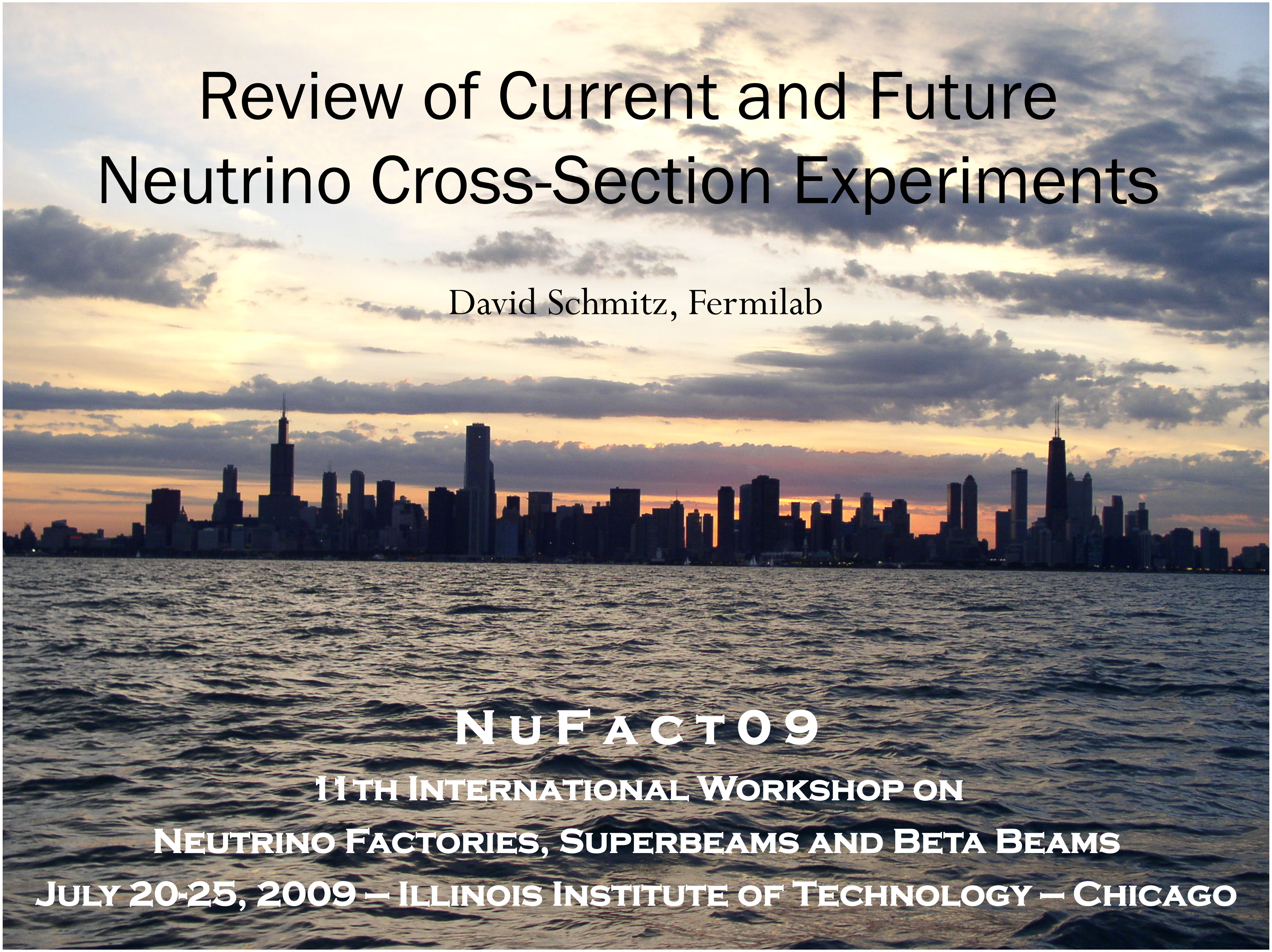


Review of Current and Future Neutrino Cross-Section Experiments

David Schmitz, Fermilab

NuFact09
11th International Workshop on
Neutrino Factories, Superbeams and Beta Beams
July 20-25, 2009 – Illinois Institute of Technology – Chicago

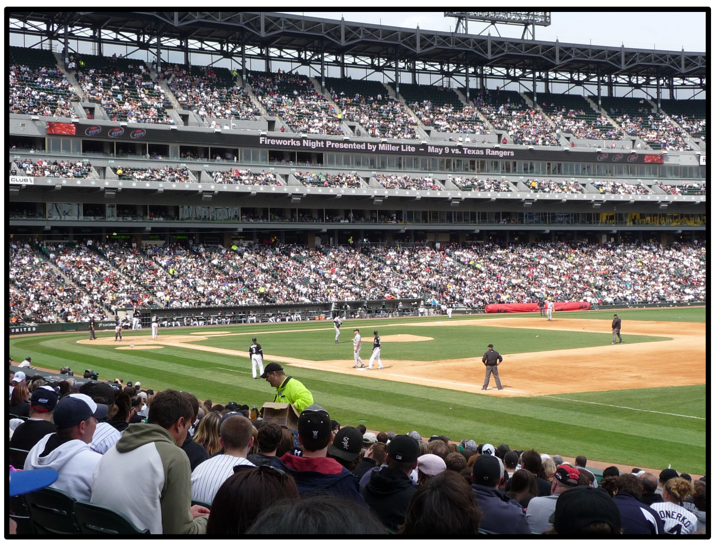
Outline

- Quick Audience Survey
- Introduction
- Relevant Energies and Targets
- Current Cross-Section Experiments
  - Recent Results and Mysteries
- Future Cross-Section Experiments

White Sox Survey

- Mark Buehrle pitched the 18th perfect game in Major League Baseball history yesterday across the street immediately following the morning session. **Please tell me someone saw it??**

- I was at home writing this talk…



18th perfect game -- ever

Mark Buehrle is mobbed by his teammates. (Phil Velasquez/Tribune) >>> **More photos**

White Sox win 5-0, tied with Detroit for first in division

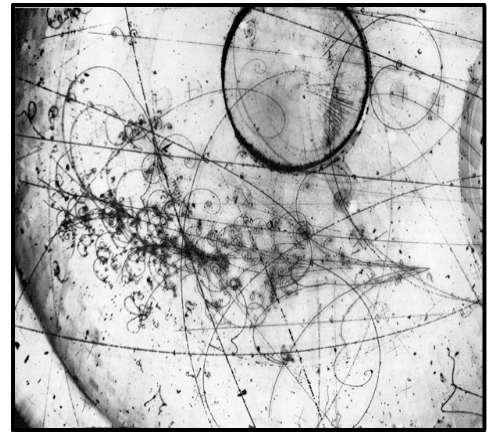
Photos: Perfection | Buehrle | Sox

- **The catch:** Wise in the 9th
- **First Fan:** Obama calls (with video)
- **The support:** Fields' grand slam
- **Rosenblog:** Rooting for Buehrle
- **Black Jack:** Sox back on track
- **Video:** Postgame | Watch again
- **Fan photos:** Send us yours
- **History:** 2007 no-hitter | By team
- **More:** Complete coverage

Introduction

- There has been a recent surge of progress and pubished results in neutrino cross-section physics! Both experimental measurements and theoretical modelings.
- There are new, dedicated experiments
- I will attempt to give just a flavor of things – the measurements and the mysteries
- Please see the many great talks from **NuInt09** or Working Group 2 from **NuFact09 (WG2)** for all the details
  - http://nuint09.ifae.es/Welcome.html
  - http://nufact09.iit.edu/wg2.shtml#wg2tueam

Introduction



- Neutrino cross-sections first measured in bubble chambers in the 1970's and 80's
  - ANL, BNL, FNAL, CERN, IHEP
  - very successful experiments; observation of neutral currents
  - some low Z targets, deuterium
  - x-sec measurements suffered small statistics and poor knowledge of their neutrino fluxes
- Measured cross-sections with higher statistics in the 90's, 00's
  - ex. NuTeV
  - rich physics programs; DIS, structure functions, strange sea, QCD
  - neutrino energies generally higher
- Some data have large uncertainties (20-40%) or show discrepancies that we would like to understand

Introduction

- Discovery of neutrino oscillations in the last decade has meant two things for neutrino cross-section physics:

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- Discovery of neutrino oscillations in the last decade has meant two things for neutrino cross-section physics:
  1. suddenly we really care about cross-sections in the 0.5-10 GeV range where they are not well measured and the channels are complicated
  2. suddenly there are lots of high intensity neutrino beams around the world in the 0.5-10 GeV range for making these measurements
- Future oscillation experiments require a detailed understanding of neutrino interaction mechanisms:
  - θ_{23} – ν_μ disappearance
  - θ_{13} – ν_e appearance
- Both use CC interactions as signal, but have different, complicated, and sometimes irreducible backgrounds. Also, neutrino energy reconstruction must be very well understood

Introduction

- Can't we just cancel the cross-section uncertainties once the experiment is running?
  - Fluxes & Detectors at Near/Far locations can be VERY different
    - detector designs are often not identical
    - beam acceptances change the fluxes
    - flux oscillates away or appears between detectors

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  - Experiments can spend years characterizing events in their detectors to come up with effective models for fluxes and neutrino cross-sections in order to match their data
  - experimental sensitivities can change as a result
  - Better to have accurate *a priori* knowledge of the event rates for ALL event types in order to design better experiments with accurate sensitivities. <u>Particulary good when you are building 100's of kilotons for B's of $.</u>

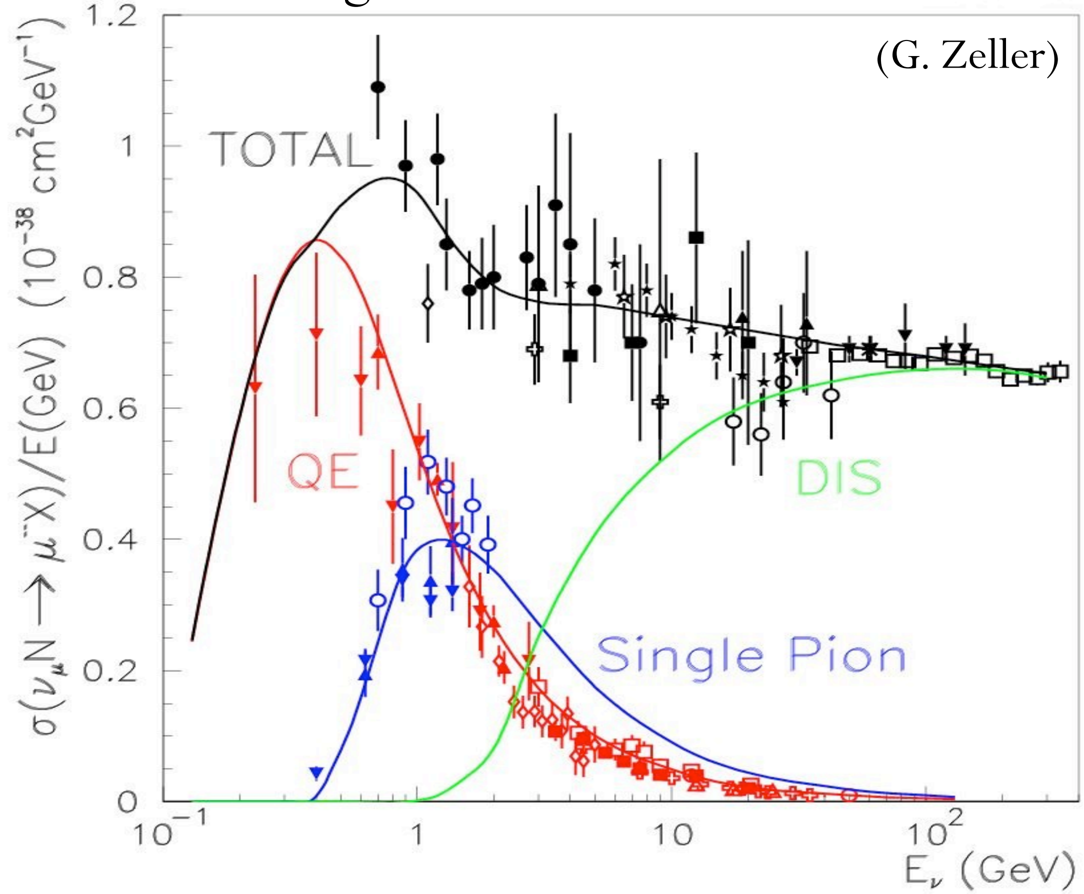
Energies and Targets

- Neutrino energy ranges and detector target materials are crucial aspects of an experiment *vis-à-vis* neutrino cross-sections
- The dominant interaction channels change rapidly across the few GeV neutrino energy region
- Many resonances must be considered in this energy region
- Nuclear effects are very complicated and not well known, so the target nucleus has a large impact on how well we can remove backgrounds and understand the kinematics of the final state

Energies and Targets

of the oscillation experiments

charged-current cross-sections

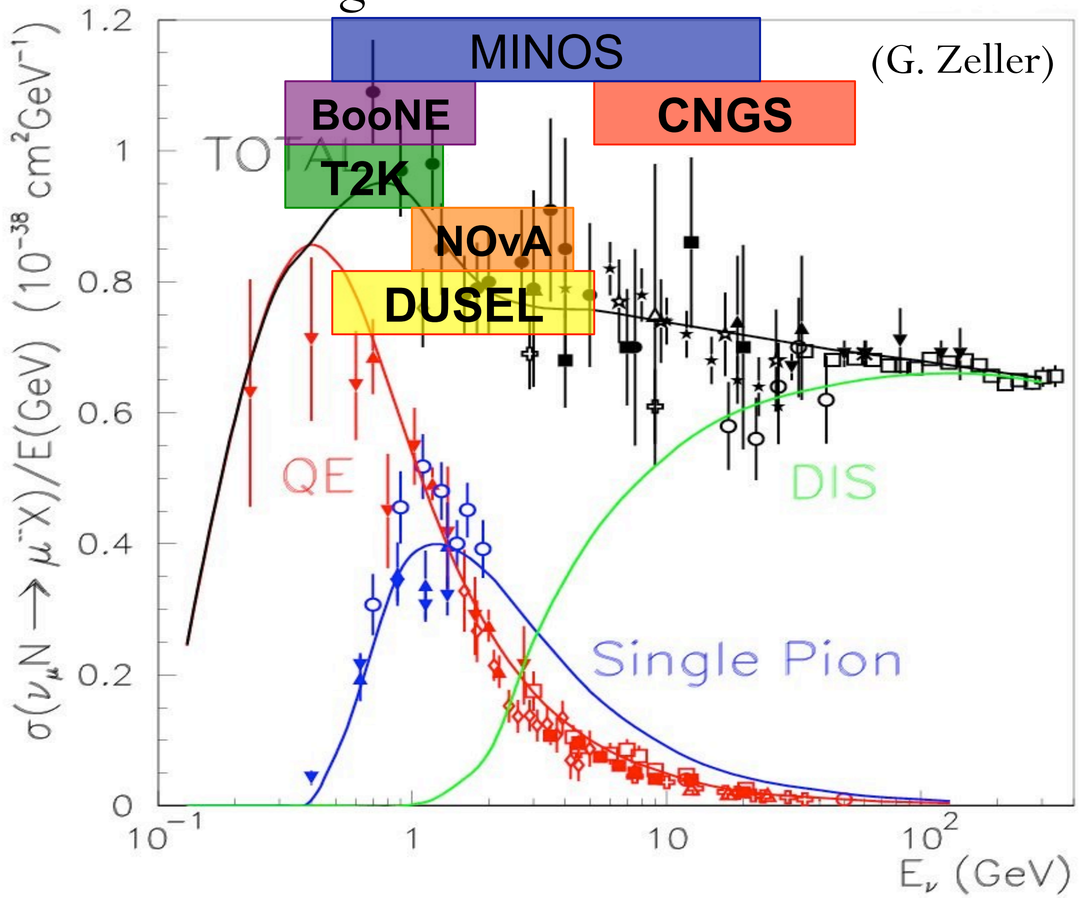


Energies and Targets

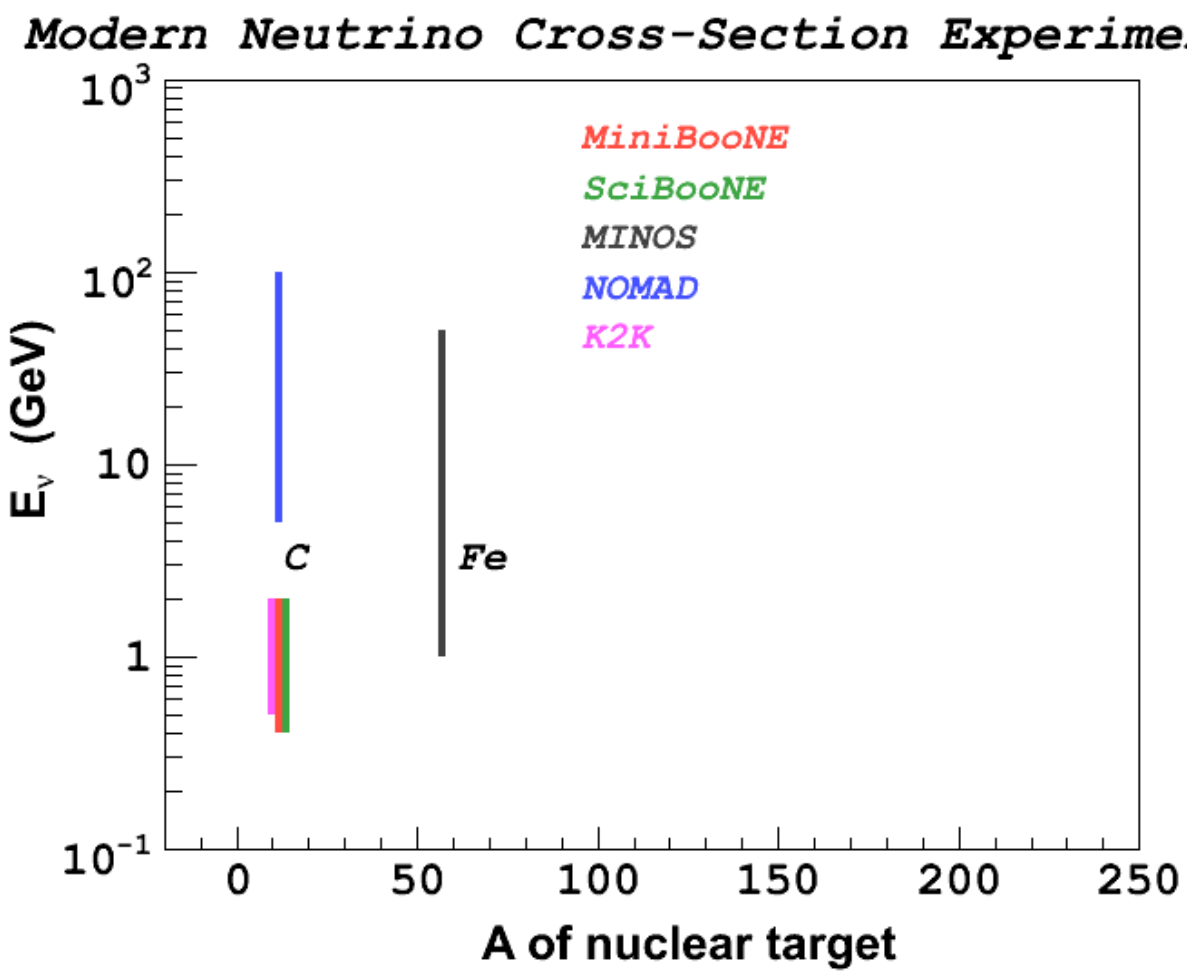
of the ociallation experiments

- Target Materials:
  - MINOS = Fe
  - BooNE = C
  - CNGS = Pb, Ar
  - T2K = H_2O, C
  - NOvA = C
  - DUSEL = H_2O, Ar

