K2K Cross Section Studies

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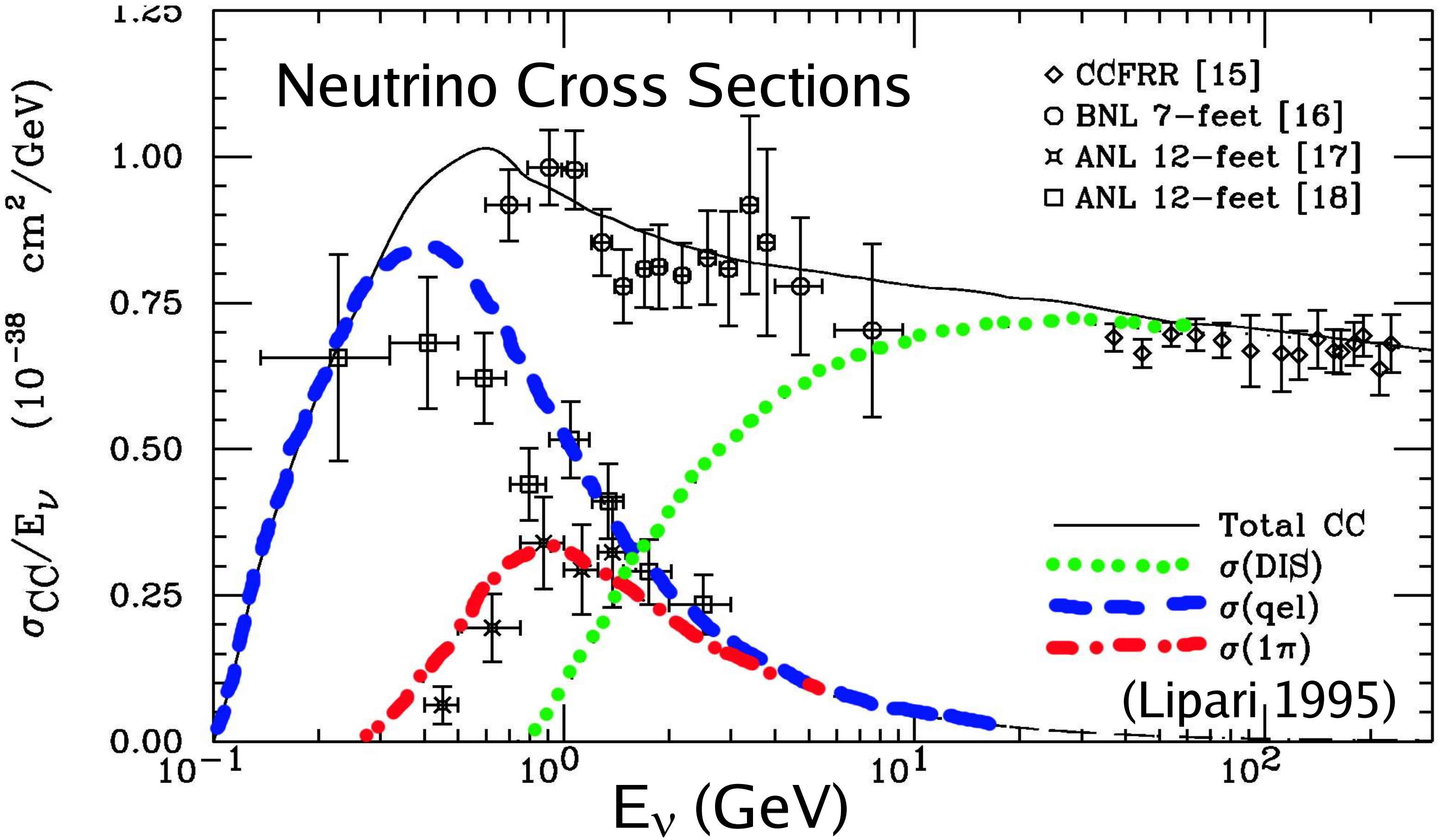
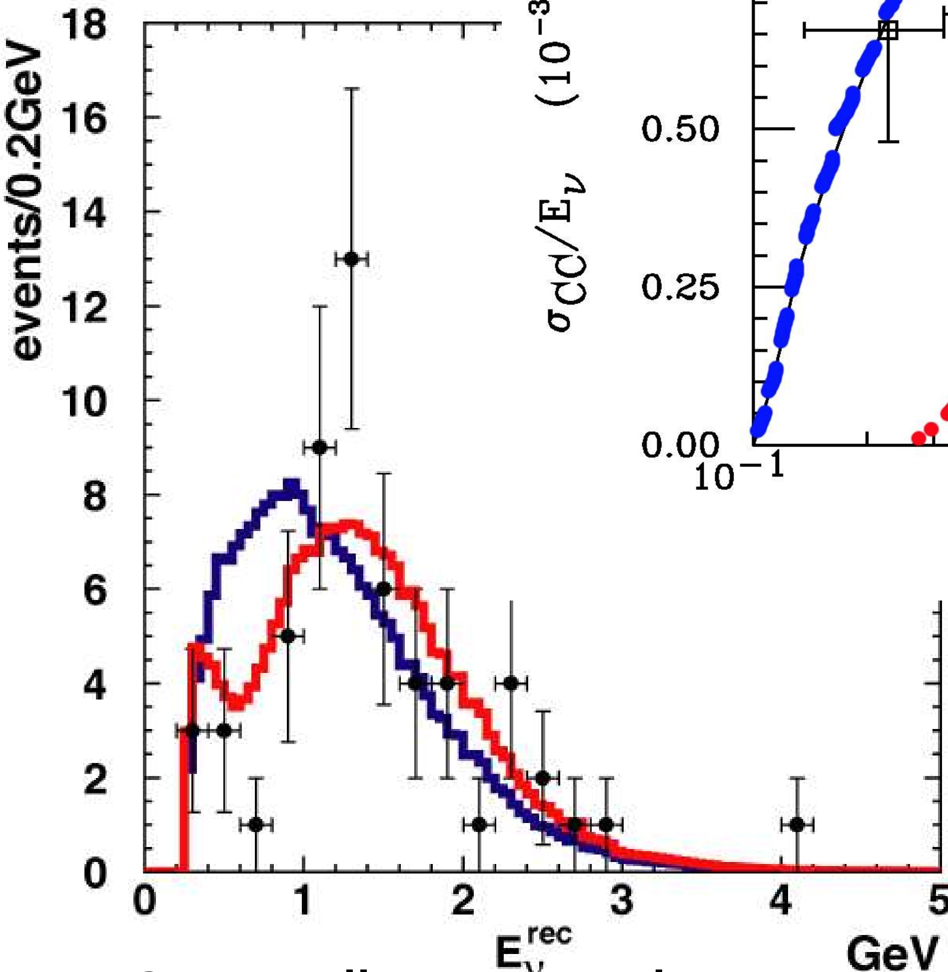
0. K2K experiment and NEUT interaction code
1. NC single π^0/(All CC) in 1KT Cherenkov detector
2. CC-Coherent Pion Production in SciBar detector
3. MA-QE from shape fit to SciFi detector data

