

Review of Current and Future Neutrino Cross-Section Experiments

David Schmitz, Fermilab

WIN '09

**22ND INTERNATIONAL WORKSHOP ON
WEAK INTERACTIONS AND NEUTRINOS
SEPTEMBER 13-19, 2009 – PERUGIA, ITALY**

Outline

- Introduction (motivation and context)
- The relevant neutrino energies and nuclear targets
- Summary of recent results and open questions
- Status and prospects of neutrino cross-section experiments on the horizon



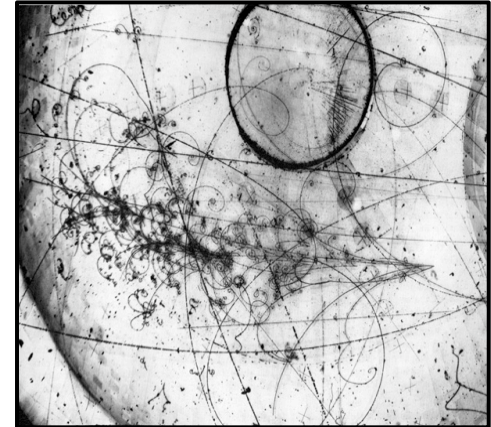
Introduction

- There has been a recent surge of progress and published 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
- Please see the many great talks from **NuInt09, NuFact09 (WG2)**, and here at **WIN09 (DG3)** for many details
 - <http://nuint09.ifae.es/Welcome.html>
 - <http://nufact09.iit.edu/wg2.shtml#wg2tueam>
 - <http://win09.lngs.infn.it/program>



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 **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 (20-100%) or show discrepancies that we would like to understand



Introduction

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 1. suddenly we really care about neutrino 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



Introduction

- 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**.
- **Neutrino energy reconstruction** must be very well understood, as oscillations are an energy dependent phenomenon



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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 - experimental sensitivities can change as a result



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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.
Particularly good when you are building 100's of kilotons for B's of \$.



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

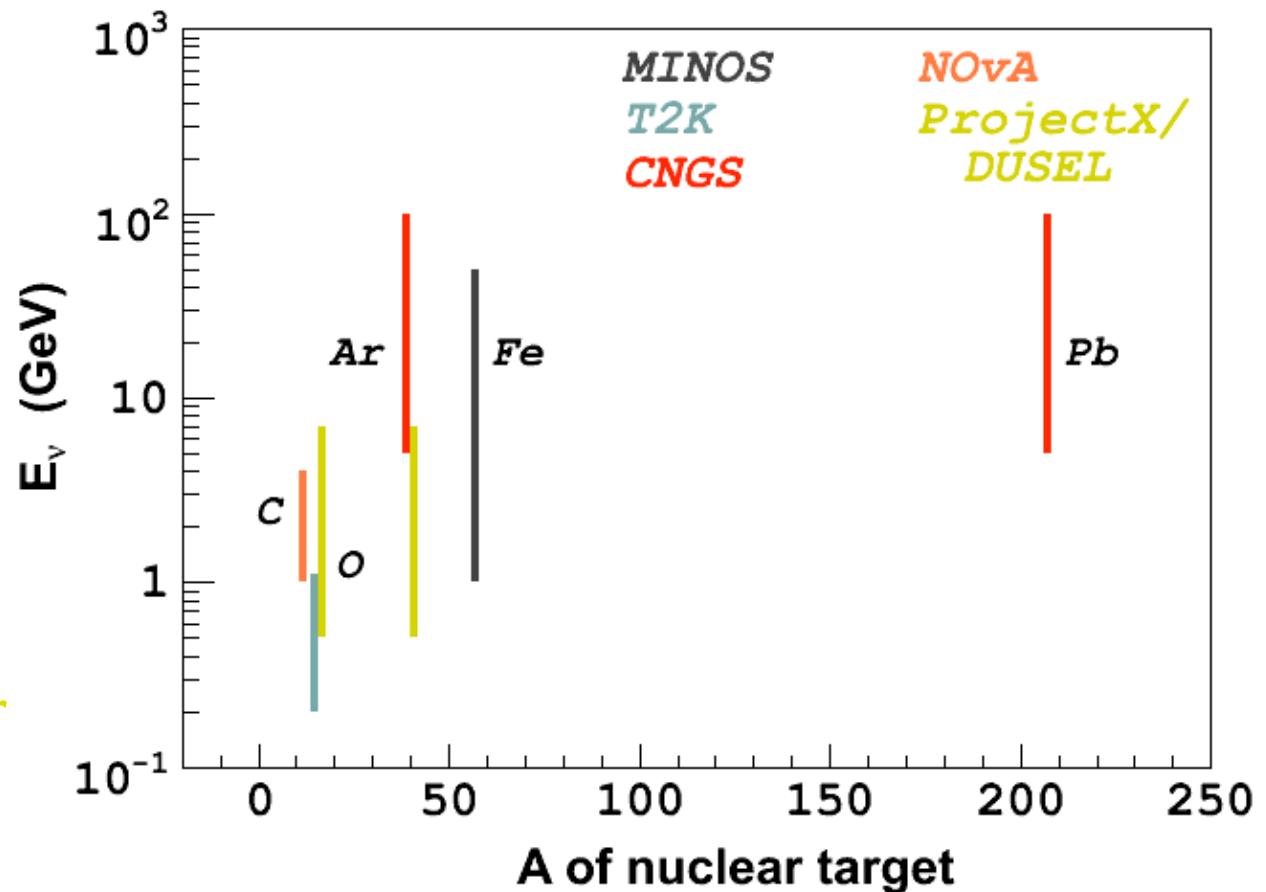


Energies and Targets

of the LBL
oscillation experiments

- Target Materials:
 - MINOS = Fe
 - CNGS = Pb, Ar
 - T2K = H₂O
 - NOvA = C
 - DUSEL = H₂O, Ar

LBL Neutrino Oscillation Experiments

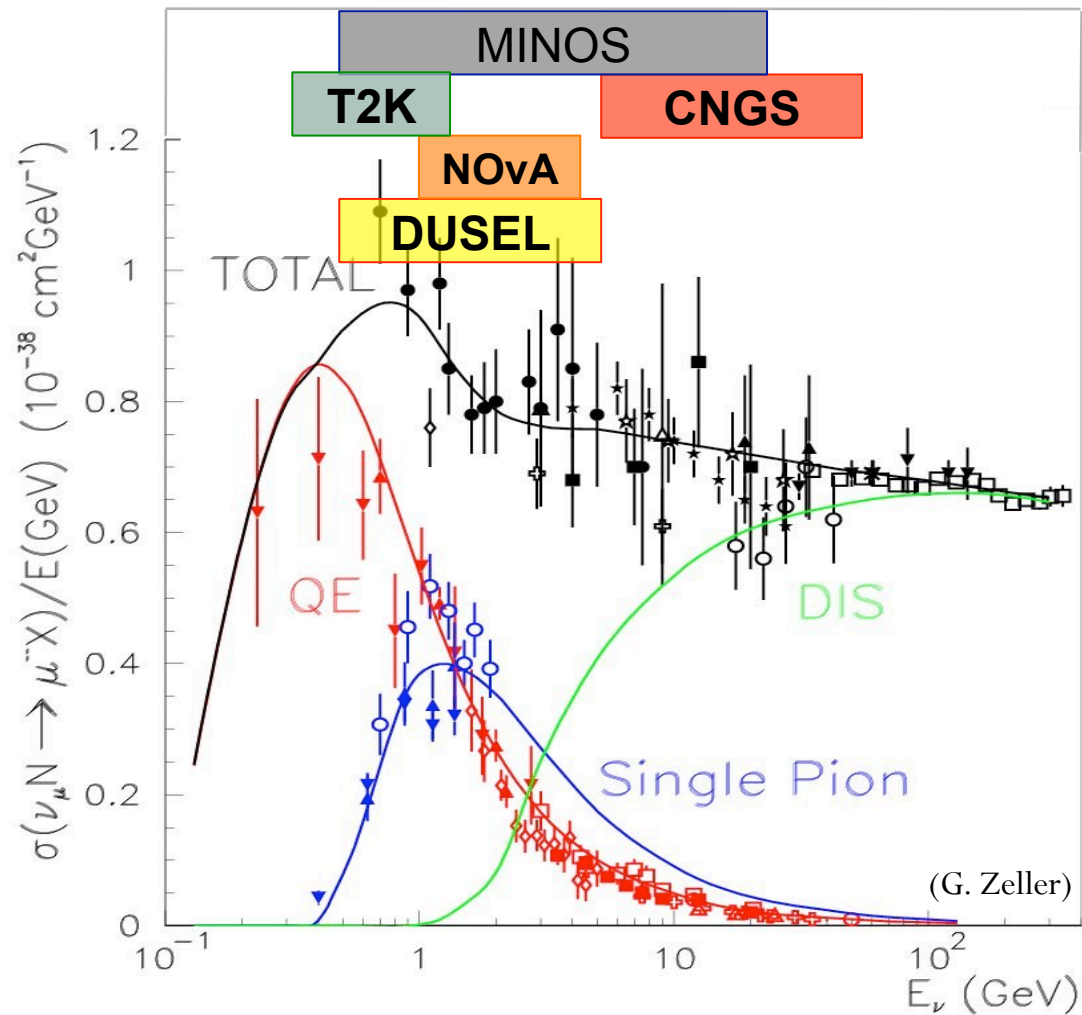


Energies and Targets

of the LBL
oscillation experiments

- projection onto the neutrino energy axis tells us which interactions we are most interested in for these experiments

ν_μ charged-current cross-sections



Energies and Targets

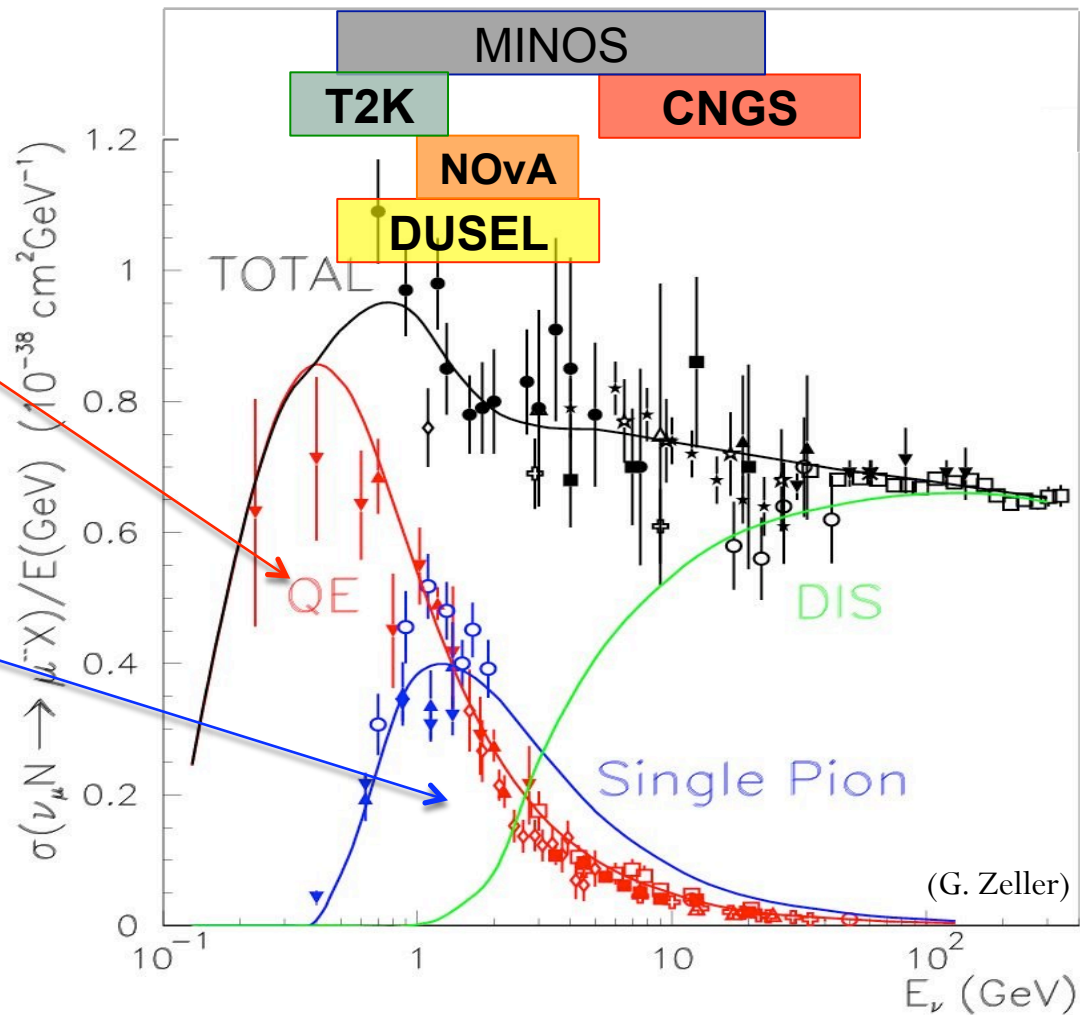
of the LBL
oscillation experiments

Quasi-Elastic
signal channel in LBL
oscillation experiments

CC π^+
background for
 ν_μ disappearance

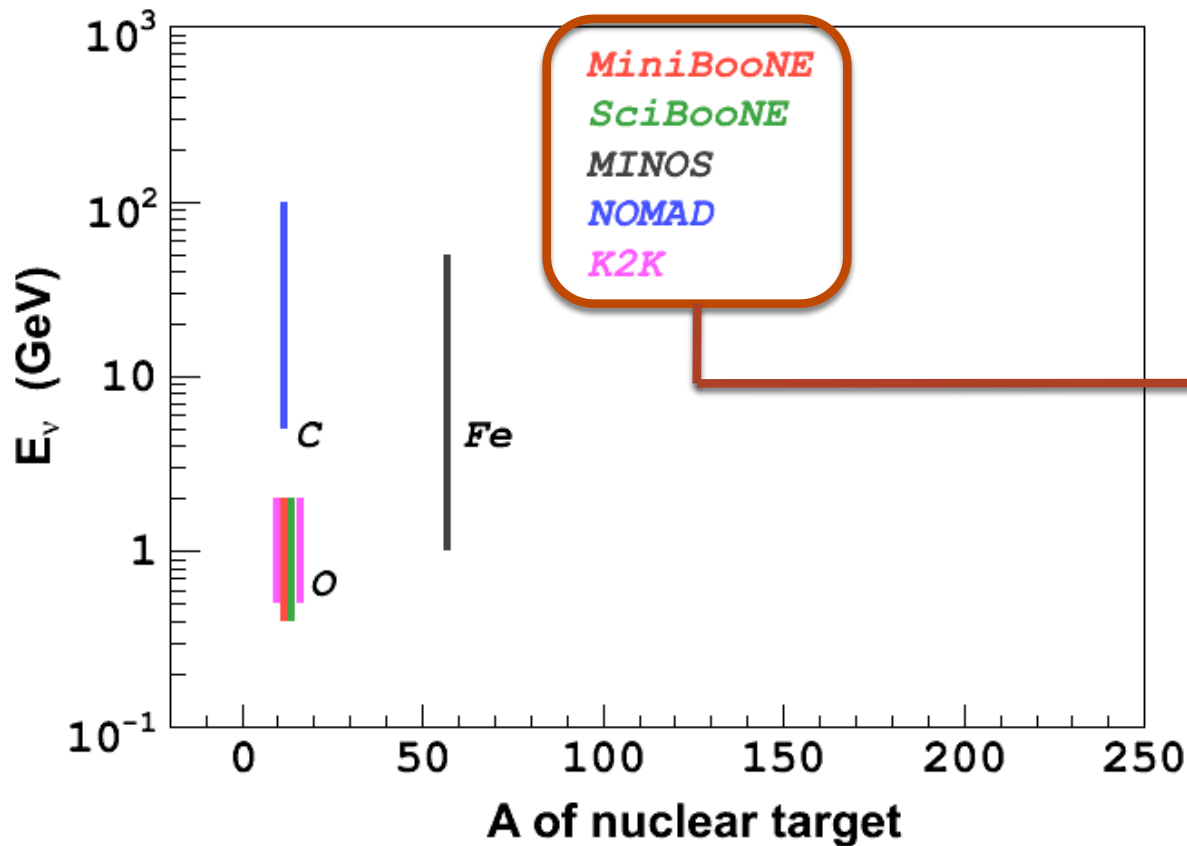
NC π^0
background for
 ν_e appearance

ν_μ charged-current cross-sections



Energies and Targets

Modern Neutrino Cross-Section Experiments



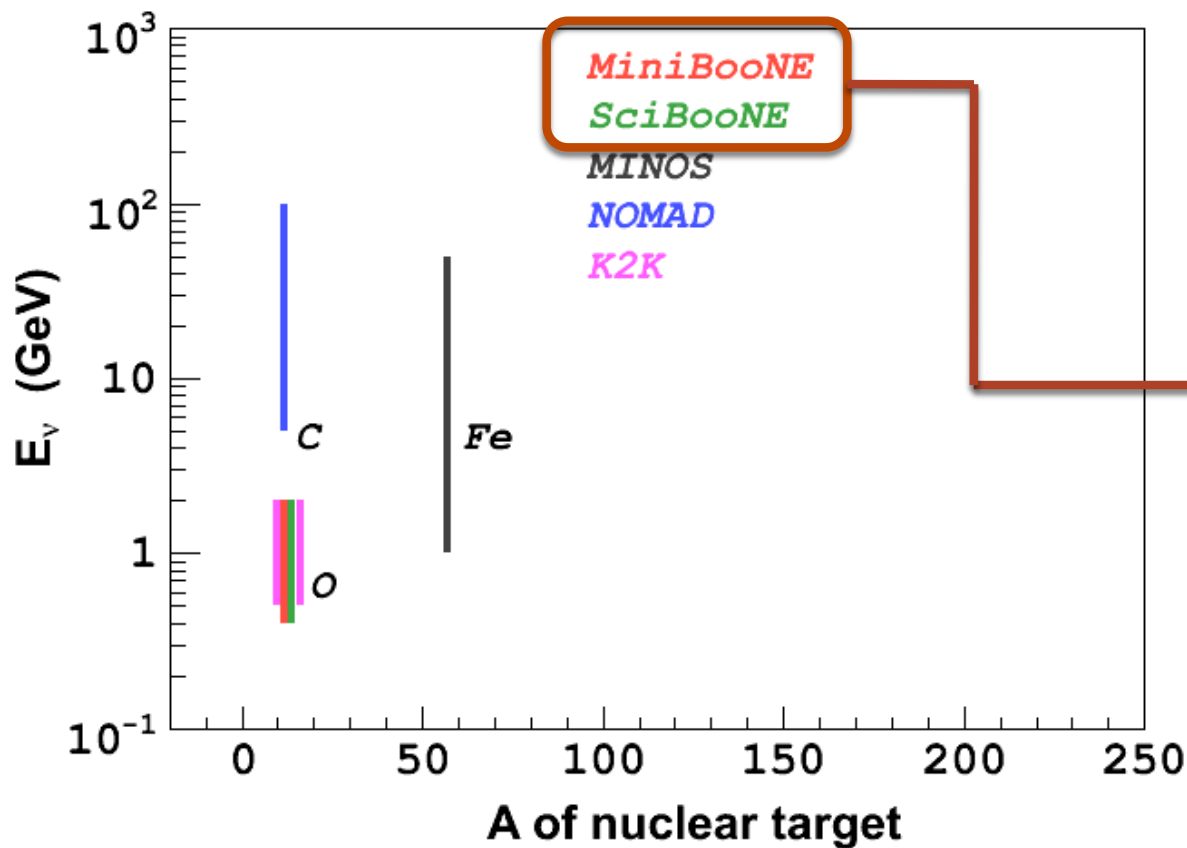
of the cross-section experiments

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



Energies and Targets

Modern Neutrino Cross-Section Experiments



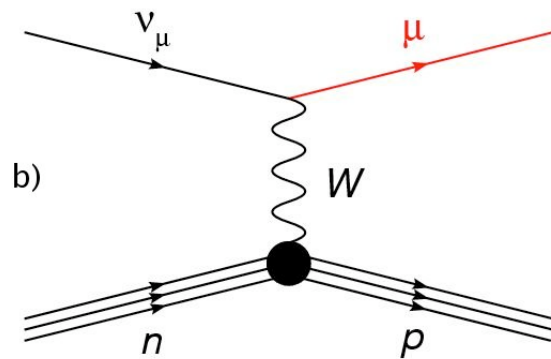
of the cross-section experiments

in fact, a very complete presentation covering the new results of **MiniBooNE** and **SciBooNE** will be given by Y. Hayato in DG3 on Wednesday



