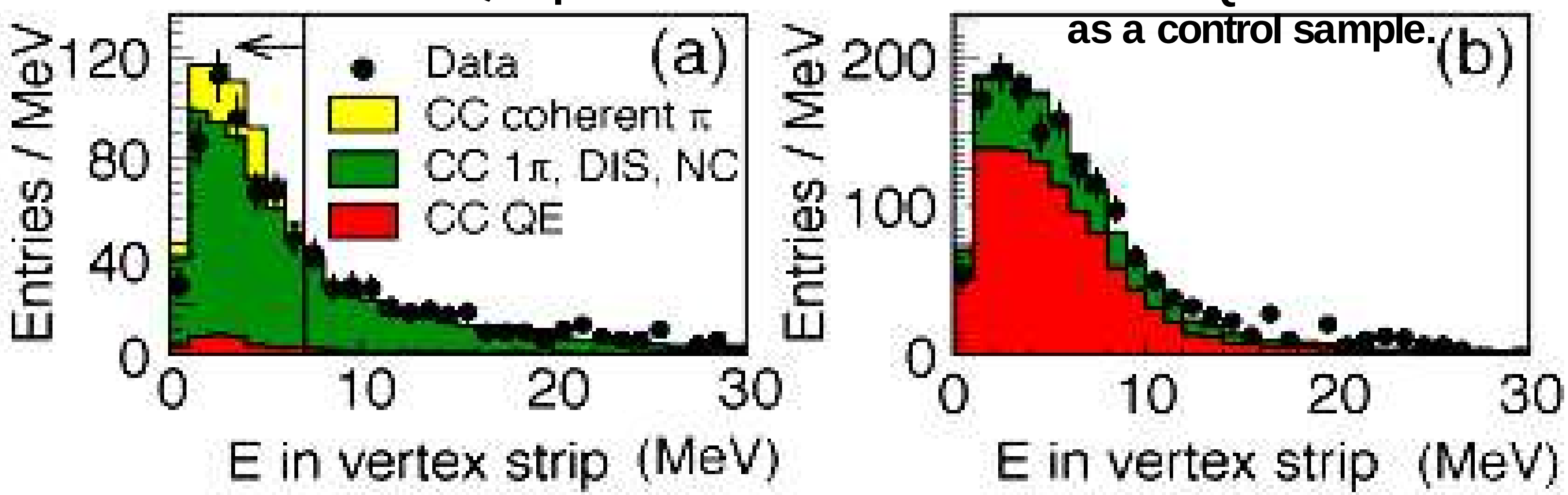
Normalized by
total CC events



Further purify expected CC coherent pion
reject events with a lot of vertex activity

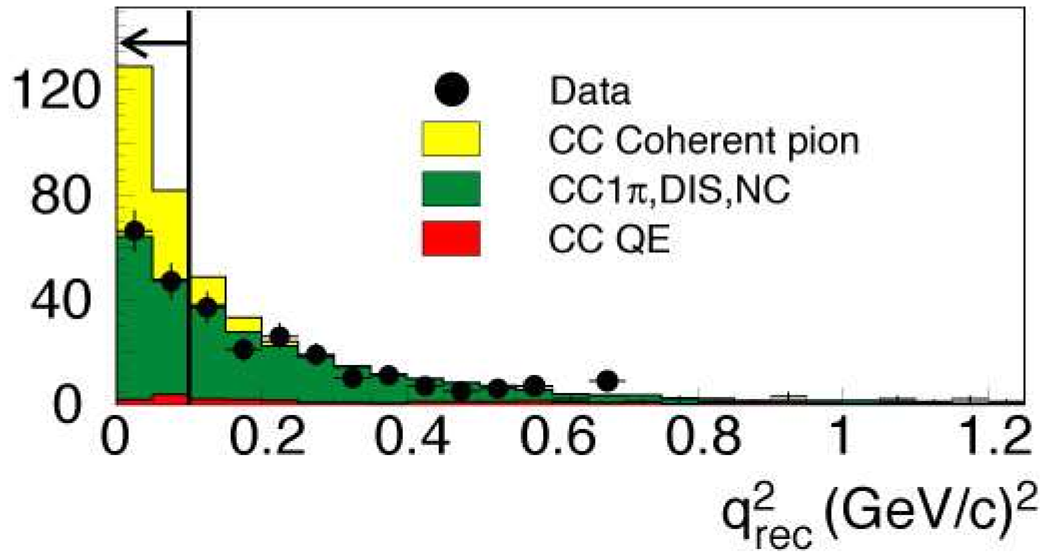
2-track nonQE pion-like

2trk CC QE
as a control sample.



CC coherent pion results

M. Hasegawa, et al., Phys. Rev. Lett. 95 (2005)



Select the 113 events with $Q^2_{rec} < 0.1$ (GeV/c)2

Coherent Pion content expected
21.1% efficiency 47.1% purity

Mesurement relative to all CC events

$$\frac{\sigma_{CCcoh\pi}}{\sigma_{All\ CC}} = (0.04 \pm 0.29\ \text{stat}\ {}^{+0.32}_{-0.35}\ \text{syst}) \times 10^{-2}$$