Motivations

Improve knowledge of Cross Sections



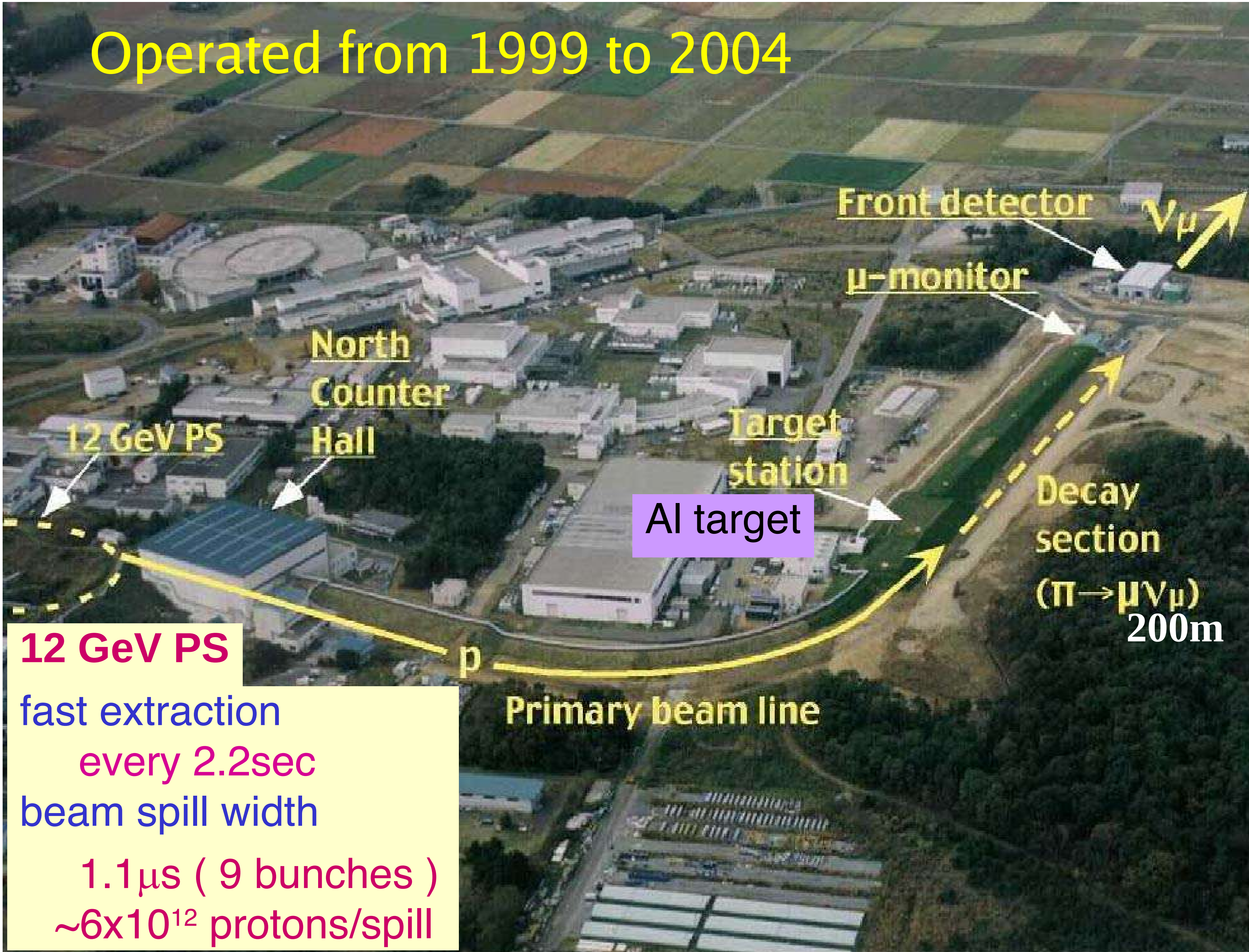


K2K oscillation result

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

K2K beamline at KEK in Tsukuba, Japan

Operated from 1999 to 2004



12 GeV PS

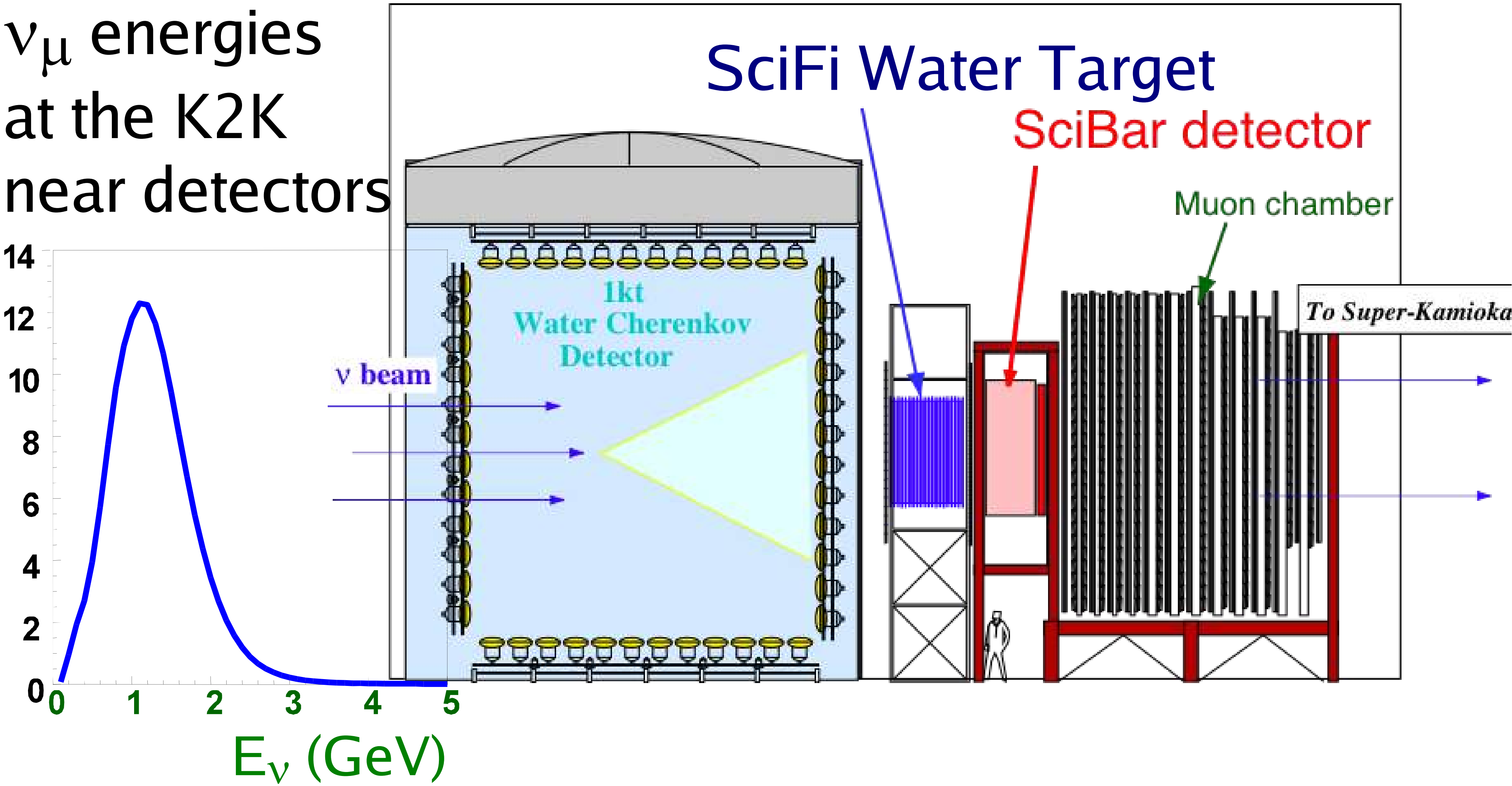
fast extraction
every 2.2sec

beam spill width
1.1μs (9 bunches)
~6x10^12 protons/spill

K2K beam and near detectors

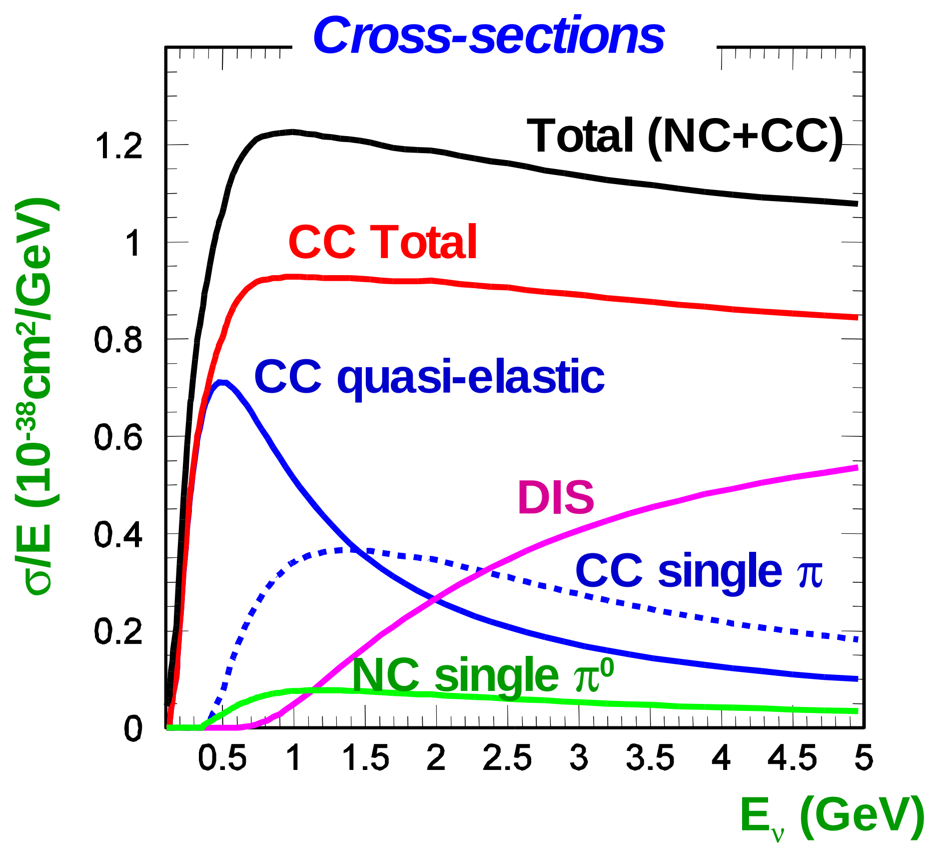
98% pure ν_μ beam   target materials: H_2O, HC, Fe

ν_μ energies at the K2K near detectors



The NEUT neutrino interaction model

Charged current quasi-elastic	ν + N -> l + N'
Neutral current elastic	ν + N -> ν + N
CC/NC single π (η,K) resonance	ν + N -> l(ν) + N' + π
NC coherent pion (not CC !)	ν + A -> ν + A + π^0
CC/NC deep inelastic scattering	ν + q -> l(ν) + had



ν = neutrino (e, μ or τ)

l = lepton (e, μ or τ)

From 100 MeV to 10 TeV

(cosmic ray induced neutrinos too!)

More about the interaction models

Quasi-elastic follows Llewelyn-Smith
using dipole form factors and M_A^{QE} = 1.1 GeV
(For neutrino beam, target is always neutron)

Resonance production from Rein and Sehgal
18 resonances, $M_A^{1\pi}$ = 1.1 GeV
(Coherent pion production also from Rein and Sehgal)

Deep inelastic Scattering from GRV94
PYTHIA/JETSET for hadron final states
Bodek-Yang correction in Resonance-DIS overlap region

Description and references available in Ch. 4 of hep-ex/0606032

Nuclear Effects in the NEUT model

Fermi-gas model for interaction target C, O, Fe
nucleon momentum, Pauli blocked final states

Rescattering as hadrons leave interaction target
Pion rescattering, charge exchange, absorption
Proton rescattering

Hadron STARTS in the nucleus
not identical to hadron scattering experiments
use cascade model of Bertini, et al.

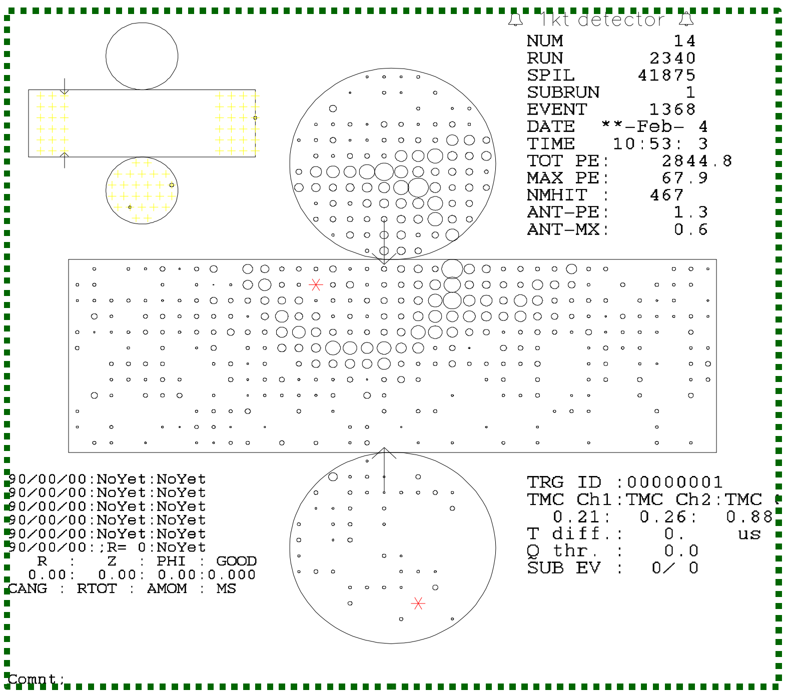
Description and references available in Ch. 4 of hep-ex/0606032

