Charged current single pion to quasi-elastic cross section ratio in MiniBooNE

Steven Linden

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Motivation

Oscillation searches needed for leptonic CP violation.

One approach: search for ν_μ disappearance with charged current quasi-elastic events (CCQE).

Single charged pion events ($CC\pi^+$) can look like CCQE if pion is not detected.

Need to know the $CC\pi^+$/CCQE ratio precisely to remove this background.

Uncertainty on this ratio currently a large obstacle to such searches.

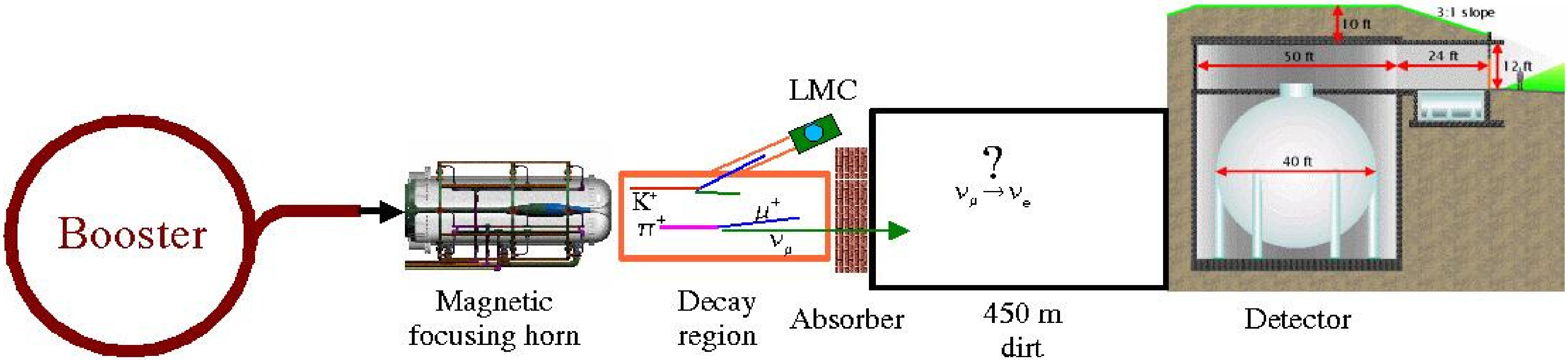
Application to other oscillation studies as well – e.g. using $CC\pi^+$ as a signal channel for ν_μ disappearance or ν_e appearance.

Data is needed for theorists studying resonant and coherent pion production – test improvements and alternatives to the Rein-Sehgal model, etc.

For example, using $CC\pi^+$ data in MiniBooNE we have compared various parameterisations the axial and vector form factors.

Measurement on nuclear target may provide insight into nuclear structure – test modelling of intra-nuclear re-interactions, etc.

MiniBooNE



FNAL Booster delivers 8 GeV protons to the beamline.

Protons collide with beryllium target, producing pions and kaons.

Magnetic horn focuses positively charged kaons and pions.

These mesons decay, producing muon neutrinos.

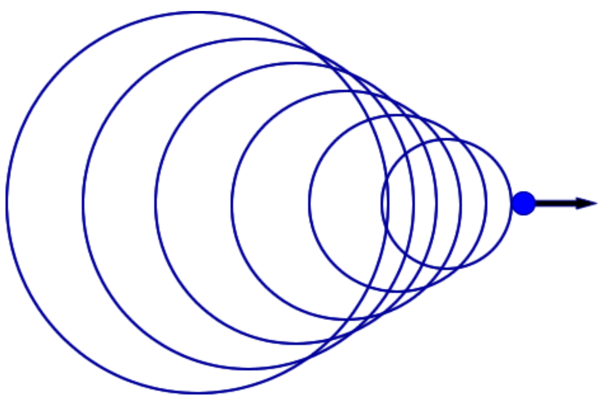
Other products are stopped in the absorber or in the dirt before reaching the detector.

