Measurement of the Single Charged Pion Production Cross Section in Charged-Current Neutrino-Carbon Interactions

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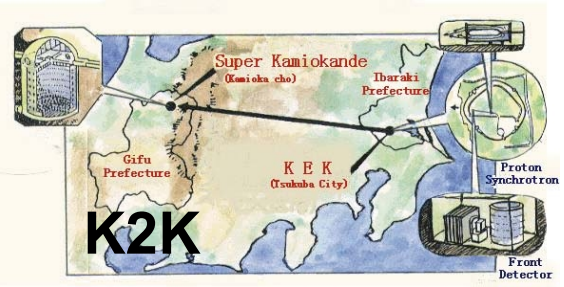
June 28, 2007



STONY BROOK
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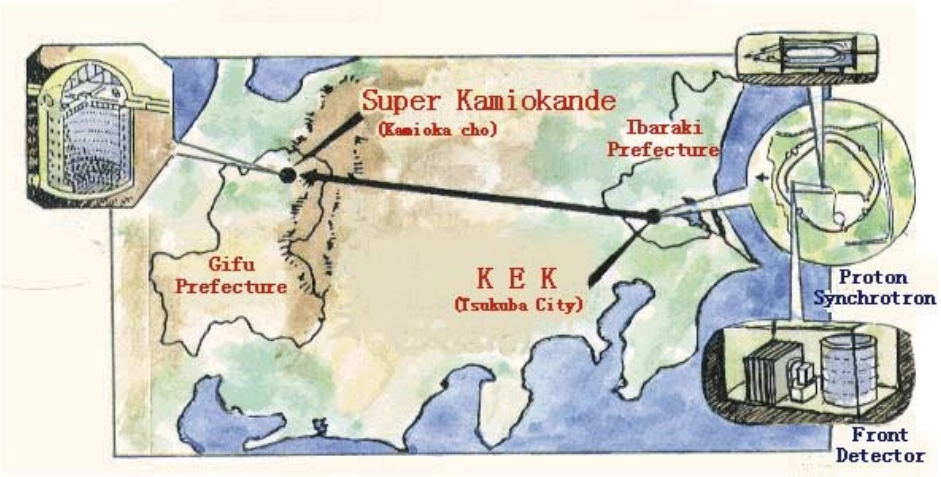
Outline

- Intro to the K2K experiment and motivation for neutrino cross section measurements
- neutrino interactions
- description of K2K and the SciBar detector
- description of analysis method
- summary of results and outlook

The K2K Experiment

Goal: To confirm the observation of atmospheric neutrino oscillation using accelerator-produced neutrinos

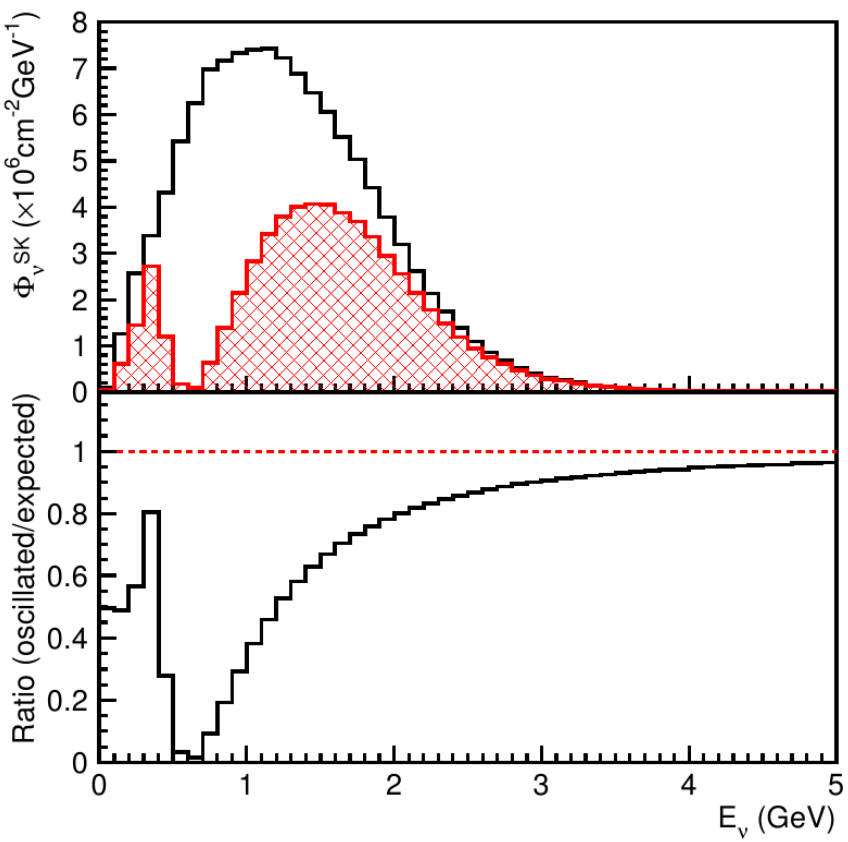


- muon neutrinos w/ average energy 1.3 GeV produced by accelerator at KEK and detected by a suite of near detectors
- neutrinos detected at Super-Kamiokande (SK) 50 kt water Cherenkov detector 250 km away
- June 1999 – November 2004
- Final oscillation results published in 2006 [Phys. Rev. D 74, 072003 (2006)]

Oscillation Signature in K2K

$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2\ (\mathrm{eV}^2) L\ (\mathrm{km})}{E_\nu\ (\mathrm{GeV})}\right)$$

L = 250 km, probability is E_ν–dependent



1) measure interaction rate and energy spectrum at near detector
2) extrapolate to SK
3) measure interaction rate and energy spectrum at SK
4) compare SK measurement with extrapolation
5) oscillation signature: deficit of muon neutrino interactions and distortion of energy spectrum with respect to extrapolation

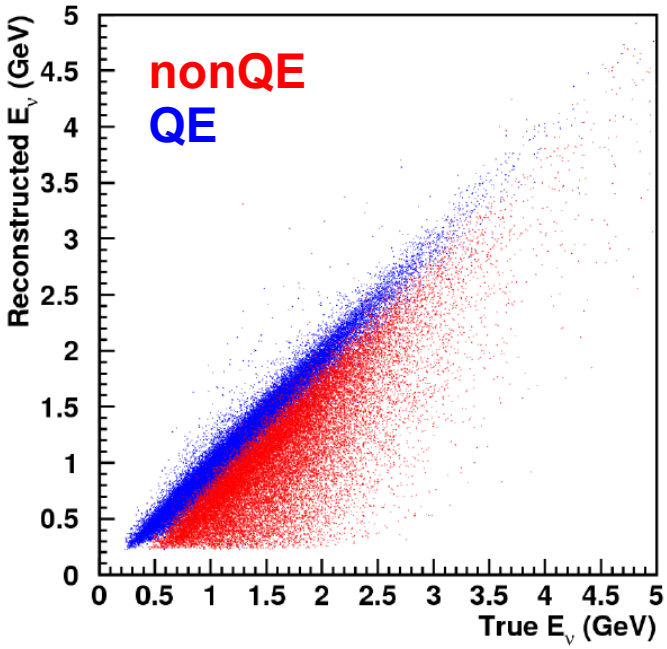
Motivation for Cross Section Studies

To measure energy spectrum at SK, sample of single muon events is used. Energy reconstructed assuming quasi-elastic.

QE: $\nu_\mu n \rightarrow \mu^- p$

$$E_\nu = \frac{E_\mu m_n - \frac{1}{2} m_\mu^2}{m_n - E_\mu + p_\mu \cos\theta_\mu}$$

BUT, not all single muon events are QE → many nonQE interactions contaminate the sample.

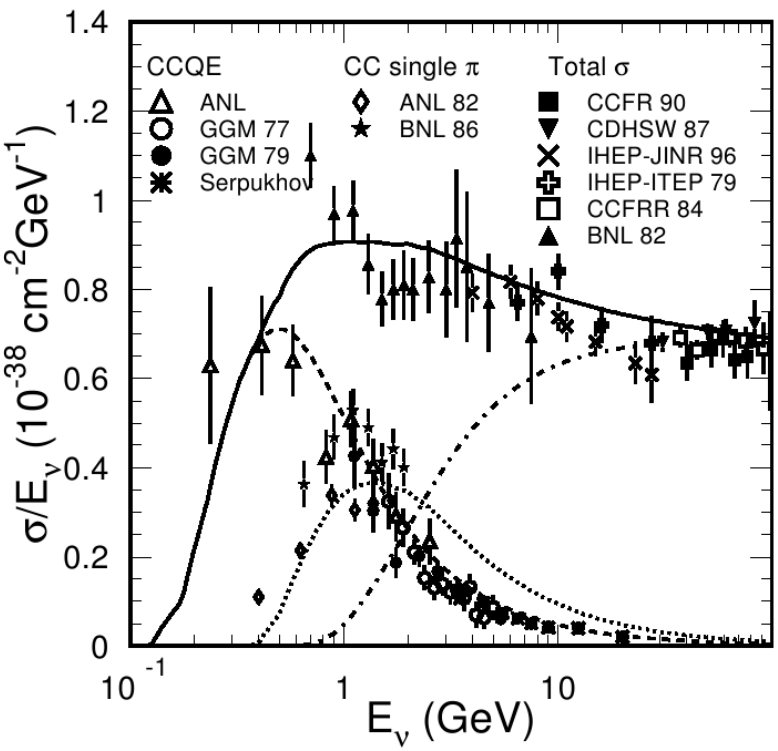


To predict energy spectrum at SK, need to predict number of nonQE interactions in single muon sample.

Motivation for Cross Section Studies

Current and future oscillation experiments planning on making high statistics measurements of oscillation parameters.

Systematic errors due to cross section uncertainties are becoming significant!



Expected oscillation signal for many experiments is near 1 GeV – cross section measurements especially important in this region.

Significant contributions from quasi-elastic, pion production from resonance, and DIS.

Neutrino Interactions

Charged-current (CC)

- quasi-elastic (QE) $\nu_\mu n \rightarrow \mu^- p$
- single pion production via resonance excitation (CC1π)

$$\nu_\mu N \rightarrow \mu^- N^*, N^* \rightarrow N' \pi$$

- deep-inelastic scattering (CC DIS) $\nu_\mu N \rightarrow \mu^- X$
- coherent pion production (CC coherent) $\nu_\mu A \rightarrow \mu^- A \pi$

(negligible for K2K)

Neutral-current (NC)

- elastic $\nu_\mu N \rightarrow \nu_\mu N$
- NC1π $\nu_\mu N \rightarrow \mu^- N^*, N^* \rightarrow N' \pi$
- DIS $\nu_\mu N \rightarrow \nu_\mu X$
- coherent π $\nu_\mu A \rightarrow \nu_\mu A \pi$

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%**

CC Coherent Pion Production

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

Event Selection:

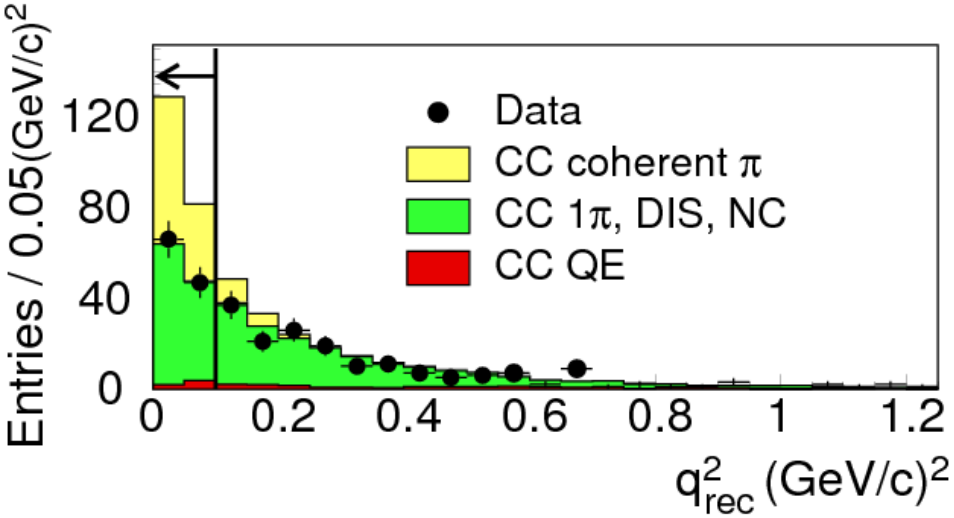
CC, 2 tracks, nonQE-like

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)

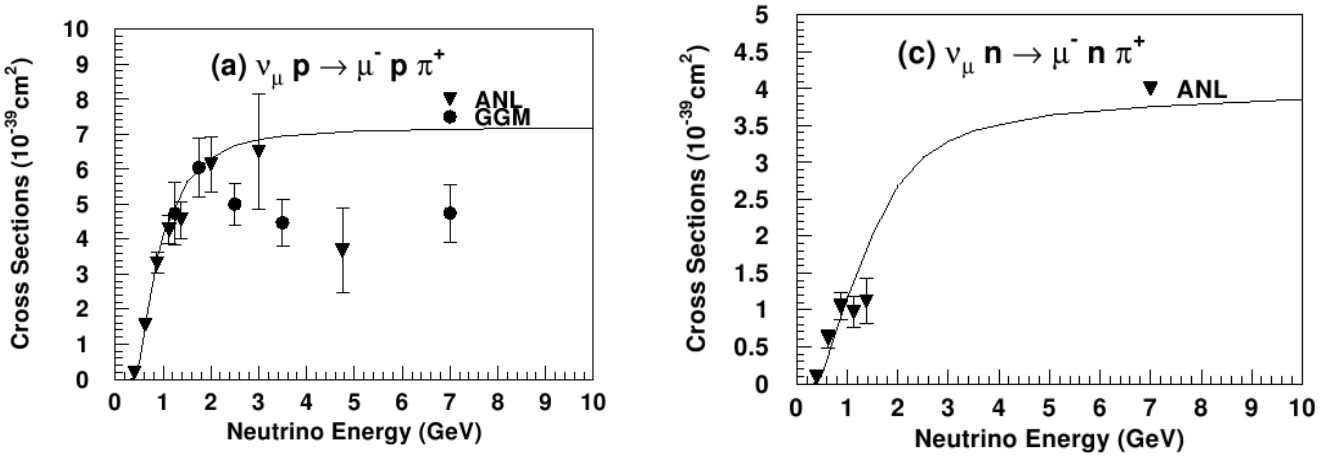
CC1π Interactions

Single pions via resonance production in CC ν_μ interactions:

$$\left.\begin{array}{ll}\nu_\mu p \rightarrow \mu^- p\pi^+ & (\mathrm{CCp}\pi^+)\\ \nu_\mu n \rightarrow \mu^- n\pi^+ & (\mathrm{CCn}\pi^+)\end{array}\right\} \mathrm{CC1}\pi^+$$

$$\nu_\mu n \rightarrow \mu^- p\pi^0 \quad (\mathrm{CCp}\pi^0)$$

measurement of π^+ modes



Simulated based on model by Rein and Sehgal (1981):

- Cross section for each *μNπ* final state is calculated as a coherent superposition of all the possible contributing resonances, W<2 GeV/c^2
- phenomenological parameter: axial-vector mass, M_A, set at 1.1 GeV/c^2 based on K2K data

$$F_A(q^2) \propto (1 - q^2/M_A^2)^{-2}$$

Other Neutrino Interactions

quasi-elastic and elastic scattering based on Llewellyn Smith model (1972), parameter 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.

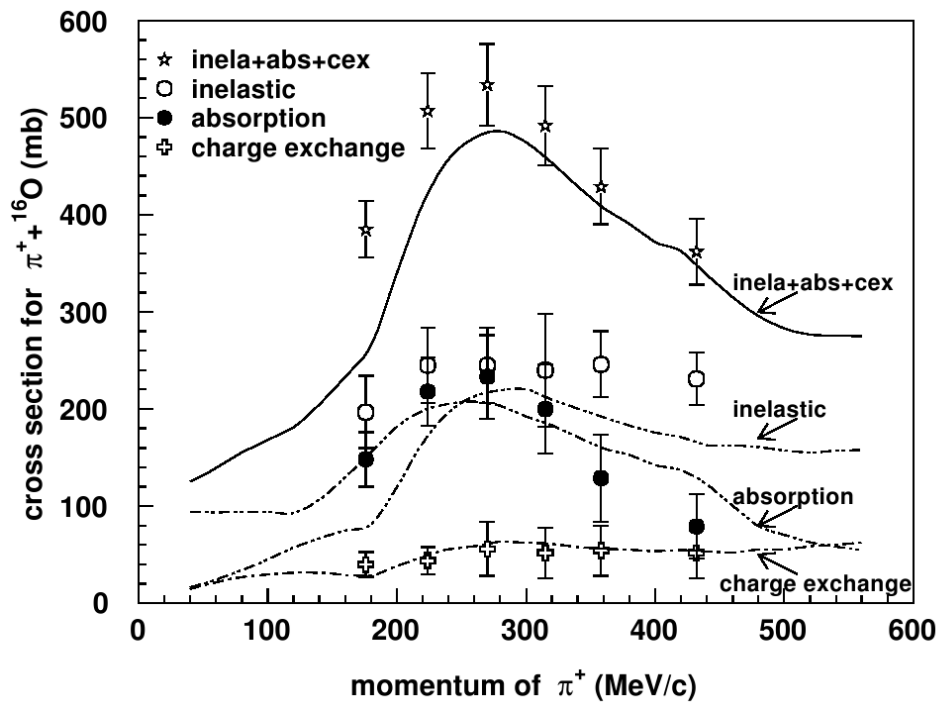
NC coherent pion production based on Rein and Sehgal model with correction by Marteau et al.

single K and η production also simulated based on Rein and Sehgal resonance model

Nuclear Interactions

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

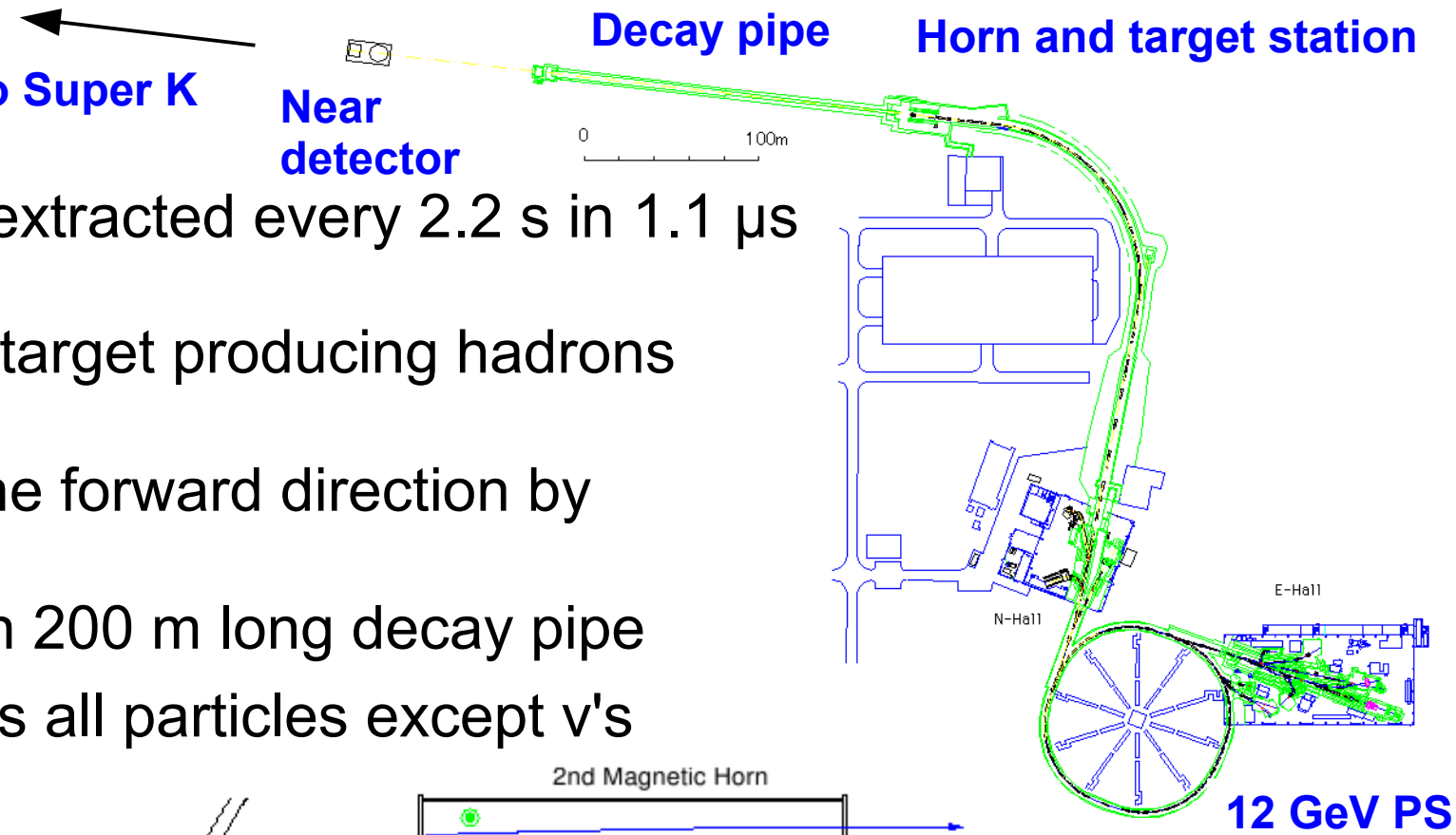
Relativistic Fermi gas model. Momentum distribution of nucleons is flat up to fixed Fermi surface momentum (225 MeV/c for C). Pauli exclusion effect is taken into account.



