Neutrino Cross-sections
PIC 2012

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Outline

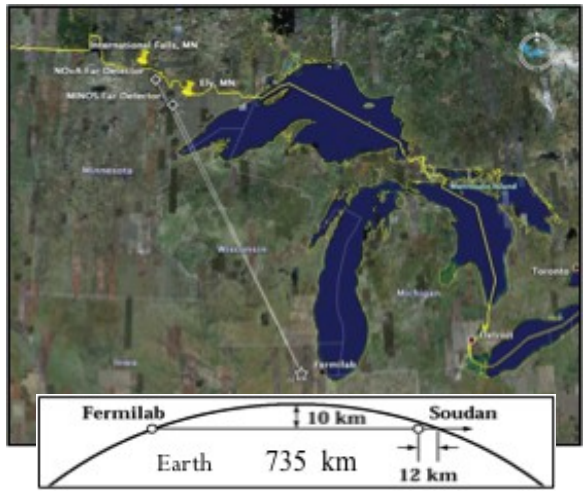
- Introduction
  - Why we care about neutrino cross-sections
  - Types of neutrino interactions
- Recent measurements
  - MiniBooNE
  - T2K
  - MINERνA
  - ArgoNeuT
- Conclusion

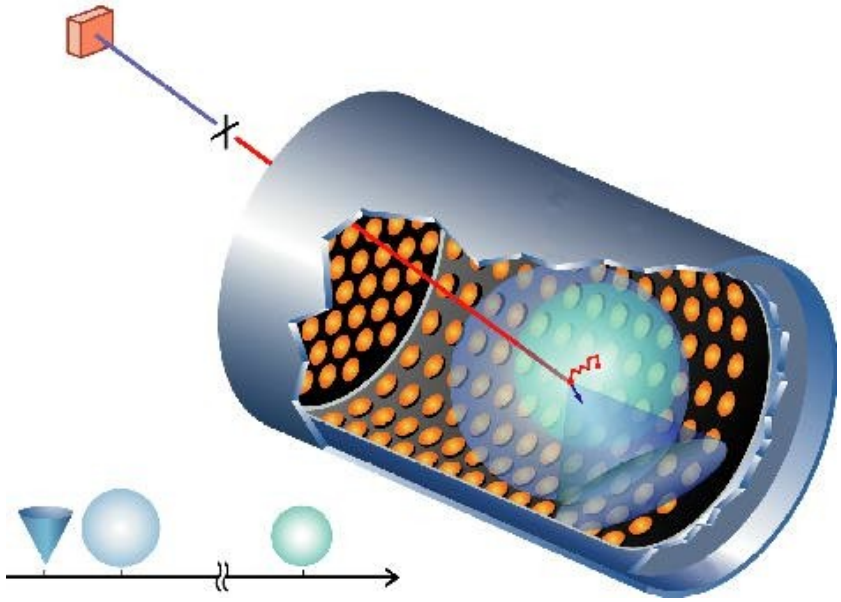
Introduction

- Why do we care about neutrino cross-sections?
  - A major focus of the global neutrino physics program:

Neutrino Oscillations

Can be studied via short and long baseline accelerator-based experiments



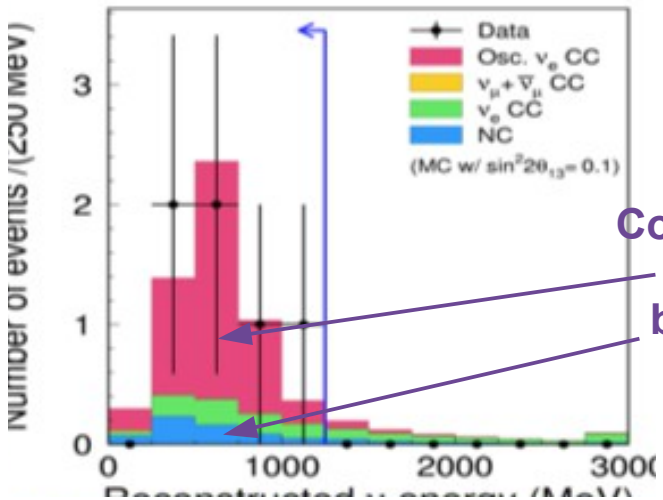


- May answer many interesting questions:
  - Why is neutrino mixing so different than quark mixing?
  - Is there CP violation in the neutrino sector?
  - Are there sterile neutrinos?

Introduction

- Why do we care about neutrino cross-sections?
  - Knowledge of neutrino cross-section is crucial to oscillation measurements

T2K – Neutrino 2012



Combination of signal and background

TABLE III. Contributions from various sources and the total relative uncertainty for $\sin^2 2\theta_{13}$=0 and 0.1, and $\delta_{CP} = 0$.

T2K -- PRL 107, 041801 (2011)

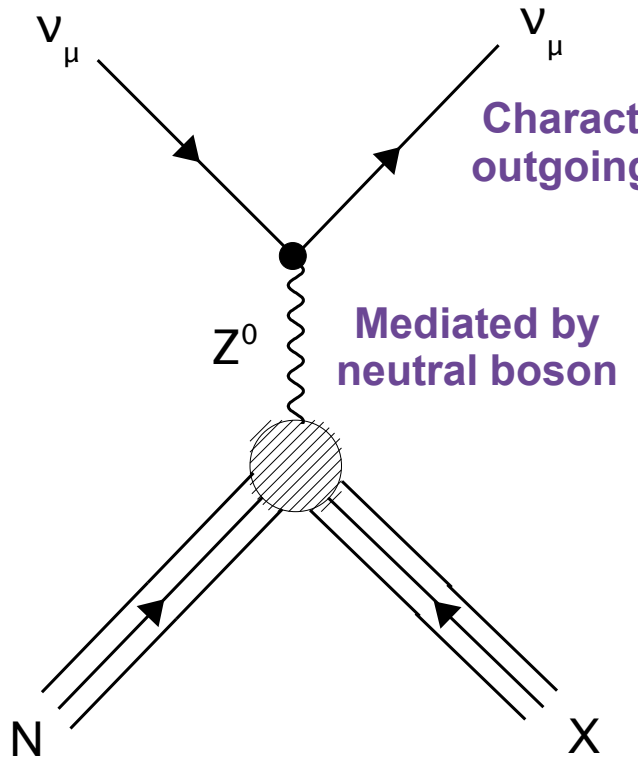
Source	$\sin^2 2\theta_{13} = 0$	$\sin^2 2\theta_{13} = 0.1$
(1) neutrino flux	$\pm$ 8.5%	$\pm$ 8.5%
(2) near detector	$^{+5.6}_{-5.2}$%	$^{+5.6}_{-5.2}$%
(3) near det. statistics	$\pm$ 2.7%	$\pm$ 2.7%
(4) cross section	$\pm$ 14.0%	$\pm$ 10.5%
(5) far detector	$\pm$ 14.7%	$\pm$ 9.4%
Total $\delta N_{SK}^{exp}/N_{SK}^{exp}$	$^{+22.8}_{-22.7}$%	$^{+17.6}_{-17.5}$%

Cross-sections in the 0.2-10 GeV range are particularly crucial to accelerator-based oscillation measurements.

-> these cross-sections are the focus of this talk.