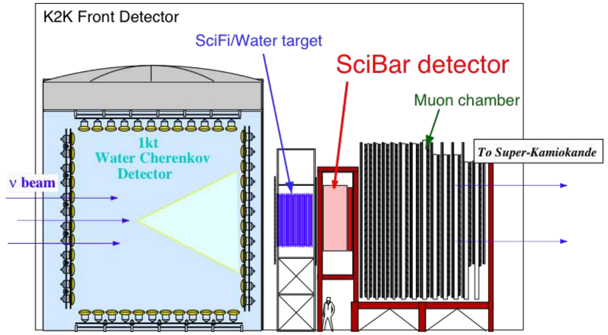
Compute upper bound

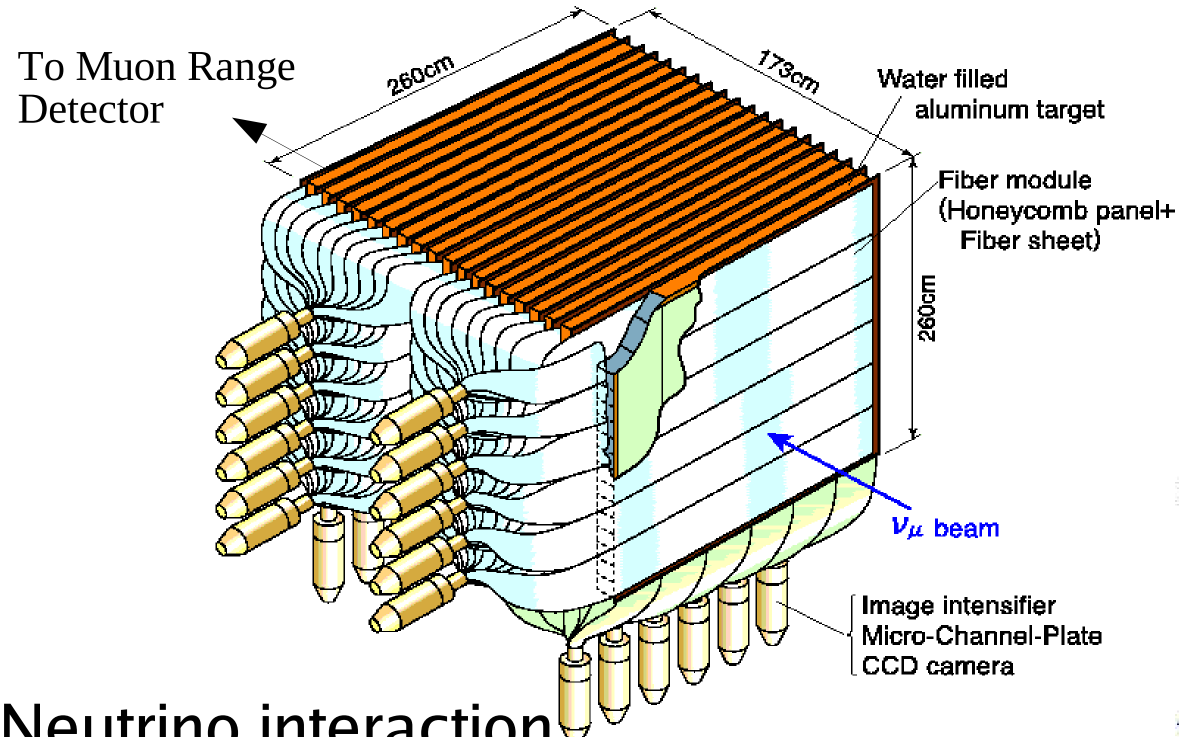
$$\frac{\sigma_{CCcoh\pi}}{\sigma_{All\ CC}} < 0.60 \times 10^{-2}\ (\text{at } 90\%\ \text{CL})$$

This is ~30% of Rein-Sehgal model

Largest systematics: $\sigma_{\text{Resonant Pion}}$ and pion reinteractions in carbon

Scintillating Fiber (SciFi) detector



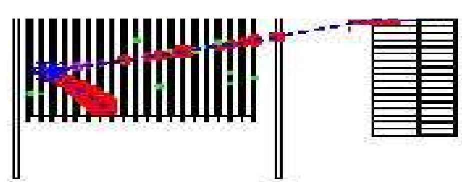


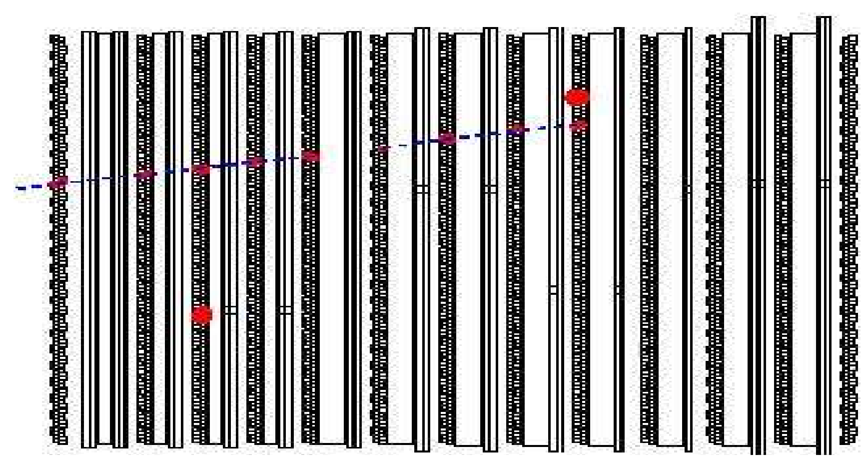
~1 degree angle resolution

Require muon in the
muon range detector
$P\mu$ > 600 MeV

Recoil proton threshold
is three layers in SciFi
Pp > 600 MeV
(so proton not always seen)