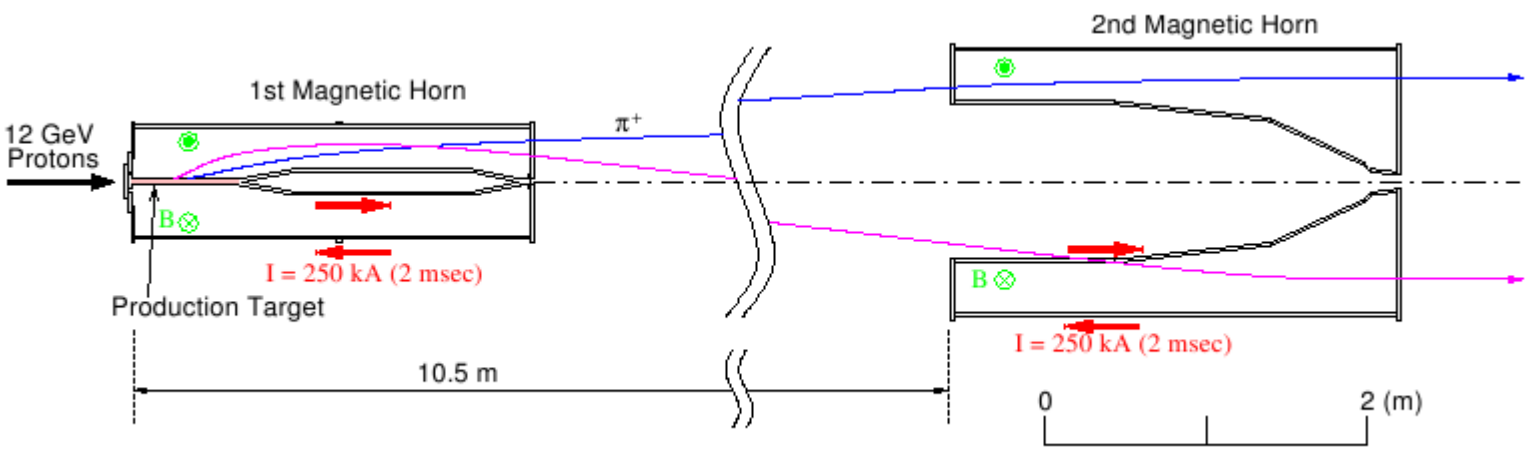
Interactions of outgoing particles inside the nucleus:

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

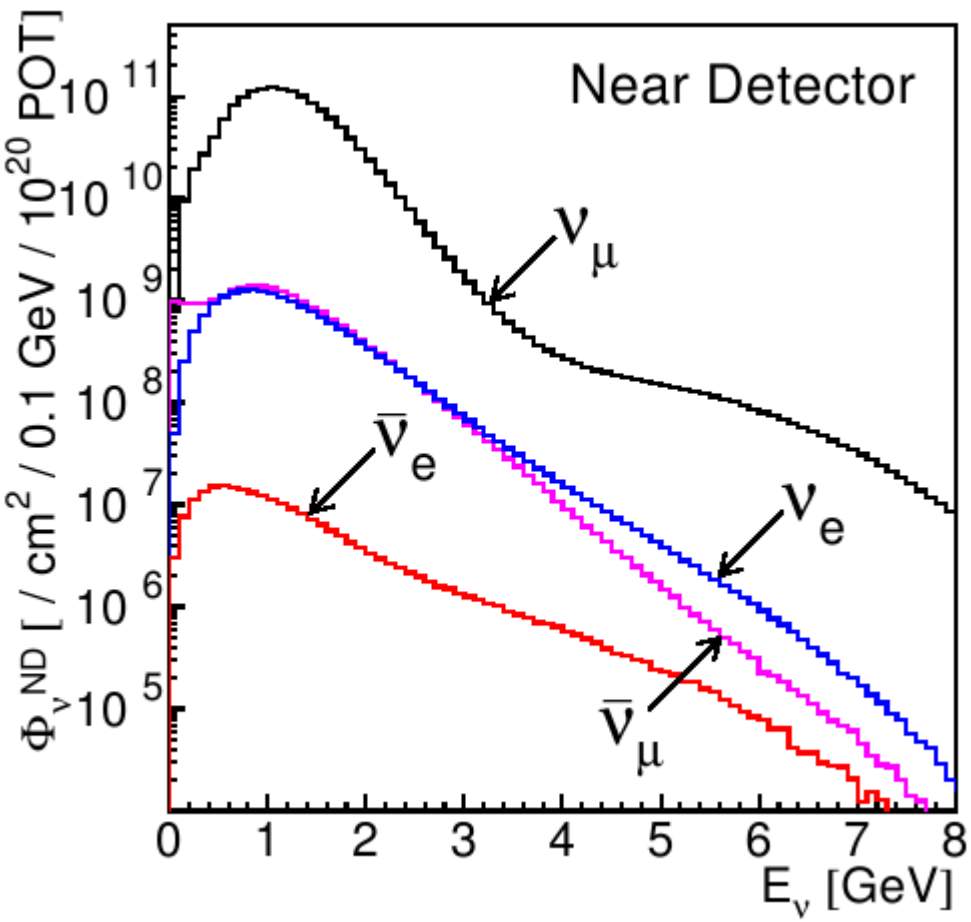
K2K Neutrino Beam



- 12 GeV protons extracted every 2.2 s in 1.1 μs "spill"
- protons hit an Al target producing hadrons (mainly π's)
- π^+'s focused in the forward direction by magnetic horns
- $\pi^+ \rightarrow \mu^+ \nu_\mu$ decay in 200 m long decay pipe
- beam dump stops all particles except ν's



K2K Neutrino Beam



beam is 97.3% pure muon neutrino at near detector

mean neutrino energy = 1.3 GeV

Beam Monitors:

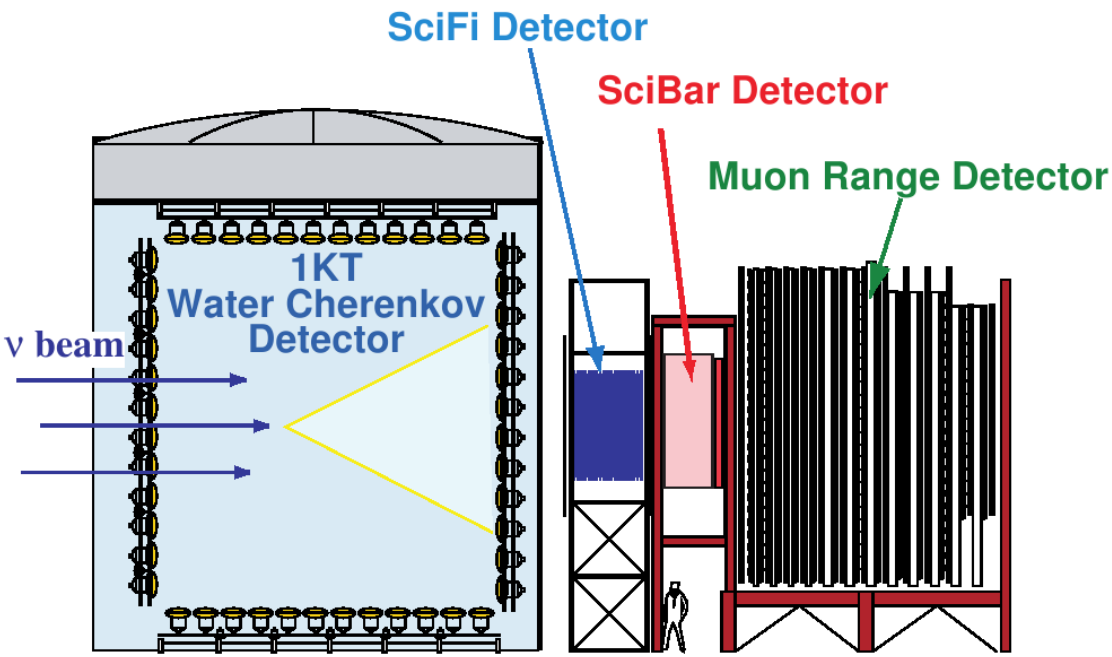
- check intensity, transportation efficiency, position and profile of proton beam

- profile of muons that penetrate the beam dump (p_μ>5.5 GeV/c) is monitored

- pion monitor installed occasionally just past horns to measure direction, momentum of pions

→ neutrino beam direction is controlled within +- 1 mrad

K2K Near Neutrino Detectors



set of near detectors 300 m downstream from target

to measure direction, flux, and energy spectrum of neutrinos before oscillation

1 kiloton water Cherenkov detector (**1KT**): mini Super-K

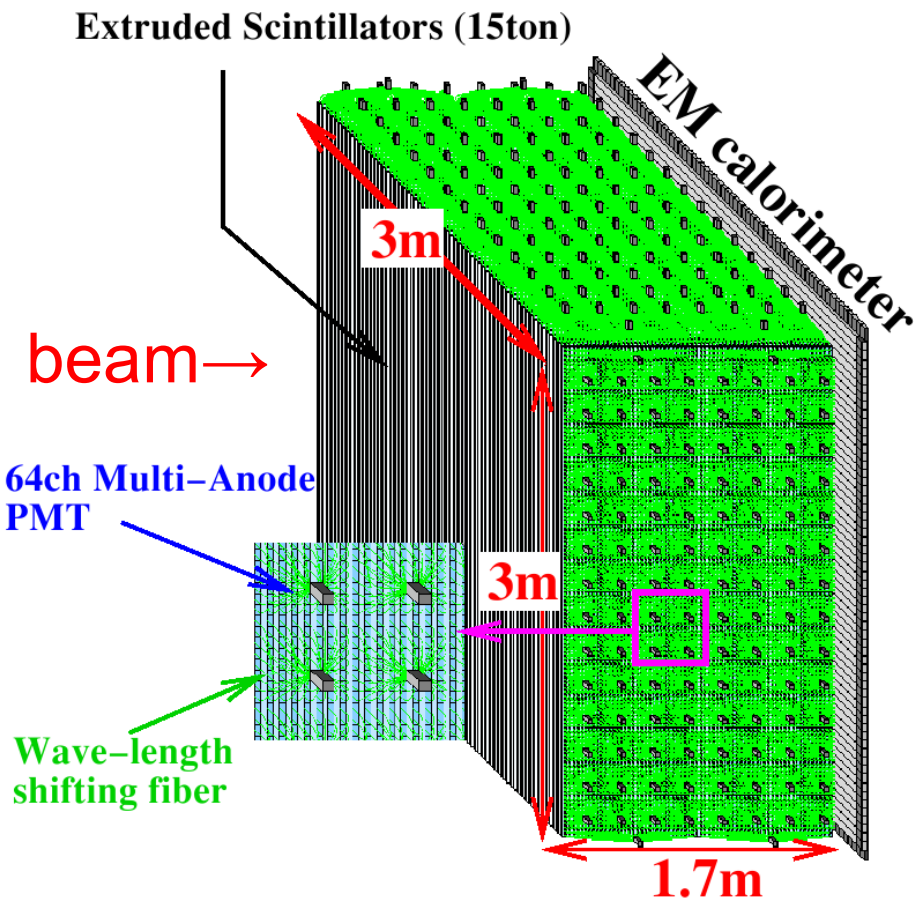
Scintillating Fiber detector (**SciFi**): scintillating fibers with water target

Lead Glass calorimeter (**LG**): for K2K-I only

Scintillating Bar detector (**SciBar**): scintillator bars, for K2K-II only

Muon Range Detector (**MRD**): alternating layers of iron and drift tubes

SciBar



- 14,848 **Sci**ntillating **Bar**s
- material: polystyrene (C_8H_8)
- fully active detector
- light guided by WLS fibers to 64-channel MAPMTs
- volume: 1.7 x 3 x 3 m^3 (~15 tons)
- fiducial: 1.35 x 2.6 x 2.6 m^3 (~9 tons)

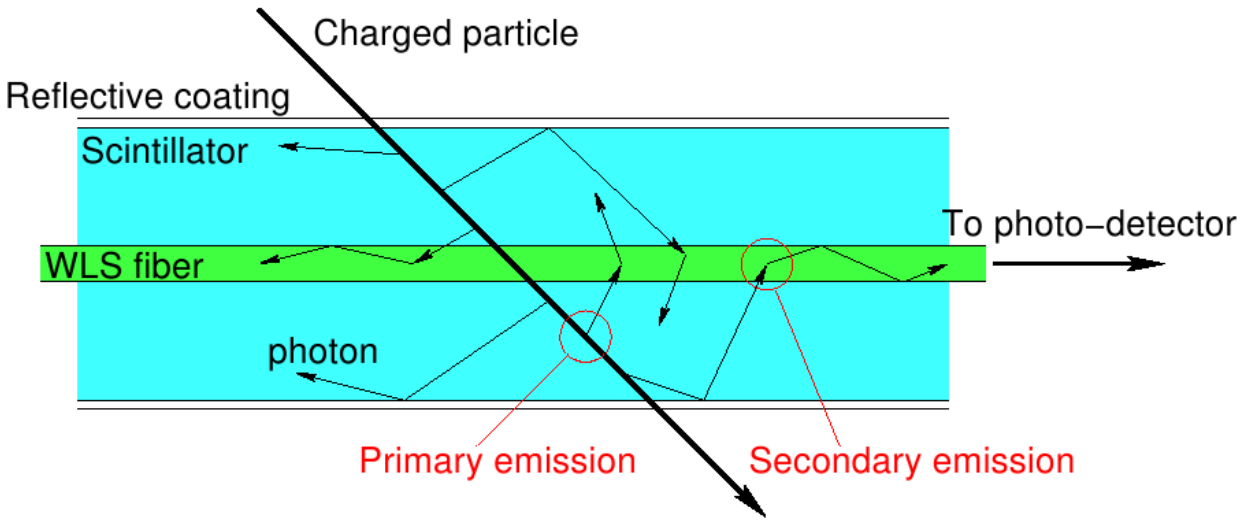
- 64 layers along the beam direction
- each layer: x plane and y plane,
- plane is 116 bars

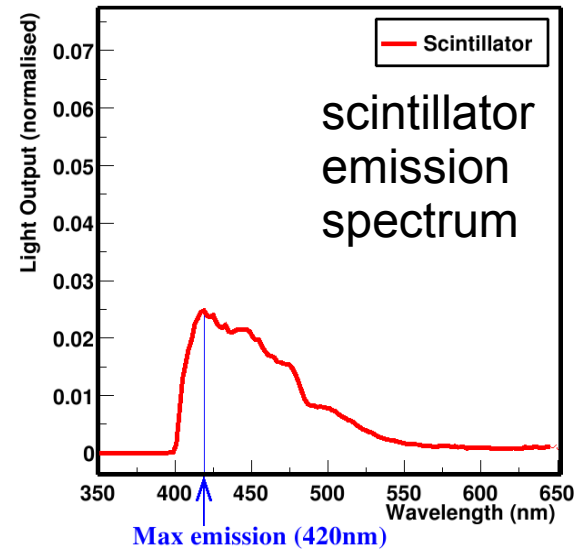
Upgrade to near detector (replaced a lead glass detector)

Oct. 2003 – Nov. 2004

- downstream of SciBar is Electron Catcher (EC) made of lead and scintillating fibers

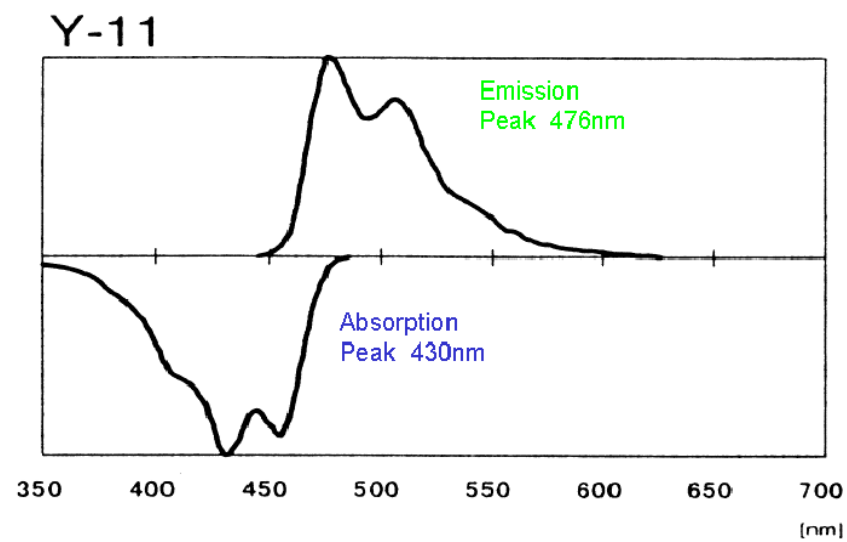
SciBar – Bars and WLS Fibers





- rectangular bars: 2.5 x 1.3 x 300 cm^3
- polystyrene (C_8H_8), TiO_2 coating
- 1.8 mm diameter hole for fiber

- 1.5 mm diameter WLS fiber
- Kuraray Y11(200) MS
- polystyrene core, inner cladding of acrylic and outer cladding of polyfluor