Introduction

- Types of Neutrino-Nucleus Interactions:



Characterized by outgoing neutrino

Mediated by neutral boson

"Neutral Current"

Background to ν_e appearance

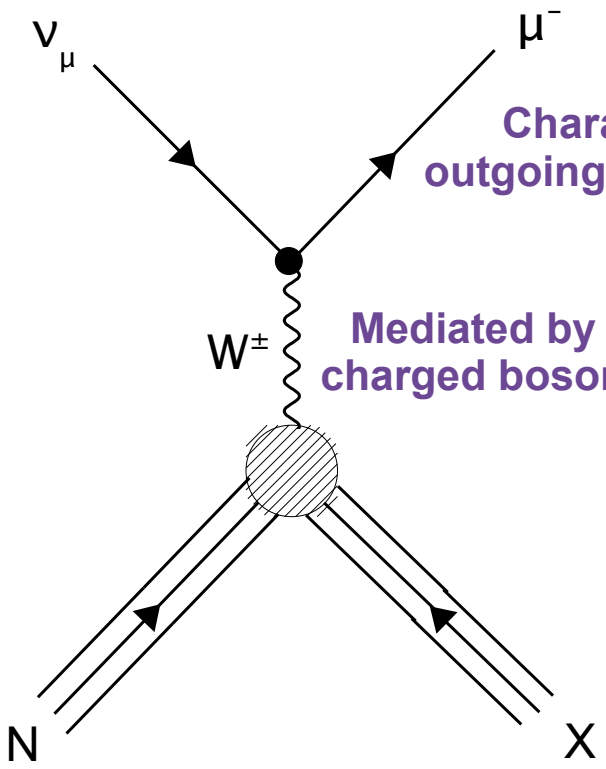
Examples

NC π^0	$\nu_\mu + n \longrightarrow \nu_\mu + p + \pi^0$
NC elastic	$\nu_\mu + n \longrightarrow \nu_\mu + p$
NC inclusive	$\nu_\mu + n \longrightarrow \nu_\mu + X$
NC π	$\nu_\mu + n \longrightarrow \nu_\mu + p + \pi^0$

Background to ν_μ disappearance

Introduction

- Types of Neutrino-Nucleus Interactions:



"Charged Current"

Examples

CC Inclusive	$\nu_\mu + n \rightarrow \mu^- + X$
CC π	$\nu_\mu + n \rightarrow \mu^- + p + \pi$
CC Quasi-elastic	$\nu_\mu + n \rightarrow \mu^- + p$

Signal channel in oscillation experiment

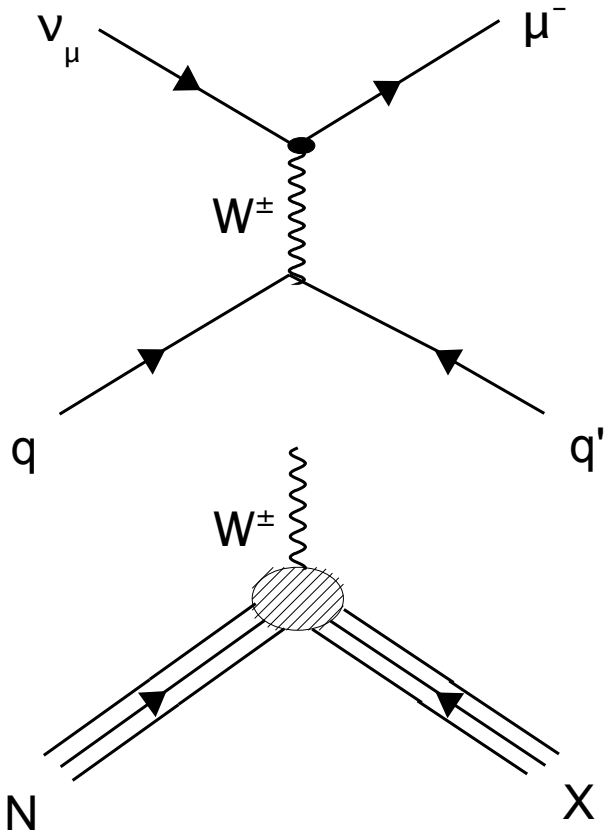
Cross-section experiments generally sit in ν_μ beams

→ cross-section measurements are generally of ν_μ channels

Introduction

What do we know about neutrino cross-sections?

Interaction is a combination of quark-level process



And nucleon component parameterized by form factors; taken from experiment

The nucleon is usually contained within a heavy nucleus, which further complicates the situation

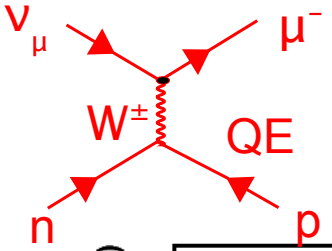
	Materials	Energy Range (GeV)
MiniBooNE	CH_2	0.2-2 (BNB)
SciBooNE	C_8H_8	0.2-2 (BNB)
T2K ND280	C,O,$H_2$0	0.2-2 (JPARC)
MINERvA	CH,C,Pb,Fe,$H_2$0,He	1-20 (NuMI)
NOMAD	CH	3-100 (SPS)
MINOS	Fe	1-20 (NuMI)
ArgoNeuT	Ar	1-20 (NuMI)

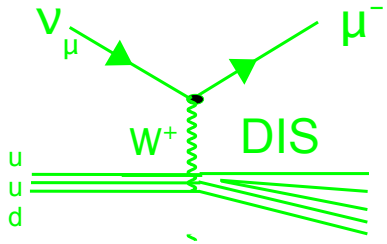
Effect of nucleus is poorly understood, but can have big impact on interpretation of oscillation results

→ **understanding nuclear effects is a major goal of cross-section experiments**

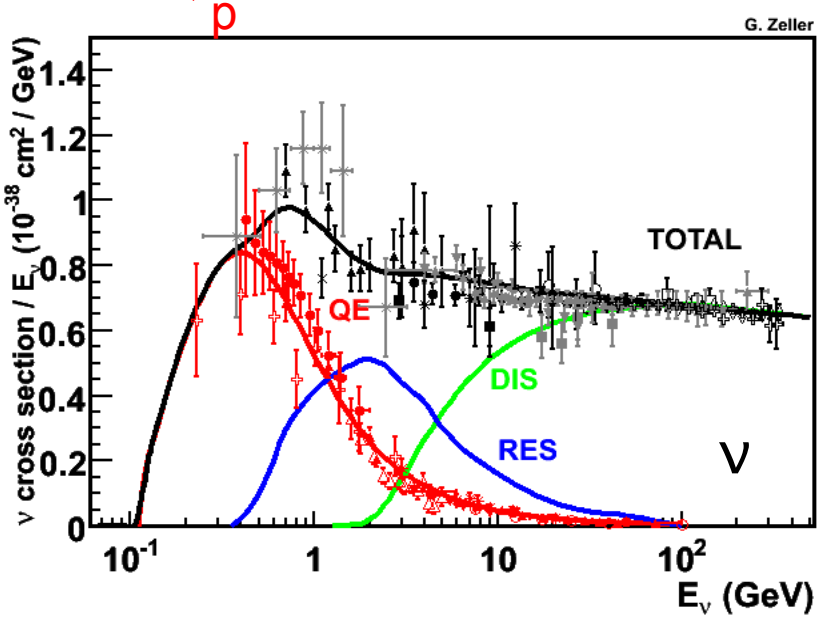
Introduction

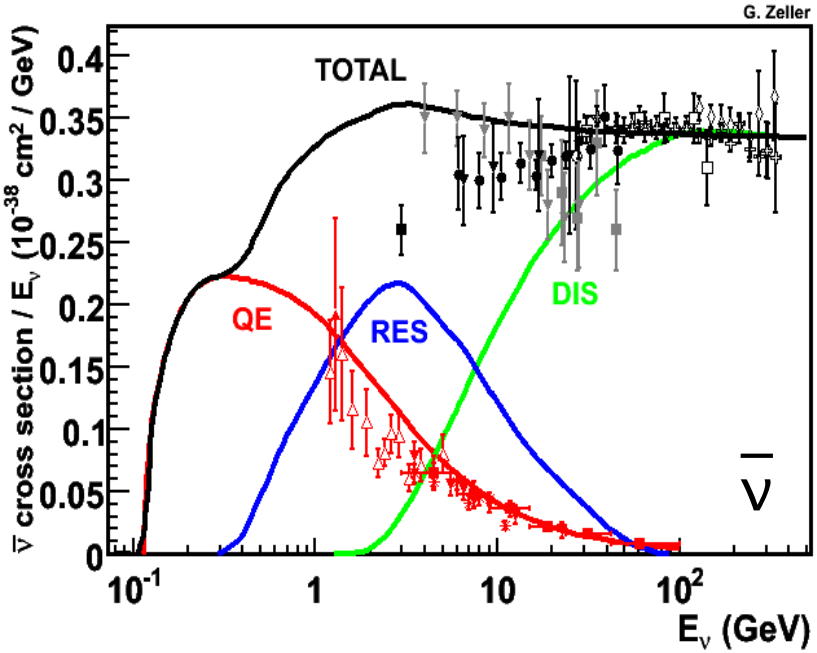
- What do we know about neutrino cross-sections?