NC single π^0 in the water Cherenkov detector

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

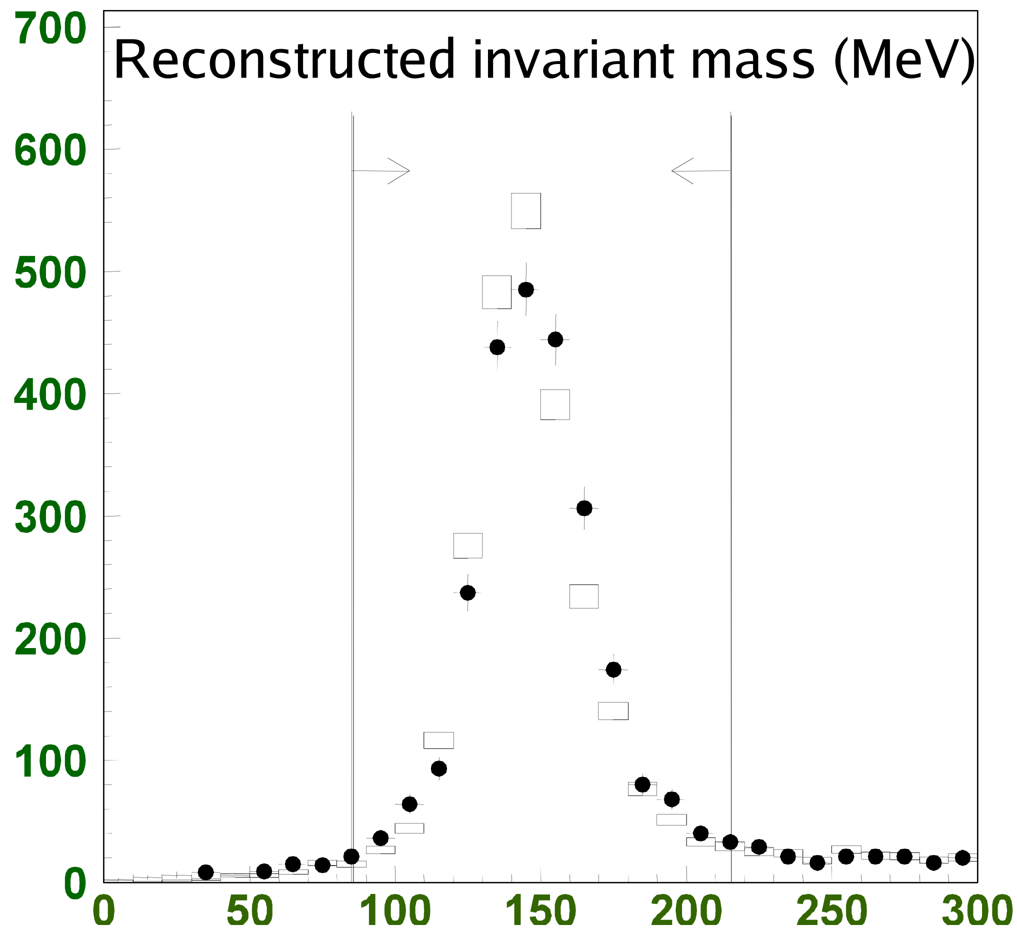
Neutral Current (no muon),

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



Typical π^0 candidate

has two electron-like rings

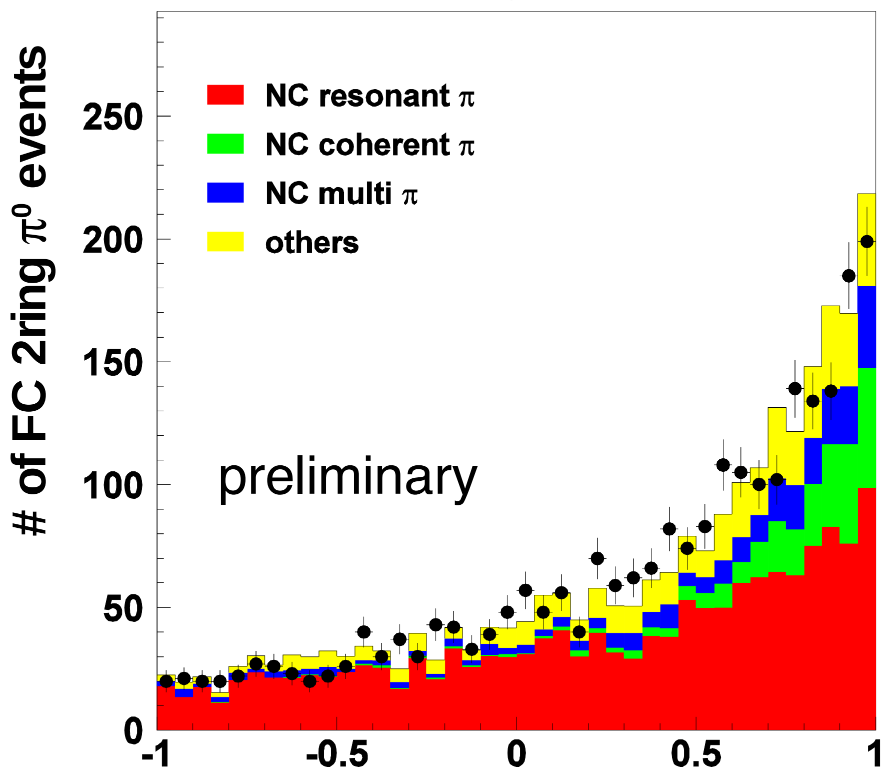


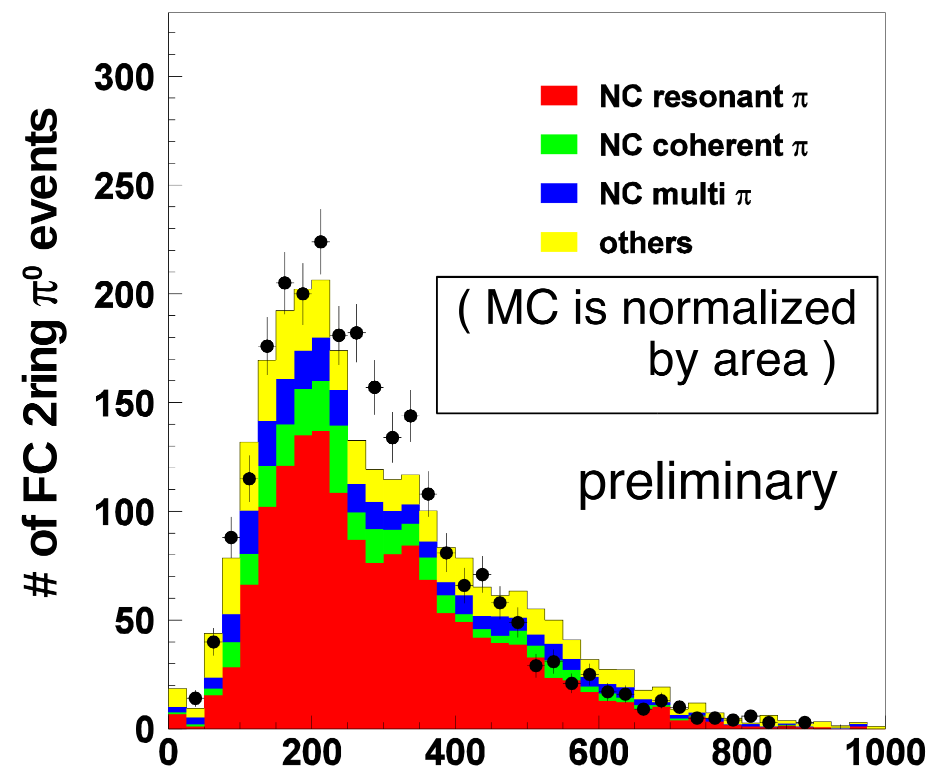
with the right invariant mass

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 $\cos\theta_\pi$ $\qquad$ 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.

$$\frac{\text{signal in 25 ton fiducial volume} \quad (3.61 \pm 0.07\ \text{stat} \pm 0.36\ \text{syst}) \times 10^3}{\text{all muon-like in 25t fiducial volume} \quad (5.65 \pm 0.03\ \text{stat} \pm 0.26\ \text{syst}) \times 10^4}$$

NC1π^0/μ ratio at $\langle E\nu \rangle \sim 1.3$ GeV
$= 0.064 \pm 0.001$ stat $\pm$ 0.007 syst.
(Prediction from our MC = 0.065)

S. Nakayama, et al., Phys. Lett. B 619 (2005) hep-ex/0408134

Model issues related to the analysis

$NC1\pi^0/\mu$ ratio at <$E\nu$> ~ 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%)

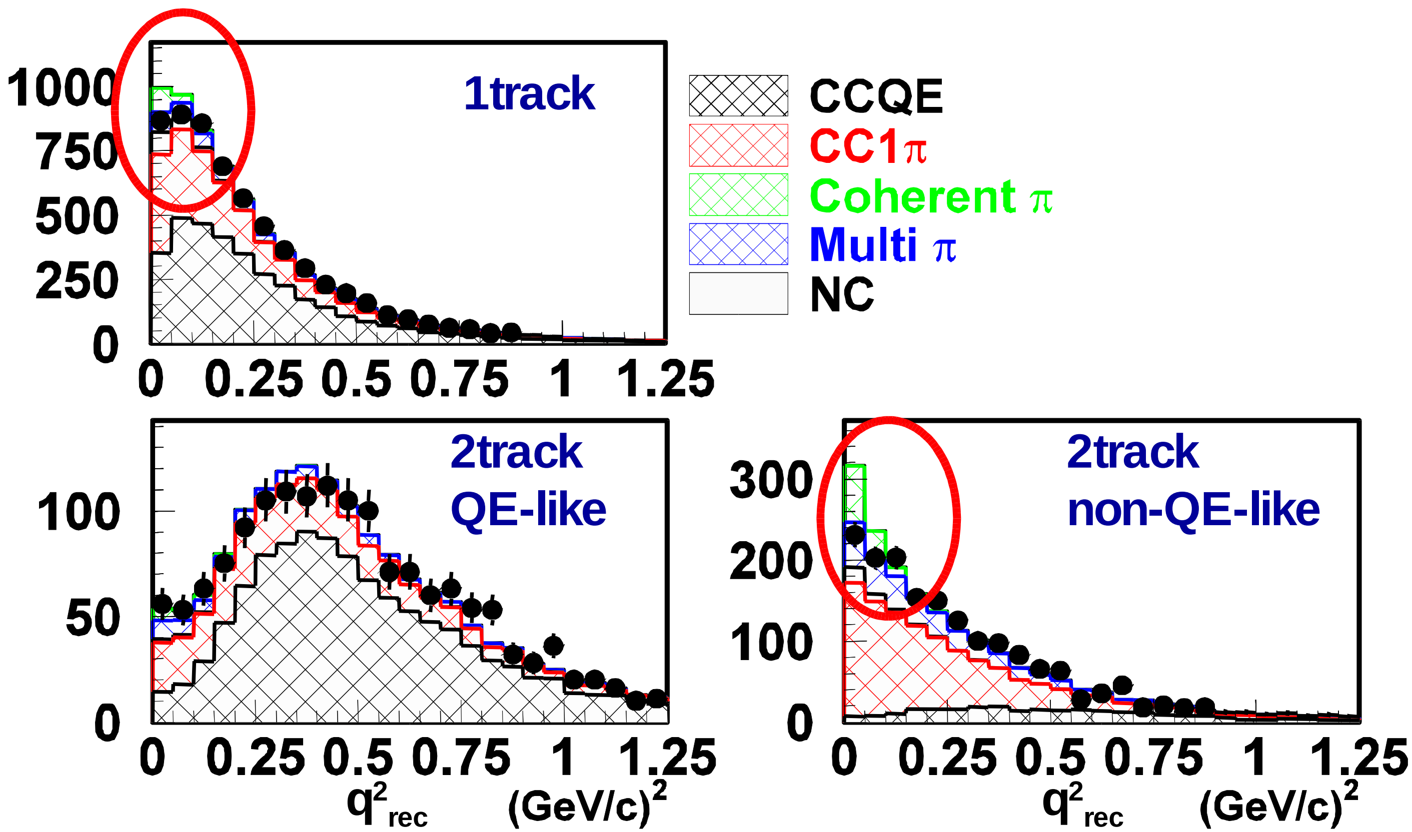
S. Nakayama, et al., Phys. Lett. B 619 (2005) hep-ex/0408134

Coherent π^+ production and very low Q2

$Q2 < 0.1\ (GeV/c)^2$

Plots below from SciBar detector

Seen also in SciFi detectors

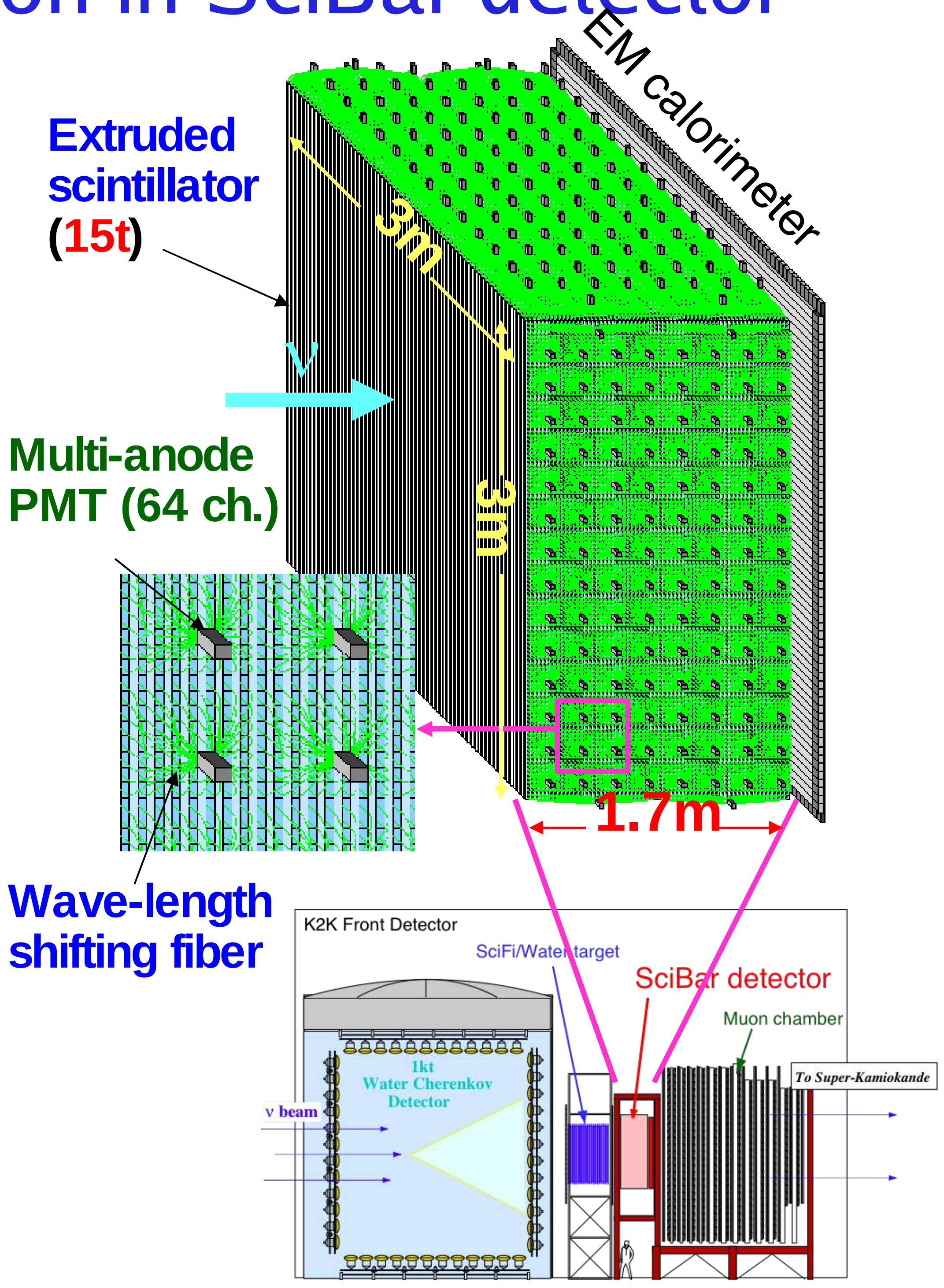


CC coherent pion in SciBar detector

Fully active scintillator detector (neutrino target HC)