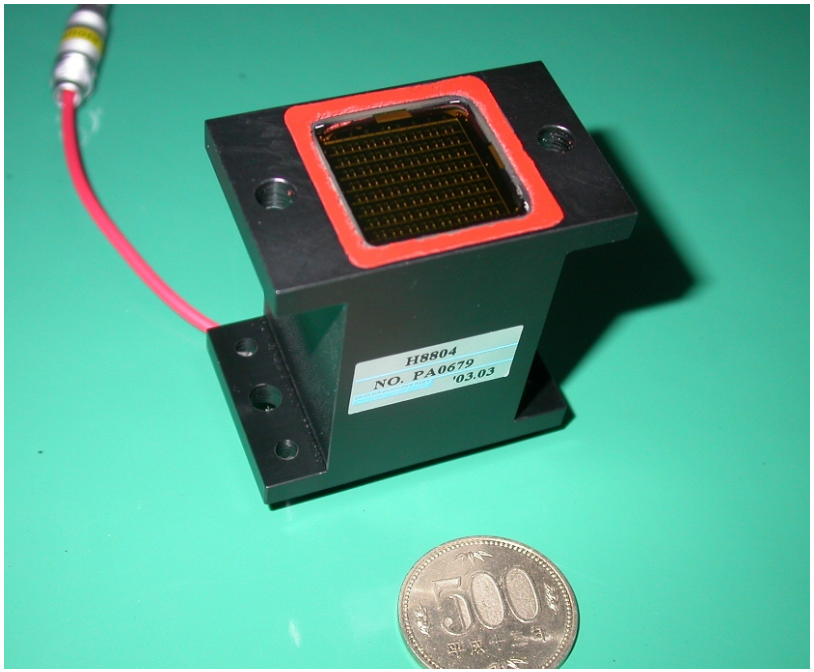


fiber emission and absorption spectrum

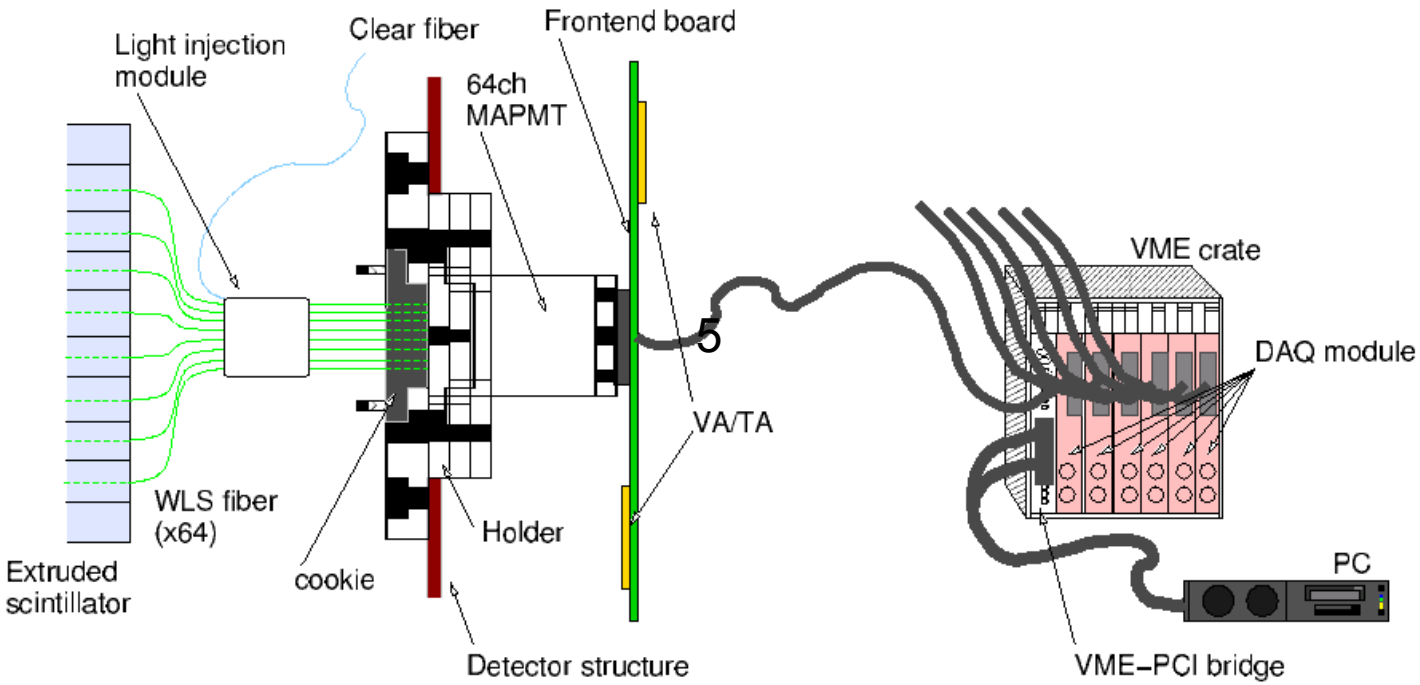
SciBar - MAPMTs

Hamamatsu H8804 multi-anode PMT

- 64 channels in 8x8 array
- each pixel 2 x 2 mm^2
- typical gain $3x10^5$ at ~800V
- bialkali cathode sensitive to wavelengths 300-650 nm
- fibers mounted to PMT face using plastic fixture shown below, 1 fiber per MAPMT pixel



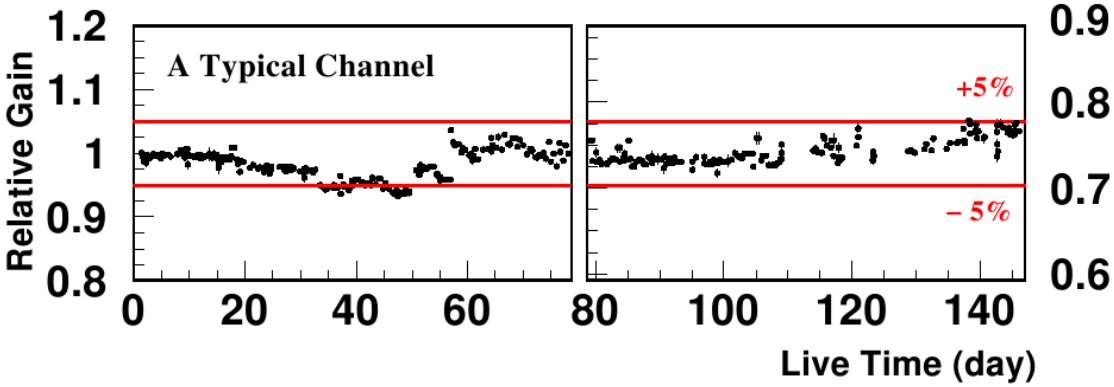
SciBar - Readout



Charge info for each channel
Timing info for groups of 32 channels

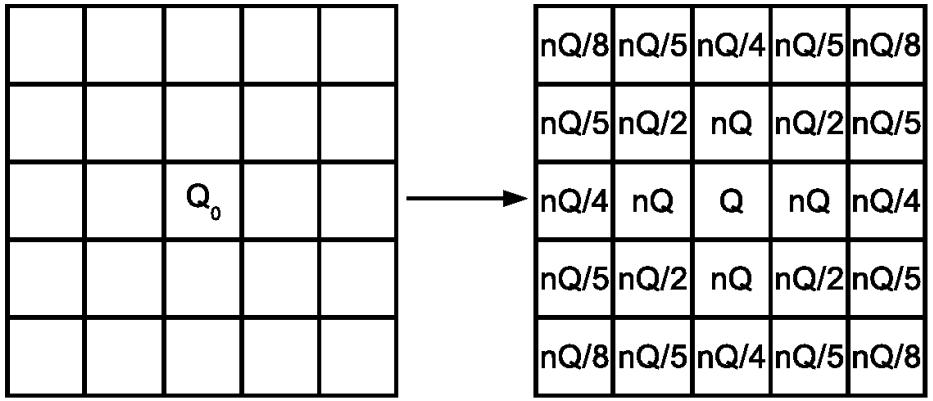
timing resolution 1.3 ns
noise level 0.3 pe

Gain Monitoring:



Detector Simulation

Crosstalk in the MAPMT ~3% in neighboring channels



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

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

Attenuation length of light in fiber ~350 cm by measurement

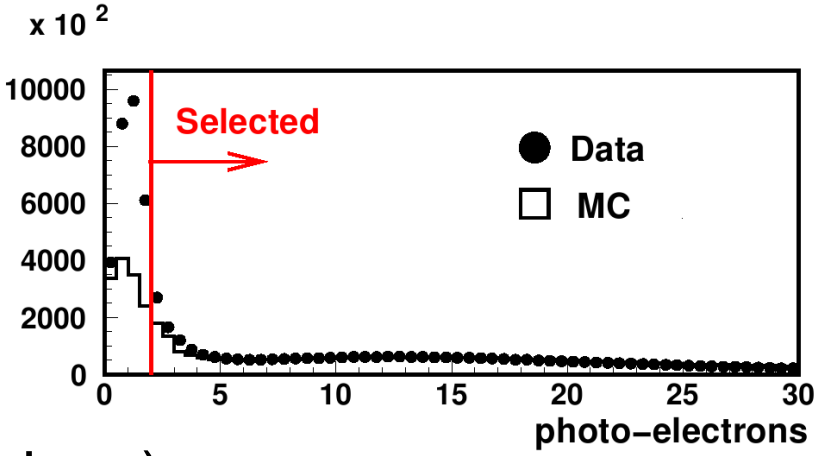
Light yield calibration measured for each bar ~20 p.e. for MIP

travel time for light in fiber: 16 ns/cm

PMT energy resolution of 40%

Event Reconstruction

Crosstalk correction to both data and MC to reduce the number of hits from crosstalk before tracking.



Hit Threshold:
only hits with > 2 pe are used

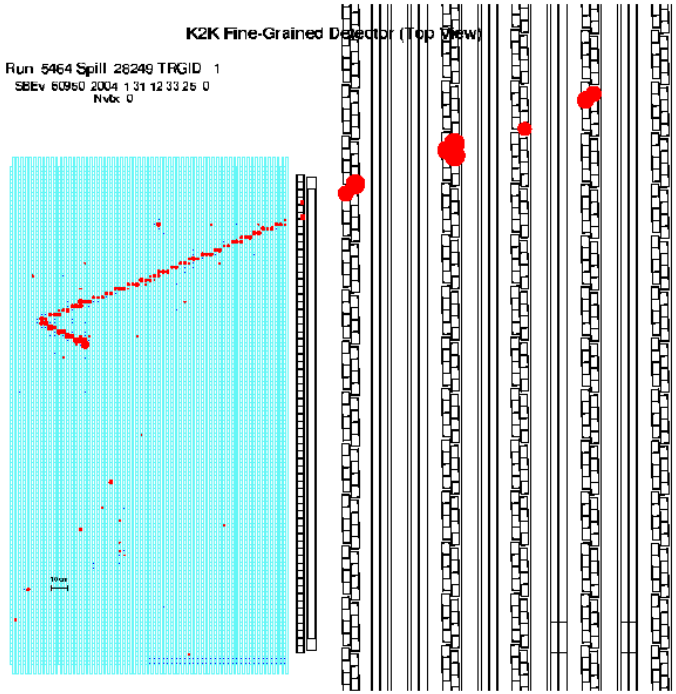
Tracking:
SciBar has TWO 2D views (x-z and y-z)
- Cellular automaton tracking algorithm applied separately to each view - requires hits in 3 consecutive layers (8 cm → 450 MeV/c for proton)
- 3D reconstruction by matching z-track edges and timing of 2D tracks

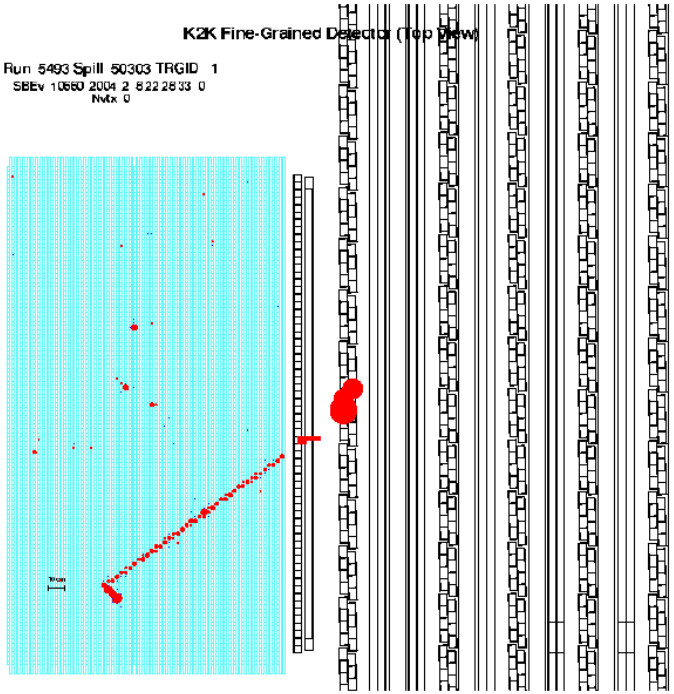
reconstruction efficiency for single track passing through 4 or more layers (10 cm) is 99%
(efficiency is lower for multiple tracks because of overlapping tracks in one or both views)

CC Event Selection

Select CC events by identifying the muon.

- match SciBar track to track or first layer hits in the MRD (momentum threshold 450 MeV/c)
- SciBar-MRD track is within the spill time and exits SciBar
- set of events where SciBar-MRD matched track is found is the MRD sample, our CC-enriched sample
- veto events if there is any hit in the first layer to reject incoming particles





Purity of CC events in the MRD sample is 96%

Muon Energy Reconstruction

muon energy reconstructed by range of SciBar-MRD track and expected dE/dx in SciBar, EC, and MRD

$$E_\mu = E_\mu^{SciBar} + E_\mu^{EC} + E_\mu^{MRD}$$
$$= L_{SciBar}(\frac{dE}{dx})_{SciBar} + L_{EC}(\frac{dE}{dx})_{EC} + E_\mu^{MRD}$$

dE/dx is 2.10 MeV/cm for SciBar and 11.25 MeV/cm for EC

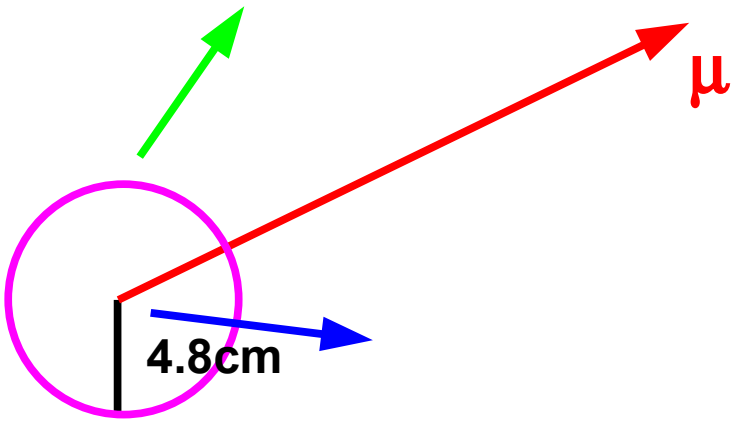
energy deposited in MRD from GEANT3-based range to energy lookup table, includes the muon mass

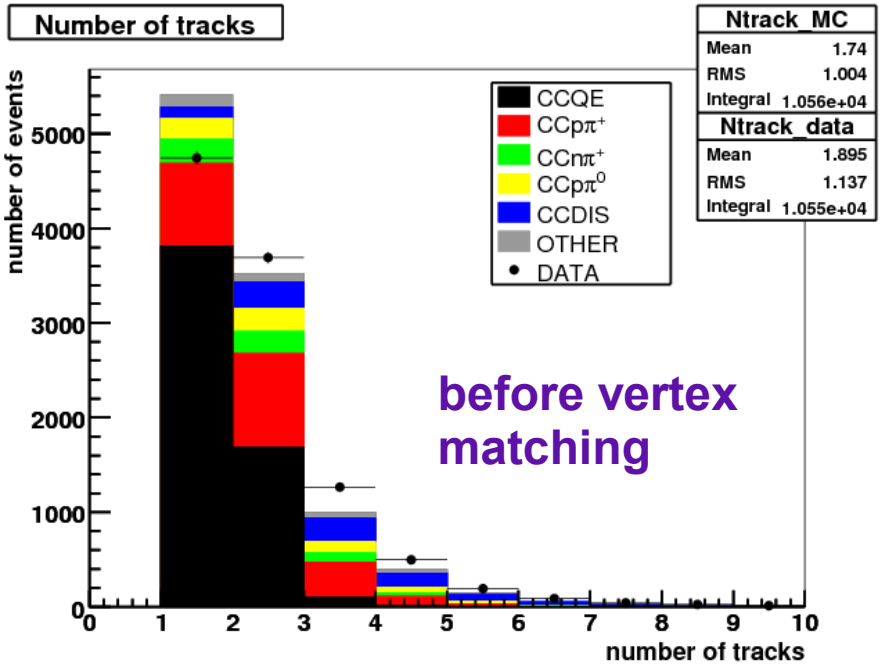
Momentum resolution ~ 90 MeV/c
Angular resolution ~ 1.4 degrees

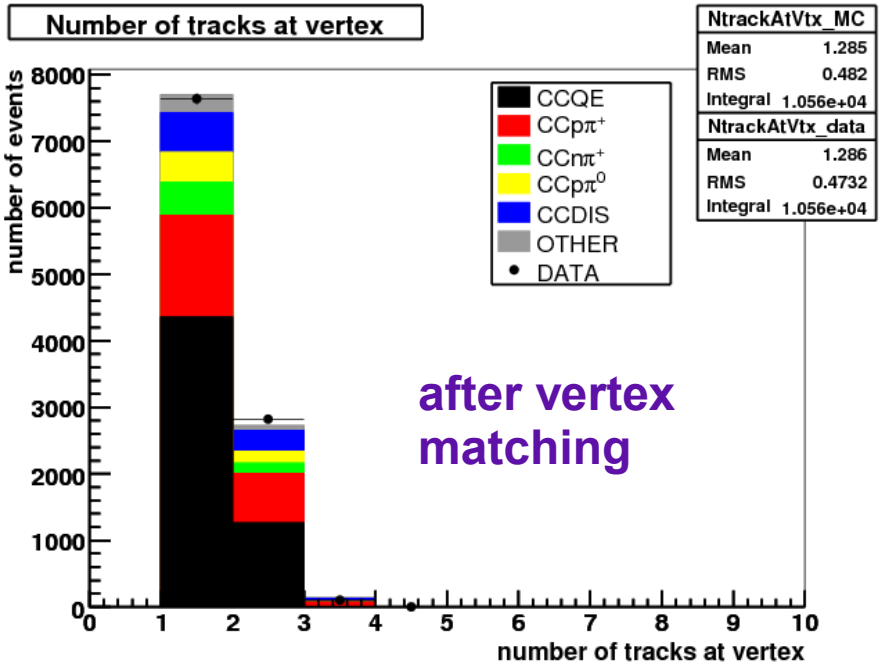
Vertex Matching

upstream edge of SciBar-MRD track is the reconstructed vertex

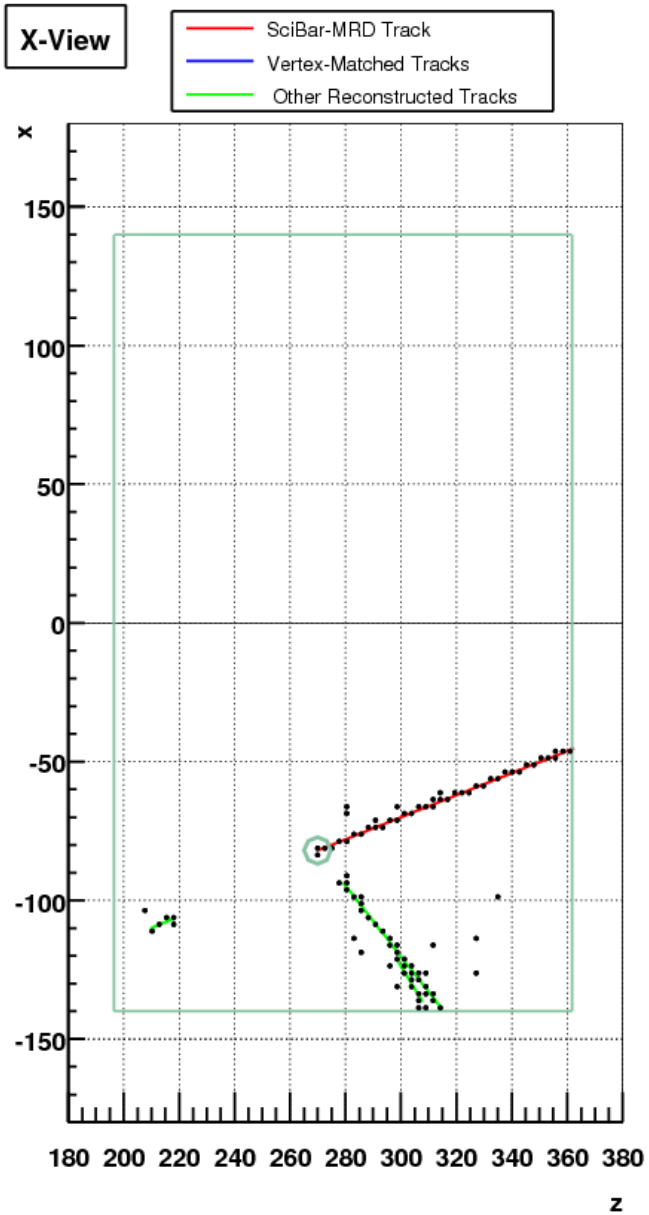
Vertex matching cut: consider tracks that are less than 4.8 cm from reconstructed vertex
(4.8 cm is 3σ in z, >5σ in x and y)