charged-current cross-sections

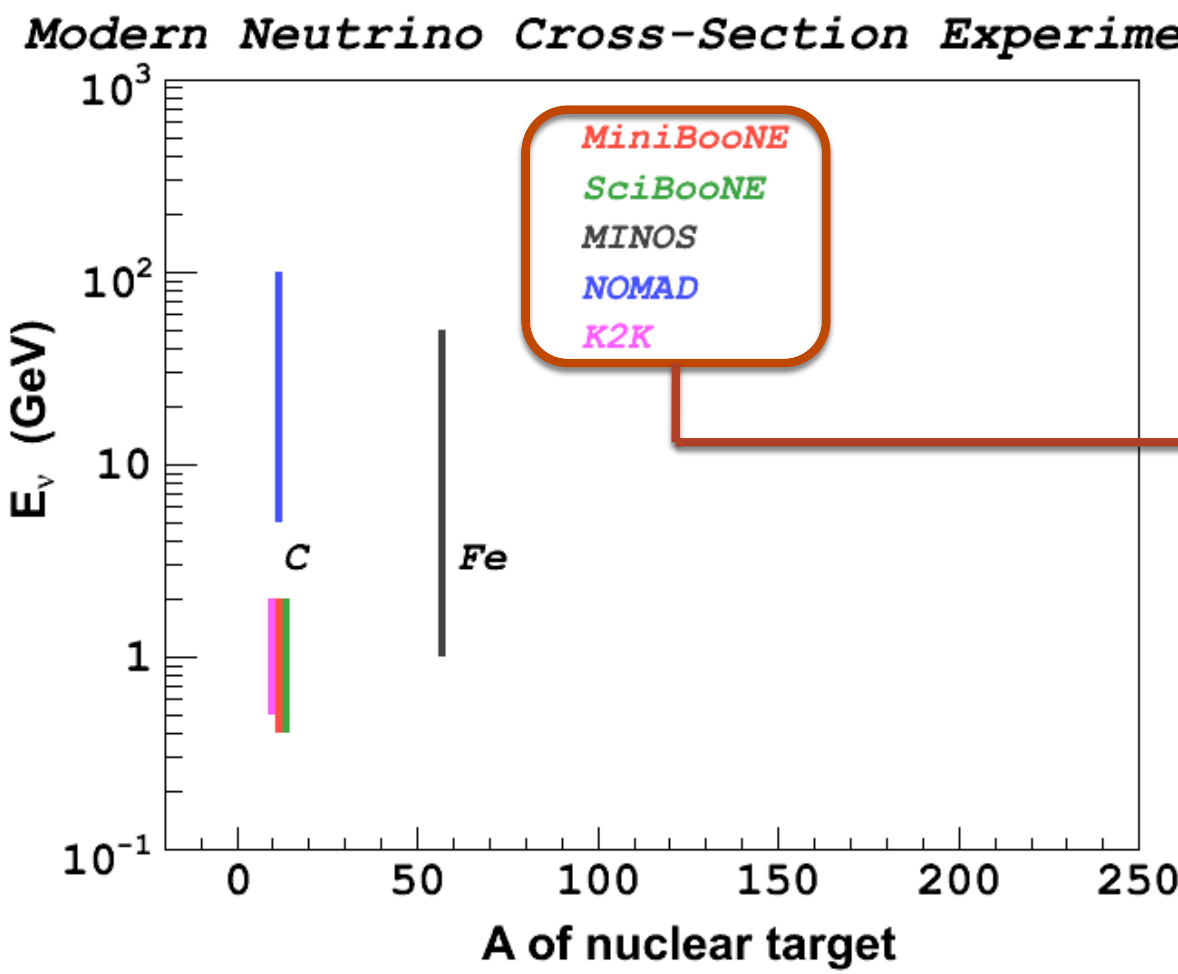


Energies and Targets



of the cross-section experiments

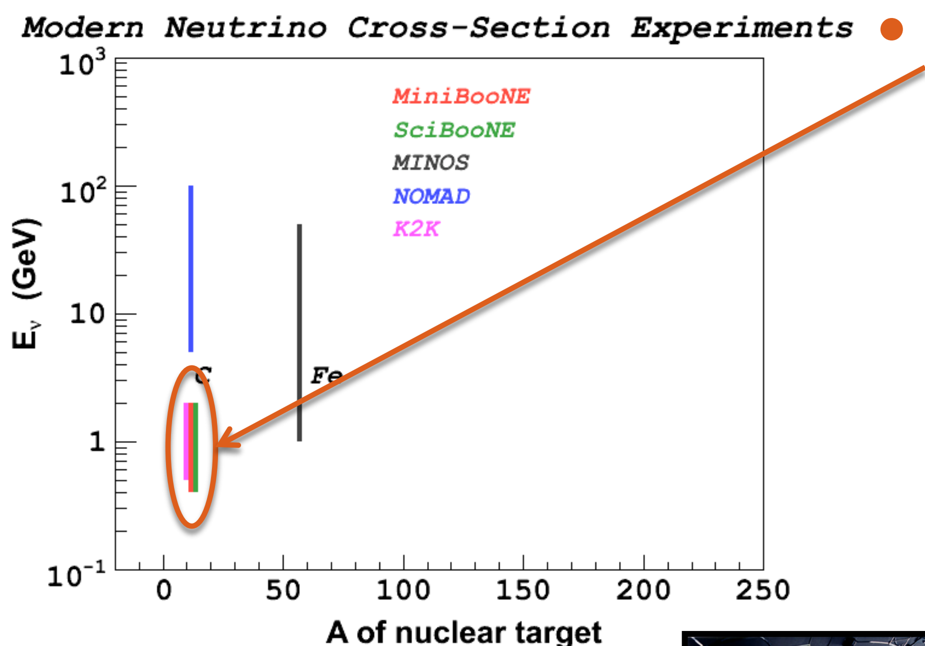
Energies and Targets



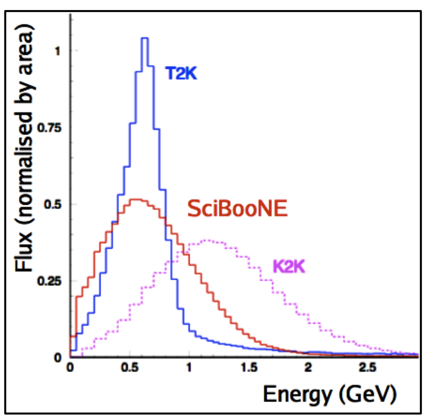
of the cross-section experiments

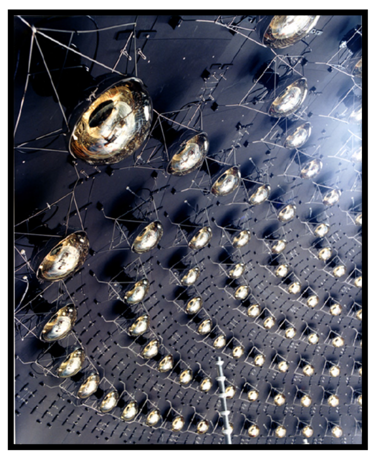
recent results and/or currently analyzing and publishing new cross-section data

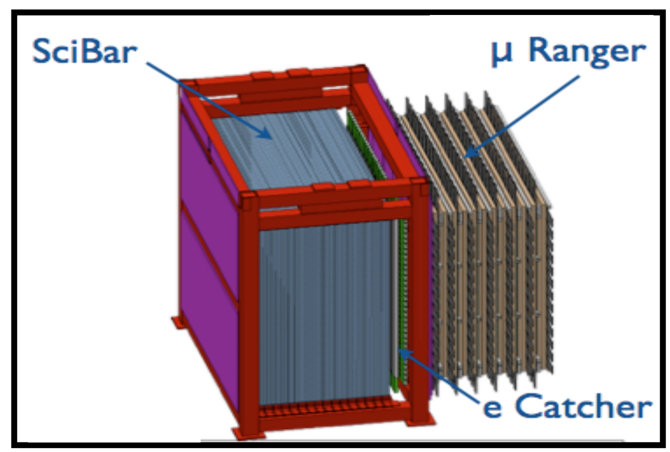
Energies and Targets



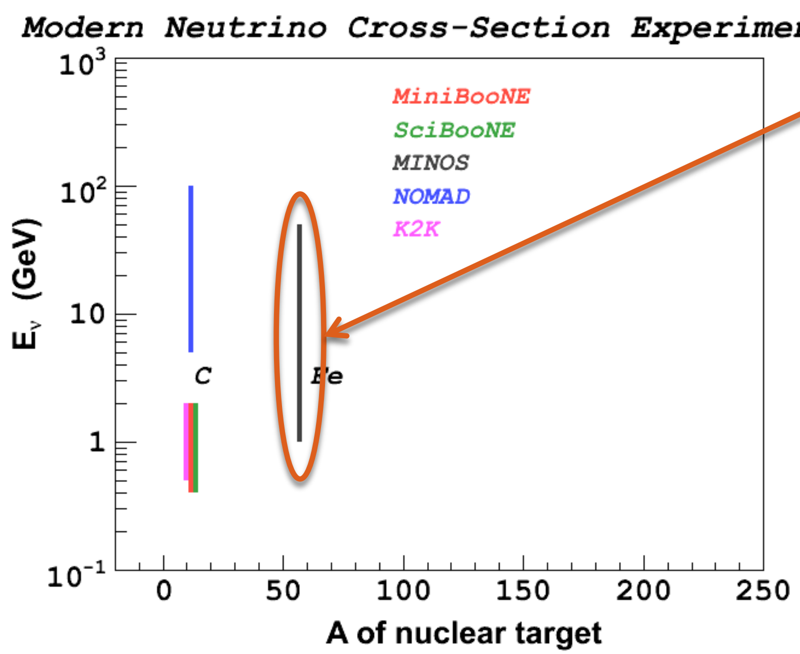
- MiniBooNE/SciBooNE/K2K
  - same target nucleus (carbon)
  - 0.2-1.5 GeV, near QE peak
  - SciBar det also in K2K beam
  - very different detectors
    - MiniBooNE is Cherenkov detector (CH_2)
    - SciBooNE is fine-grained tracking detector (CH)



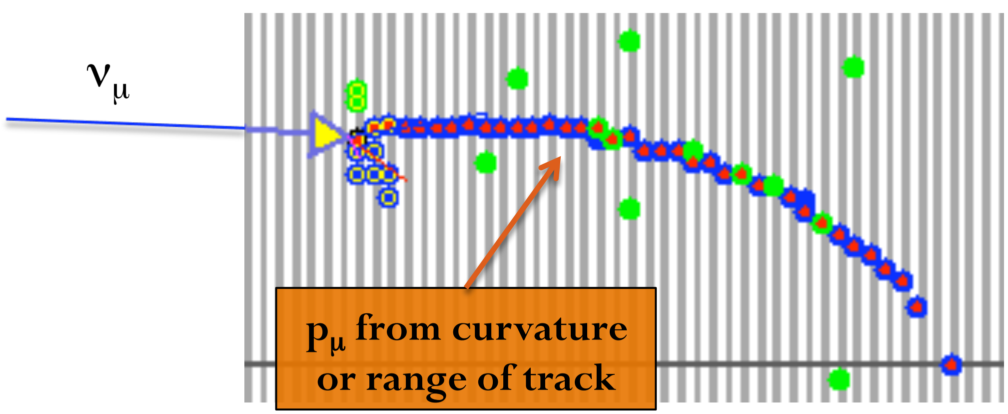


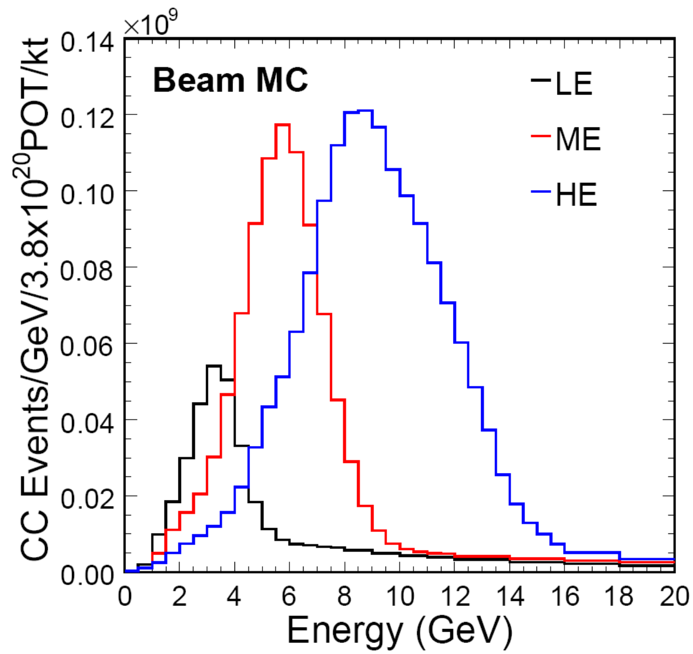


Energies and Targets

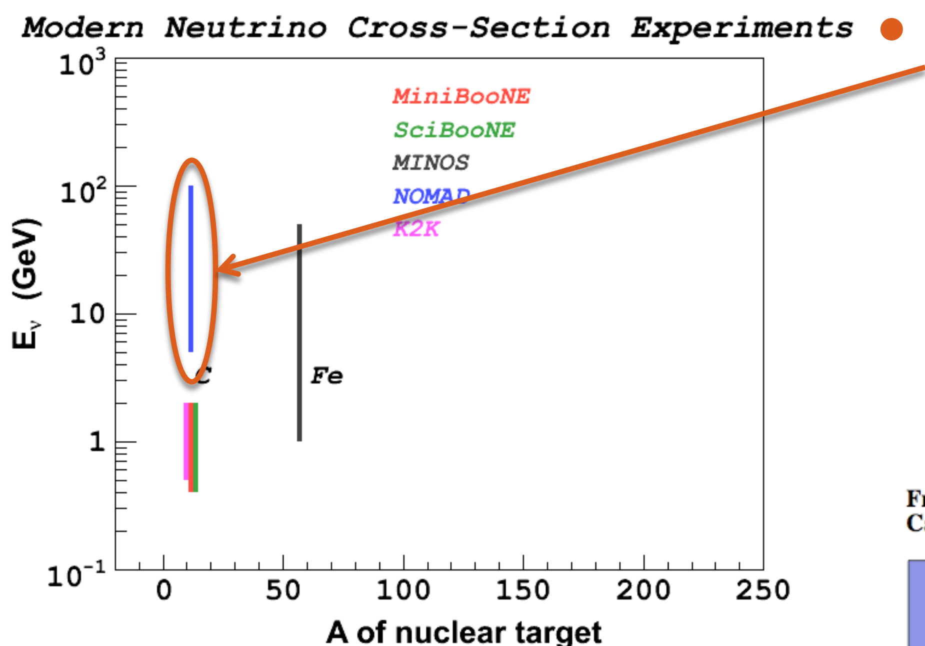


- MINOS Near Detector
  - heavy target nucleus (Fe)
  - broad band beam (FNAL NuMI)
  - magnetized Iron-scintillator calorimetric detector

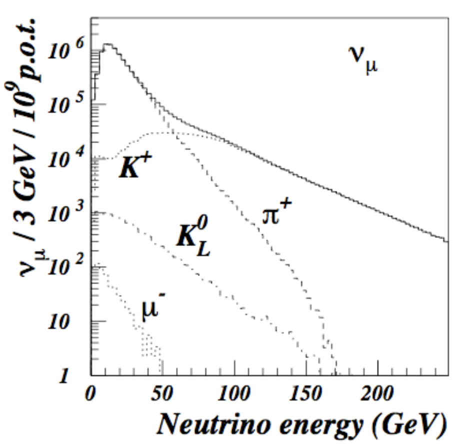


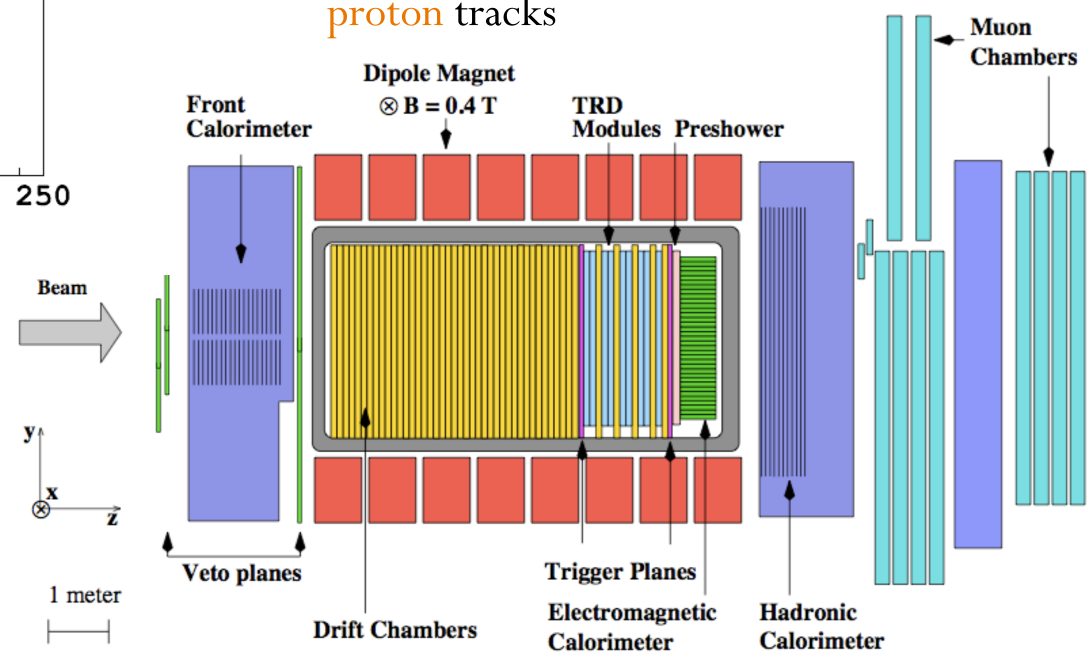


Energies and Targets



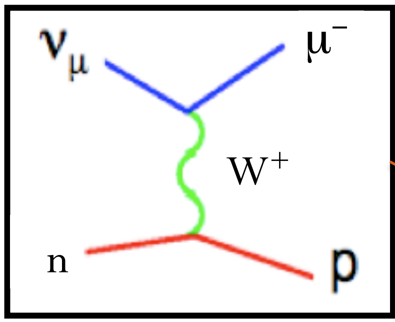
- NOMAD
  - target same as BooNEs (C)
  - higher energy beam (3-200 GeV)
  - drift chamber tracking detector
    - high resolution on muon **AND** proton tracks

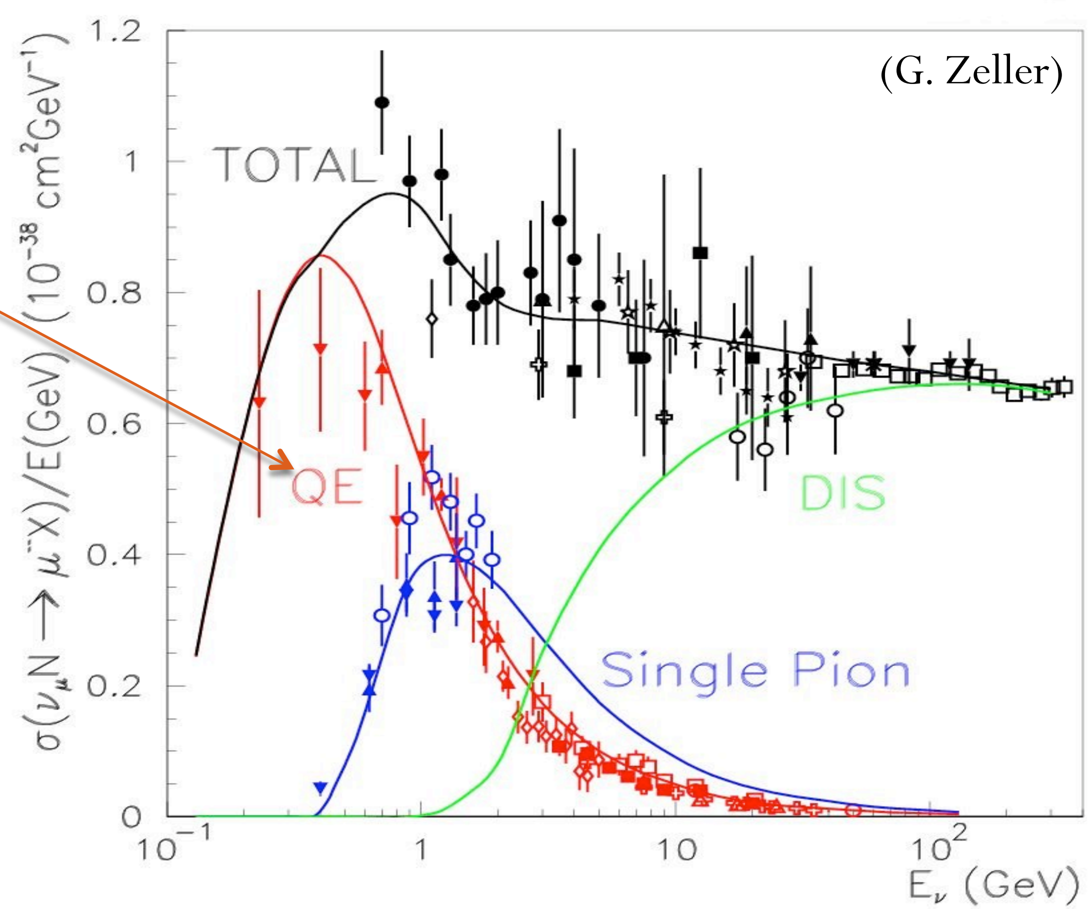




The Interactions (CCQE)

- Charged-Current Quasi-Elastic Scattering





- oscillation signal channel
- can reconstruct E_ν with or without the proton, so possible in Cherenkov detectors or calorimetric detectors

The Interactions (CCQE)

- <u>Charged-Current Quasi-Elastic Scattering</u>

L. Alvarez, NuFact 09 Plenary

- Lots of recent results! More complicated than it seems…
- Typically simulated with Relativistic Fermi Gas Model formalism of Smith and Moniz, NP B43, 605 (1972).
- Uncertainty in CCQE cross-section dominated by axial-vector form factor. Written in dipole form:

well known from β decay experiments ($Q^2 = 0$)

$$F_A(Q^2) = F_A(0)\left(1 + \frac{Q^2}{M_A^2}\right)^{-2}$$

- Axial mass can be measured from the Q^2 distribution of QE neutrino-nucleon events. Affected by both the shape and rate of distribution.