The Interactions (CCQE)

- Charged-Current Quasi-Elastic Scattering

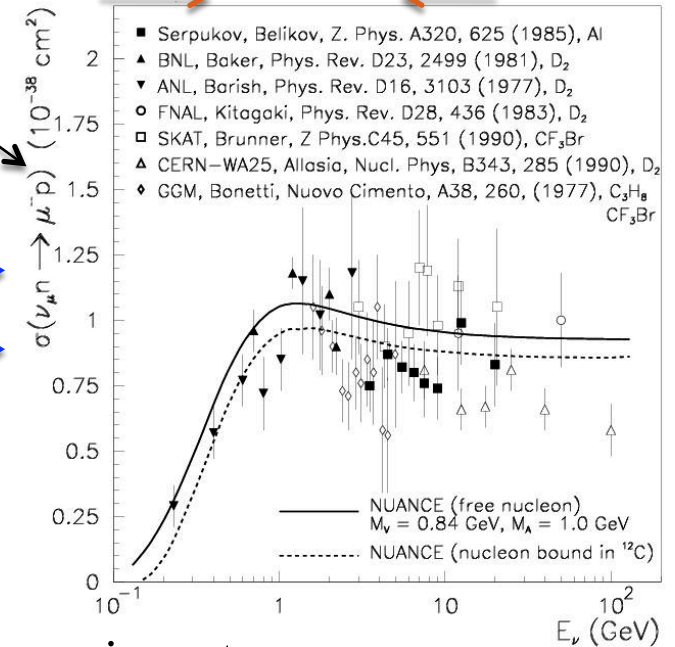


no $/E(\text{GeV})$

~40% spread
across expts

10-20% errors on data sets

relevant for osc expts



- CCQE is the signal channel for most oscillation experiments

- a clean final state with two easily identifiable particles (μ, p) or (e, p)
- muons and electrons simple to separate for ν_μ/ν_e ID
- final state allows **neutrino energy reconstruction** with one or both tracks

$$E_\nu^{QE} = \frac{2(m_N - \epsilon_B) - (\epsilon_B^2 - 2m_N\epsilon_B + m_\ell^2 + \Delta M^2)}{m_N + \epsilon_B - E_\ell + p_\mu \cos(\theta_\ell)}$$



The Interactions (CCQE)

- Charged-Current Quasi-Elastic Scattering

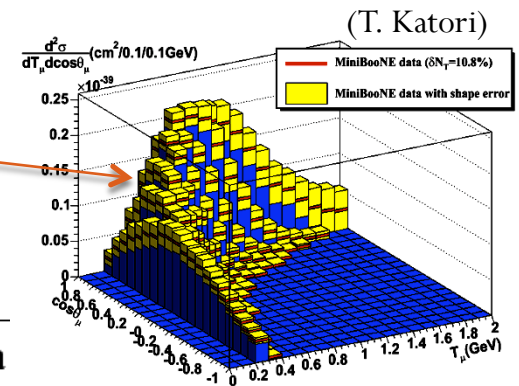
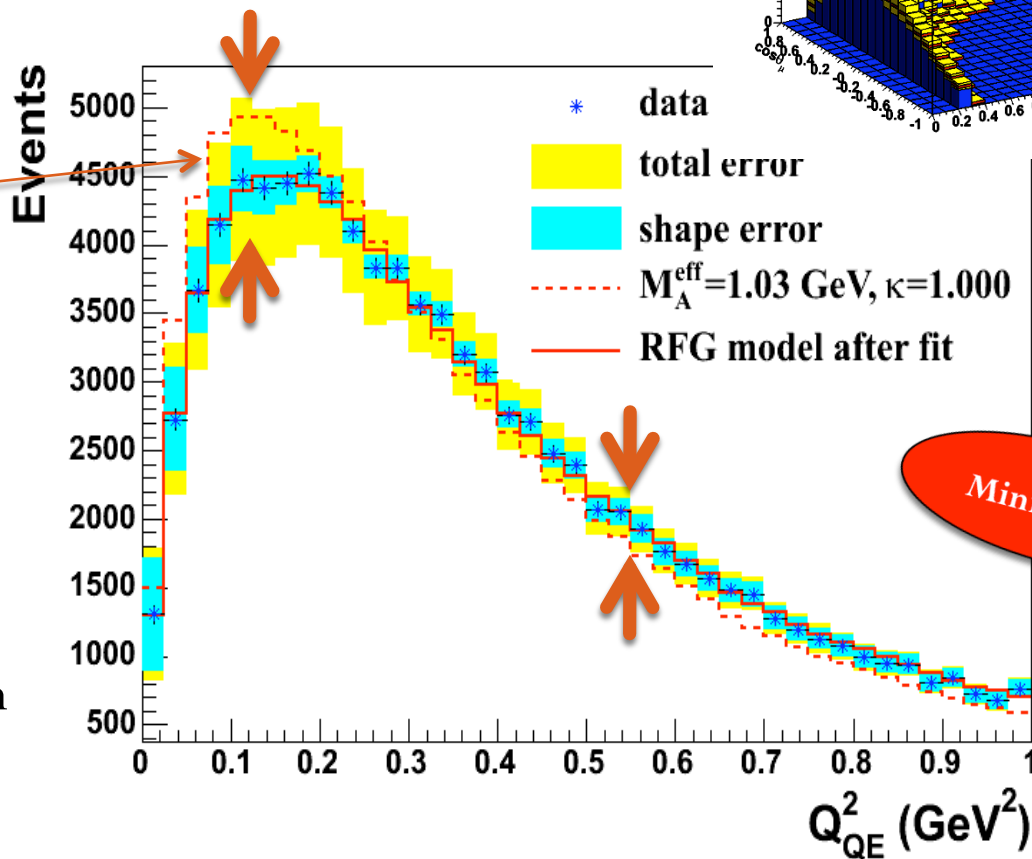
- 146,070 ν_μ QE events on carbon (76% purity)

- Q^2 distribution is used to compare to default QE model used in event generator

- deficit seen at lowest Q^2
- excess at higher Q^2

- MiniBooNE is the first to extract an absolute **double differential cross-section** in ν quasi-elastic scattering*

* $d^2\sigma / (d(\cos\theta_\mu)dT_\mu)$

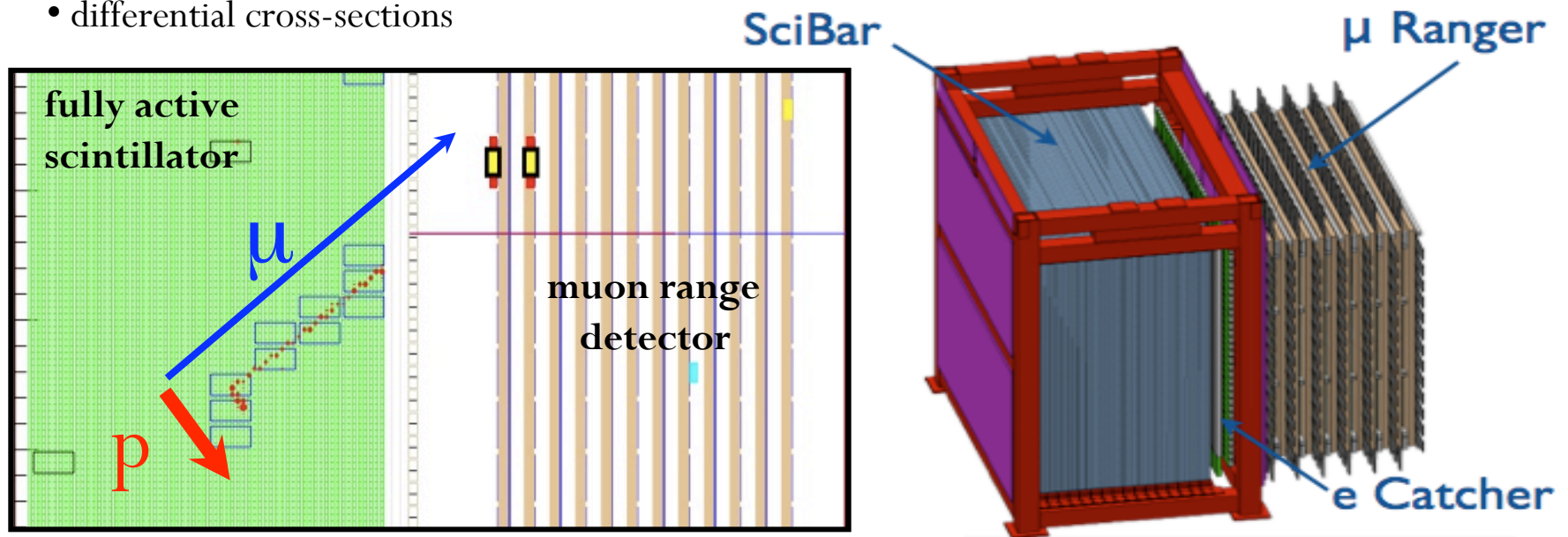


The Interactions (CCQE)

- Charged-Current Quasi-Elastic Scattering



- SciBooNE is a fully active scintillator detector/target
- 2,680 2-track ν_μ QE events on carbon (69% purity)
- have preliminary measurement of $\sigma_{\text{CCQE}}(E)$ from $E_\nu = 0.6 - 1.6$ GeV
- active analysis
 - 1 track vs 2 track; active contained vs muon range detector
 - differential cross-sections



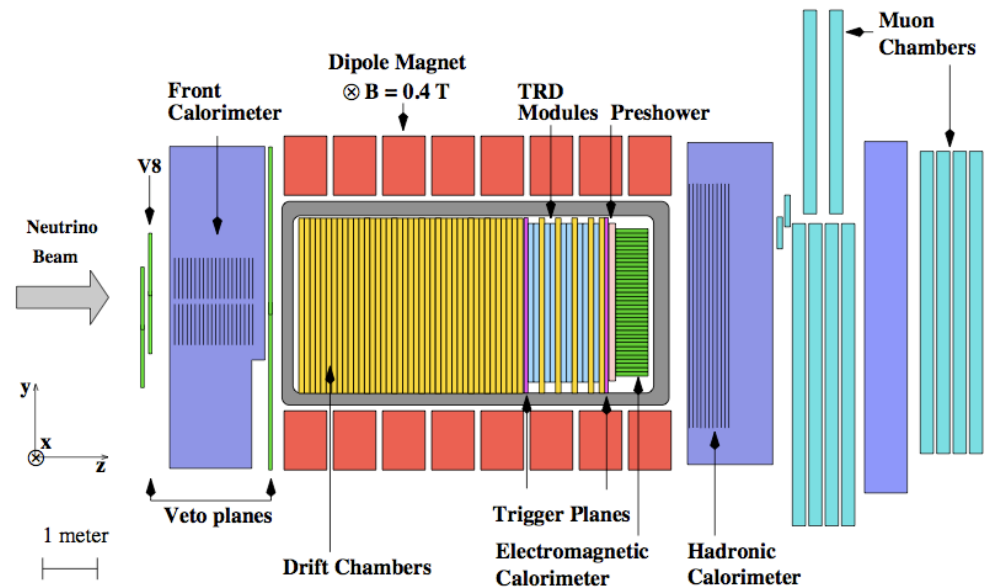
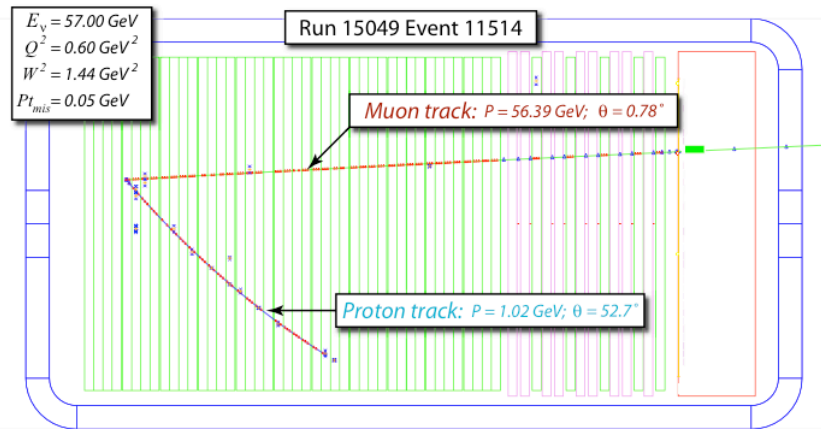
The Interactions (CCQE)

- Charged-Current Quasi-Elastic Scattering



- NOMAD collaboration recently published a quasi-elastic cross-section for neutrinos and antineutrinos
- target nucleus same as BooNEs **carbon**
- higher energy neutrino flux $E_\nu = 3 - 200 \text{ GeV}$
- drift chamber tracking detector, high resolution on **muon AND proton** tracks

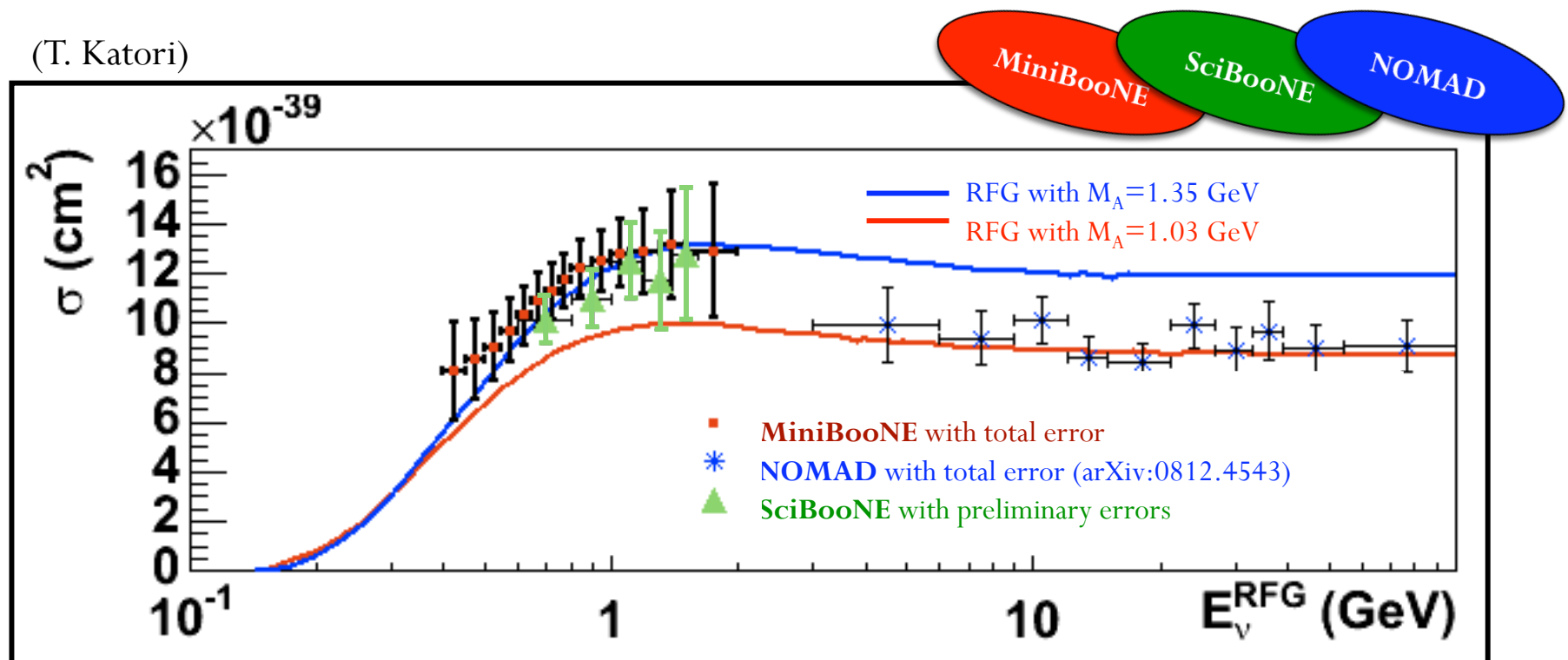
arXiv:0812.4543v3



The Interactions (CCQE)

- Charged-Current Quasi-Elastic Scattering

(T. Katori)



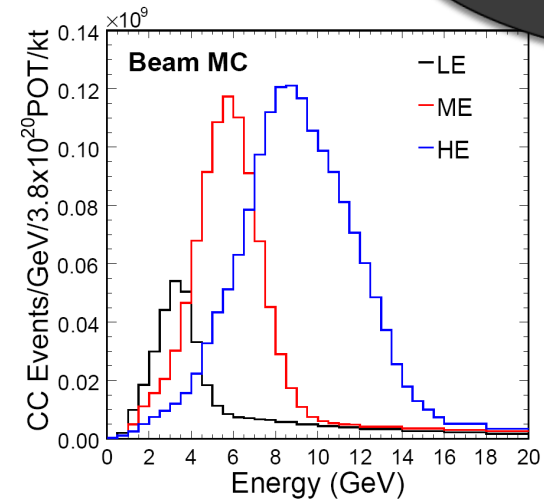
- MiniBooNE/SciBooNE in agreement, but tension with higher energy NOMAD results. All three on carbon. This is not understood.