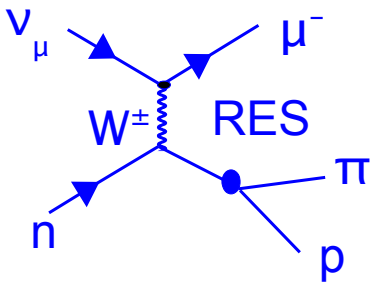




Nucleon form factors and nuclear effects have to be taken from data, but the data have larger error bars





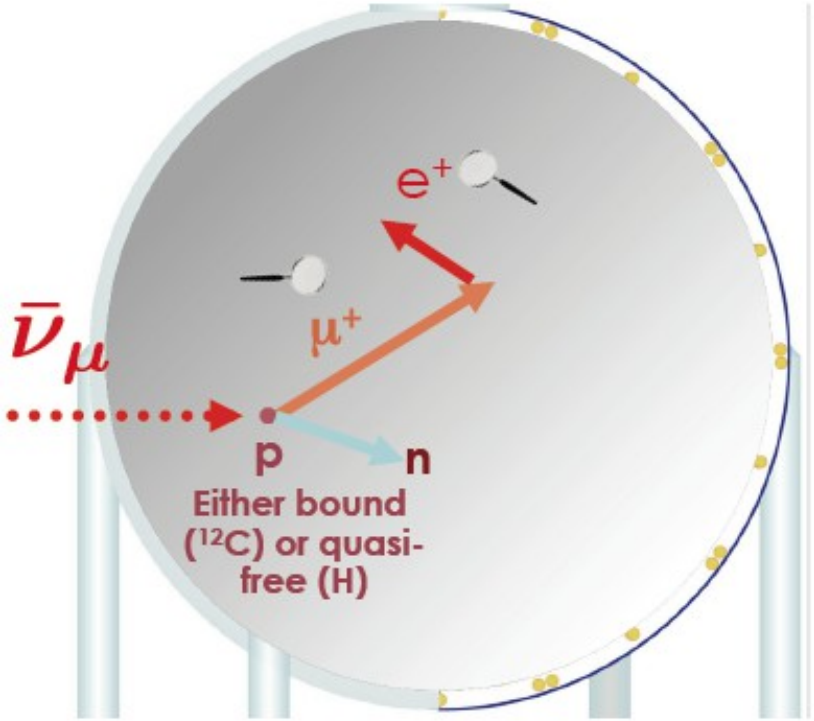


Dominant interaction type changes dramatically over the 0.2-10 GeV energy range of interest
→Complicates reconstruction neutrino energy (critical for oscillation measurements)

Introduction

- How do we measure neutrino cross-sections?

Set a particle detector in front of a neutrino beam → Then count the number of neutrino interactions and normalize by number of nucleii in the detector and the number of incoming neutrinos



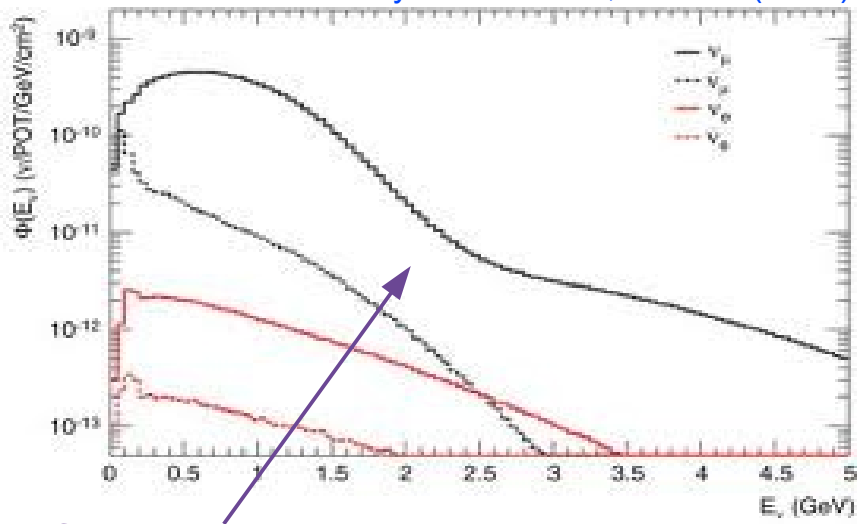
$$\sigma = \frac{N_{obs} - N_{bgd}}{\Phi * N_{targets} * \varepsilon}$$

Number of neutrinos (flux)

Number of nuclei

Reconstruction efficiency

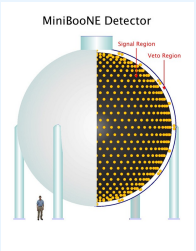
MiniBooNE -- Phys. Rev. D. 79, 072002 (2009)



Experiments spend a lot of time and manpower counting the number of incoming neutrinos (and understanding their energy)

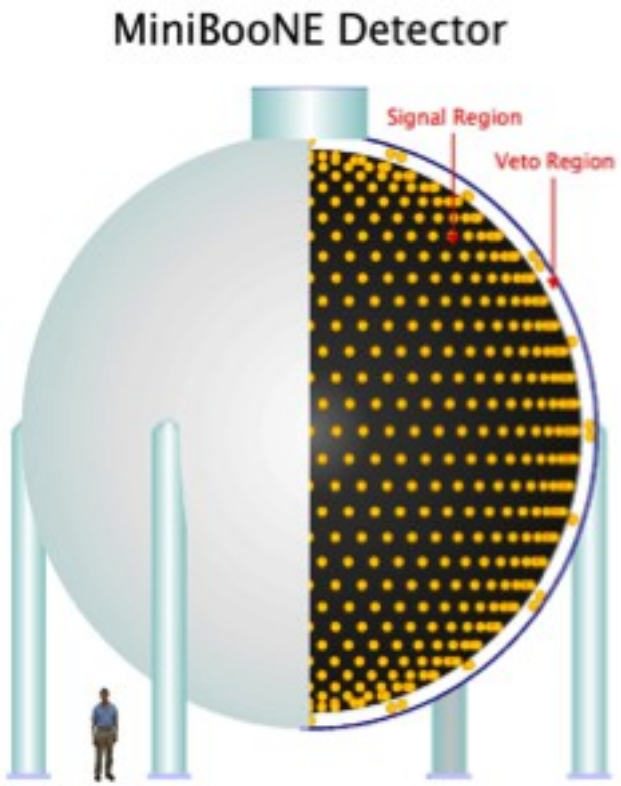
Recent Neutrino Cross-Section Measurements

I focus on very recent measurements, but these results build on the foundation developed by older experiments such as K2K, MINOS, SciBooNE, and NOMAD (not mentioned discussed here due to time constraints)