The Interactions (CCQE)

MiniBooNE

- <u>Charged-Current Quasi-Elastic Scattering</u>
- MiniBooNE has an enormous sample of single-track (Cherenkov detector) ν_μ-Carbon QE events
- MiniBooNE is the first to extract an absolute double differential cross-section in ν quasi-elastic scattering
- Absolute normalization of flux using pion production data from the HARP experiment (SciBooNE also)

Euro. Phys. J C 52:29-53 (2007)

Hadron Production Summary Talk. R. Schroeter, NuFact 09, WG2

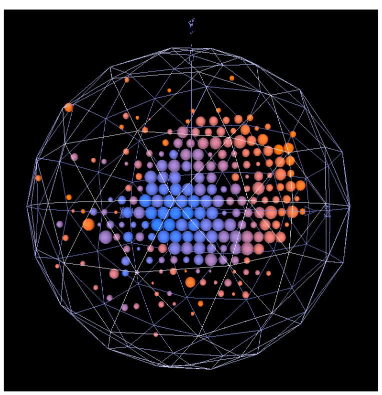
The Interactions (CCQE)

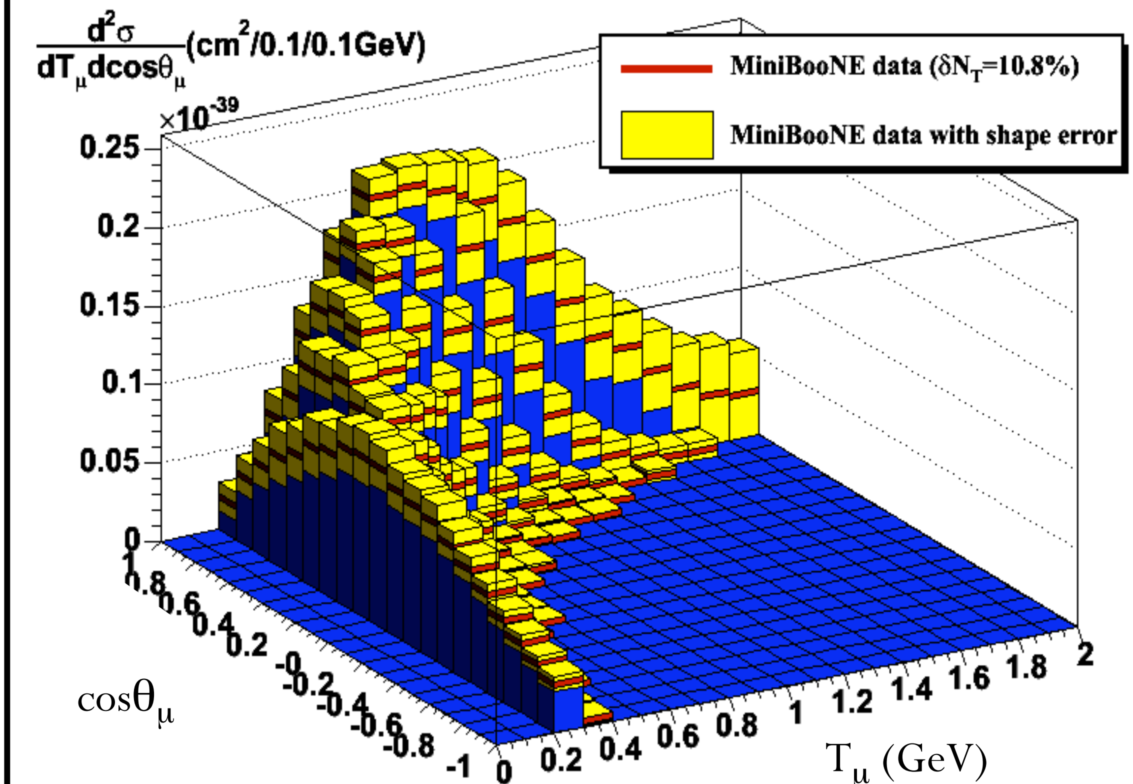
MiniBooNE

- Charged-Current Quasi-Elastic Scattering

R. Tayloe, NuFact 09, WG2

- 146,070 ν_μ QE events (76% purity, 27% ε)
- provide distributions of full μ kinematics ($\cos\theta_\mu, T_\mu$)
- first CCQE absolute differential cross-sections





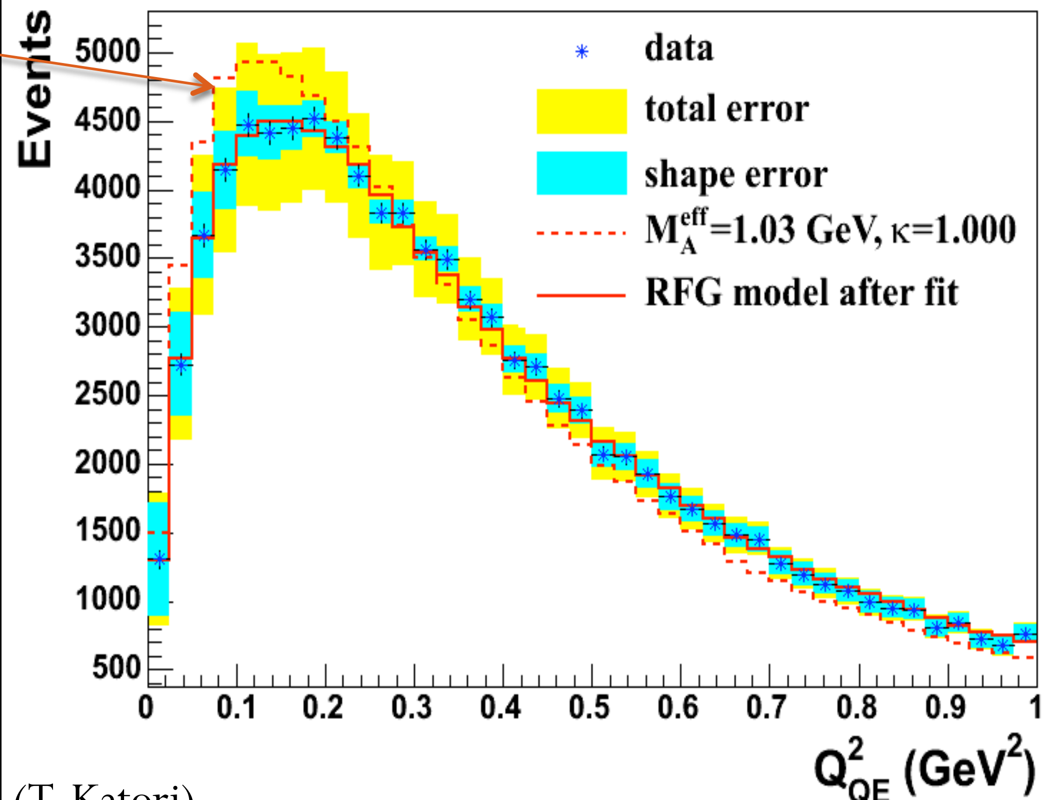
(T. Katori)

The Interactions (CCQE)

MiniBooNE

- <u>Charged-Current Quasi-Elastic Scattering</u>

• Q^2 distribution used to compare to QE model used in event generator with default **M_A^{QE} = 1.03 GeV**



(T. Katori)

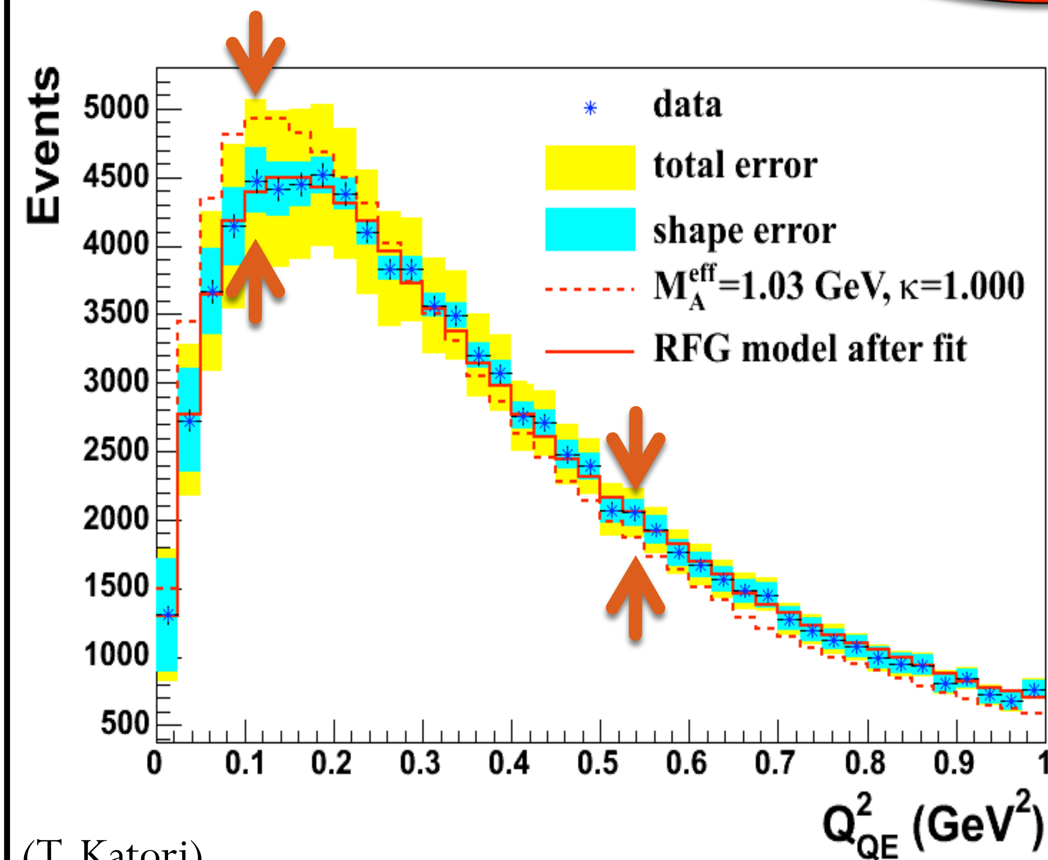
The Interactions (CCQE)

MiniBooNE

- Charged-Current Quasi-Elastic Scattering

• Q^2 distribution used to compare to QE model used in event generator with default
M_A^{QE} = 1.03 GeV

• Fit performed to extract new model parameters to better describe the MiniBooNE data
M_A^{QE} = 1.35 ± 0.17 GeV
scaling parameter to increase Pauli blocking in the model
κ = 1.007 ± 0.007



(T. Katori)

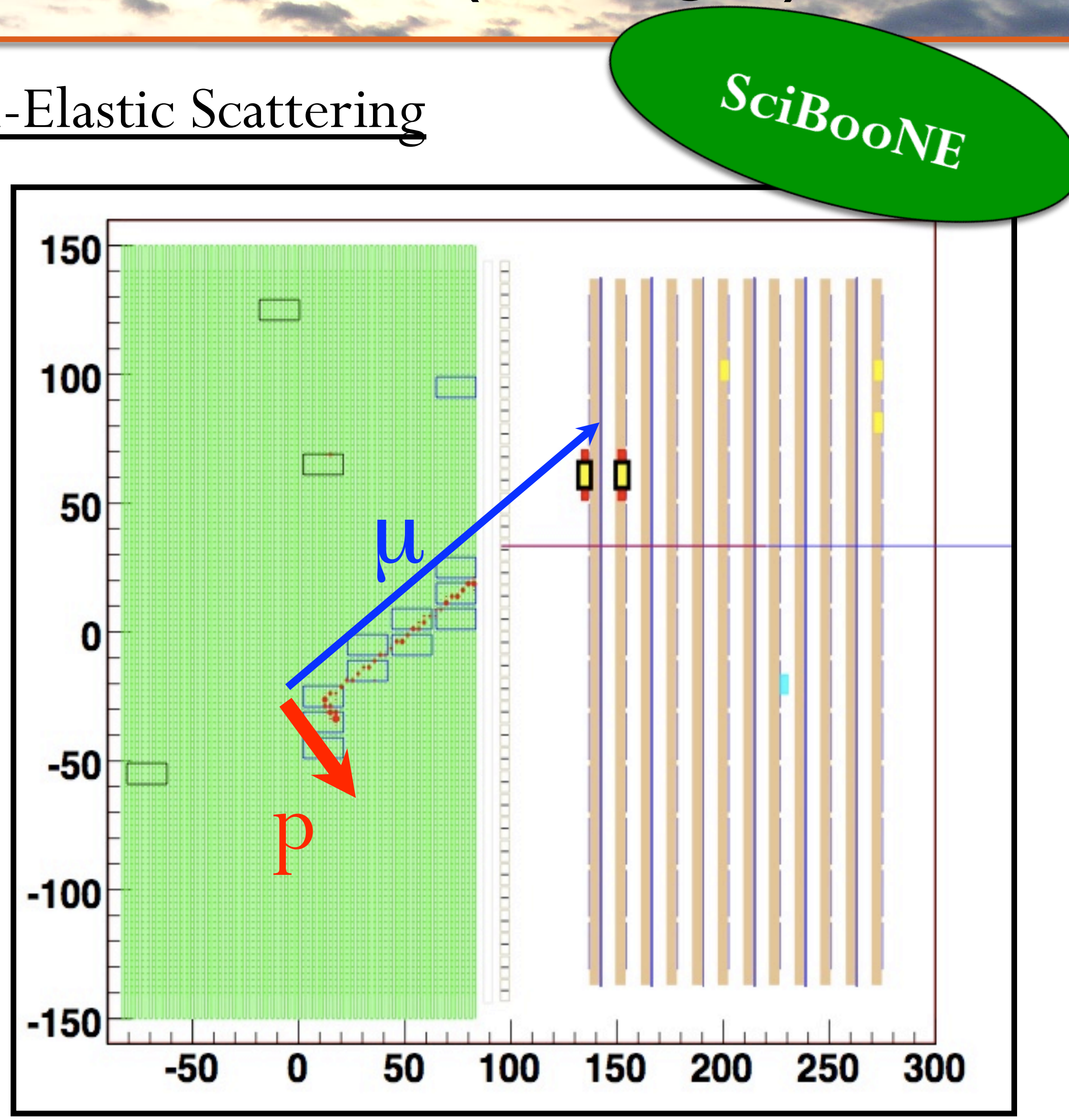
The Interactions (CCQE)

- Charged-Current Quasi-Elastic Scattering

R. Tayloe, NuFact 09, WG2

- can clearly resolve final state by identifying the proton track as well as the muon

- 2,680 ν_μ QE events (69% purity, 2.3% ε)



The Interactions (CCQE)

SciBooNE

- Charged-Current Quasi-Elastic Scattering

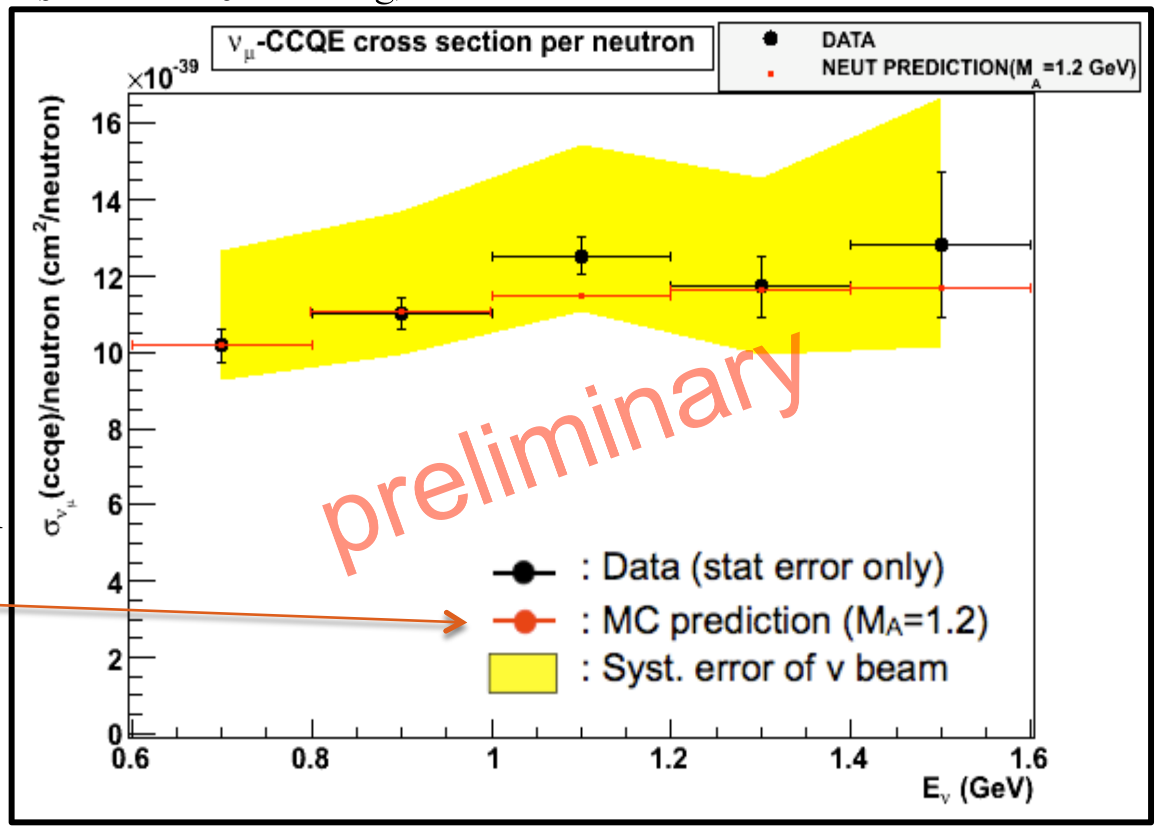
(J. Alcaraz, J. Walding)

- can clearly resolve final state by identifying the proton track as well as the muon

- 2,680 ν_μ QE events (69% purity, 2.3% ε)

- agrees with RFG prediction (with a higher M_A)

- ~ consistent with MiniBooNE measurement



The Interactions (CCQE)

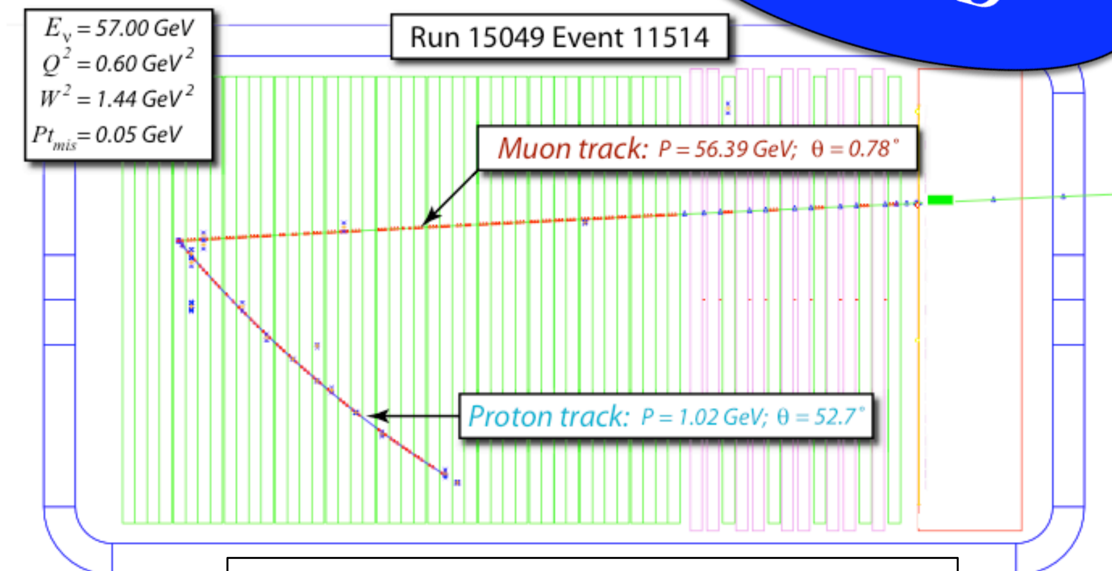
- Charged-Current Quasi-Elastic Scattering

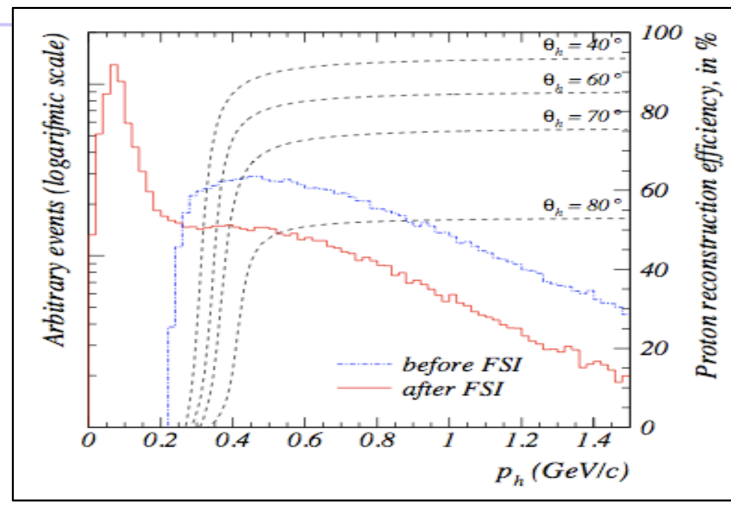
R. Gran, NuFact 09, WG2

• combined 1-track (muon only) and 2-track (muon+proton) samples for measuring CCQE cross-section

• nuclear effects cause migration from 2-track to 1-track, so inclusion of both minimizes systematic from knowing this migration

NOMAD





arXiv:0812.4543v3

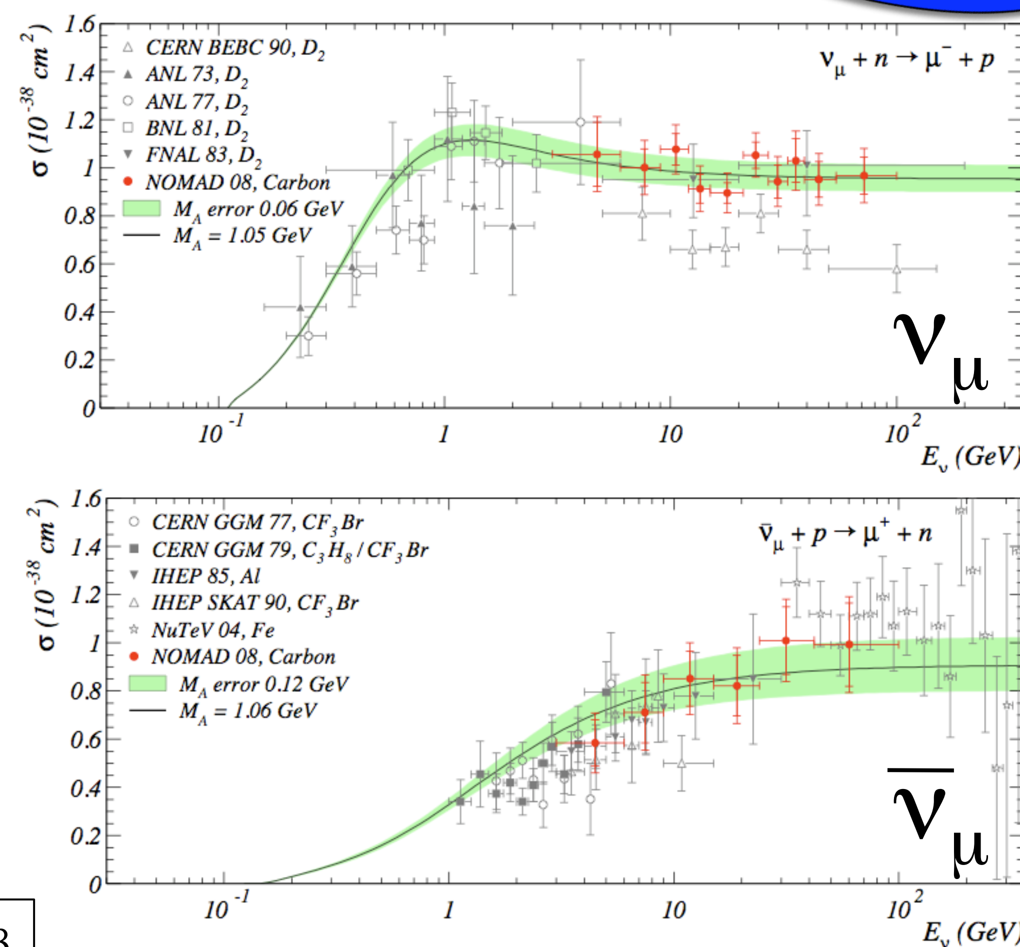
The Interactions (CCQE)