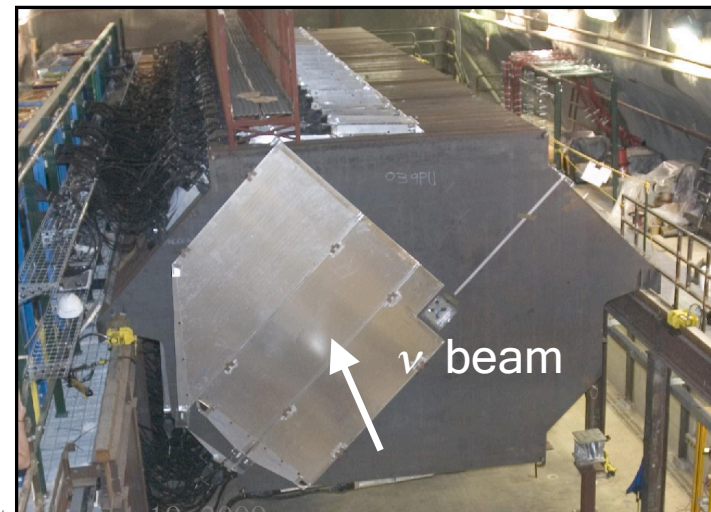
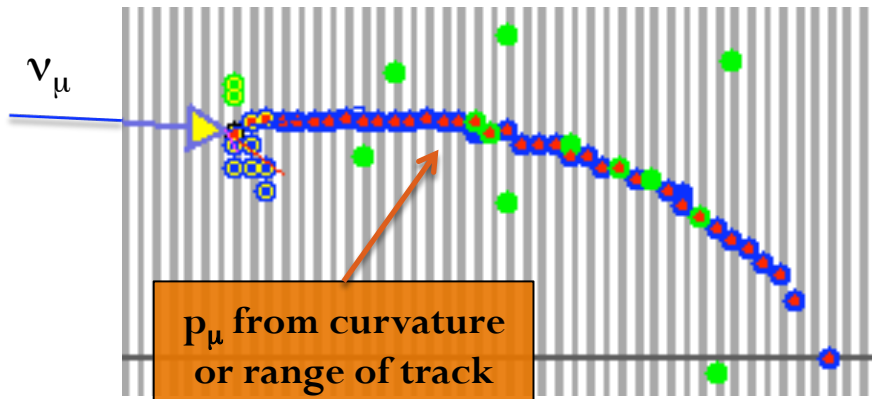
The Interactions (CCQE)

- Charged-Current Quasi-Elastic Scattering

- MINOS has recently presented total CC cross-sections and **CCQE results on iron**
- Main Injector Neutrino Beam (NuMI) at Fermilab, low-energy configuration, $E_\nu \sim 1 - 5 \text{ GeV}$
- 344,736 ν_μ QE events (61% purity)



MINOS

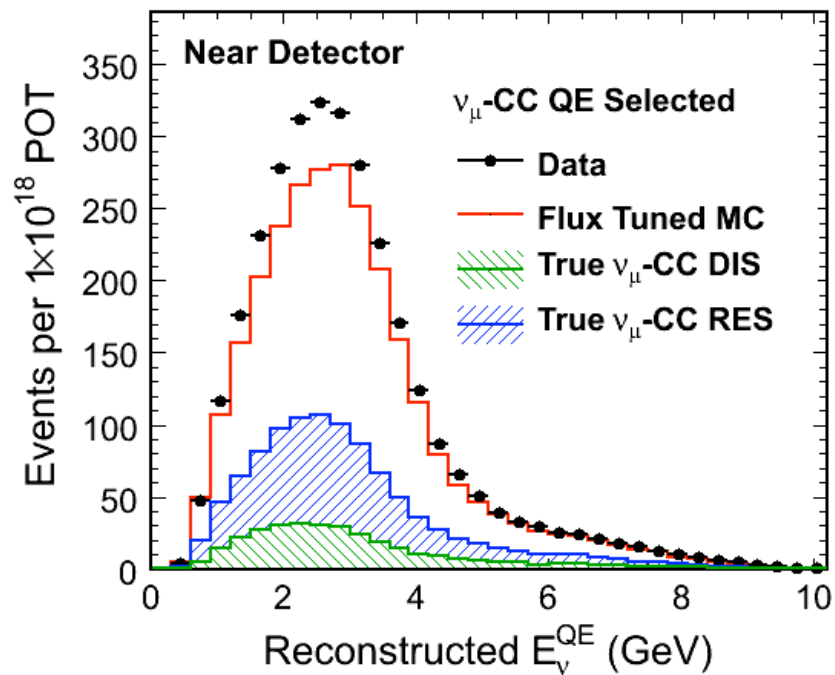


The Interactions (CCQE)

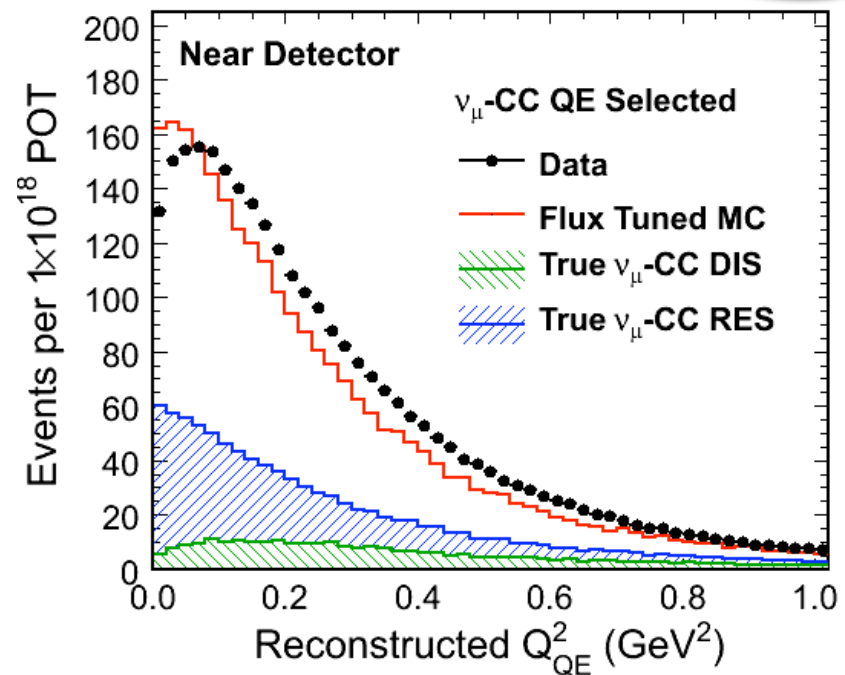
- Charged-Current Quasi-Elastic Scattering

MINOS

MINOS Preliminary



MINOS Preliminary

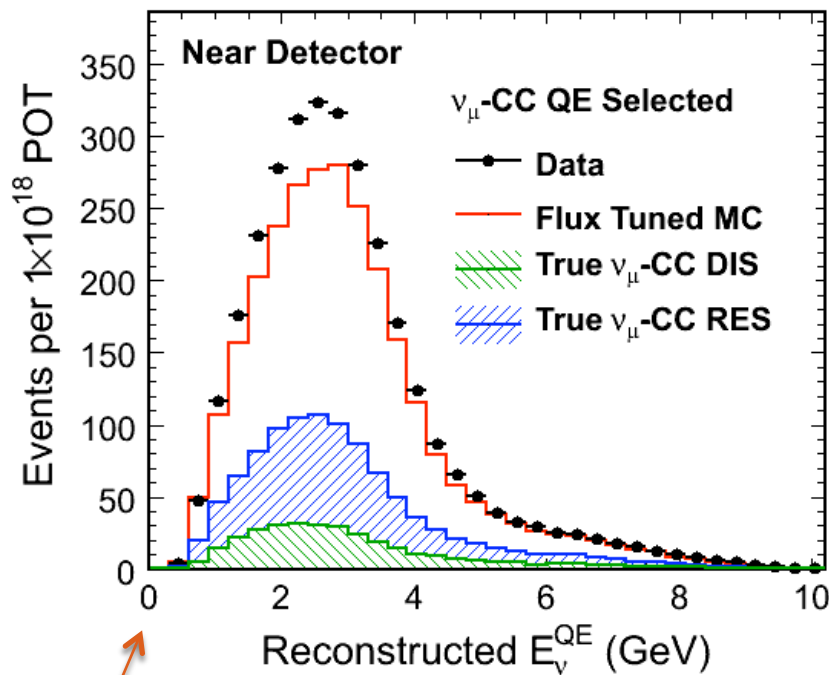


The Interactions (CCQE)

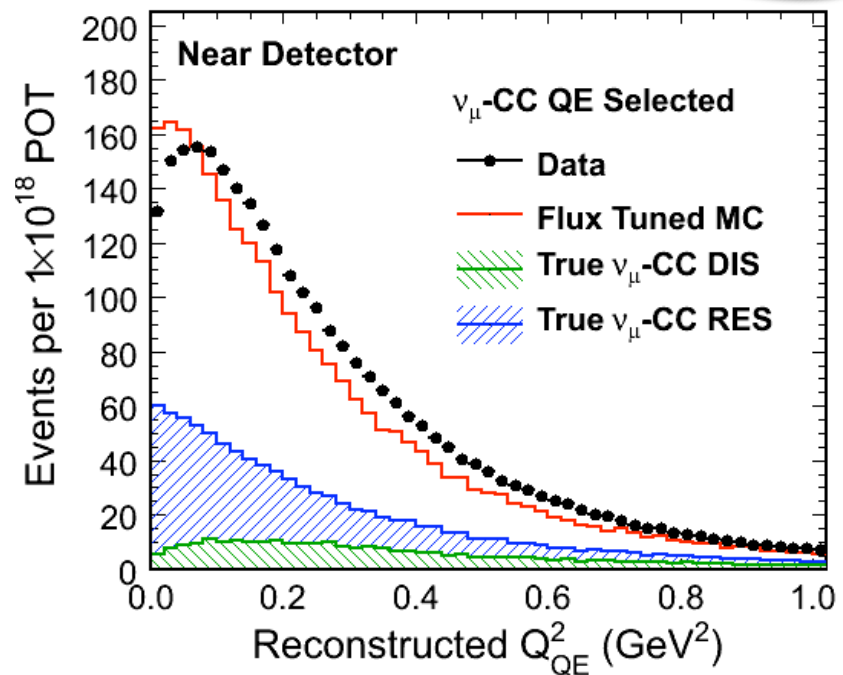
- Charged-Current Quasi-Elastic Scattering

MINOS

MINOS Preliminary



MINOS Preliminary



- Similar E_ν excess to those seen in Sci/MiniBooNE data

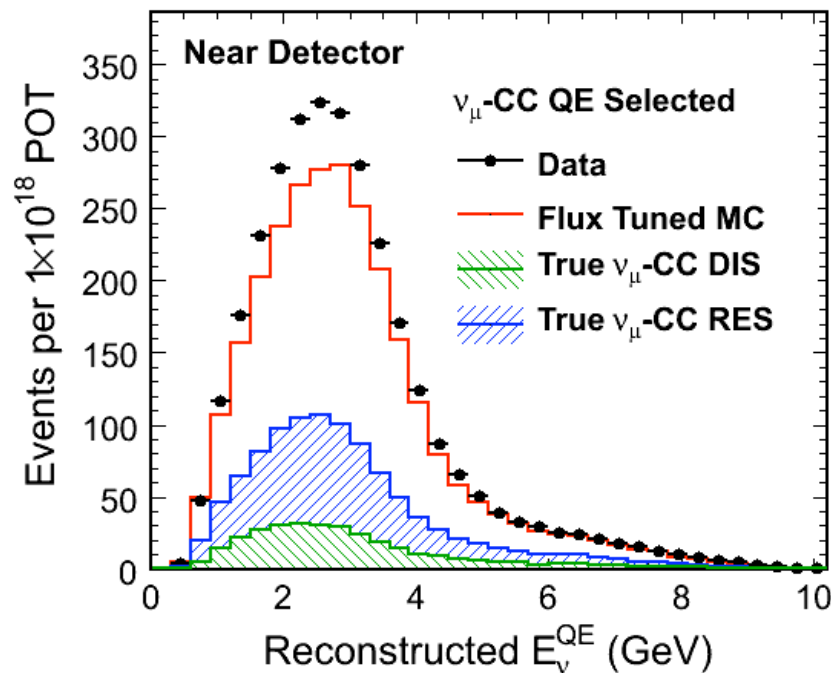


The Interactions (CCQE)

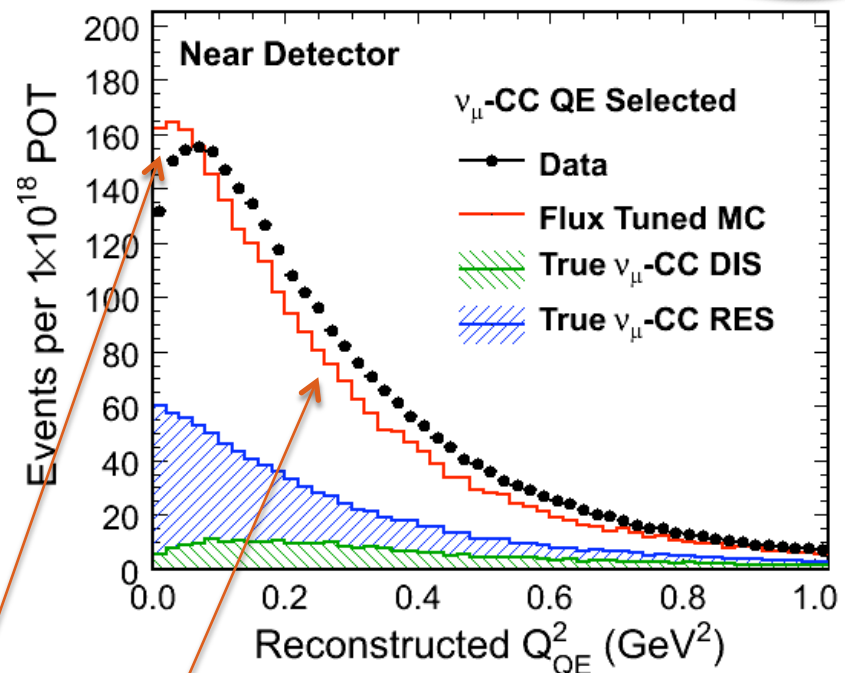
- Charged-Current Quasi-Elastic Scattering

MINOS

MINOS Preliminary



MINOS Preliminary



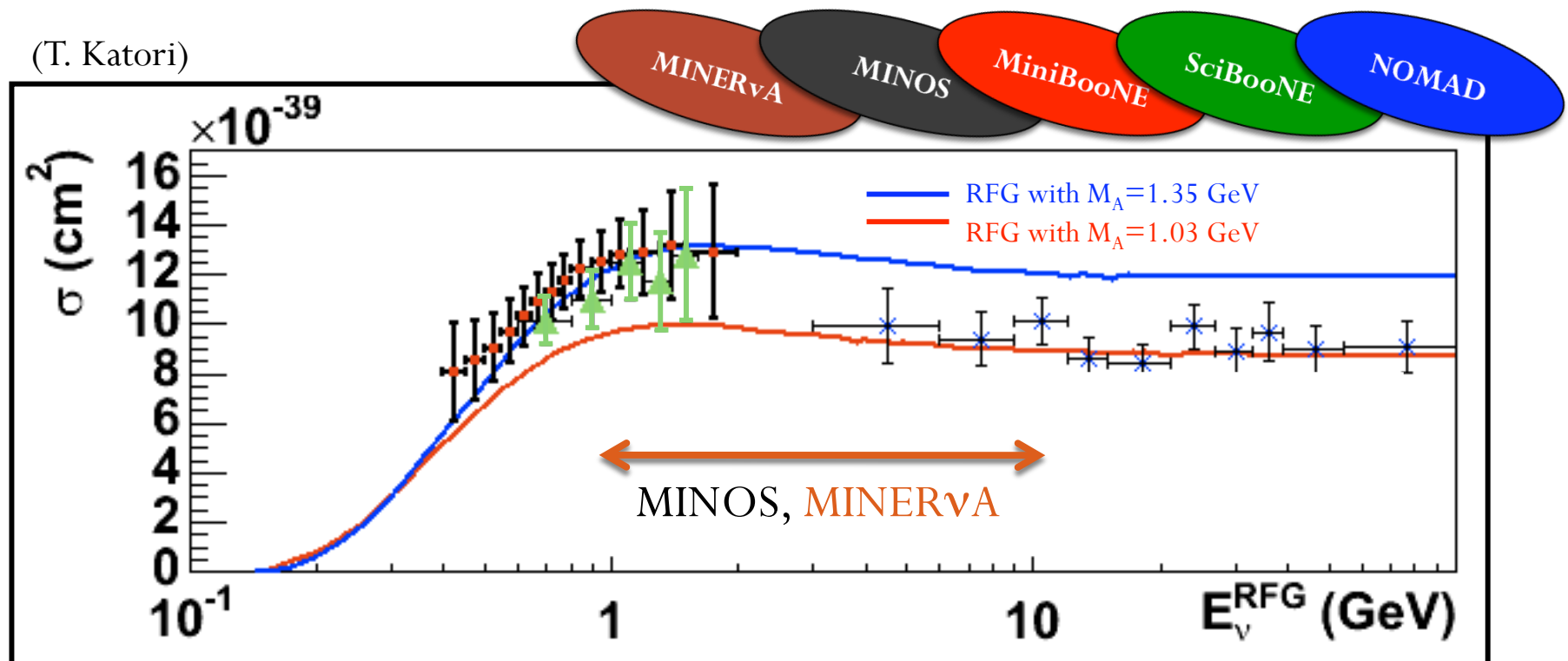
- Similar Q^2 shape disagreements to those seen in MiniBooNE data, but at higher energies and on iron instead of carbon



The Interactions (CCQE)

- Charged-Current Quasi-Elastic Scattering

(T. Katori)



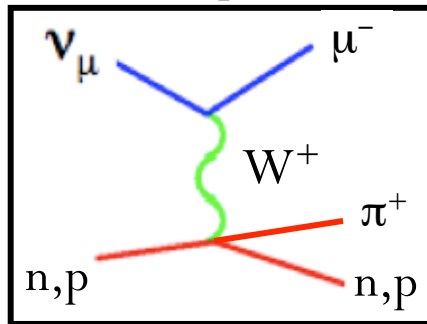
It is important to have data points from
MINOS and MINERvA to fill in this region



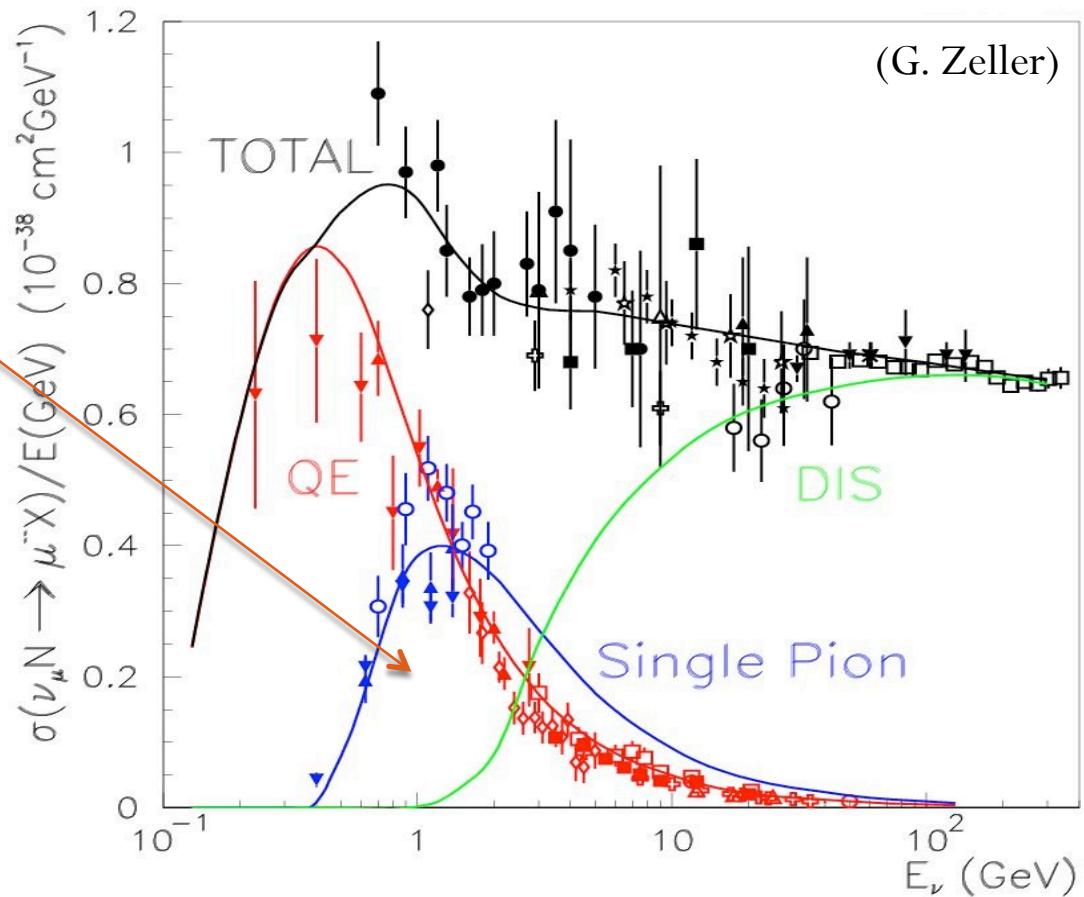
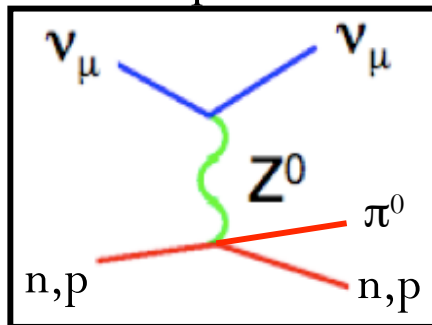
The Interactions (CC/NC π)