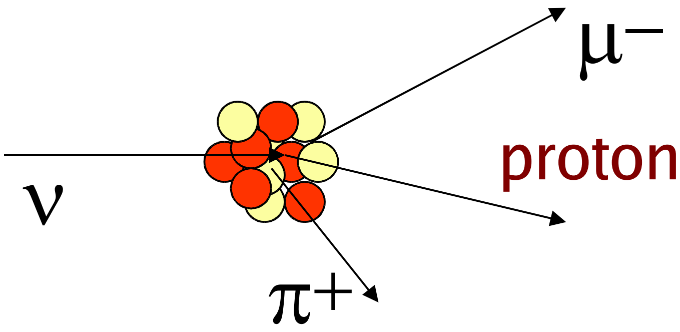
Low thresholds for protons and pions

and proton vs pion particle ID via dE/dx

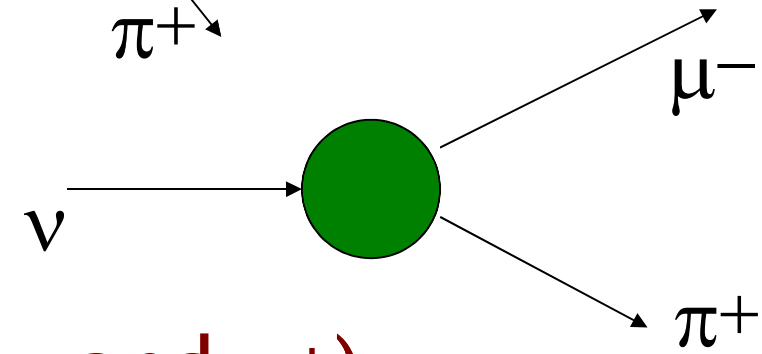


CC coherent pion selection

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

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

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

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

A binding energy term is included in Enu but for brevity is not printed here

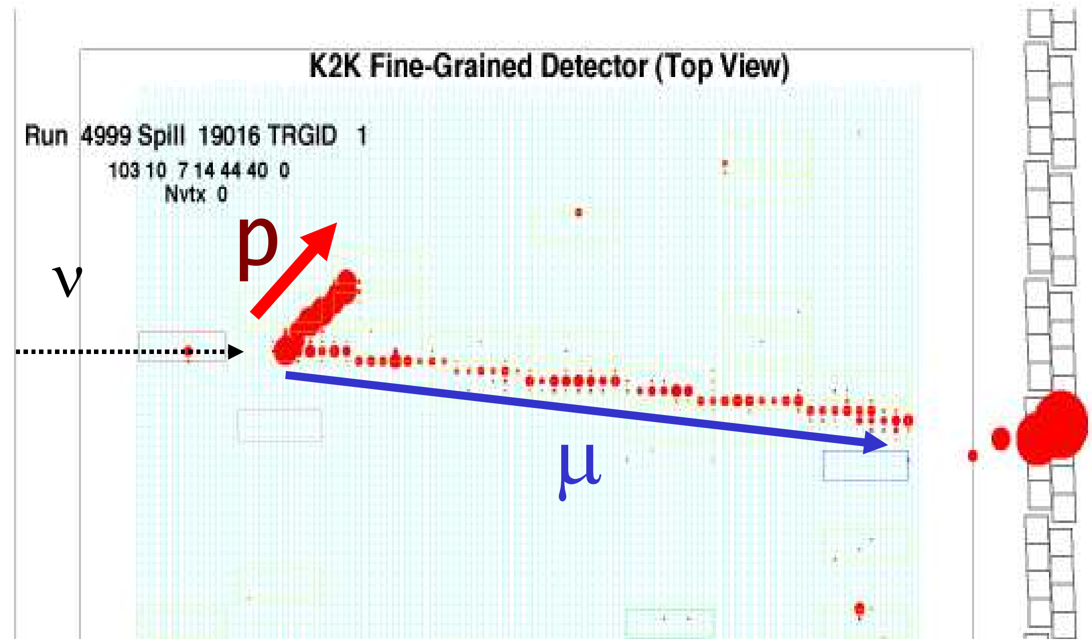
Produce enhanced non-QE subsamples

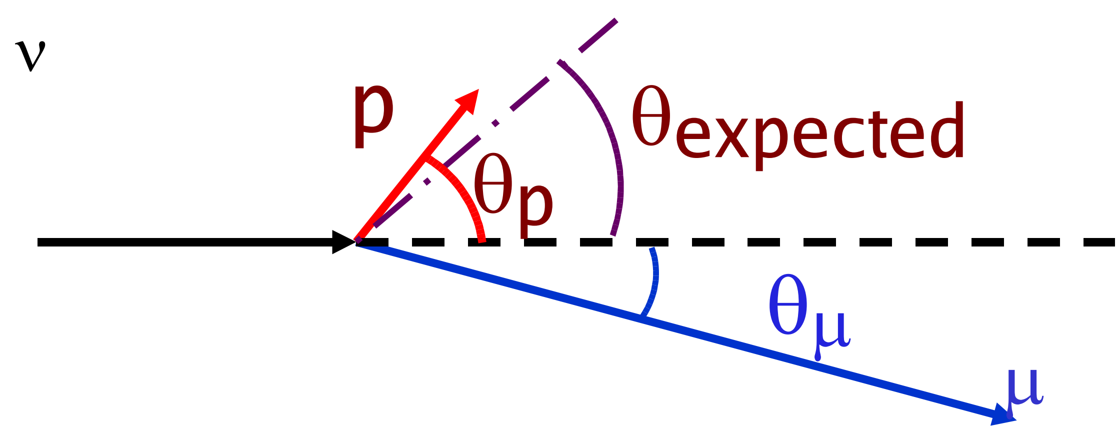
Still CCQE kinematics
Take events with two tracks

Predict where the recoil proton should be

Divide into
QE enhanced
nonQE enhanced
subsamples

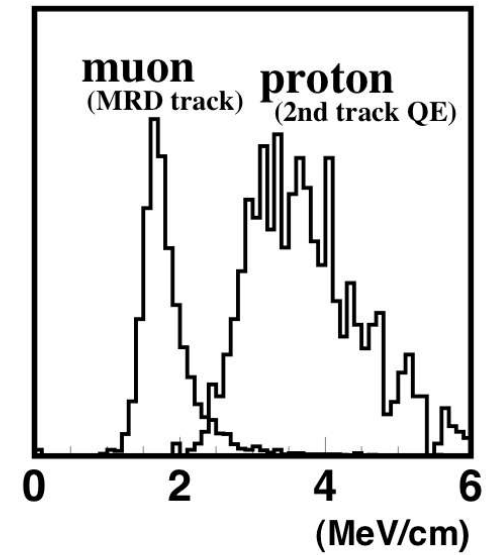
CCQE candidate in SciBar



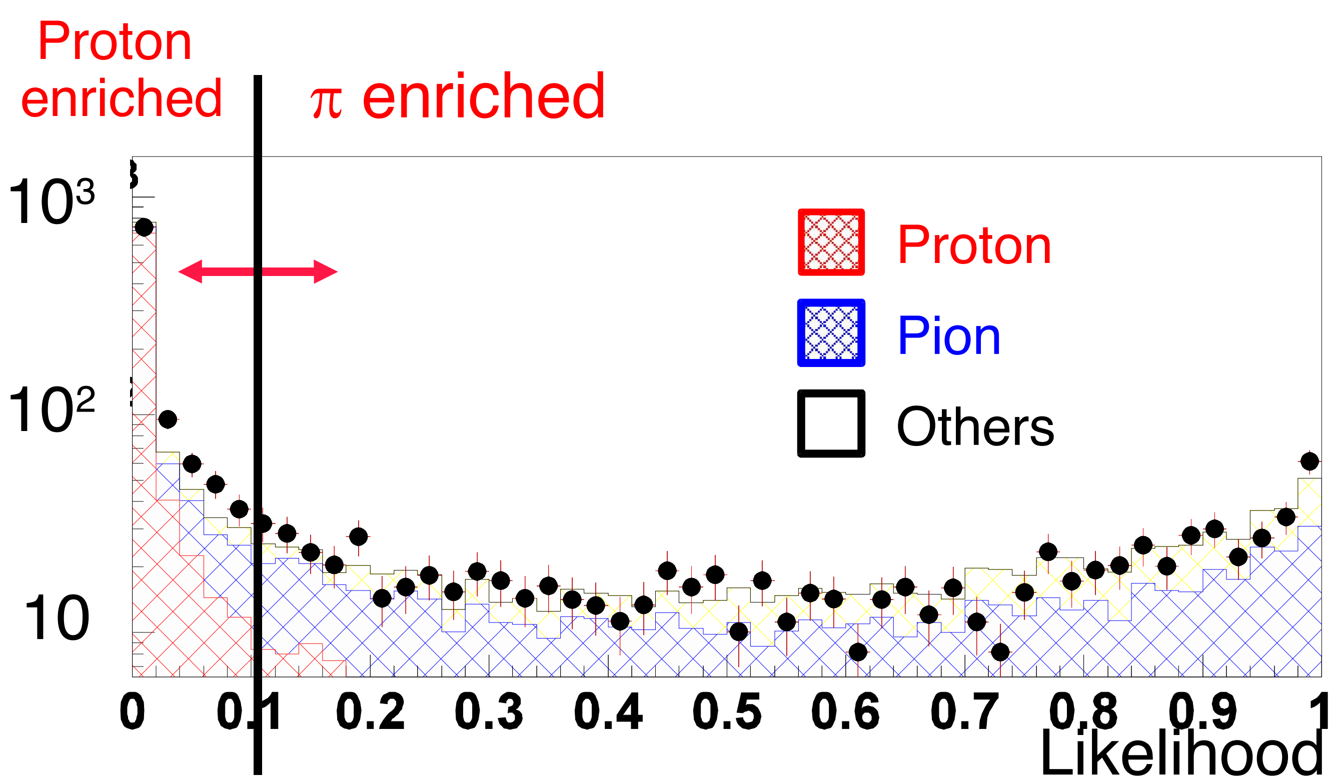


Pion vs proton via dE/dx

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



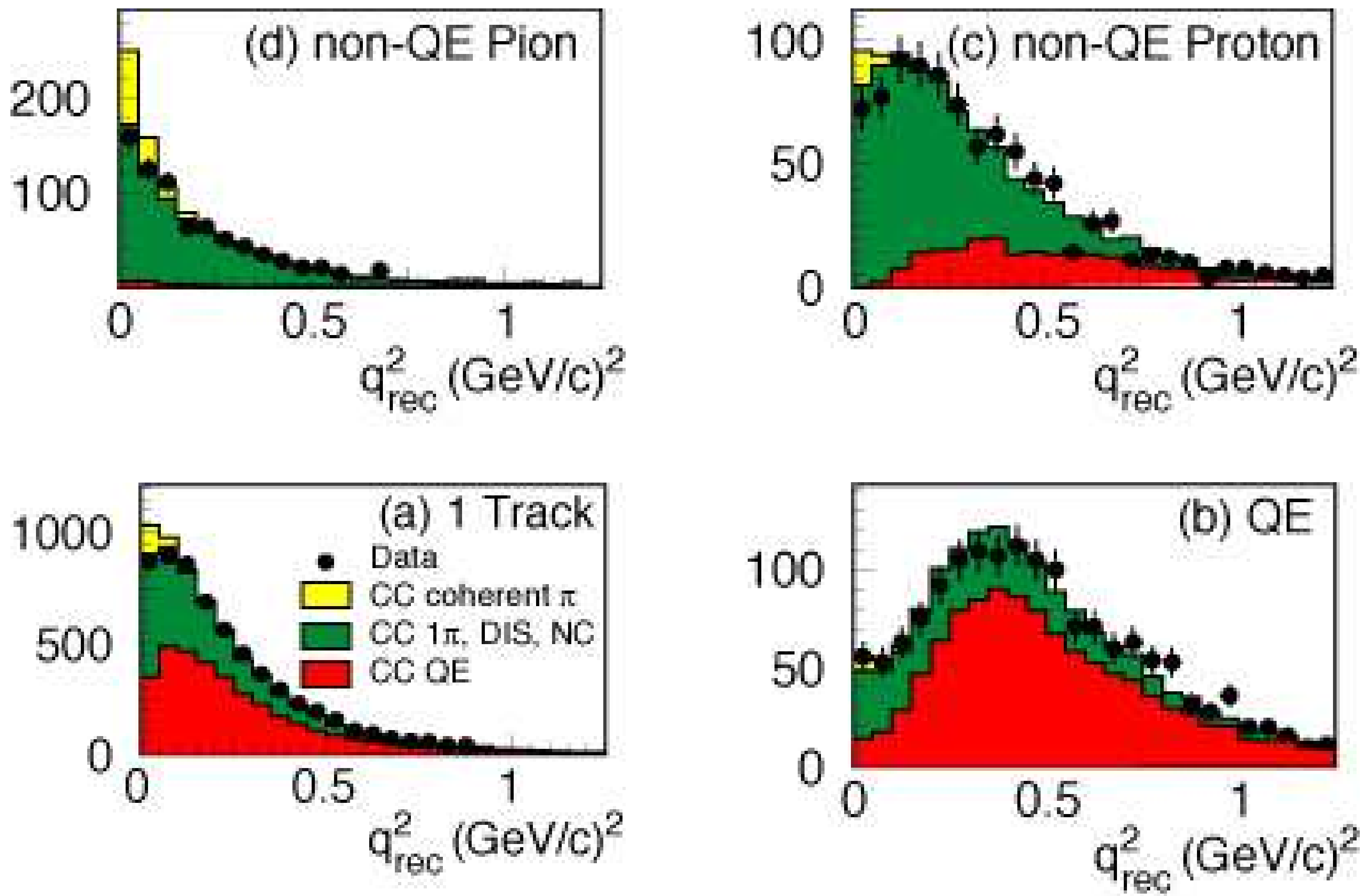
Average dE/dx from data (muon and proton)