NOMAD

- <u>Charged-Current Quasi-Elastic Scattering</u>

• can identify μ^+ and μ^- from track bend directions

• present both neutrino and antineutrino QE cross-sections above 3 GeV



arXiv:0812.4543v3

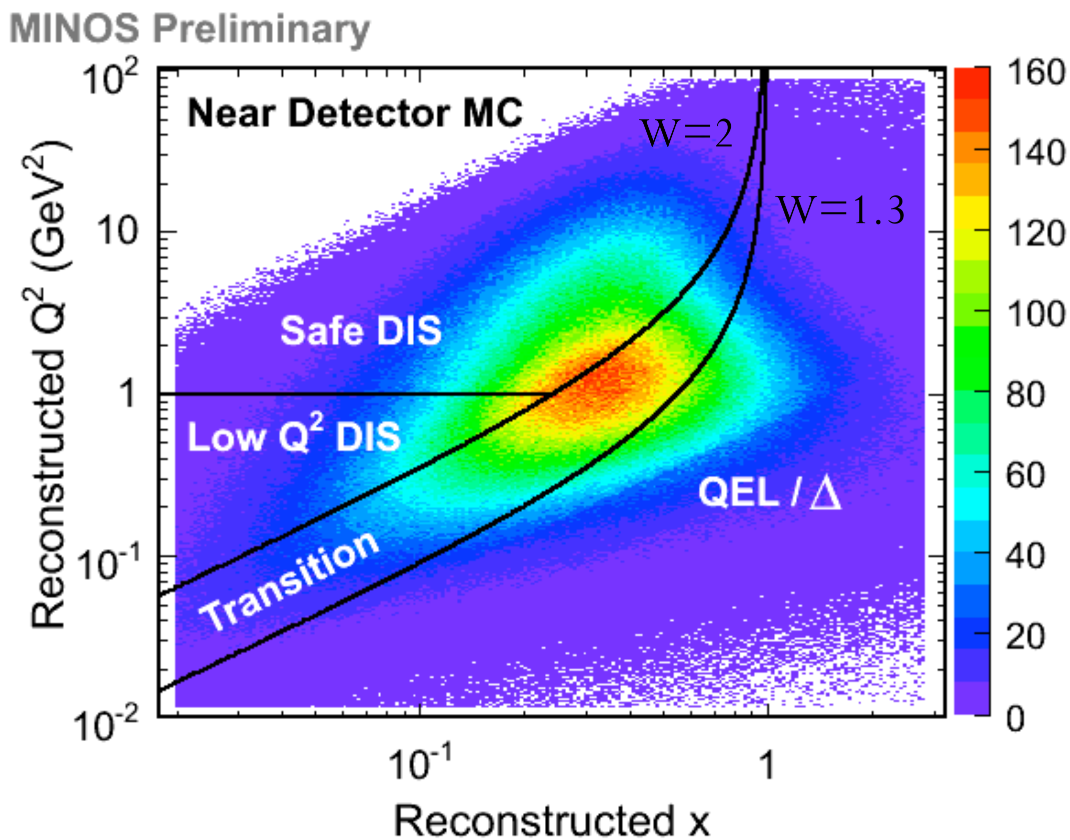
The Interactions (CCQE)

MINOS

- Charged-Current Quasi-Elastic Scattering

- The MINOS Near Detector sees interactions over a large range of Q^2 and x

- The sections to the right correspond roughly to regions where different generators are used



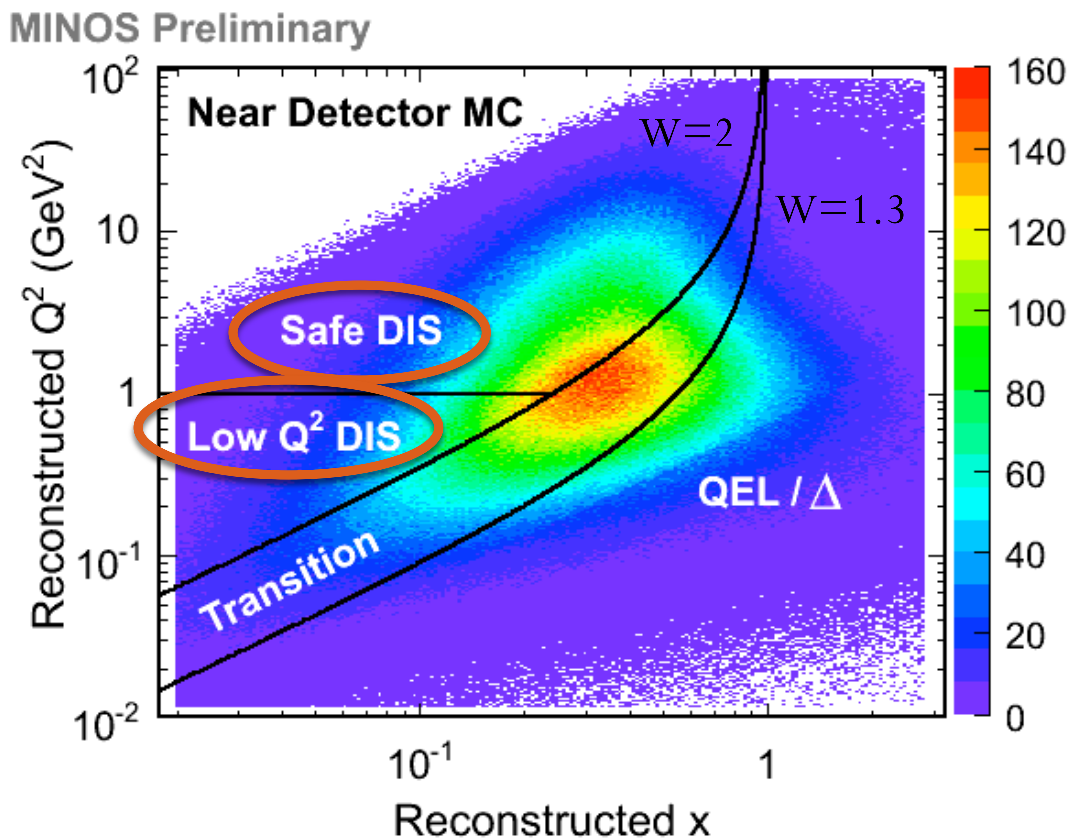
R. Gran, NuFact 09, WG2
M. Dorman, NuInt 09

The Interactions (CCQE)

MINOS

- <u>Charged-Current Quasi-Elastic Scattering</u>

• DIS regions show reasonable data/MC agreement



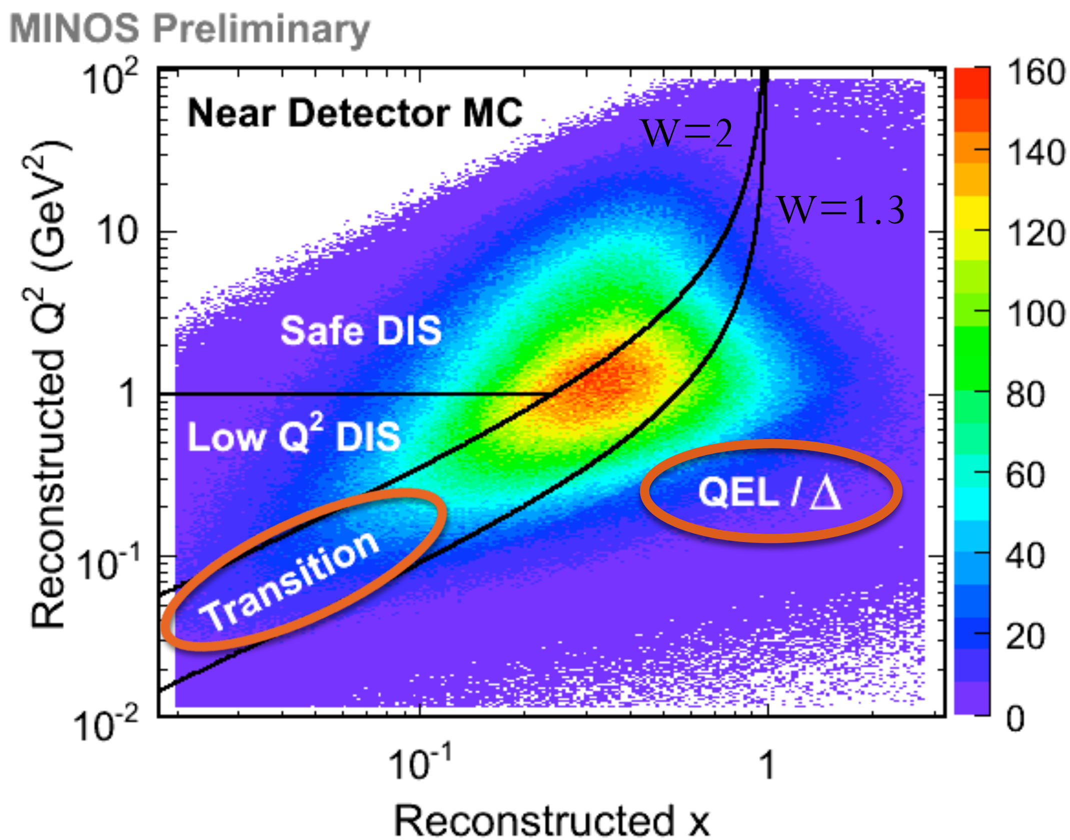
The Interactions (CCQE)

MINOS

- Charged-Current Quasi-Elastic Scattering

• DIS regions show reasonable data/MC agreement

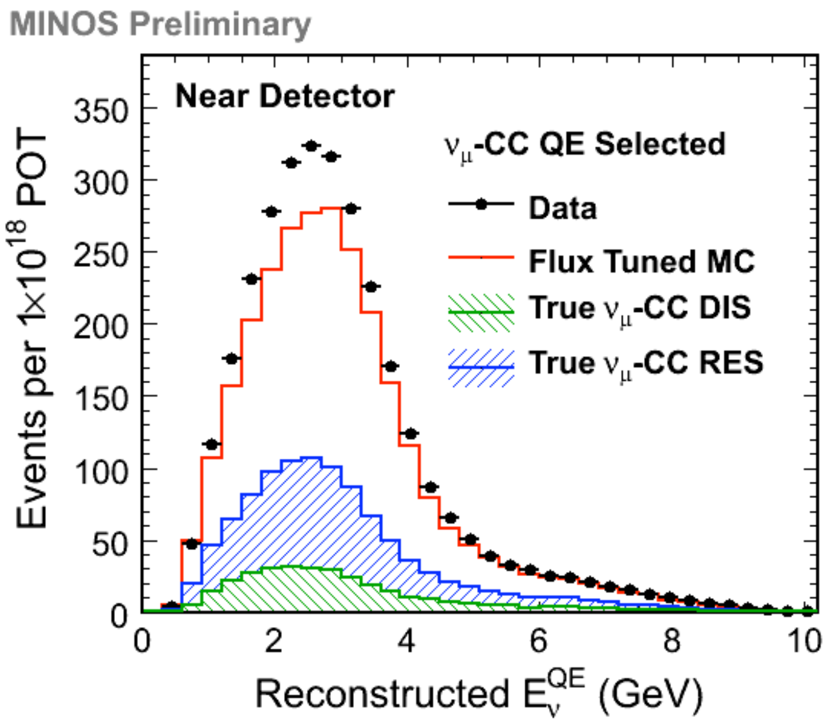
• Transition and QEL/Δ regions show evidence of mis-modeling of nuclear effects and Q^2 shape disagreements

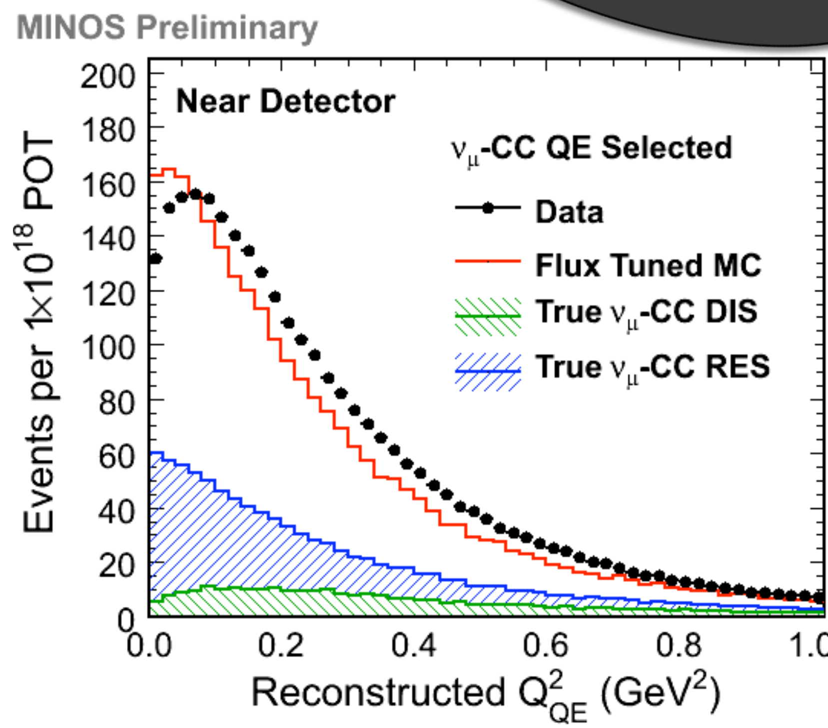


The Interactions (CCQE)

- Charged-Current Quasi-Elastic Scattering

MINOS





The Interactions (CCQE)

MINOS

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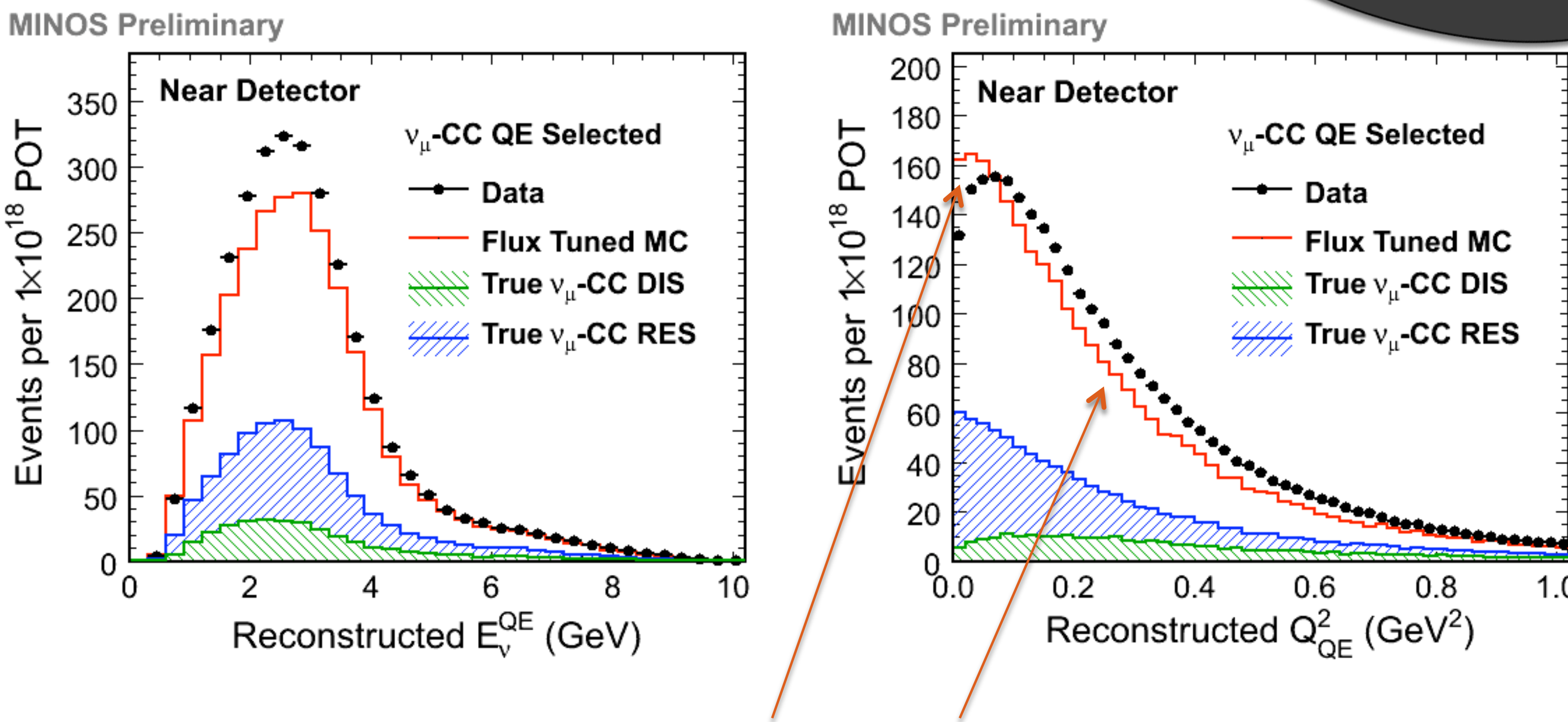


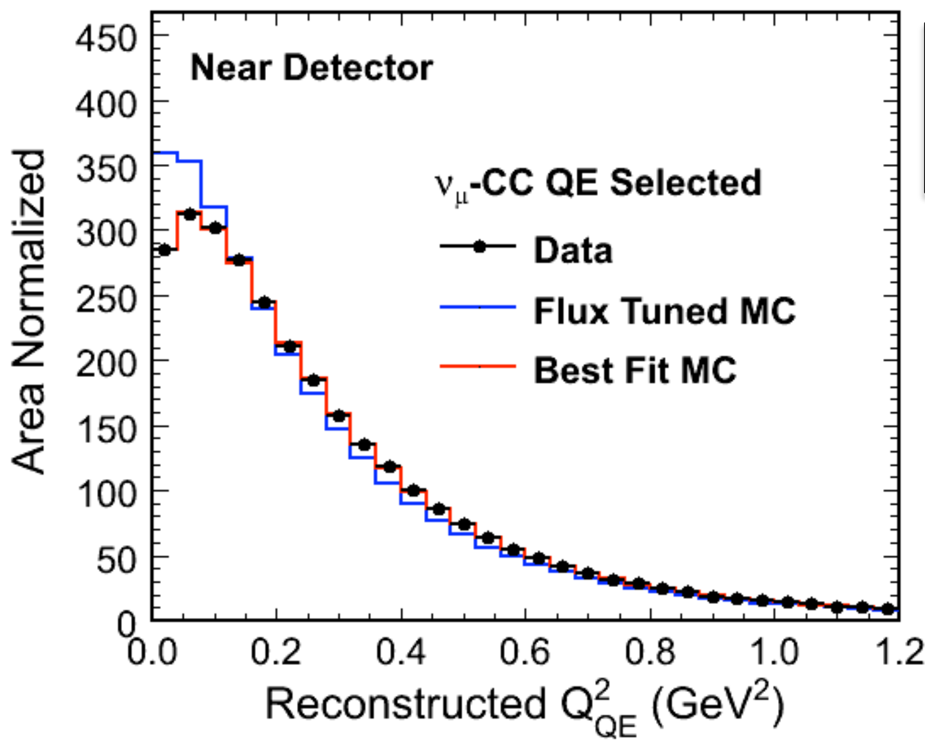
- Similar shape disagreements to those seen in MiniBooNE data, but at higher energies and on iron instead of carbon

The Interactions (CCQE)

MINOS

- Charged-Current Quasi-Elastic Scattering

MINOS Preliminary



MINOS Preliminary

$M_A^{QE} = 1.19\ ^{+0.09}_{-0.10}\ \text{(fit)}\ ^{+0.12}_{-0.14}\ \text{(syst) GeV}$