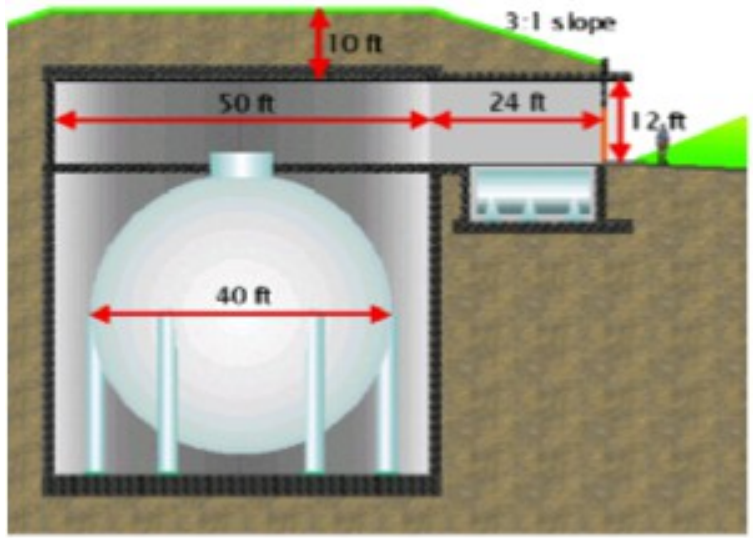


MiniBooNE

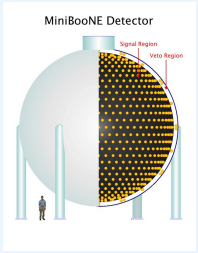
- MiniBooNE:



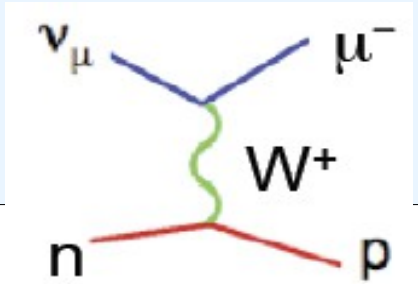
- Cherenkov detector; 12.2 meter diameter sphere of mineral oil; in Booster beam at Fermilab
- Famous as short-baseline oscillation experiment, but a prolific source of cross-section measurements
- Relatively low energy
  - <Eν> ~ 700 MeV



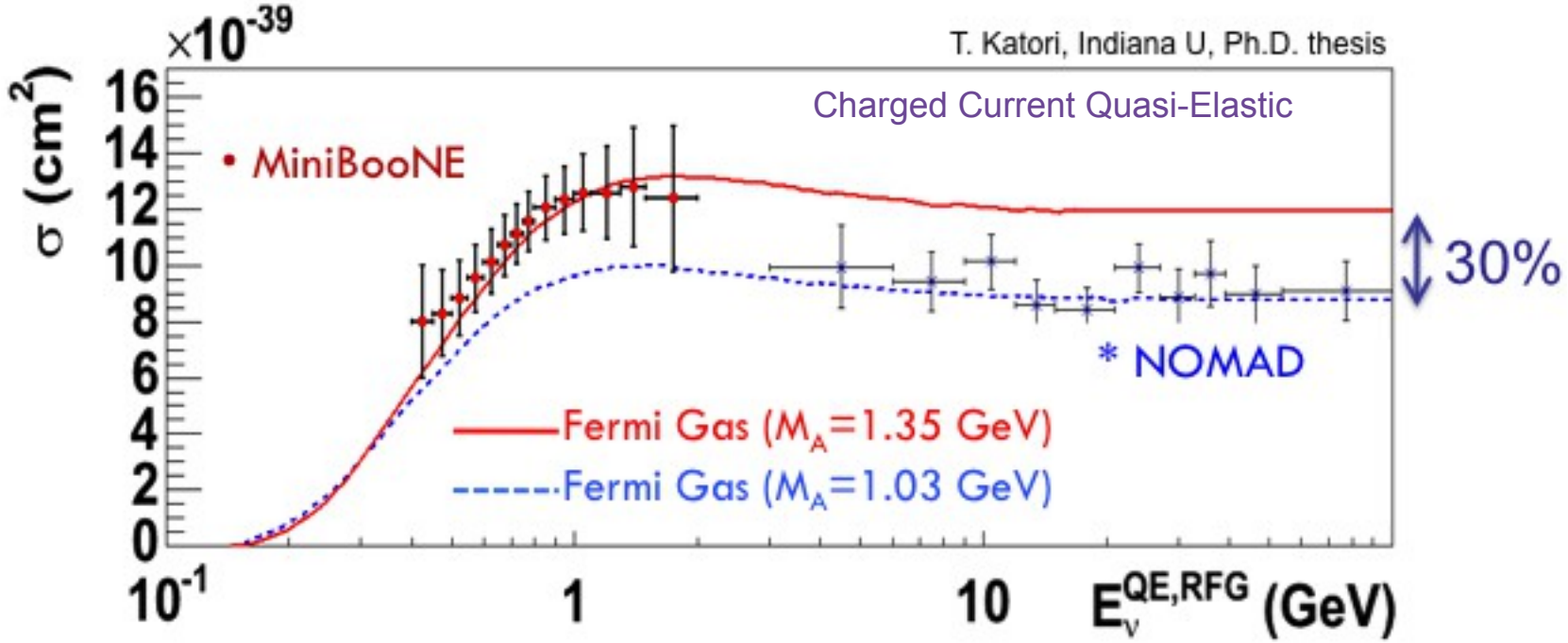
Detector



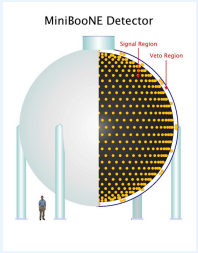
MiniBooNE



- One of MiniBooNE's first cross-section measurements created a mystery:



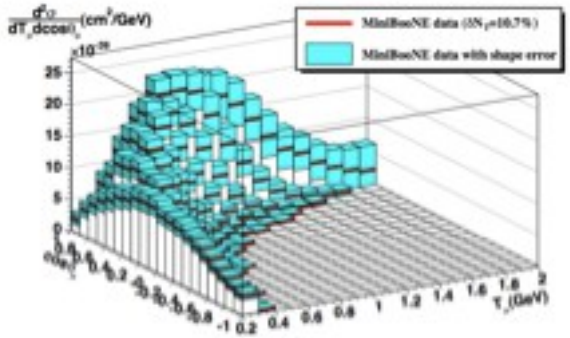
- Tension between MiniBooNE and higher energy measurements
- Possibly a hint of nuclear effects?