- Single Pion Production

CC π^+/π^0 production



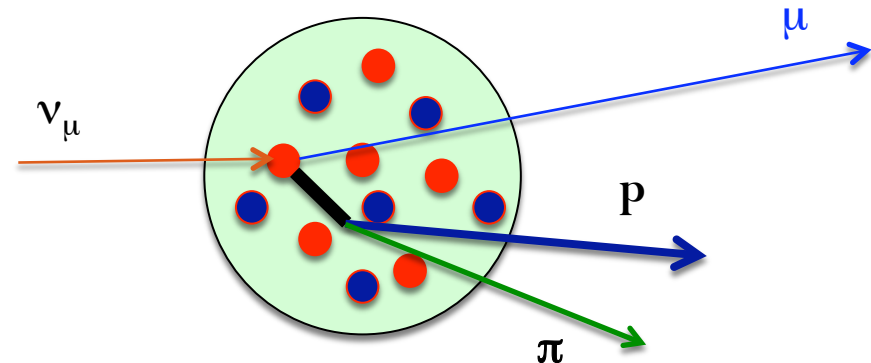
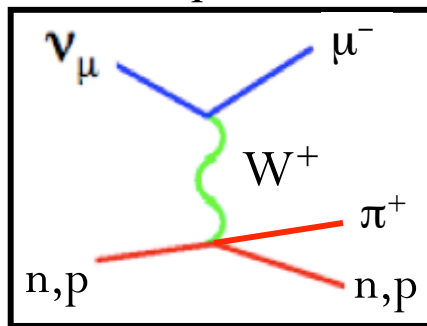
NC π^0 production



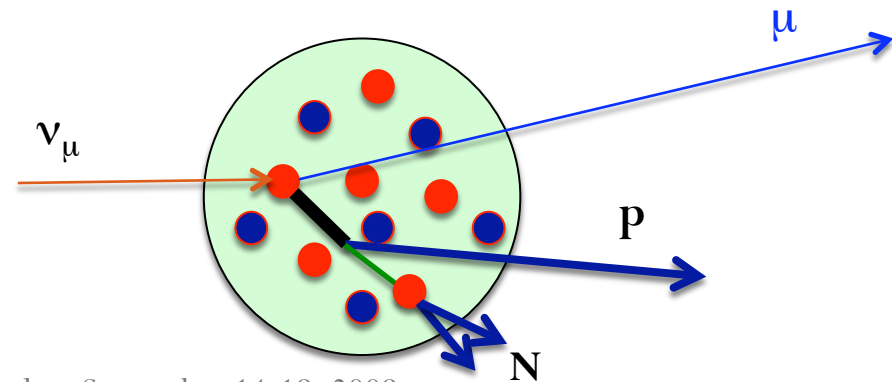
The Interactions (CC π^+)

- Single Pion Production

CC π^+ production



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



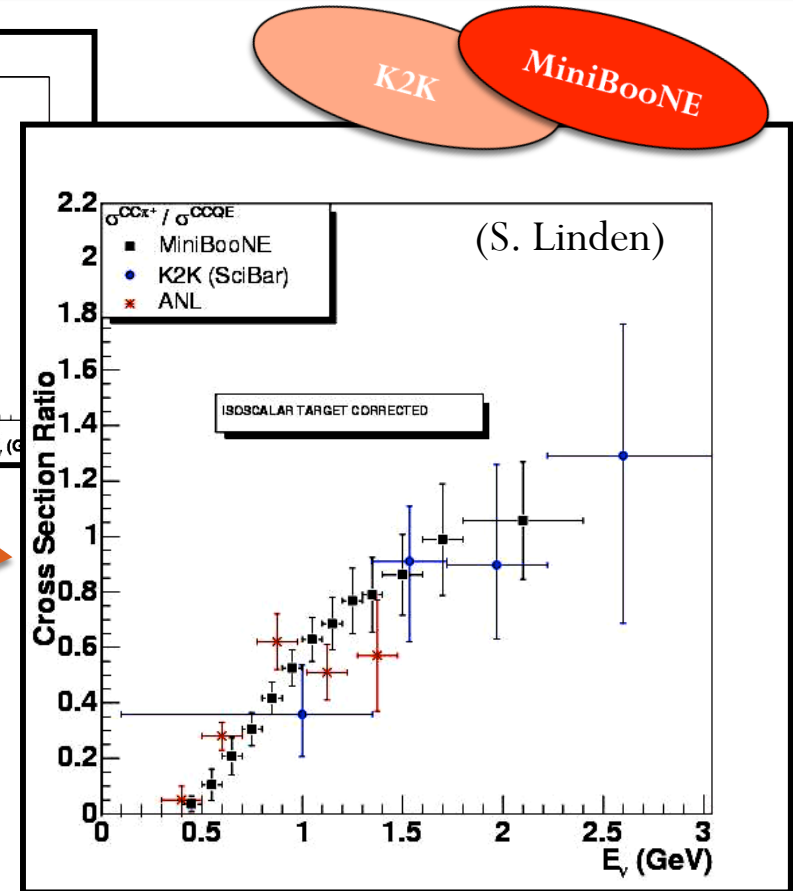
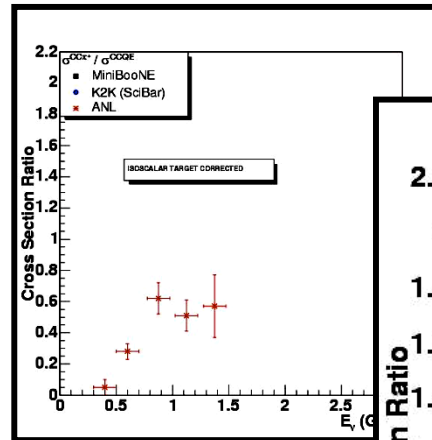
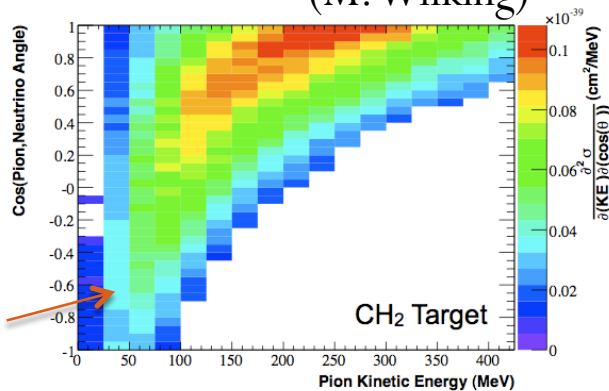
The Interactions (CC π^+)

- Single Pion Production

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

- 26 years between ANL and K2K/MiniBooNE results
- Cross-section ratio to CCQE
- Entering the realm of absolute differential cross-sections of π^+ production for the first time*

* $d^2\sigma / (d(\cos\theta_\pi)dT_\pi)$



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

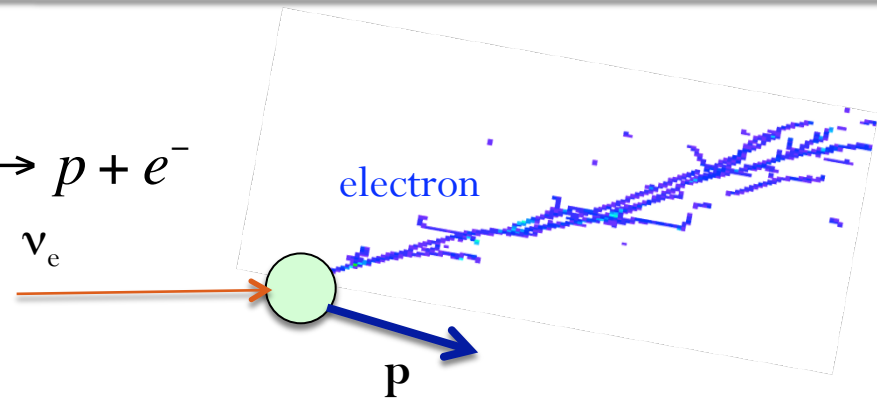
MiniBooNE: arXiv:0904.3159 [hep-ex]



The Interactions (NC π^0)

- Single Pion Production

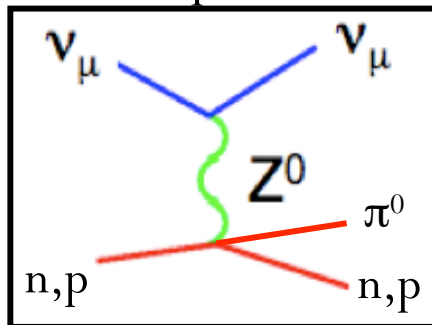
$$\nu_e + n \rightarrow p + e^-$$



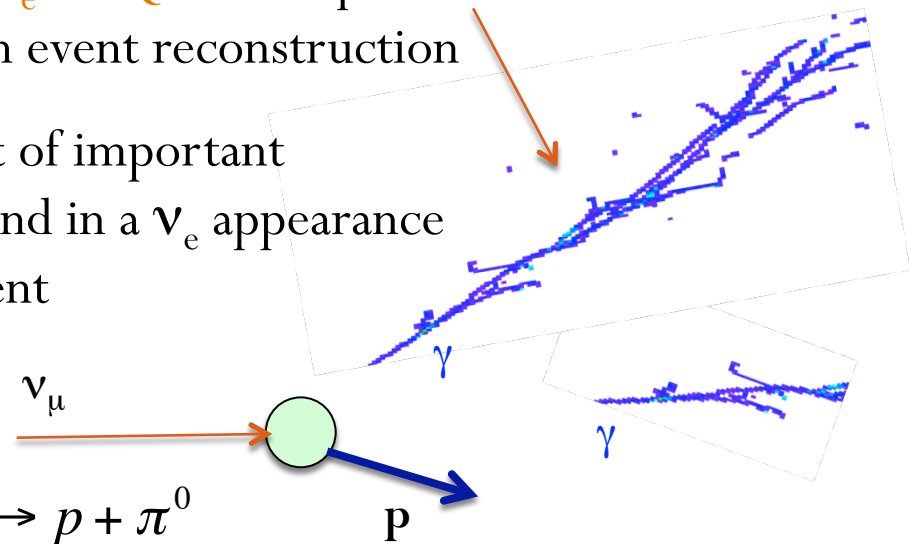
- Neutral pions create a **reducible bkgd to ν_e CCQE** if one photon is missed in event reconstruction

- miscount of important background in a ν_e appearance experiment

NC π^0 production



$$\nu_\mu + p \rightarrow p + \pi^0$$

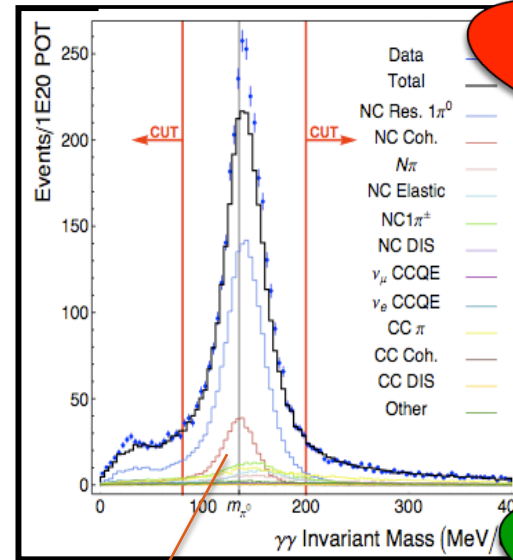
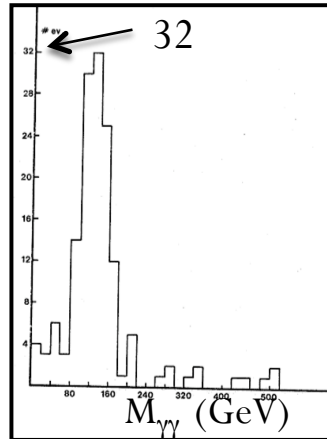


The Interactions ($\text{NC } \pi^0$)

- Single Pion Production

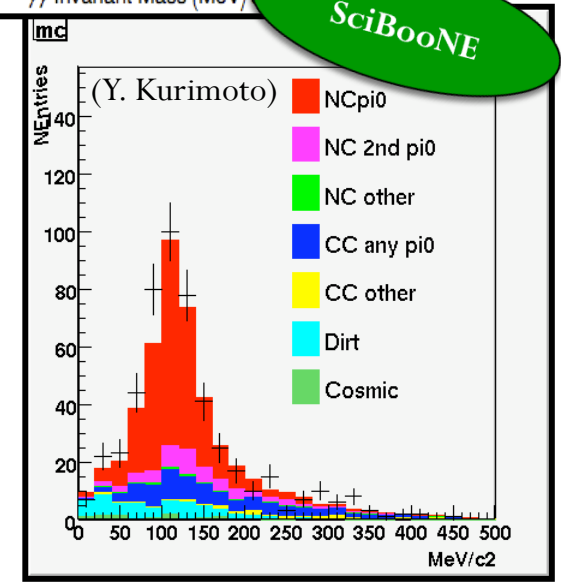
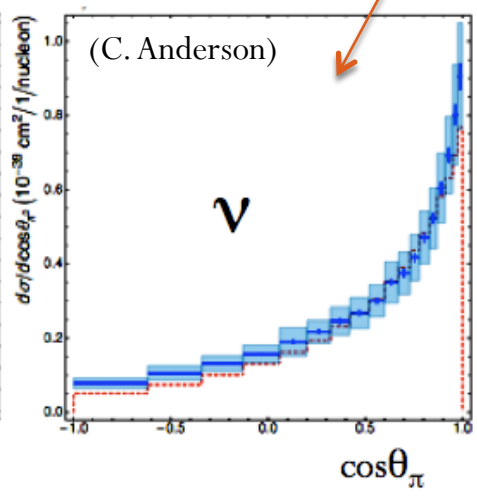
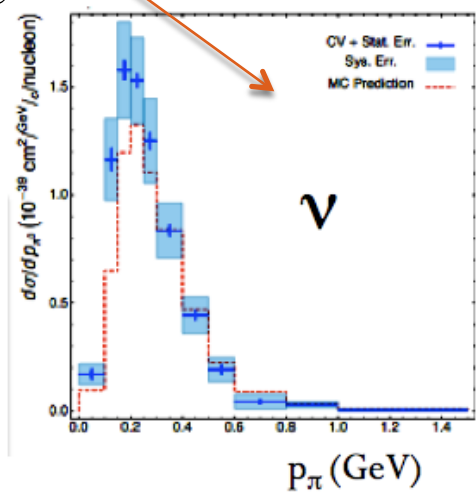
GGM, 240 NC π^0 events
Nucl. Phys. **B135**, 45 (1978)

- About 30 years this time
- Again, absolute differential cross-sections possible for the first time



MiniBooNE

(C. Anderson)



SciBooNE



The Interactions

- Other Channels
- With apologies, I have left out far more than I have been able to show:
 - NC elastic scattering
 - MiniBooNE, SciBooNE
 - CC π^0 production
 - MiniBooNE
 - CC inclusive cross-section
 - MINOS, NOMAD, NuTeV
 - NC/CC coherent pion production
 - MiniBooNE, SciBooNE
 - Extraction of CCQE model parameters, axial mass
 - MiniBooNE, SciBooNE, MINOS, K2K, NOMAD

for much more detail on the channels discussed here and some not, see:

Y. Hayato, DG3, Wednesday



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

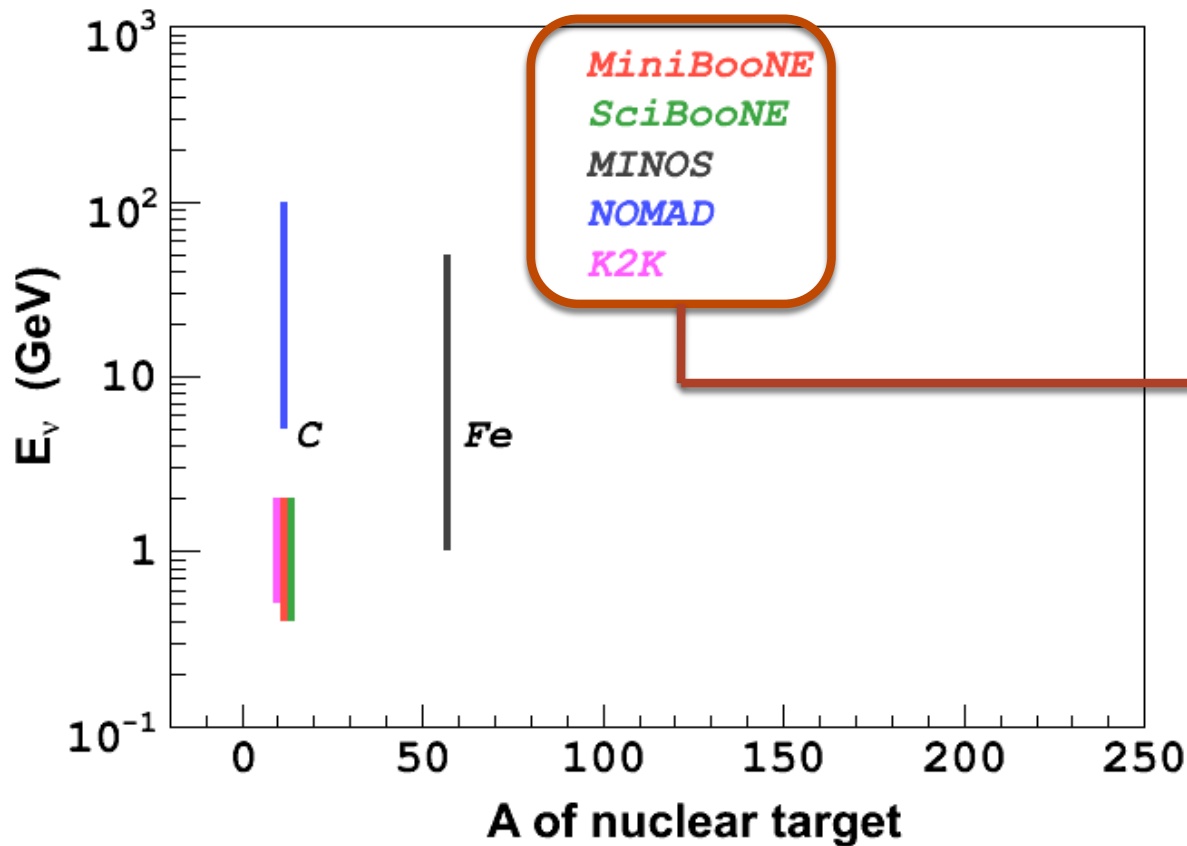
- **ArgoNeuT** and **MicroBooNE** are new Liquid Argon TPC neutrino experiments at Fermilab which will measure interaction rates on argon at these energies for the first time
 - very important for planning possible LAr TPC detectors for future long baseline neutrino oscillation experiments
- **MINERvA** is a new experiment at Fermilab that will answer many of the open questions
 - A strong collaboration of both experimentalists and theorists
 - neutrinos and antineutrinos
 - multiple nuclear targets in a single detector
- The **T2K ND280** at J-PARC includes a broad cross-section measurement agenda