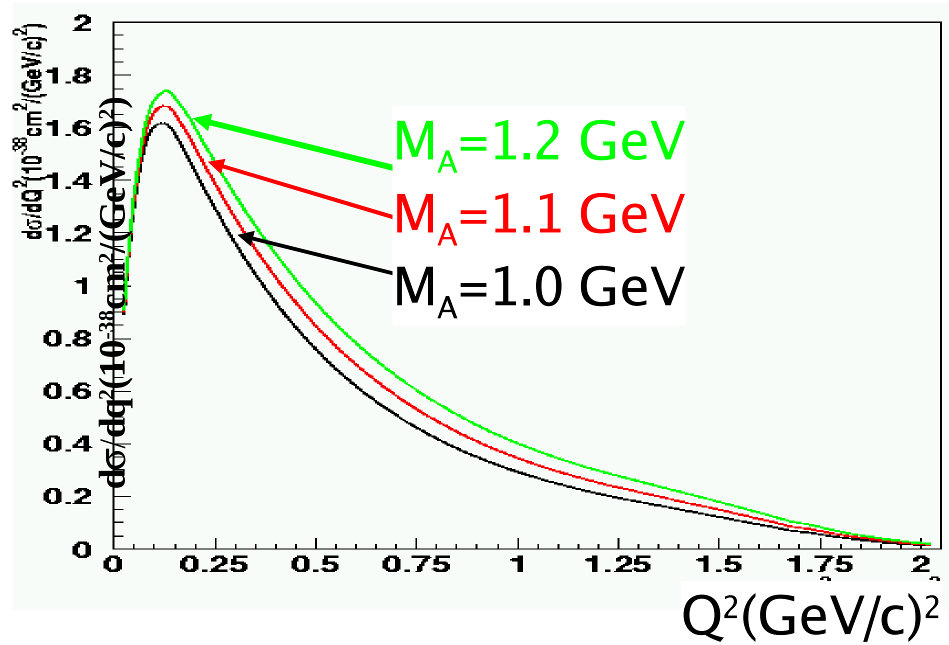
Neutrino interaction
Target is Water
in Aluminum tanks
(70% H2O, 22% Al, 8% HC)



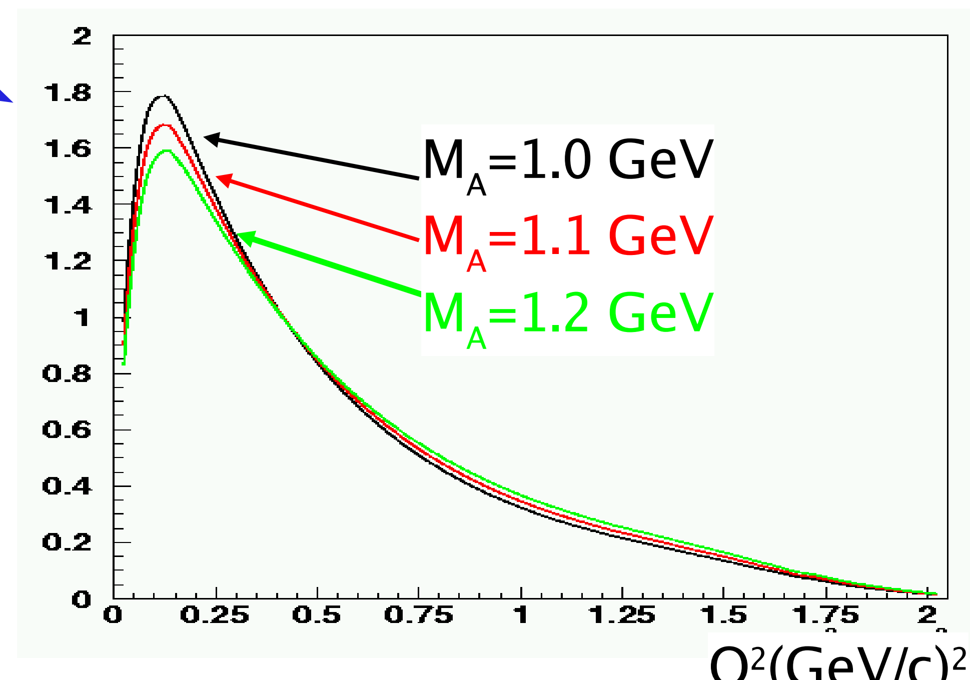


Axial mass and shape of Q^2 distribution

Absolute
Quasi-elastic
Cross section
(includes normalization)