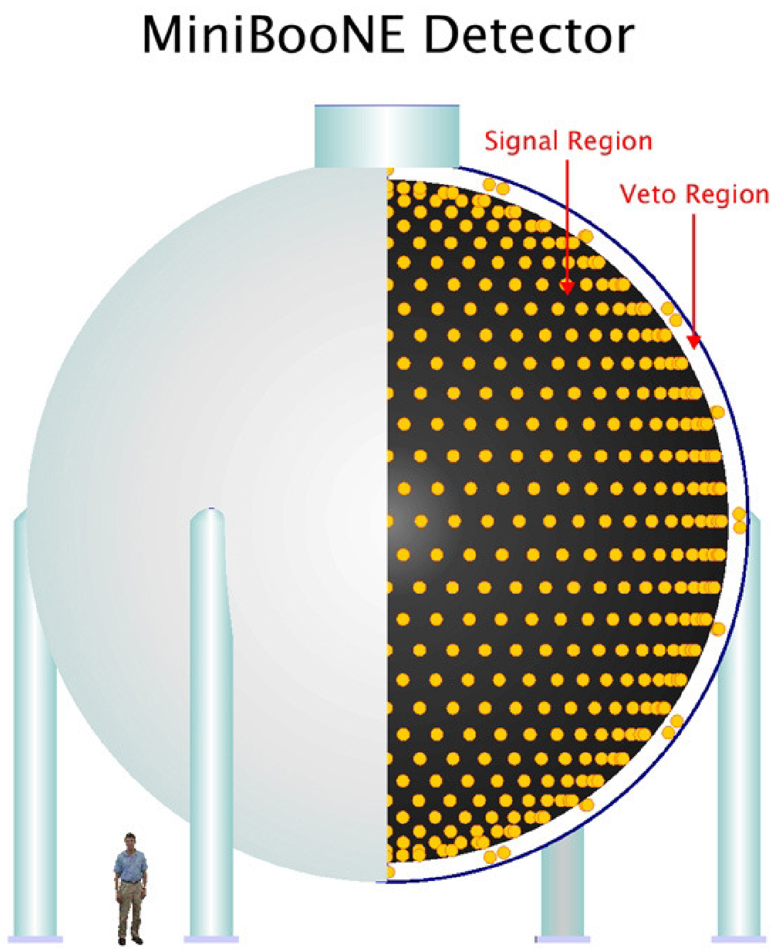
MiniBooNE Detector

- 12 m. diameter spherical tank
- Filled with 800 tons of mineral oil (CH_2)
- Active region lined with 1280 PMTs
- Outer veto region with 240 PMTs

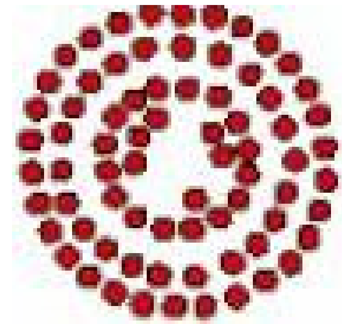
Charged particles in the detector produce mainly Čerenkov light, with a small fraction of light from scintillation.

Čerenkov radiation is analogous to a sonic boom; it occurs when a charged particle is moving faster than the speed of light in the medium.





Particle Detection and Identification in MiniBooNE

Muon:	Little deflection; long, straight track	→ Filled in ring	
Electron:	Scatters multiple times and stops after travelling a short distance.	→ Thin, fuzzy ring	

The length of time for which a particle emits Cerenkov radiation is small compared to the length of an event.

Can divide events into distinct ‘sub-events’.

Fitters characterize each sub-event as electron-like or muon-like, and fit for the kinetic energy and direction of the particle’s track.