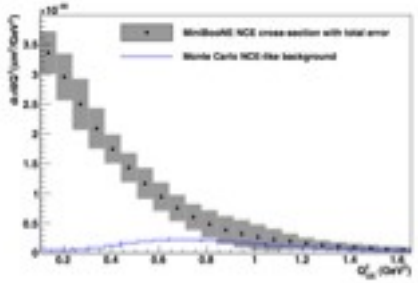


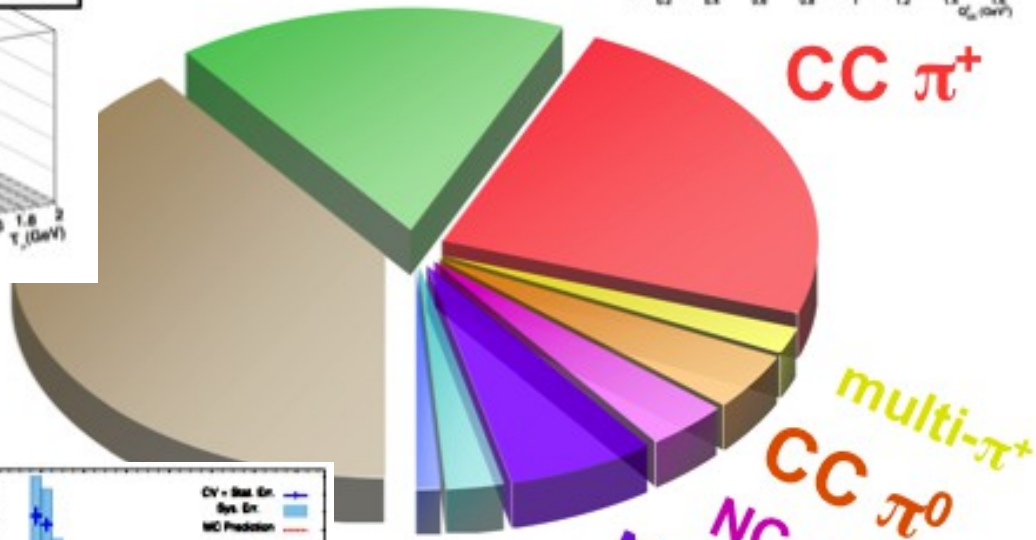
MiniBooNE

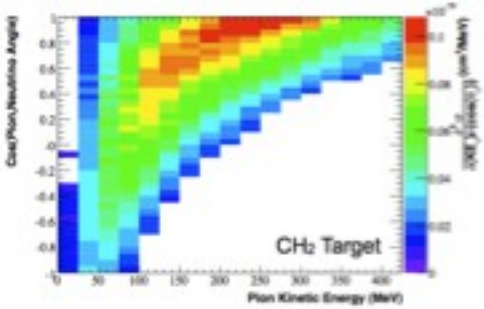
PRD 81, 09005 (2010) **PRD 83**, 052007 (2011)
PRL 100, 032301 (2008) **PRD 83**, 052009 (2011)
PRD 82, 092005 (2010) **PRD 81**, 013005 (2010)
PRL 103, 081801 (2009) **PL B664**, 41 (2008)

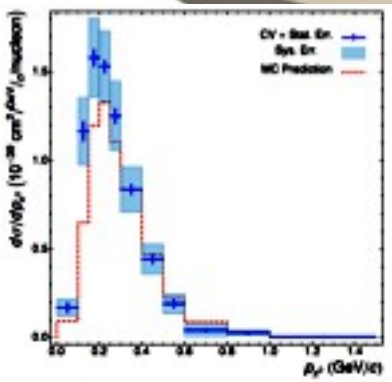
- MiniBooNE is currently completing a very impressive cross-section program:

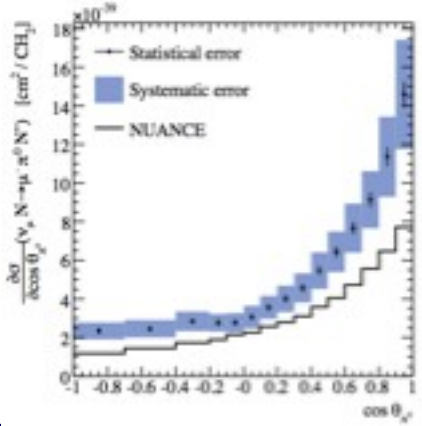








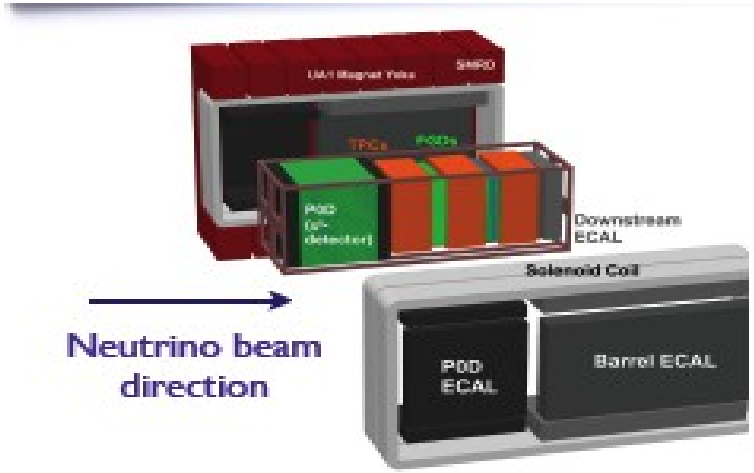


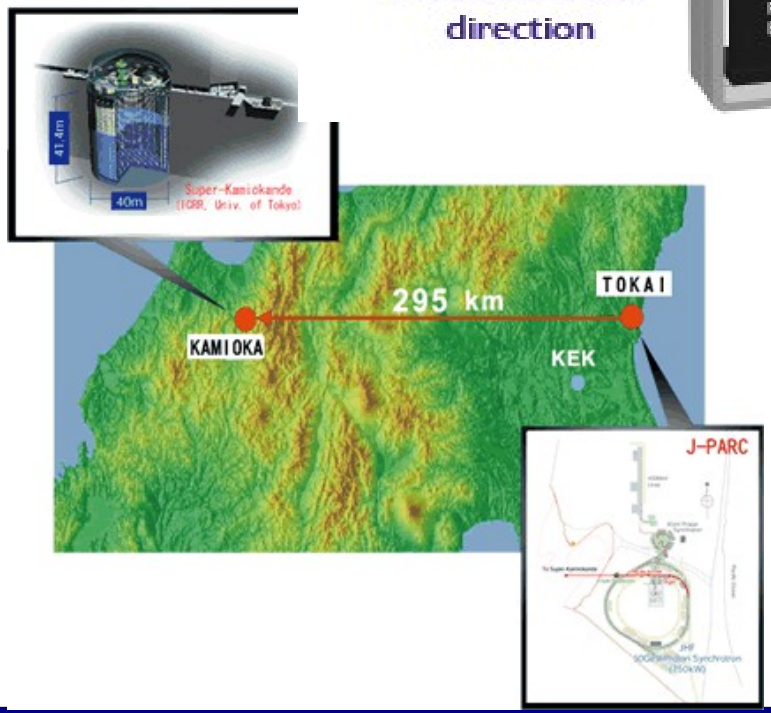


Also working on re-analysis of data in light of new understanding of nuclear effects

T2K Near Detector (ND280)

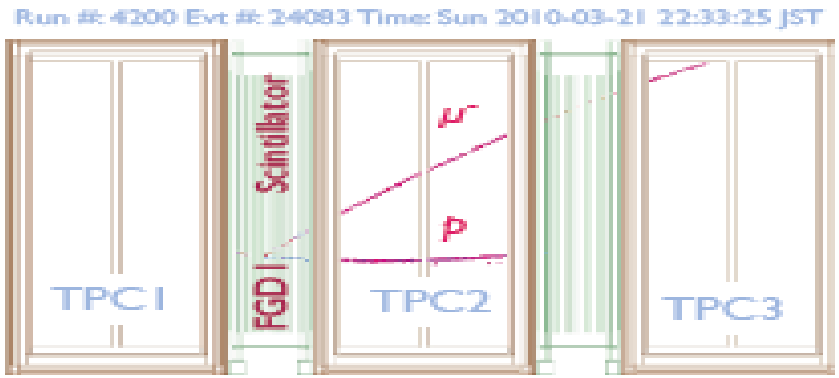
- T2K Near Detector:



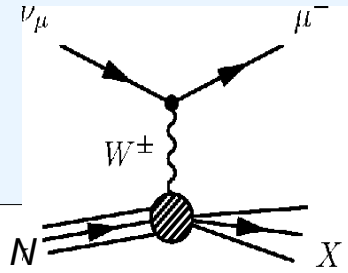


- Suite of detectors that serves as near companion to Super-K for long-baseline studies
- Will measure cross-sections and other inputs to oscillation results
- Similar energy range to MiniBooNE
  - <Eν> ~ 850 MeV