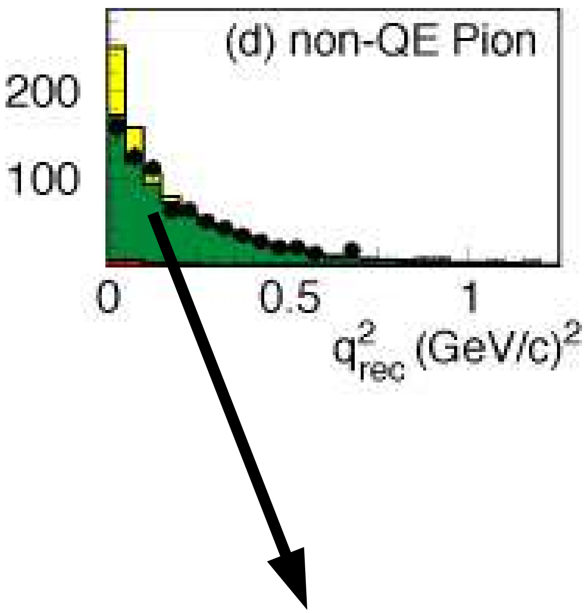
CC coherent pion subsamples

Reconstructed Q^2 for four sub-samples

Normalized by total CC events



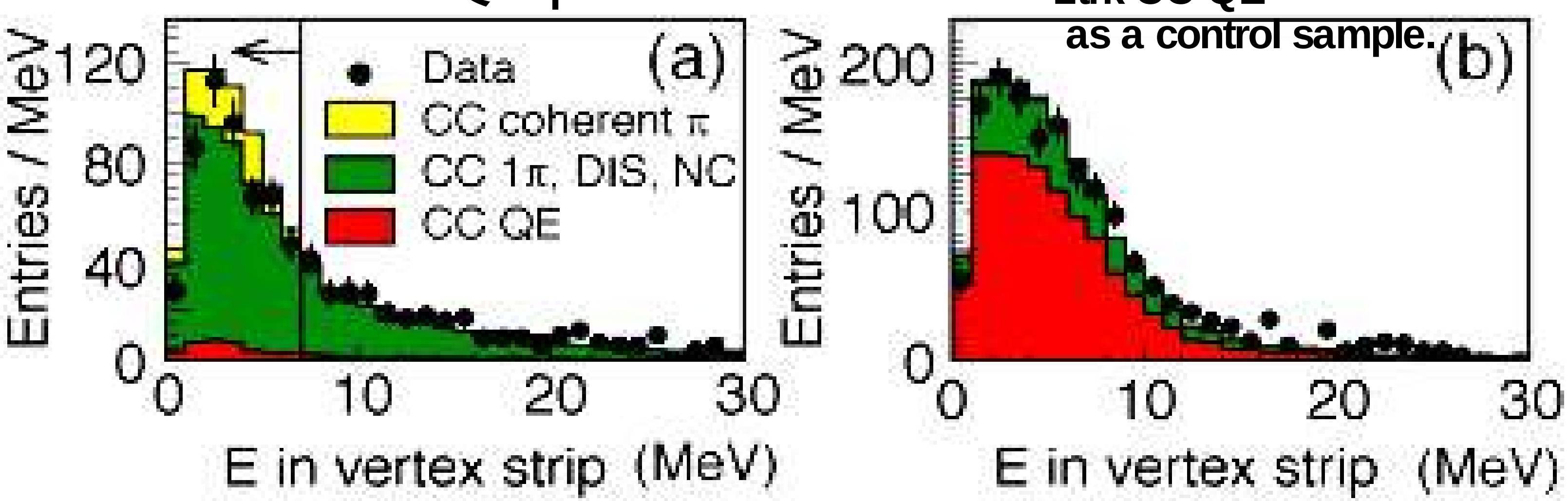
Vertex activity cut



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

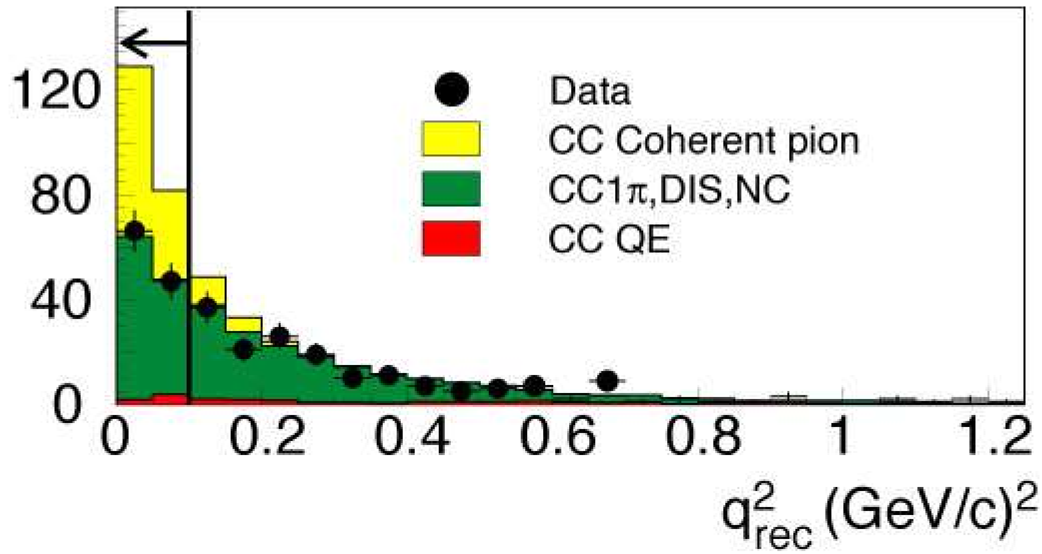
2-track nonQE pion-like

2trk CC QE
as a control sample.



CC coherent pion results

M. Hasegawa, et al., Phys. Rev. Lett. 95 (2005) hep-ex/0506008



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

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

This is ~30% of Rein-Sehgal model

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

Progress since then

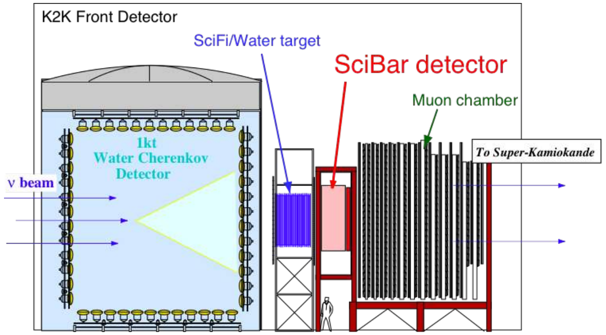
Two recent examples
(not the only work on the topic)

Lalakulich and Paschos, hep-ph/0501109
Rein and Sehgal, hep-ph/0606185

Muon mass must be included in
Charged current π^+ interactions.
Gives rise to some cancellation
at low Q2 for these energies

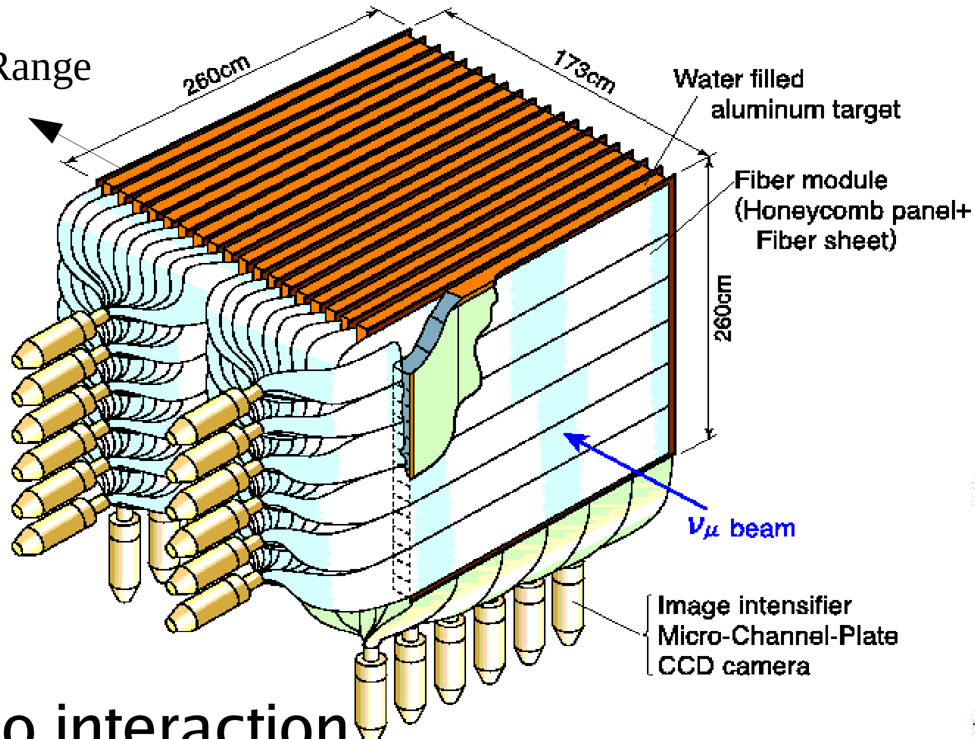
Quasi-elastic Axial Form Factor studies and quasielastic axial mass parameter

Scintillating Fiber (SciFi) detector



~1 degree angle resolution

To Muon Range Detector



Require muon in the muon range detector

$P\mu > 600$ MeV

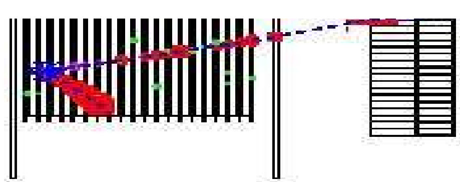
Recoil proton threshold is three layers in SciFi

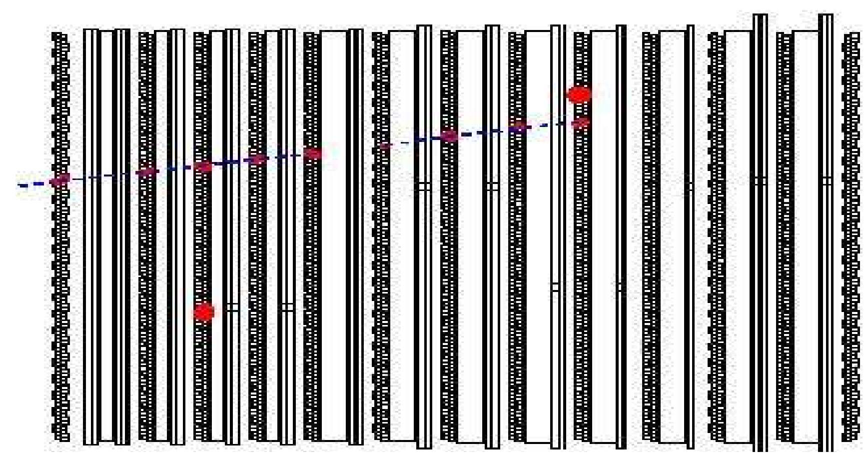
$Pp > 600$ MeV

(so proton not always seen)

