# Charged-Current $\pi^+$ Production at K2K

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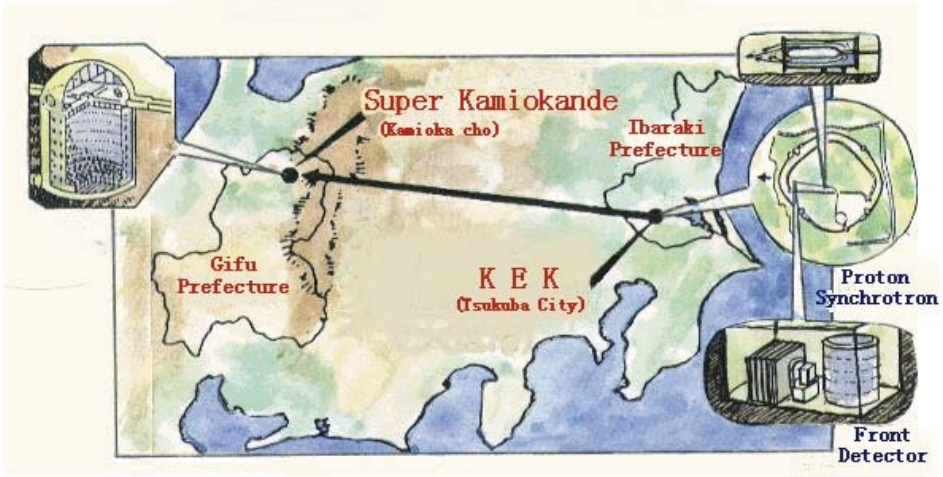
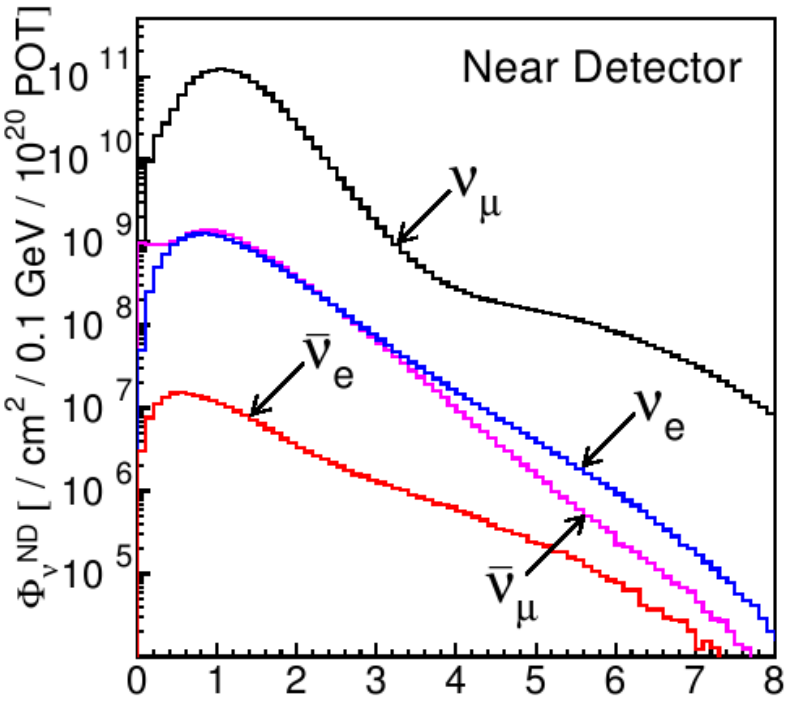
# Outline

- K2K and the SciBar detector
- coherent $\pi^+$ result (2005)
- MC model
- event selection
- resonant $\pi^+$ production measurement
- summary

# The K2K Experiment

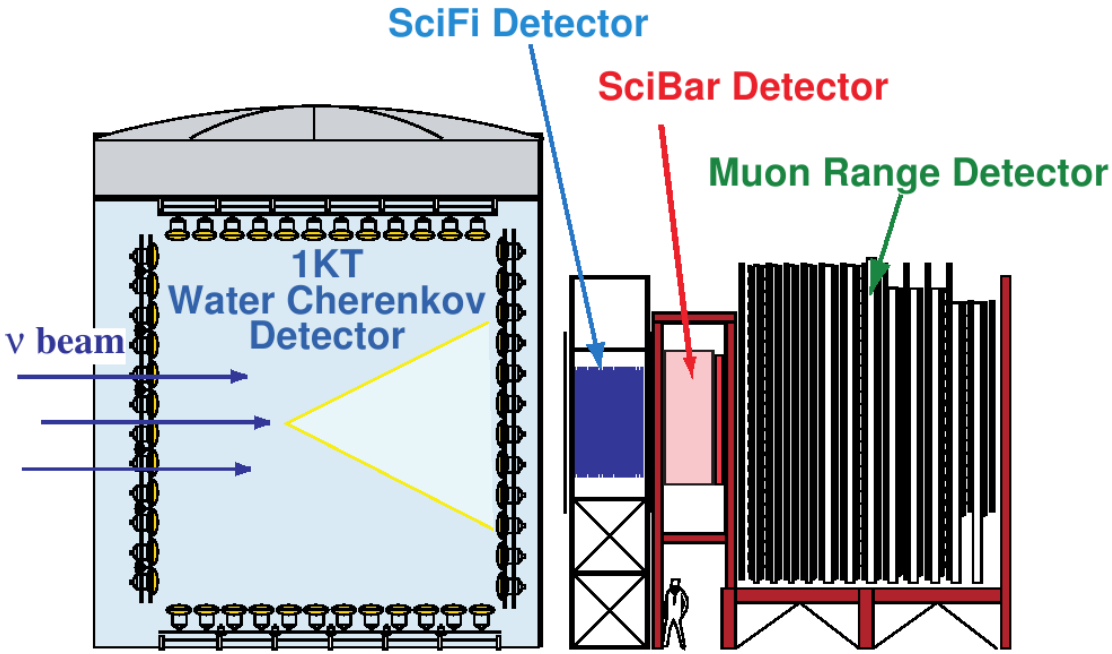
KEK to Kamioka Long-Baseline Neutrino Oscillation Experiment
June 1999 – November 2004



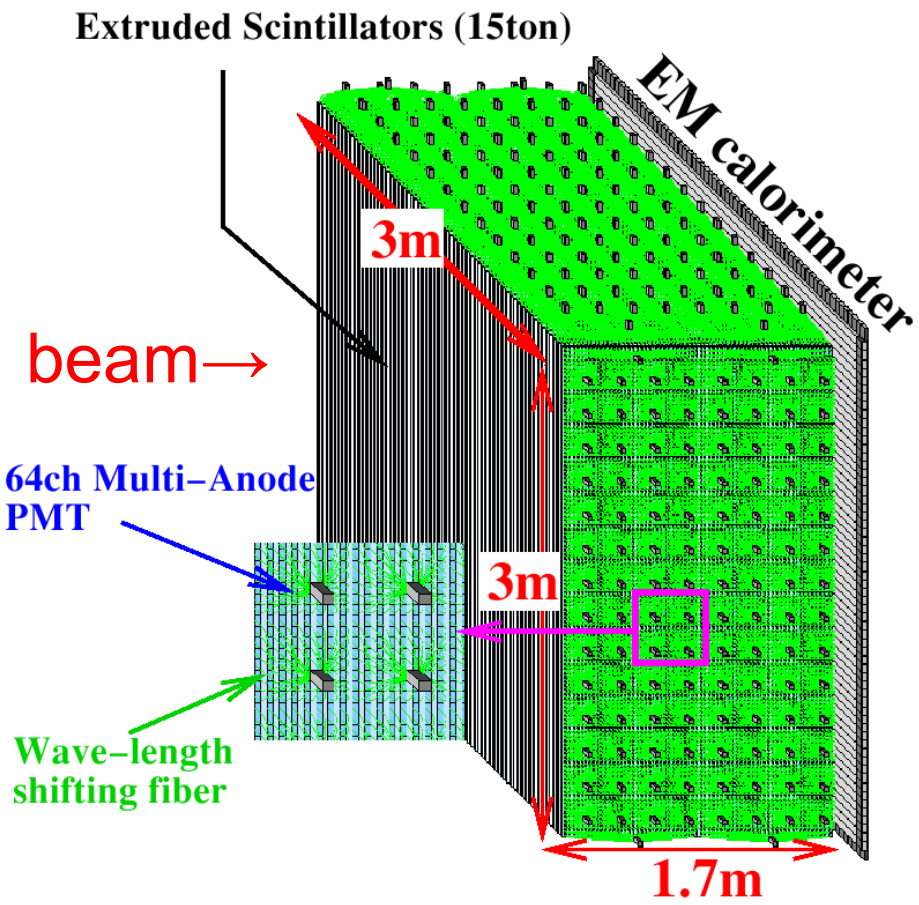




97.3% pure $\nu_\mu$

$E_\nu$ (avg) = 1.3 GeV



# SciBar




Upgrade to near detector (replaced a lead glass detector)

Oct. 2003 – Nov. 2004

- fully active detector
- 14,848 **Sci**ntillating **Bar**s
- polystyrene ($C_8H_8$)
- light guided by WLS fibers to 64-channel MAPMTs
- 1.7 x 3 x 3 $m^3$ (~15 tons)

- one plane is 116 bars
- one layer is an x-plane and a y-plane
- 64 layers along the beam direction

# CC Coherent Pion Production

$\nu_\mu A \rightarrow \mu^- A \pi^+$ measurement made using SciBar data

## Event Selection:

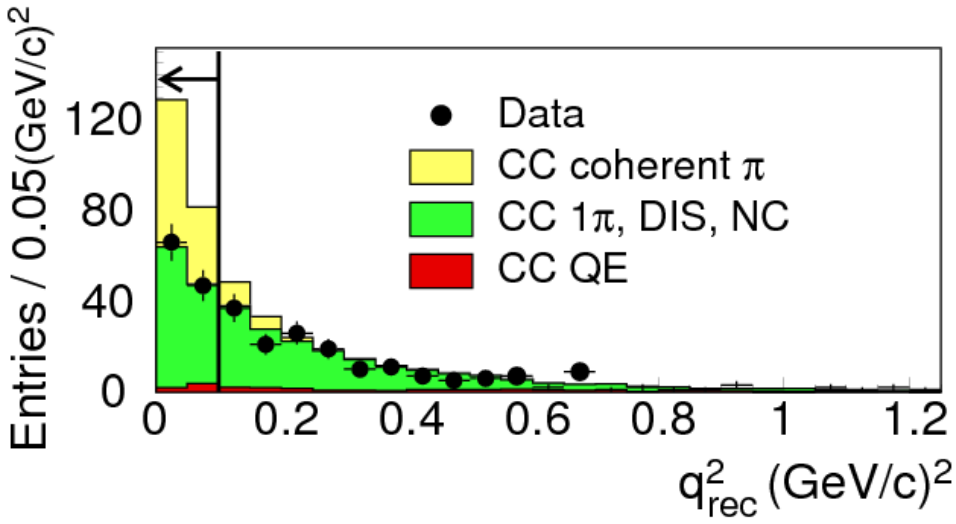
CC, 2 tracks, nonQE-like

2nd track pion-like and forward

low vertex activity

$q^2_{rec}$<0.1 GeV$^2$

(~47% pure)




result is consistent with no CC coherent pion production

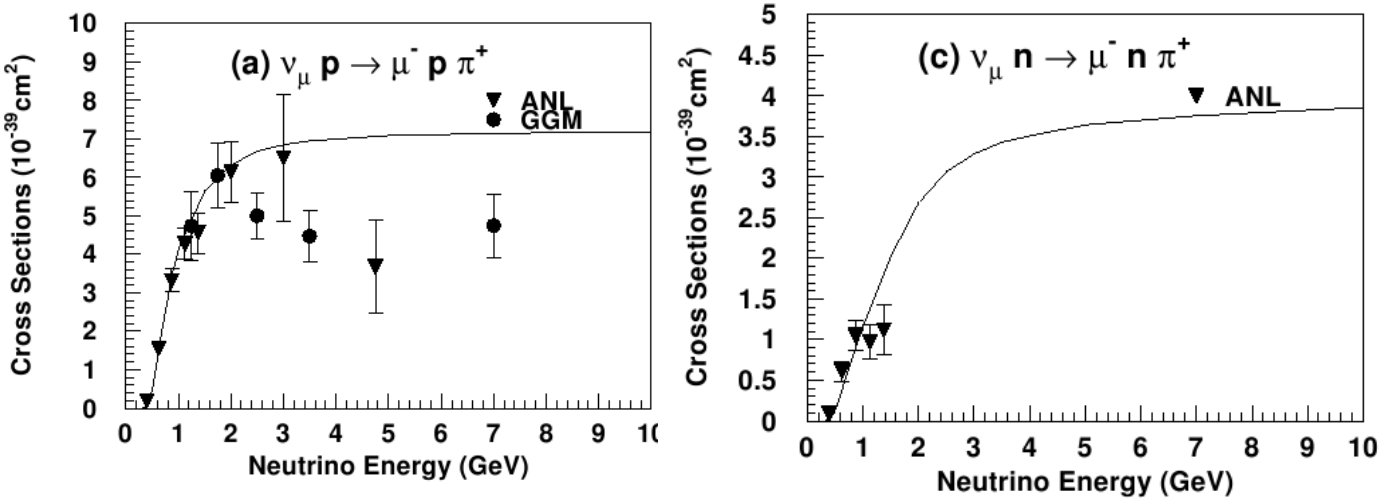
upper limit of 0.60 x $10^{-2}$ at 90% confidence level for CC coherent pion production cross section relative to the total CC cross section

PRL **95**, 252301 (2005)

# CC1π Interactions

## Single $\pi^+$ via resonance production in CC $\nu_\mu$ interactions:

$$\left.\begin{array}{l} \nu_\mu p \to \mu^- p \pi^+ (CCp\pi^+) \\ \nu_\mu n \to \mu^- n \pi^+ (CCn\pi^+) \end{array}\right\} CC1\pi^+$$




## Rein and Sehgal model:

- Cross section for each final state is calculated as a coherent superposition of all the possible contributing resonances, W<2 GeV/$c^2$
- axial-vector mass, $M_A$ = 1.1 GeV/$c^2$ (based on K2K data)
- also used for resonant single K and η production

# Other Neutrino Interactions

quasi-elastic and elastic scattering based on Llewellyn Smith model, $M_A^{QE}$ = 1.1 GeV/$c^2$ (based on K2K data)

Deep inelastic scattering with GRV94 structure functions. We use the correction to GRV94 proposed by Bodek&Yang which reduces the cross section for low $q^2$.