    (peak @ 600 MeV w/ long tail)
- B = 0.2 T Magnetic field

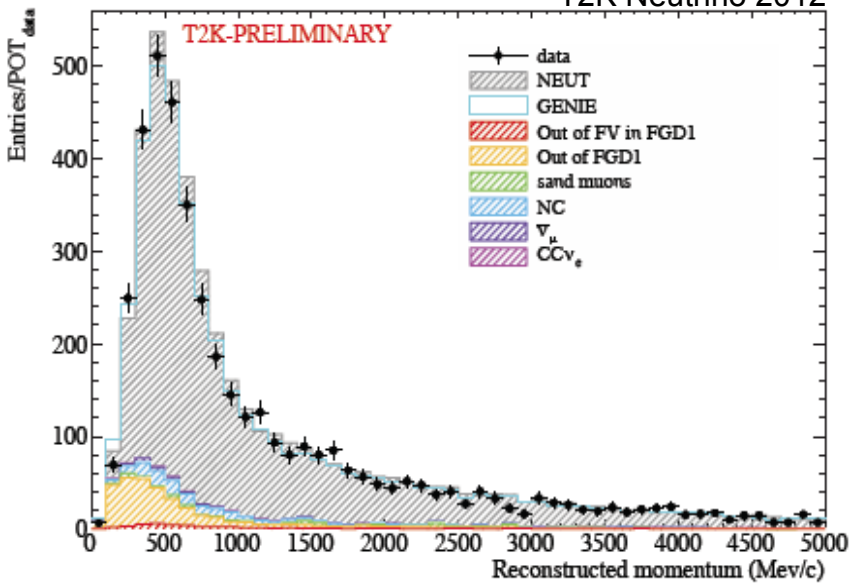


T2K Near Detector (ND280)

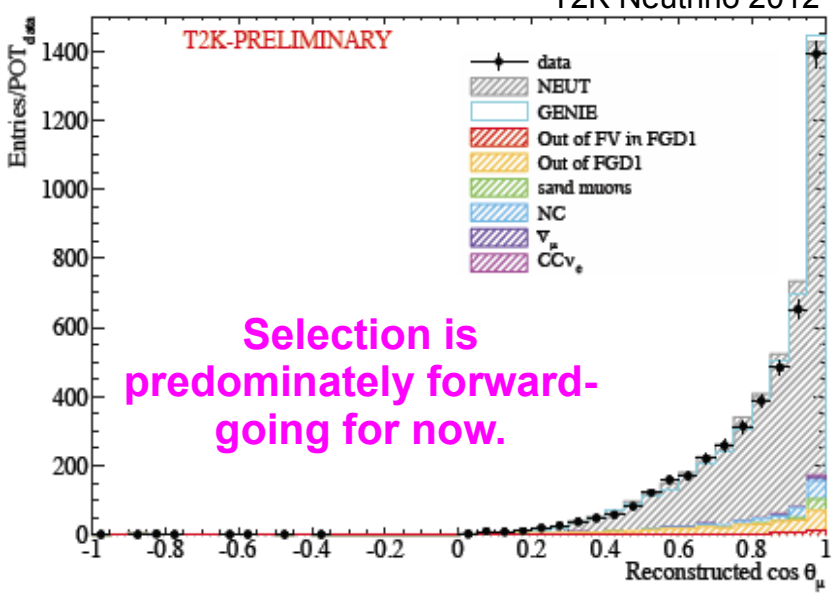


- T2K's first cross-section measurements -- CC Inclusive:

T2K Neutrino 2012



T2K Neutrino 2012



Selection is predominately forward-going for now.

$$\langle \sigma_{CC} \rangle_\phi = (6.93 \pm 0.13(stat) \pm 0.085(syst)) \times 10^{-39} \frac{\text{cm}^2}{\text{nucleons}}$$

Measurement

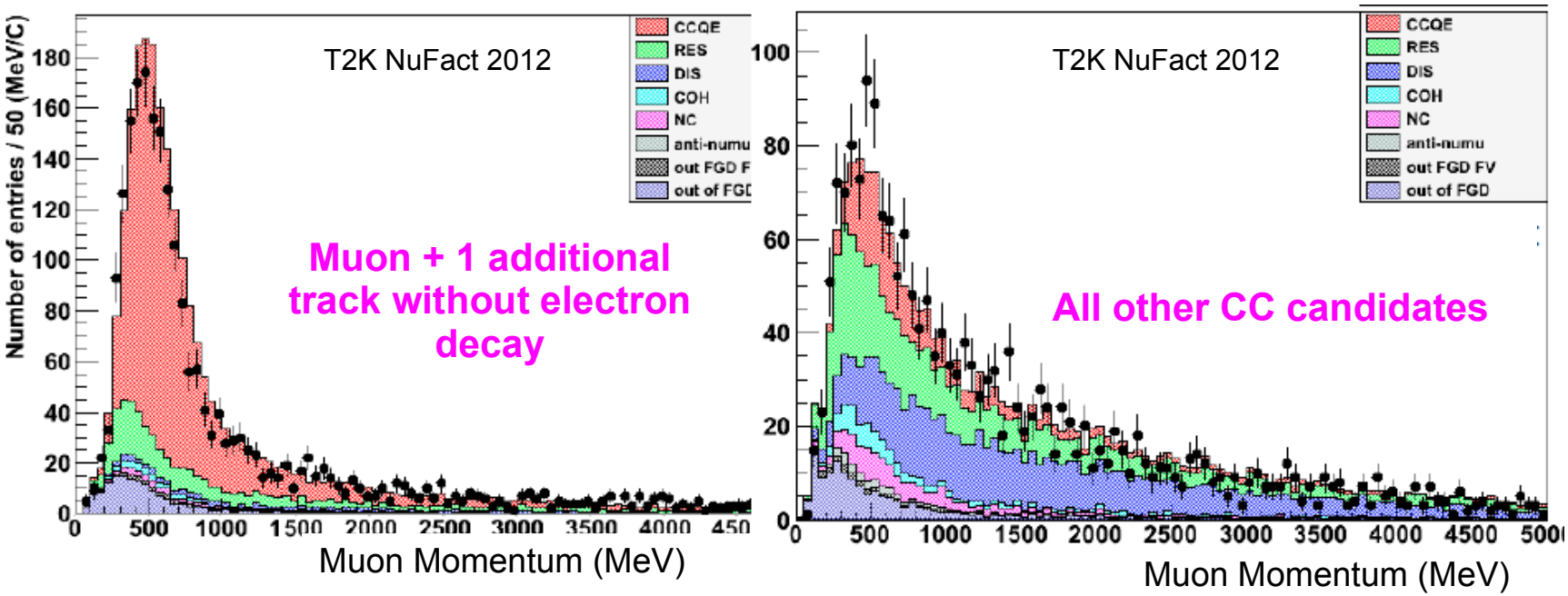
$$\langle \sigma_{CC}^{NEUT} \rangle_\phi = 7.26 \times 10^{-39} \frac{\text{cm}^2}{\text{nucleons}}$$

$$\langle \sigma_{CC}^{GENIE} \rangle_\phi = 6.68 \times 10^{-39} \frac{\text{cm}^2}{\text{nucleons}}$$

Theory Predictions

T2K Near Detector (ND280)