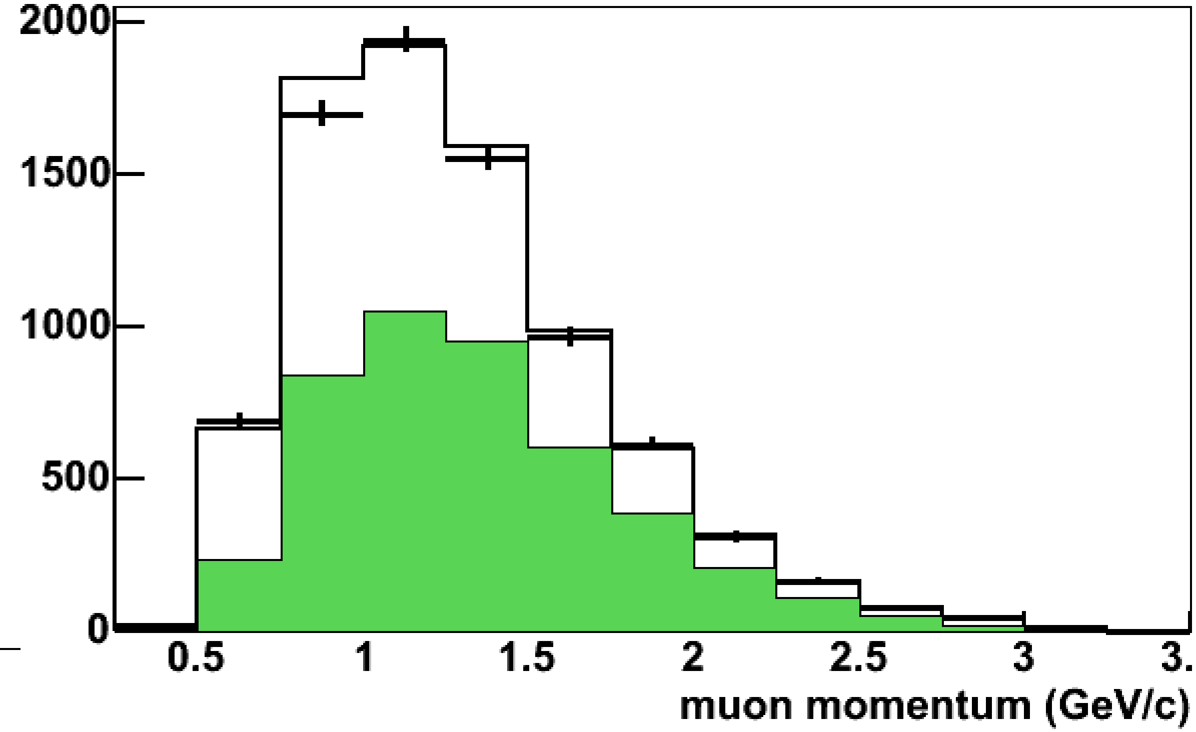
Neutrino interaction Target is Water in Aluminum tanks

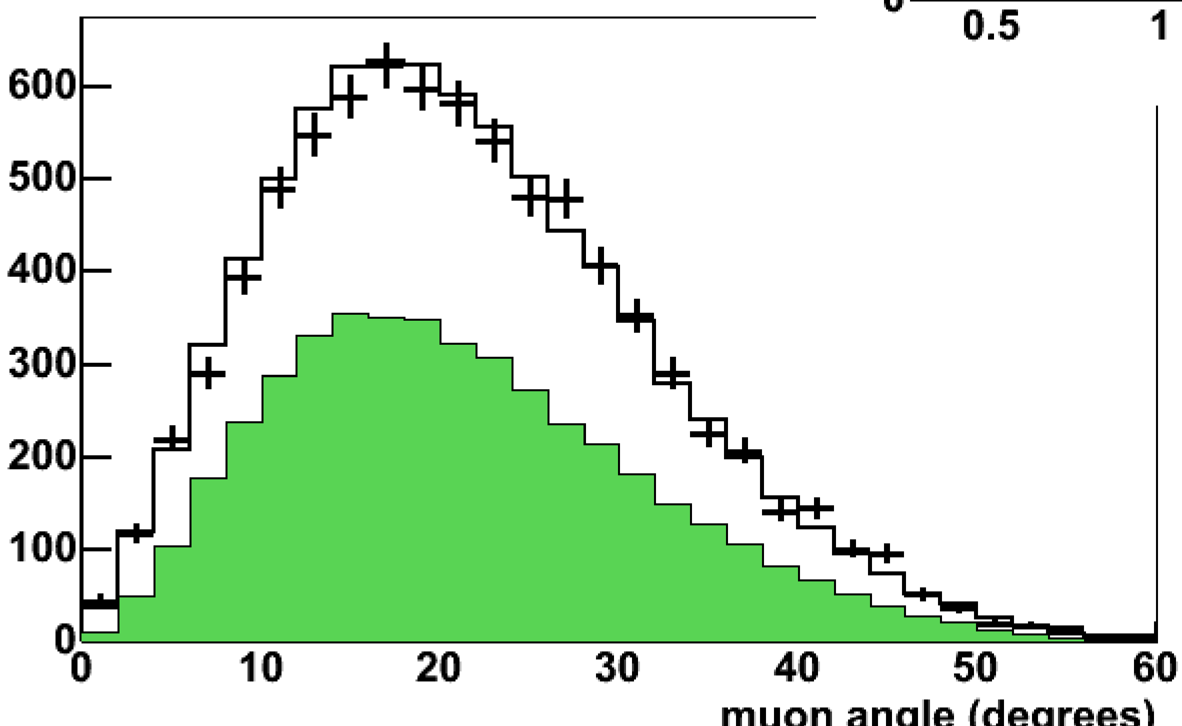
(70% H_2O, 22% Al, 8% HC)





Some basic distributions from SciFi

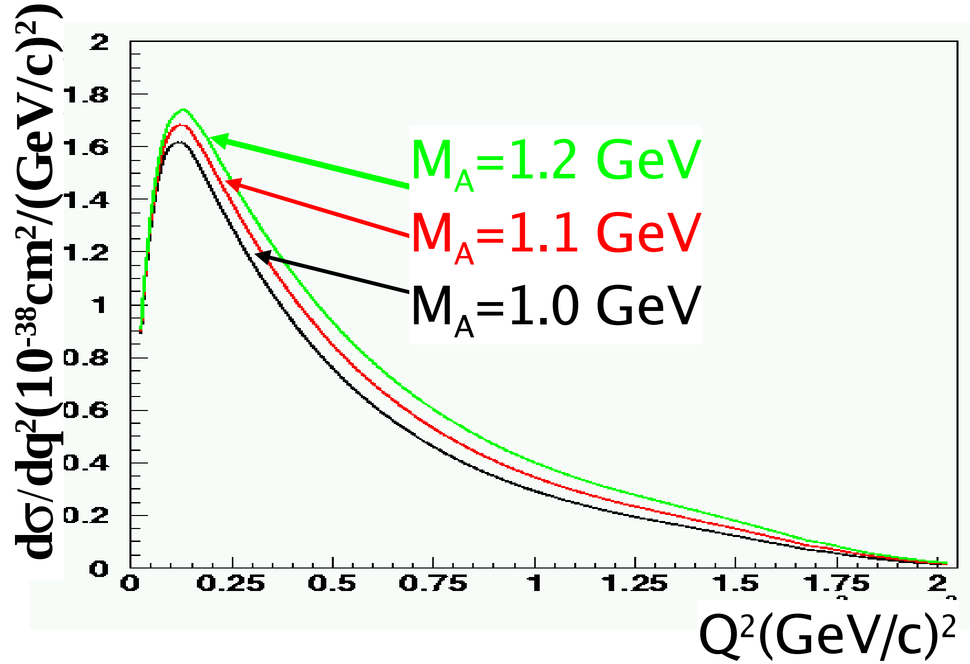




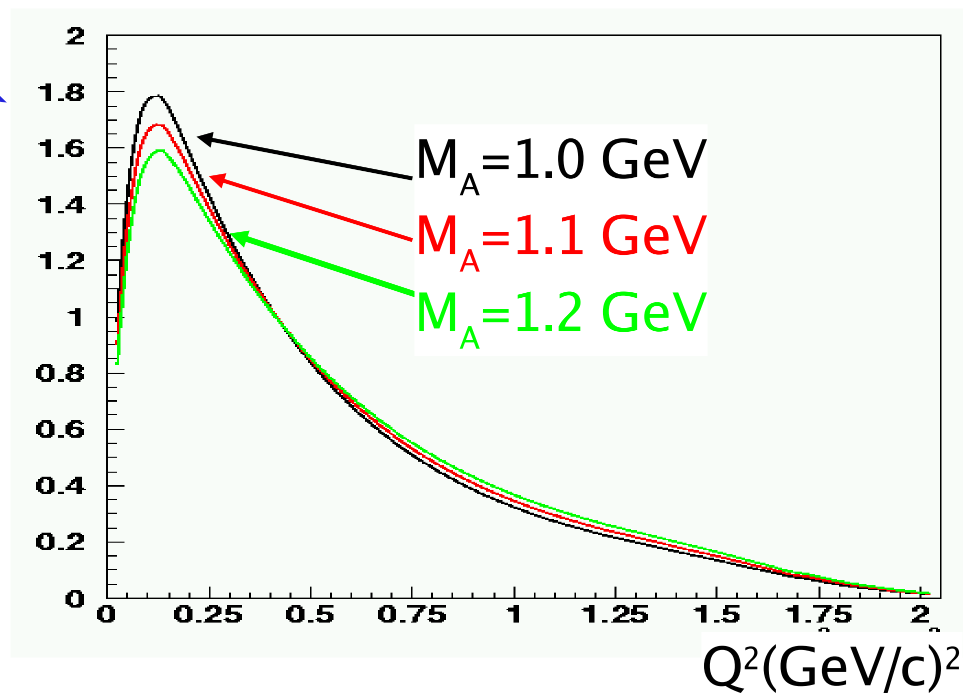
No MA fitting yet
Uses best fit flux from
fits to all K2K
near detector data
hep-ex/0606032

Axial mass and shape of Q^2 distribution

Absolute
Quasi-elastic
Cross section
(includes normalization)