$k^{Fermi} = 1.28 \times k^{Fermi}$

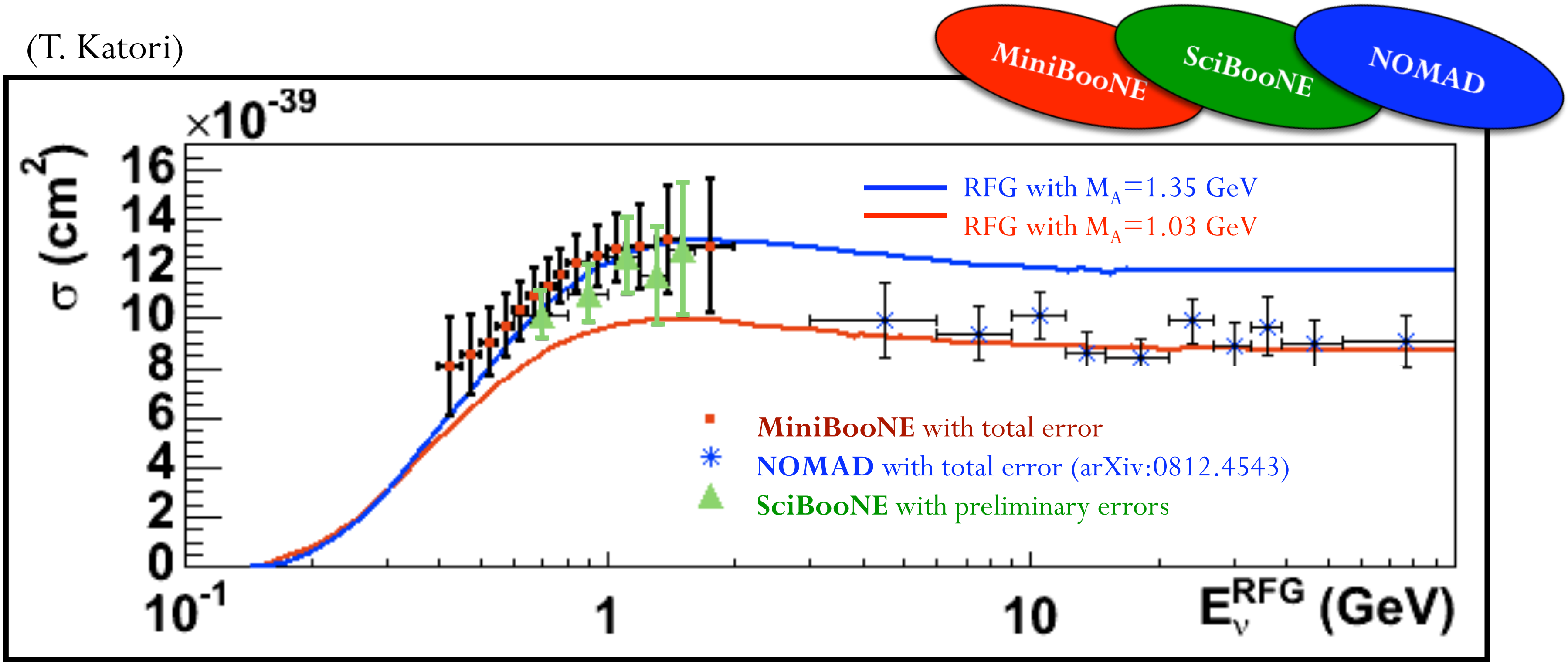
- fit favors a higher value of the axial mass and increases the Fermi momentum by 28% as an effective low Q^2 suppression

- no absolute cross-section values extracted yet – to come

The Interactions (CCQE)

- Charged-Current Quasi-Elastic Scattering

(T. Katori)

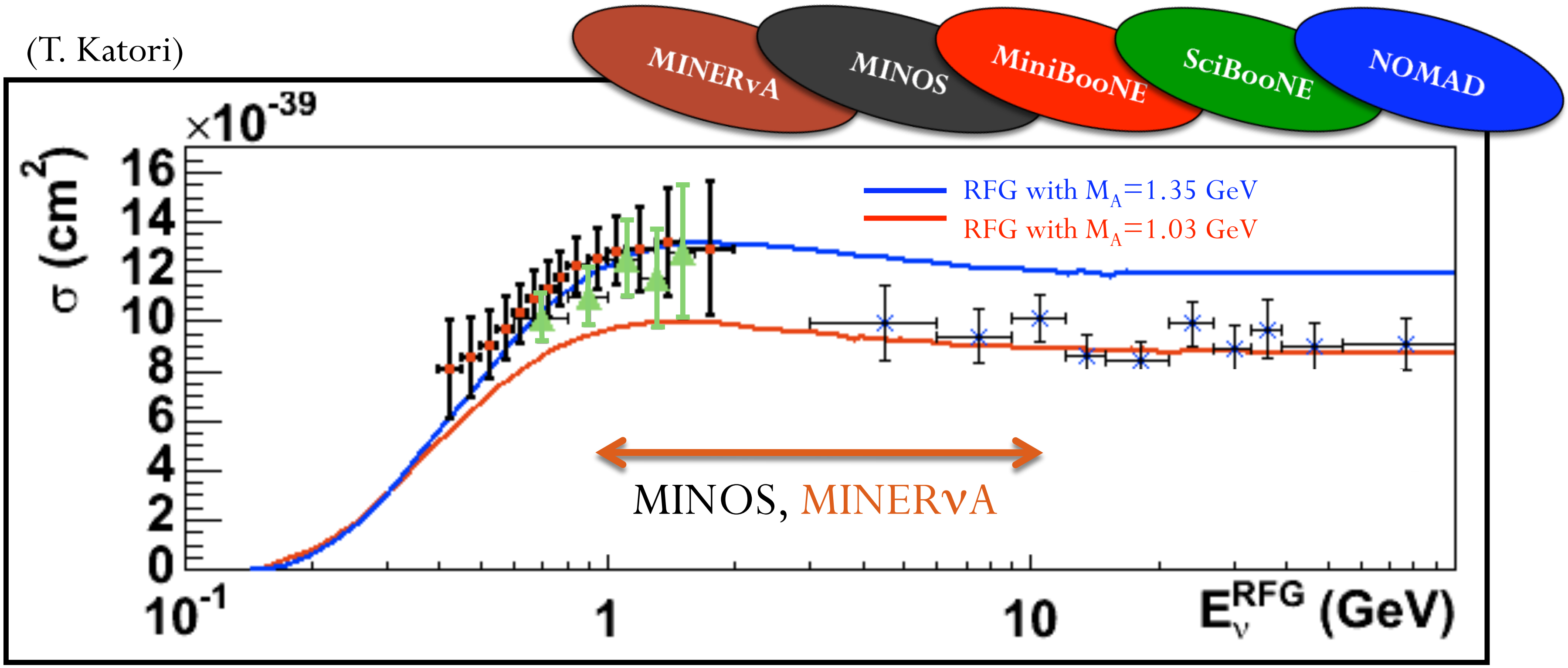


• MiniBooNE/SciBooNE in agreement, but tension with higher energy NOMAD results. All three on carbon.

The Interactions (CCQE)

- Charged-Current Quasi-Elastic Scattering

(T. Katori)



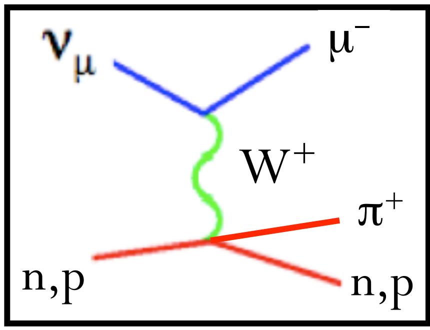
Will be very exciting to get data points from MINOS and MINERvA to fill in this region!

The Interactions (CC/NC π)

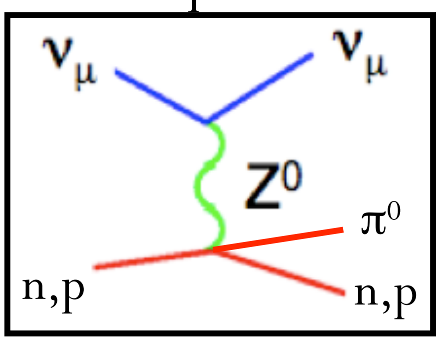
- Single Pion Production

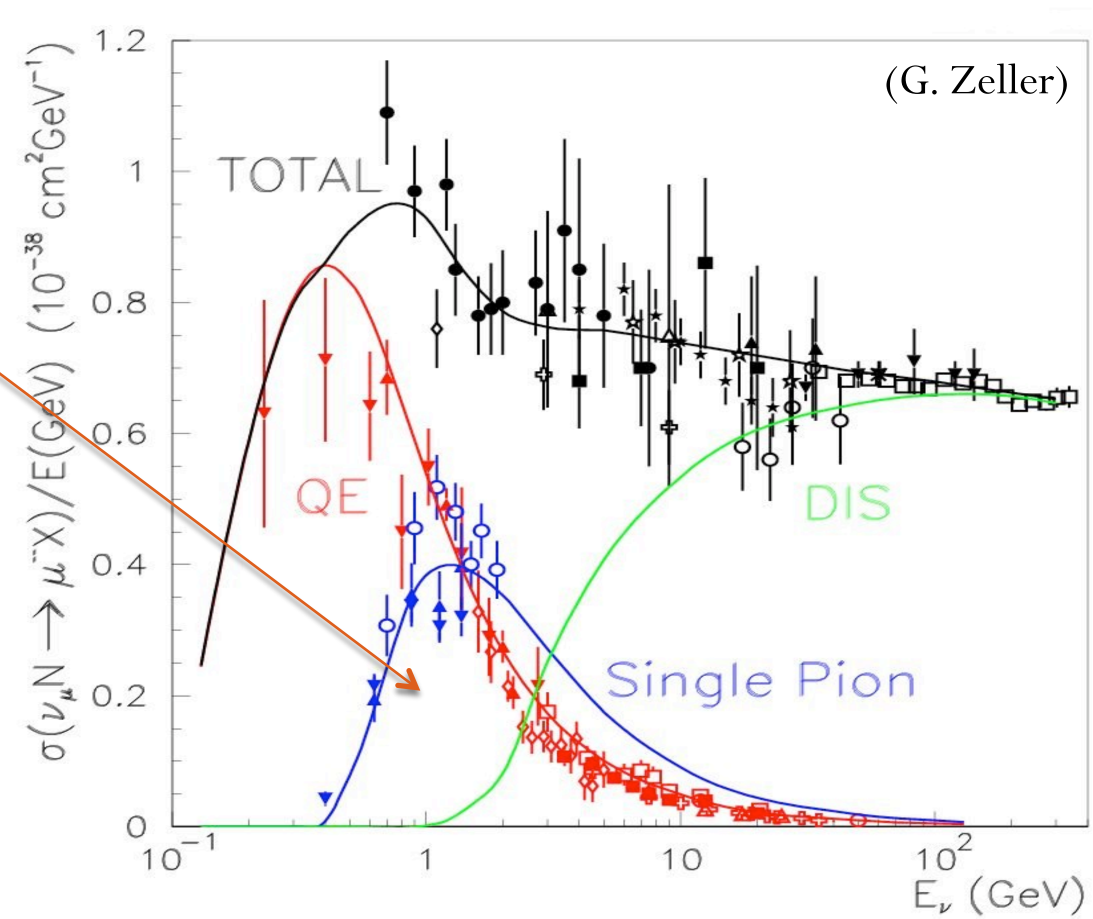
J. Catala-Perez, NuFact 09, WG2

CC π^+/π^0 production



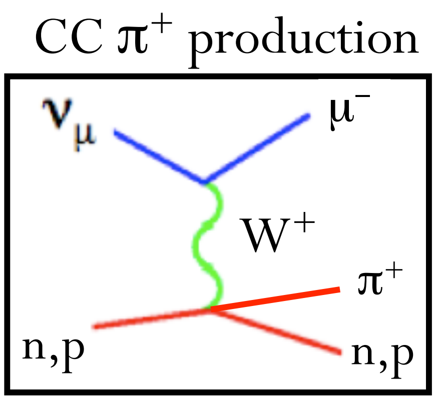
NC π^0 production

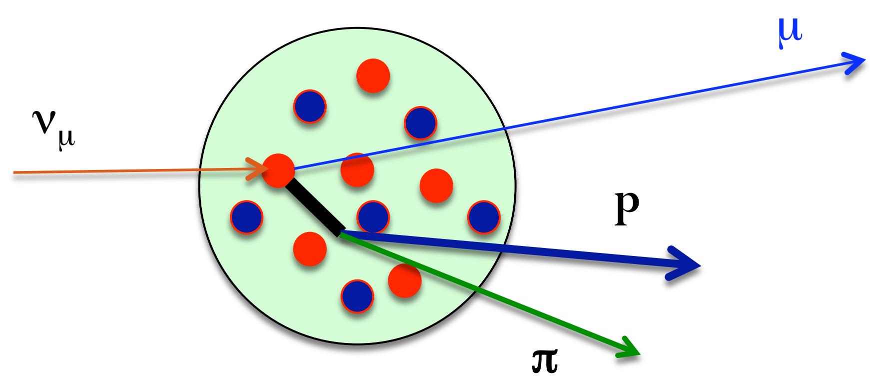




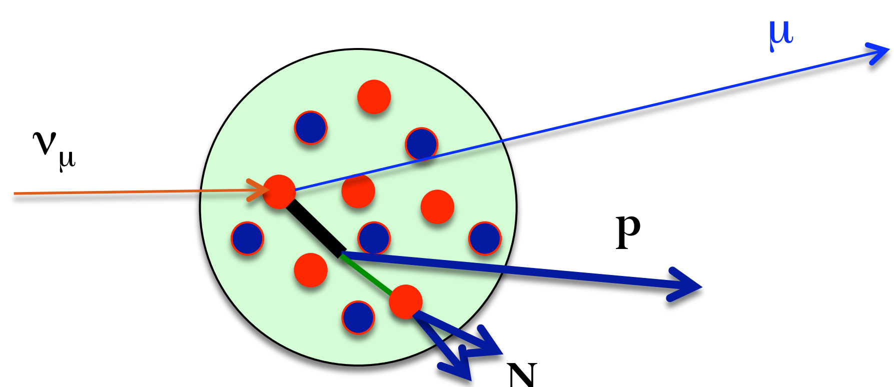
The Interactions (CC π^+)

- <u>Single Pion Production</u>





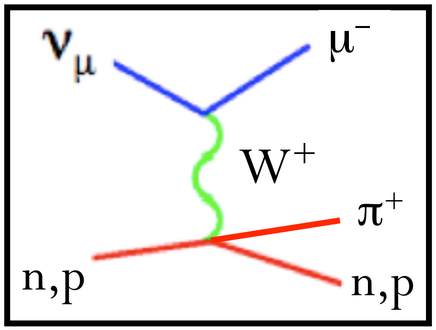
- Pion absorption creates irreducible bkgd to CCQE
- Pion absorption causes missing energy in event reconstruction – affects oscillation measurements
- Nuclear effects strike again…



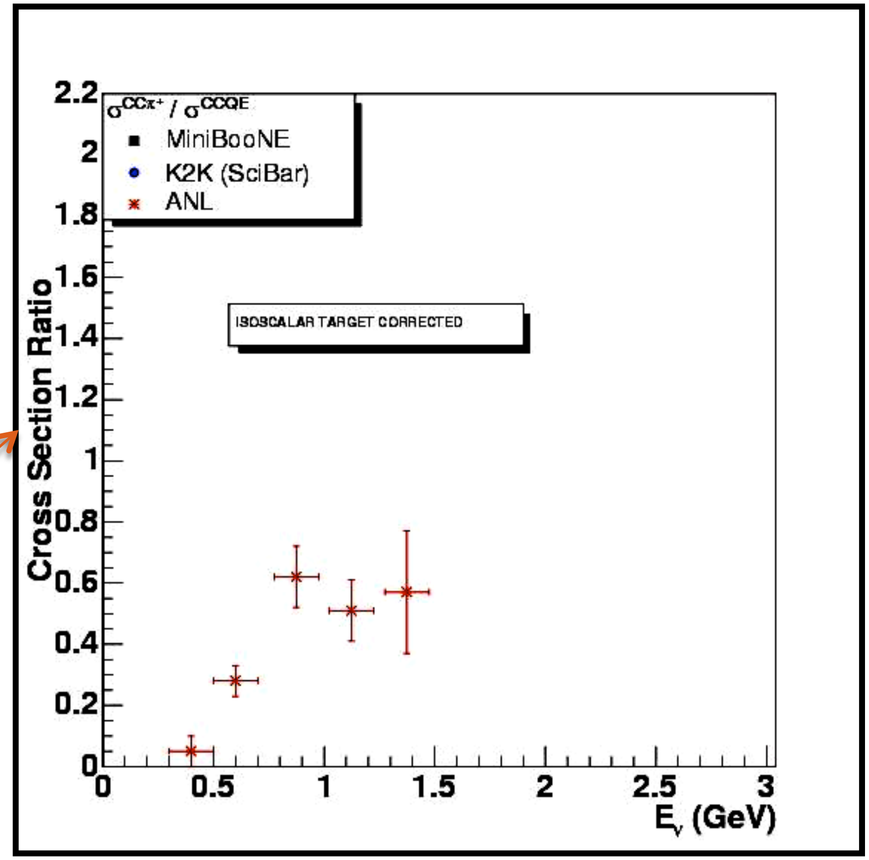
The Interactions (CC π^+)

- Single Pion Production

CC π^+ production



- Cross-section ratio to CCQE

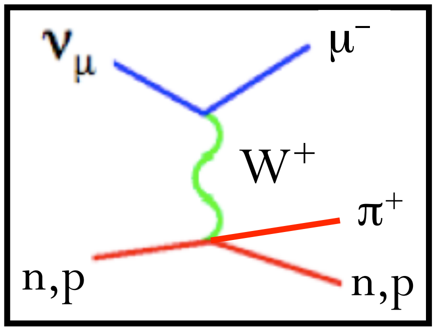


ANL: Phys. Rev. **D25**, 1161 (1982), deuterium

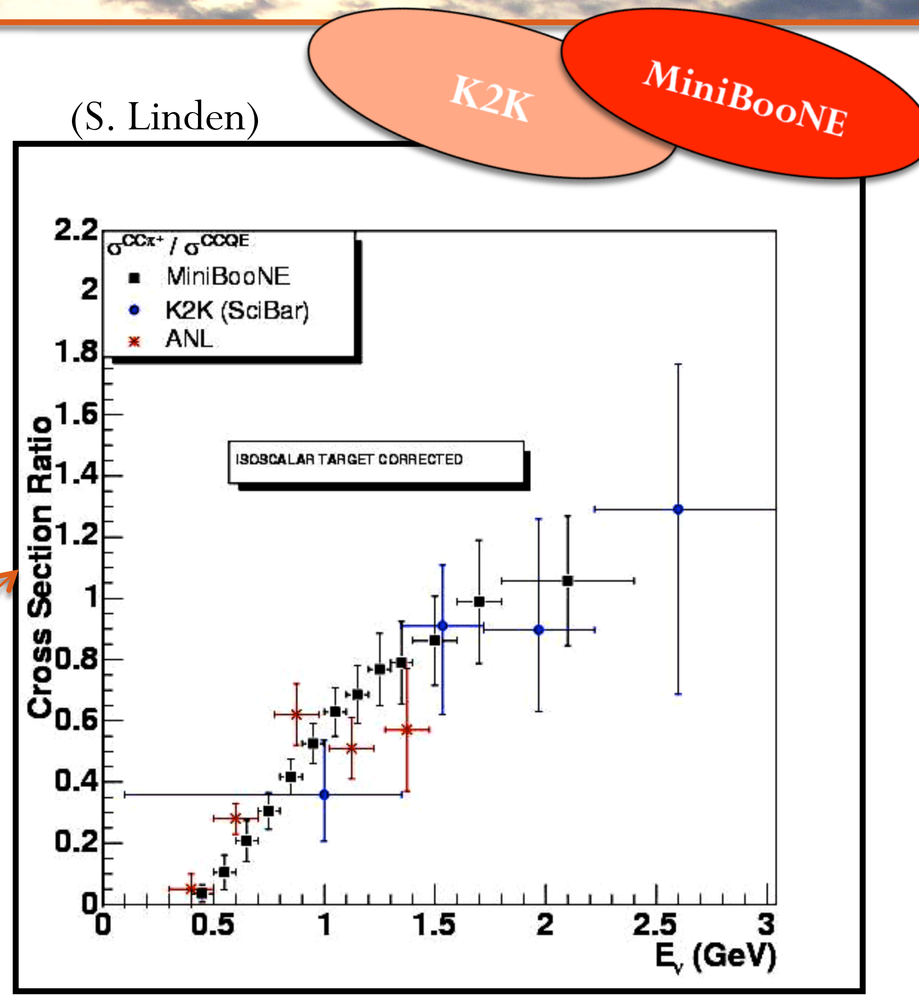
The Interactions (CC π^+)

- <u>Single Pion Production</u>

CC π^+ production



(S. Linden)



- Cross-section ratio to CCQE
- K2K and MiniBooNE results…

  26 years later

K2K: Phys. Rev. **D78**, 032003 (2008)

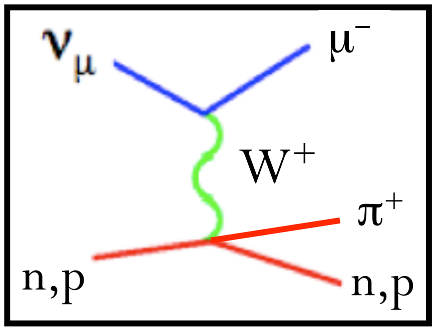
MiniBooNE: arXiv:0904.3159 [hep-ex]

The Interactions (CC π^+)

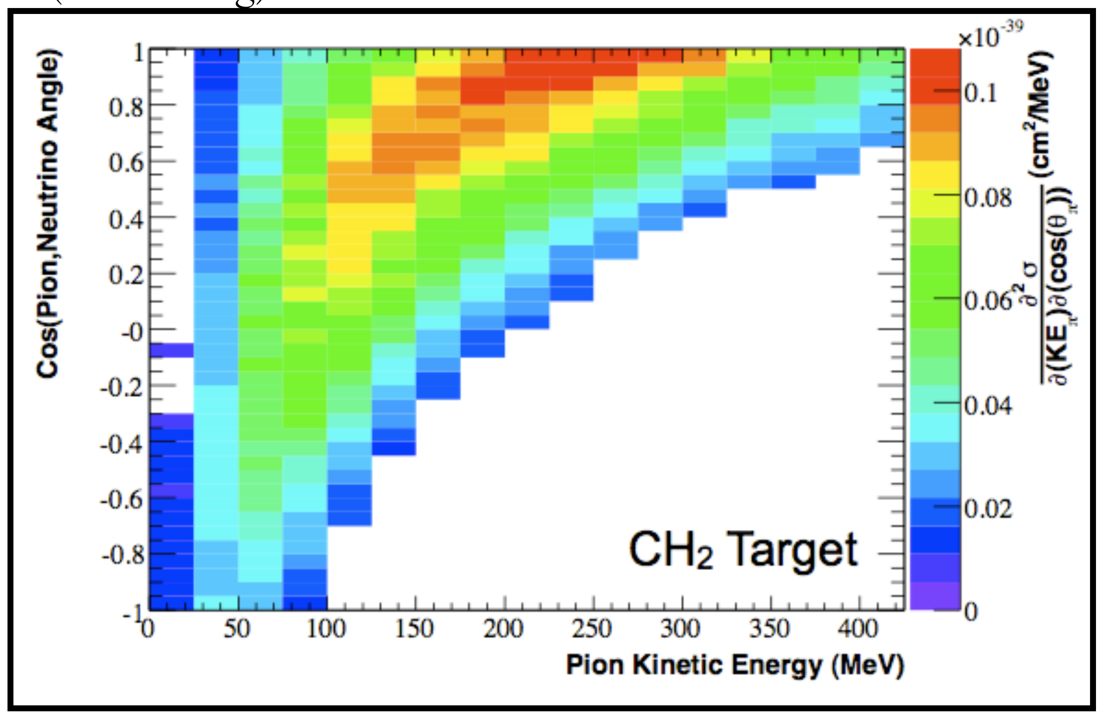
MiniBooNE

- Single Pion Production

CC π^+ production



(M. Wilking)