NC coherent pion production based on Rein and Sehgal model with correction by Marteau et al.

CC coherent pion production is ignored in model (based on SciBar measurement)

| Interaction type | Percent of Total |
|---|---|
| **Charged-current (CC)** | **72%** |
| $\nu_\mu n \rightarrow \mu^- p$ | 32% |
| $\nu_\mu p \rightarrow \mu^- p\pi^+$ | 18% |
| $\nu_\mu n \rightarrow \mu^- n\pi^+$ | 6% |
| $\nu_\mu n \rightarrow \mu^- p\pi^0$ | 5% |
| $\nu_\mu N \rightarrow \mu^- X$ | 9% |
| CC (other) | 2% |
| **Neutral-current (NC)** | **28%** |

# Nuclear Interactions

**Neutrino interaction with p,n is occurring inside the nucleus → must consider the effect of the nuclear medium**

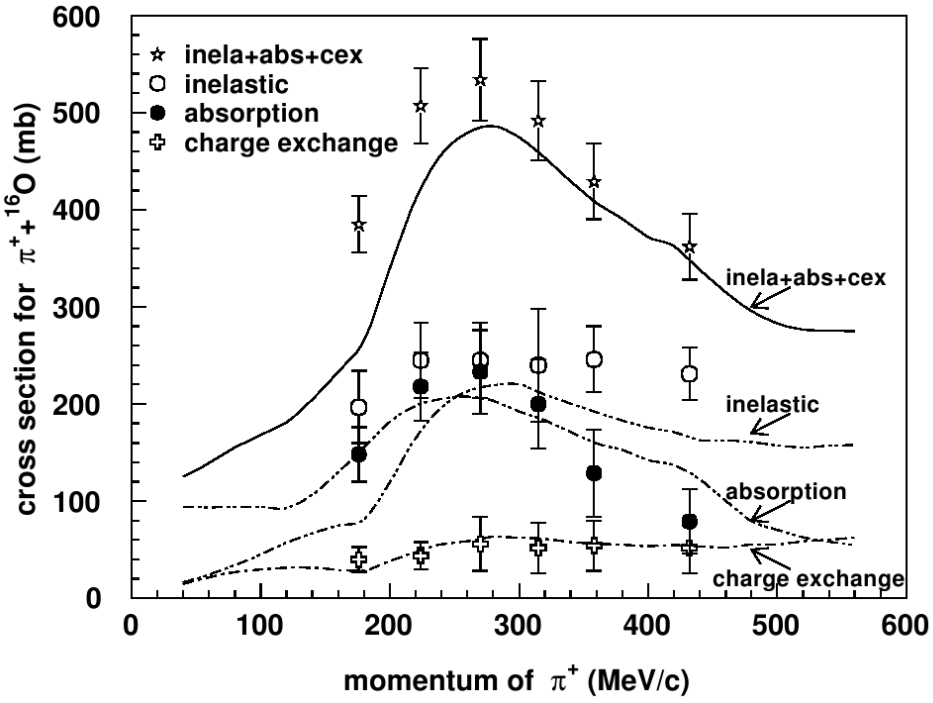
Relativistic Fermi gas model
Fermi surface momentum = 225 MeV/c for C

Pauli exclusion effect

Nuclear potential = 27 MeV for C

Interactions of outgoing particles inside the nucleus:

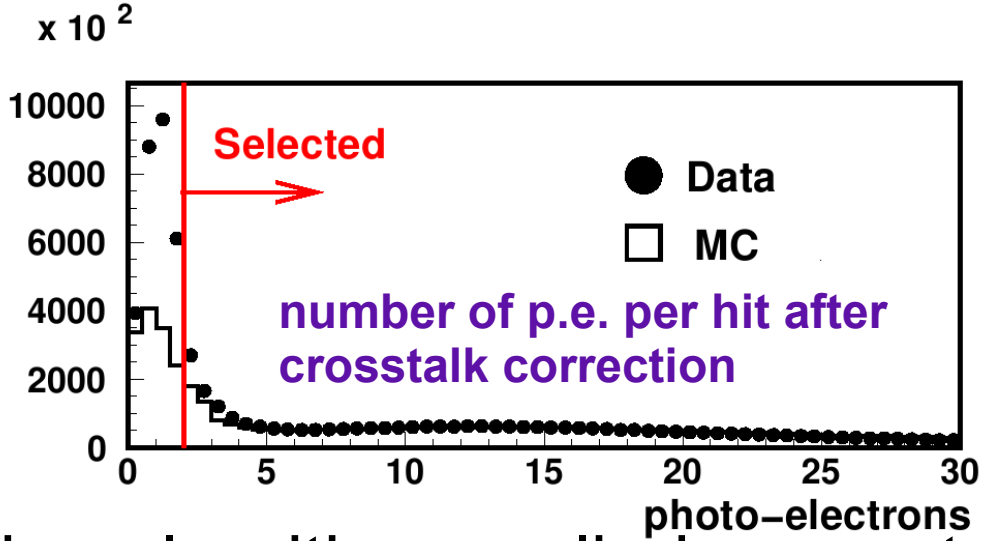
- nucleon rescattering
- pion absorption, inelastic scattering, charge exchange
- delta absorption (in resonance production)



# SciBar Event Reconstruction

Crosstalk correction

Hit Threshold: > 2 p.e.



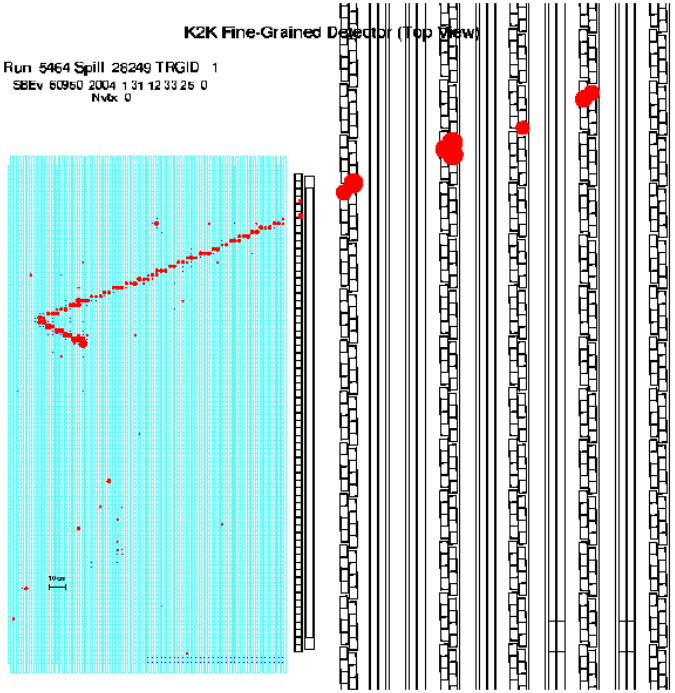

Tracking:

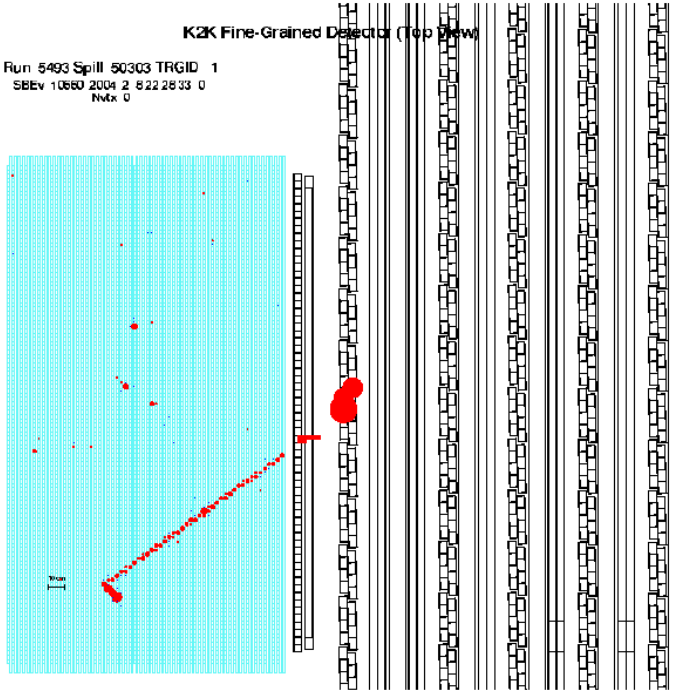
- Cellular automaton tracking algorithm applied separately to x-z and y-z projections
- require hits in 3 consecutive layers (8 cm → 450 MeV/c for proton)
- 3D reconstruction by matching z-track edges and timing of 2D tracks
- reconstruction efficiency for single track passing through 4 or more layers (10 cm) is 99%

# CC Event Selection

**Select CC events by identifying the muon.**

- match SciBar track to track or first layer hits in the MRD (muon momentum threshold 450 MeV/c)
- set of events where SciBar-MRD matched track is found is the MRD sample, our CC-enriched sample
- Purity of CC events in the MRD sample is 96%



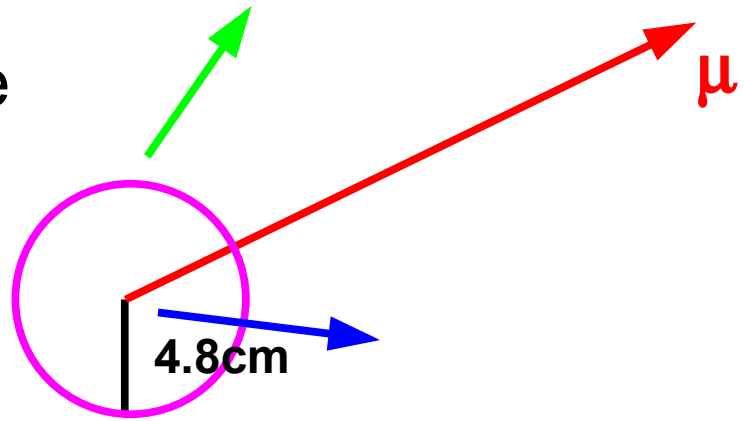



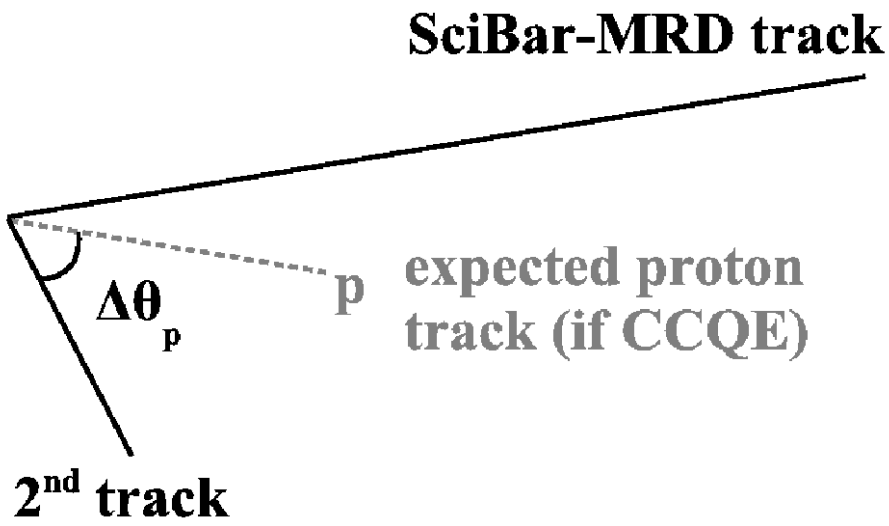

$p_\mu$ resolution ~ 90 MeV/c

$\theta_\mu$ ~ 1.4 degrees

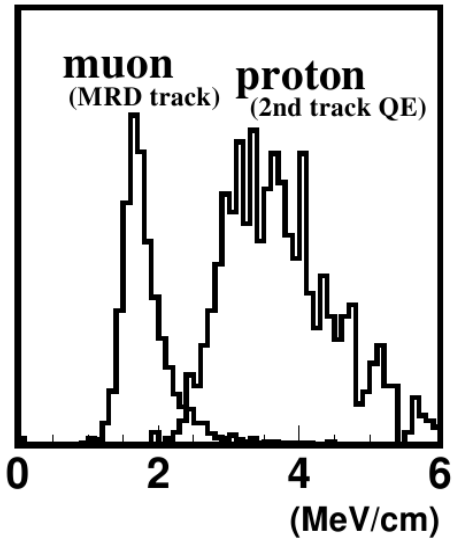
# Event Classification

1) Vertex matching: Cut tracks that are not “at vertex”