This analysis: Shape Only

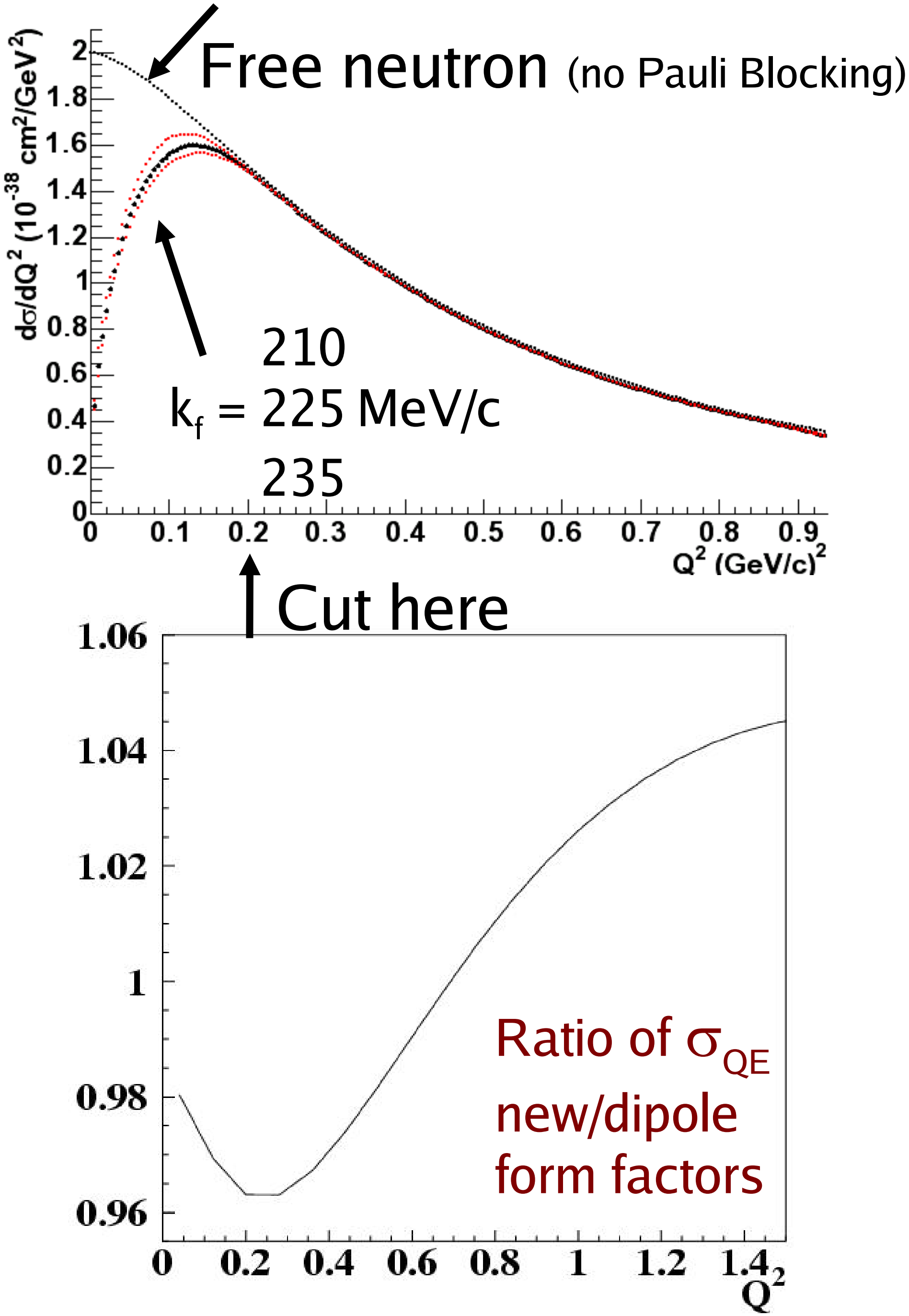


Measure Q^2 for each event still assuming QE interaction

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

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

Other model effects that change the shape



Pauli Blocking in (Fermi Gas) model And CC Coherent Pion uncertainty contribute at low Q^2.

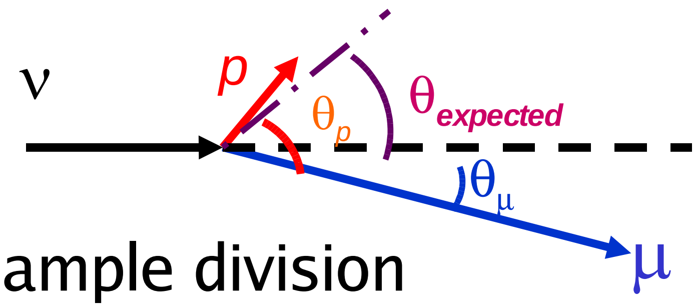
We exclude this region from the fit.

QE cross section calculation also depends on vector form factors.

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

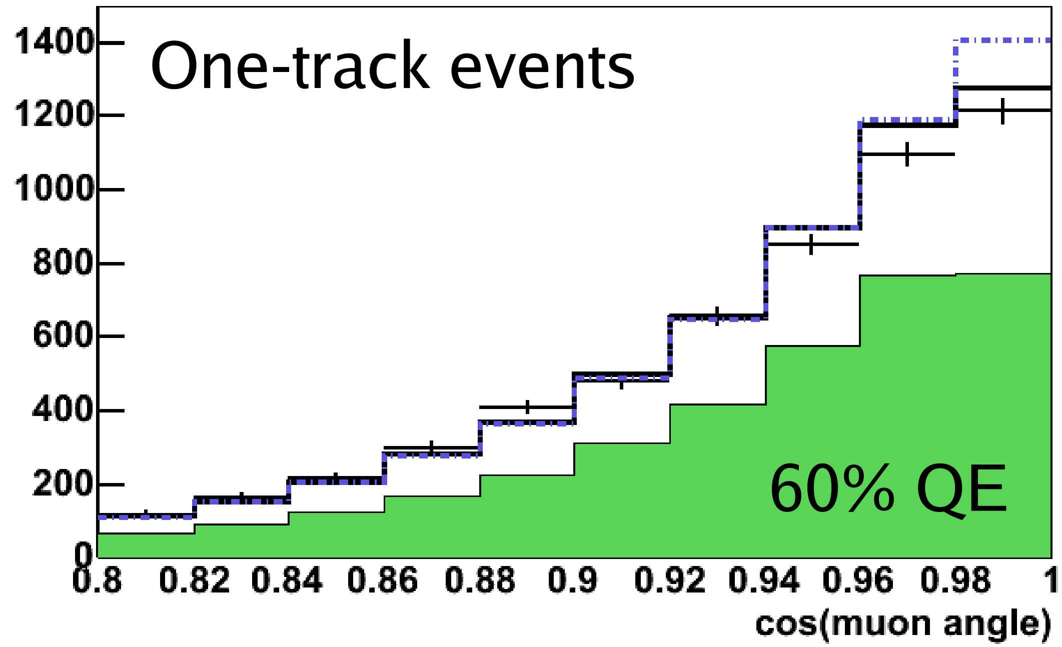
These, plus a second axial mass parameter (we take $M_A^{1\pi}$=1.1 GeV) affect the nonQE background

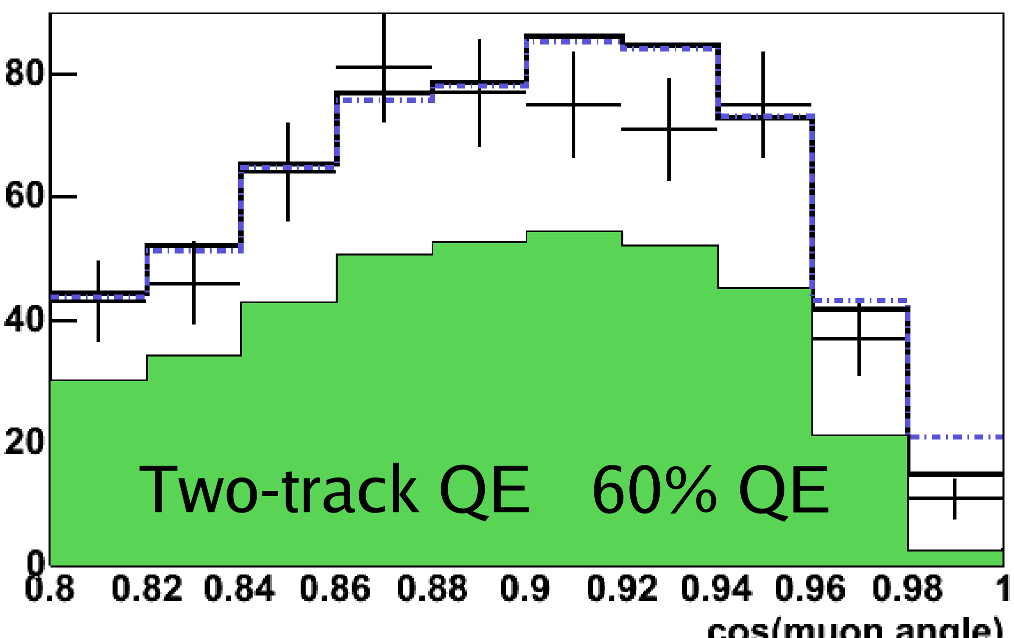
Muon angle again, divide into subsamples

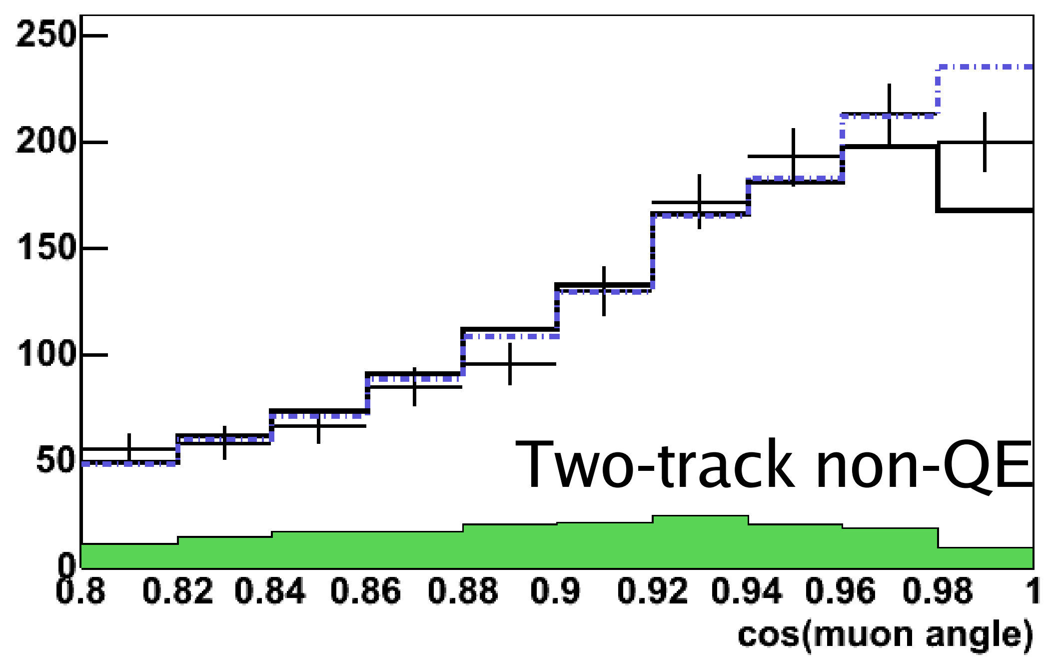


Subsample division

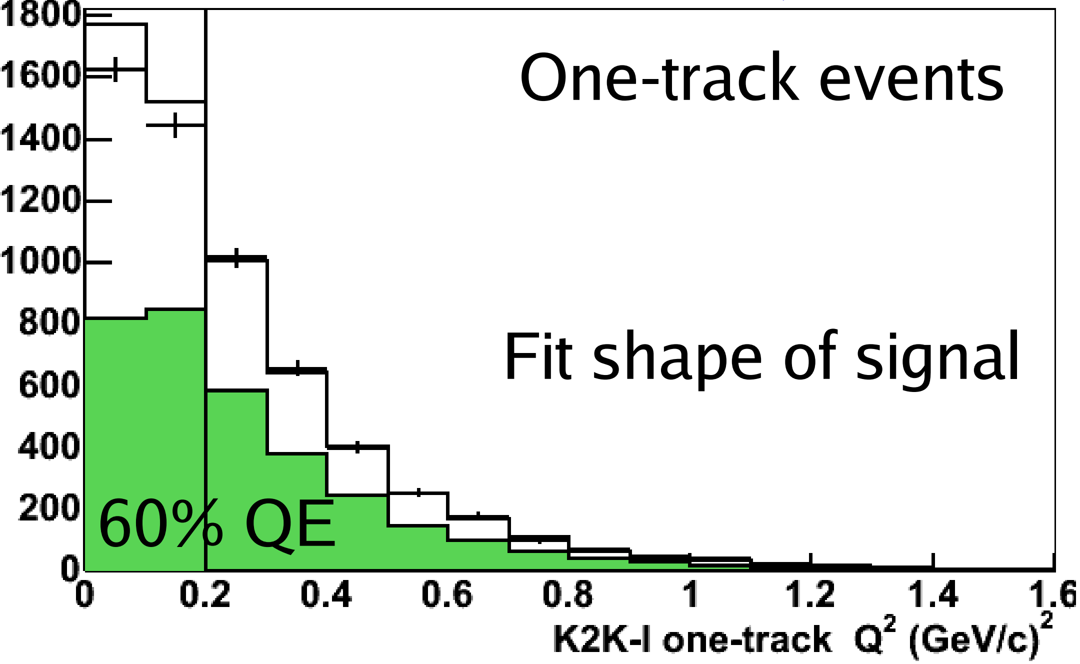
No MA fitting yet...