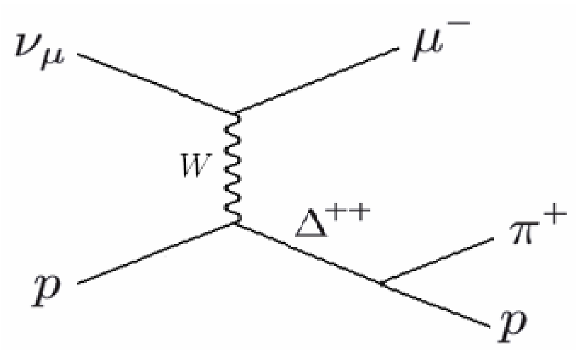
CCπ+ and CCQE Events in MiniBooNE

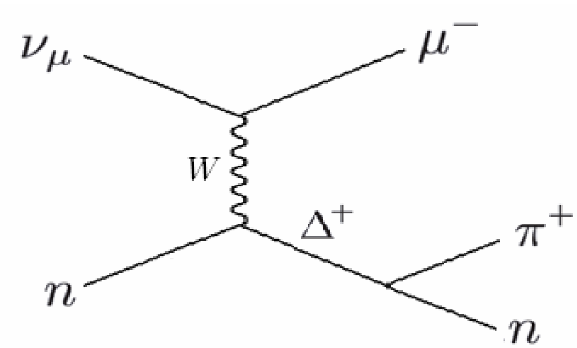
CCπ⁺ Resonant

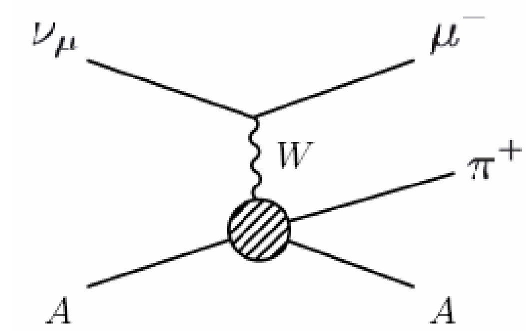
$$\nu_\mu p \rightarrow \mu^- \Delta^{++} \rightarrow \mu^- p \pi^+$$
$$\nu_\mu n \rightarrow \mu^- \Delta^{+} \rightarrow \mu^- n \pi^+$$

CCπ⁺ Coherent

$$\nu_\mu A \rightarrow \mu^- A \pi^+$$

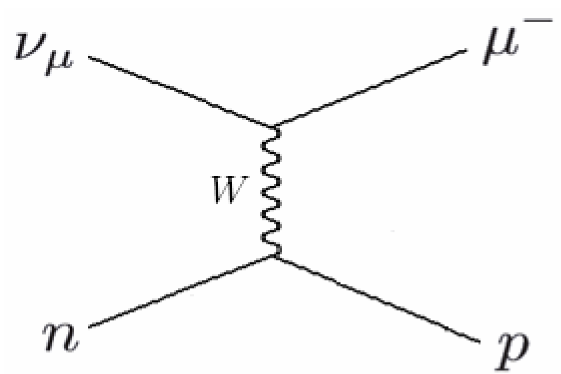






CCQE

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



We expect about 24% of neutrino events to be CCPi+ and 40% CCQE.

Of the CCPi + events, less than 10% are expected to be produced coherently.

$CC\pi^+$/CCQE Ratio Measurement

Measure the $CC\pi^+$ to CCQE cross section ratio rather than the absolute $CC\pi^+$ cross section in order to eliminate flux uncertainties.

Monte Carlo used to predict the cut efficiency and signal fraction as a function of energy for each sample.

Use these to correct the raw numbers of events in each sample to true number of events of each type.

f = signal fraction = (signal events passing cuts)/(events passing cuts)

ε = cut efficiency = (signal events passing cuts)/(signal events)

U = Energy unsmearing matrix (I'll discuss this in a moment)

$$\frac{\sigma_{ccpip,i}}{\sigma_{ccqe,i}} = \frac{\epsilon^{-1}_{ccpip,i} * \sum_j U_{ij} * f_{ccpip,j} * N_{ccpip-cuts,j}}{\epsilon^{-1}_{ccqe,i} * \sum_j U_{ij} * f_{ccqe,j} * N_{ccqe-cuts,j}}$$

Observed Ratio and Corrected Ratio

Observed ratio: Ratio of $CC\pi^+$-like to CCQE-like events defined in terms of final state particles.

Includes corrections for re-interactions in the detector.