“T2K Cross Section Measurements” S. Boyd,
DG3, Wednesday



Energies and Targets

Modern Neutrino Cross-Section Experiments



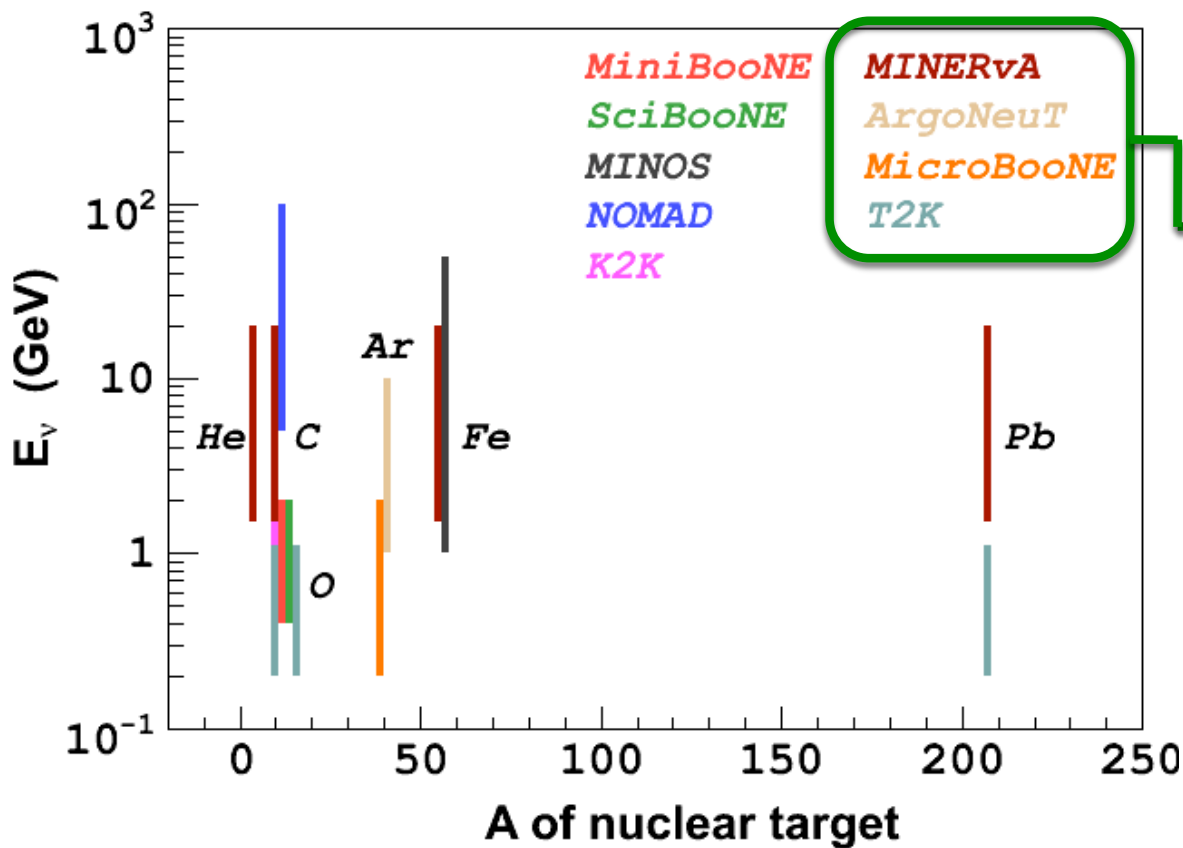
of the cross-section experiments

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



Energies and Targets

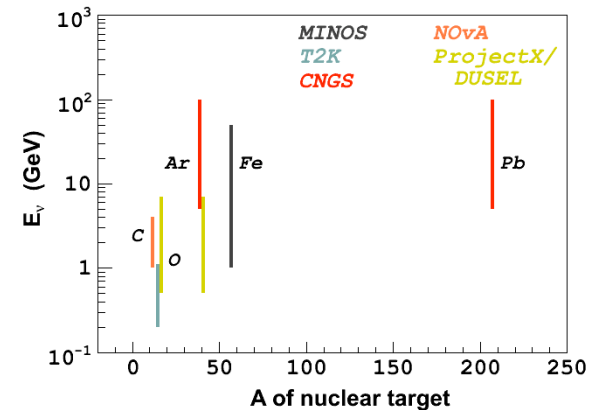
Modern Neutrino Cross-Section Experiments



of the cross-section experiments

near future neutrino cross-section experiments

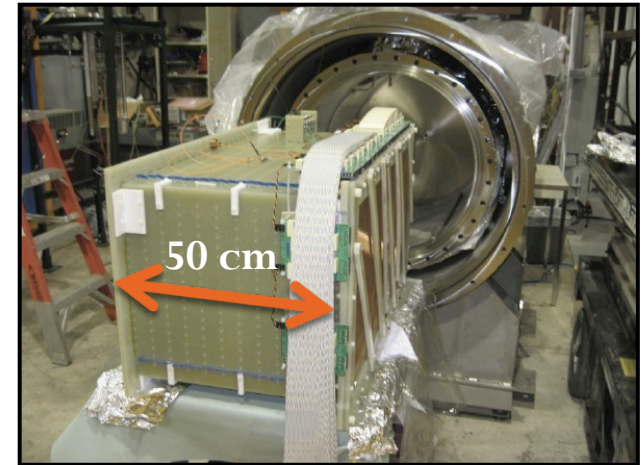
LBL Neutrino Oscillation Experiments



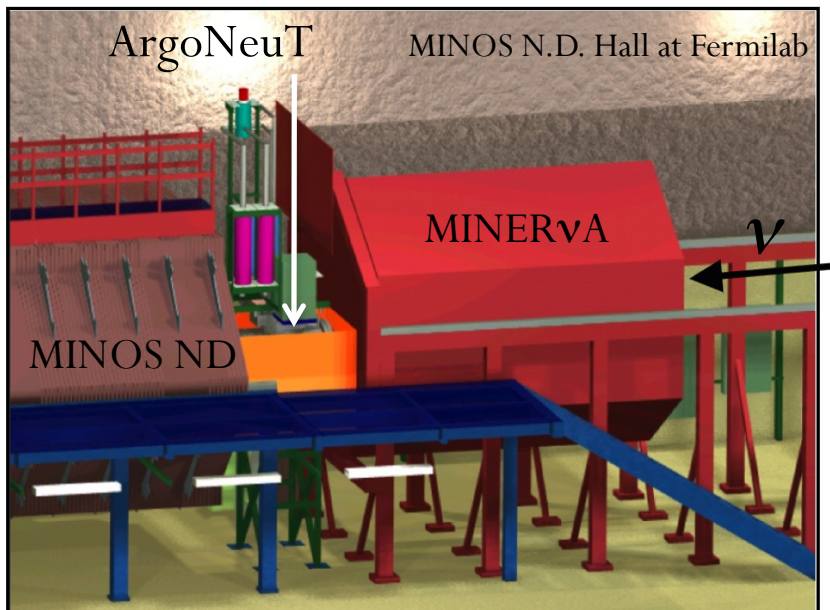
Liquid Argon

• ArgoNeuT

- First Liquid Argon TPC to go in ‘low-energy’ neutrino beam, $E_{peak} \sim 3$ GeV, and first in the US at any energy
- Important step in LAr TPC R&D program for neutrino physics



ArgoNeuT TPC before going into the cryostat

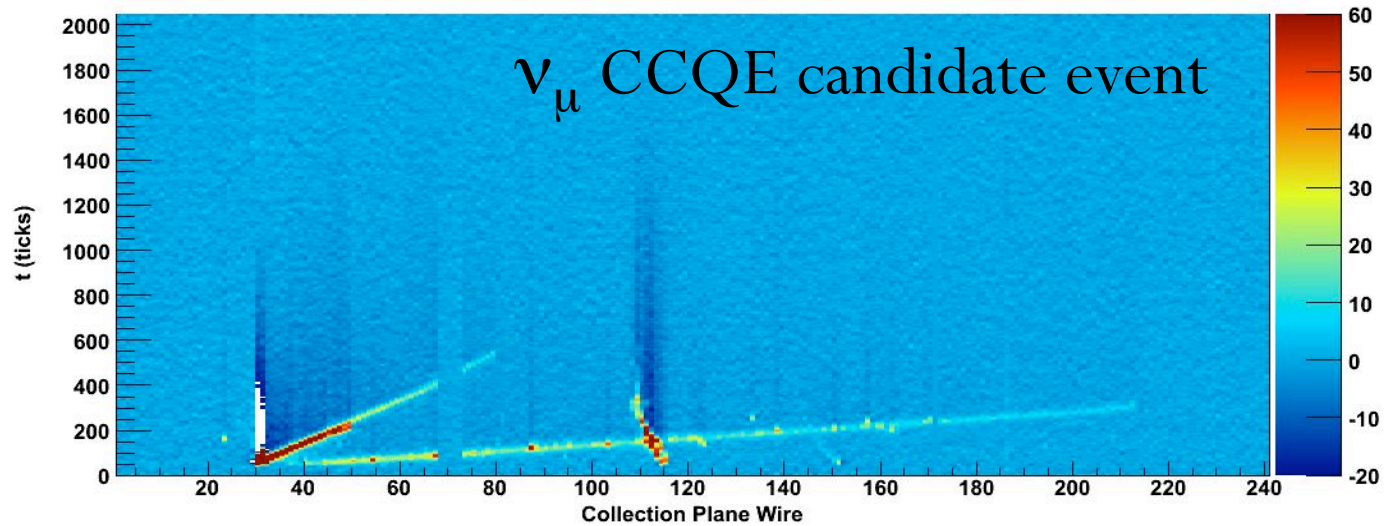


- LAr TPCs desirable for their ‘bubble-chamber quality’ events, e/γ ID, and low-energy threshold
- ArgoNeuT 170 L (0.3 t argon) Liquid Argon TPC
- Recorded neutrino data in the NuMI beam at Fermilab this spring

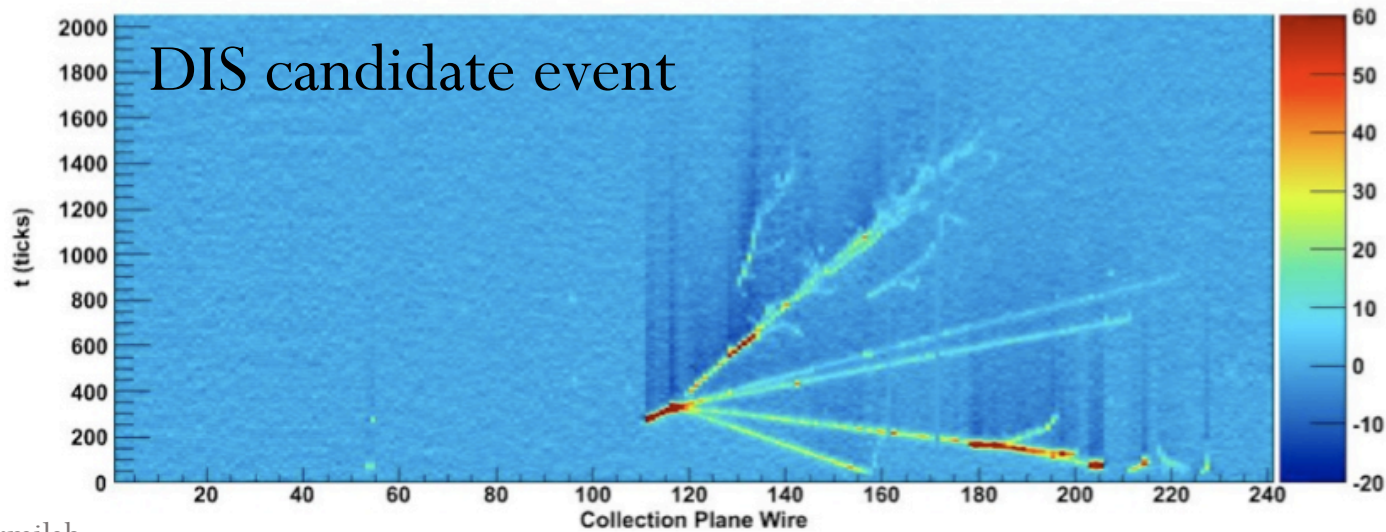


Liquid Argon

NuMI
→
Beam



NuMI
→
Beam



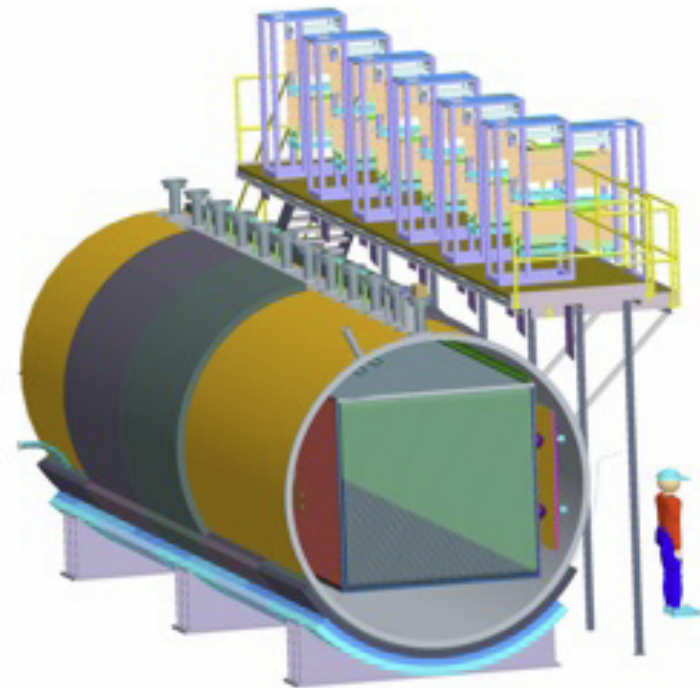
Liquid Argon

- **MicroBooNE**

- 170 ton vessel to sit in Booster Neutrino Beam at FNAL in ~ 2012
- Part of staged R&D to testing feasibility of large LAr detectors
- Rich physics program including low-energy cross-sections on argon

	BNB	NuMI
Total Events	145k	60k
ν_{μ} CCQE	68k	25k
NC π^0	8k	3k
ν_e CCQE	0.4k	1.2k
POT	6×10^{20}	8×10^{20}

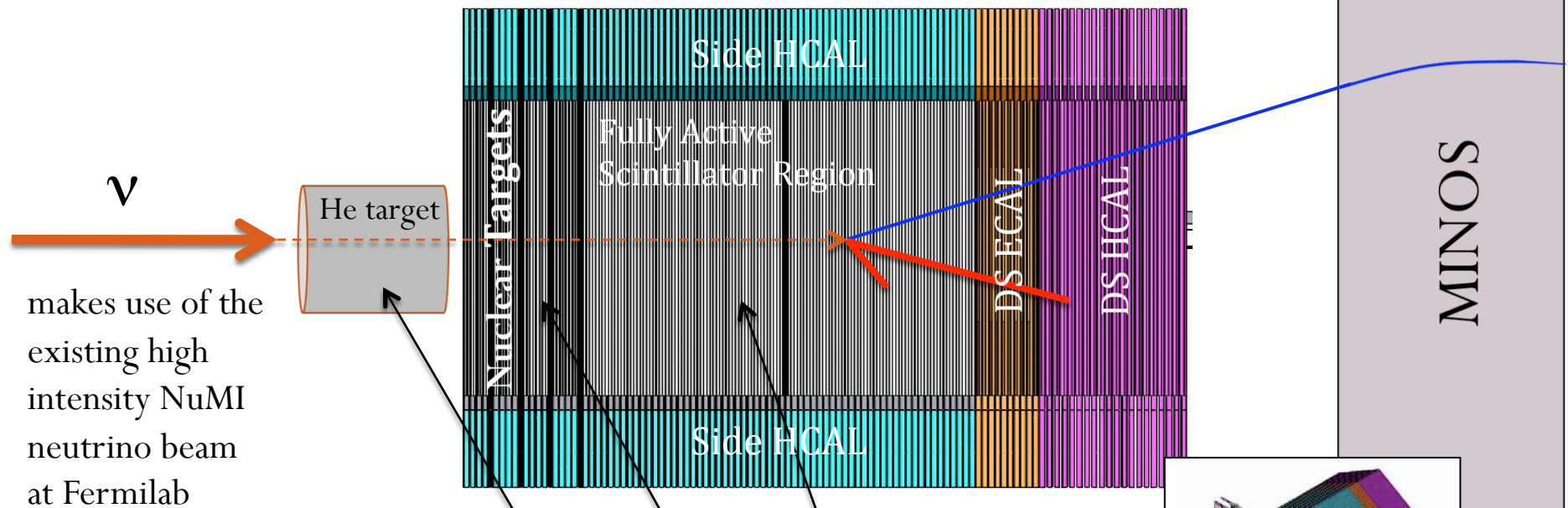
Expected Event Rates for MicroBooNE.



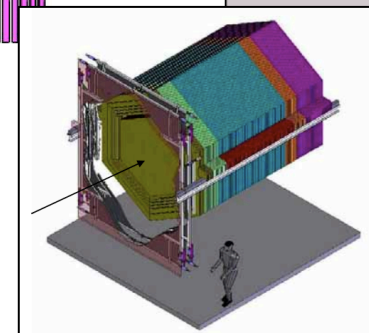
MINER ν A

- MINER ν A is a dedicated neutrino-nucleus cross-section experiment

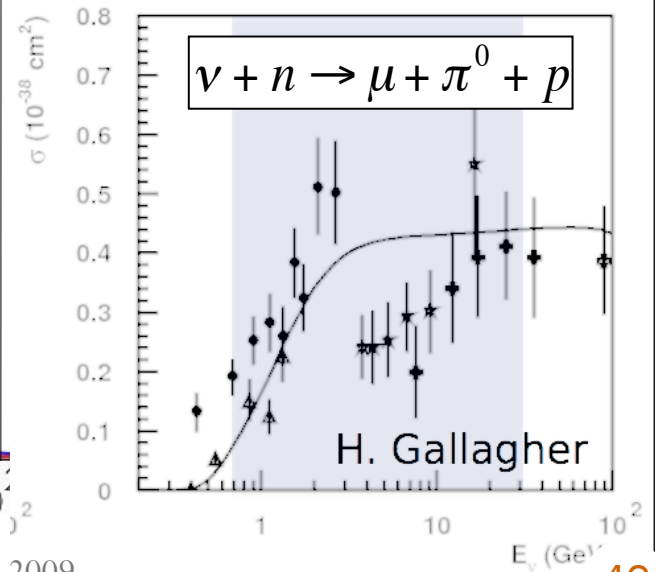
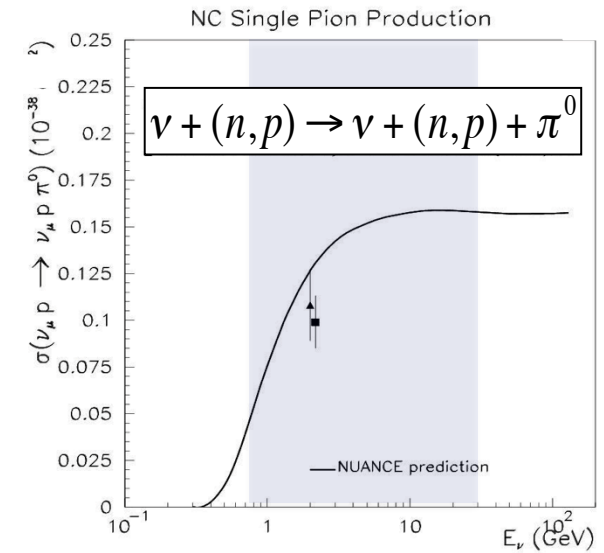
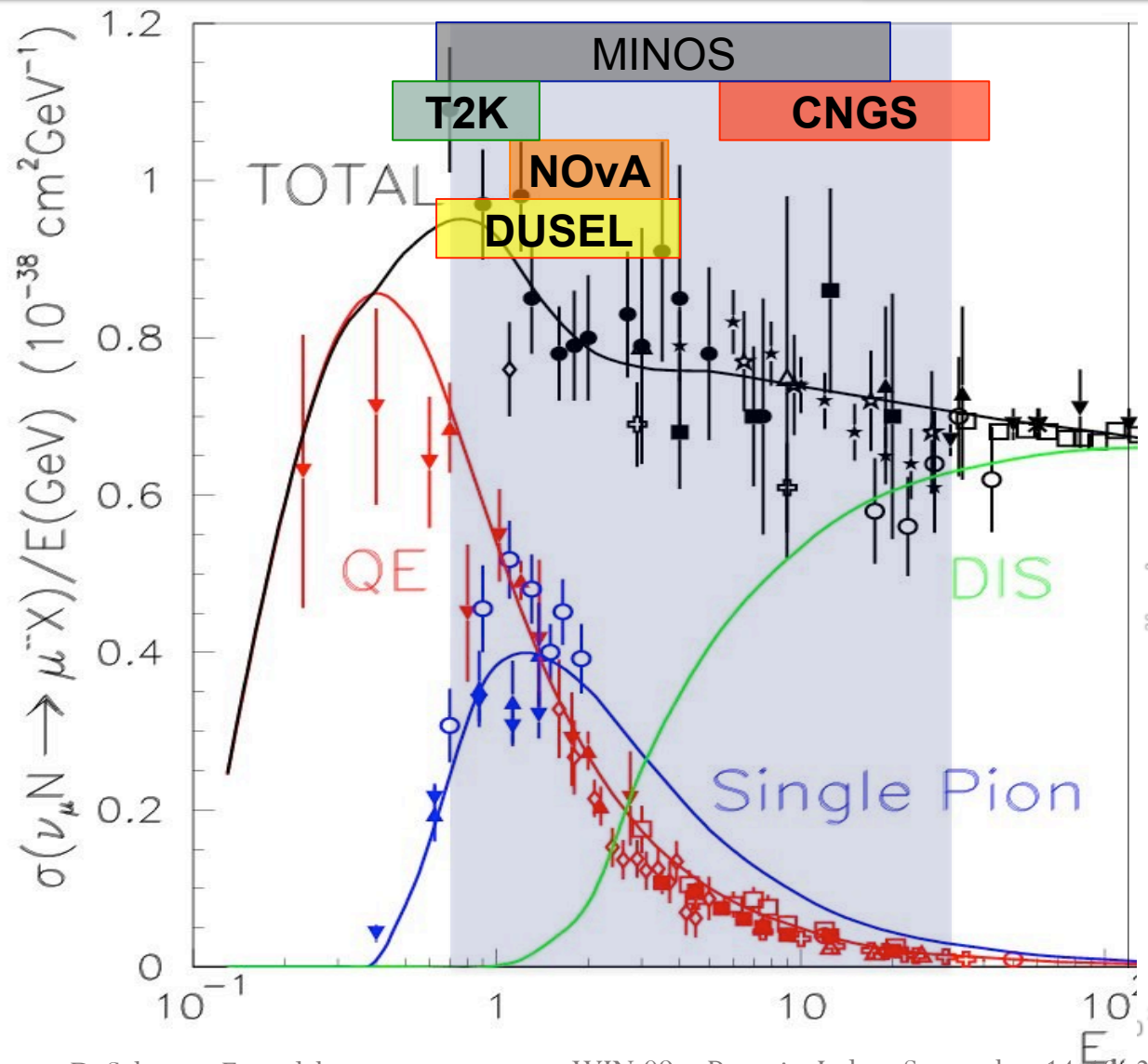
Finely segmented, fully active scintillator tracking region surrounded by ECAL and HCAL



range of nuclear targets (He, C, Fe, Pb, CH) for study of **nuclear effects** in neutrino interactions