This analysis: Shape Only

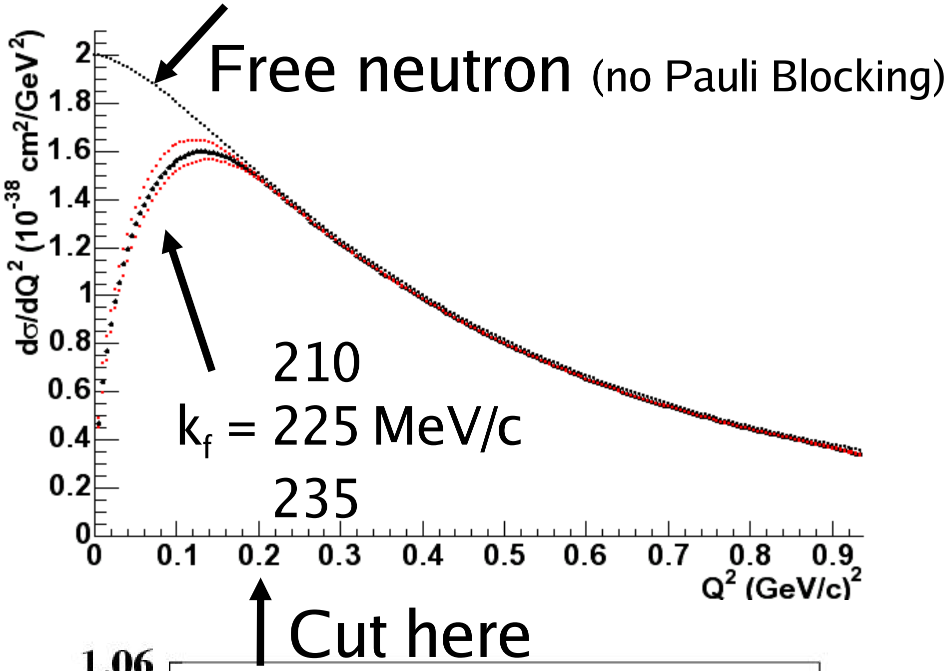


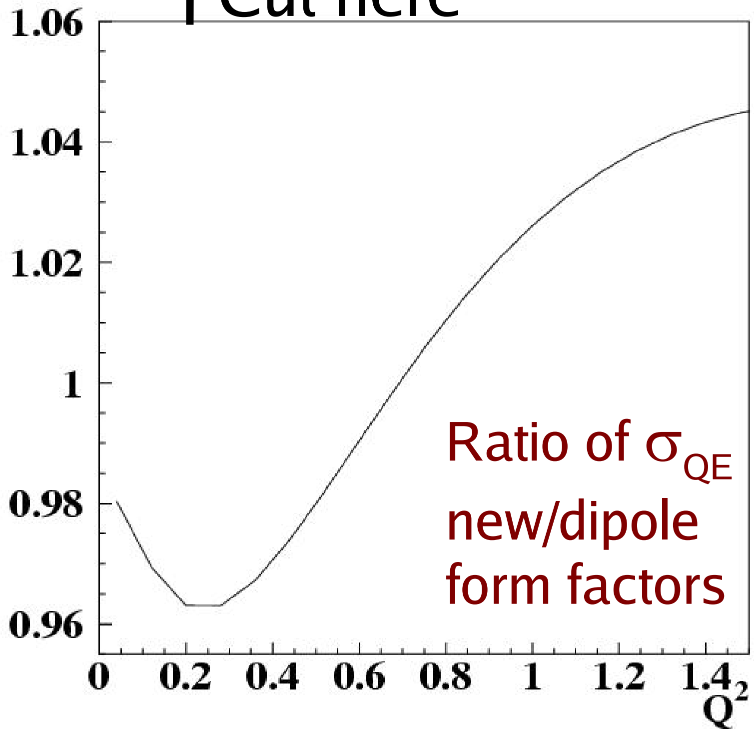
Measure Q^2 for each event
still assuming QE interaction

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

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

Other model effects that change the shape





Pauli Blocking in (Fermi Gas) model
And CC Coherent Pion uncertainty
contribute at low Q2.

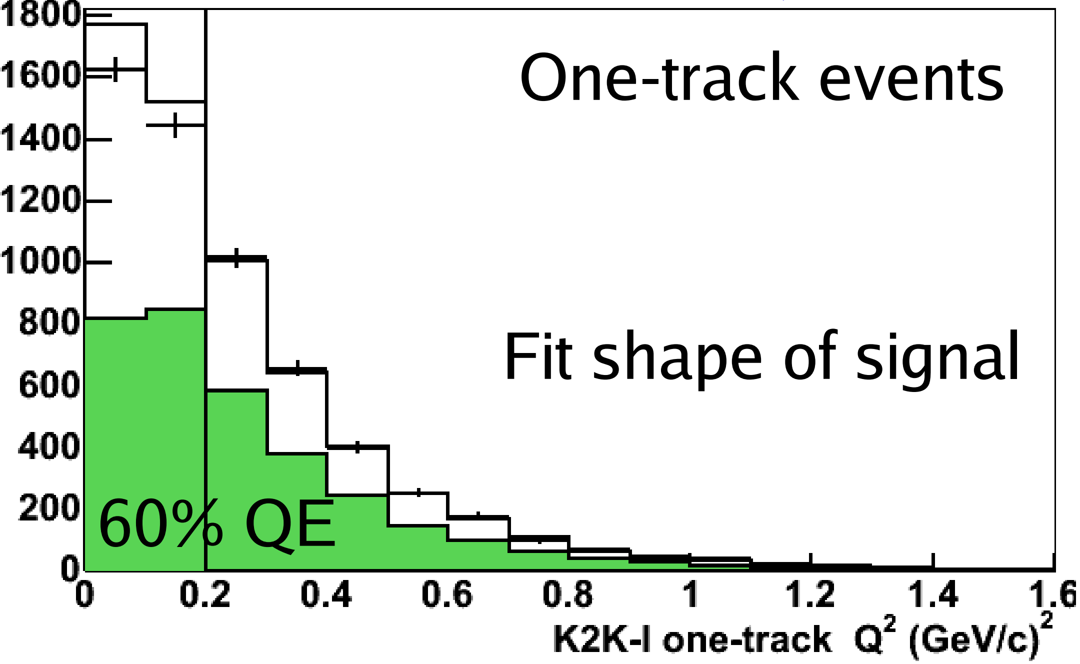
We exclude this region from the fit.

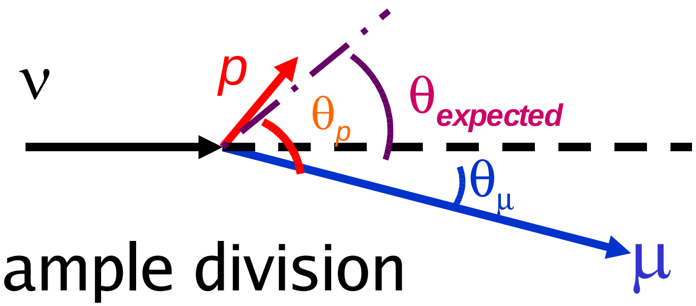
QE cross section calculation also depends on vector form factors.

We use updated form factors from fits to electron scattering data.