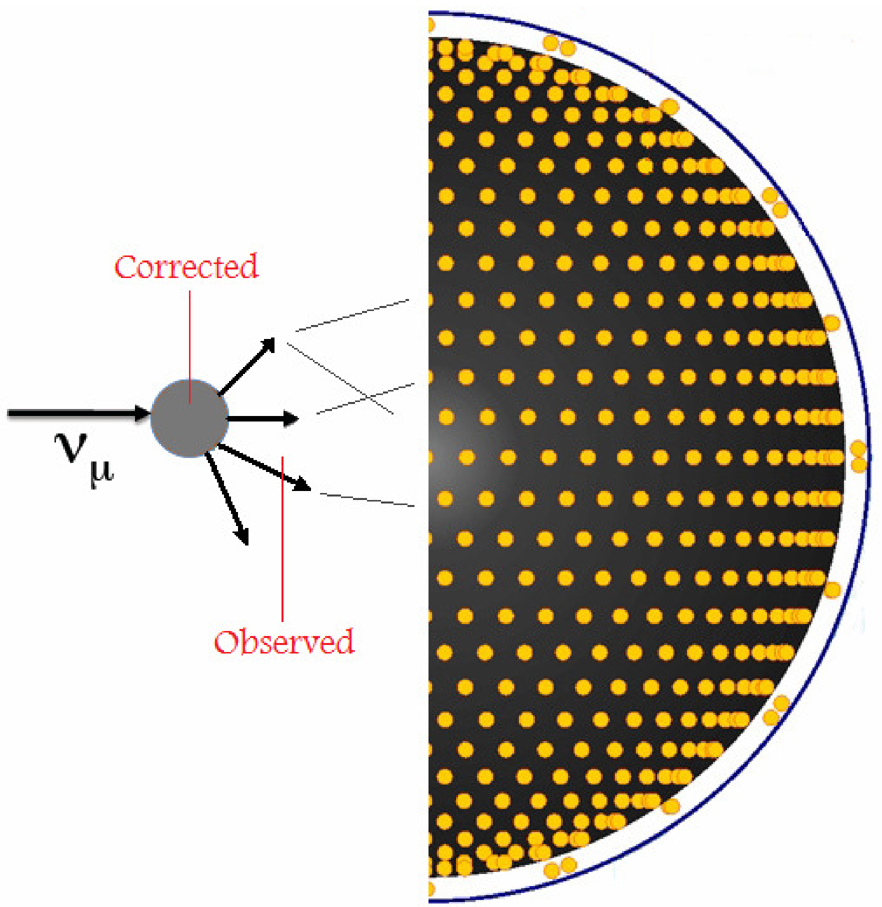
$CC\pi^+$-like:
- One μ^- and no other muons
- One π^+ and no other pions
- No additional hadrons other than protons or neutrons

CCQE-like:
- One μ^- and no other muons
- No hadrons other than protons or neutrons

Corrected ratio: Ratio of $CC\pi^+$ to CCQE events defined in terms of nucleon-level interaction.

Includes corrections for re-interactions in the nucleus and in the detector.

More model-dependent, but needed to compare results with previous experiments.



Event Selection

Our event selection is quite simple.

$CC\pi^+$ events are identified by:

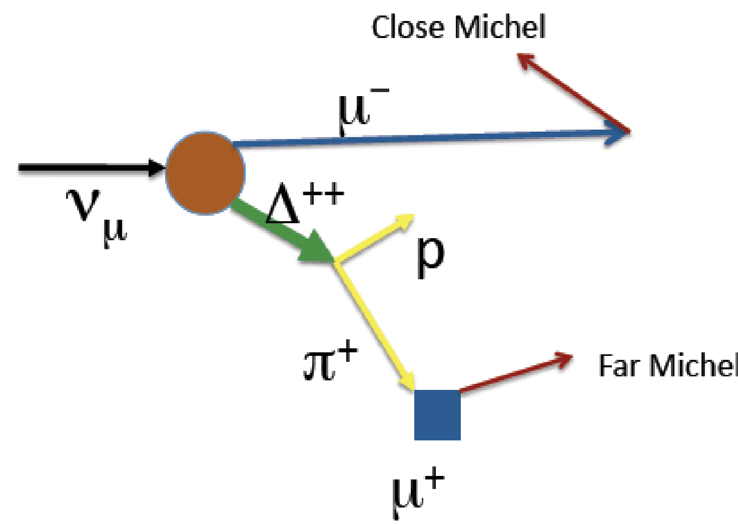
1. The outgoing muon
2. The decay electron at the end of the muon's track
3. The decay positron at the end of the pion's track

CCQE events are identified by:

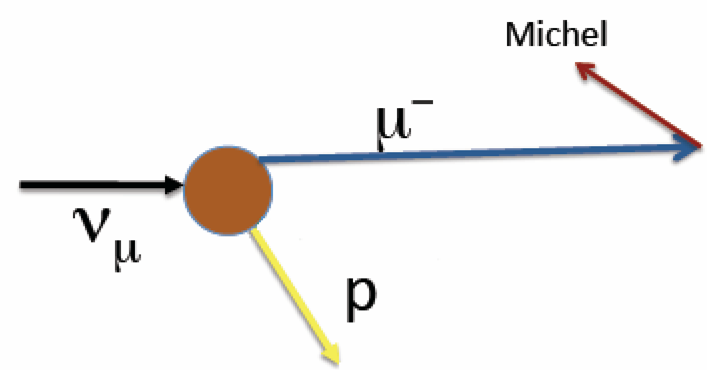
1. The outgoing muon
2. The decay electron at the end of the muon's track

These simple cuts are very effective at selecting the event samples.

Additional cuts are used to improve purity.



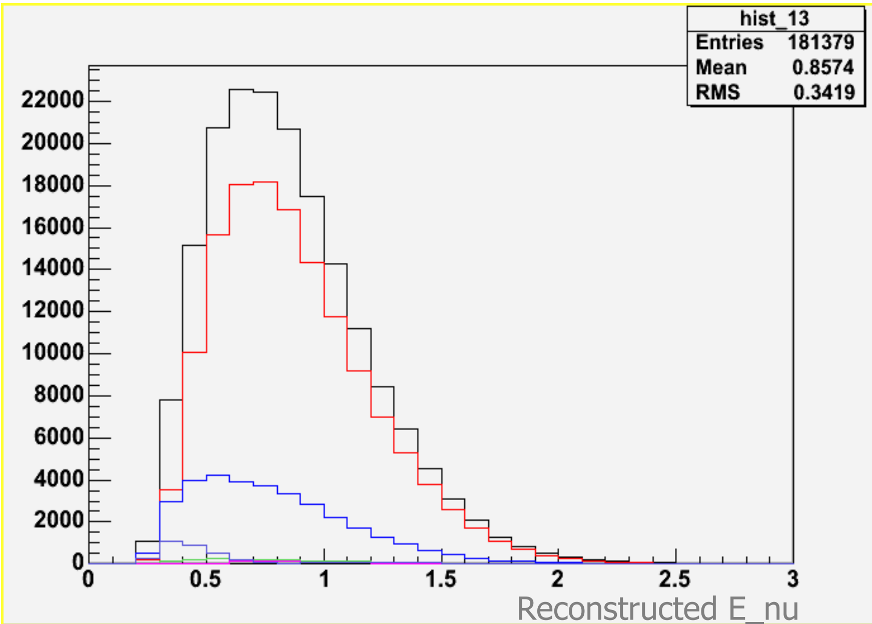
$CC\pi^+$ event



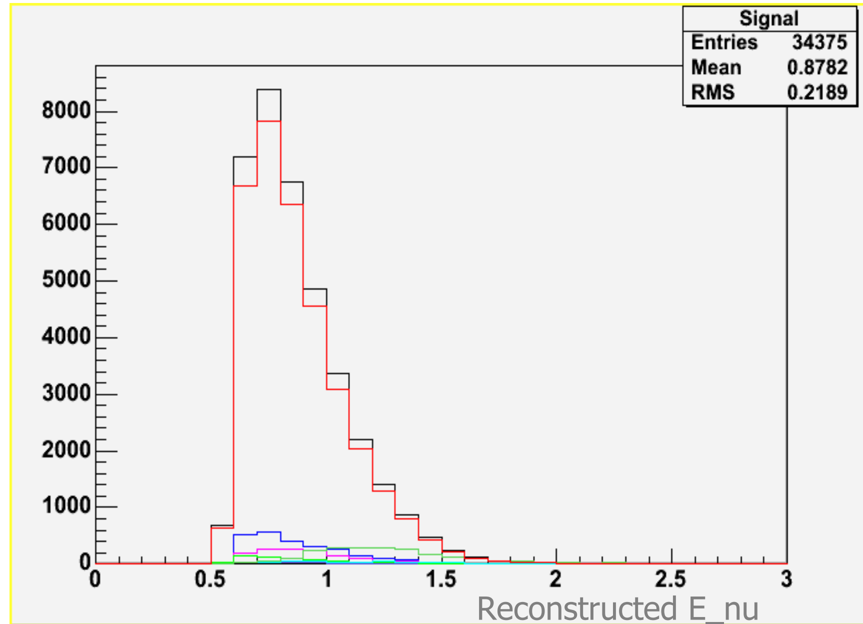
CCQE event

Event Samples

CCQE Sample



CCπ^+ Sample



CCQE (red)	72.0 %
CCπ^+ resonant (blue)	18.3 %
CCπ^+ coherent (green)	1.1 %
NCπ^0 (dark purple)	2.0 %
Multi-pion (light purple)	0.5 %
Other	6.1 %

CCπ^+ total	86.8%
CCπ^+ resonant (red)	80.9%
CCπ^+ coherent (dark blue)	5.9 %