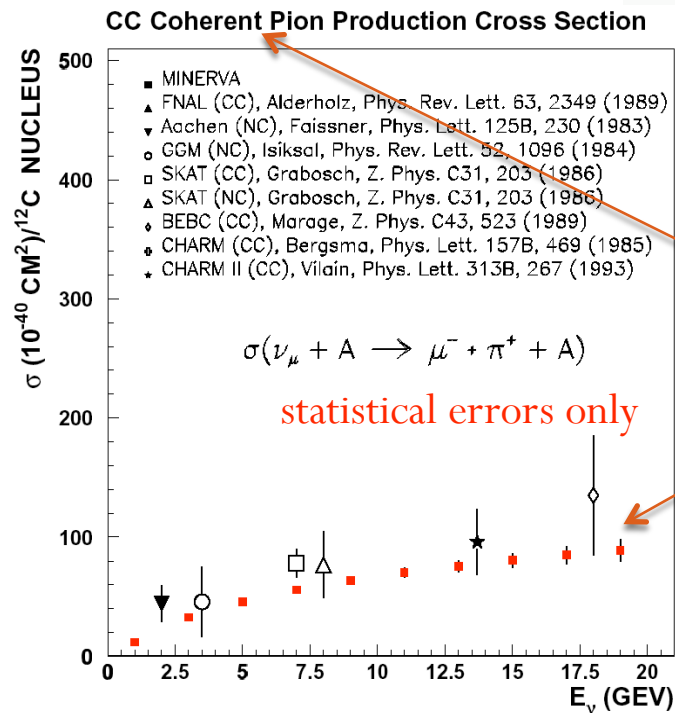
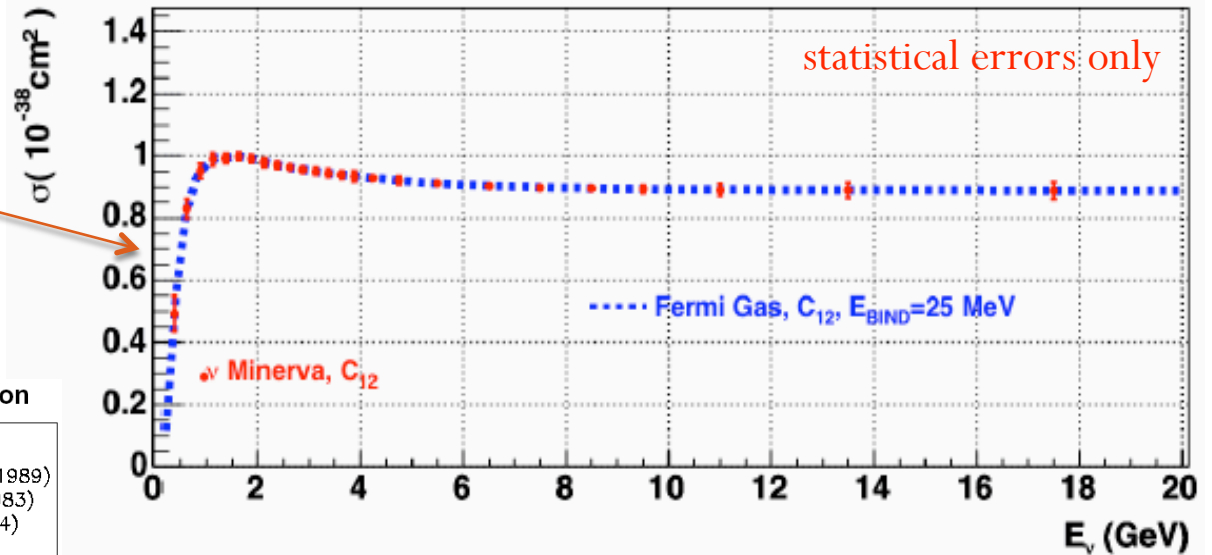
MINERνA Energy Range



MINERvA Physics

- Some examples:

Expected CCQE results including efficiency estimates



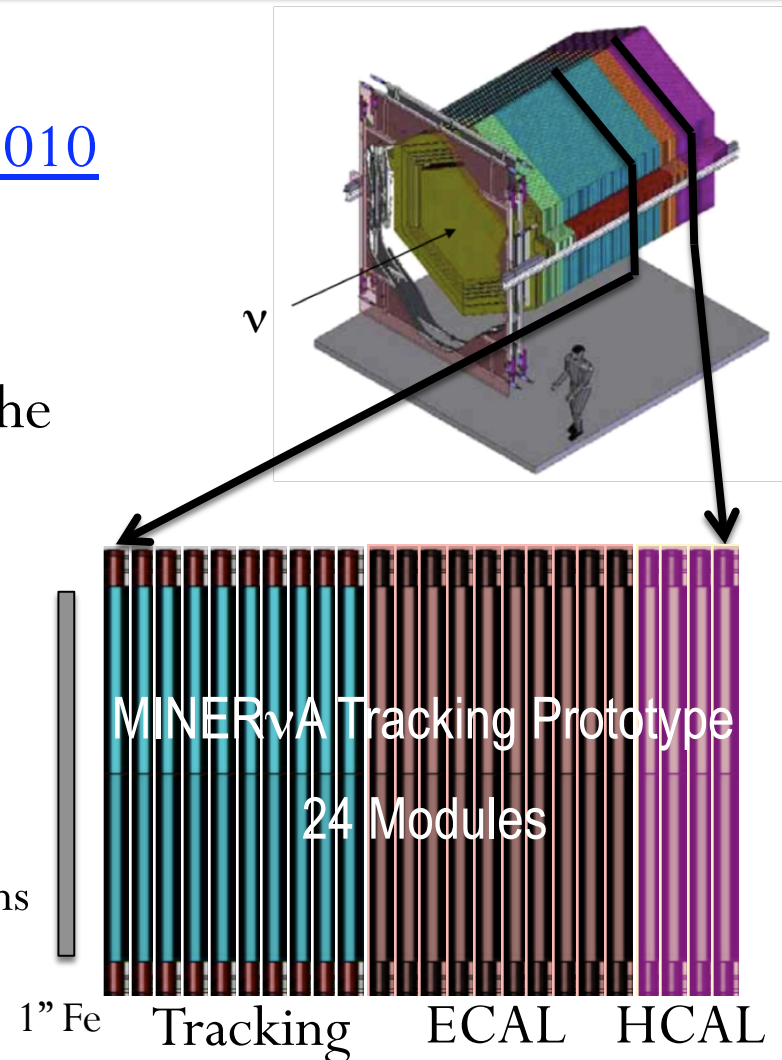
Coherent pion production occurs off the nucleus as a whole, leaving it in the ground state. Low rate.

Note, MINERvA's nuclear targets allow the first measurement of the A -dependence of σ_{coh} across a wide A range



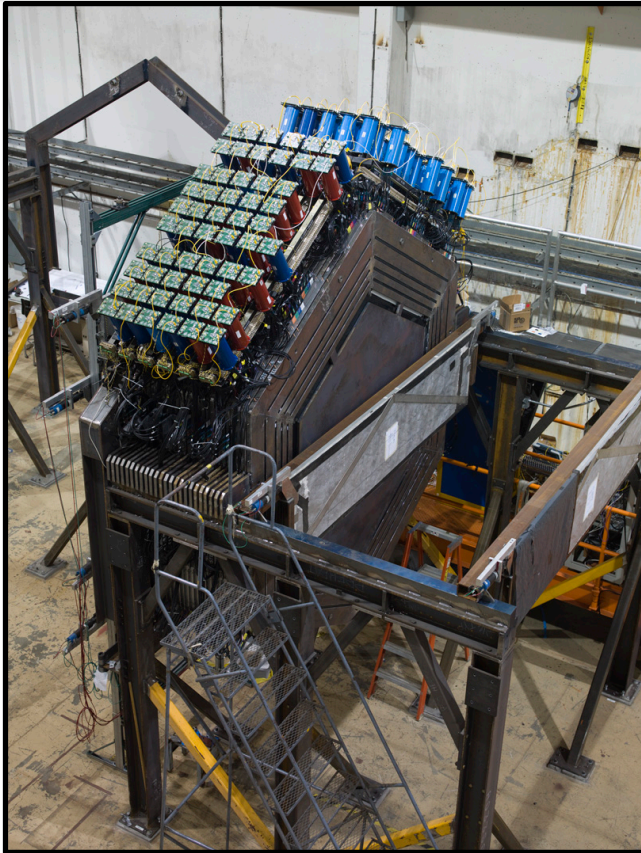
MINER ν A Status

- 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



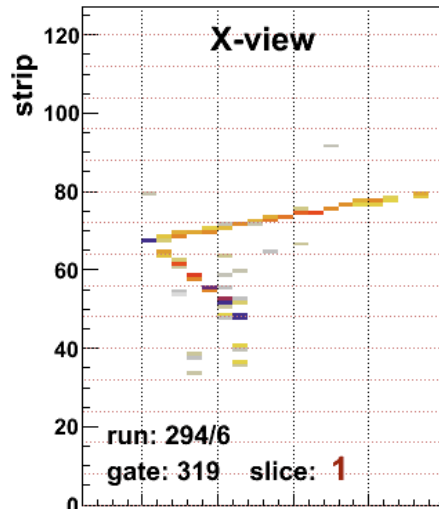
MINERvA Tracking Prototype

April – June, 2009

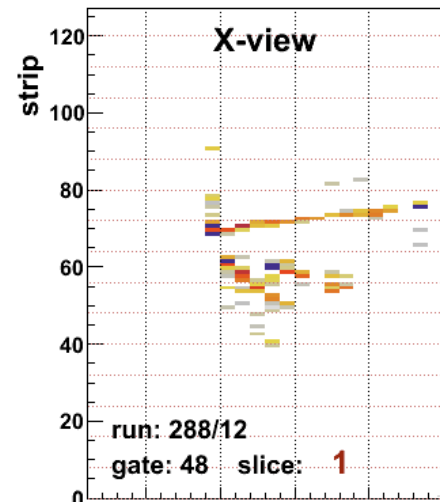


MINERνA Tracking Prototype

ν_μ CCQE
candidate
event



ν_μ CC π^0
candidate
event

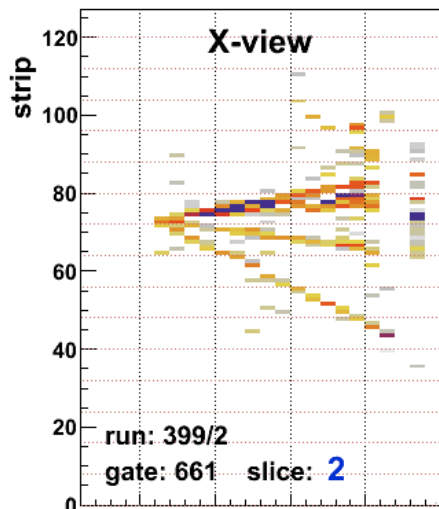


NuMI

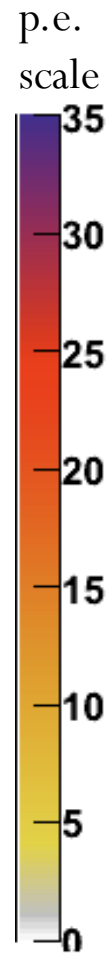
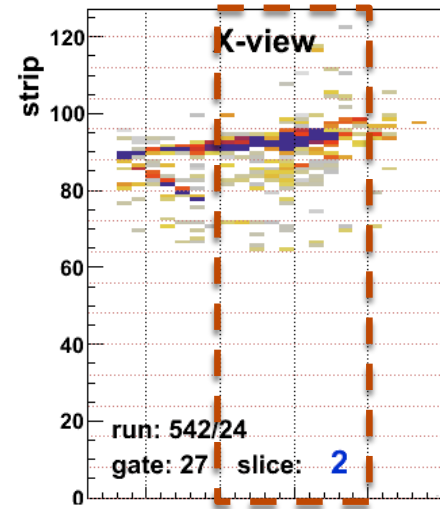


Beam

Deep
Inelastic
candidate
event



ν_e CCQE
candidate
event

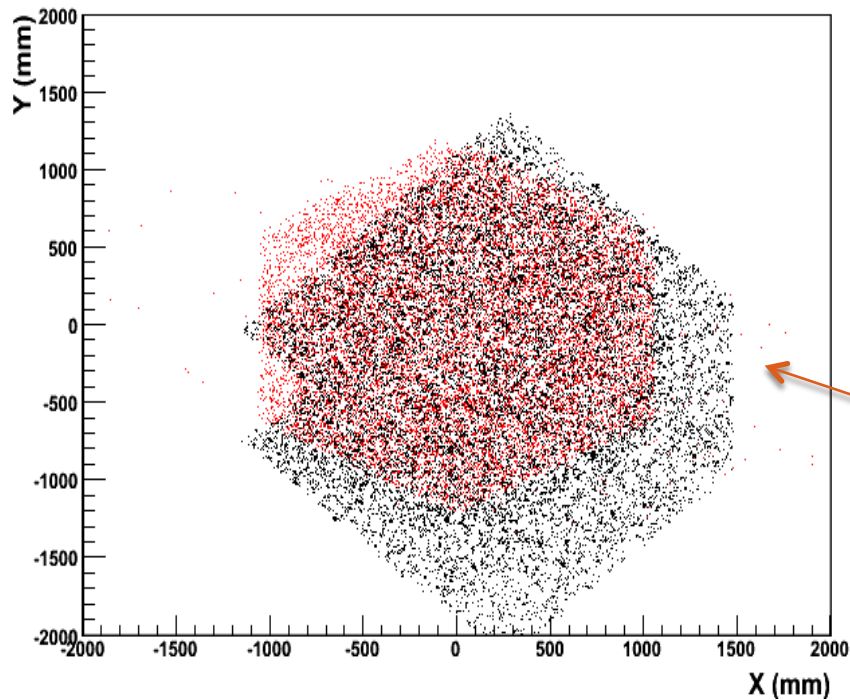


MINOS

ECAL



MINOS Works, too...



A unique kind of collaboration

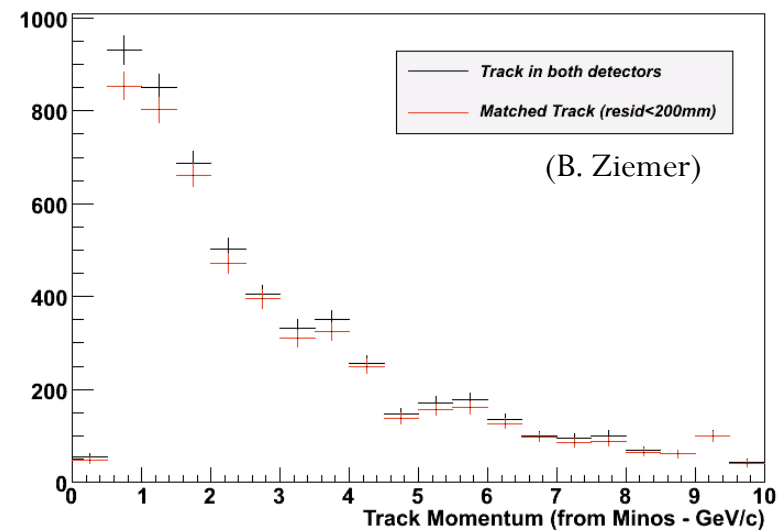
MINOS kindly shares their data with the MINERvA collaboration to act as a muon spectrometer

All tracks in **MINERvA (red)** and MINOS (black) in MINERvA coordinate system



approximate fraction of muons which escape MINERvA detector 90% (for QE)

approximate fraction of those which are picked up by MINOS 92% (for QE)



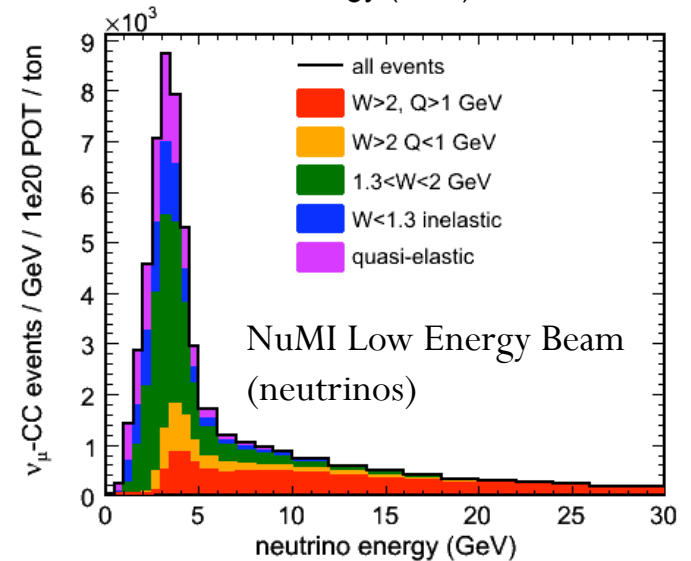
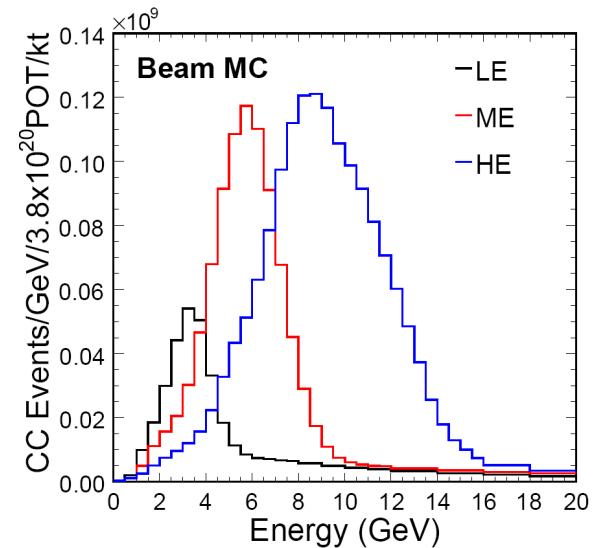
MINOS



MINERvA Physics Data

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

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 challenging and interesting
 - important for the next generation of precision neutrino physics experiments
- The dedicated experiment, **MINERvA**, will go a long way towards finding many answers starting next year



Advertisement

- Two upcoming **workshops to be held at Fermilab**
- All are invited and registration is free!
- Workshop on Physics with a high intensity proton source (pre- and post-Project X)
 - Nov 9-10, 2009
 - http://www.fnal.gov/directorate/Longrange/Steering_Public/workshop-physics-4th.html
- Muon Collider physics workshop
 - Nov 10-12, 2009
 - http://www.fnal.gov/directorate/Longrange/Steering_Public/workshop-muoncollider.html
- Late afternoon of Nov. 10: joint meeting of the two workshops



Thank you!