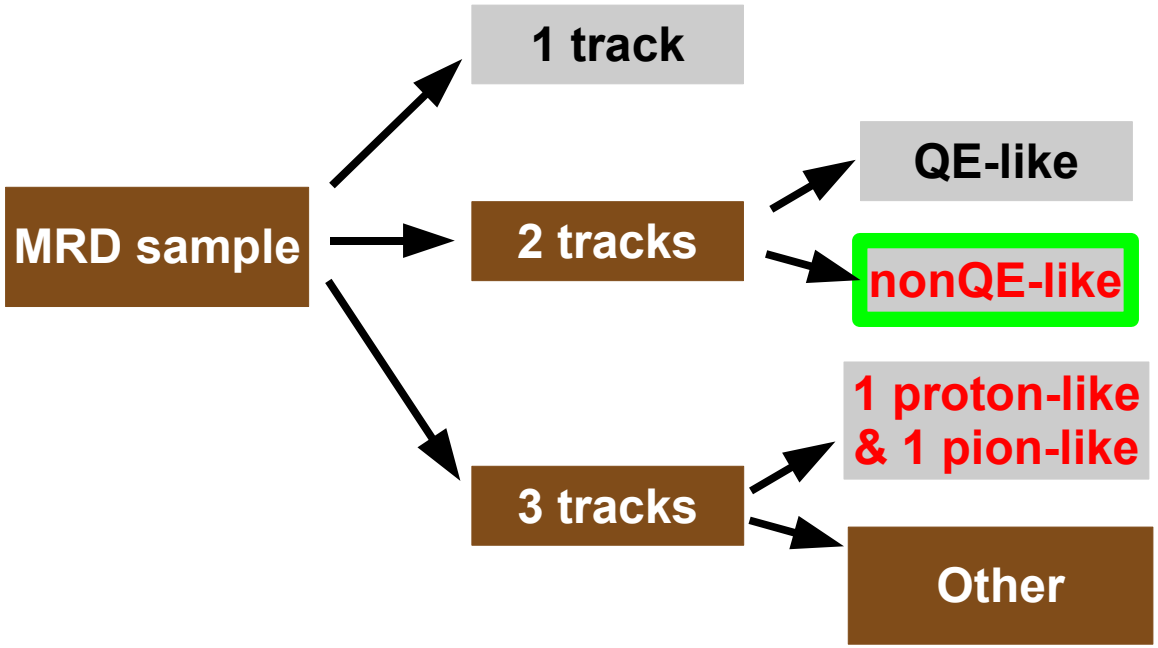




2) For 2-track events, separation in QE-like and nonQE-like based on direction of 2nd track




3) Particle ID: Muon Confidence Level (MuCL), likelihood variable based on dE/dx to separate protons from pions

# Event Classification

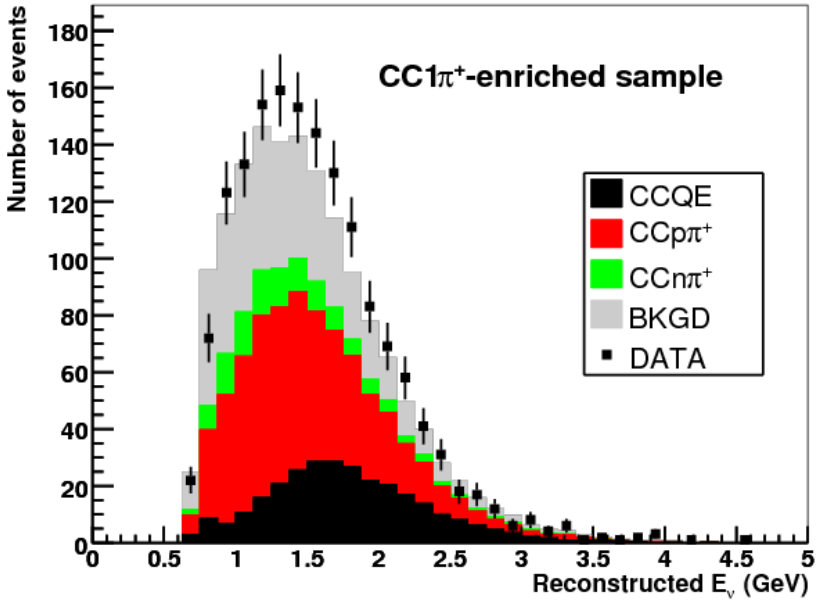


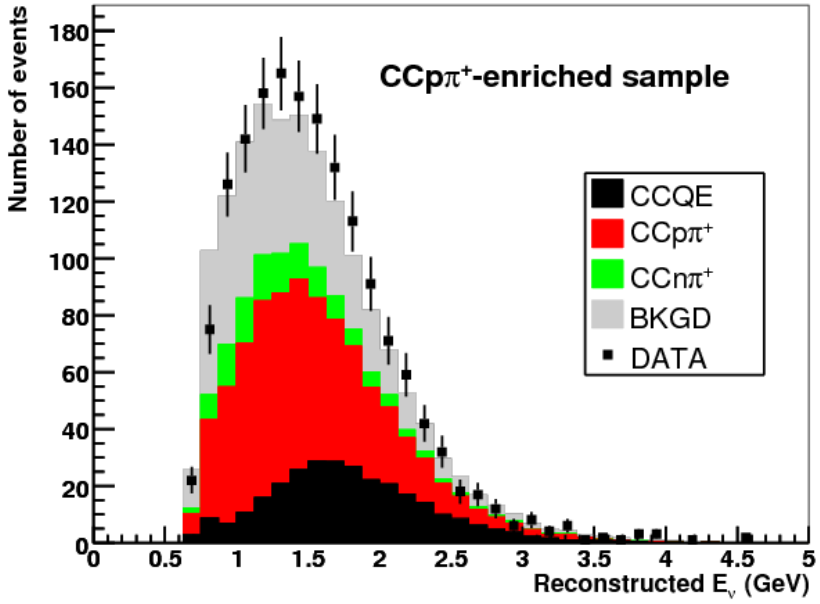

**CCQE-enriched: 8894 evts, 60% purity, 60% eff**

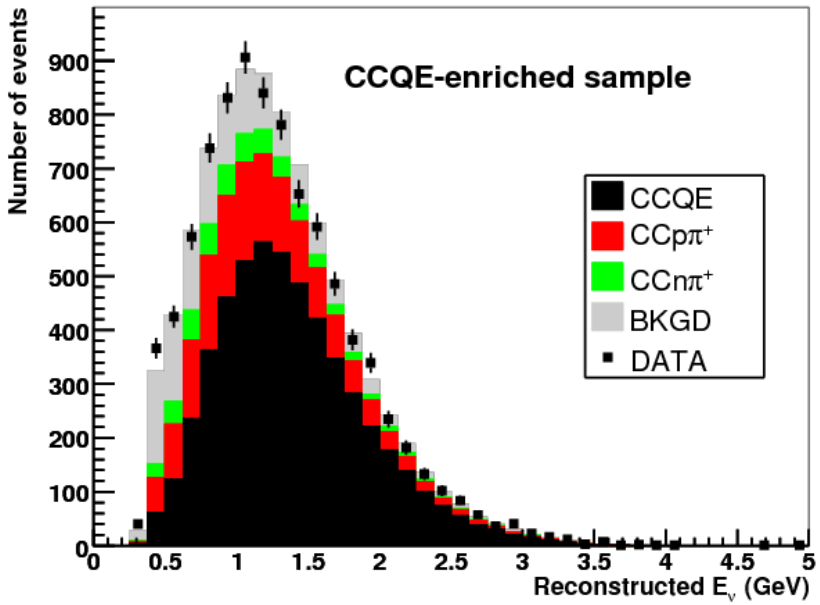
**CCp$\pi^+$-enriched: 1619 evts, 41% purity, 13% eff**

**CC1$\pi^+$-enriched: 1566 evts, 48% purity, 11% eff**

# Neutrino Energy Reconstruction




$$E_\nu = \frac{E_\mu(m_N - V) + \frac{1}{2}\left(m_X^2 - (m_N - V)^2 - m_\mu^2\right)}{(m_N - V) - E_\mu + p_\mu \cos\theta_\mu}$$

N = nucleon target (p, n)

X = outgoing baryon (p, Δ)

V = nuclear potential = 27 MeV

# Goal

Measure the cross section for inclusive ($CC1\pi^+$) and exclusive ($CCp\pi^+$) resonant single pion production relative to the CCQE cross section (to avoid large uncertainties in absolute flux measurement)

$$R_{inc} = \frac{\sigma^{CC1\pi^+}}{\sigma^{CCQE}}, \; R_{exc} = \frac{\sigma^{CCp\pi^+}}{\sigma^{CCQE}}$$

Measure both the total cross section ratio and the neutrino energy dependent ratio, energy bins shown in table →

| $E_\nu$ Range (GeV) |
|---|
| 0.00-1.35 |
| 1.35-1.72 |
| 1.72-2.22 |
| $> 2.22$ |

Will describe the $CC1\pi^+$ measurement, but method is same for the $CCp\pi^+$ measurement, using the appropriate enriched sample

# Analysis Strategy

Subtract the MC-predicted background from the CC1$\pi^+$- and CCQE-enriched samples → $S_\pi$, $S_{QE}$

(background = everything except CC1$\pi^+$ and CCQE)

Efficiency of CC1$\pi^+$ in $S_\pi$

$$\begin{pmatrix} S_\pi \\ S_{QE} \end{pmatrix} = \begin{pmatrix} e_\pi^{CC1\pi^+} & e_\pi^{CCQE} \\ e_{QE}^{CC1\pi^+} & e_{QE}^{CCQE} \end{pmatrix} \begin{pmatrix} N^{CC1\pi^+} \\ N^{CCQE} \end{pmatrix}$$

background-subtracted CC1$\pi^+$ and CCQE samples

Migration Matrix (predicted by MC)

number of CC1$\pi^+$,CCQE interactions in our data

**Cross Section Ratio:** $$R = \frac{N^{CC1\pi^+}}{N^{CCQE}}$$

# Analysis Strategy

For energy-dependent cross section ratio, migration matrix accounts for migration among neutrino energy bins and between CC1$\pi^+$ and CCQE samples.

Still consider only overall normalization of CCQE cross section.

$$\begin{pmatrix} S_{\pi,1} \\ S_{\pi,2} \\ S_{\pi,3} \\ S_{\pi,4} \\ \hline S_{QE} \end{pmatrix} = \begin{array}{|c|c|} \hline \multicolumn{1}{|c|}{\text{4x4 CC1}\pi^+ \text{ to CC1}\pi^+} & \text{4x1 CCQE to CC1}\pi^+ \\ \hline \text{1x4 CC1}\pi^+ \text{ to CCQE} & \text{1x1 CCQE to CCQE} \\ \hline \end{array} \begin{pmatrix} N_1^{CC1\pi^+} \\ N_2^{CC1\pi^+} \\ N_3^{CC1\pi^+} \\ N_4^{CC1\pi^+} \\ \hline N^{CCQE} \end{pmatrix}$$

$$R_e = \frac{N_e^{CC1\pi^+}}{f_e N^{CCQE}}$$

$f_e$ is fraction of CCQE in energy bin $e$ (predicted by MC)

# Systematic Errors

- **Nuclear effects:** consider uncertainty in model for pion inelastic scattering (+-30%), pion absorption (+-30%), proton rescattering (+-10%), and Fermi surface momentum (+- 5 MeV/c)

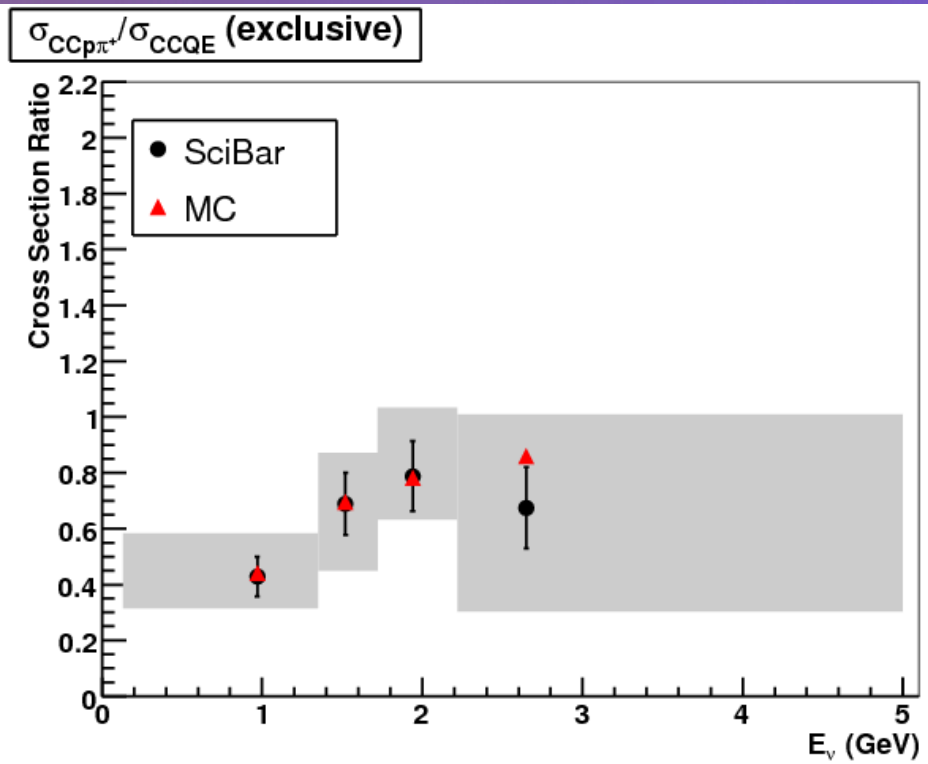
- **Detector simulation:** uncertainty in model for crosstalk (+-0.0025), PMT energy resolution (+-10%), and scintillator quenching (+-0.0023)

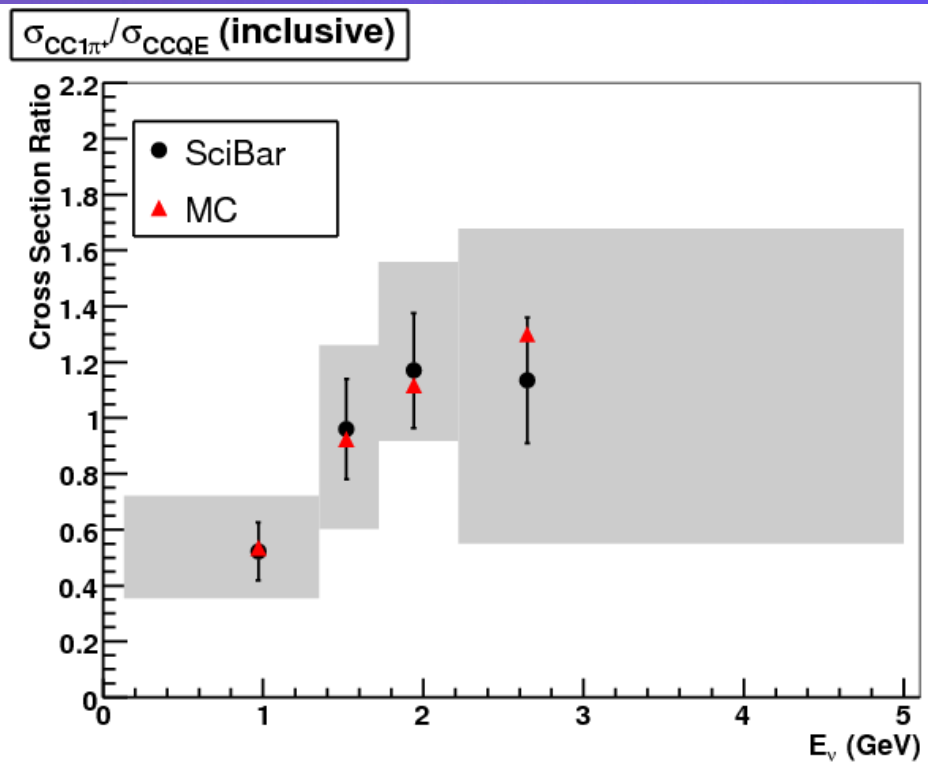
- **Reconstruction:** uncertainty in hit threshold (+-15%) and angular resolution (+-0.009), energy scale (+-2.7%)