CCQE (dark green)	5.2 %
Multi-pion (light purple)	3.8 %
CCπ^0 (light green)	1.5 %
DIS (light blue)	1.0 %
Other	1.6 %

Energy Unsmearing

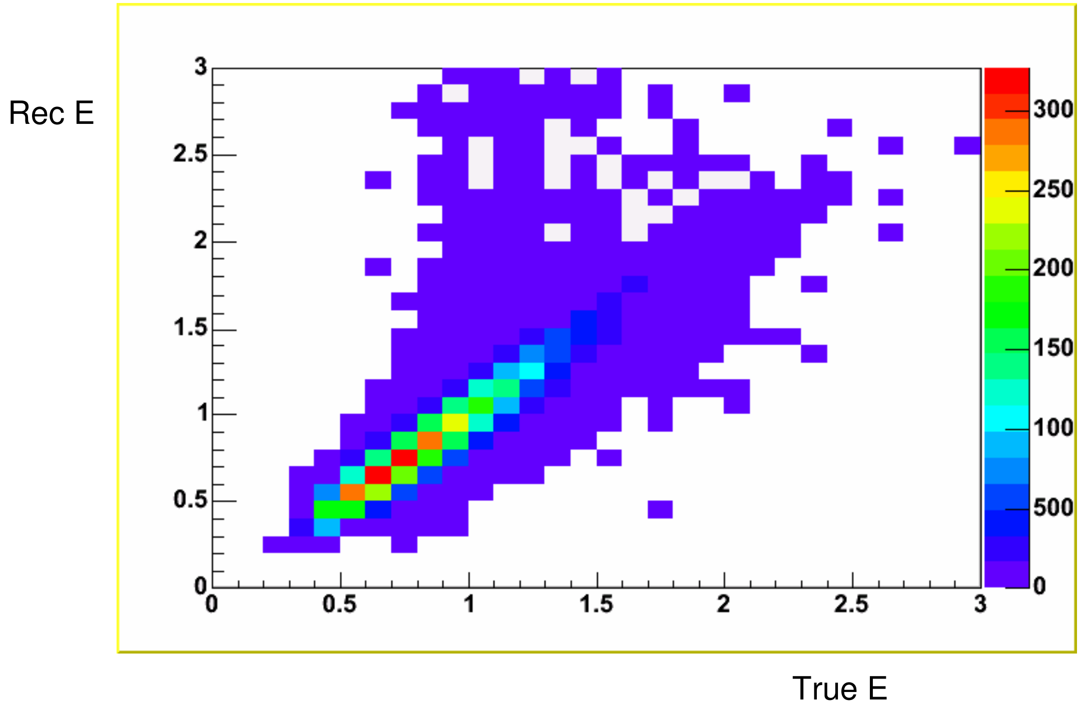
Reconstructed neutrino energy is in general not the same as true neutrino energy due to smearing in reconstruction.

We need to deconvolute or unsmear our neutrino energy distributions to obtain a physically meaningful quantity.

The first step is easy: use MC to form a migration matrix of reconstructed energy vs. true energy.

The standard approach is to then normalize each true energy bin to form a smearing matrix and invert to find the unsmearing matrix.