WIN '09

**22ND INTERNATIONAL WORKSHOP ON
WEAK INTERACTIONS AND NEUTRINOS
SEPTEMBER 13-19, 2009 – PERUGIA, ITALY**

Extras

The Interactions (CCQE)

- Charged-Current Quasi-Elastic Scattering
- 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.



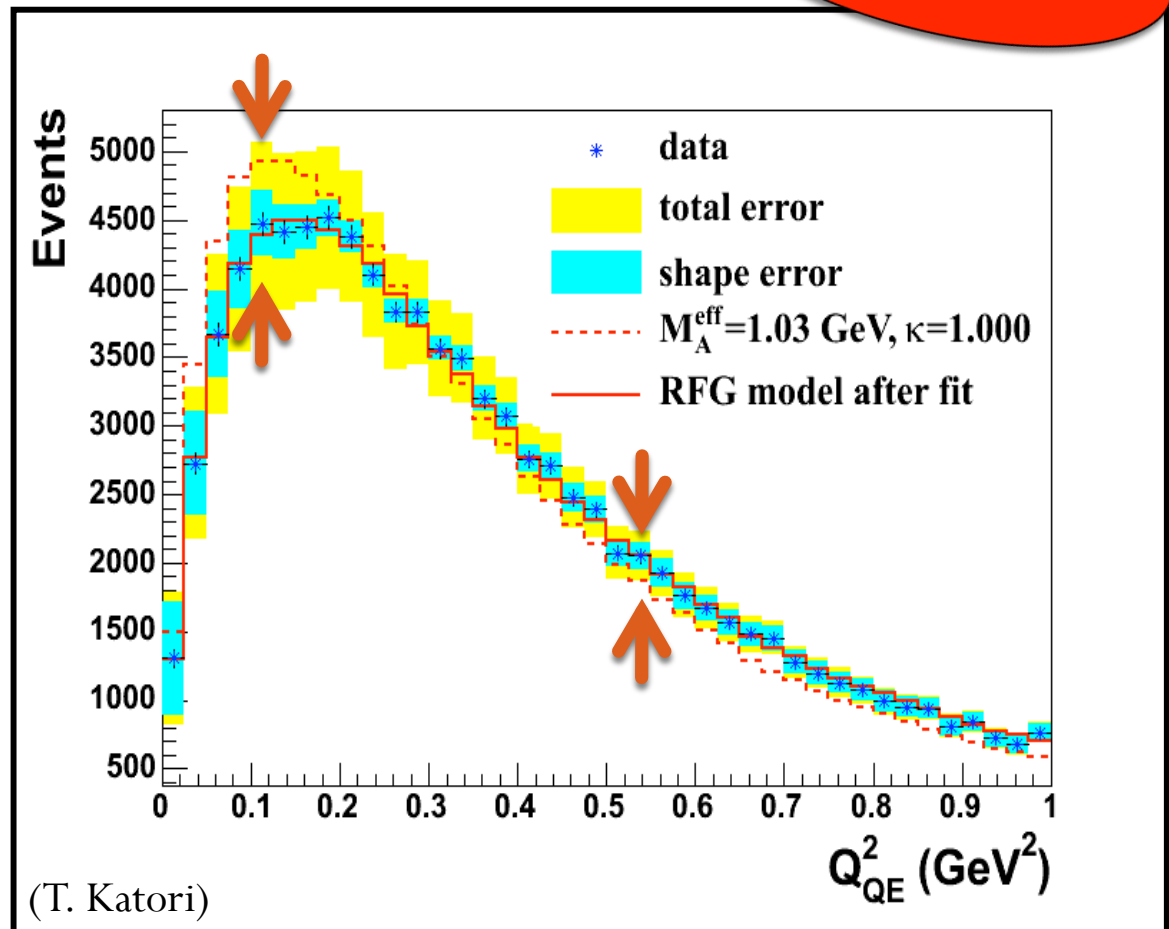
The Interactions (CCQE)

- Charged-Current Quasi-Elastic Scattering

MiniBooNE

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

- Fit performed to extract new model parameters to better describe the MiniBooNE data
 $M_A^{QE} = 1.35 \pm 0.17 \text{ GeV}$
scaling parameter to increase Pauli blocking in the model
 $\kappa = 1.007 \pm 0.007$



The Interactions (CCQE)

SciBooNE

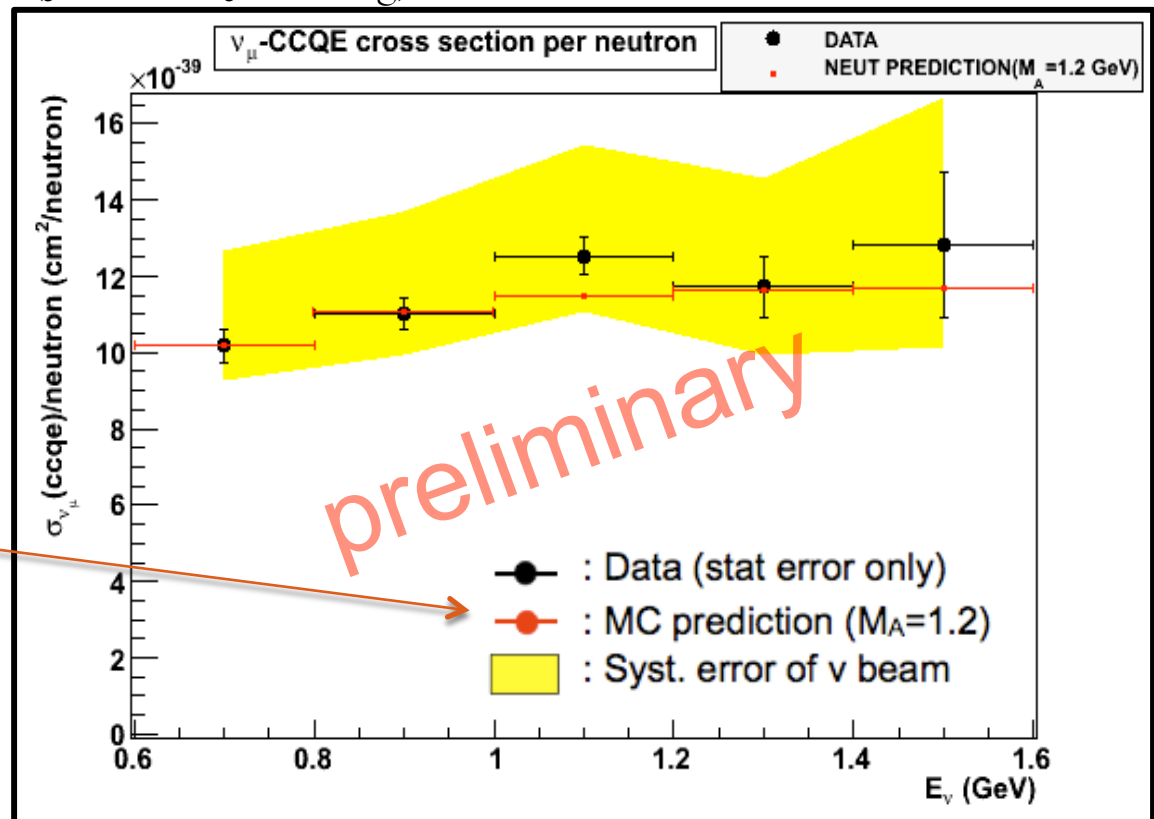
- Charged-Current Quasi-Elastic Scattering

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

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

- agrees with model prediction already scaled based on MiniBooNE result (that is, preliminary result consistent with MiniBooNE)

(J. Alcaraz, J. Wolding)

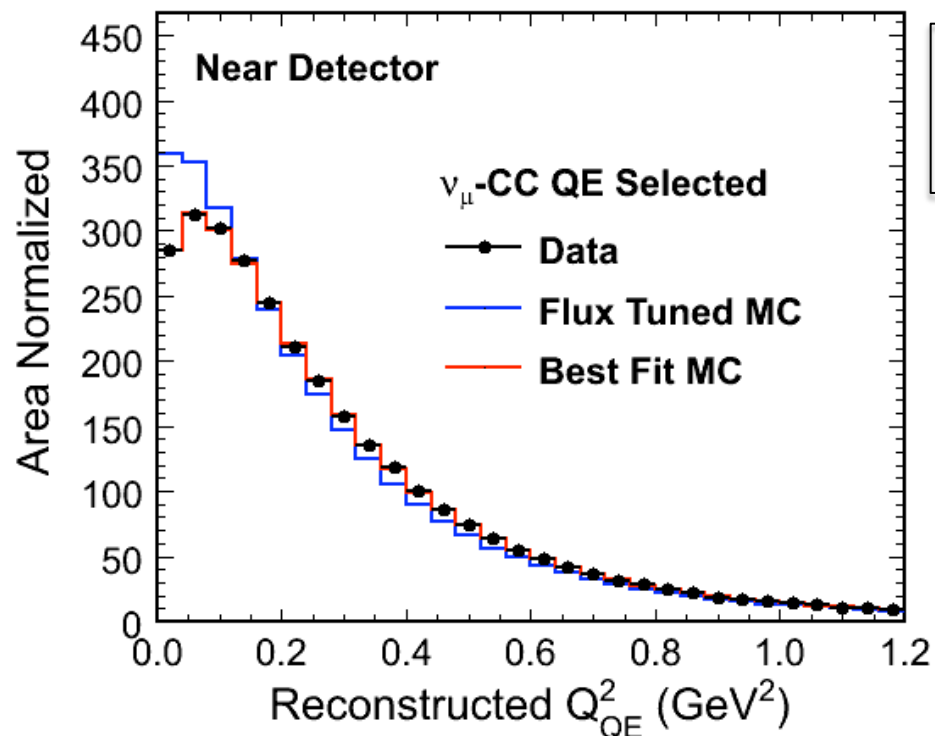


The Interactions (CCQE)

- Charged-Current Quasi-Elastic Scattering

MINOS

MINOS Preliminary



MINOS Preliminary

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

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

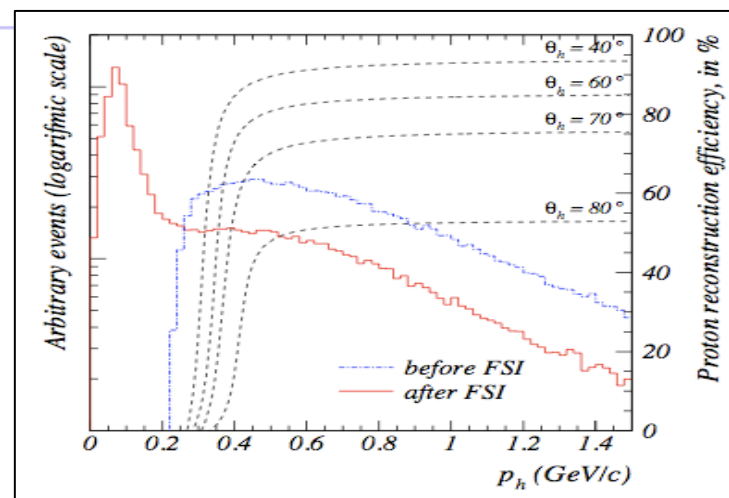
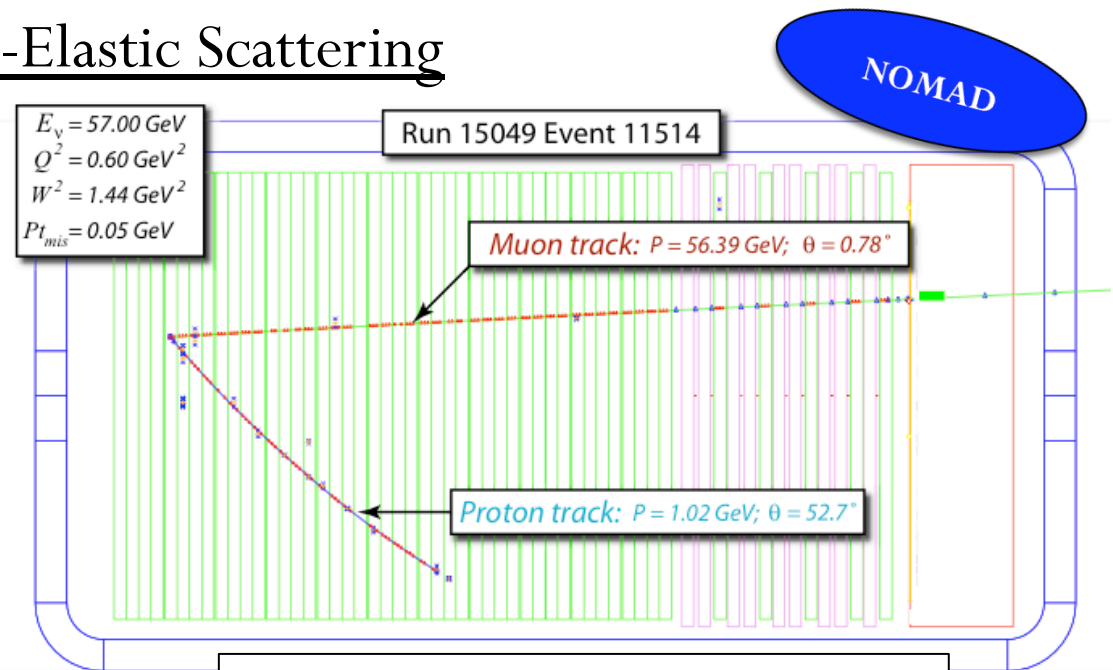
- fit favors a higher value of the axial mass and increases the Fermi momentum by 28% as an effective low Q^2 suppression
- no absolute cross-section values extracted yet – to come



The Interactions (CCQE)

- Charged-Current Quasi-Elastic Scattering

- 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



arXiv:0812.4543v3

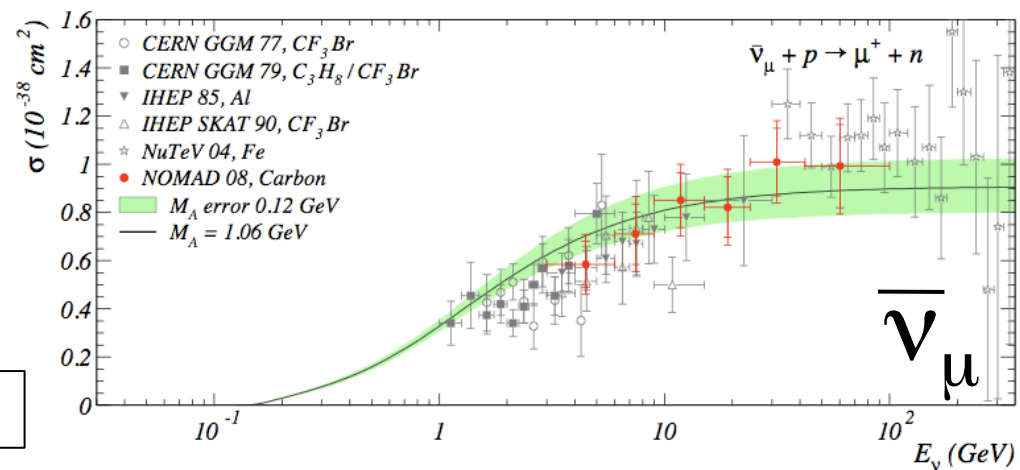
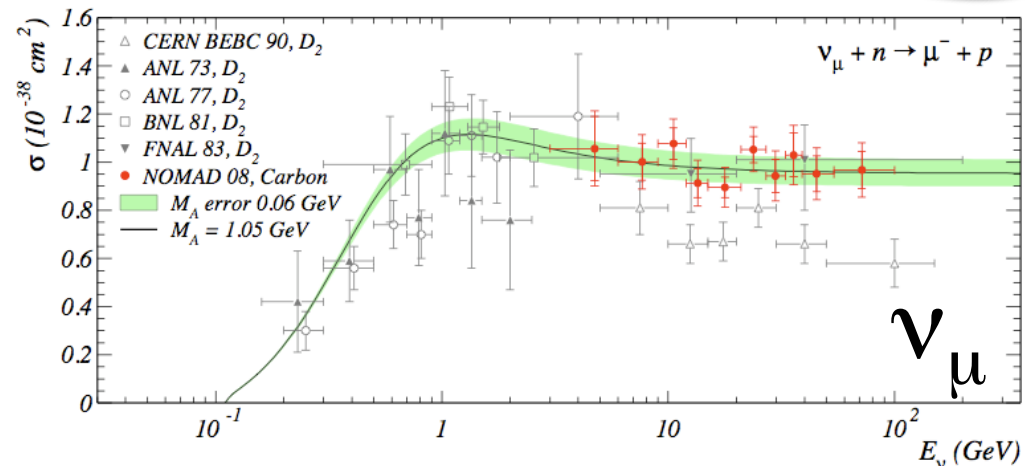


The Interactions (CCQE)

- Charged-Current Quasi-Elastic Scattering



- can identify μ^+ and μ^- from track bend directions
- present both neutrino and antineutrino QE cross-sections above 3 GeV



arXiv:0812.4543v3

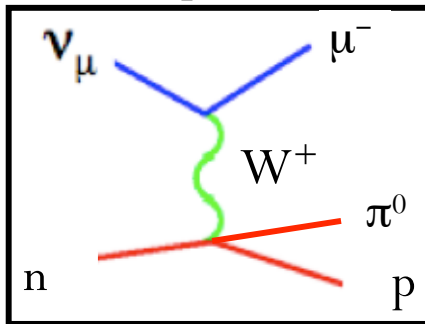


The Interactions (CC π^0)

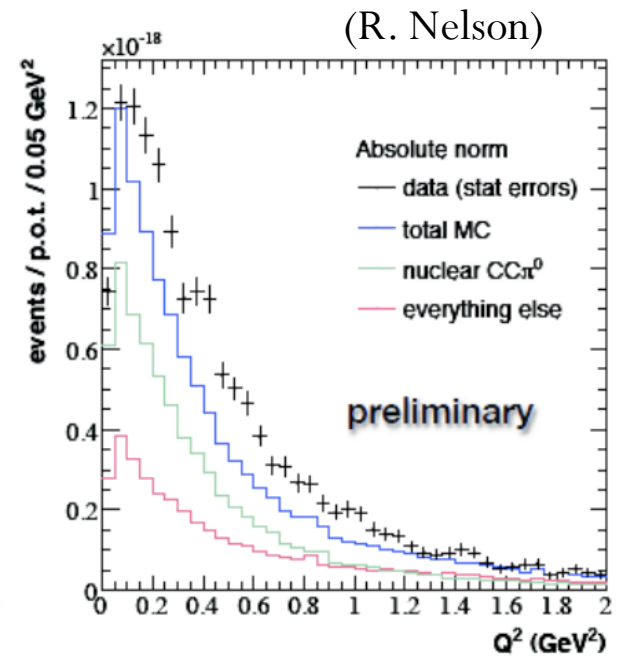
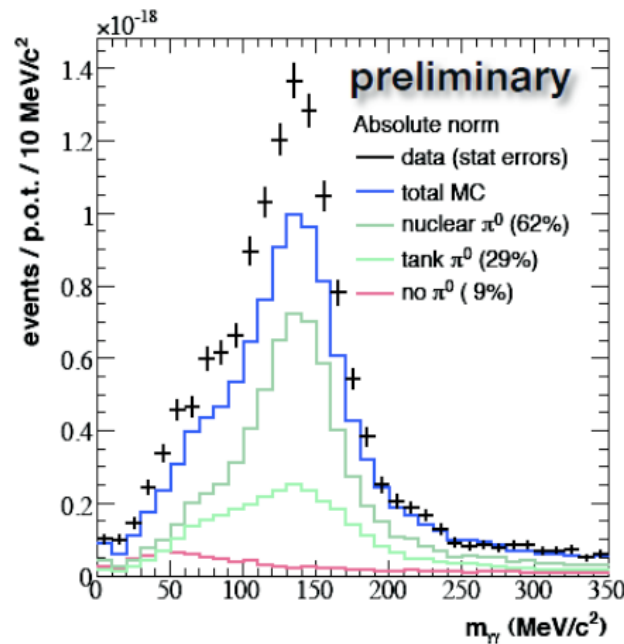
MiniBooNE