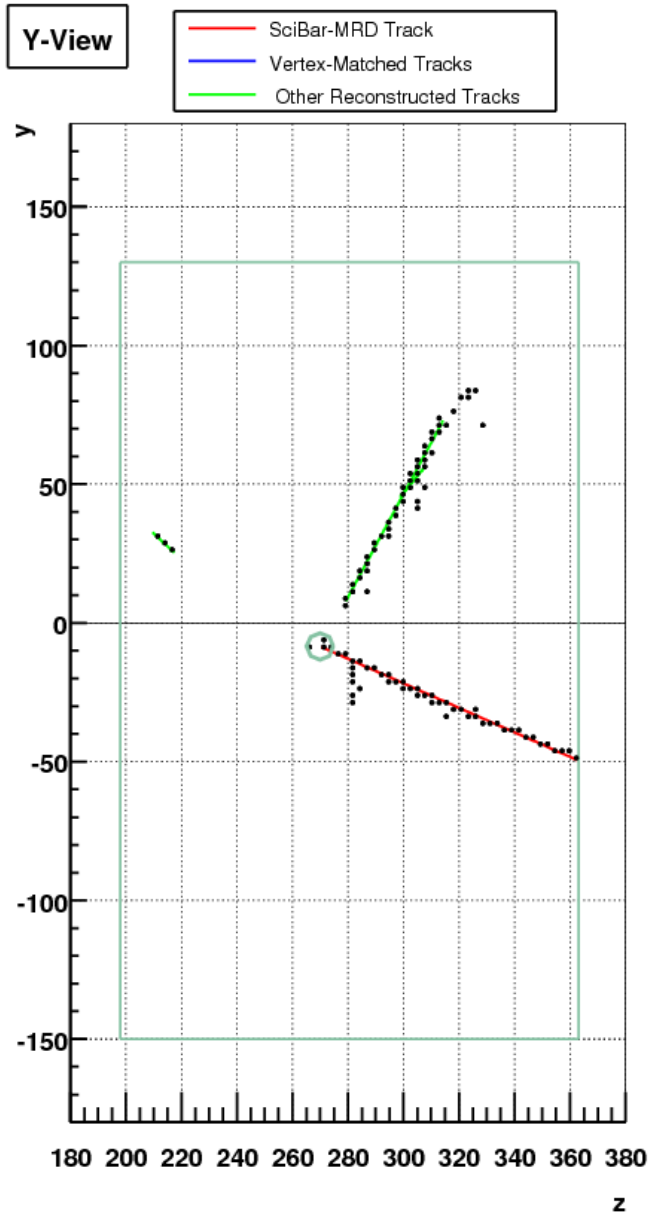




Vertex Matching



(top view)



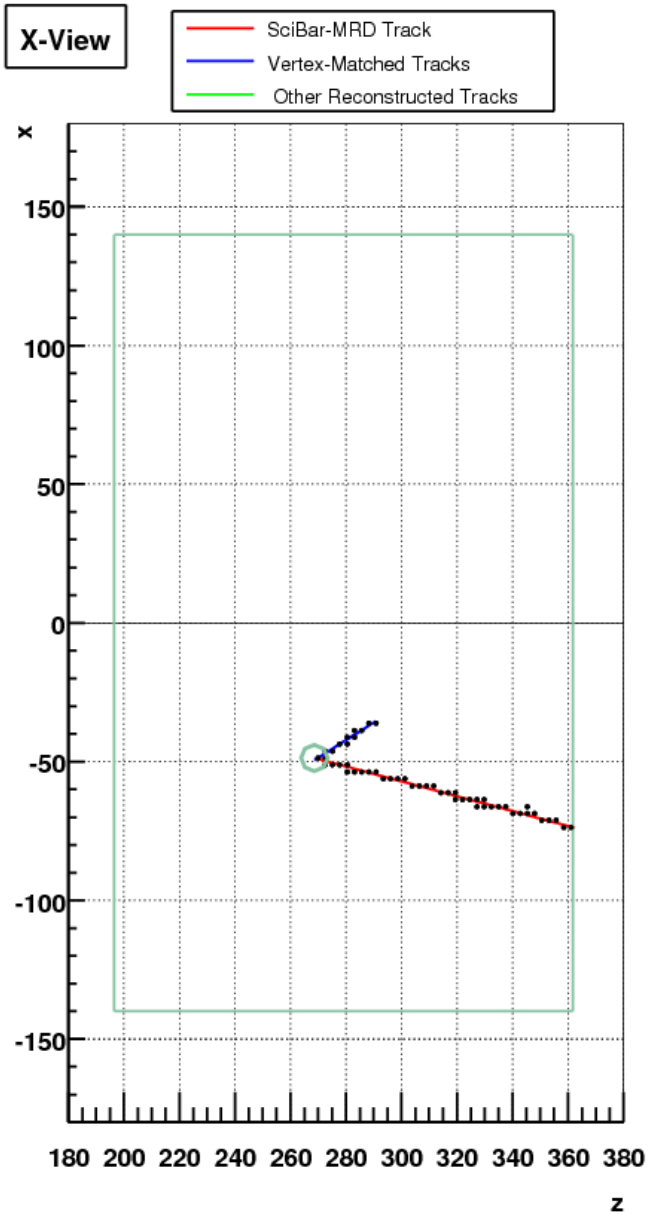
(side view)

SciBar-MRD track is in red

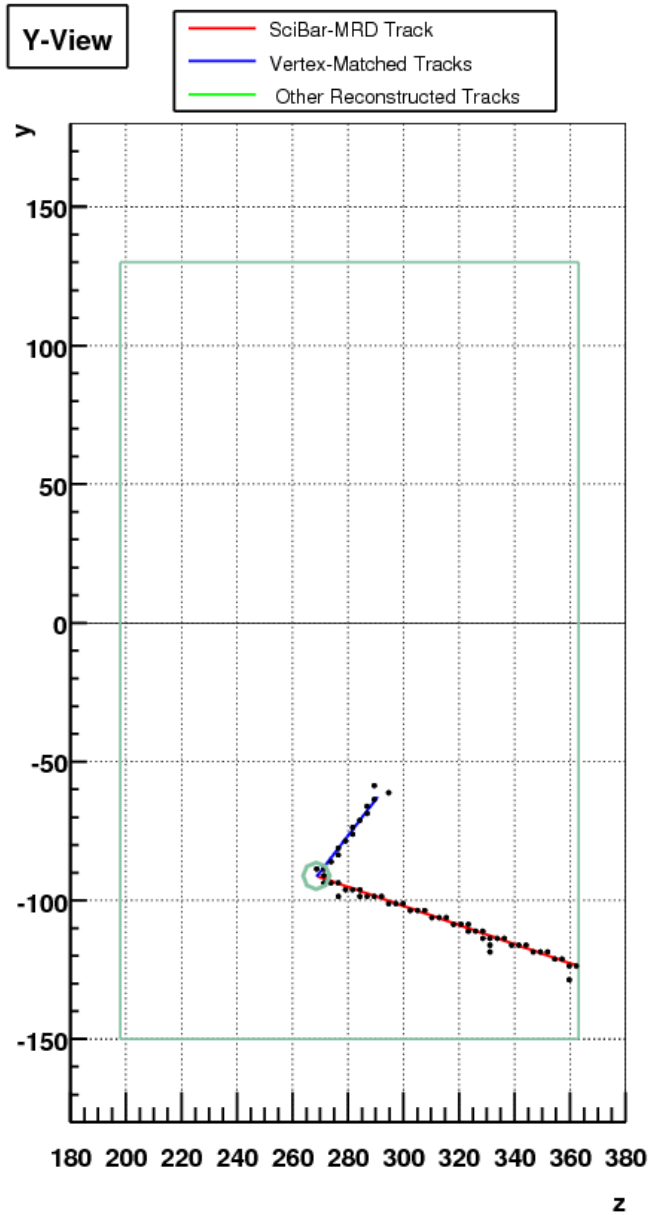
Before vertex matching:
4 tracks

After vertex matching:
1 track

Vertex Matching



(top view)



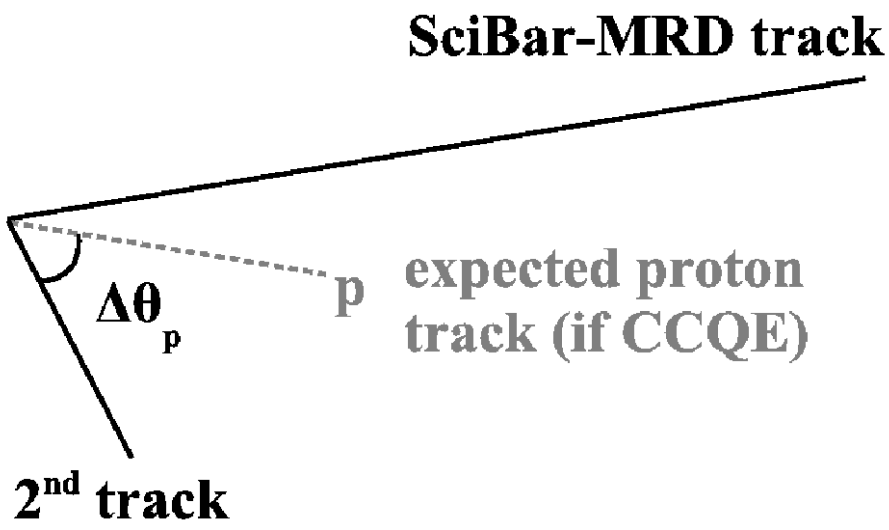
(side view)

SciBar-MRD track is in red

Before vertex matching:
2 tracks

After vertex matching:
2 tracks

QE/nonQE Separation

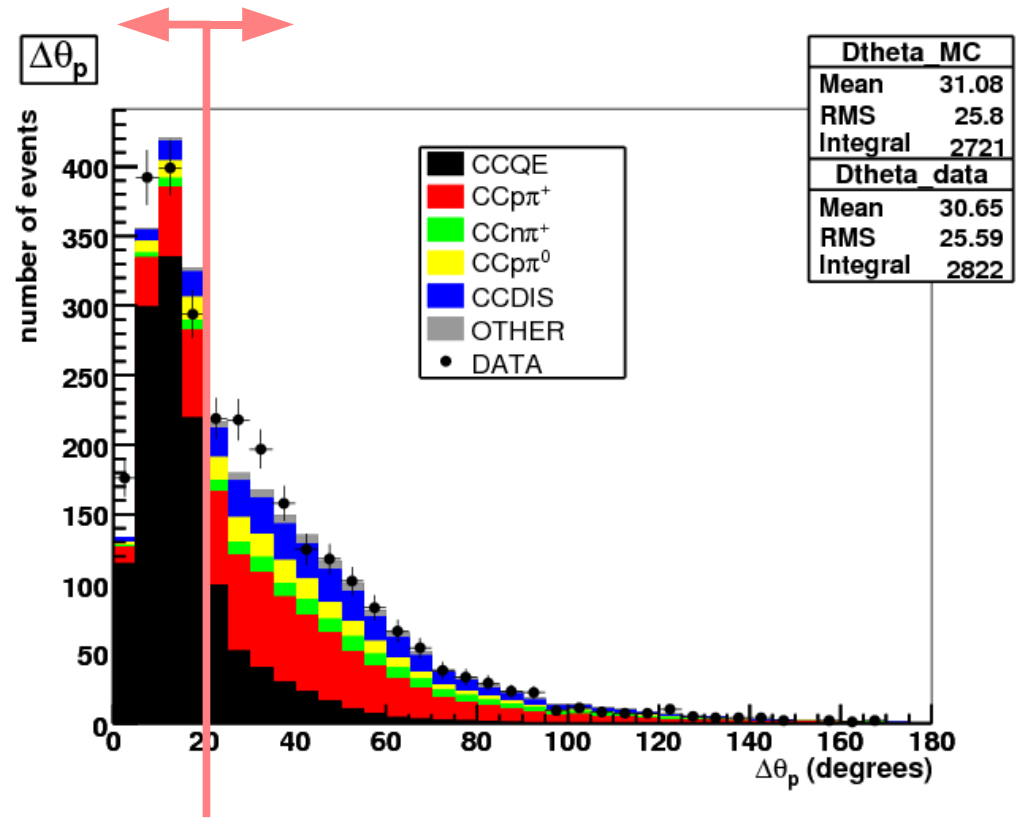


For 2 track events, divide into QE-like and nonQE-like based on direction of second track

$\Delta\theta_p$ = difference in expected proton direction and observed 2nd track direction

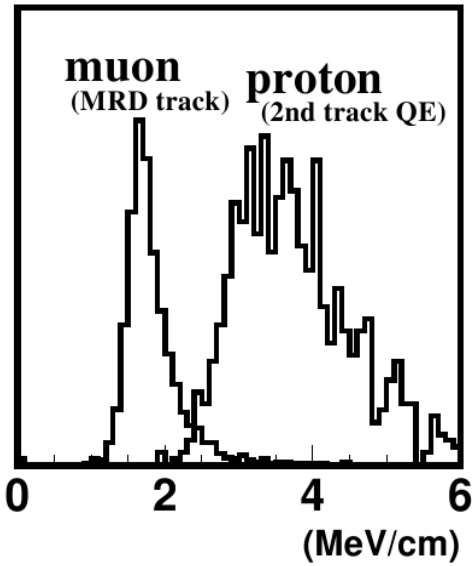
cut at 20 degrees

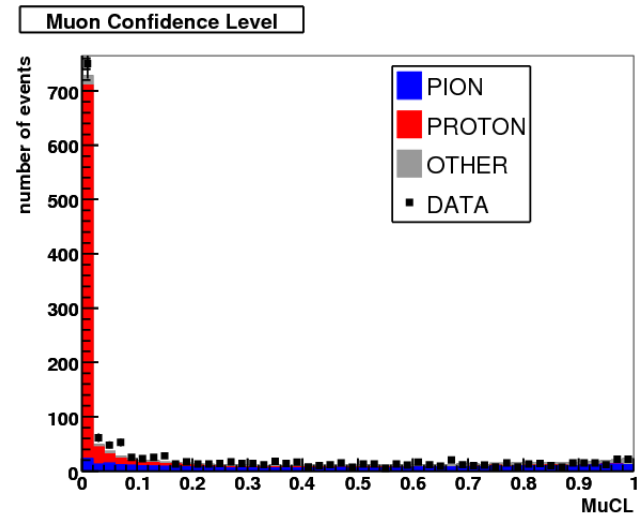
QE-like nonQE-like



Particle ID

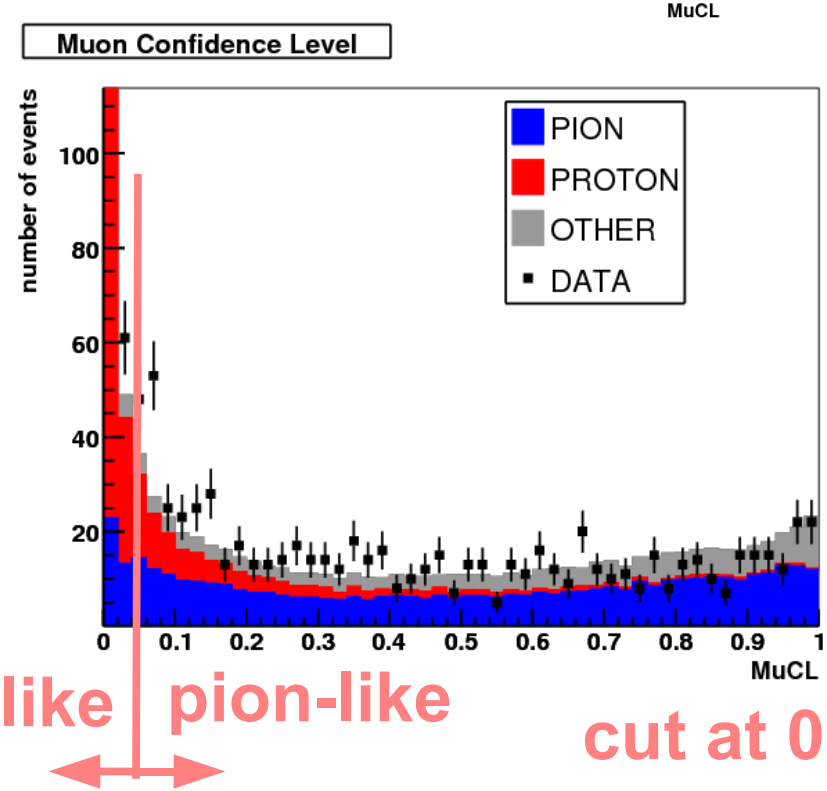
dE/dx for muons (MIPs) and protons clearly separated





For nonQE events, divide into proton-like and pion-like based on particle ID of second track

MuCL = muon likelihood variable based on energy deposited per plane



cut at 0.04

Analysis Overview

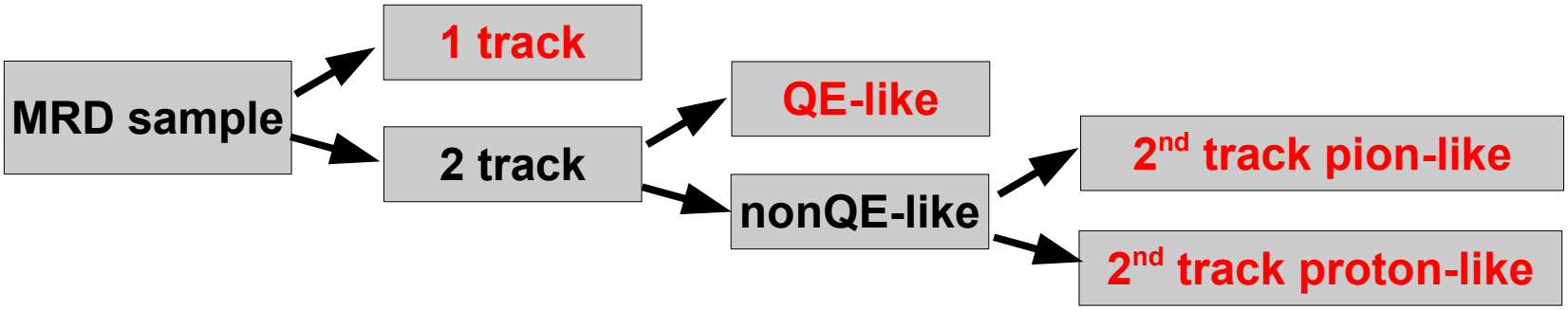
measurement of absolute neutrino flux has large uncertainties → we measure $CC1\pi^+$ cross section relative to the CCQE cross section

Analysis Strategy:

- bin the data based on muon kinematic variables
- perform maximum likelihood fit based on Poisson statistics
- fit gives cross sections of $CC1\pi^+$ and CCQE in data relative to nominal MC prediction
- cross section ratio is extracted from the results of the fit
- measure both the total cross section ratio for entire neutrino energy range and the energy-dependent cross section ratio.