Matrix inversion, however, has serious problems of numerical instability and is not always viable. It wasn't practical in our case.



Energy Unsmearing

Bayes's Theorem:

$$P(T_i|R_j) = \frac{P(R_j|T_i)P(T_i)}{P(R_j)}$$

$$= \frac{P(R_j|T_i)P(T_i)}{\Sigma_l P(R_j|T_l)P(T_l)}$$

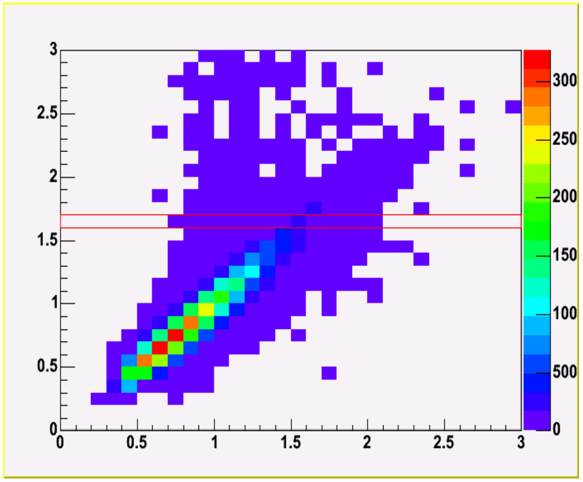
$$= \frac{M_{ij}}{\Sigma_l M_{lj}}$$

Our method uses Bayes's theorem, treating the true energy distribution assumed in the MC as the prior probabilities.

All the problems associated with matrix inversion are avoided.

The result is, however, biased by our MC. This is not necessarily a bad thing, but as a result we need to include a systematic uncertainty on the unsmearing.

See: G. D'Agostini, Nucl. Instr. Meth. A362, 487 (1995)