- Single Pion Production

CC π^0 production

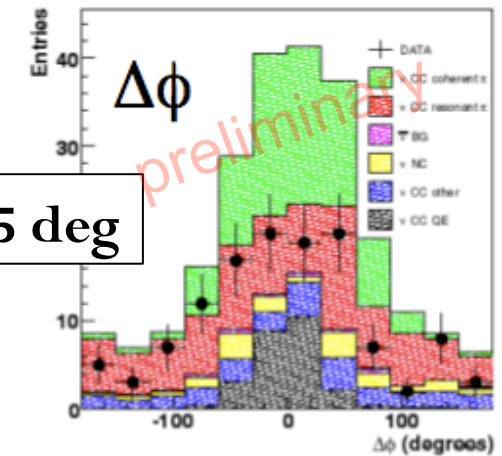


- development of 3 Cherenkov ring fitter has made possible the study of CC π^0 production

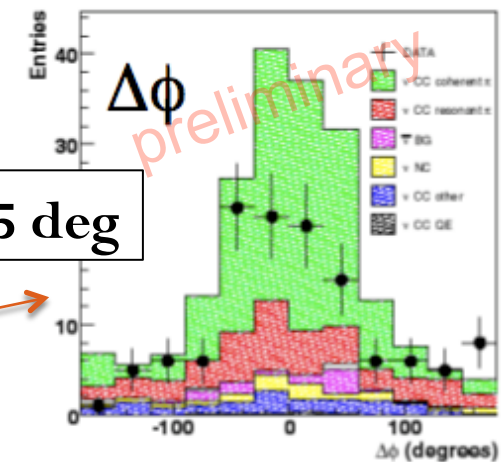


The Interactions (coherent)

- Coherent Single Pion Production (CC/NC)
- 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



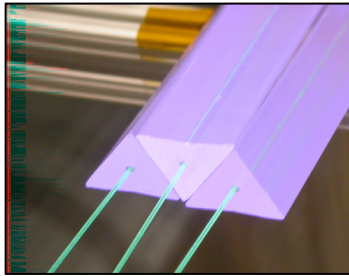
$\theta_\pi > 35$ deg



$\theta_\pi < 35$ deg

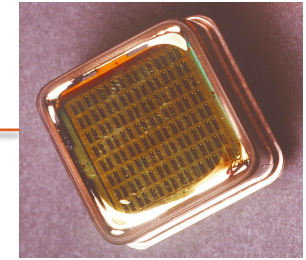


MINERvA Design

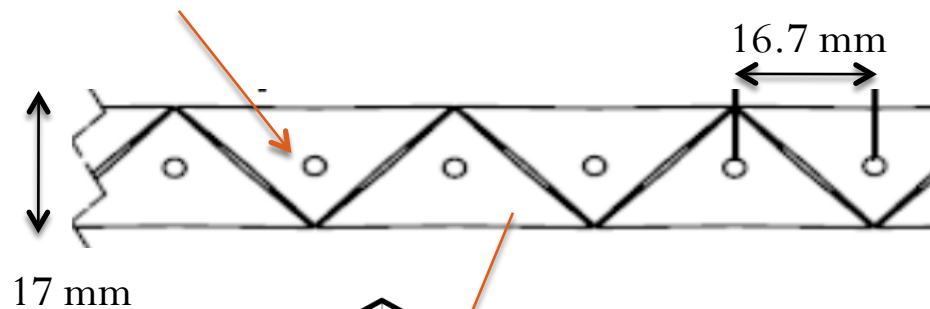


extruded plastic scintillator
+ wavelength shifting fibers

triangular geometry allows
charge sharing for better pos res.

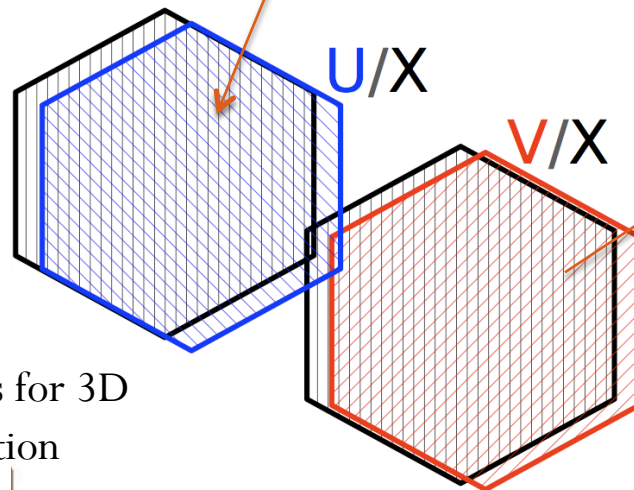


64 anode
PMTs

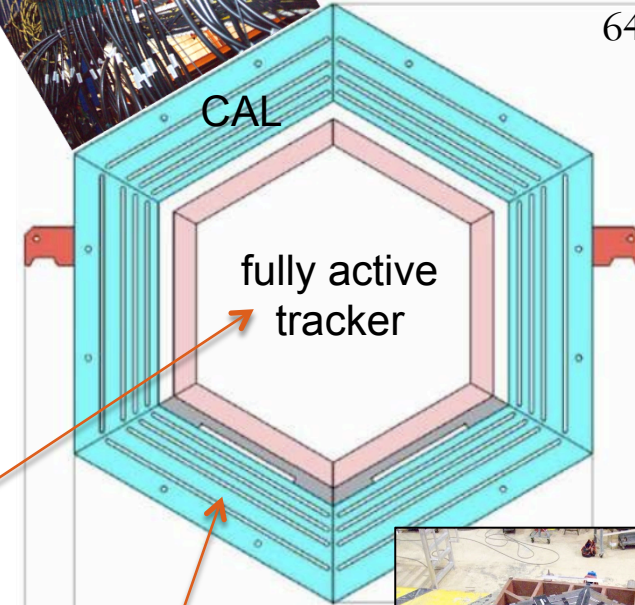
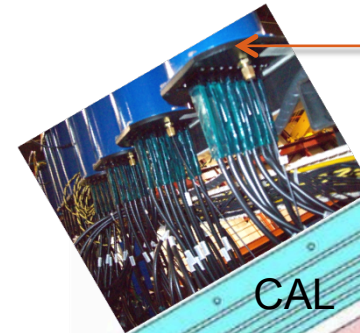


17 mm

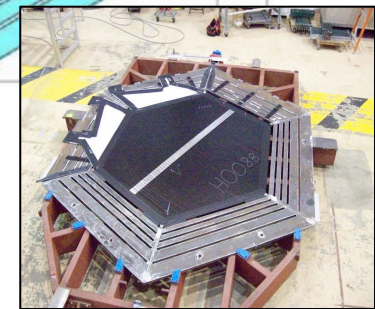
16.7 mm



three views for 3D
reconstruction

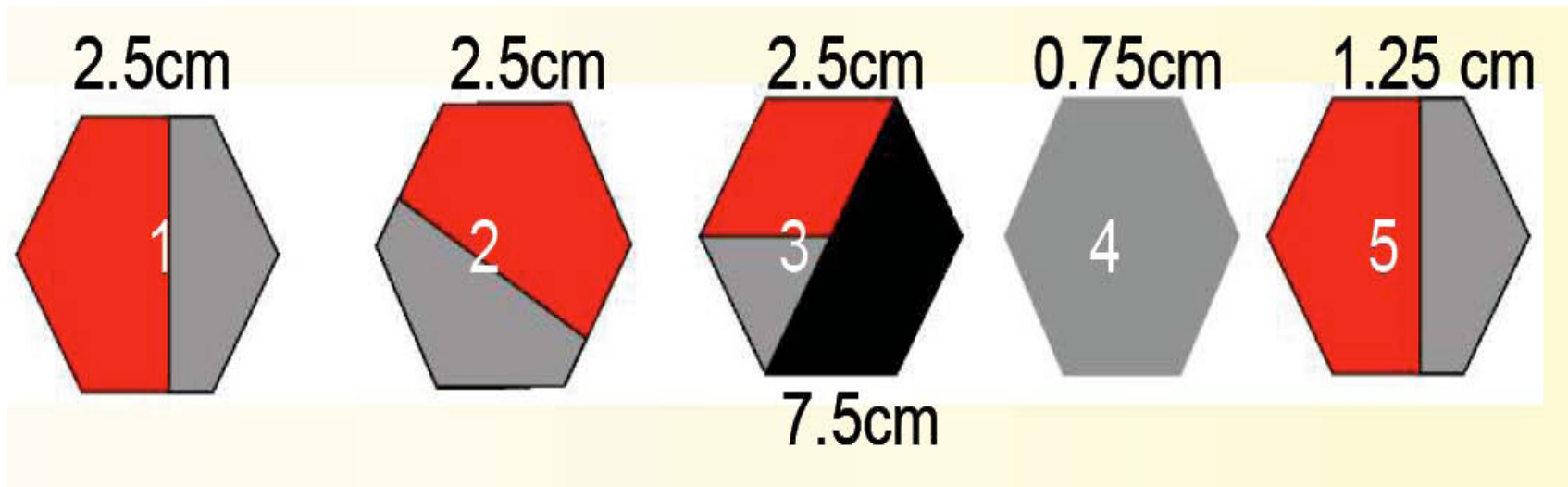


iron outer detector
instrumented for EM
calorimetry



MINER ν A Nuclear Targets

- Red = Iron, Grey = Lead, Black = Carbon



- First two targets: High statistics, compare lead and iron
- Third target: Compare lead, iron, and carbon with same detector geometry
- Last targets: Thin for low energy particle emission studies, high photon detection
- ^4He cryogenic target in front of detector



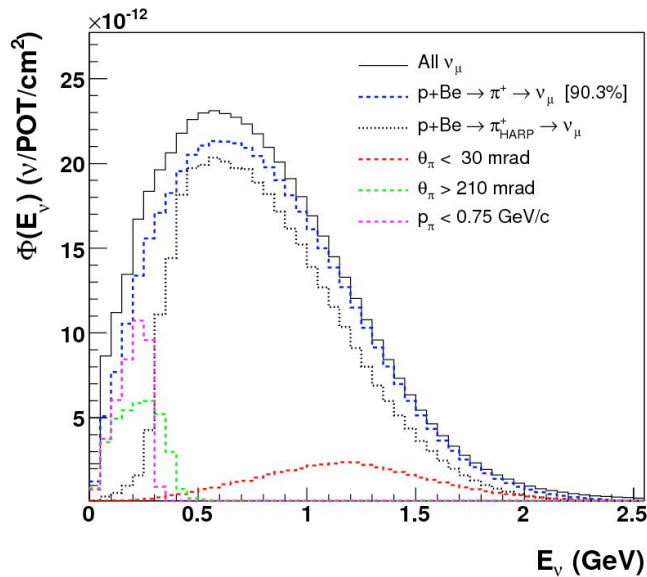
MINER ν A Water Target

- People often ask, “Isn’t water a pretty important nuclear target in neutrino physics?”
- And MINER ν A has heard your calls...
- have been in contact with group at TRIUMF who built water “bags” for T2K
- working also with Fermilab engineers for ability to install this design and for a possible new design
- decision to be made very soon

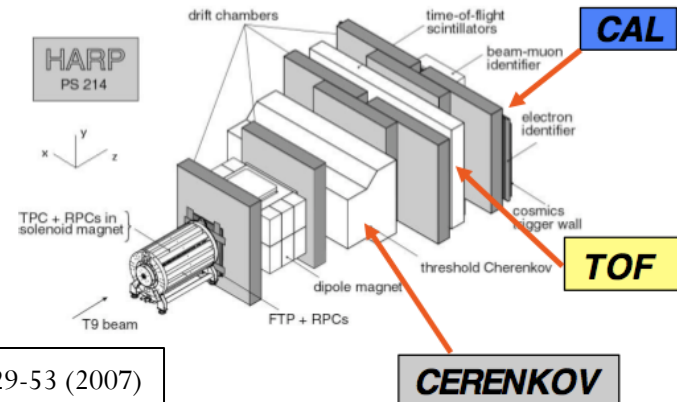


HARP & the BNB Flux

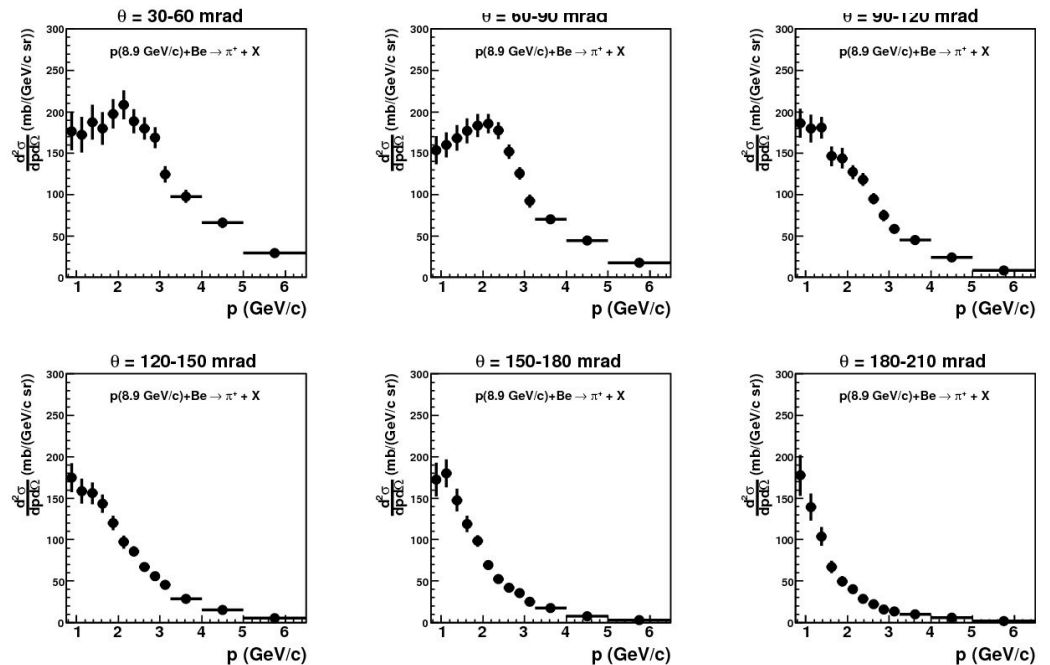
- MiniBooNE and SciBooNE both in Booster Neutrino Beam at Fermilab
 $E_\nu \sim 0.2 - 1.5 \text{ GeV}$



- Absolute normalization of flux using pion production data from the **HARP** experiment

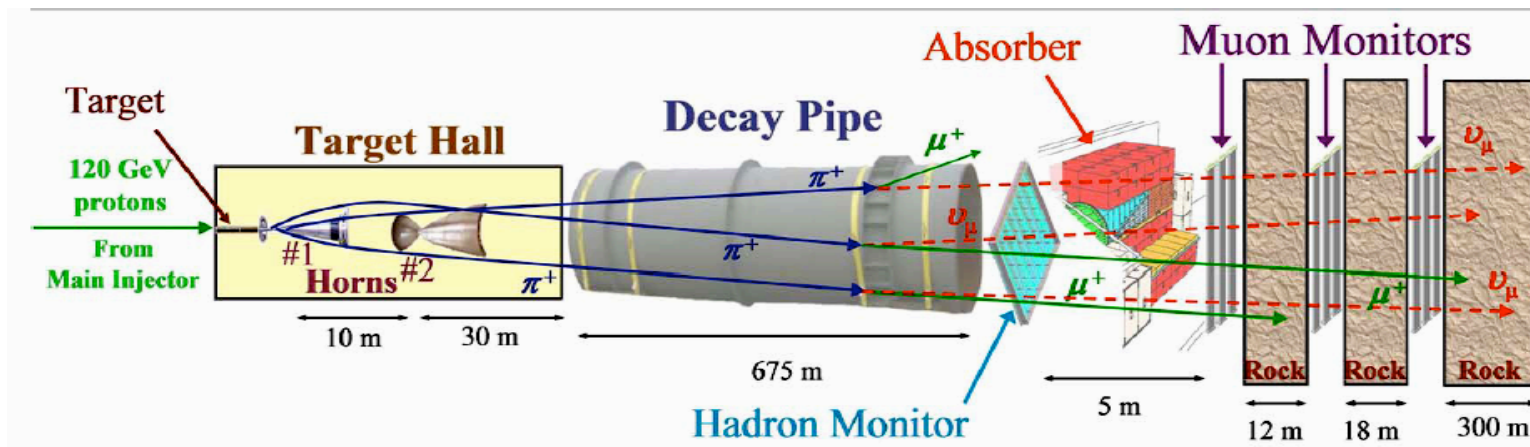
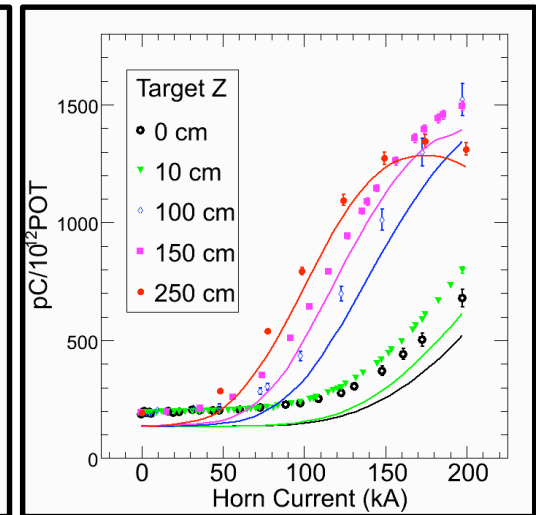
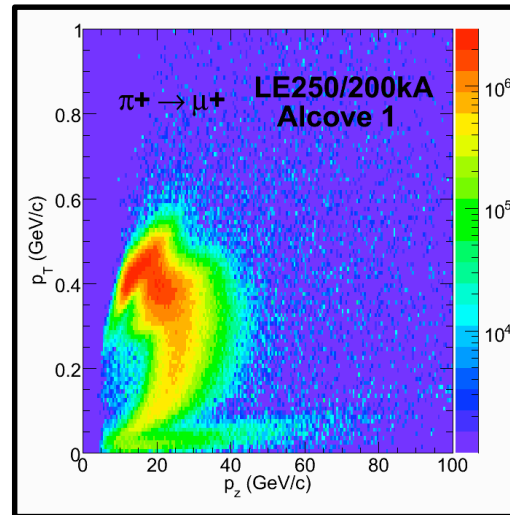


Euro. Phys. J C 52:29-53 (2007)



MINERvA & the NuMI Flux

- Goal to reach $\sim 5\%$ absolute flux estimate through a combination of approaches:
 - in situ measurements using **muon monitors** and beam taken at various horn currents and target positions in the NuMI beamline



MINERvA & the NuMI Flux

- Goal to reach $\sim 5\%$ absolute flux estimate through a combination of approaches:
 - in situ measurements using [muon monitors](#) and beam taken at various horn currents and target positions in the NuMI beamline
 - recent new beam simulation [G4](#)
 - particle production experiment [MIPP](#) at Fermilab. Analysis in progress of data with NuMI target