Events Selected for Analysis

Sample	Data (# events)	MC (# events) (normalized)
MRD	10561 ± 103	10561 ± 17
1-track	7638 ± 87	7698 ± 14
2-track	2822 ± 53	2721 ± 8.5
2-track QE	1261 ± 36	1237 ± 5.8
2-track nonQE pion	750 ± 27	707 ± 4.3
2-track nonQE proton	811 ± 28	777 ± 4.5
3-track	100 ± 10	138 ± 1.9
4+-track	1.0 ± 1.0	4.1 ± 0.3



Events Selected for Analysis

Data and MC divided into samples: **1-track, 2-track QE, 2-track nonQE pion, and 2-track nonQE proton.**

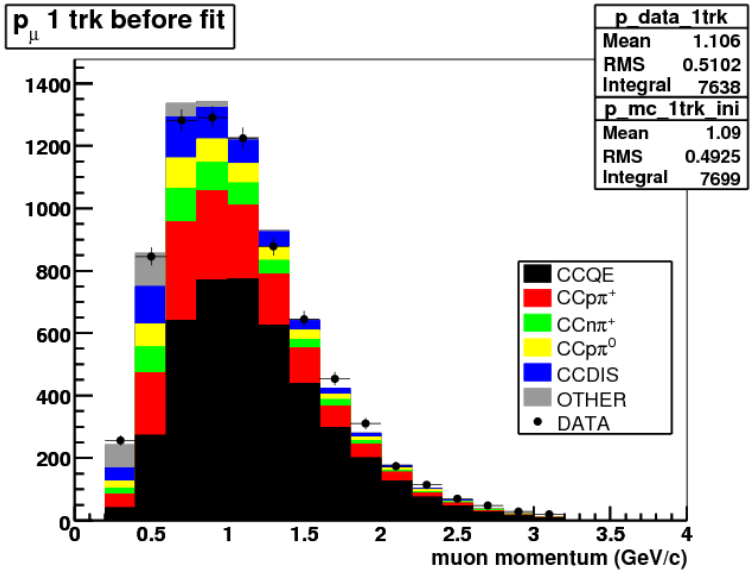
MC events further divided based on:
- **interaction type** – CCQE, CC1π^+, and background.
- **true neutrino energy**

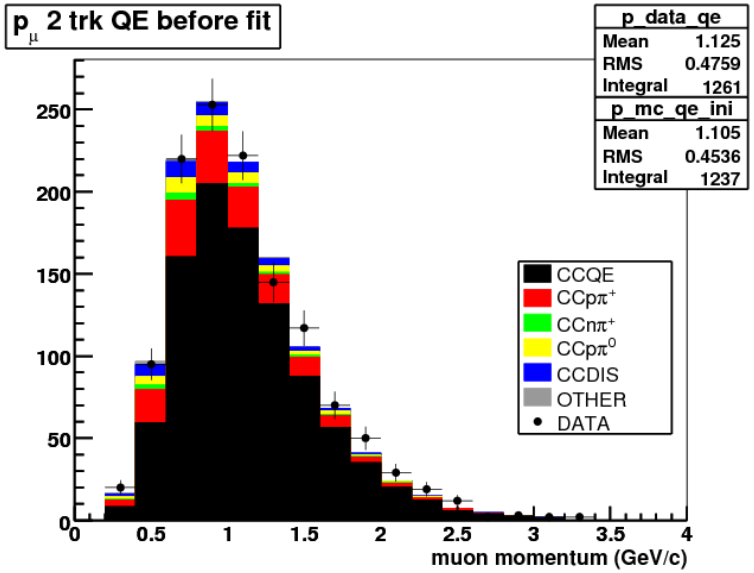
E_ν Range (GeV)
0.00-1.35
1.35-1.72
1.72-2.22
> 2.22

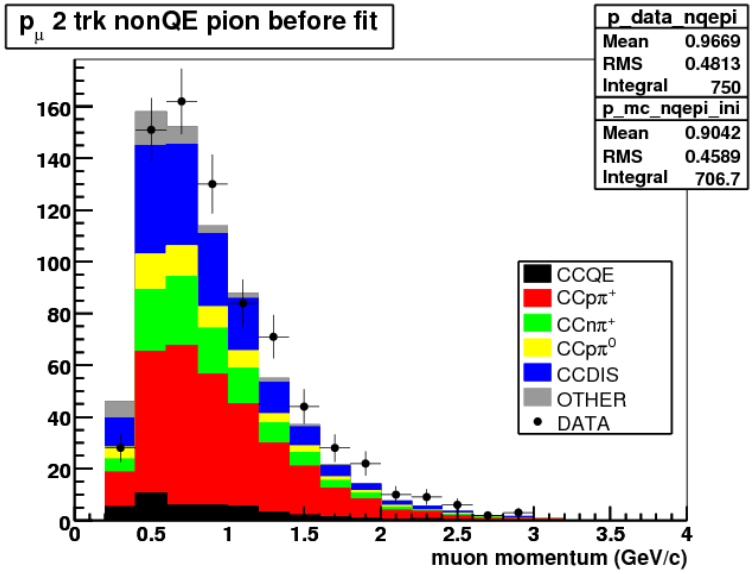
Sample	CCQE	CCpπ^+	CCnπ^+	CC1π^0	CC DIS	Other
Fiducial Volume	32	18	6	5	9	30
MRD	52	22	6	6	9	5
1-track	57	20	6	6	8	3
2-track QE	78	13	1	3	4	1
2-track nonQE pion	6	41	15	8	24	6
2-track nonQE proton	32	38	3	12	12	3

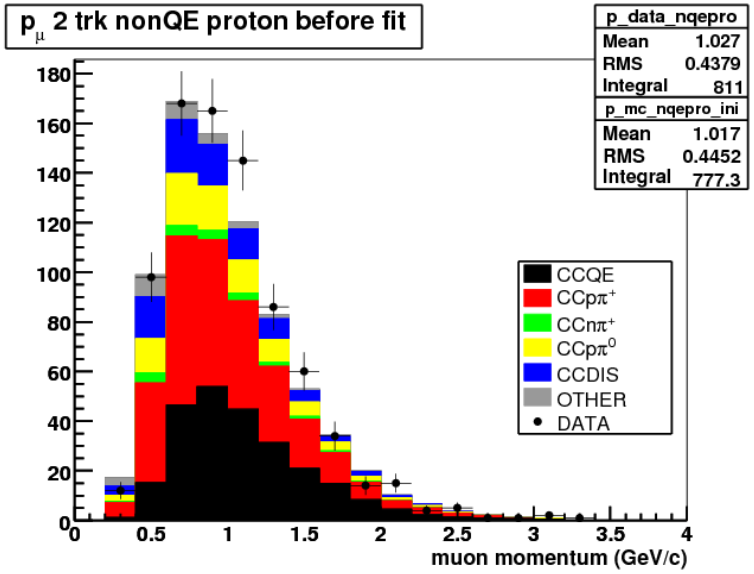
Data and MC binned in **p_μ vs. θ_μ bins** (0.2 GeV/c, 10° bins)

Data and Nominal MC μ Momentum

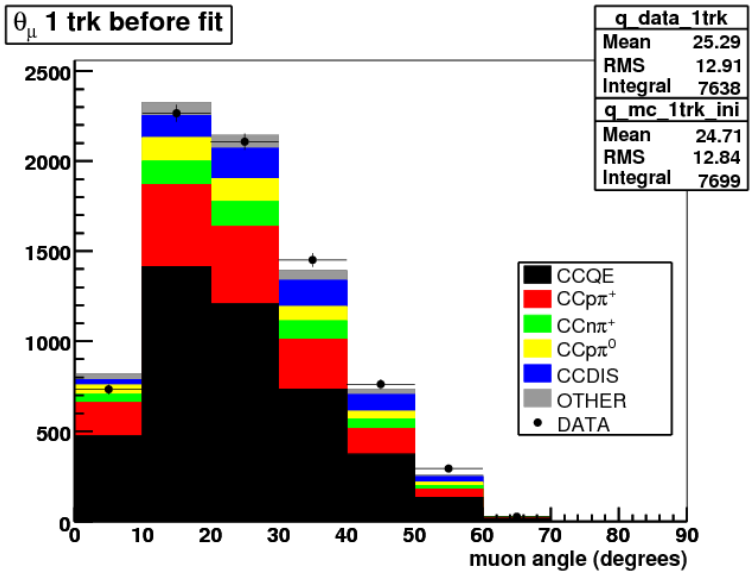


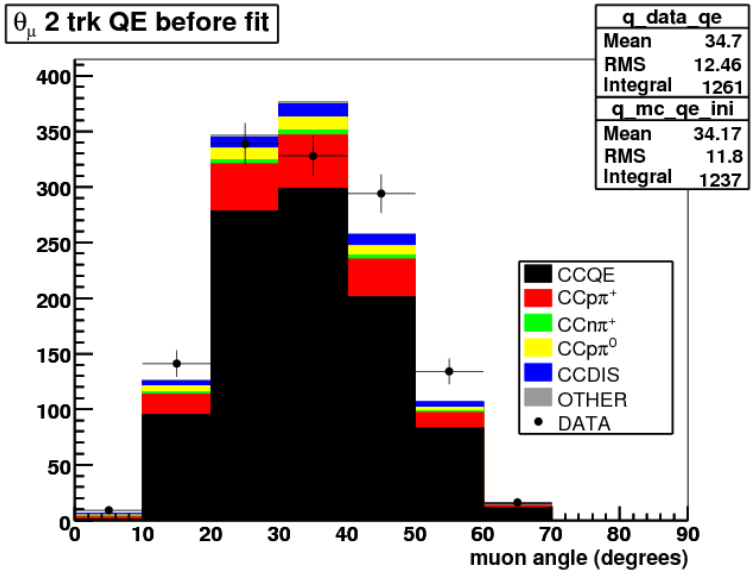


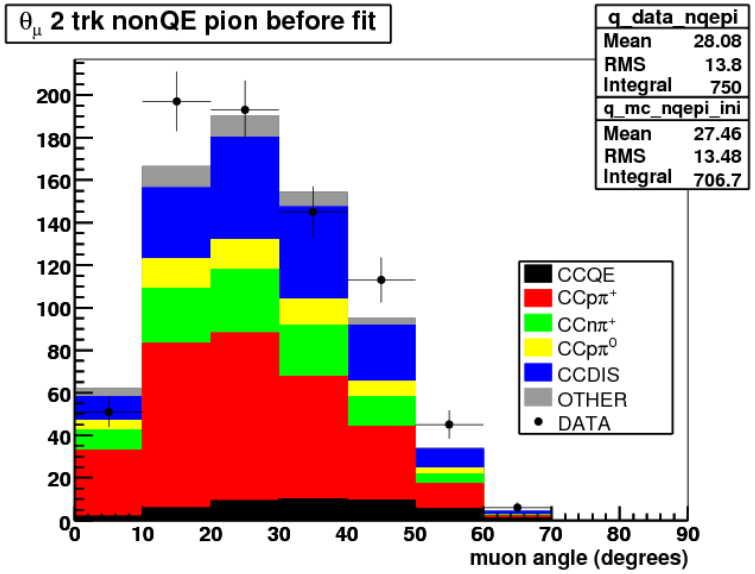


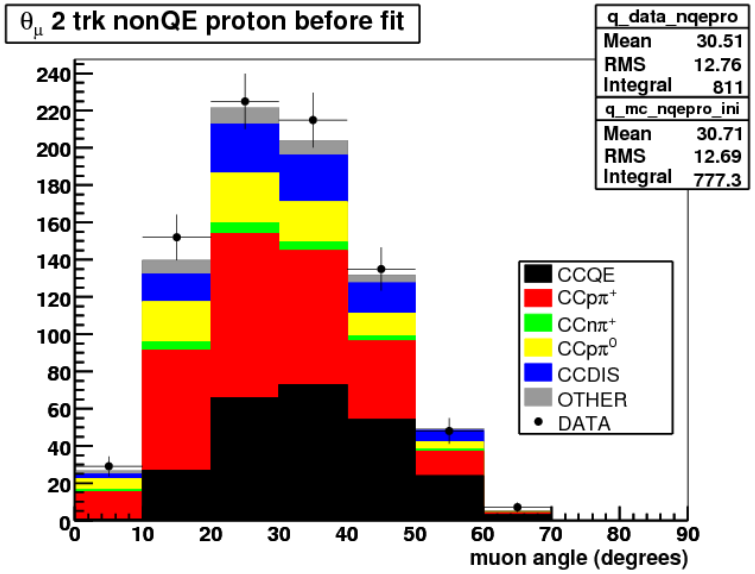


Data and Nominal MC μ Angle









Fitting

Maximum Likelihood Method for Poisson Statistics:

Maximizing the likelihood ratio is equivalent to minimizing the quantity

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

s = sample (1 track, 2 track QE, etc.)

i = bin in p_μ vs. θ_μ distribution

N^{exp}_{is} = number expected events in bin i,sample s

N^{obs}_{is} = number observed events in bin i,sample s

Fitting

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_v

 # CCQE events with E_v 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_v bin e

R^{CCQE}: reweights CCQE interactions

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

Fitting

R^{CCQE} is not energy-dependent.

→ We are fitting only for the overall normalization of the CCQE cross section.

Why do we fix the energy-dependency of the CCQE cross section to the MC prediction?

The shape of CCQE cross section has already been studied in K2K (using SciFi data, published in 2006), and we consider uncertainties in the shape as a systematic error.

Fitting

Since the MRD sample is a very pure CC sample, we use it to normalize MC to data.

The normalization condition is:

$$\sum_{is} N_{is}^{exp} = \sum_{is} N_{is}^{obs}$$

i.e. force the total number of expected events to be equal to the total number of data events.

The normalization factor **α** enforces the above condition.

α is recalculated at every iteration of the fit using the current fit parameters and the nominal MC.

Fitting

- Note that the **background is not fixed**. CCQE and CC1π^+ are allowed to vary freely, but the total number of events is fixed. Thus the background also varies (because it is scaled by **α**).

$$N^{Bkgd} = N^{total} - N^{CCQE} - N^{CC1\pi^+}$$

- The **systematic error on the muon momentum scale (Psc)** is estimated to be **2.7%** due to uncertainties in the model used for MRD energy reconstruction. Psc is a free parameter in the fit, but it is constrained within its systematic error by the addition of this term to the fitting function:

$$F_{Psc} = \frac{(P_{sc} - 1)^2}{\sigma^2_{P_{sc}}}$$

Calculating Cross Section Ratio

$$R_e = \frac{\sigma^{CC1\pi^+}_{data,e}}{\sigma^{CCQE}_{data,e}}$$

measured value of CC1π⁺ to CCQE cross section ratio in E_ν bin *e*

$$= \frac{N^{CC1\pi^+}_{\boxed{data},MRD1\&2,e}}{N^{CC1\pi^+}_{\boxed{MC}MRD1\&2,e}} \times \frac{N^{CCQE}_{\boxed{MC}MRD1\&2,e}}{N^{CCQE}_{\boxed{data},MRD1\&2,e}} \times R_{MC,e}$$

From nominal MC

From fitted MC

MC prediction

$$R_e \approx \frac{R_e^{CC1\pi^+}}{R^{CCQE}} R_{MC,e}$$

Fitting Results (E_ν-independent)

Parameter	Best Fit Value
P_{sc}	0.974 ± 0.004
R^{CCQE}	0.764 ± 0.070
$R_0^{CC1\pi^+}$	0.758 ± 0.139

χ^2/dof = 228/184 = 1.24

$$\frac{\alpha}{\alpha(nominal)} = 1.24$$

Note that, e.g.

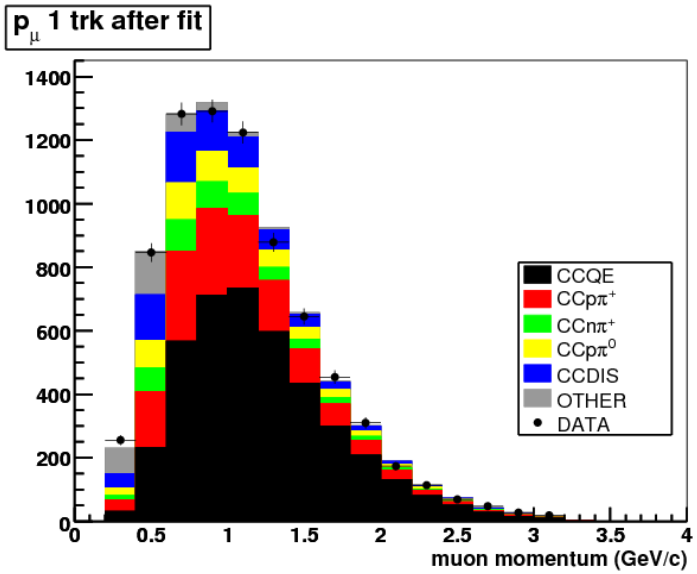
$$\frac{N^{CCQE}(after\ fit)}{N^{CCQE}(nominal)} = \frac{\alpha}{\alpha(nominal)} \times R^{CCQE}$$

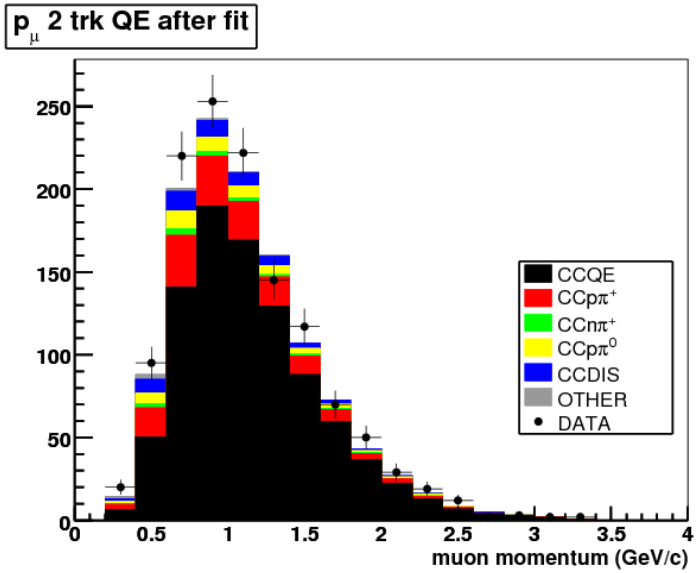
$$\frac{N^{CC1\pi^+}(after\ fit)}{N^{CC1\pi^+}(nominal)} = 0.94$$

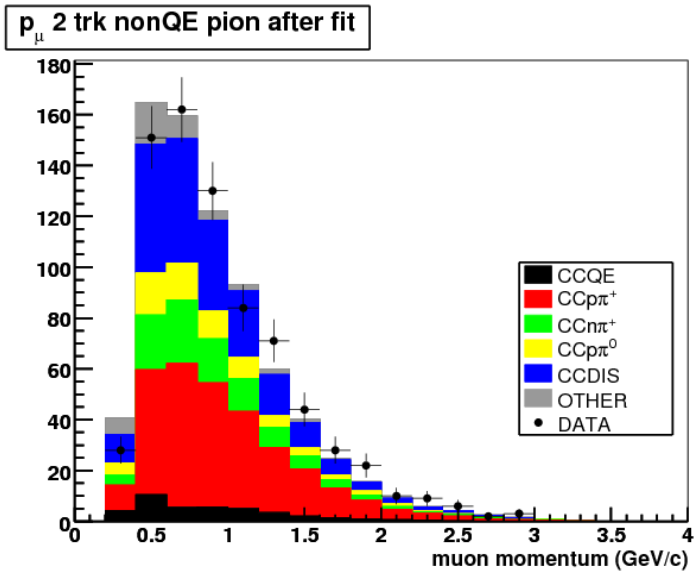
$$\frac{N^{CCQE}(after\ fit)}{N^{CCQE}(nominal)} = 0.95$$

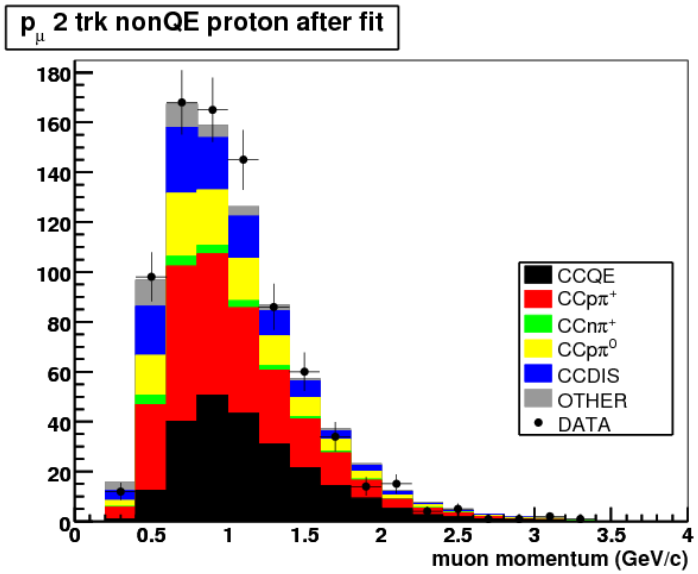
$$\frac{N^{Bkgd}(after\ fit)}{N^{Bkgd}(nominal)} = 1.24$$