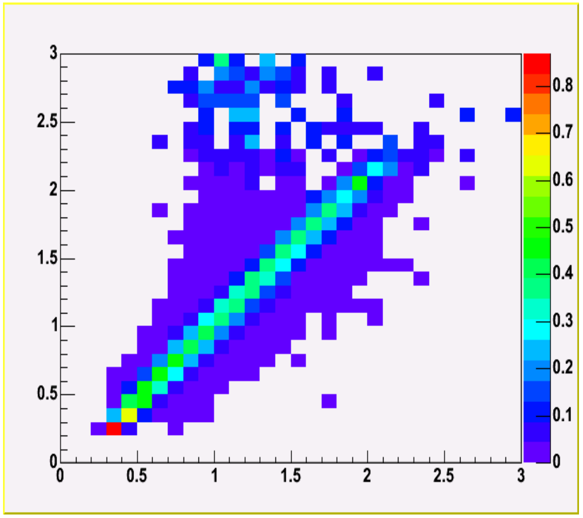


Migration Matrix

↓

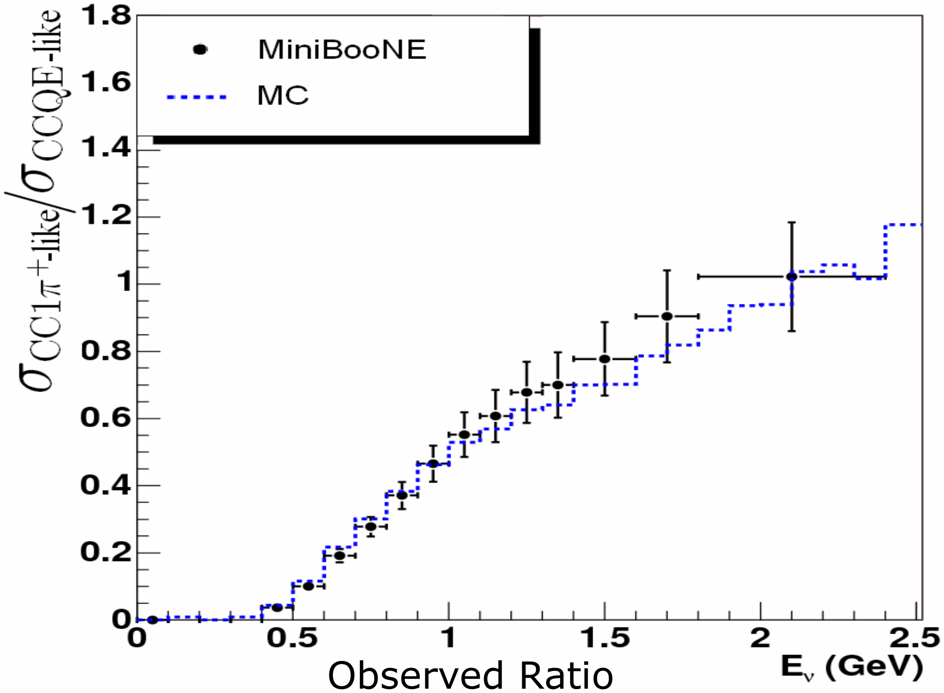
Normalize by reconstructed energy

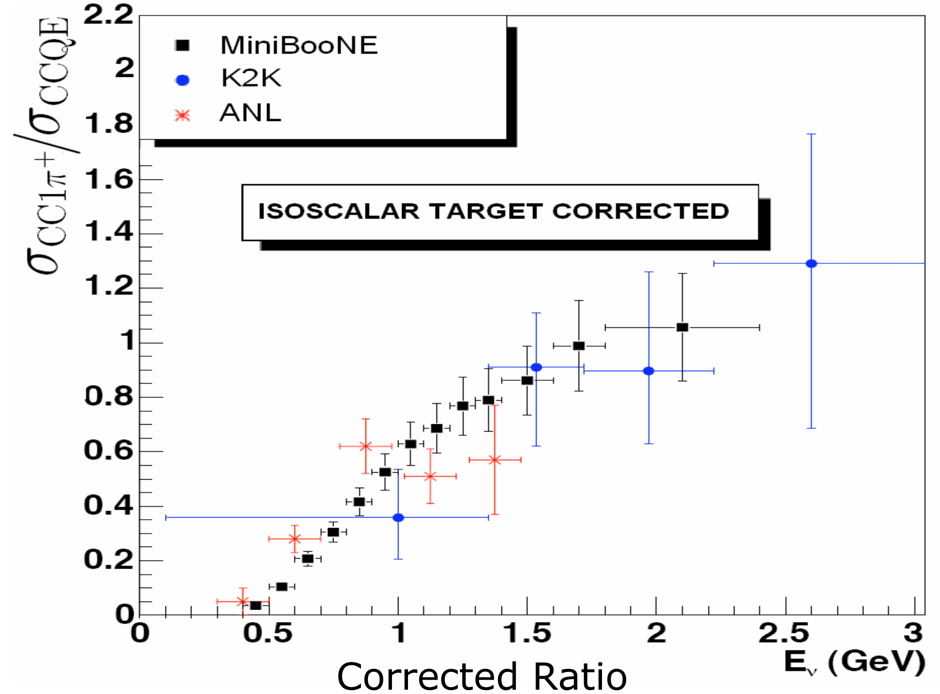
↓



Unsmearing matrix

Results





At left: Observed ratio (without nuclear corrections) compared with Monte Carlo based on Rein-Sehgal and Smith-Moniz.

At right: Corrected ratio (with corrections for nuclear re-scattering) compared with previous measurements at ANL (1) and K2K (2).

Here the MiniBooNE and K2K ratios have been corrected for an isoscalar target (ANL's measurement was already on an isoscalar target).

Rough breakdown of fractional uncertainty: 8% rescattering in detector, 6% neutrino cross-sections, 4% detector simulation, 2% flux, 2% statistics

(1) G.M. Radecky et al., Phys. Rev. D 25, 1161 (1982)
(2) K2K Collaboration: A. Rodriguez et al., arXiv:0805.0186

Summary

This is the first high-precision CCπ^+ cross section measurement.

Our results are consistent with both previous experiments and predictions based on the Rein-Sehgal and Smith-Moniz models.

A paper is available at arXiv:0904.3159v1 [hep-ex] and has been submitted to PRL.

These results are an important step toward:

- Improving our models for pion production
- Understanding intra-nuclear re-interactions
- Removing backgrounds in future oscillation experiments that (we hope) will lead to θ_{13} and CP violation.