- **Neutrino Interaction Model:** uncertainty in $M_A^{QE}$ (+-0.1 GeV/$c^2$, shape only), Bodek/Yang correction to DIS structure functions (+-30%), observed discrepancy in DIS cross section (+-40%)

- **Neutrino Energy Spectrum Measurement:** +- 1σ for seven neutrino energy bins

# Results

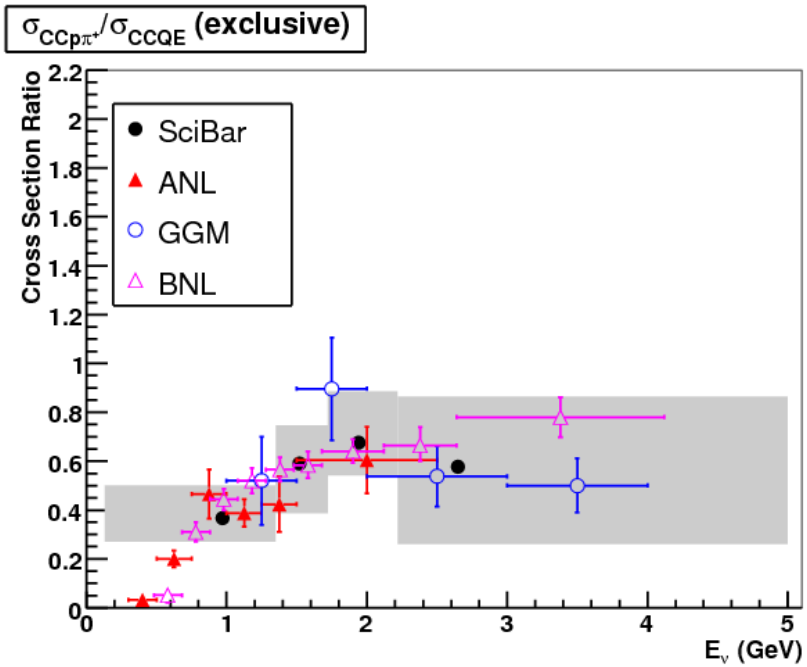


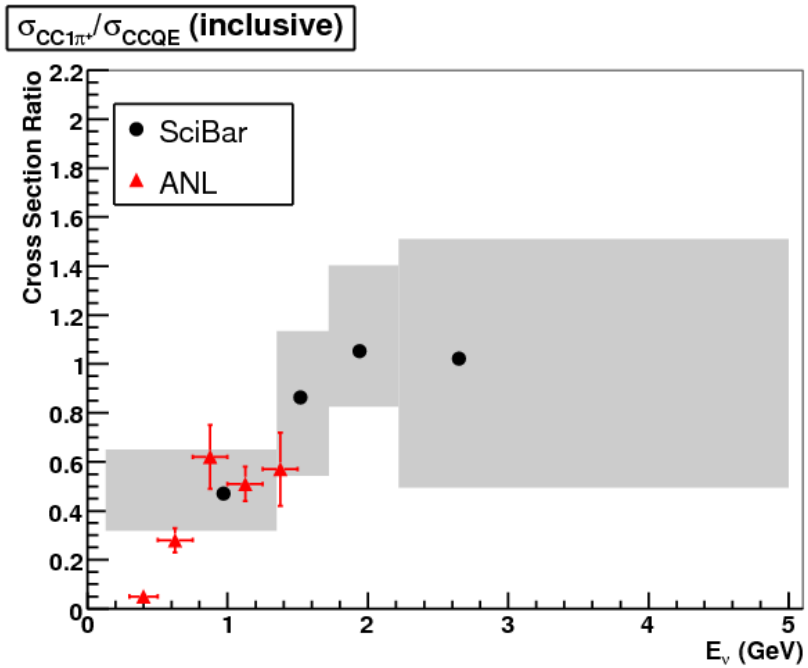




| Energy Range (GeV) | Cross Section Ratio $R_e = \frac{\sigma_e^{CC p\pi^+}}{\sigma_e^{CCQE}}$ |
|---|---|
| >0.00 | $0.614 \pm 0.061(\text{stat.})^{+0.084}_{-0.028}(\text{nucl.})^{+0.087}_{-0.077}(\text{syst.})$ |
| 0.00-1.35 | $0.429 \pm 0.071(\text{stat.})^{+0.070}_{-0.052}(\text{nucl.})^{+0.119}_{-0.073}(\text{syst.})$ |
| 1.35-1.72 | $0.689 \pm 0.112(\text{stat.})^{+0.116}_{-0.147}(\text{nucl.})^{+0.085}_{-0.151}(\text{syst.})$ |
| 1.72-2.22 | $0.788 \pm 0.126(\text{stat.})^{+0.156}_{-0.005}(\text{nucl.})^{+0.141}_{-0.093}(\text{syst.})$ |
| ≥2.22 | $0.674 \pm 0.146(\text{stat.})^{+0.097}_{-0.138}(\text{nucl.})^{+0.286}_{-0.311}(\text{syst.})$ |

| Energy Range (GeV) | Cross Section Ratio $R_e = \frac{\sigma_e^{CC 1\pi^+}}{\sigma_e^{CCQE}}$ |
|---|---|
| >0.00 | $0.850 \pm 0.080(\text{stat.})^{+0.127}_{-0.039}(\text{nucl.})^{+0.119}_{-0.109}(\text{syst.})$ |
| 0.00-1.35 | $0.522 \pm 0.103(\text{stat.})^{+0.089}_{-0.088}(\text{nucl.})^{+0.146}_{-0.098}(\text{syst.})$ |
| 1.35-1.72 | $0.960 \pm 0.179(\text{stat.})^{+0.205}_{-0.208}(\text{nucl.})^{+0.129}_{-0.227}(\text{syst.})$ |
| 1.72-2.22 | $1.170 \pm 0.206(\text{stat.})^{+0.260}_{-0.029}(\text{nucl.})^{+0.203}_{-0.142}(\text{syst.})$ |
| ≥2.22 | $1.135 \pm 0.225(\text{stat.})^{+0.193}_{-0.218}(\text{nucl.})^{+0.456}_{-0.494}(\text{syst.})$ |

# Comparison to Other Experiments




**ANL:** Argonne 12 foot bubble chamber, hydrogen and deuterium target, peak neutrino energy 0.5 GeV

**GGM:** CERN bubble chamber, propane-freon target, neutrino energy < 10 GeV

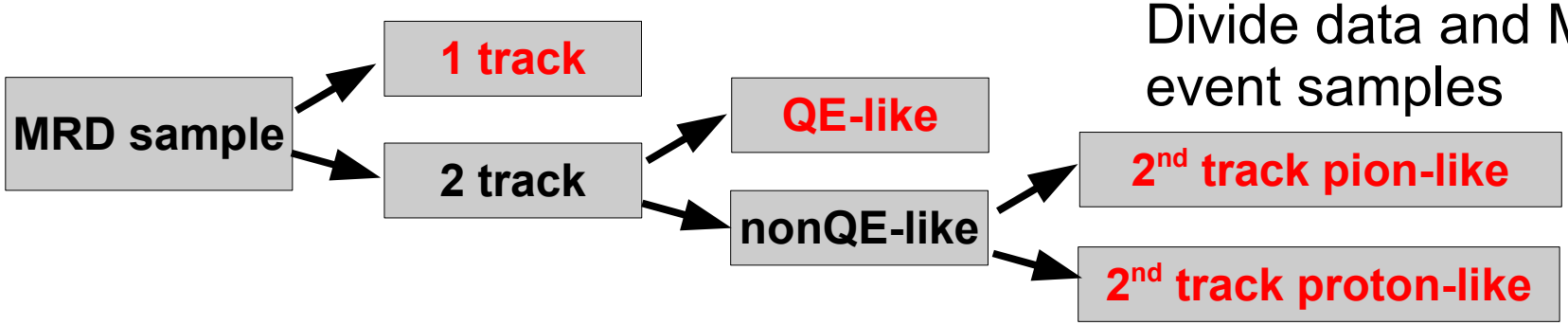
**BNL:** Brookhaven 7 foot bubble chamber, deuterium target, mean neutrino energy 1.6 GeV

**NOTE: SciBar data points have been scaled to take into account the fact that our target material ($C_8H_8$) has more protons than neutrons.**

# Cross-Check Analysis

**An independent analysis is done using same data but a different method:**

Bin the data using muon kinematic variables and perform a maximum likelihood fit based on Poisson statistics




Divide data and MC into four event samples

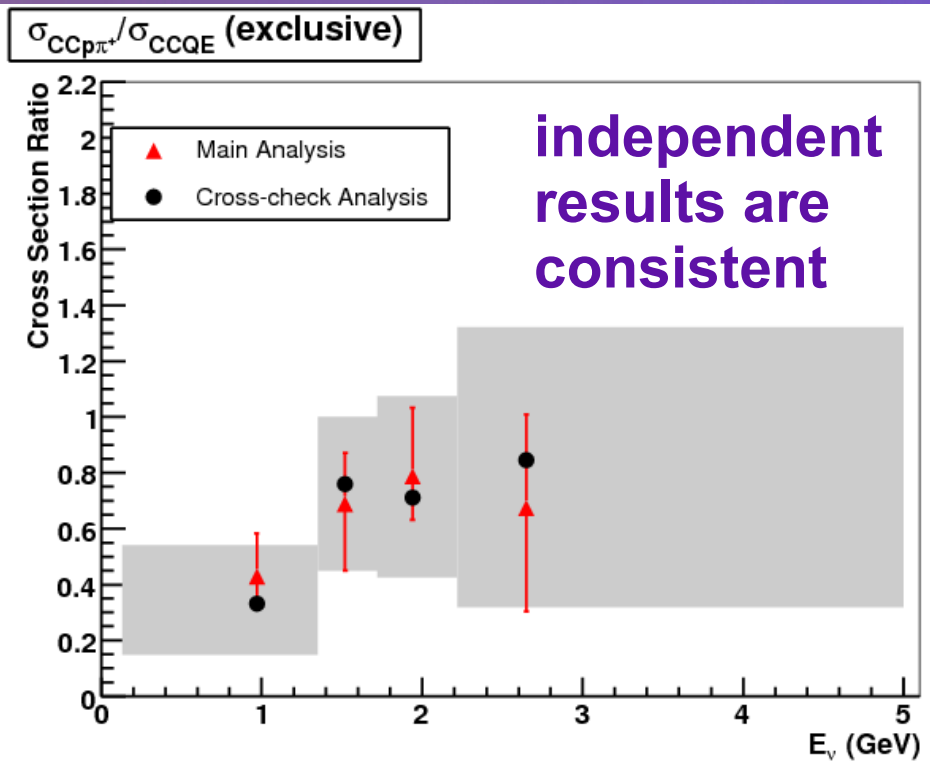
MC events further divided based on:

- **interaction type** – CCQE, CC1$\pi^+$, and background.
- **true neutrino energy**

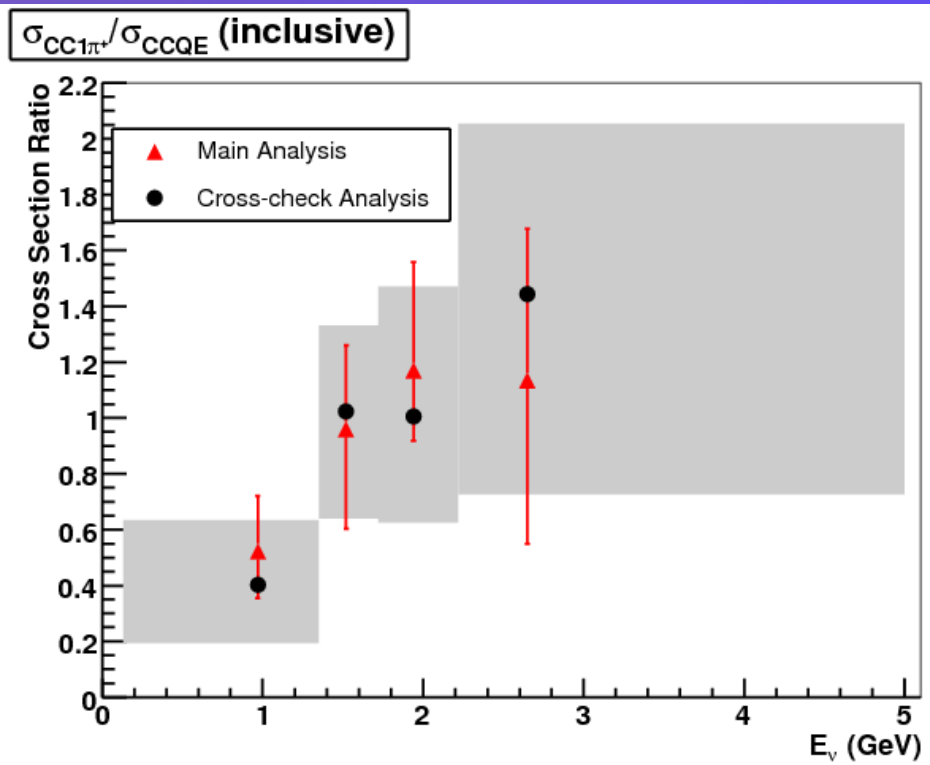
Data and MC binned in **$p_\mu$ vs. $\theta_\mu$ bins** (0.2 GeV/c, 10° bins)