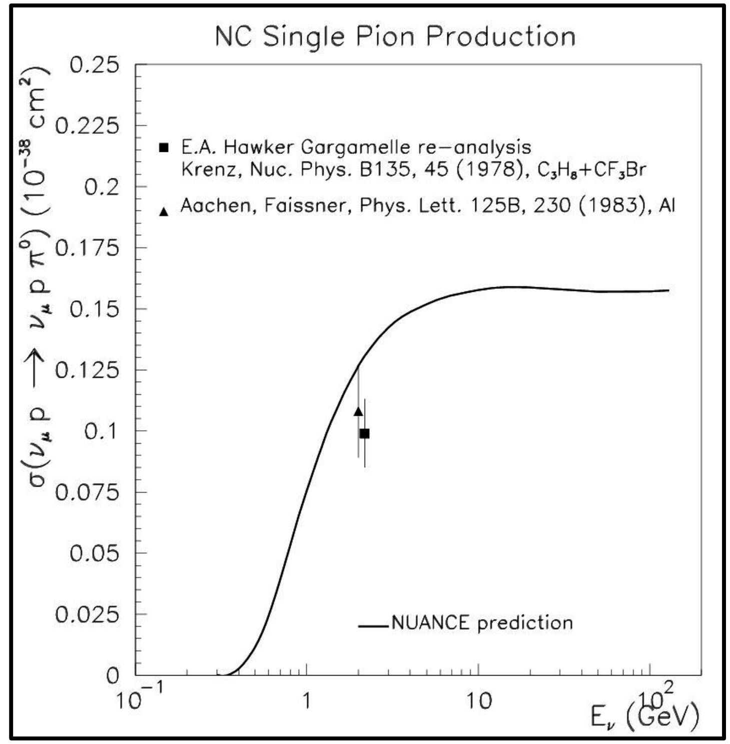
- Cross-section ratio to CCQE
- Entering the realm of absolute differential cross-sections of π^+ production for the first time

$\sigma(E_\nu)$, $d\sigma/dQ^2$, $d^2\sigma/dT_\mu d\theta_\mu$, $d\sigma/dT_\mu$, $d\sigma/d\theta_\mu$, $d\sigma/dT_\pi$, $d\sigma/d\theta_\pi$, $\mathbf{d^2\sigma/dT_\pi d\theta_\pi}$

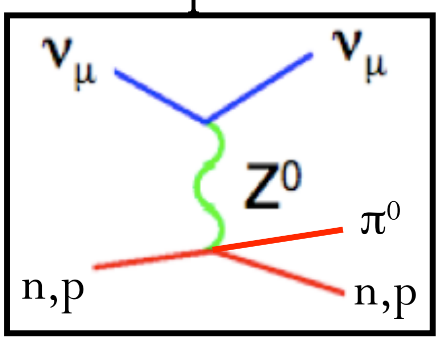
The Interactions (NC π^0)

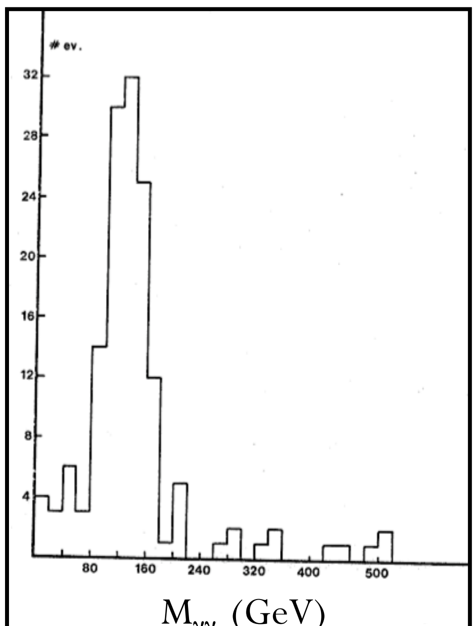
- <u>Single Pion Production</u>

- very little data available on this channel
- NC π^0's are critical background to ν_e appearance searches for LBL experiments



NC π^0 production





GGM, 240 NC π^0 events
Nucl. Phys. **B135**, 45 (1978)

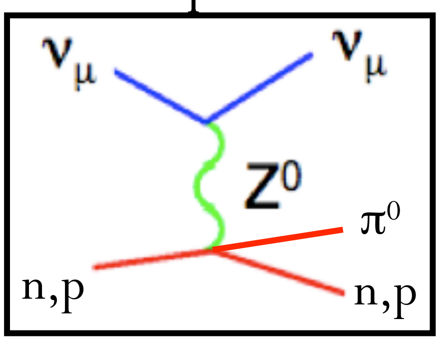
The Interactions (NC π^0)

- Single Pion Production

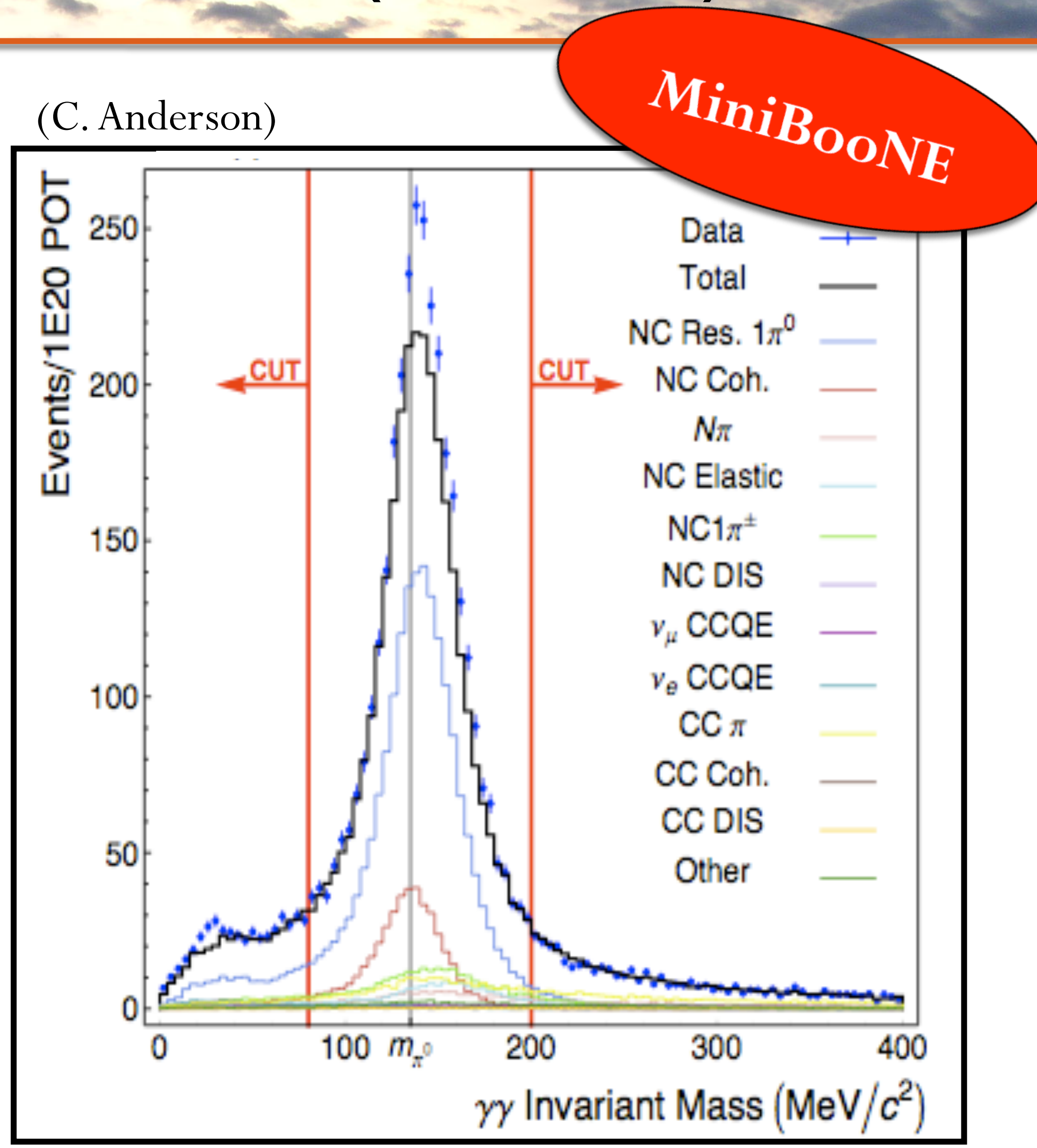
• 21,542 ν_μ NC π^0 events (73% purity, 36% ε)

• 2,305 $\overline{\nu}_\mu$ NC π^0 events (58% purity, 36% ε)

NC π^0 production



(C. Anderson)



The Interactions (NC π^0)

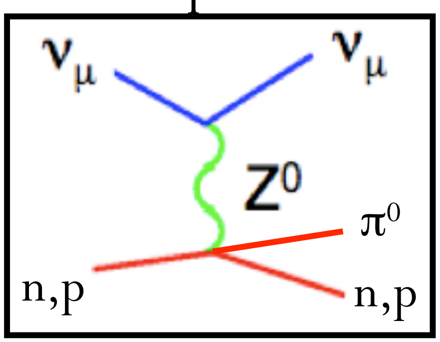
MiniBooNE

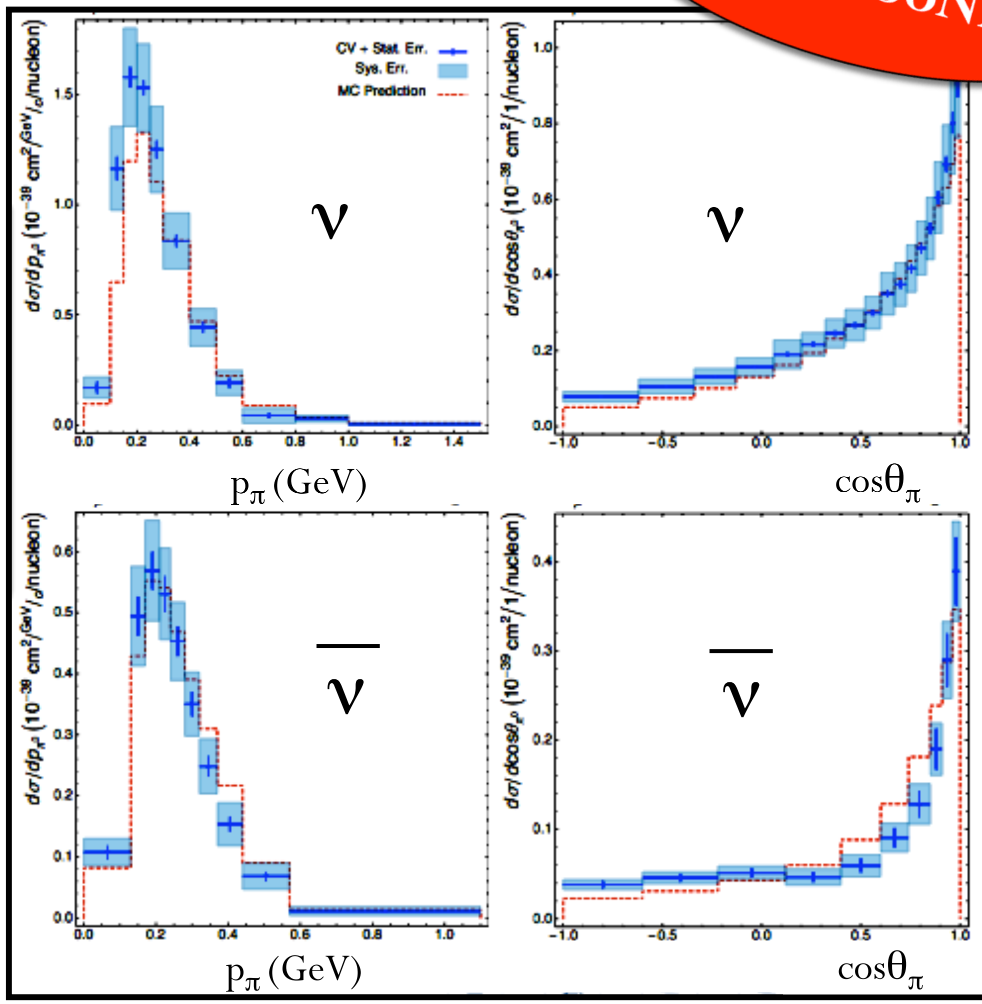
- <u>Single Pion Production</u>

(C. Anderson)

- 21,542 ν_μ NC π^0 events (73% purity, 36% ε)
- 2,305 $\overline{\nu}_\mu$ NC π^0 events (58% purity, 36% ε)
- first NC π^0 absolute differential cross-sections

NC π^0 production



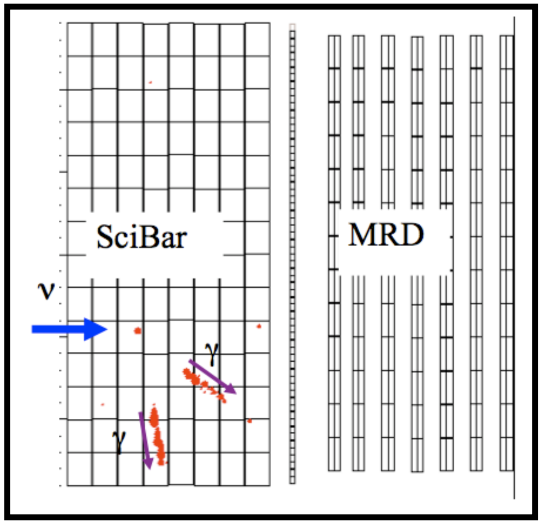


The Interactions (NC π^0)

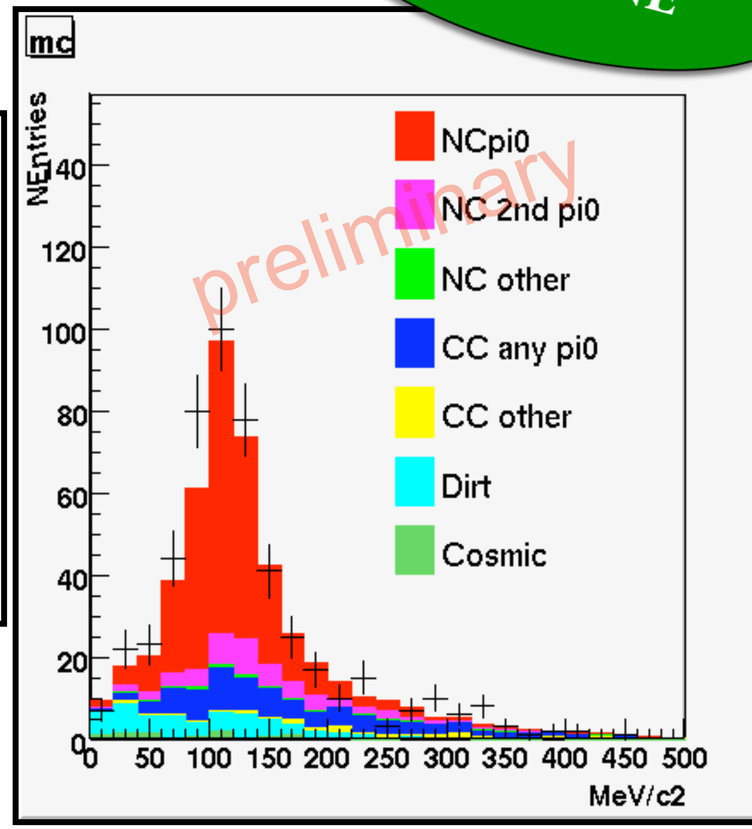
SciBooNE

- Single Pion Production

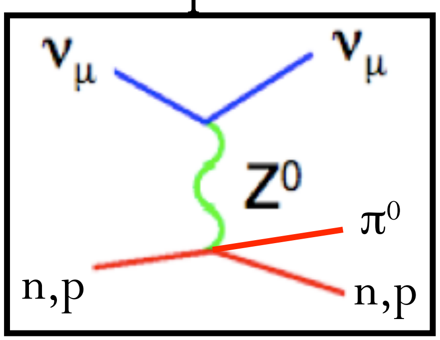
• 545 ν_μ NC π^0 events (63% purity)



(Y. Kurimoto)



NC π^0 production



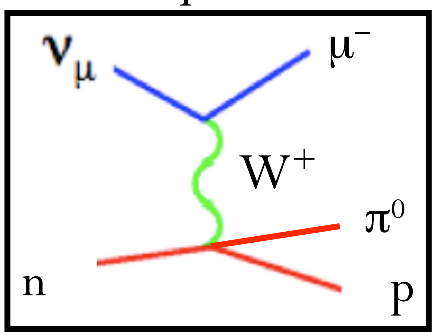
$$\frac{\sigma(\text{NC } \pi^0)}{\sigma(\text{CC inclusive})} = 7.7 \pm 0.6(\text{stat}) \pm 0.6(\text{prelim syst}) \times 10^{-2}$$

The Interactions (CC π^0)

MiniBooNE

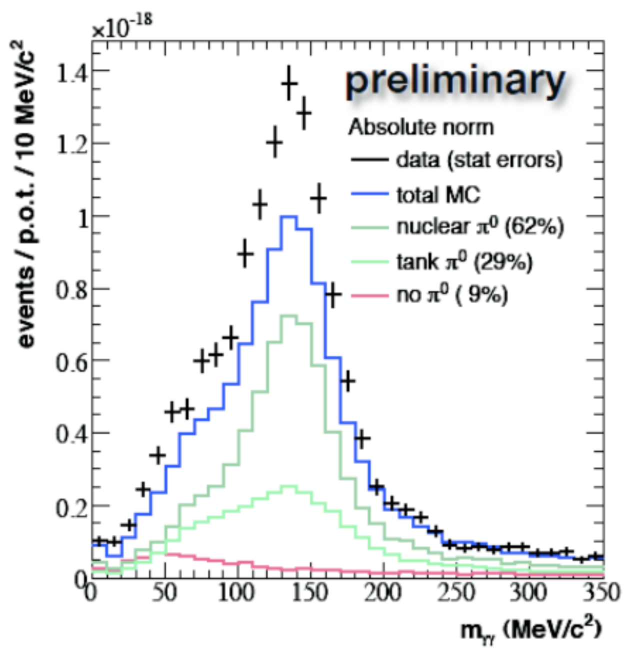
- Single Pion Production

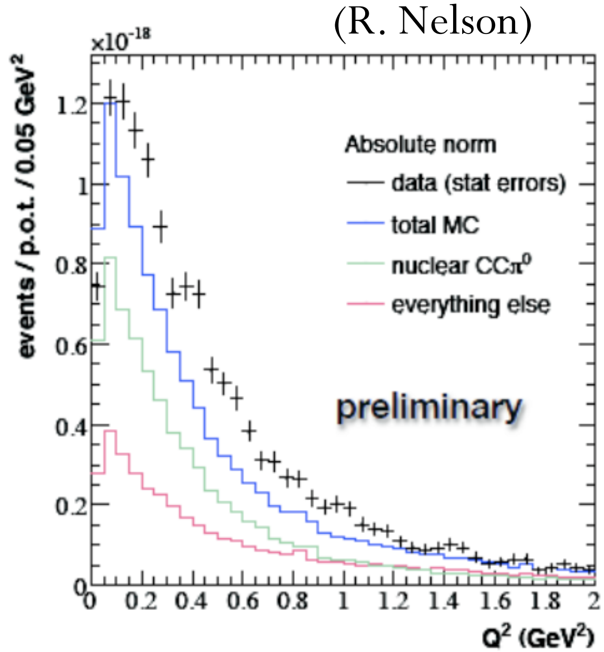
CC π^0 production



- development of 3 Cherenkov ring fitter has made possible the study of CC π^0 production

(R. Nelson)



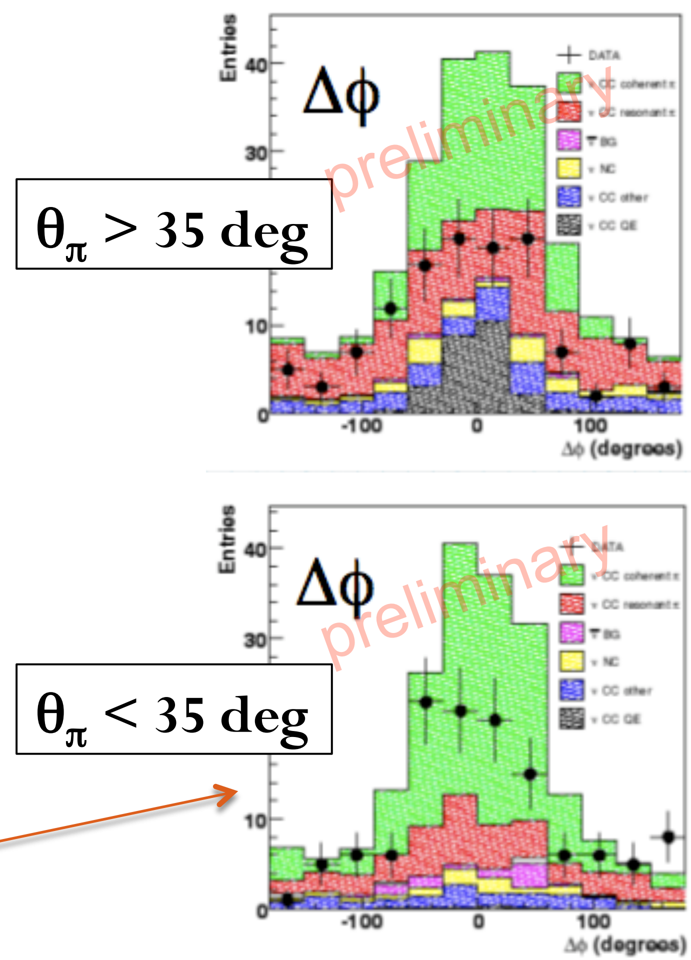


The Interactions (coherent)