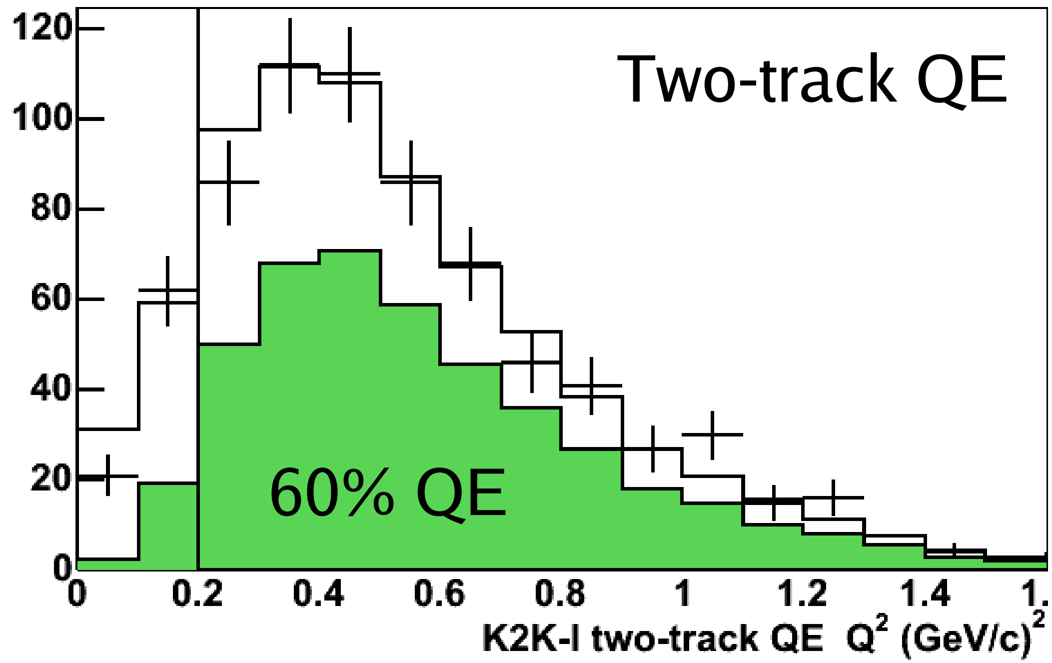
These, plus a second axial mass parameter (we take MA1π=1.1 GeV) affect the nonQE background

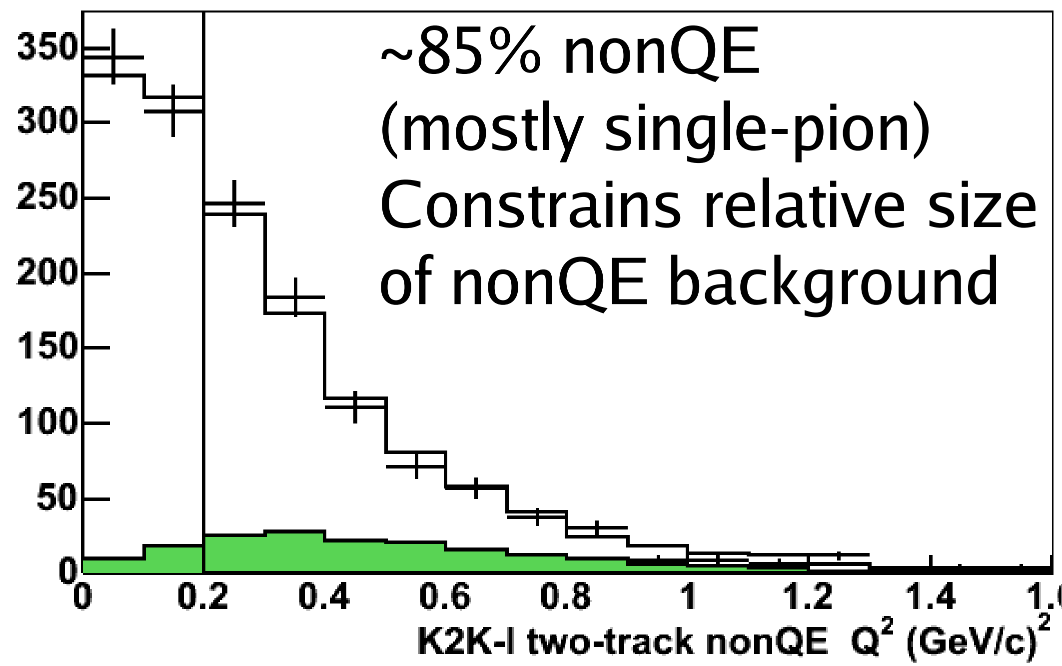
Reconstructed Q^2 for subsamples (after fitting)





Subsample division
(as in slides 9 and 10 but no PID)





Results for effective Quasi-elastic M_A on Oxygen

M_A = 1.20±0.12 GeV (χ^2 = 261/235 dof) shape only

Can be compared with Deuterium bubble chamber results (primarily also shape fits) with older vector form factors
K2K result M_A = 1.23±0.12 Deuterium M_A ~ 1.03±0.03

Most significant errors:	
Muon momentum scale	0.07
Relative flux and normalization	0.06
MA 1π	0.03
relative nonQE fraction	0.03
Nuclear rescattering	0.03
Statistics only	0.03