Fit gives number of CCQE, CC1$\pi^+$, and bkgd. interactions in data relative to MC – can extract cross section ratio from this

# Cross-Check Analysis




**independent results are consistent**




**0.614 +0.135,-0.102**
**0.556 +0.186,-0.194**

**0.850 +0.192,-0.141**
**0.735 +0.222,-0.231**

Major differences between this analysis and main analysis:
1) energy-scale is a free parameter
2) background is not fixed to MC prediction (in main analysis, background fluctuations considered only as a systematic error)

# Summary

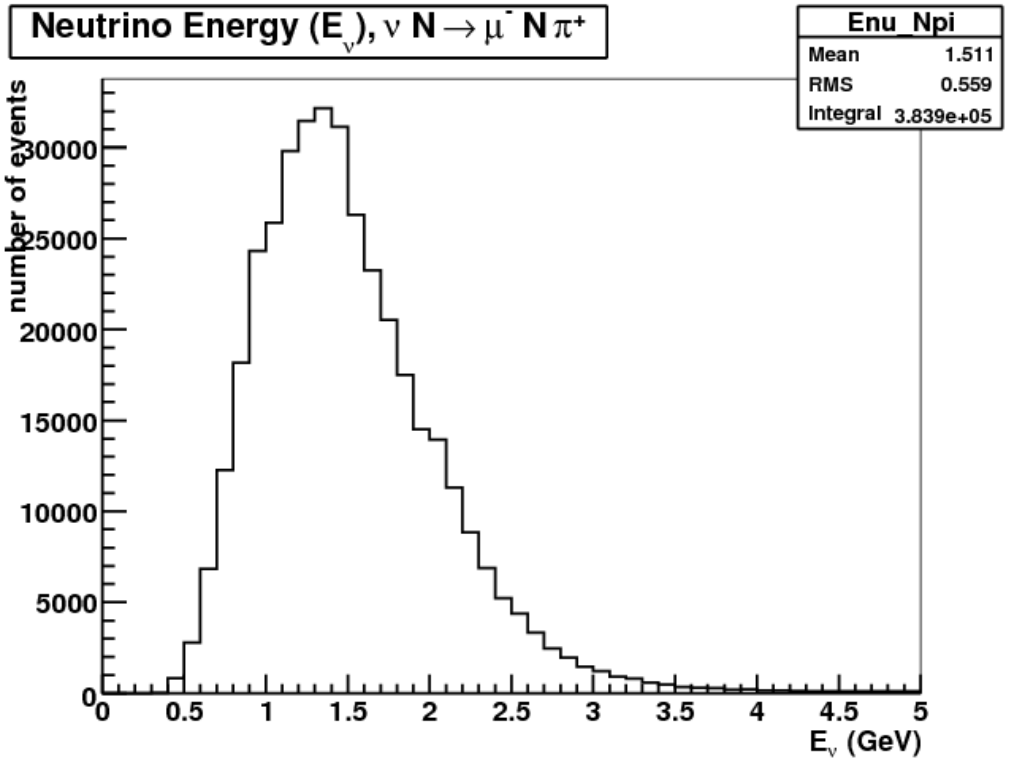
- Both coherent and resonant single $\pi^+$ production has been studied at K2K using data from the SciBar detector

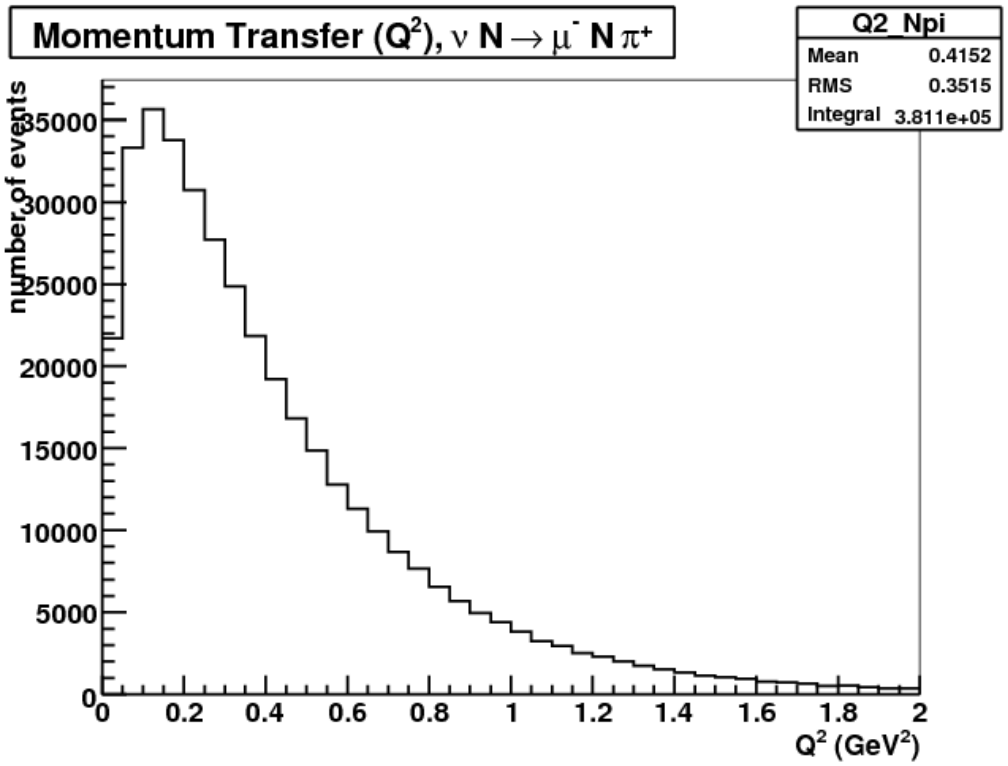
- data is consistent with no CC coherent pion production (published in 2005)

- cross section for resonant single $\pi^+$ production relative to the CCQE cross section is consistent with our MC model and results from previous experiments (paper will be submitted for publication this summer)

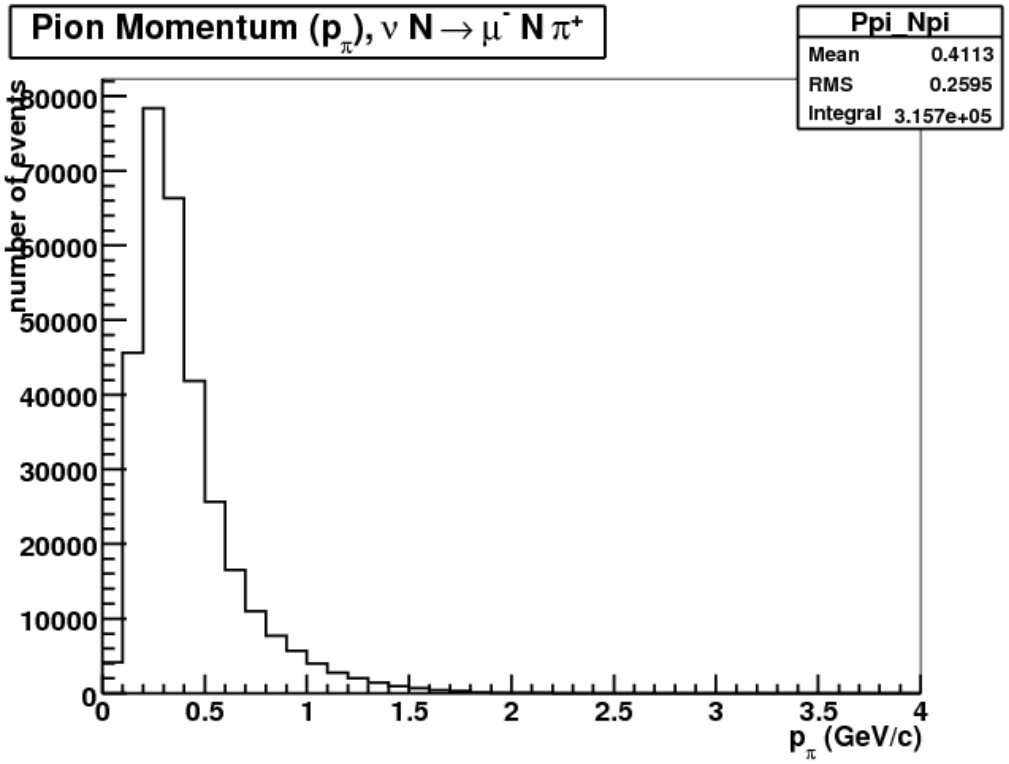
# Backup Slides

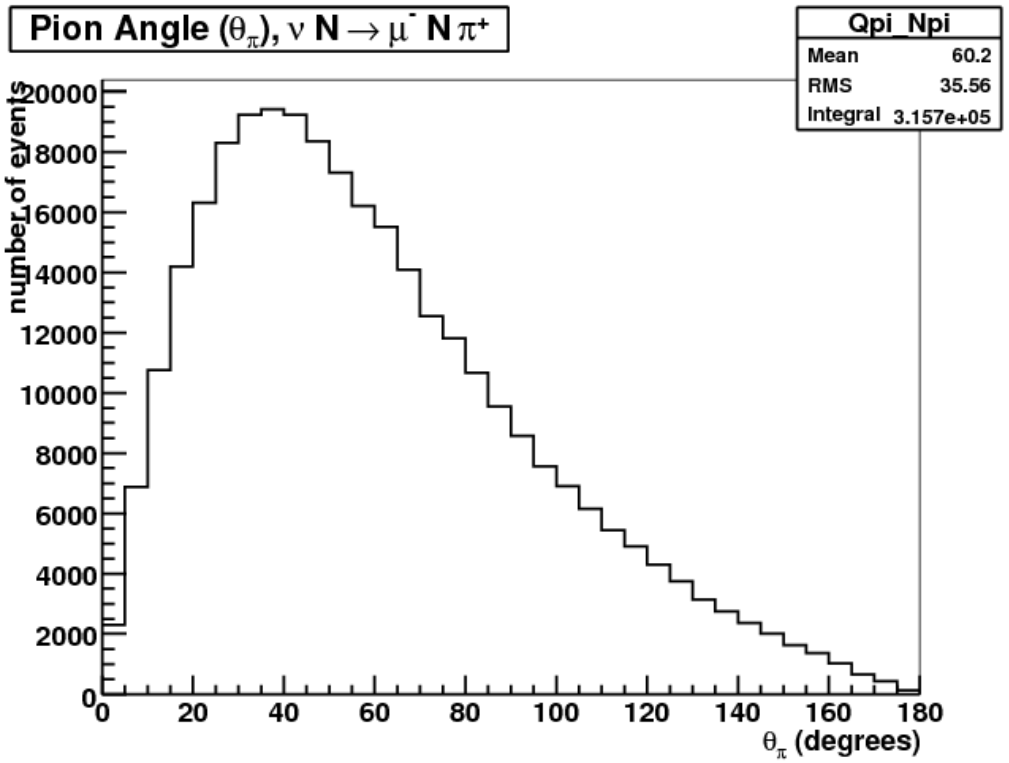
# CC1$\pi^+$ Events



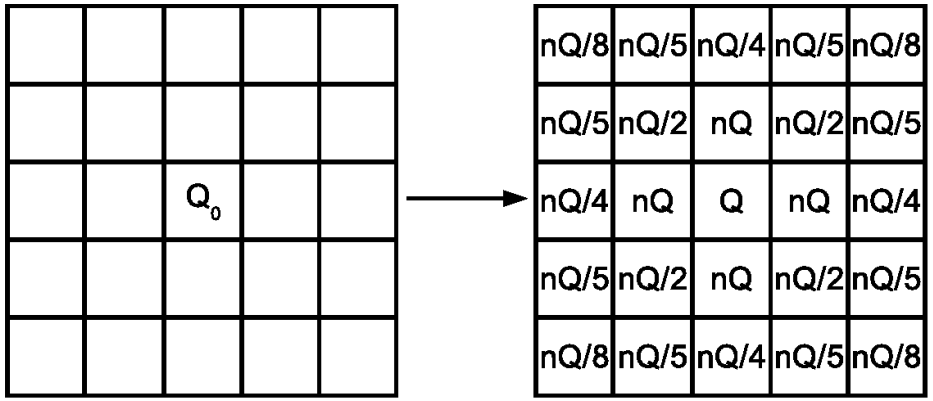
# CC1$\pi^+$ Events



# SciBar Detector Simulation

Crosstalk in the MAPMT ~3% in neighboring channels




Attenuation length of light in fiber ~350 cm by measurement

Light yield calibration measured for each bar ~20 p.e. for MIP

travel time for light in fiber: 16 cm/ns

PMT energy resolution of 40%

Scintillator quenching for protons: Birks' constant (*c*) measured with SciBar prototype in proton beam

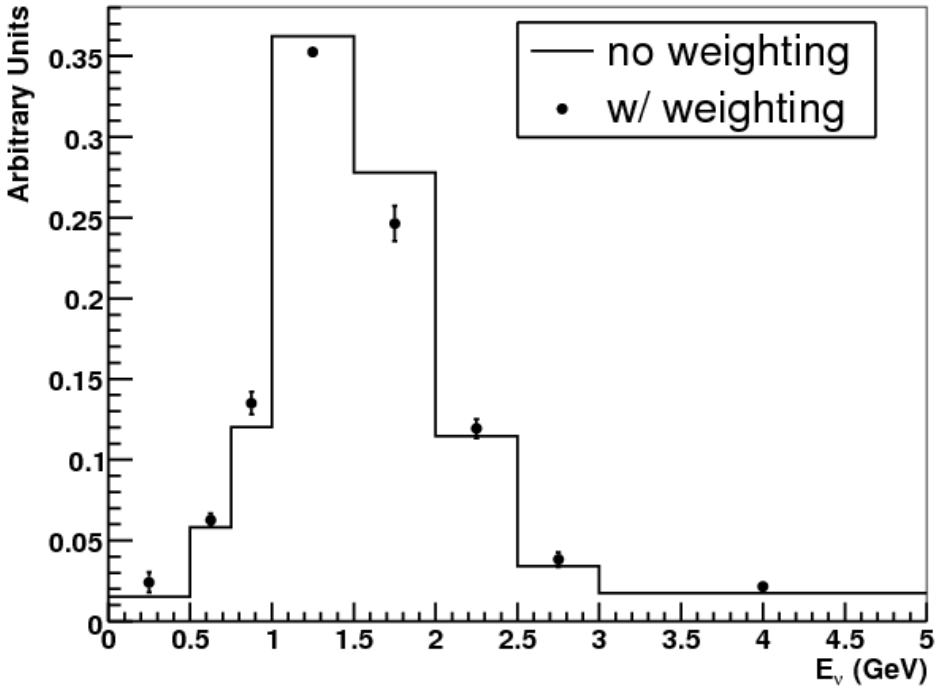
$$\frac{\Delta E_{vis}}{\Delta E_{loss}} \propto \frac{1}{1 + c \cdot dE/dx\,(expected)}$$

# Measured Energy Spectrum

Data from all near detectors is used to measure the neutrino energy spectrum in 8 energy bins.