Data and Best Fit MC μ Momentum

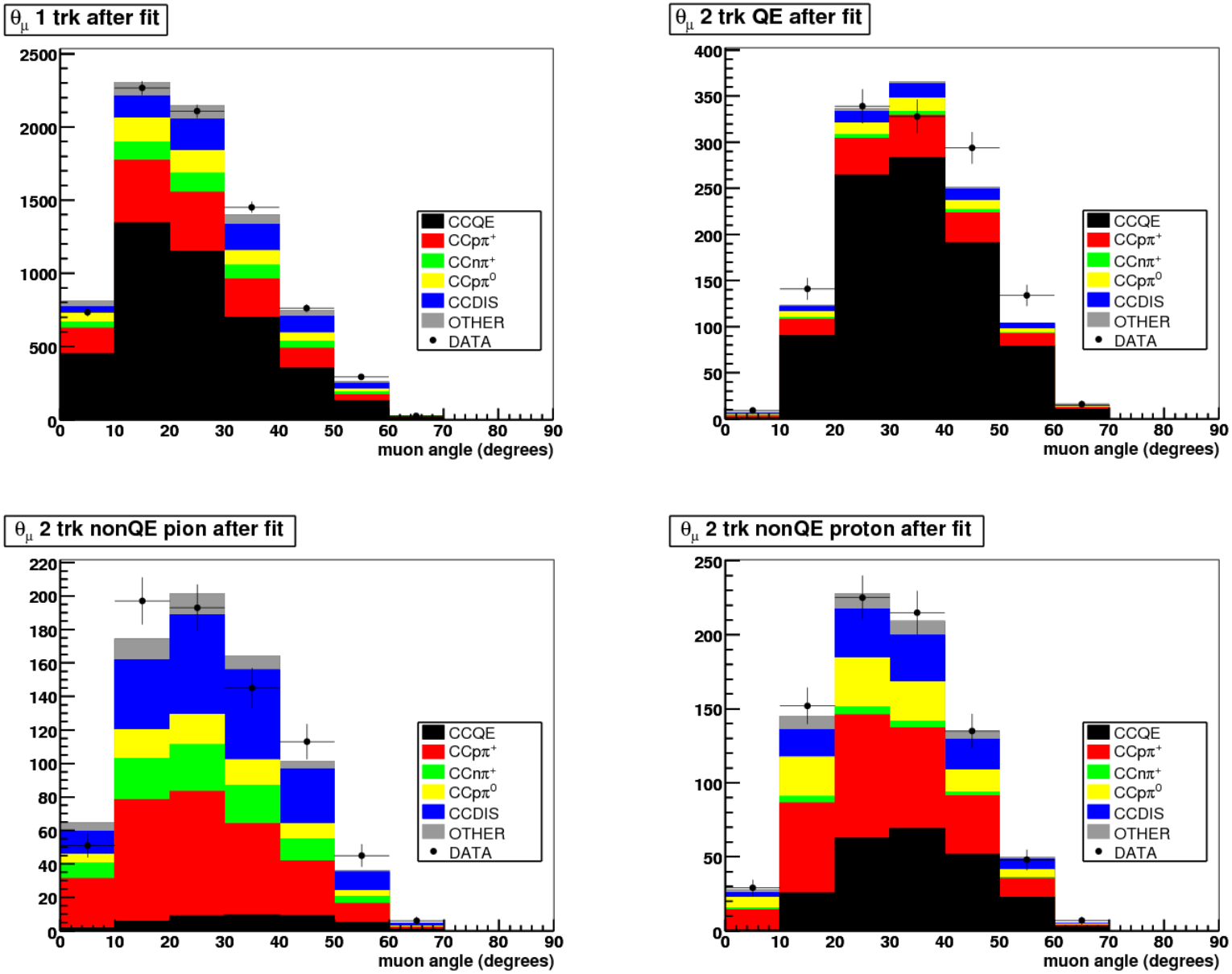








Data and Best Fit MC μ Angle



Fitting Results (E_ν-dependent)

Parameter	Best Fit Value
P_{sc}	0.977 ± 0.005
R^{CCQE}	0.725 ± 0.071
$R_0^{CC1\pi^+}$	0.545 ± 0.190
$R_1^{CC1\pi^+}$	0.801 ± 0.163
$R_2^{CC1\pi^+}$	0.652 ± 0.170
$R_3^{CC1\pi^+}$	0.798 ± 0.207

χ^2/dof = 227/181 = 1.25

E_ν (GeV)	$\frac{N^{CC1\pi^+}(after\ fit)}{N^{CC1\pi^+}(nominal)}$
0-1.35	0.71
1.35-1.72	1.05
1.72-2.22	0.85
>2.22	1.05

$$\frac{N^{CCQE}(after\ fit)}{N^{CCQE}(nominal)} = 0.95$$

$$\frac{\alpha}{\alpha(nominal)} = 1.31$$

$$\frac{N^{Bkgd}(after\ fit)}{N^{Bkgd}(nominal)} = 1.31$$

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 resolution (+-10%), and scintillator quenching (+-0.0023)

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

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

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

Inclusive vs. Exclusive

We can measure both the inclusive (**$CC1\pi^+$**) and exclusive (**$CCp\pi^+$**) cross section ratios.

Method to measure exclusive cross section is same except that $CCn\pi^+$ events are considered part of the background.

I present the final results of both measurements here.

Cross Section Results

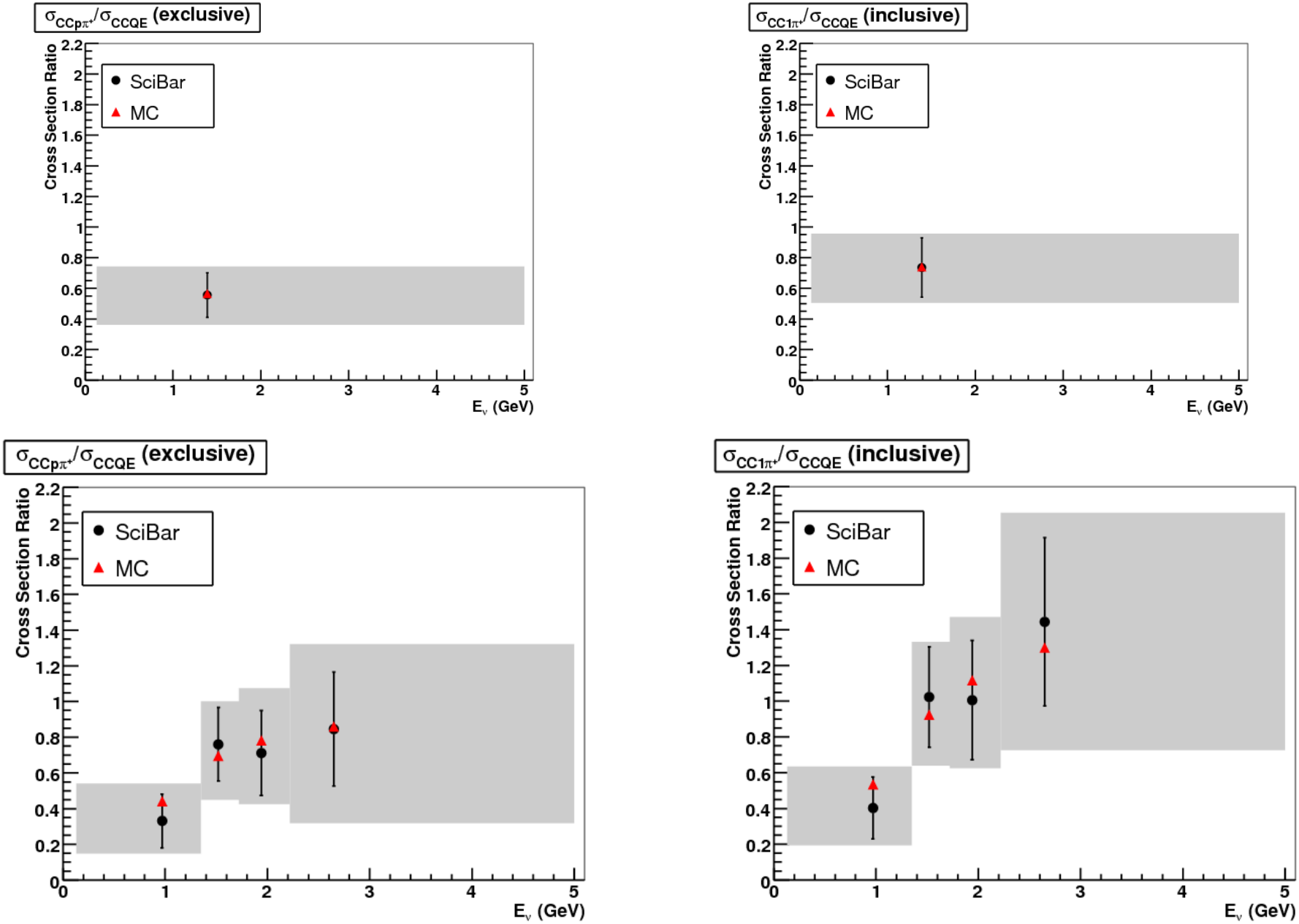
Energy Range (GeV)	Cross Section Ratio $R_e = \frac{\sigma_e^{CC1\pi^+}}{\sigma_e^{CCQE}}$
>0.00	$0.735 \pm 0.194(\text{fit})^{+0.076}_{-0.103}(\text{nucl})^{+0.078}_{-0.073}(\text{syst})$
0.00-1.35	$0.403 \pm 0.173(\text{fit})^{+0.087}_{-0.072}(\text{nucl})^{+0.128}_{-0.093}(\text{syst})$
1.35-1.72	$1.023 \pm 0.281(\text{fit})^{+0.072}_{-0.217}(\text{nucl})^{+0.107}_{-0.141}(\text{syst})$
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 ($CC1\pi^+$)

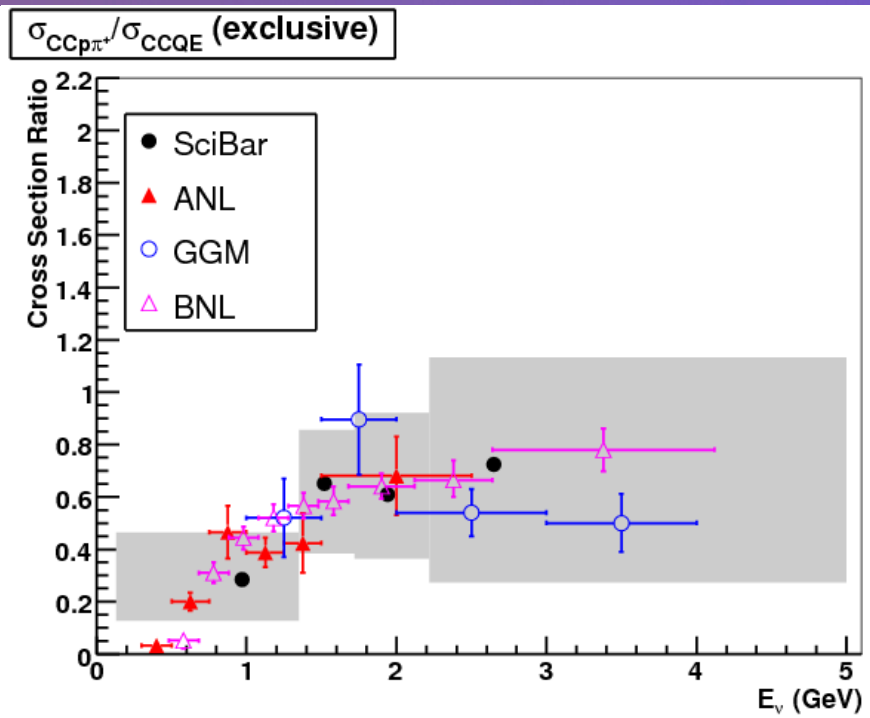
Energy Range (GeV)	Cross Section Ratio $R_e = \frac{\sigma_e^{CCp\pi^+}}{\sigma_e^{CCQE}}$
>0.00	$0.556 \pm 0.145(\text{fit})^{+0.079}_{-0.072}(\text{nucl})^{+0.086}_{-0.106}(\text{syst})$
0.00-1.35	$0.331 \pm 0.151(\text{fit})^{+0.113}_{-0.035}(\text{nucl})^{+0.092}_{-0.097}(\text{syst})$
1.35-1.72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

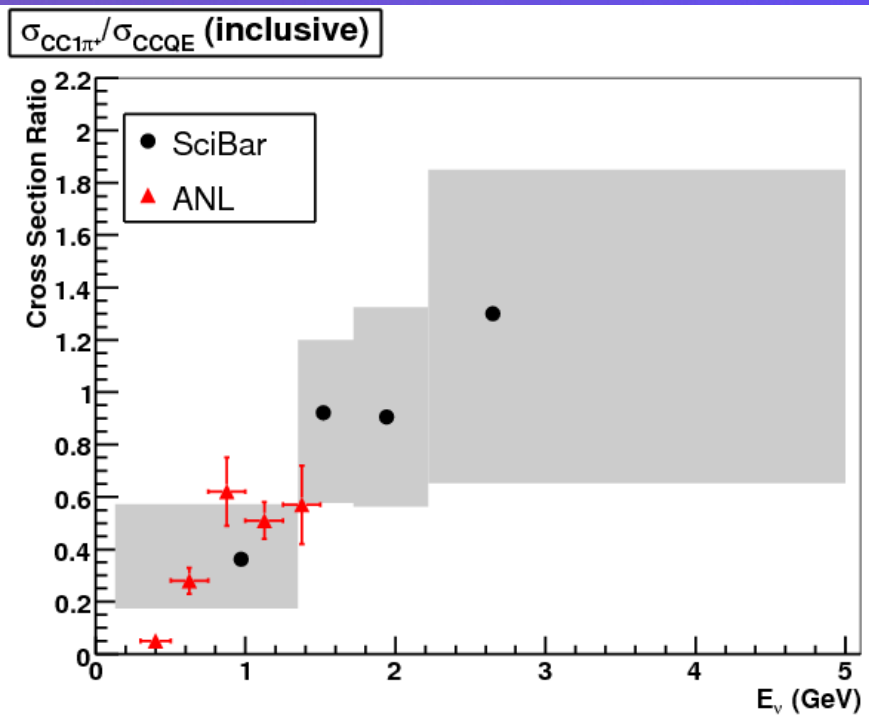
EXCLUSIVE ($CCp\pi^+$)

Comparison to Model



Comparison to Other Experiments





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

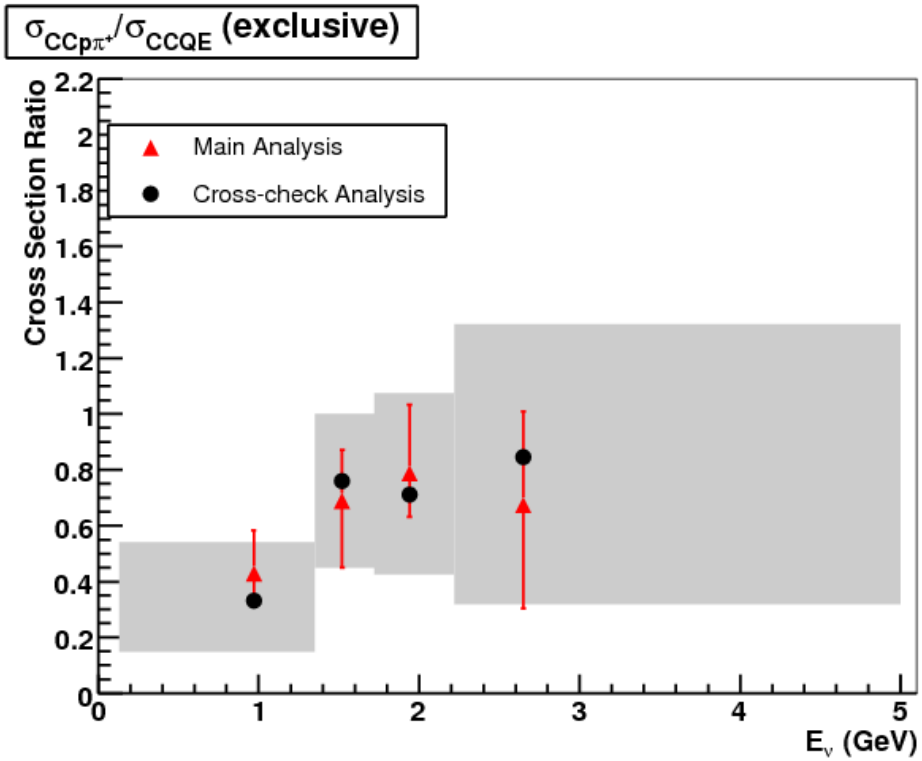
GGM: CERN bubble chamber, propane-freon target, neutrino energy < 10 GeV

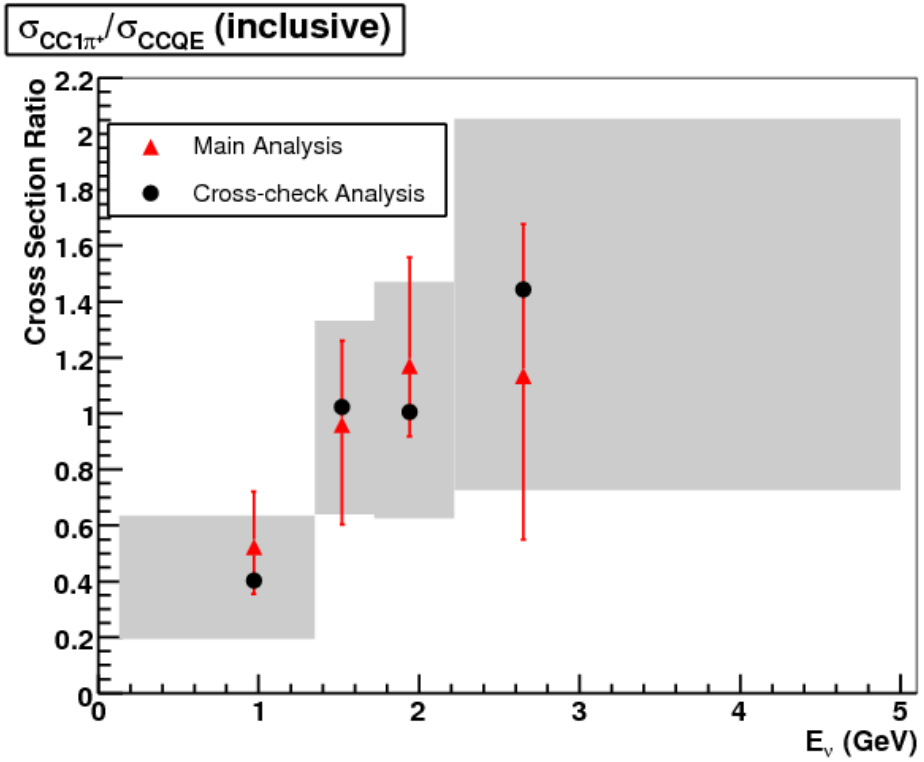
BNL: Brookhaven 7 foot bubble chamber, deuterium target, mean neutrino energy 1.6 GeV

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.

Verification by Independent Analysis

There were actually two independent analyses done using SciBar data to measure the inclusive and exclusive $CC1\pi^+$ to CCQE cross section ratios. Used same sample of events, but different method. Results are consistent.





Summary

- we measured the inclusive and exclusive $CC1\pi^+$ to CCQE cross section ratio in neutrino interactions with carbon using data from the K2K-SciBar detector
- results of this analysis are consistent with the MC prediction and previous experimental measurements
- this measurement provides a valuable cross-check in a region with few measurements

Outlook

- Paper presenting these results is currently in the process of K2K internal review, will be submitted for publication by end of summer
- Will be more results coming from K2K-SciBar data: CC multi π, M_A^{QE}, $CC\pi^0$
- SciBar detector has been moved to Fermilab and will be used in the SciBoone experiment for neutrino cross section measurements

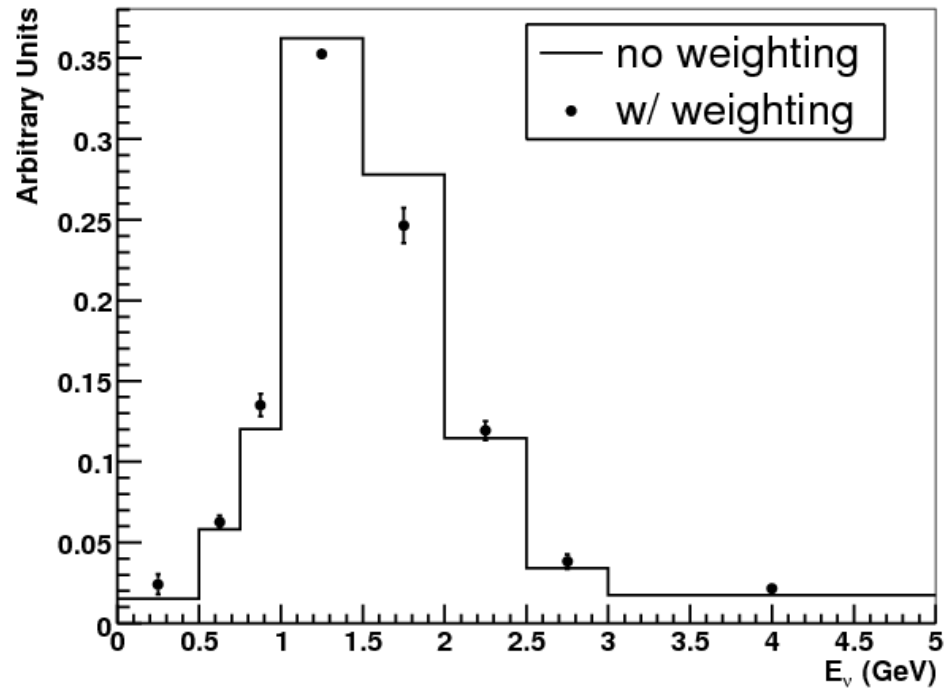
Backup Slides

Measured Energy Spectrum

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

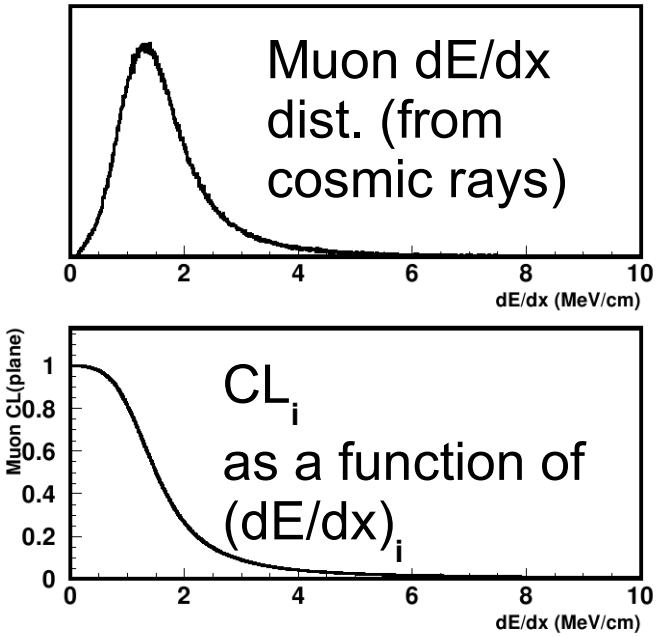
Then the predicted energy spectrum from the beam-MC is reweighted to match the measurement.