Our data has a flatter Q^2 spectrum than MC prediction

K2K default MC uses M_A=1.1 GeV dipole vector form factors

RG, Jeon, et al., submitted to PRD, hep-ex/0603034

Final neutrino oscillation results using the K2K data

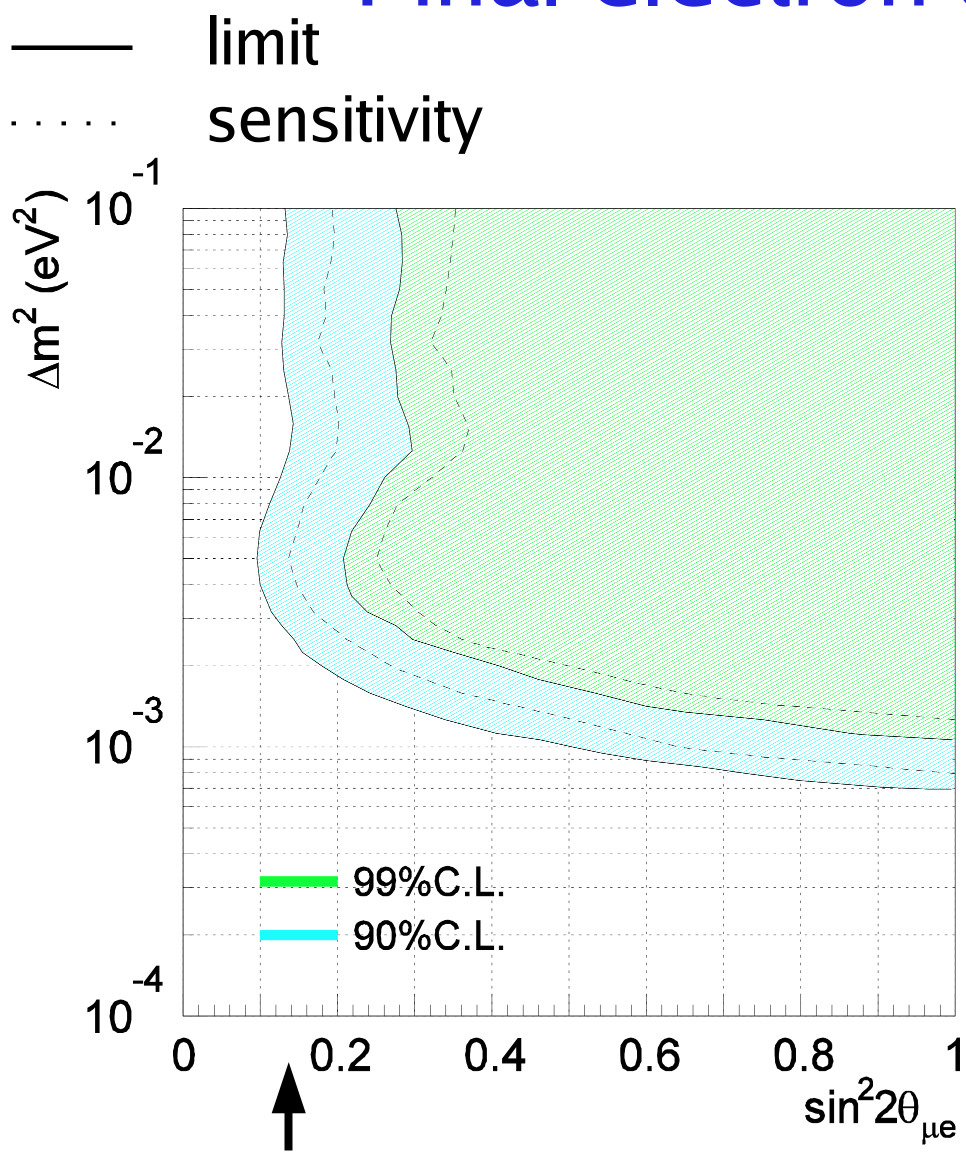
HARP hadron measurements
for new far/near extrapolation

Updated Super-Kamiokande reconstruction

Electron neutrino appearance analysis
now uses entire data set.

(Other smaller refinements)

Final electron appearance result



one event observed
expected background 1.7 events

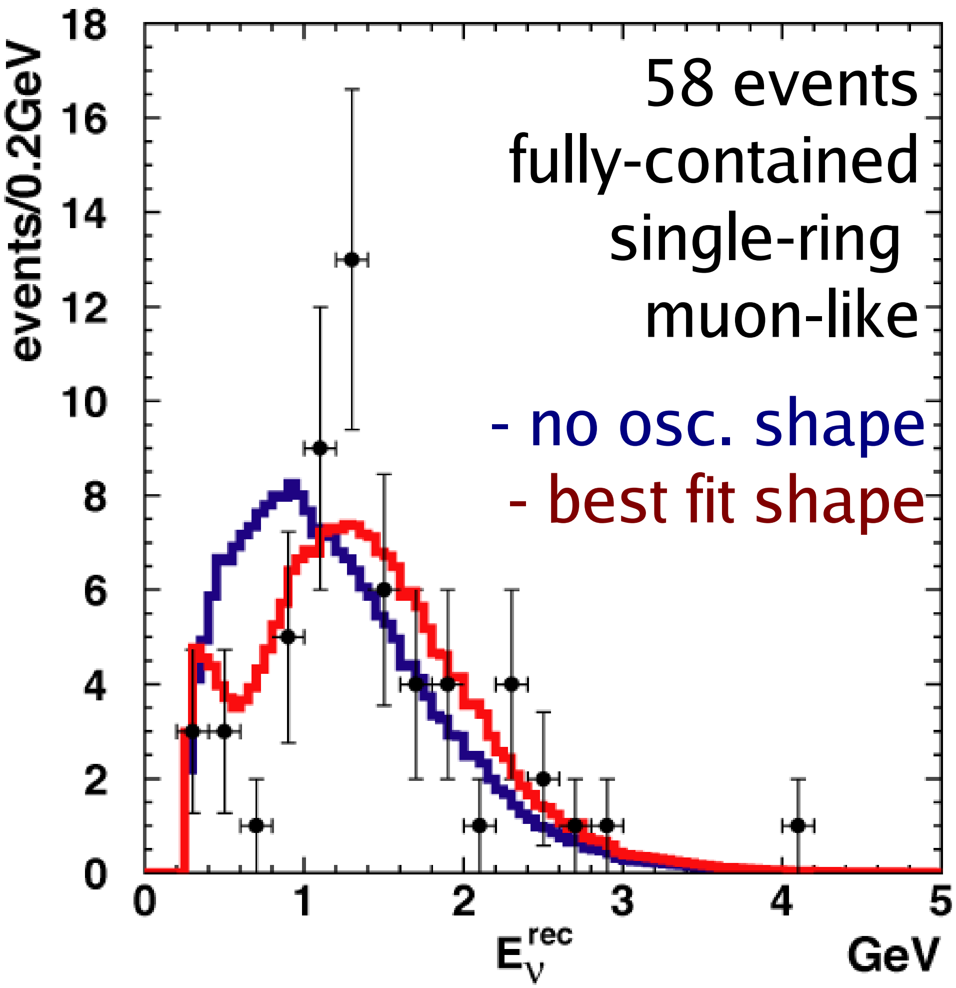
background consists of
1.32 from muon neutrinos
0.38 from beam electron neutrinos