- Coherent Single Pion Production (CC/NC)

H. Tanaka, NuFact 09, WG2

- Coherent interaction with nucleus leaving it intact, but producing a pion
- very small rate compared to inelastic processes
- many intriguing results recently from K2K, MiniBooNE, SciBooNE
  - K2K first to see no evidence for CC coherent pion production
  - MiniBooNE did see evidence for NC coherent pion production, though below the prediction
  - Active analysis for SciBooNE
    - preliminary evidence for some CC coherent, but pions more forward than model predicts



The Interactions

- Other Channels
- With apologies, I have not shown recent results on:
  - NC elastic scattering
    - MiniBooNE
    - SciBooNE
  - CC inclusive measurements
    - MINOS
    - NOMAD
    - NuTeV

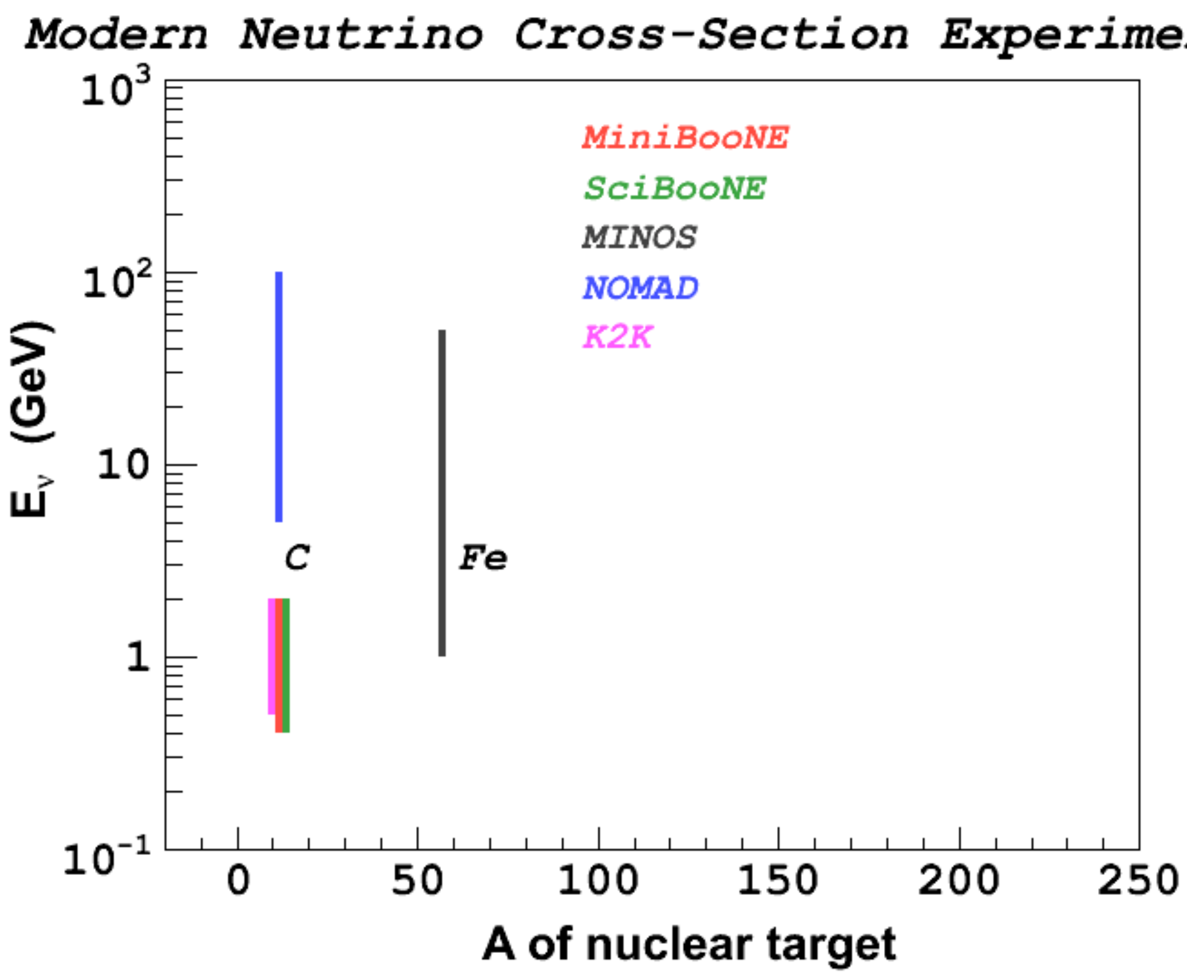
Some Intermediate Conclusions

- High statistics CCQE samples show discrepancies with present MC predictions
- We are just now beginning to make real comparisons for other channels between binned data and MC predictions
  - CC π^+/π^0 production
  - NC elastic and NC π^0 production
  - CC/NC coherent interactions off the nucleus as a whole
- Theorists are interested in this problem. Wonderful!!
- We must work with them directly or provide data they can use
- **Event rates of exclusive final states off some target nucleus**
  - not corrected back to the nucleon
  - nuclear effects (FSI) are part of this challenging theoretical problem

The Future

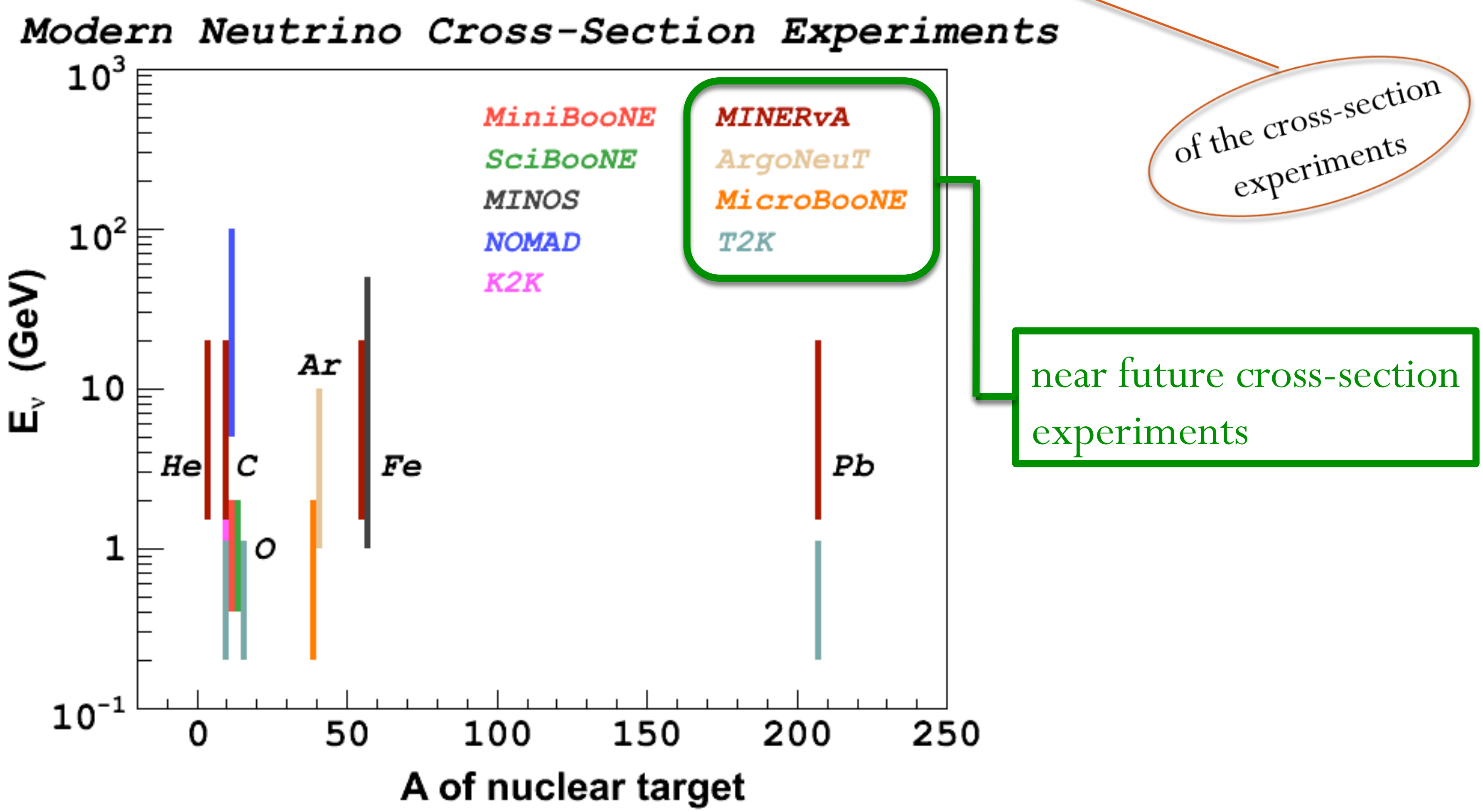
- MINERνA is a new experiment at Fermilab that will answer many of these questions
  - A strong collaboration of both experimentalists and theorists
  - neutrinos and antineutrinos
  - multiple nuclear targets in same detector
- The T2K ND280 at J-PARC includes a broad cross-section measurement agenda
- There are new LAr experiments at Fermilab which will measure interaction rates on argon at these energies for the first time
  - ArgoNeuT and MicroBooNE
  - very important for planning possible LArTPC detectors for DUSEL and elsewhere to make these measurements

Energies and Targets



of the cross-section experiments

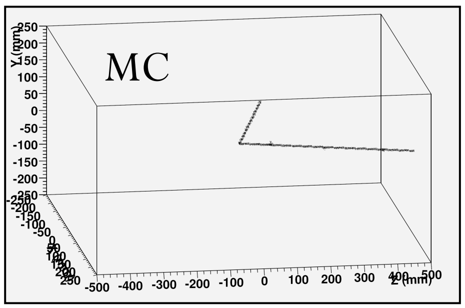
Energies and Targets

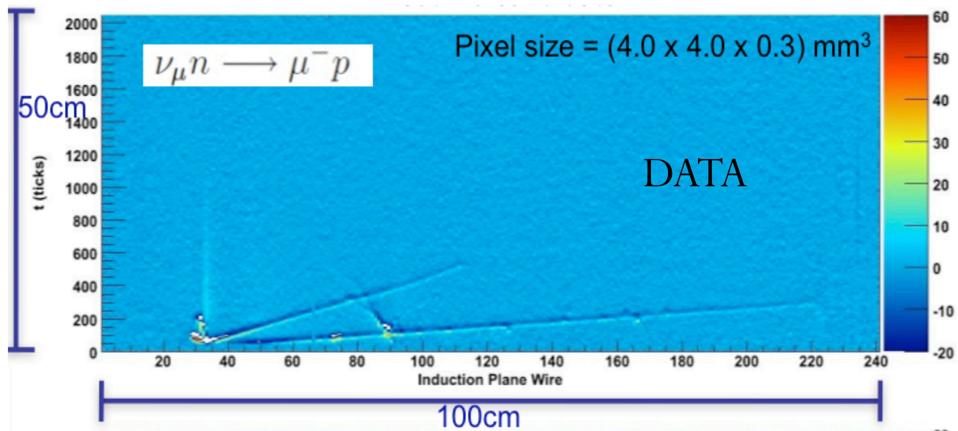


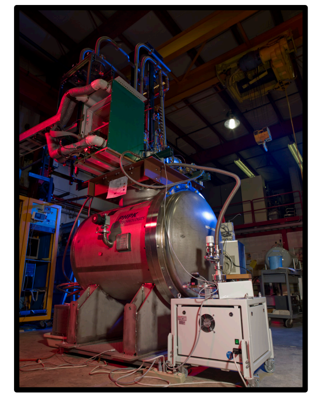
Liquid Argon

M. Antonello, NuFact 09, WG2
O. Palamara, NuFact 09, WG1-2

- ArgoNeuT
  - 0.3 ton vessel filled in May, 2009
  - Took first data in the NuMI ν beam at FNAL







- MicroBooNE
  - 170 ton vessel to sit in Booster Beam at FNAL
  - part of staged approach to testing feasibility of large LAr detectors
  - rich physics program including x-sections on Ar

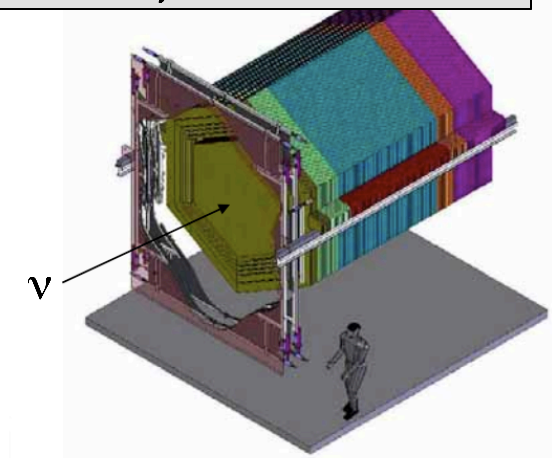
	BNB	NuMI
Total Events	145k	60k
ν_μ CCQE	68k	25k
NC π^0	8k	3k
ν_e CCQE	0.4k	1.2k
POT	6x10^{20}	8x10^{20}

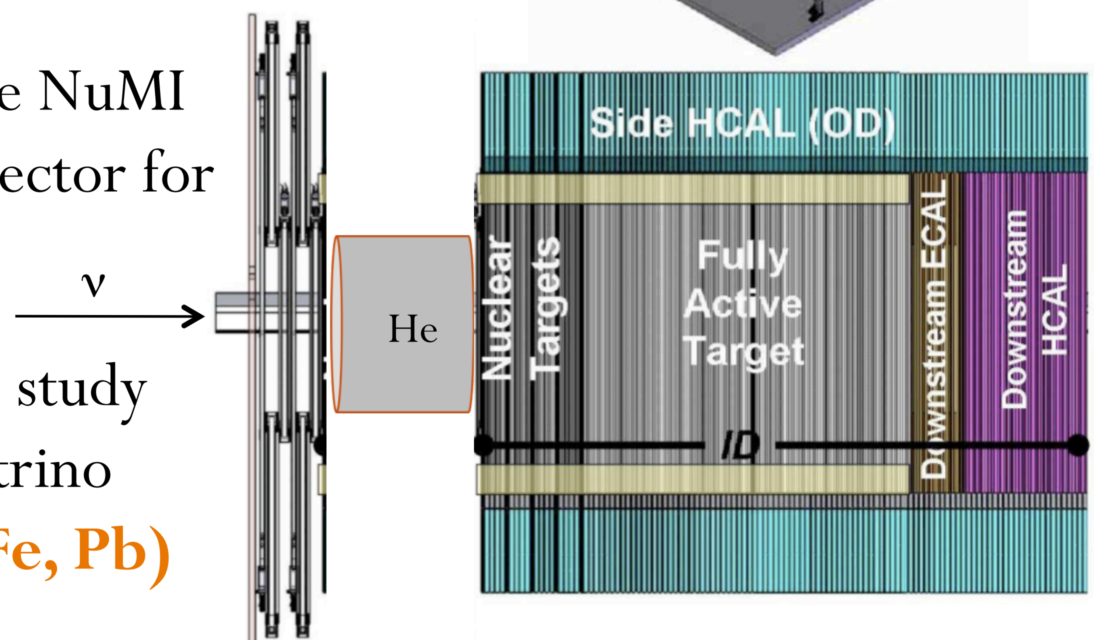
Expected Event Rates for MicroBooNE.

MINERνA

- MINERνA is a dedicated **neutrino-nucleus** cross-section experiment
- Finely segmented, fully active scintillator tracking region surrounded by ECAL and HCAL
- make use of existing intense NuMI beam and MINOS near detector for muon spectrometer
- range of nuclear targets for study of **nuclear effects** in neutrino interactions **(He, C, CH, Fe, Pb)**

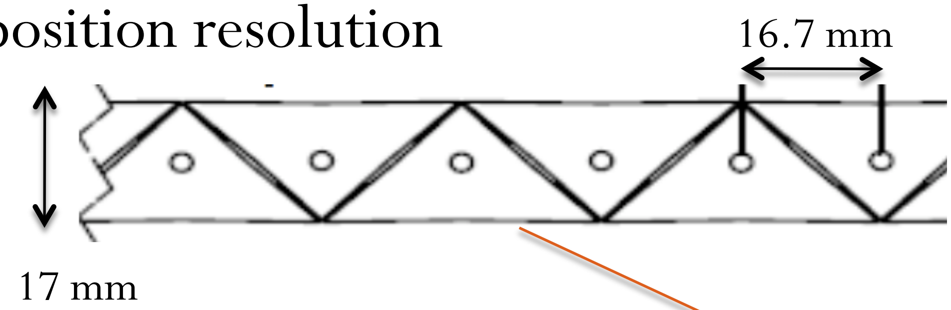
B. Eberly, NuFact 09, WG2



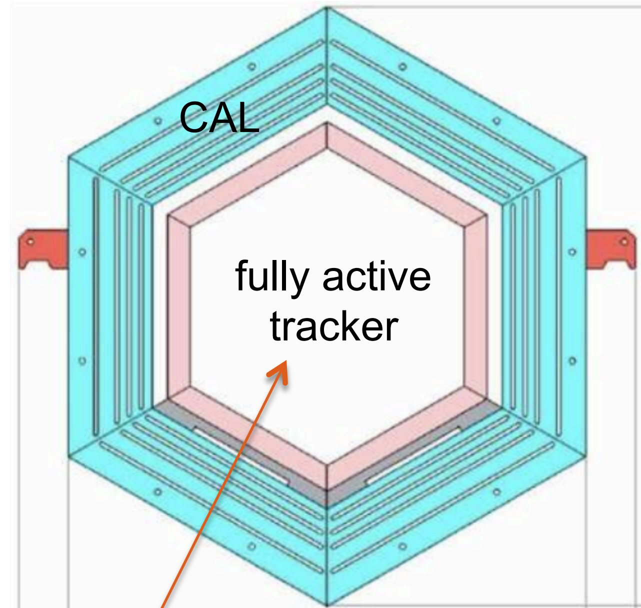


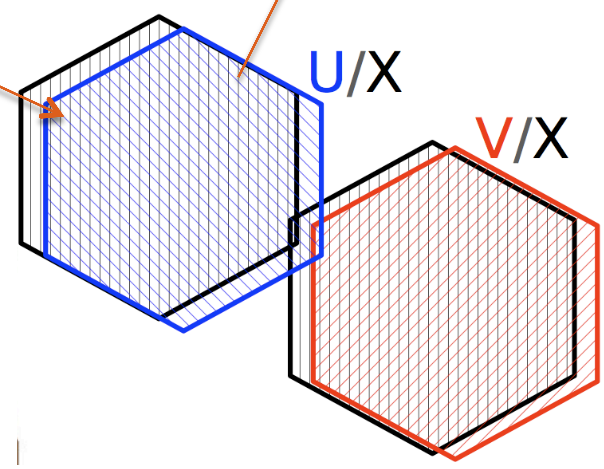
MINERνA

- fully active scintillator planes
- triangular geometry allows charge sharing for better position resolution