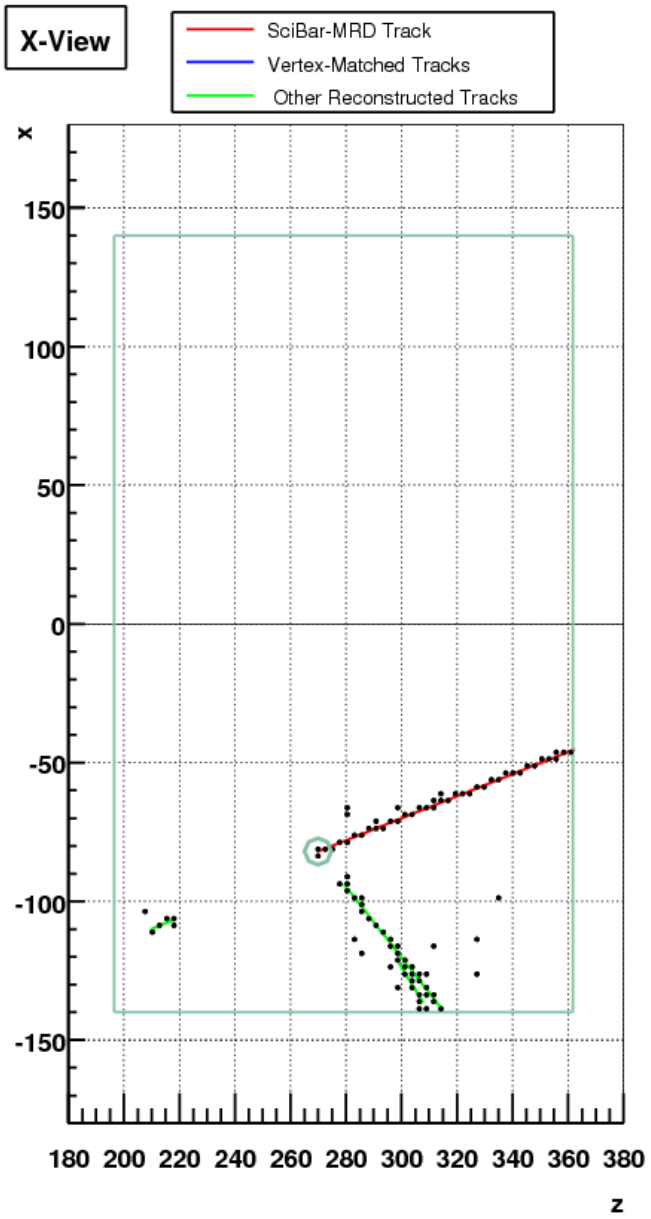
Then the predicted energy spectrum from the beam-MC is reweighted to match the measurement.

Error of the reweighting factors and correlation among them is considered as a systematic error.

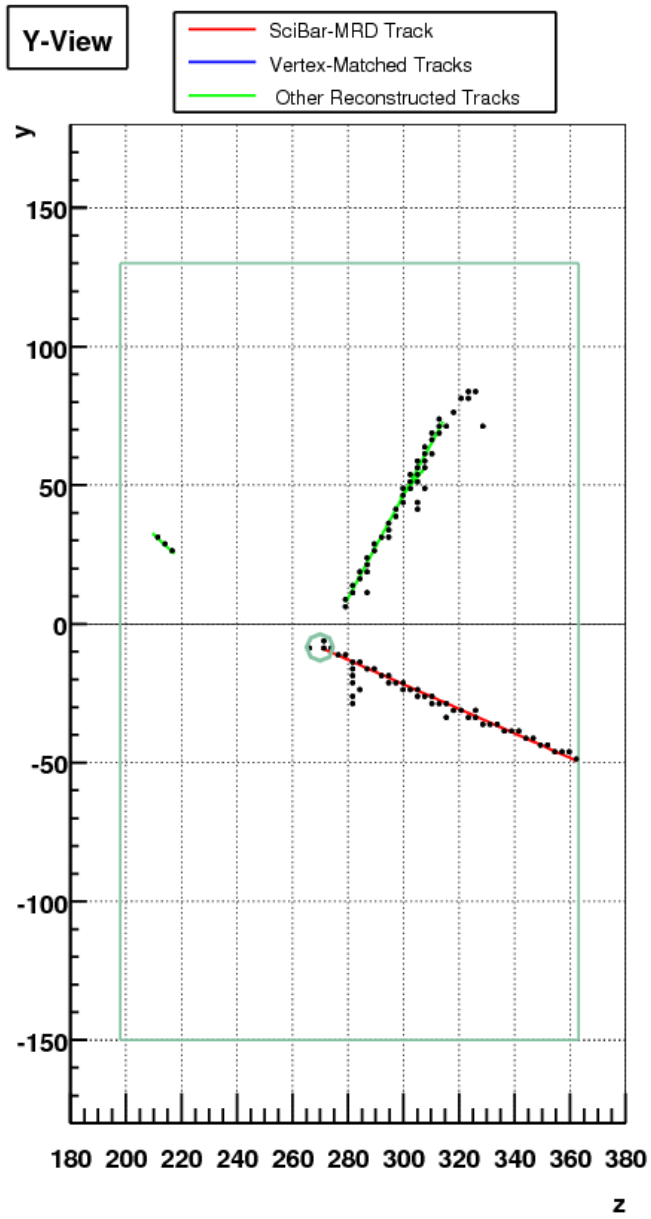



| $E_\nu$ (GeV) | Weighting factor |
|---|---|
| 0.00-0.50 | 1.657 |
| 0.50-0.75 | 1.107 |
| 0.75-1.00 | 1.154 |
| 1.00-1.50 | $\equiv 1$ |
| 1.50-2.00 | 0.911 |
| 2.00-2.50 | 1.069 |
| 2.50-3.00 | 1.152 |
| $>$3.00 | 1.260 |

# Vertex Matching




(top view)



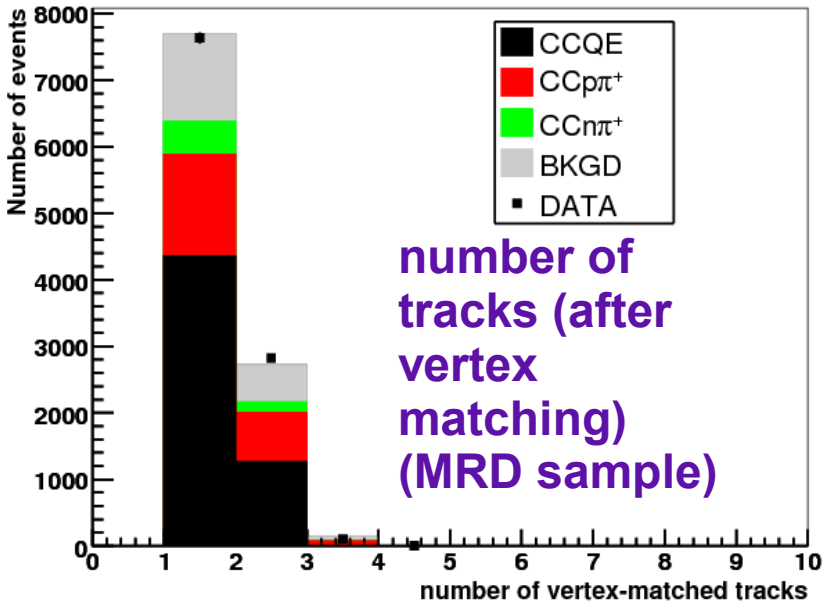

(side view)

SciBar-MRD track is in red

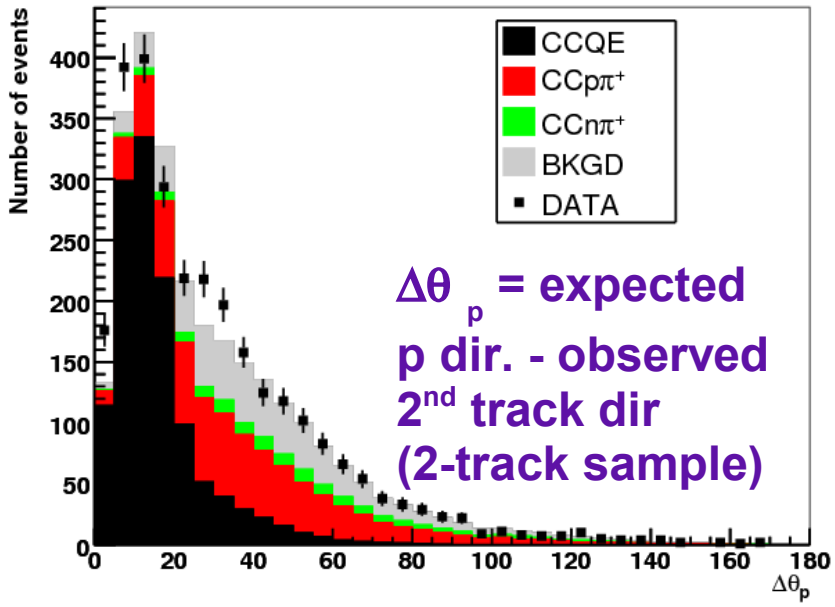
Before vertex matching:
**4 tracks**

After vertex matching:
**1 track**

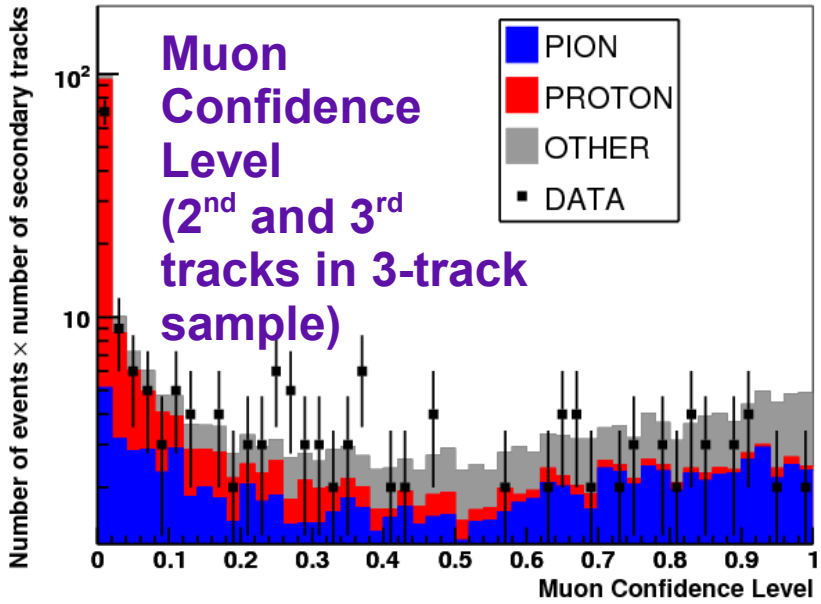
# Event Classification




number of tracks (after vertex matching) (MRD sample)




$\Delta\theta_p$ = expected p dir. - observed 2nd track dir (2-track sample)




Muon Confidence Level (2nd and 3rd tracks in 3-track sample)

# Summary of Systematic Errors

## Exclusive overall cross section ratio

| source of systematic | error | |
|---|---|---|
| **MC statistics** | +0.009 | -0.009 |
| **Model effects** | | |
| $M_A$ (CCQE) $\pm 0.1$ | +0.021 | -0.021 |
| Bodek/Yang Corr $\pm 30\%$ | -0.021 | +0.023 |
| N$\pi$ weighting | $\pm$ 0.056 | |
| Neutrino Flux | +0.010 | -0.008 |
| Sub-total | +0.065 | -0.064 |
| **Nuclear effects** | | |
| $\pi$ absorption $\pm 30\%$ | +0.053 | -0.015 |
| $\pi$ inelastic scattering $\pm 30\%$ | +0.062 | -0.022 |
| proton rescattering $\pm 10\%$ | +0.021 | -0.007 |
| Fermi motion ($\pm$ 5MeV/c) | $\pm$ 0.004 | |
| Sub-total | +0.084 | -0.028 |
| **Detector effects** | | |
| Cross talk $\pm 0.25\%$ | +0.035 | -0.021 |
| PMT resolution $\pm 10\%$ | +0.025 | -0.010 |
| Quenching constant $\pm 0.0023$ | +0.005 | +0.012 |
| Sub-total | +0.045 | -0.023 |
| **Reconstruction effects** | | |
| Hit threshold $\pm 15\%$ | $\pm$ 0.035 | |
| Muon momemtum scale $\pm 2.7\%$ | -0.004 | +0.003 |
| Angular resolution (smeared by 0.009) | $\pm$ 0.007 | |
| Sub-total | +0.036 | -0.036 |
| Total | +0.121 | -0.082 |