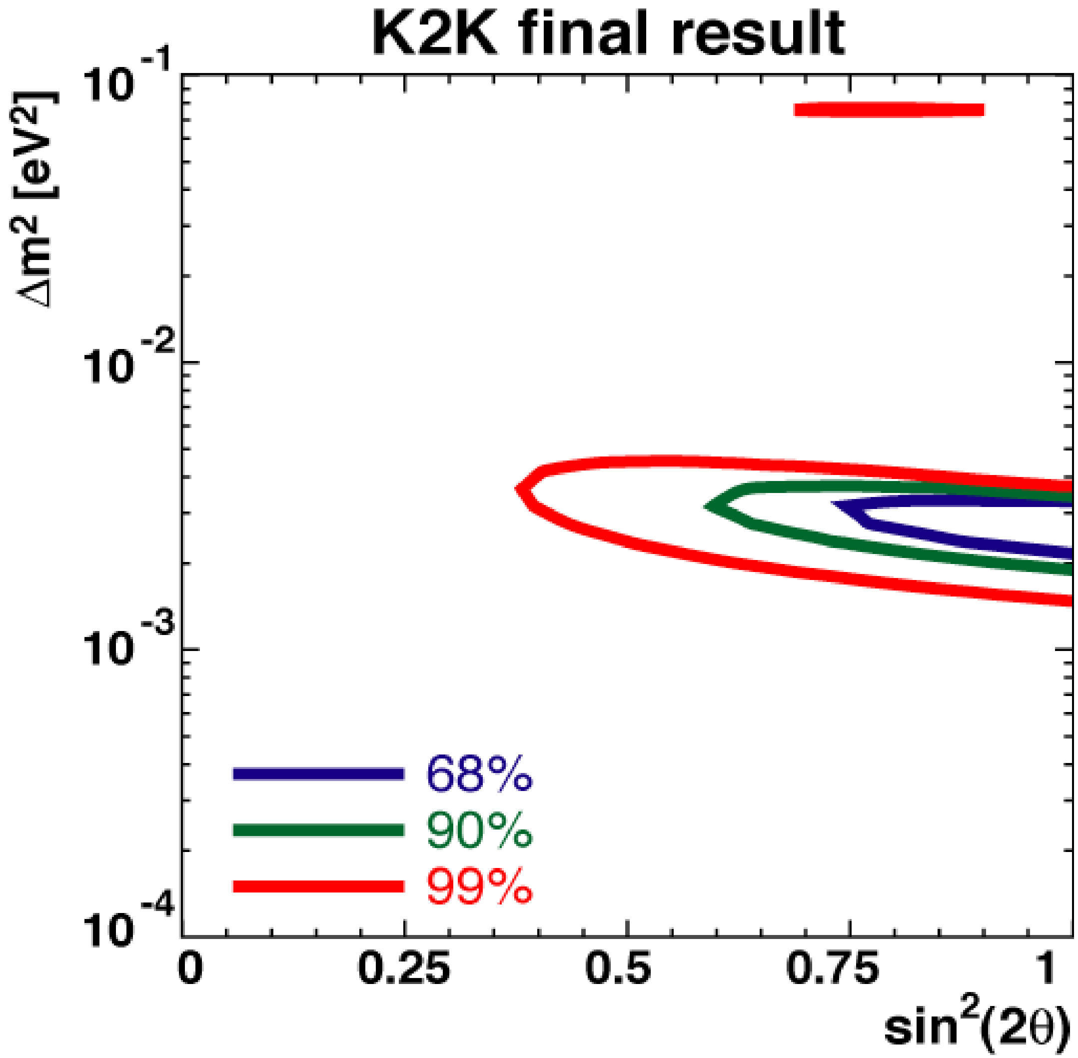
Upper limit (90%CL) $\sin^2 2\theta_{\mu e} < 0.13$ at $\Delta m^2 = 2.8\text{x}10^{-3}$ eV^2
(Two-flavor analysis)

Yamamoto, Zalipska, et al., PRL 96 (2006)