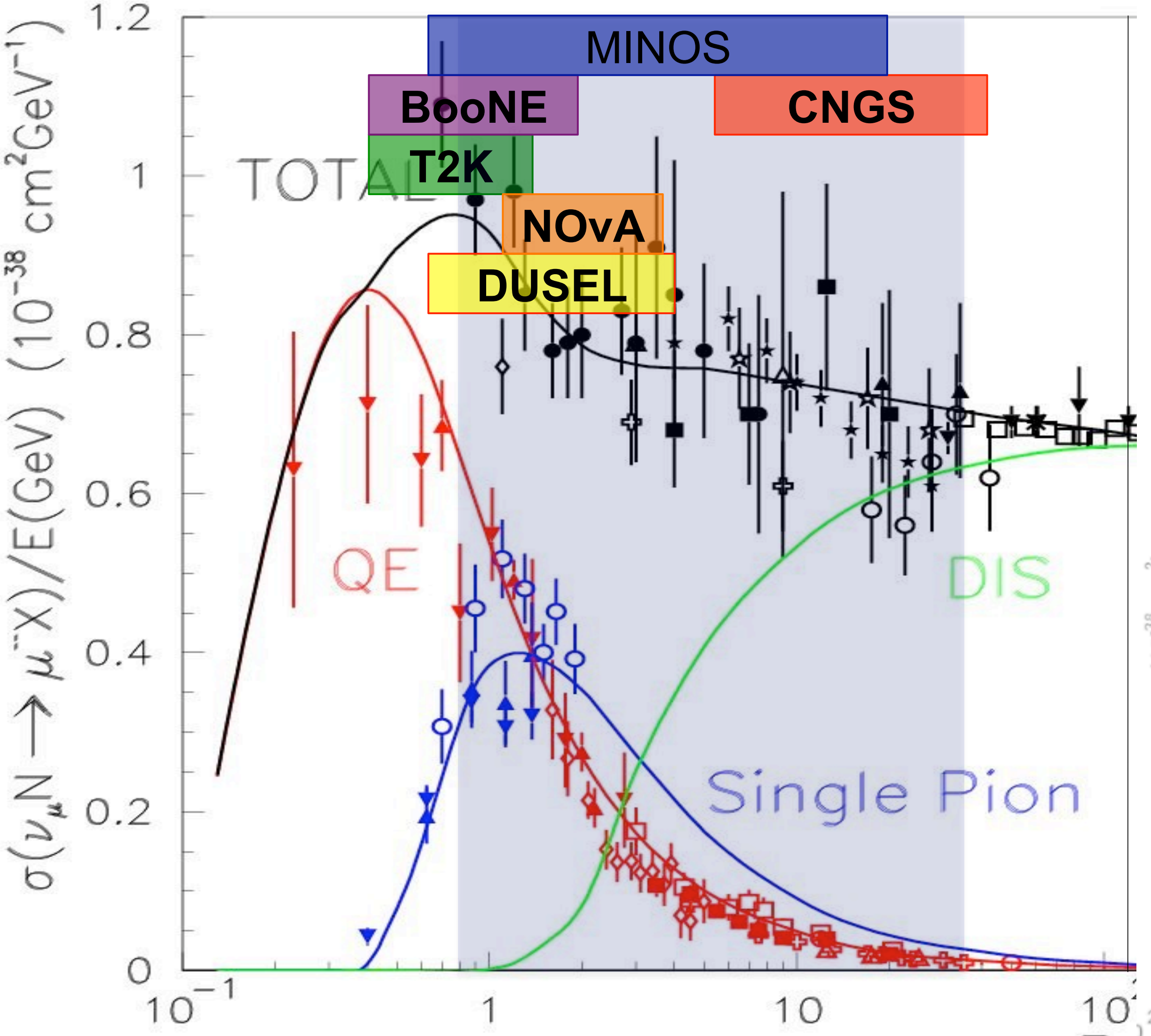


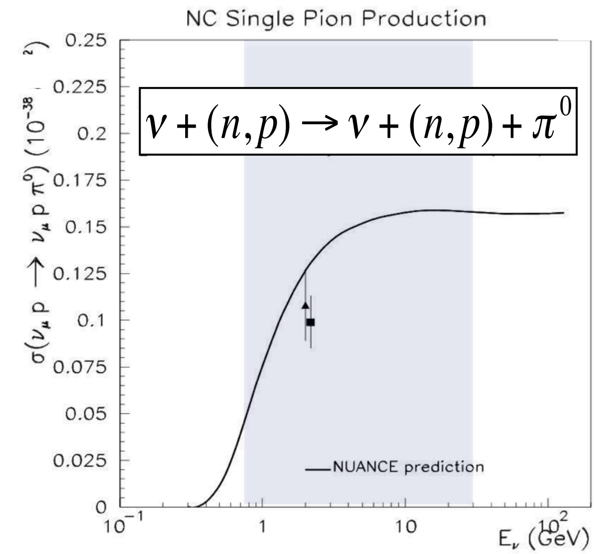
- Tracking/ECAL modules alternate U/X V/X ID views
- HCAL Fe + scint plane
- OD scintillator bars

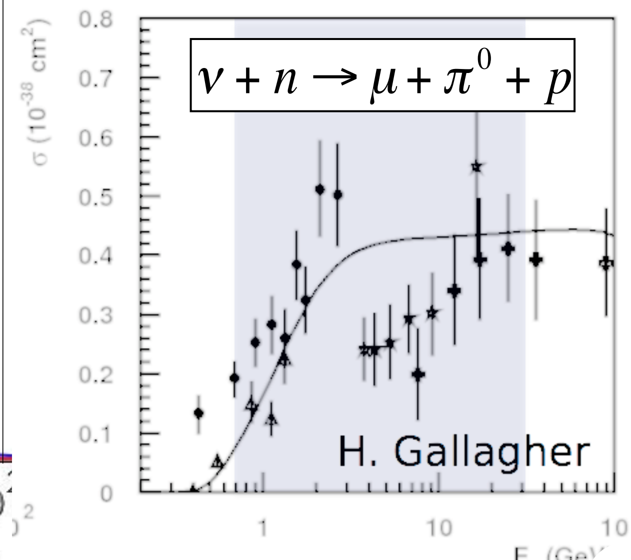




MINERνA Energy Range

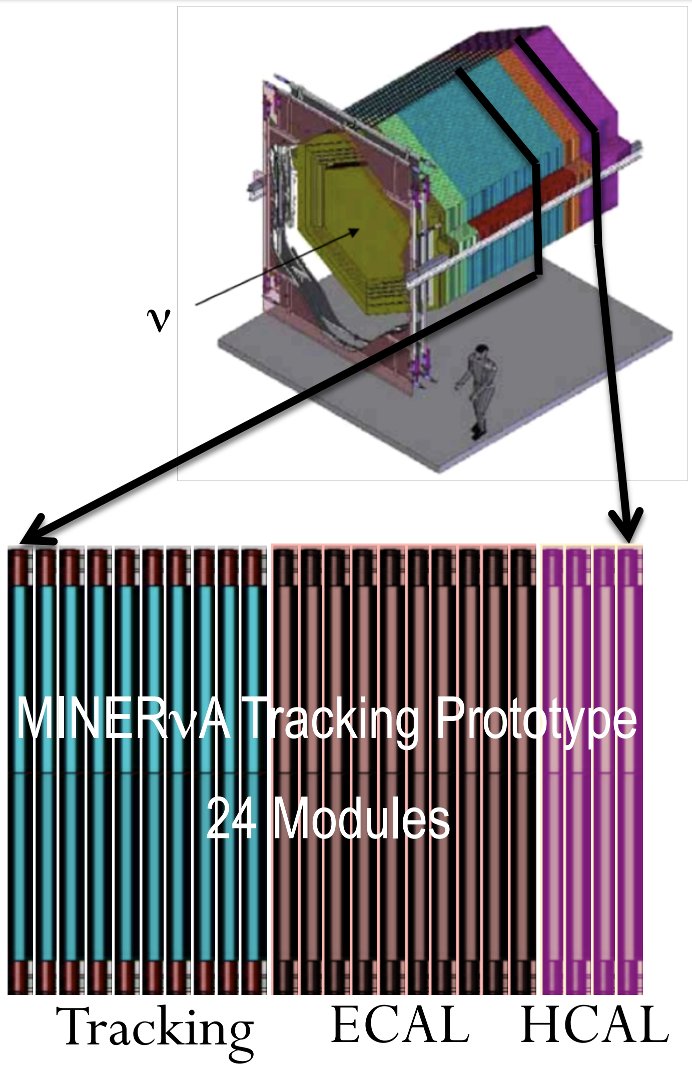




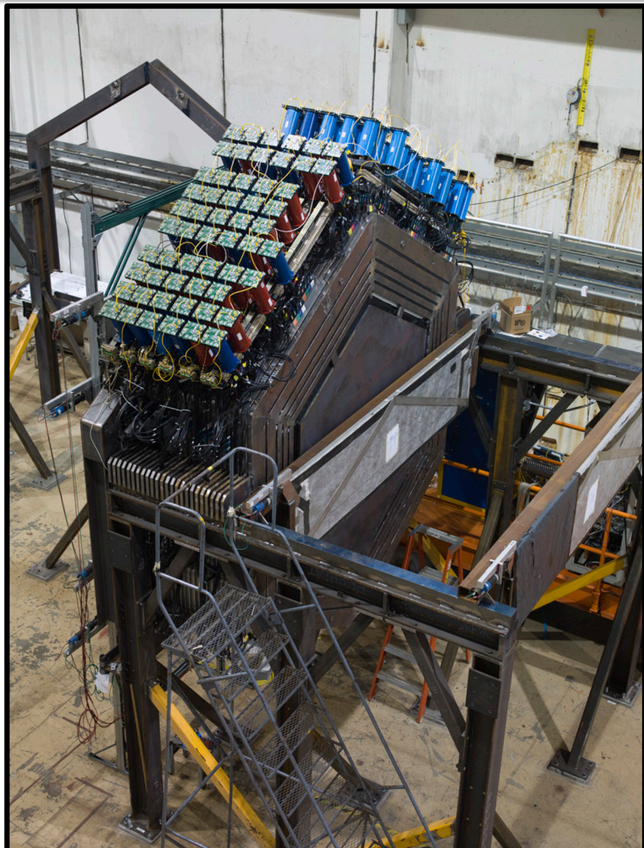


MINERνA Status

- Phased installation in Fall/Winter 2009-10 with completion in spring 2010
- Ran with a detector prototype in the NuMI beam for two months before the recent shutdown
- comprehensive tests of :
  - detector design
  - component production and assembly
  - calibration techniques and implementations
  - event reconstruction
  - physics performance and analysis



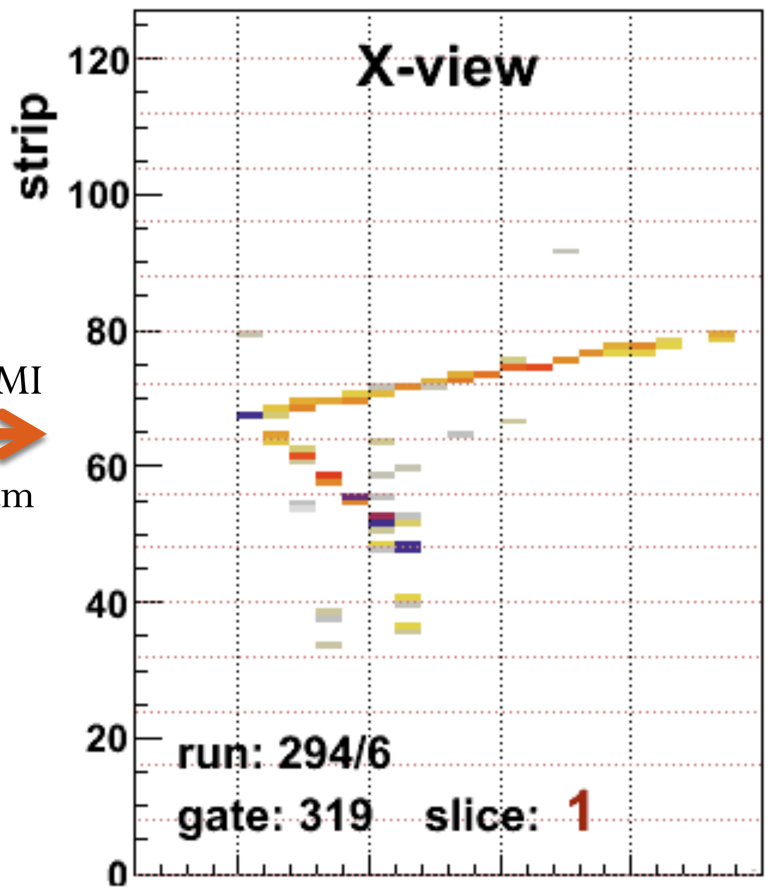
MINERνA Tracking Prototype



April – June, 2009

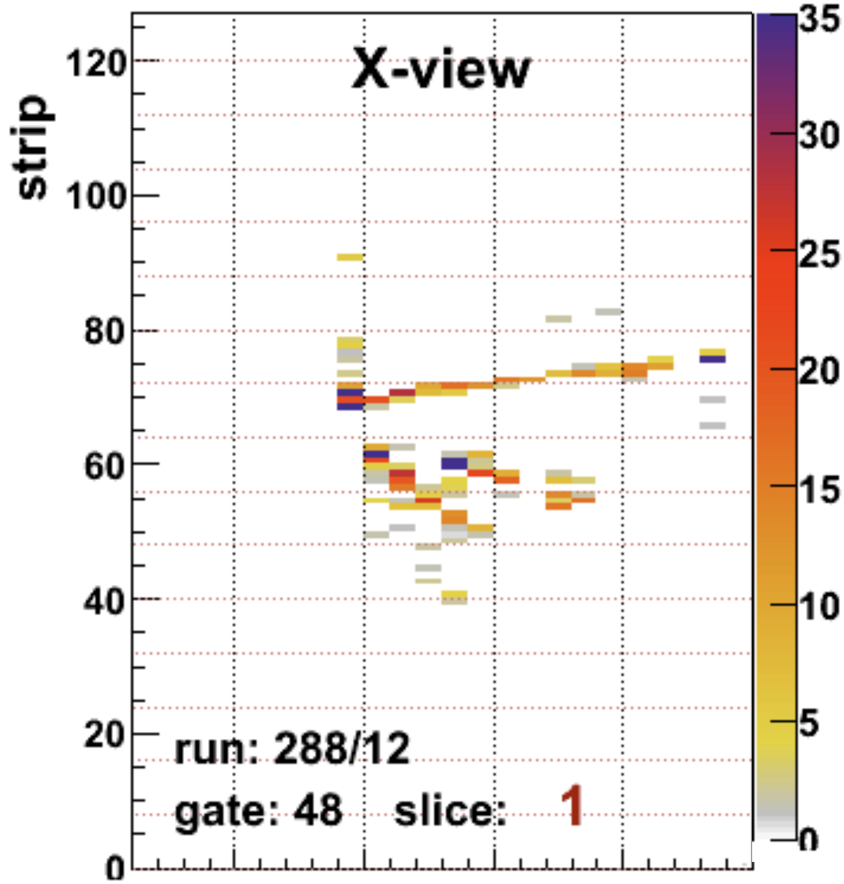
MINERνA Status – It Works!

ν_μ CCQE candidate event



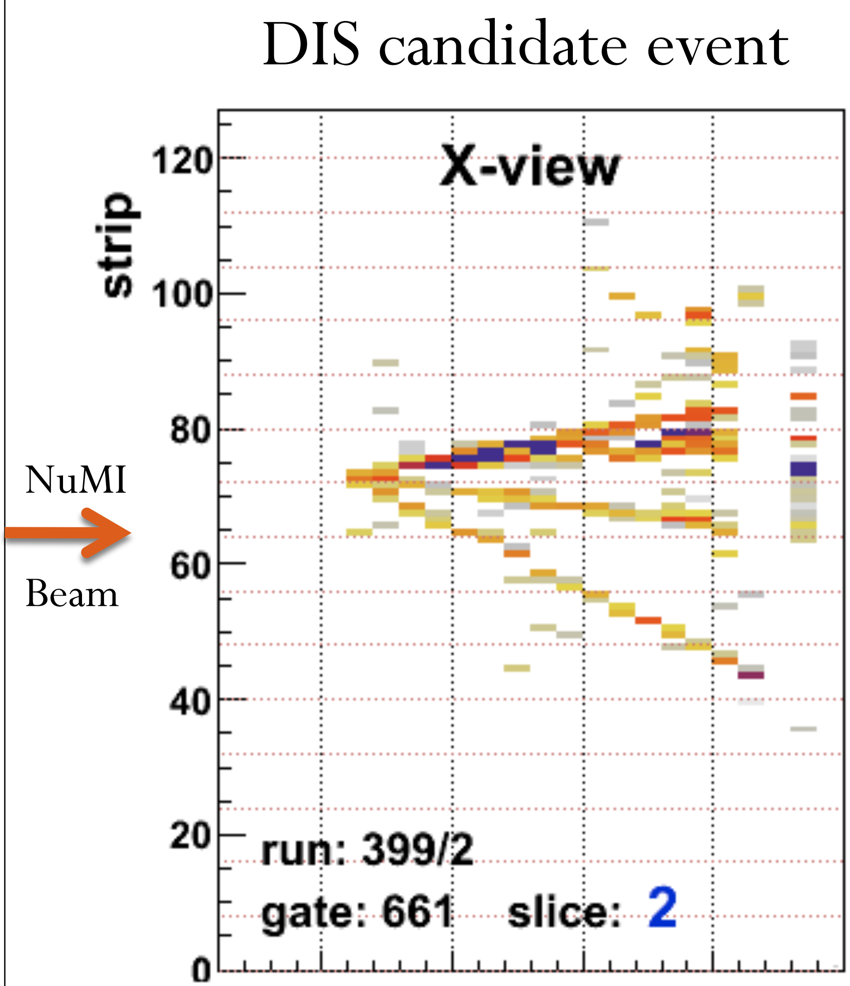
NuMI
Beam

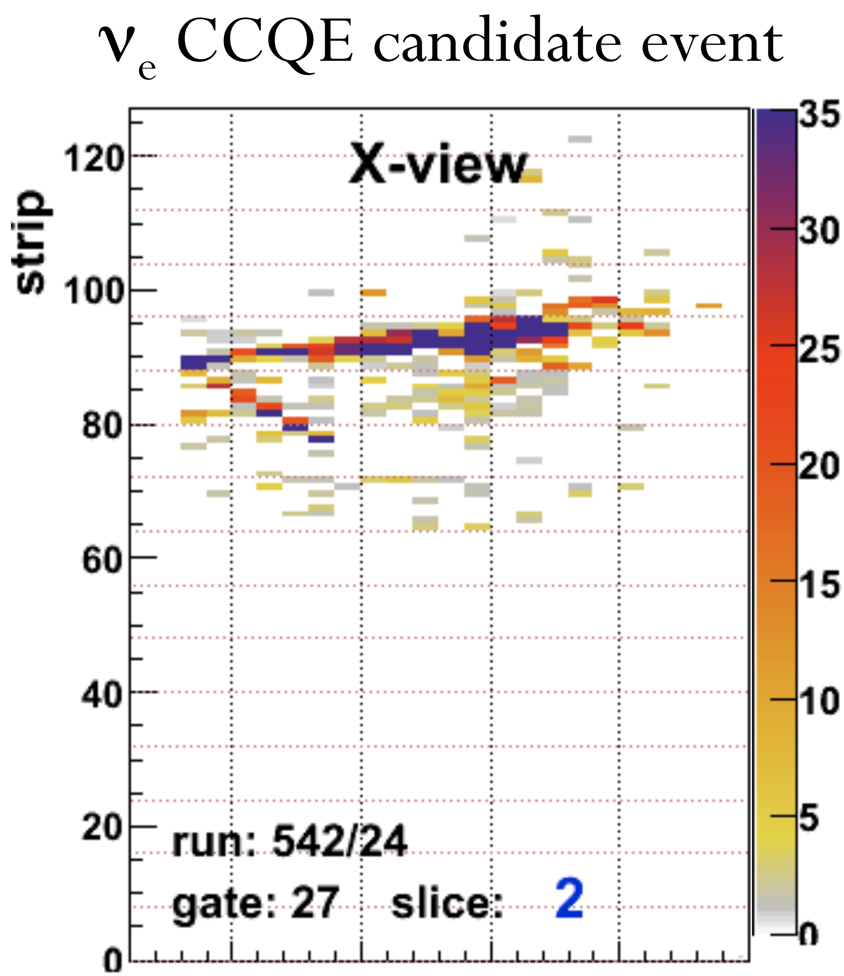
ν_μ CC π^0 candidate event



MINOS

MINERνA Status – It Works!



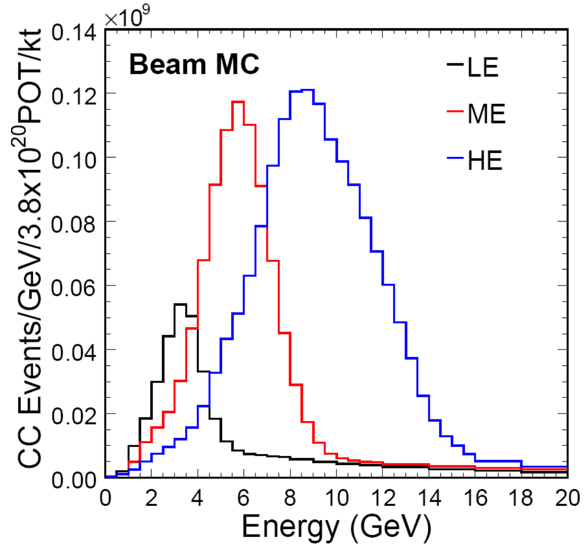


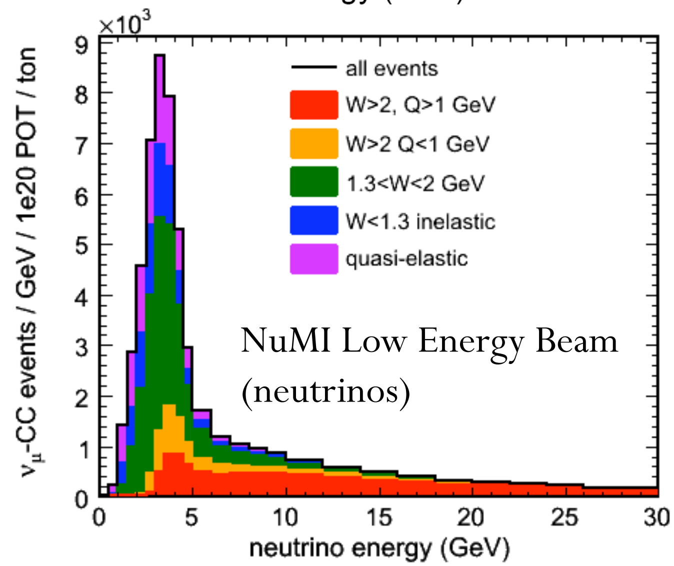
MINOS

MINERνA Physics Data

- Current Run Plan, beginning in 2010
  - 4e20 POT low energy beam
  - 12e20 POT medium energy beam

Quasi-elastic	0.8 M
Resonance production	1.7 M
Resonance to DIS transition	2.1 M
DIS low Q^2 and structure functions	4.3 M
Coherent pion production	89k CC, 44k NC
charm/strange production	230 k
He target	0.6 M
C target	0.4 M
Fe target	2.0 M
Pb target	2.5 M





Summary

- An explosion of neutrino cross-section data in recent years
  - absolute cross-sections
  - differential cross-sections, most for the first time ever
- Intriguing differences to the Monte Carlos are being seen in several channels at various energies on multiple targets
- Most likely a combination of the interaction models and mis-modeled nuclear effects – quite a puzzle!
- Important to solve
  - intellectually interesting
  - important for the next generation of precision neutrino physics experiments
- The dedicated experiment, MINERνA, will go a long way towards finding many answers starting next year, so stay tuned


Thank you!
NuFact09
11th International Workshop on
Neutrino Factories, Superbeams and Beta Beams
July 20-25, 2009 – Illinois Institute of Technology – Chicago