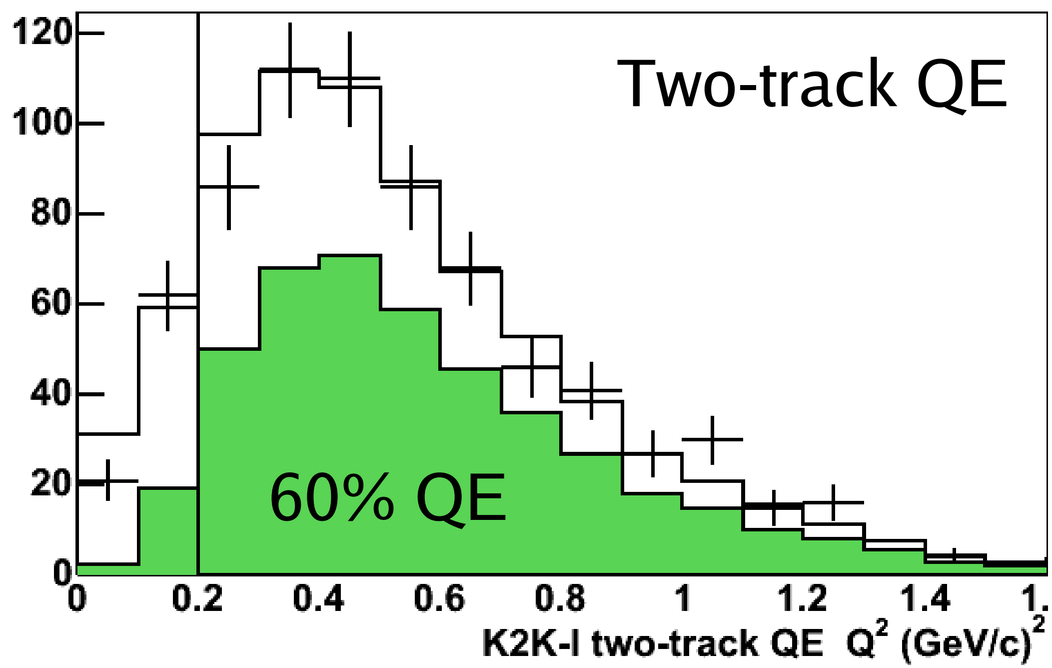


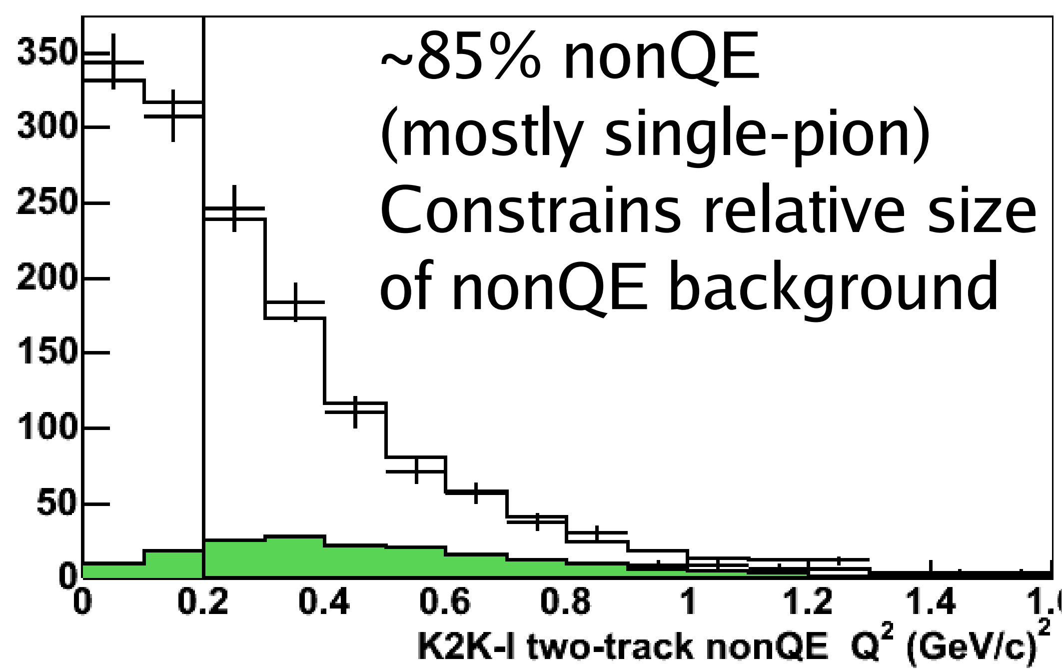




Reconstructed Q^2 for subsamples (after fitting)







Results for effective Quasi-elastic M_A on Oxygen

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

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

Most significant errors:	
Muon momentum scale	0.07
Relative flux and normalization	0.06
M_A 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

RG, Jeon, et al., accepted by PRD, hep-ex/0603034

Compare with results on Deuterium

Reslts from bubble chamber experiments
(Primarily also shape fits)

Deuterium $M_A \sim 1.03 \pm 0.03$

But they use “Olsson, et al.” vector form form factors

Rerun the K2K-SciFi analysis with their assumptions
in order to make comparison

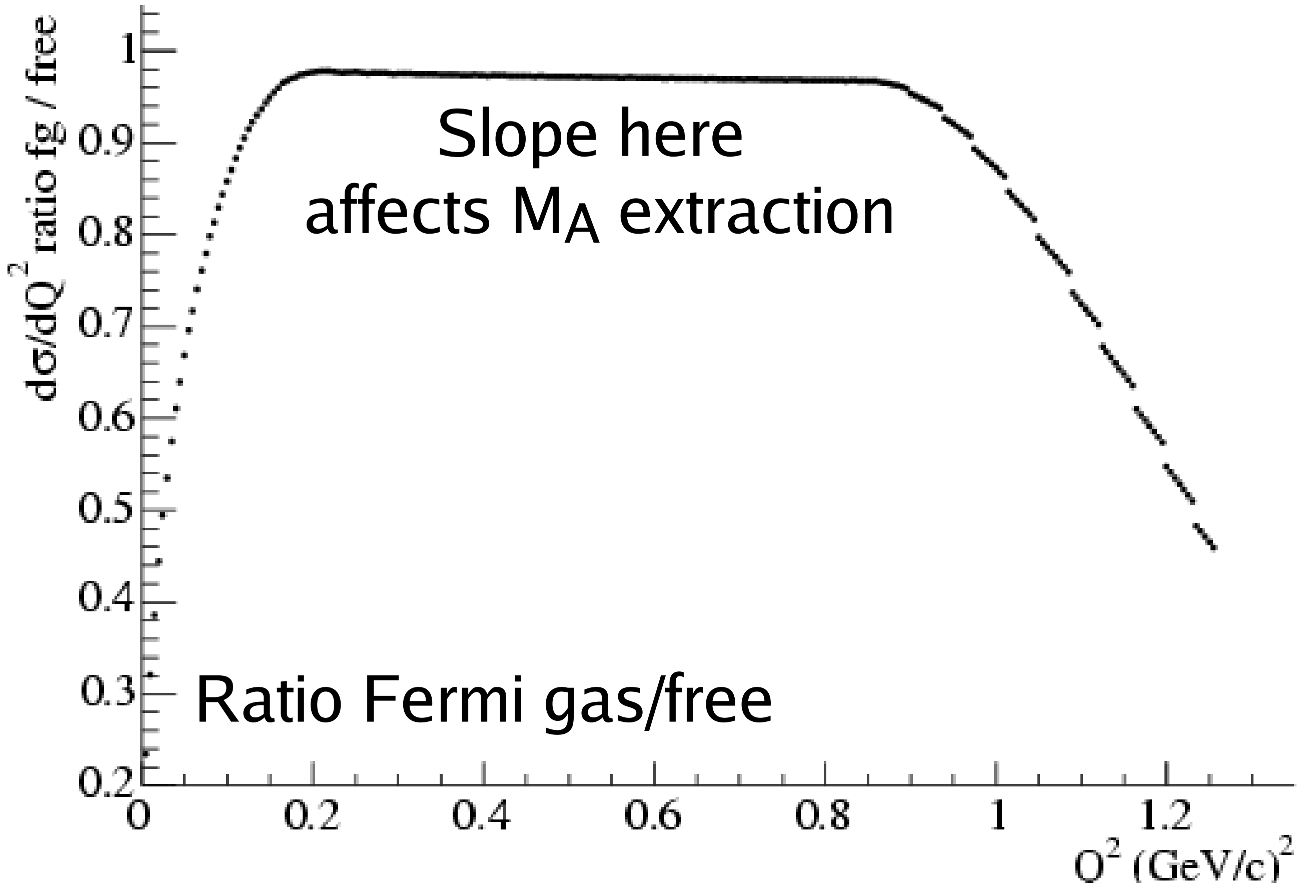
K2K result $M_A = 1.23 \pm 0.12$

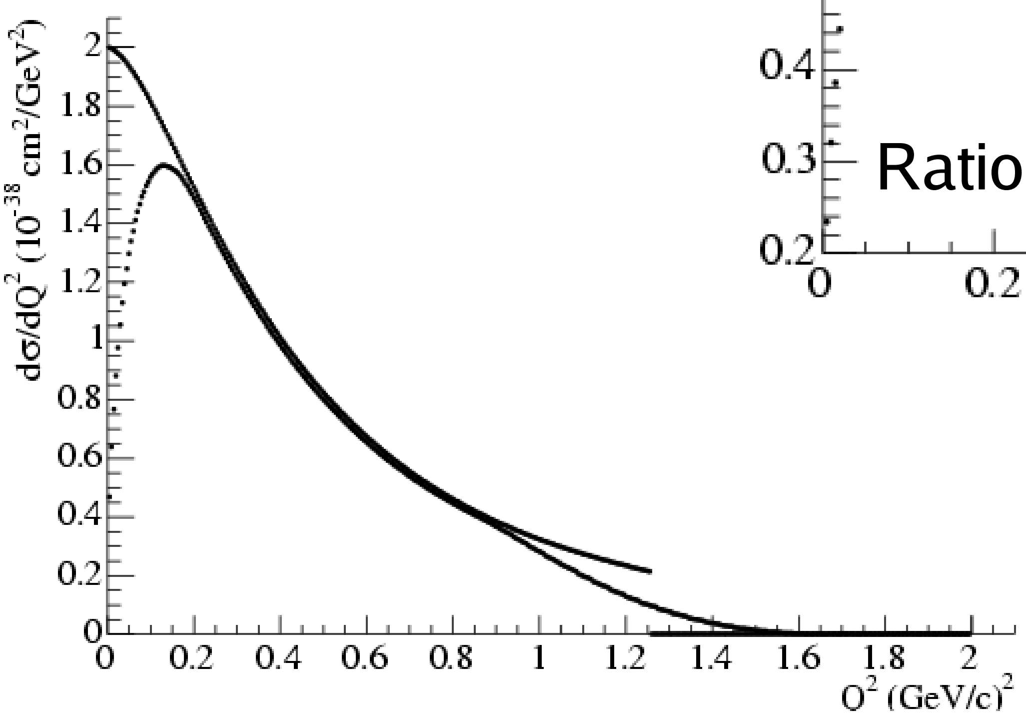
In agreement at the 2-sigma level

More about the relevant Q^2 region

Calculation by
Nakamura + Seki

Compare 1 GeV QE
for free neutron
and in oxygen
(Fermi gas model)





My list of interesting questions

Should nuclear effects modify the Q^2 distribution?
At what level?
(or is the 2-sigma discrepancy due to experiment?)

This result is from a shape fit.
What if normalization information is available?

Can we extract information about very-low Q^2?

We should not expect a dipole axial form factor?

Compare cross sections for Iron and Water

Muon Range Detector is made of iron
The Cerenkov detector is made of water

Compare these two high-rate detectors
to learn about the iron/water cross section

$$\frac{\text{Muon Range Det. (Data/MC)}}{\text{Water Cerenkov (Data/MC)}} = 1.04 \pm \underset{\text{stat.}}{0.003} \, {}^{+0.08}_{-0.11}$$

Beam and spectrum systematics partially cancel.
Fiducial mass errors are significant (-6%)
Because of different energy thresholds
neutrino model errors do NOT cancel perfectly ~5%

In Ch. 6 of M.H. Ahn, et al., hep-ex/0606032

Conclusions

K2K neutrino interaction results
with modest precision.

Systematic errors are dominating.
Mix of model errors and detector errors
depending on the study

The models we use
do not produce great agreement with these data
there is a need for improvement