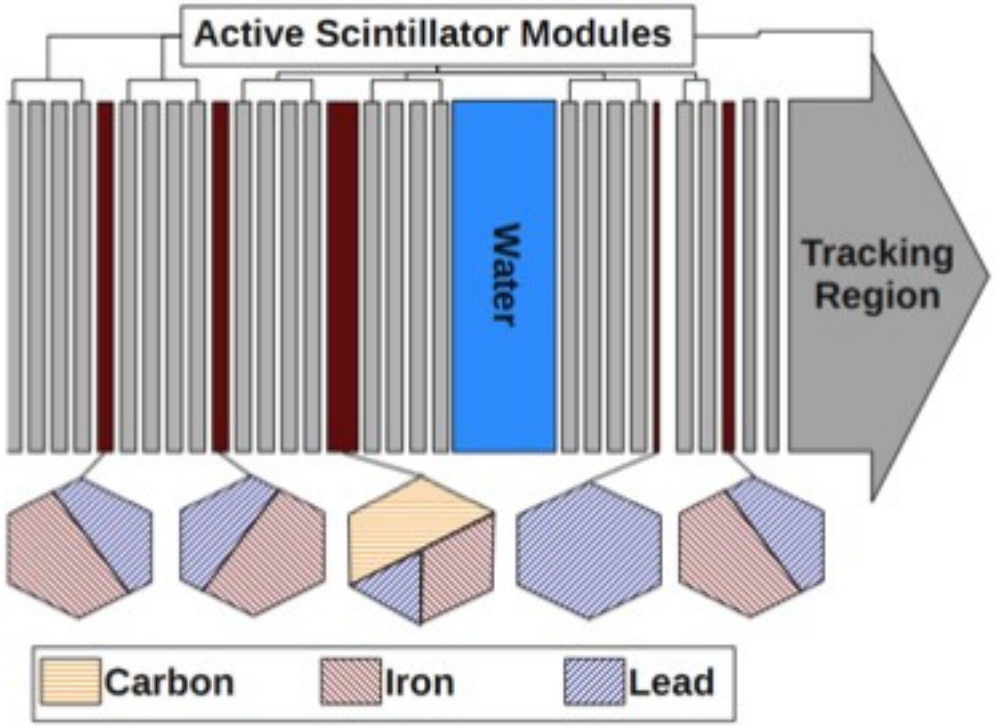
- T2K has also identified CCQE and non-CCQE samples:



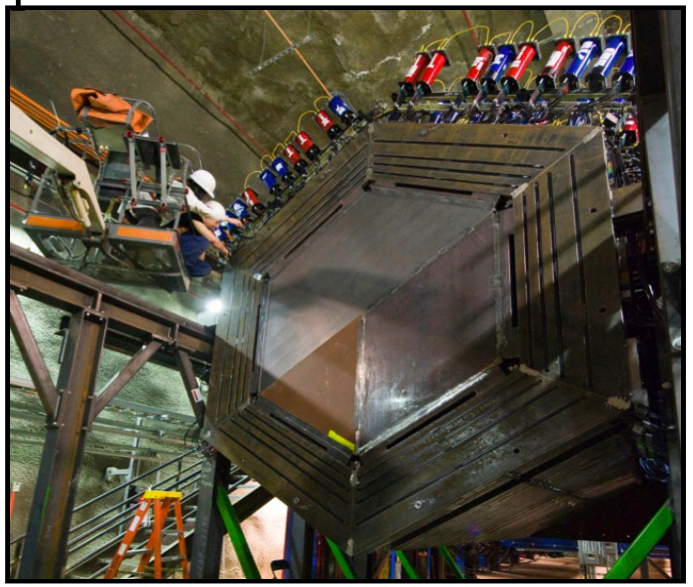
- Used to constrain event rates at far detector as part of measurement of $\nu_\mu \rightarrow \nu_e$
  - Fits extract cross section parameters (e.g. QE M_A and QE norm) that reduce systematic uncertainties at far detector.
- Cross-sections coming soon

MINERvA

- MINERvA: A dedicated neutrino cross-section experiment

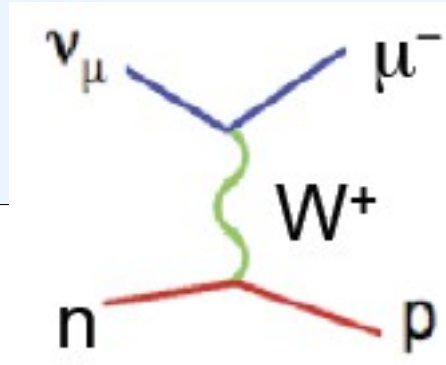


- Large volume of plastic scintillator (CH) interspersed with nuclear targets
- Sits in NuMI beamline at Fermilab directly upstream of MINOS near detector, which is used as a muon spectrometer

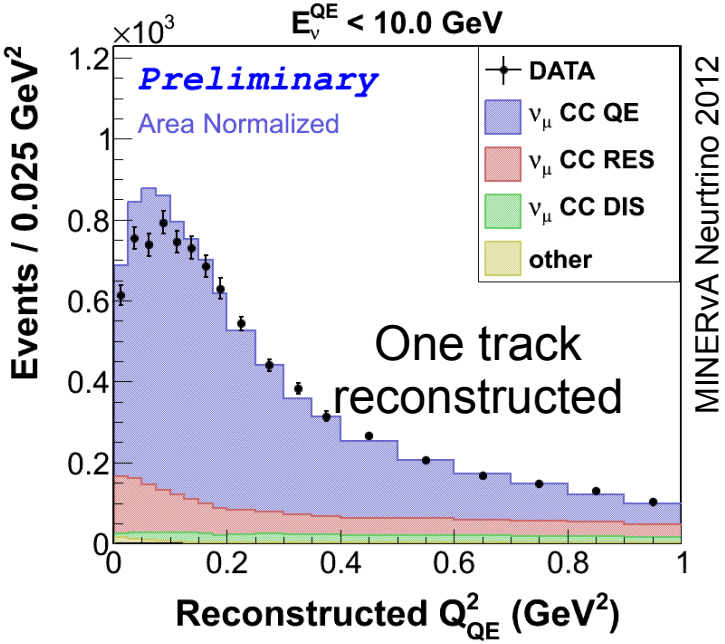


Nuclear targets made of carbon, iron, lead, water and helium will help unravel nuclear component of cross-sections

MINERvA

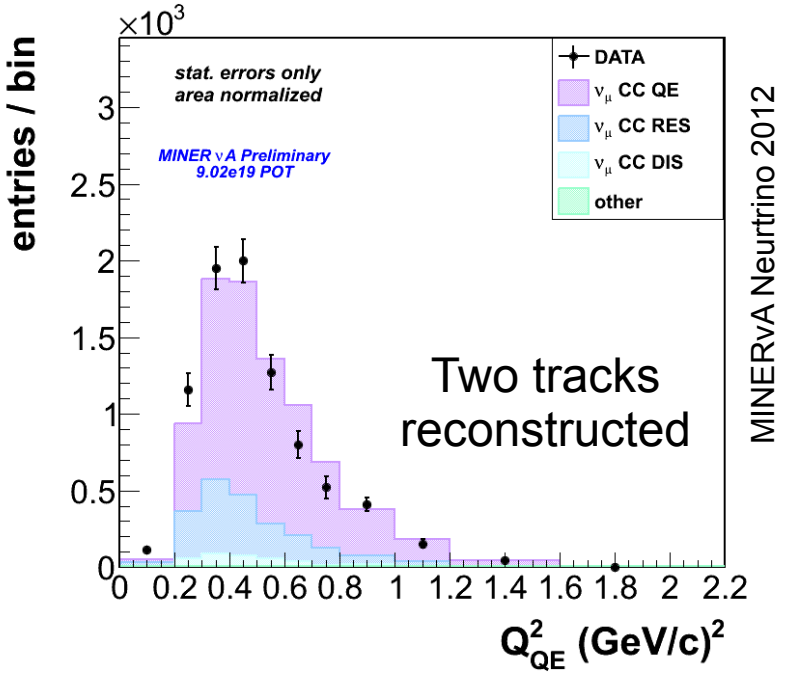


- First neutrino CCQE results:



Large dataset + large volume = high precision cross-section measurements (coming soon!)