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



E_ν (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

Particle ID – Muon Confidence Level



Confidence level that a particle is a muon for i^{th} plane (CL_i):

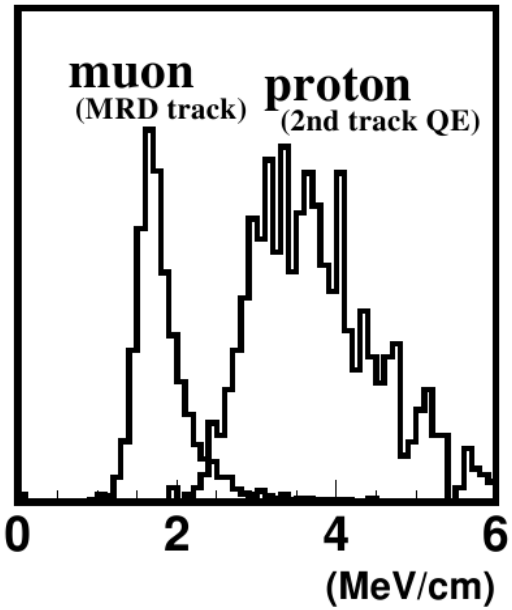
fraction of events in the muon dE/dx distribution above the observed $(dE/dx)_i$ for the particle traversing the ith plane

To get MuCL:

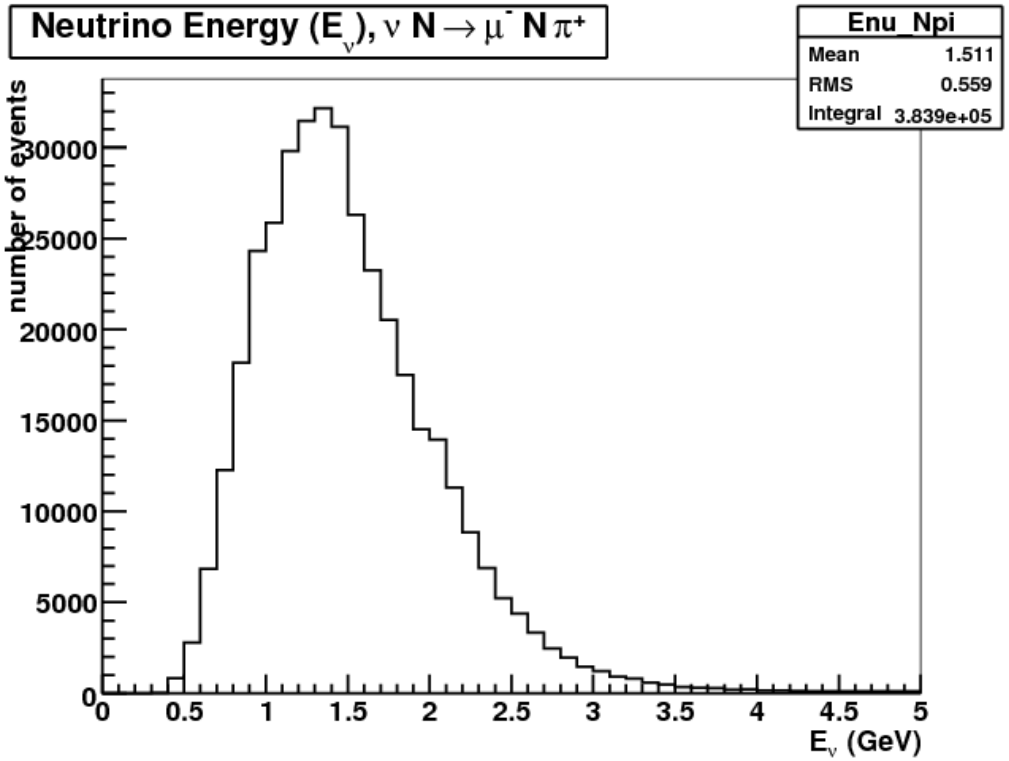
- let Cl_i be independent random variables with uniform p.d.f
- let CL be the random variable defined by $CL=\Pi CL_i$
- MuCL is the c.d.f. for CL

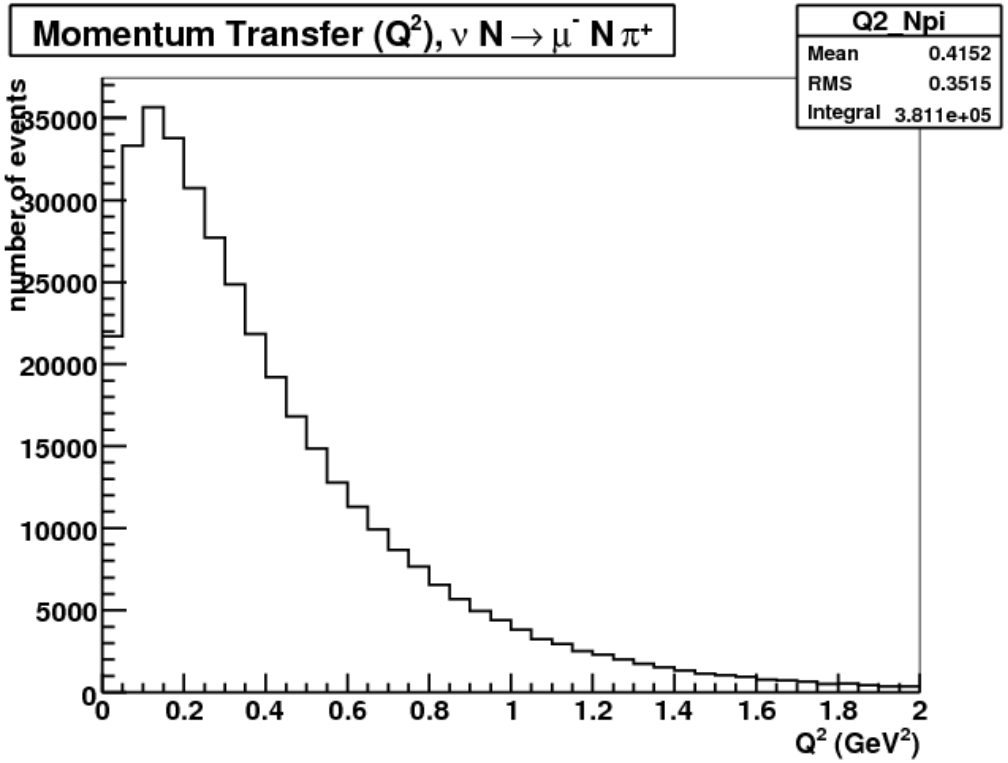
$$\mathrm{MuCL} = \Pi CL_i \times \Sigma_j \frac{(-\ln \Pi CL_i)^j}{j!}$$

dE/dx

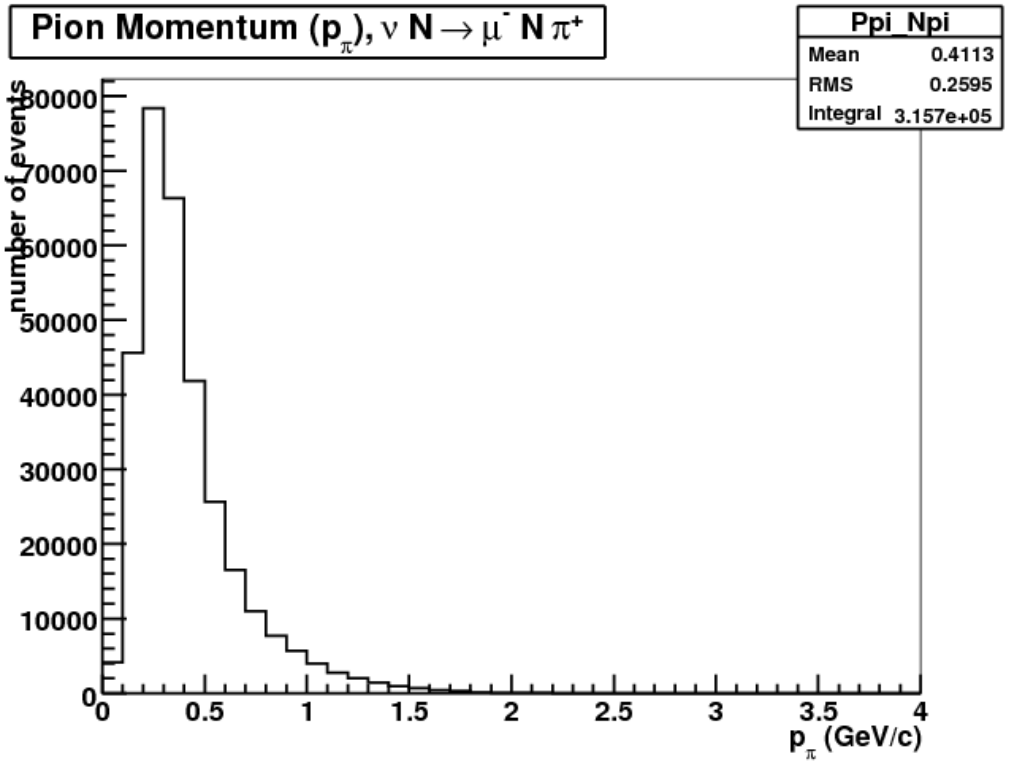


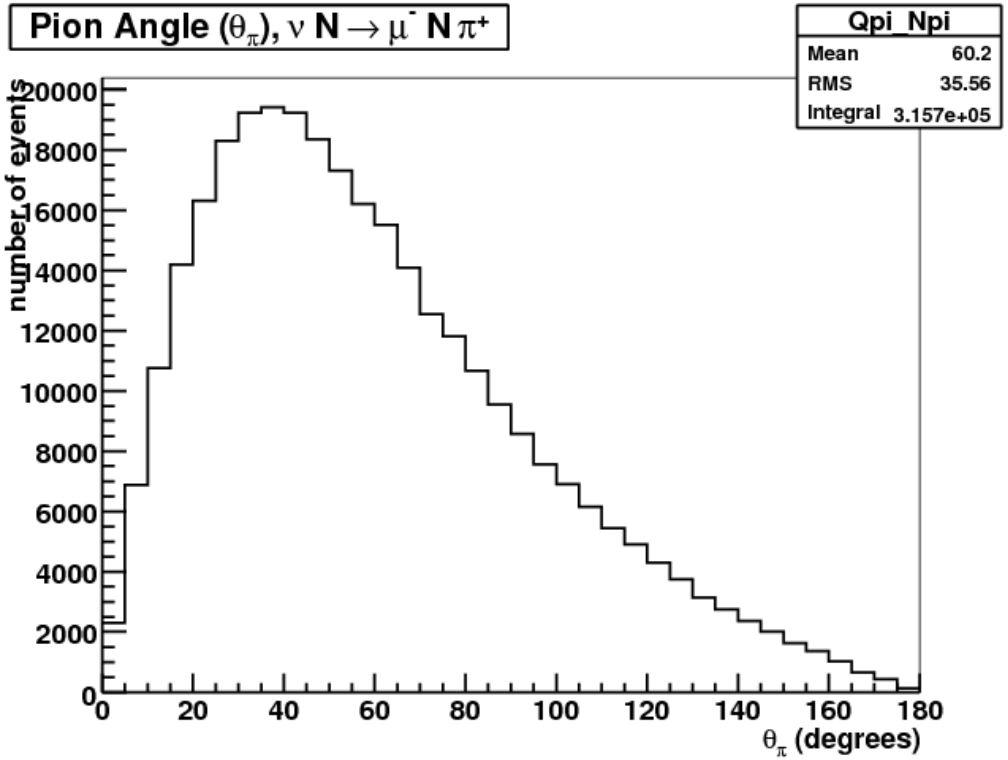
CC1π⁺ Events (MC)



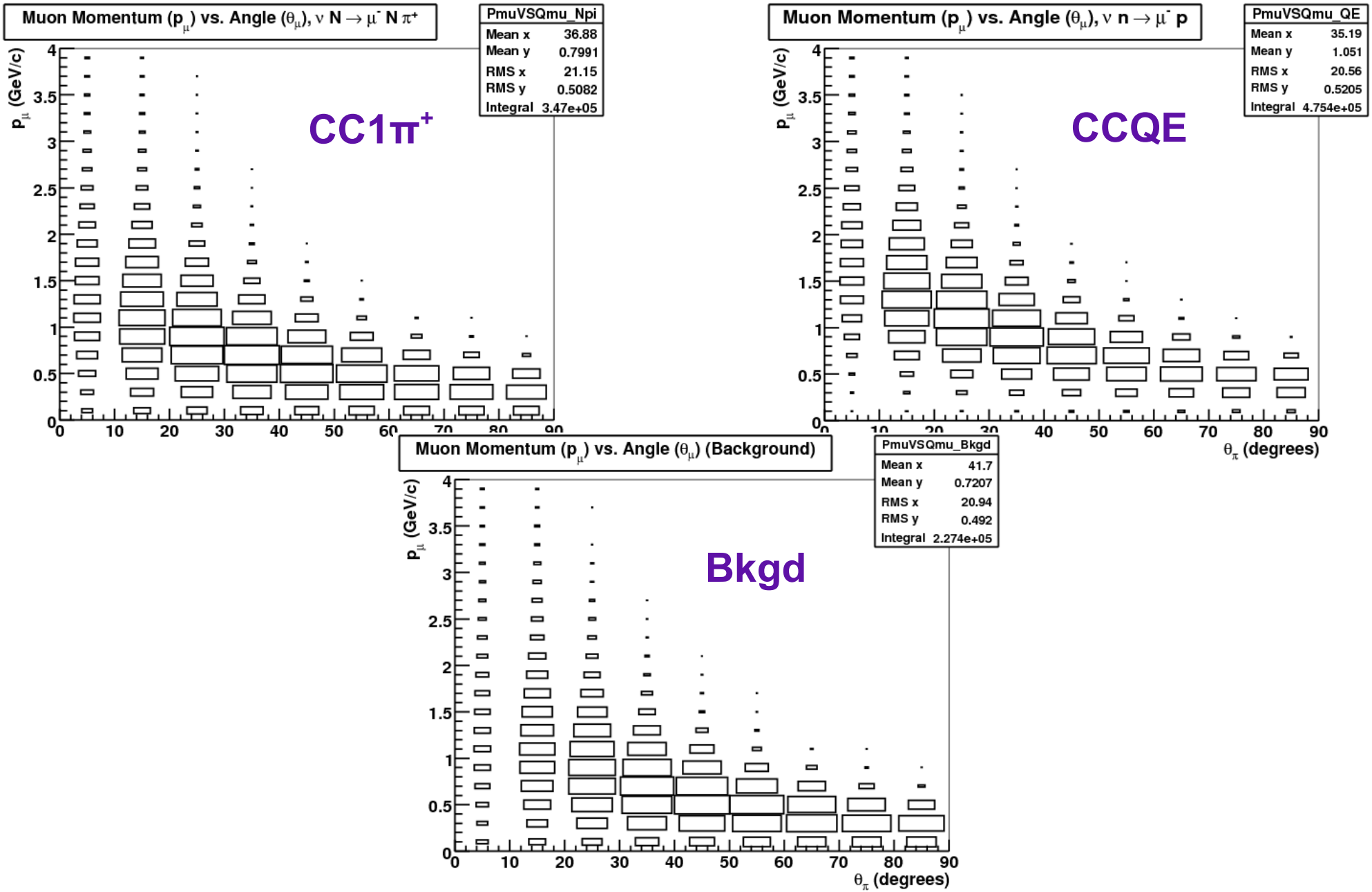


CC1π⁺ Events (MC)





μ Momentum vs. Angle (MC)



Fitting: Chi2/nbins

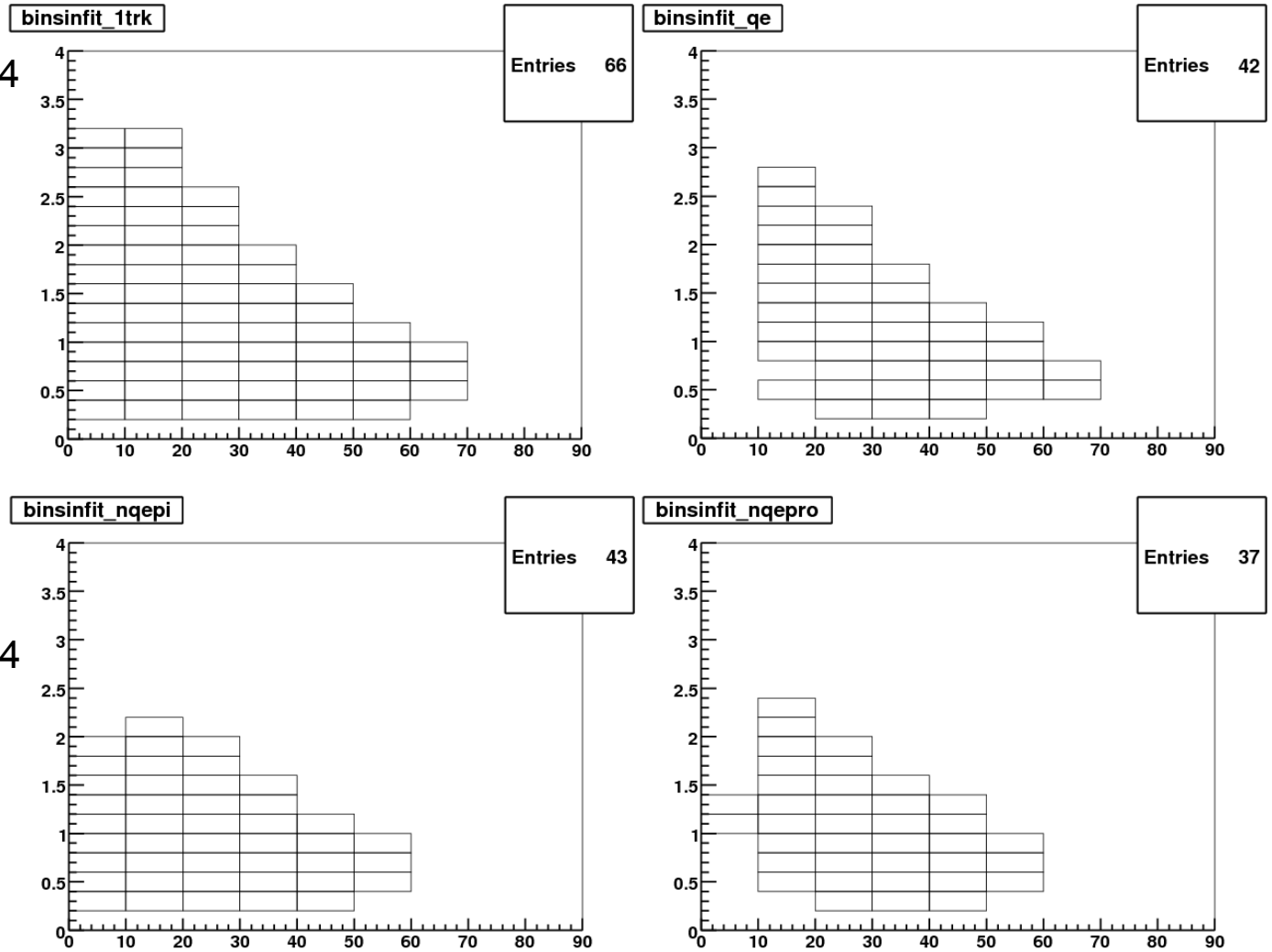
Before fitting 283/184 = 1.54

sample	**χ^2/nbins**
1-track	113/66
2-track QE	58/42
2-track nonQE pion	70/43
2-track nonQE proton	42/37

for energy-independent inclusive fit:

After fitting 228/184 = 1.24

sample	**χ^2/nbins**
1-track	76/66
2-track QE	51/42
2-track nonQE pion	61/43
2-track nonQE proton	40/37



Fitting Results (Exclusive)

Parameter	Best Fit Value
P_{sc}	0.974 ± 0.003
R^{CCQE}	0.802 ± 0.062
$R_0^{CC1\pi^+}$	0.789 ± 0.155

$$\frac{\alpha}{\alpha(nominal)} = 1.18$$

χ^2/dof = 229/184 = 1.25

Parameter	Best Fit Value
P_{sc}	0.975 ± 0.005
R^{CCQE}	0.765 ± 0.065
$R_0^{CC1\pi^+}$	0.574 ± 0.223
$R_1^{CC1\pi^+}$	0.836 ± 0.179
$R_2^{CC1\pi^+}$	0.695 ± 0.193
$R_3^{CC1\pi^+}$	0.747 ± 0.247

$$\frac{\alpha}{\alpha(nominal)} = 1.24$$

χ^2/dof = 228/181 = 1.26

Fitting: Correlation Matrices

INCLUSIVE

	P_{sc}	R^{CCQE}	$R_0^{CC1\pi^+}$
P_{sc}	1.000	-0.309	-0.126
R^{CCQE}	-0.309	1.000	0.843
$R_0^{CC1\pi^+}$	-0.126	0.843	1.000

	P_{sc}	R^{CCQE}	$R_0^{CC1\pi^+}$	$R_1^{CC1\pi^+}$	$R_2^{CC1\pi^+}$	$R_3^{CC1\pi^+}$
P_{sc}	1.000	-0.064	0.248	0.008	0.042	-0.404
R^{CCQE}	-0.064	1.000	0.795	0.610	0.633	0.565
$R_0^{CC1\pi^+}$	0.248	0.795	1.000	0.437	0.679	0.441
$R_1^{CC1\pi^+}$	0.008	0.610	0.437	1.000	0.291	0.570
$R_2^{CC1\pi^+}$	0.042	0.633	0.679	0.291	1.000	0.282
$R_3^{CC1\pi^+}$	-0.404	0.565	0.441	0.570	0.282	1.000

EXCLUSIVE

	P_{sc}	R^{CCQE}	$R_0^{CC1\pi^+}$
P_{sc}	1.000	-0.310	-0.091
R^{CCQE}	-0.310	1.000	0.773
$R_0^{CC1\pi^+}$	-0.091	0.773	1.000

	P_{sc}	R^{CCQE}	$R_0^{CC1\pi^+}$	$R_1^{CC1\pi^+}$	$R_2^{CC1\pi^+}$	$R_3^{CC1\pi^+}$
P_{sc}	1.000	-0.054	0.279	0.013	0.039	-0.406
R^{CCQE}	-0.054	1.000	0.763	0.557	0.584	0.450
$R_0^{CC1\pi^+}$	0.279	0.763	1.000	0.438	0.670	0.358
$R_1^{CC1\pi^+}$	0.013	0.557	0.438	1.000	0.302	0.514
$R_2^{CC1\pi^+}$	0.039	0.584	0.670	0.302	1.000	0.235
$R_3^{CC1\pi^+}$	-0.406	0.450	0.358	0.514	0.235	1.000

Error Evaluation

Fitting Error in R_e

$$\Delta R_e^2(fit) = \sum_{i,j} \frac{\partial R_e}{\partial Par_i} \frac{\partial R_e}{\partial Par_j} E_{ij}$$

where E is the error matrix from the fit

For systematic error, a new set of p_μ vs θ_μ histogram templates are produced for each systematic source (i.e. Pion absorption +30%,-30%, etc.)

The fitting is done for each set of templates, and a new value of R_e is computed for each set. The systematic error is just the difference between the new value of R_e and the value computed using the nominal MC.

Summary of Systematic Errors

Inclusive Ratio, E_ν – independent $CC1\pi^+$

Condition	ΔR_0
Detector Simulation	
Crosstalk ±0.25%	+0.042,-0.010
PMT Res. ±10%	+0.006,-0.017
Birks' Const. ±0.0023	-0.010,+0.036
Reconstruction	
Threshold ±15%	±0.022
Angular res.	±0.010
Model	
M_A^{QE} ±0.1 GeV	-0.056,+0.049
Bodek/Yang Corr. ±30%	+0.003,-0.018
Neutrino Flux	+0.006,-0.028
Nuclear Effects	
π abs. ±30%	+0.046,+0.014
π inel. scat. ±30%	+0.059,-0.068
proton rescat. ±10%	-0.076,+0.004
Fermi mom.	±0.012
MC Stats.	±0.006
Total Syst. Error	**-0.126,+0.109**

Summary of Systematic Errors

Exclusive Ratio, E_ν – independent $CC1\pi^+$

Condition	ΔR_0
Detector Simulation	
Crosstalk ±0.25%	+0.045,-0.071
PMT Res. ±10%	+0.020,-0.032
Birks' Const. ±0.0023	+0.010,+0.030
Reconstruction	
Threshold ±15%	±0.052
Angular res.	±0.010
Model	
M_A^{QE} ±0.1 GeV	-0.039,+0.036
Bodek/Yang Corr. ±30%	-0.003,-0.009
Neutrino Flux	+0.007,-0.028
Nuclear Effects	
π abs. ±30%	+0.035,+0.055
π inel. scat. ±30%	+0.054,-0.057
proton rescat. ±10%	-0.041,-0.009
Fermi mom.	±0.017
MC Stats.	±0.005
Total Syst. Error	**-0.128,+0.117**

Summary of Systematic Errors

Inclusive Ratio, E_ν – dependent $CC1\pi^+$

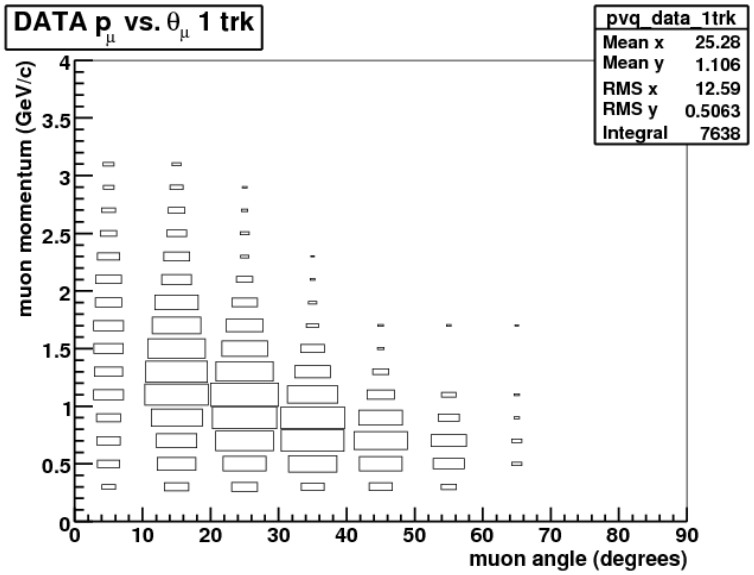
Condition	ΔR_0	ΔR_1	ΔR_2	ΔR_3
Detector Simulation				
Crosstalk ±0.25%	+0.023,+0.086	+0.031,-0.079	+0.104,+0.075	+0.058,-0.212
PMT Res. ±10%	-0.007,-0.018	+0.012,-0.026	+0.024,-0.002	-0.010,-0.077
Birks' Const. ±0.0023	+0.009,+0.042	-0.024,+0.046	-0.003,+0.100	-0.047,-0.131
Reconstruction				
Threshold ±15%	±0.013	±0.045	±0.014	±0.162
Angular res.	±0.015	±0.001	±0.021	±0.023
Model				
M_A^{QE} ±0.1 GeV	-0.039,+0.015	-0.054,+0.048	-0.031,+0.021	-0.270,+0.276
Bodek/Yang Corr. ±30%	+0.007,-0.014	+0.006,-0.021	+0.022,-0.030	-0.046,-0.037
Neutrino Flux	+0.082,-0.079	+0.061,-0.082	+0.192,-0.162	+0.047,-0.207
Nuclear Effects				
π abs. ±30%	+0.022,+0.077	+0.006,-0.053	+0.129,+0.106	+0.203,-0.052
π inel. scat. ±30%	+0.031,+0.018	+0.069,-0.173	+0.155,+0.032	+0.019,-0.243
proton rescat. ±10%	-0.072,+0.025	-0.119,-0.019	-0.063,+0.059	-0.135,-0.080
Fermi mom.	±0.004	±0.020	±0.009	±0.035
MC Stats.	±0.006	±0.015	±0.017	±0.037
Total Syst. Error	**-0.118,+0.155**	**-0.259,+0.129**	**-0.182,+0.323**	**-0.543,+0.391**

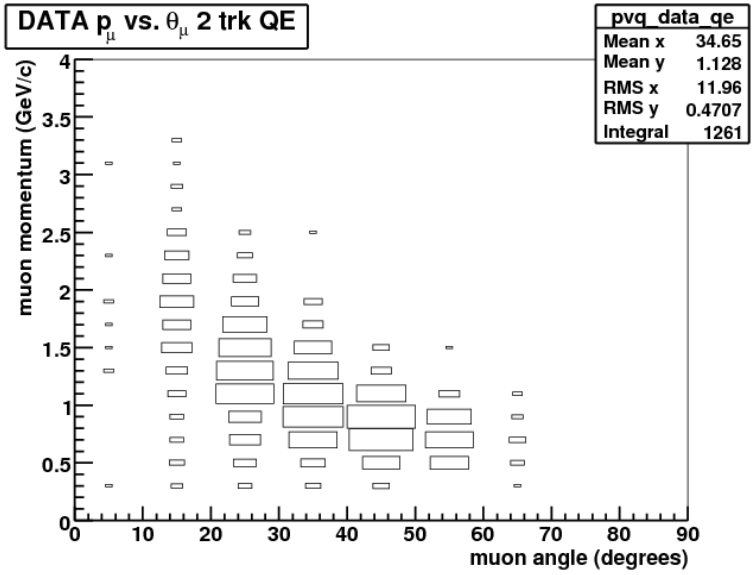
Summary of Systematic Errors

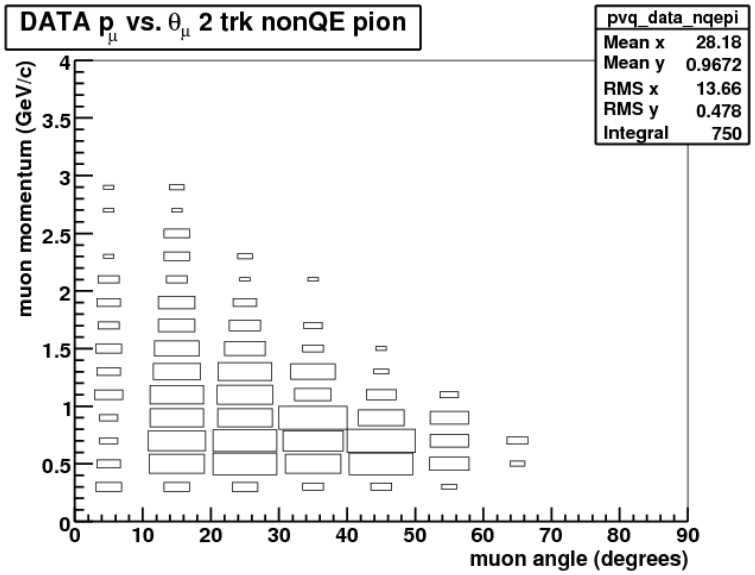
Exclusive Ratio, E_ν – dependent $CC1\pi^+$

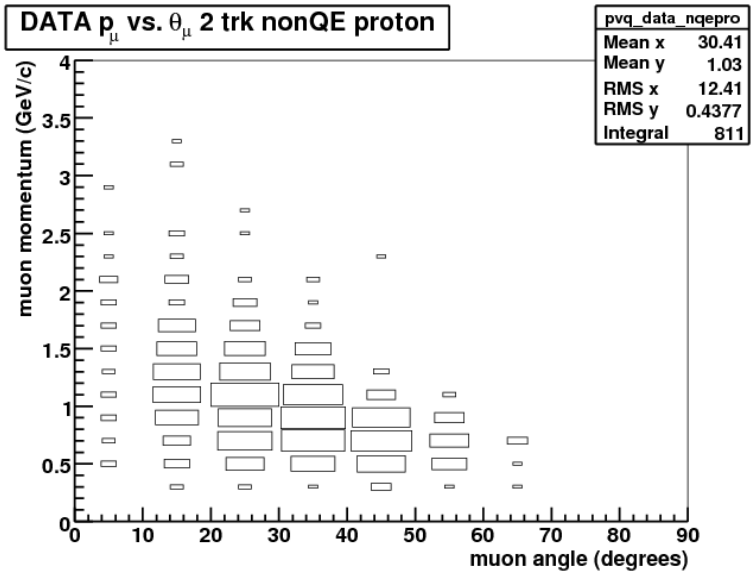
Condition	ΔR_0	ΔR_1	ΔR_2	ΔR_3
Detector Simulation				
Crosstalk ±0.25%	+0.044,-0.001	+0.026,-0.124	+0.110,-0.051	+0.045,-0.213
PMT Res. ±10%	+0.007,-0.040	+0.020,-0.040	+0.037,-0.034	+0.025,-0.086
Birks' Const. ±0.0023	+0.031,+0.033	-0.005,+0.026	+0.031,+0.072	+0.006,-0.088
Reconstruction				
Threshold ±15%	±0.029	±0.075	±0.037	±0.199
Angular res.	±0.020	±0.002	±0.025	±0.004
Model				
M_A^{QE} ±0.1 GeV	-0.035,+0.000	-0.041,+0.036	-0.022,+0.013	-0.176,+0.214
Bodek/Yang Corr. ±30%	-0.000,-0.006	-0.003,-0.011	+0.003,-0.016	-0.052,-0.017
Neutrino Flux	+0.063,-0.072	+0.040,-0.063	+0.147,-0.135	+0.053,-0.163
Nuclear Effects				
π abs. ±30%	-0.004,+0.110	-0.011,+0.005	+0.111,+0.149	+0.171,+0.053
π inel. scat. ±30%	+0.025,-0.015	+0.065,-0.136	+0.100,+0.013	+0.064,-0.097
proton rescat. ±10%	-0.030,+0.005	-0.081,-0.025	+0.009,+0.019	-0.057,-0.078
Fermi mom.	±0.011	±0.020	±0.021	±0.030
MC Stats.	±0.005	±0.012	±0.013	±0.024
Total Syst. Error	**-0.103,+0.146**	**-0.233,+0.123**	**-0.159,+0.275**	**-0.421,+0.355**

Data Momentum vs. Angle

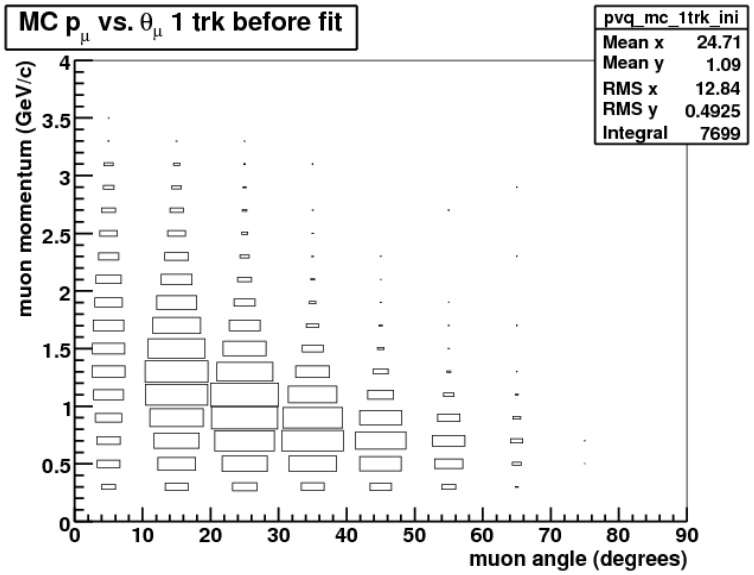


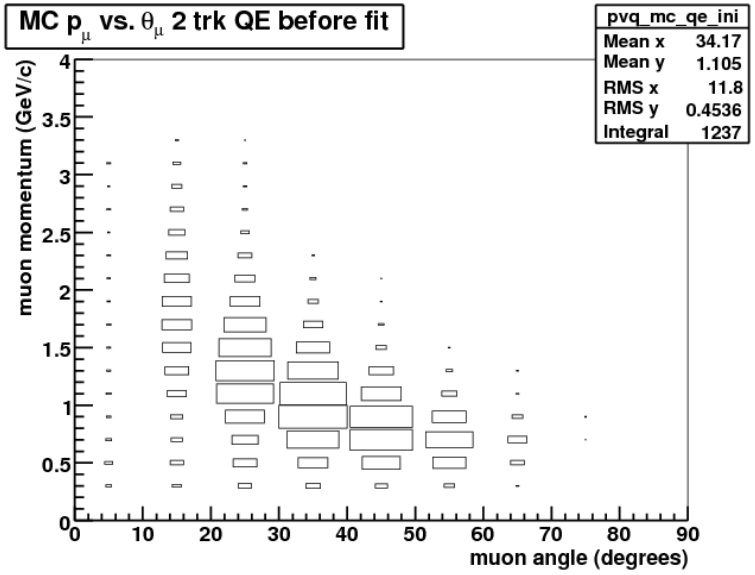


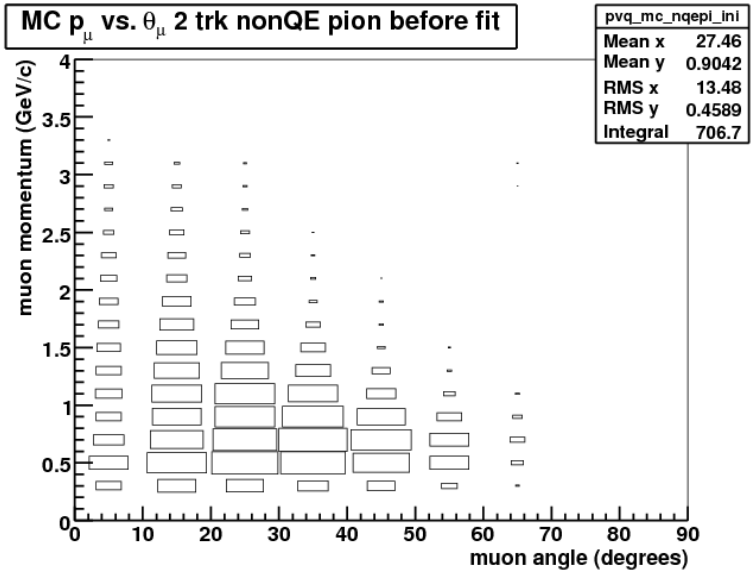


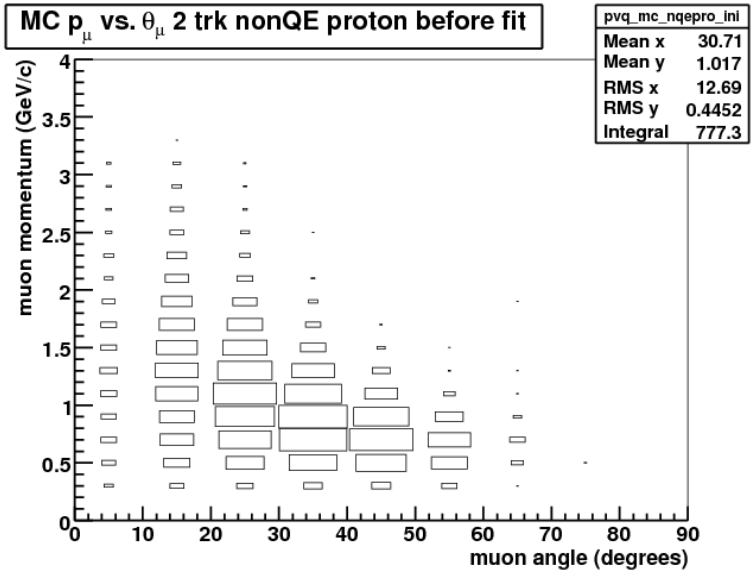


Nominal MC Momentum vs. Angle









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:

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

$$f = 6/7$$