Final ν_μ disappearance result

All neutrino events in SuperK
Observed 112, expected $158^{+9.2}_{-8.6}$





Ahn, et al. sub. to PRD hep-ex/0606032

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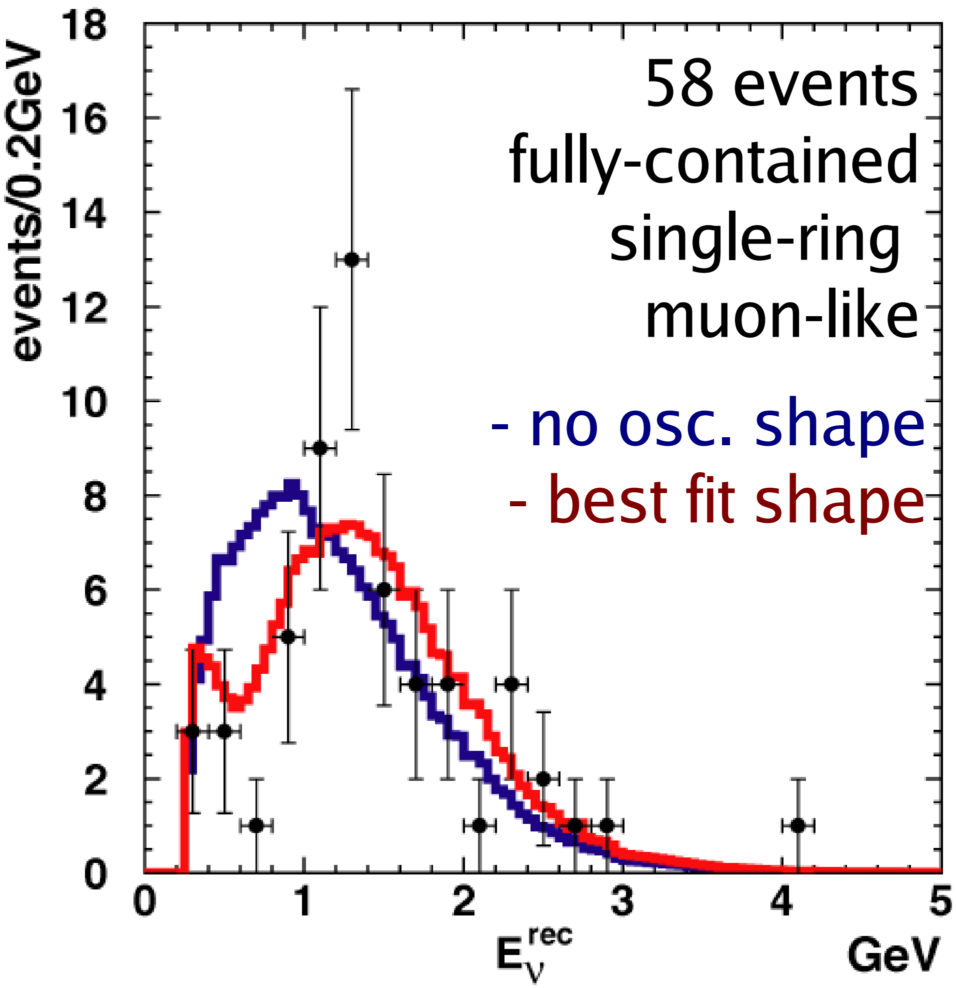
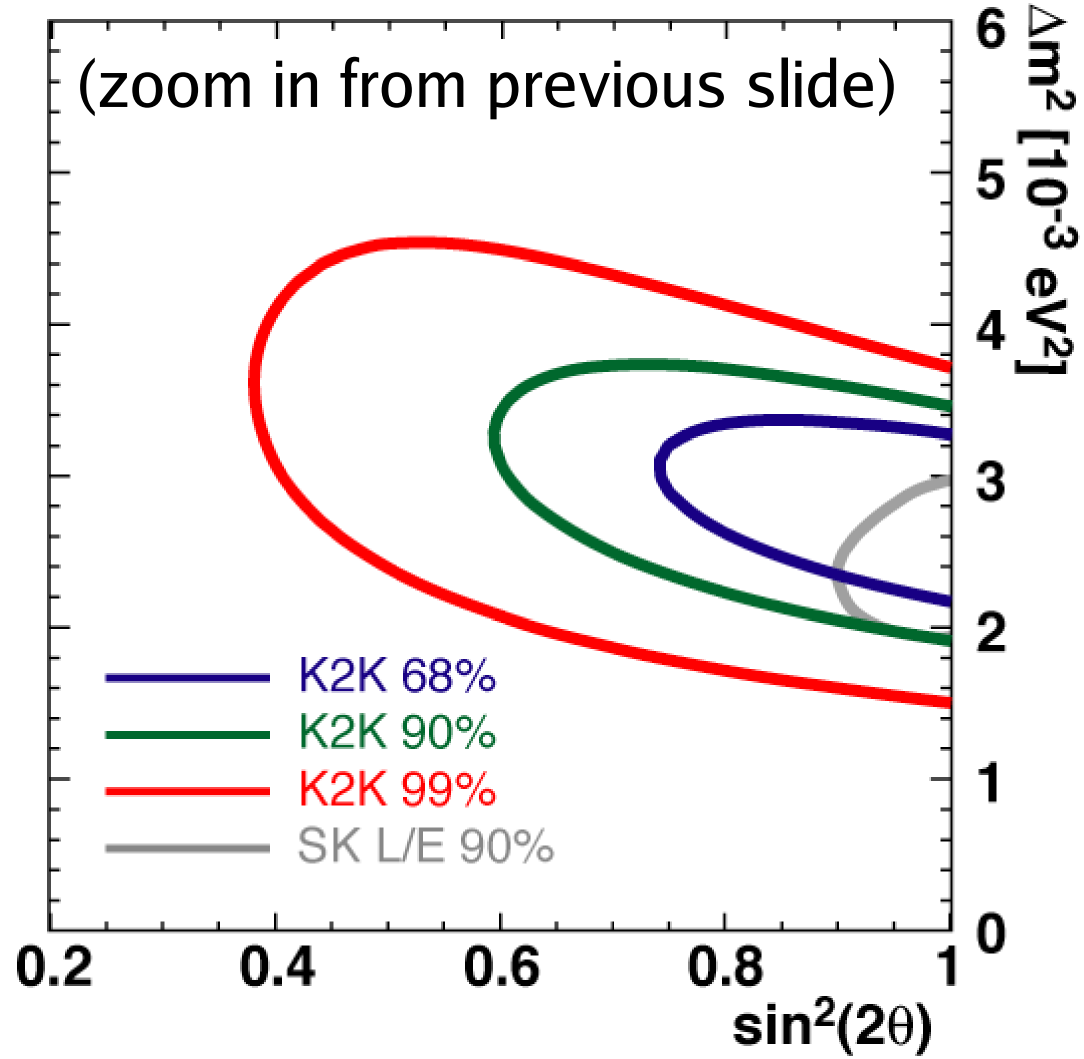


Ahn, et al. sub. to PRD hep-ex/0606032



Maximal mixing 90% CL
$1.9 \times 10^{-3} < \Delta m^2 < 3.5 \times 10^{-3}$ eV^2
Best fit in physical region 2.8×10^{-3}

Conclusions

Several cross section measurements:
Neutral Current single-pizero
Charged Current coherent pion
Shape of Quasi-elastic Q^2 spectrum

Still some ongoing cross section work

Oscillation analyses are final,
papers available now.