Q2 = 4-momentum² transferred to nucleon

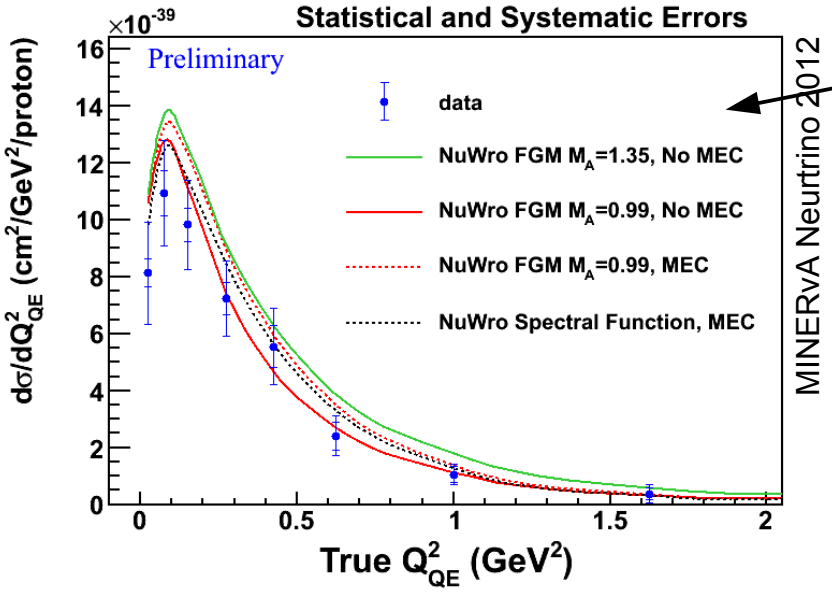


Finally segmented detector = good resolution, low background

Also, ability to measure final state multiplicity -> another handle to understand nuclear effects

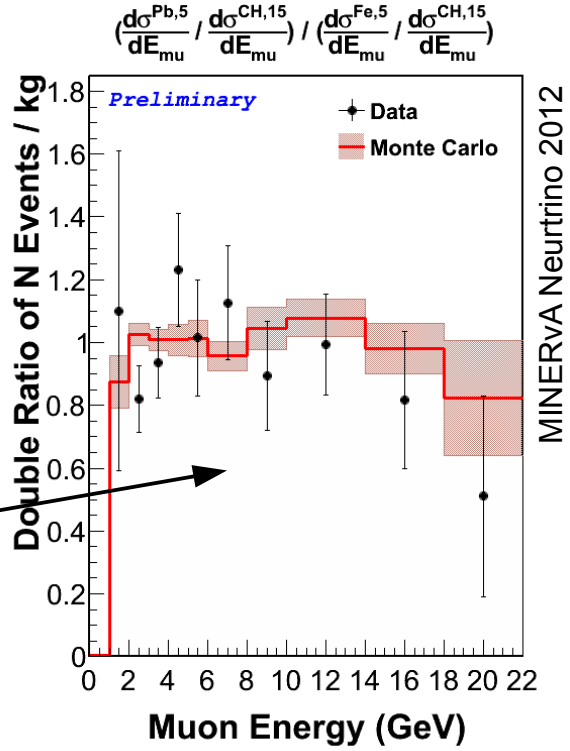
MINERvA

- Other recent MINERvA results:



First cross section measurement.
Anti-neutrino Quasi-elastic
(crucial for CP violation searches)

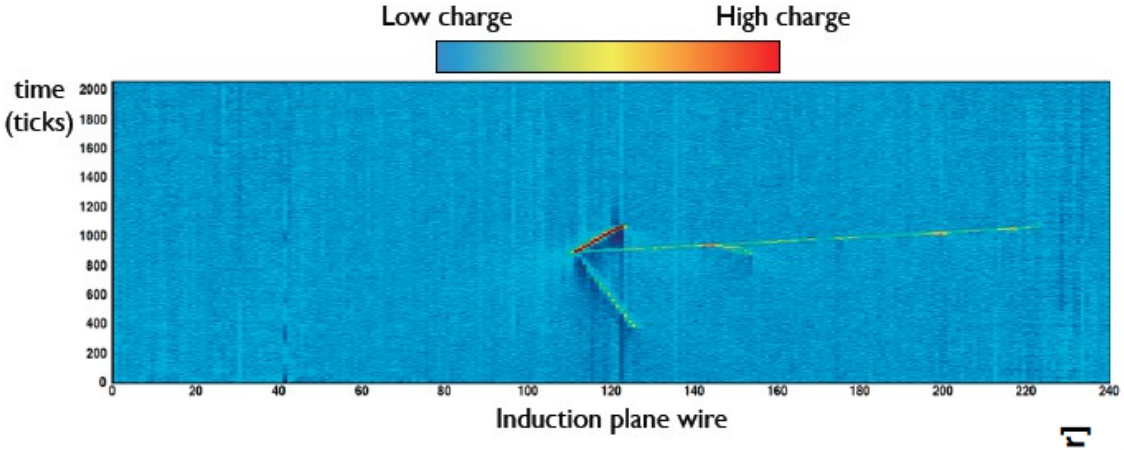
Lines show predictions with different nuclear models.



First ratio measurements from nuclear target. Currently uses small data sample → can increase statistics by ~ a factor of 20 with data on tape; even more in future.

ArgoNeuT (Argon Neutrino Test)

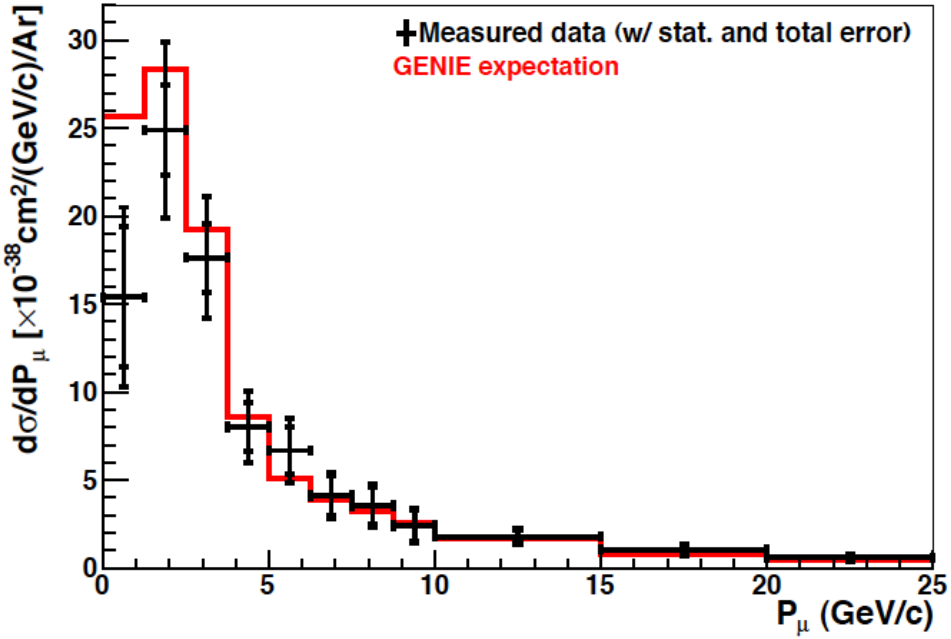
- Neutrino cross-section measurements on Liquid Argon:



ArgoNeuT: 170 liter Liquid Argon TPC in NuMI beamline at Fermilab

Offers resolution comparable to bubble chambers → ability to probe nuclear effects

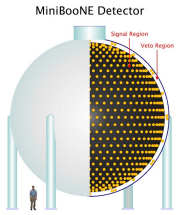
- First LAr detector to sit in a low-energy neutrino beam
- An important step in development of kiloton-scale LAr detectors

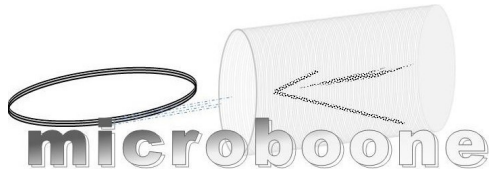


PRL 108, 16802 (2012)

Conclusion

- Precision neutrino cross section measurements are required for success of the global neutrino physics program
- Many measurements are underway
  - Current focus is very high precision measurements in 0.2-10 GeV range
  - Future measurements will emphasis quest to understand nuclear effects
- We can expect much more soon



Thank You!