Total +20% -13%

## Inclusive overall cross section ratio

| source of systematic | error | |
|---|---|---|
| **MC statistics** | +0.012 | -0.012 |
| **Model effects** | | |
| $M_A$ (CCQE) $\pm 0.1$ | +0.024 | -0.024 |
| Bodek/Yang Corr $\pm 30\%$ | -0.031 | +0.033 |
| N$\pi$ weighting | $\pm$ 0.079 | |
| Neutrino Flux | +0.013 | -0.011 |
| Sub-total | +0.090 | -0.089 |
| **Nuclear effects** | | |
| $\pi$ absorption $\pm 30\%$ | +0.089 | -0.023 |
| $\pi$ inelastic scattering $\pm 30\%$ | +0.084 | -0.029 |
| proton rescattering $\pm 10\%$ | +0.034 | -0.007 |
| Fermi motion ($\pm$ 5MeV/c) | $\pm$ 0.008 | |
| Sub-total | +0.127 | -0.039 |
| **Detector effects** | | |
| Cross talk $\pm 0.25\%$ | +0.044 | -0.034 |
| PMT resolution $\pm 10\%$ | +0.034 | -0.015 |
| Quenching constant $\pm 0.0023$ | +0.011 | +0.016 |
| Sub-total | +0.058 | -0.037 |
| **Reconstruction effects** | | |
| Hit threshold $\pm 15\%$ | $\pm$ 0.049 | |
| Muon momemtum scale $\pm 2.7\%$ | -0.005 | +0.005 |
| Angular resolution (smeared by 0.009) | $\pm$ 0.011 | |
| Sub-total | +0.050 | -0.050 |
| Total | +0.174 | -0.116 |

Total +20% -14%

# Summary of Systematic Errors

Exclusive cross section ratio

| source of systematic | error | | error | | error | | error | |
|---|---|---|---|---|---|---|---|---|
| **MC statistics** | +0.011 | -0.011 | +0.020 | -0.020 | +0.028 | -0.028 | +0.042 | -0.042 |
| **Model effects** | | | | | | | | |
| $M_A$ (CCQE) $\pm 0.1$ | +0.016 | -0.017 | +0.023 | -0.022 | +0.015 | -0.016 | +0.004 | -0.013 |
| Bodek/Yang Corr $\pm 30\%$ | -0.027 | +0.029 | -0.020 | +0.021 | -0.017 | +0.019 | -0.013 | +0.016 |
| N$\pi$ weighting | $\pm$ 0.051 | | $\pm$ 0.051 | | $\pm$ 0.057 | | $\pm$ 0.067 | |
| Neutrino Flux | +0.007 | -0.008 | +0.014 | -0.015 | +0.024 | -0.021 | +0.057 | -0.050 |
| Sub-total | +0.061 | -0.061 | +0.061 | -0.061 | +0.066 | -0.065 | +0.089 | -0.085 |
| **Nuclear effects** | | | | | | | | |
| $\pi$ absorption $\pm 30\%$ | +0.051 | -0.052 | +0.006 | -0.006 | +0.107 | +0.011 | +0.076 | +0.004 |
| $\pi$ inelastic scattering $\pm 30\%$ | +0.024 | +0.028 | +0.112 | -0.115 | +0.060 | +0.092 | +0.032 | -0.129 |
| proton rescattering $+10\%$ | +0.027 | +0.039 | +0.030 | -0.092 | +0.067 | -0.067 | +0.048 | -0.045 |
| Fermi motion ($\pm$ 5MeV/c) | $\pm$ 0.004 | | $\pm$ 0.001 | | $\pm$ 0.005 | | $\pm$ 0.018 | |
| Sub-total | +0.070 | -0.052 | +0.116 | -0.147 | +0.156 | -0.005 | +0.097 | -0.138 |
| **Detector effects** | | | | | | | | |
| Cross talk $\pm 0.25\%$ | +0.031 | +0.033 | +0.028 | -0.058 | +0.043 | -0.039 | +0.049 | -0.032 |
| PMT resolution $\pm 10\%$ | +0.012 | -0.006 | +0.021 | -0.004 | +0.042 | -0.019 | +0.024 | -0.018 |
| Quenching constant $\pm 0.0023$ | +0.020 | +0.001 | -0.022 | +0.021 | +0.039 | +0.022 | -0.027 | +0.002 |
| Sub-total | +0.040 | -0.006 | +0.041 | -0.062 | +0.072 | -0.043 | +0.055 | -0.046 |
| **Reconstruction effects** | | | | | | | | |
| Hit threshold $\pm 15\%$ | $\pm$ 0.015 | | $\pm$ 0.036 | | $\pm$ 0.036 | | $\pm$ 0.067 | |
| Muon momemtum scale $\pm 2.7\%$ | -0.035 | +0.092 | -0.116 | +0.008 | +0.088 | -0.004 | +0.225 | -0.258 |
| Angular resolution (smeared by 0.009) | $\pm$ 0.006 | | $\pm$ 0.008 | | $\pm$ 0.019 | | $\pm$ 0.119 | |
| Sub-total | +0.093 | -0.039 | +0.038 | -0.122 | +0.097 | -0.041 | +0.263 | -0.292 |
| Total | +0.138 | -0.090 | +0.144 | -0.211 | +0.210 | -0.093 | +0.302 | -0.340 |
| Total | +32% | -21% | +21% | -31% | +27% | -12% | +45% | -50% |

# Summary of Systematic Errors

Inclusive cross section ratio

| source of systematic | error | error | error | error |
|---|---|---|---|---|
| **MC statistics** | +0.015 -0.015 | +0.031 -0.031 | +0.044 -0.044 | +0.066 -0.066 |
| **Model effects** | | | | |
| $M_A$ (CCQE) $\pm 0.1$ | +0.017 -0.018 | +0.026 -0.026 | +0.019 -0.018 | -0.001 -0.013 |
| Bodek/Yang Corr $\pm 30\%$ | -0.036 +0.038 | -0.029 +0.032 | -0.030 +0.032 | -0.026 +0.029 |
| N$\pi$ weighting | $\pm$ 0.066 | $\pm$ 0.075 | $\pm$ 0.088 | $\pm$ 0.111 |
| Neutrino Flux | +0.010 -0.011 | +0.022 -0.021 | +0.034 -0.033 | +0.085 -0.077 |
| Sub-total | +0.079 -0.078 | +0.088 -0.087 | +0.102 -0.100 | +0.143 -0.138 |
| **Nuclear effects** | | | | |
| $\pi$ absorption $\pm 30\%$ | +0.059 -0.088 | +0.022 +0.014 | +0.189 -0.003 | +0.148 +0.015 |
| $\pi$ inelastic scattering $\pm 30\%$ | +0.023 +0.021 | +0.186 -0.151 | +0.050 +0.138 | +0.043 -0.197 |
| proton rescattering $\pm 10\%$ | +0.018 +0.062 | +0.084 -0.143 | -0.028 +0.114 | +0.112 -0.087 |
| Fermi motion ($\pm$ 5MeV/c) | $\pm$ 0.005 | $\pm$ 0.005 | $\pm$ 0.007 | $\pm$ 0.032 |
| Sub-total | +0.089 -0.088 | +0.205 -0.208 | +0.260 -0.029 | +0.193 -0.218 |
| **Detector effects** | | | | |
| Cross talk $\pm 0.25\%$ | +0.020 +0.033 | +0.032 -0.080 | +0.082 -0.051 | +0.074 -0.058 |
| PMT resolution $\pm 10\%$ | +0.009 -0.010 | +0.035 -0.002 | +0.054 -0.032 | +0.037 -0.029 |
| Quenching constant $\pm 0.0023$ | +0.025 -0.007 | -0.024 +0.031 | +0.058 +0.045 | -0.025 -0.011 |
| Sub-total | +0.042 -0.012 | +0.057 -0.084 | +0.114 -0.060 | +0.083 -0.069 |
| **Reconstruction effects** | | | | |
| Hit threshold $\pm 15\%$ | $\pm$ 0.020 | $\pm$ 0.046 | $\pm$ 0.054 | $\pm$ 0.109 |
| Muon momemtum scale $\pm 2.7\%$ | -0.048 +0.111 | -0.183 +0.042 | +0.107 +0.013 | +0.344 -0.396 |
| Angular resolution (smeared by 0.009) | $\pm$ 0.021 | $\pm$ 0.025 | $\pm$ 0.042 | $\pm$ 0.216 |
| Sub-total | +0.115 -0.056 | +0.067 -0.190 | +0.127 -0.068 | +0.421 -0.464 |
| Total | +0.171 -0.132 | +0.242 -0.308 | +0.330 -0.145 | +0.496 -0.540 |
| Total | +33% -25% | +25% -32% | +28% -12% | +44% -48% |

# Migration Matrix

## EXCLUSIVE ($CC p\pi^+$)

$$\begin{pmatrix} 0.277 \pm 0.003 & 0.051 \pm 0.000 \\ 0.723 \pm 0.007 & 0.949 \pm 0.003 \end{pmatrix}$$

$$\begin{pmatrix} 0.212 \pm 0.003 & 0.120 \pm 0.002 & 0.055 \pm 0.002 & 0.033 \pm 0.002 & 0.011 \pm 0.000 \\ 0.025 \pm 0.001 & 0.142 \pm 0.002 & 0.083 \pm 0.002 & 0.024 \pm 0.001 & 0.015 \pm 0.000 \\ 0.001 \pm 0.000 & 0.022 \pm 0.001 & 0.144 \pm 0.003 & 0.082 \pm 0.003 & 0.016 \pm 0.000 \\ 0.000 \pm 0.000 & 0.001 \pm 0.000 & 0.016 \pm 0.001 & 0.160 \pm 0.004 & 0.011 \pm 0.000 \\ 0.763 \pm 0.007 & 0.715 \pm 0.007 & 0.702 \pm 0.007 & 0.701 \pm 0.010 & 0.948 \pm 0.003 \end{pmatrix}$$

## INCLUSIVE ($CC p\pi^+$)

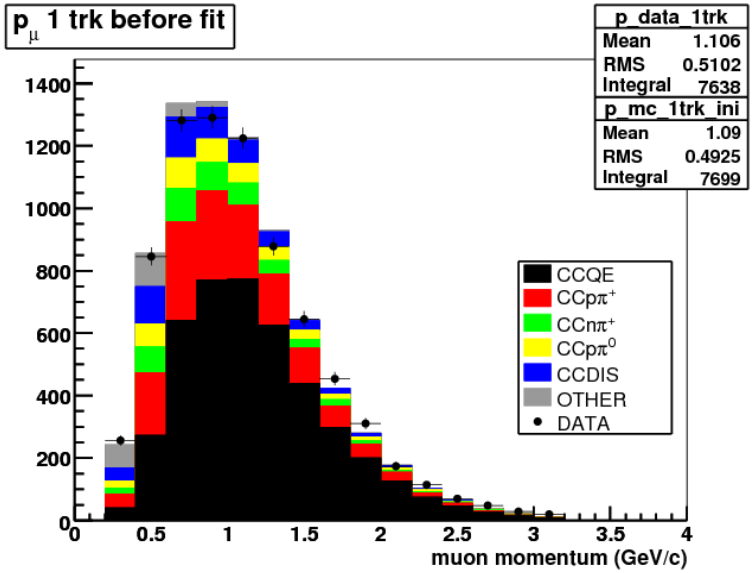
$$\begin{pmatrix} 0.250 \pm 0.003 & 0.051 \pm 0.000 \\ 0.750 \pm 0.007 & 0.949 \pm 0.003 \end{pmatrix}$$

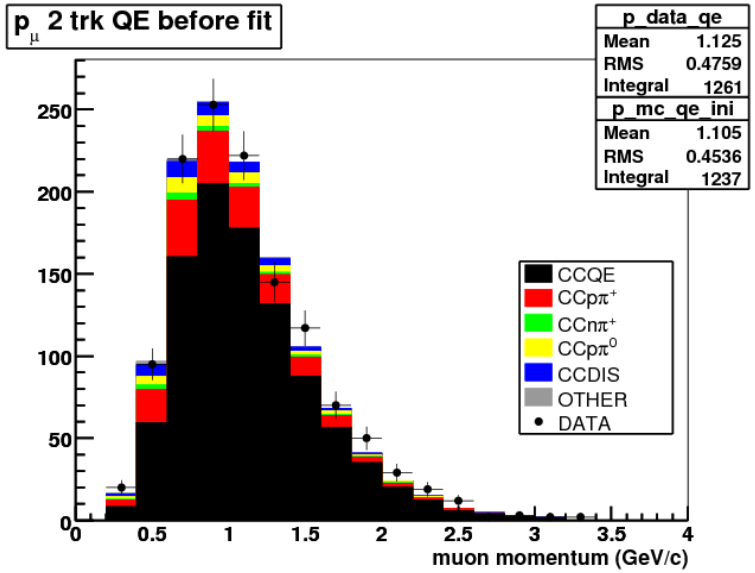
$$\begin{pmatrix} 0.203 \pm 0.003 & 0.124 \pm 0.002 & 0.069 \pm 0.002 & 0.038 \pm 0.002 & 0.011 \pm 0.000 \\ 0.023 \pm 0.001 & 0.124 \pm 0.002 & 0.081 \pm 0.002 & 0.032 \pm 0.001 & 0.015 \pm 0.000 \\ 0.001 \pm 0.000 & 0.019 \pm 0.001 & 0.117 \pm 0.002 & 0.079 \pm 0.002 & 0.016 \pm 0.000 \\ 0.000 \pm 0.000 & 0.001 \pm 0.000 & 0.012 \pm 0.001 & 0.130 \pm 0.003 & 0.011 \pm 0.000 \\ 0.773 \pm 0.007 & 0.732 \pm 0.006 & 0.721 \pm 0.006 & 0.721 \pm 0.009 & 0.948 \pm 0.003 \end{pmatrix}$$

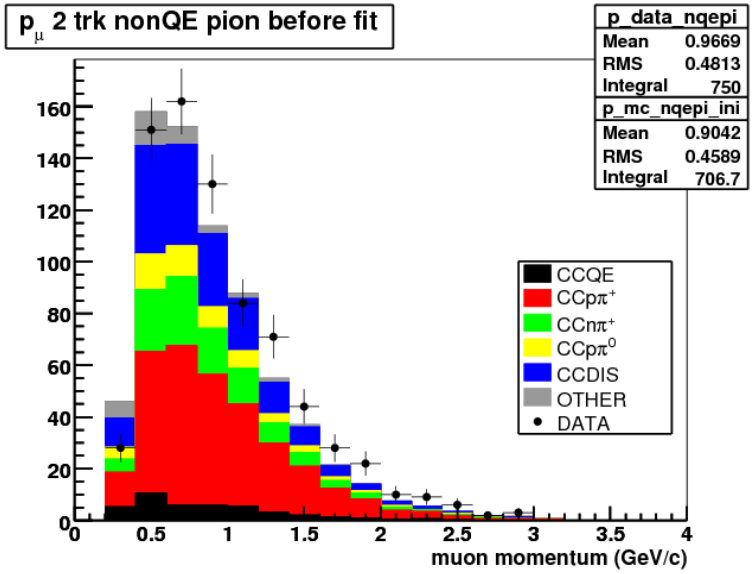
(matrix elements are normalized by e.g., $e_{\pi}^{CC1\pi^+} + e_{QE}^{CC1\pi^+} = e^{CC1\pi^+}$ so that columns sum to 1)

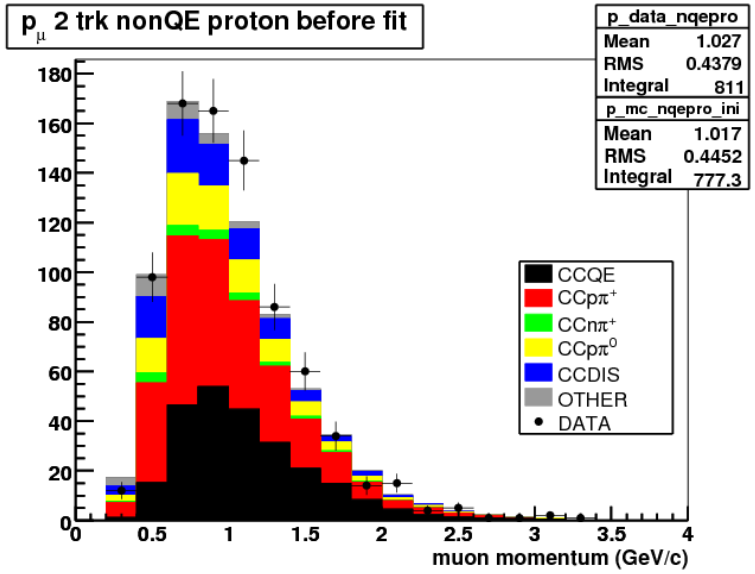
| Sample | CCQE | CC$p\pi^+$ | CC$n\pi^+$ | CC$1\pi^0$ | CC DIS | Other |
|---|---|---|---|---|---|---|
| Fiducial Volume | 32 | 18 | 6 | 5 | 9 | 30 |
| MRD | 52 | 22 | 6 | 6 | 9 | 5 |
| 1-track | 57 | 20 | 6 | 6 | 8 | 3 |
| 2-track QE | 78 | 13 | 1 | 3 | 4 | 1 |
| 2-track nonQE pion | 6 | 41 | 15 | 8 | 24 | 6 |
| 2-track nonQE proton | 32 | 38 | 3 | 12 | 12 | 3 |

# Data and Nominal MC $\mu$ Momentum

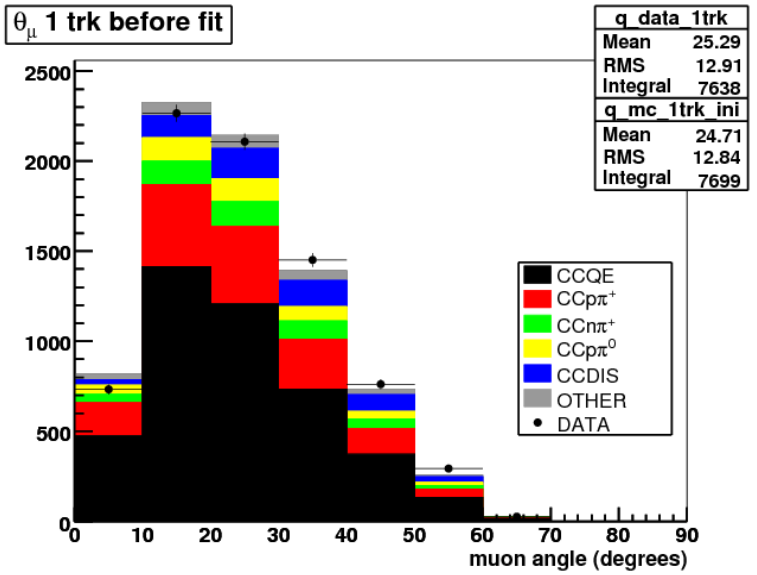


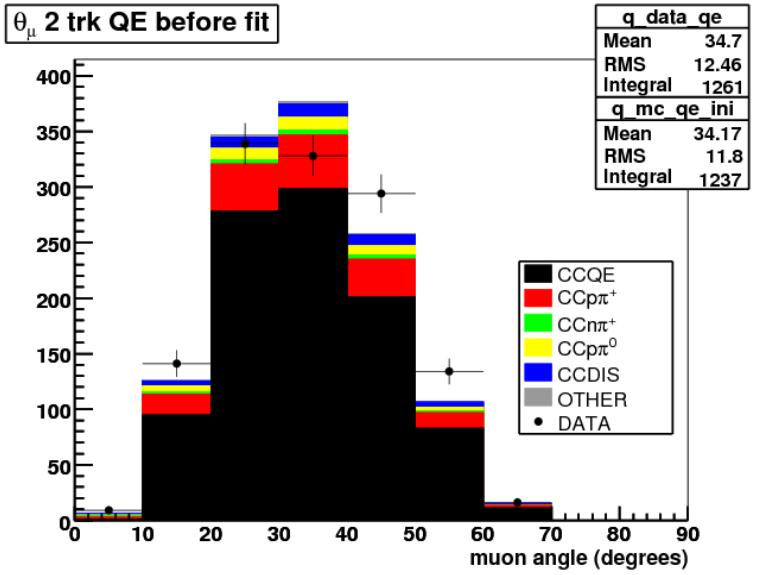



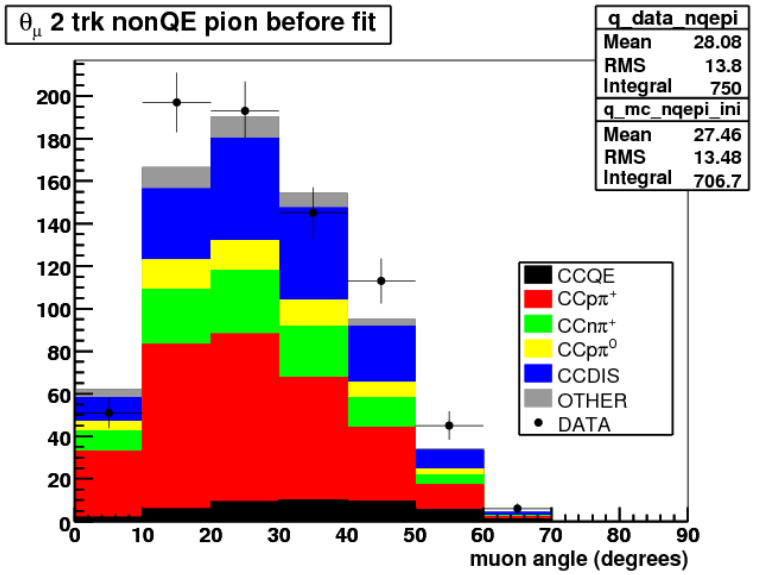



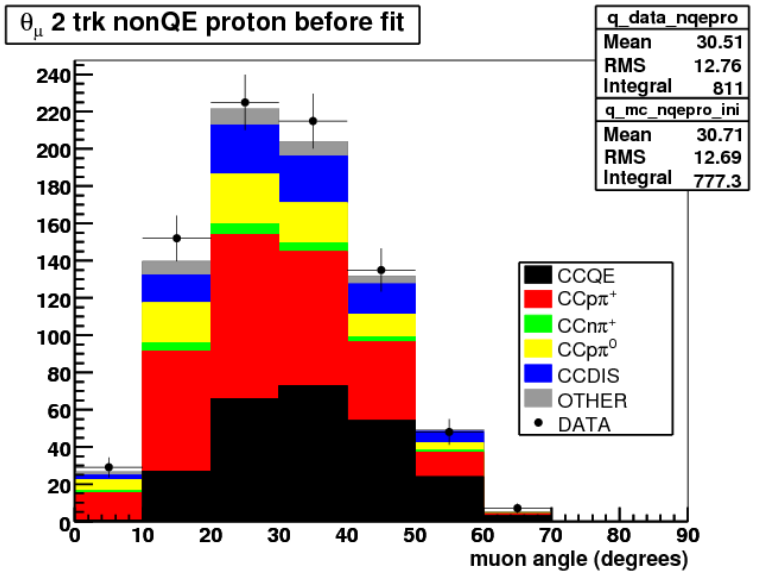



# Data and Nominal MC $\mu$ Angle



# Cross-Check Analysis

$$F = 2\sum_{is}\left[N_{is}^{exp} - N_{is}^{obs} + N_{is}^{obs}\ln\frac{N_{is}^{obs}}{N_{is}^{exp}}\right]$$

**$N^{exp}$** is a function of the **nominal MC** and the **fitting parameters**.

$$N_{is}^{exp} = \alpha\sum_{e}\left(R^{CCQE}N_{ise}^{CCQE}(P_{sc}) + R_e^{CC1\pi+}N_{ise}^{CC1\pi+}(P_{sc}) + N_{ise}^{Bkgd}(P_{sc})\right)$$

**normal-ization**

**Sum over bins of true $E_\nu$**

**# CCQE events with $E_\nu$ in bin *e* in bin *i*, sample *s* after scaling the distribution by Psc.**

**Similarly for CC1π+ and Bkgd events**

**$R_e^{CC1\pi+}$**: reweights $CC1\pi^+$ interactions in $E_\nu$ bin e

**$R^{CCQE}$**: reweights CCQE interactions

**Psc**: muon momentum scaling $p_\mu' = p_\mu/Psc$

# Cross-Check Analysis Results

| Energy Range (GeV) | Cross Section Ratio $R_e = \frac{\sigma_e^{CC1\pi^+}}{\sigma_e^{CCQE}}$ |
|---|---|
| >0.00 | $0.735 \pm 0.194(\text{fit})^{+0.076}_{-0.103}(\text{nucl})^{+0.078}_{-0.073}(\text{syst})$ |
| 0.00-1.35 | $0.403 \pm 0.173(\text{fit})^{+0.087}_{-0.072}(\text{nucl})^{+0.128}_{-0.093}(\text{syst})$ |
| 1.35-1.72 | $1.023 \pm 0.281(\text{fit})^{+0.072}_{-0.217}(\text{nucl})^{+0.107}_{-0.141}(\text{syst})$ |
| 1.72-2.22 | $1.006 \pm 0.334(\text{fit})^{+0.210}_{-0.064}(\text{nucl})^{+0.245}_{-0.170}(\text{syst})$ |
| >2.22 | $1.444 \pm 0.470(\text{fit})^{+0.207}_{-0.285}(\text{nucl})^{+0.332}_{-0.462}(\text{syst})$ |

**INCLUSIVE ($CC1\pi^+$)**

| Energy Range (GeV) | Cross Section Ratio $R_e = \frac{\sigma_e^{CCp\pi^+}}{\sigma_e^{CCQE}}$ |
|---|---|
| >0.00 | $0.556 \pm 0.145(\text{fit})^{+0.079}_{-0.072}(\text{nucl})^{+0.086}_{-0.106}(\text{syst})$ |
| 0.00-1.35 | $0.331 \pm 0.151(\text{fit})^{+0.113}_{-0.035}(\text{nucl})^{+0.092}_{-0.097}(\text{syst})$ |
| 1.35-1.72 | $0.760 \pm 0.206(\text{fit})^{+0.068}_{-0.160}(\text{nucl})^{+0.102}_{-0.170}(\text{syst})$ |
| 1.72-2.22 | $0.711 \pm 0.238(\text{fit})^{+0.182}_{-0.021}(\text{nucl})^{+0.206}_{-0.158}(\text{syst})$ |
| >2.22 | $0.846 \pm 0.319(\text{fit})^{+0.185}_{-0.097}(\text{nucl})^{+0.303}_{-0.410}(\text{syst})$ |

**EXCLUSIVE ($CCp\pi^+$)**

# Scaling

Polystyrene ($C_8H_8$) has 56 protons and 48 neutrons.

Need to know the factor by which we can scale the result down to take this into account.

Inclusive ratio:

$$\frac{\sigma(\nu p \to \mu^- p\pi^+) + \sigma(\nu n \to \mu^- n\pi^+)}{\sigma(\nu n \to \mu^- p)} = f \times \frac{\sigma(\nu(C_8H_8) \to \mu^- p\pi^+) + \sigma(\nu(C_8H_8) \to \mu^- n\pi^+)}{\sigma(\nu(C_8H_8) \to \mu^- p)}$$

$$S_p \equiv \frac{\sigma(\nu(C_8H_8) \to \mu^- p\pi^+)}{\sigma(\nu(C_8H_8) \to \mu^- p\pi^+) + \sigma(\nu(C_8H_8) \to \mu^- n\pi^+)}$$

$$S_n \equiv \frac{\sigma(\nu(C_8H_8) \to \mu^- n\pi^+)}{\sigma(\nu(C_8H_8) \to \mu^- p\pi^+) + \sigma(\nu(C_8H_8) \to \mu^- n\pi^+)}$$

$$f = (48/56)S_p + S_n$$

$$f = 0.9$$

Exclusive ratio:

$$R_{measured}(exc) = \frac{\sigma(\nu(C_8H_8) \to \mu^- p\pi^+)}{\sigma(\nu(C_8H_8) \to \mu^- p)} = \frac{56\sigma(\nu p \to \mu^- p\pi^+)}{48\sigma(\nu n \to \mu^- p)}$$

$$f = 6/7$$