Review of Current and Future Neutrino Cross-Section Experiments

David Schmitz, Fermilab

WIN '0 9

22nd International Workshop on Weak Interactions and Neutrinos

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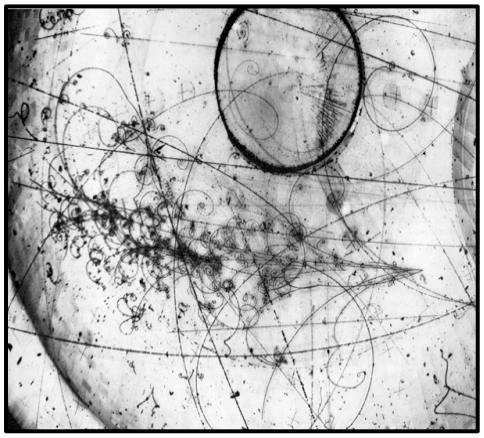
Outline

- 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 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
- 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
  - Better to have accurate *a priori* knowledge of the event rates for ALL event types in order to design better experiments with accurate sensitivities. Particulary good when you are building 100's of kilotons for B's of $.

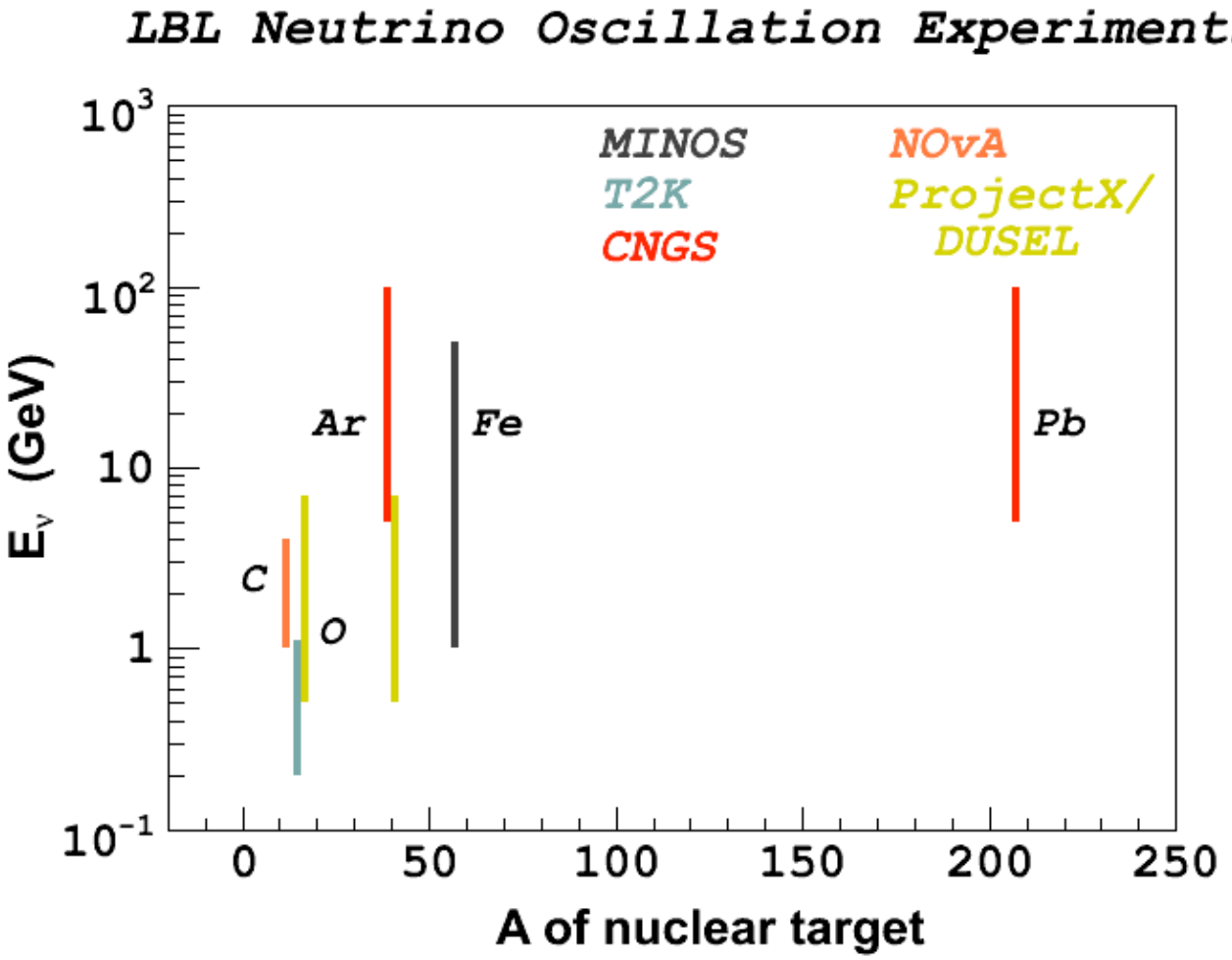
Energies and Targets

- 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

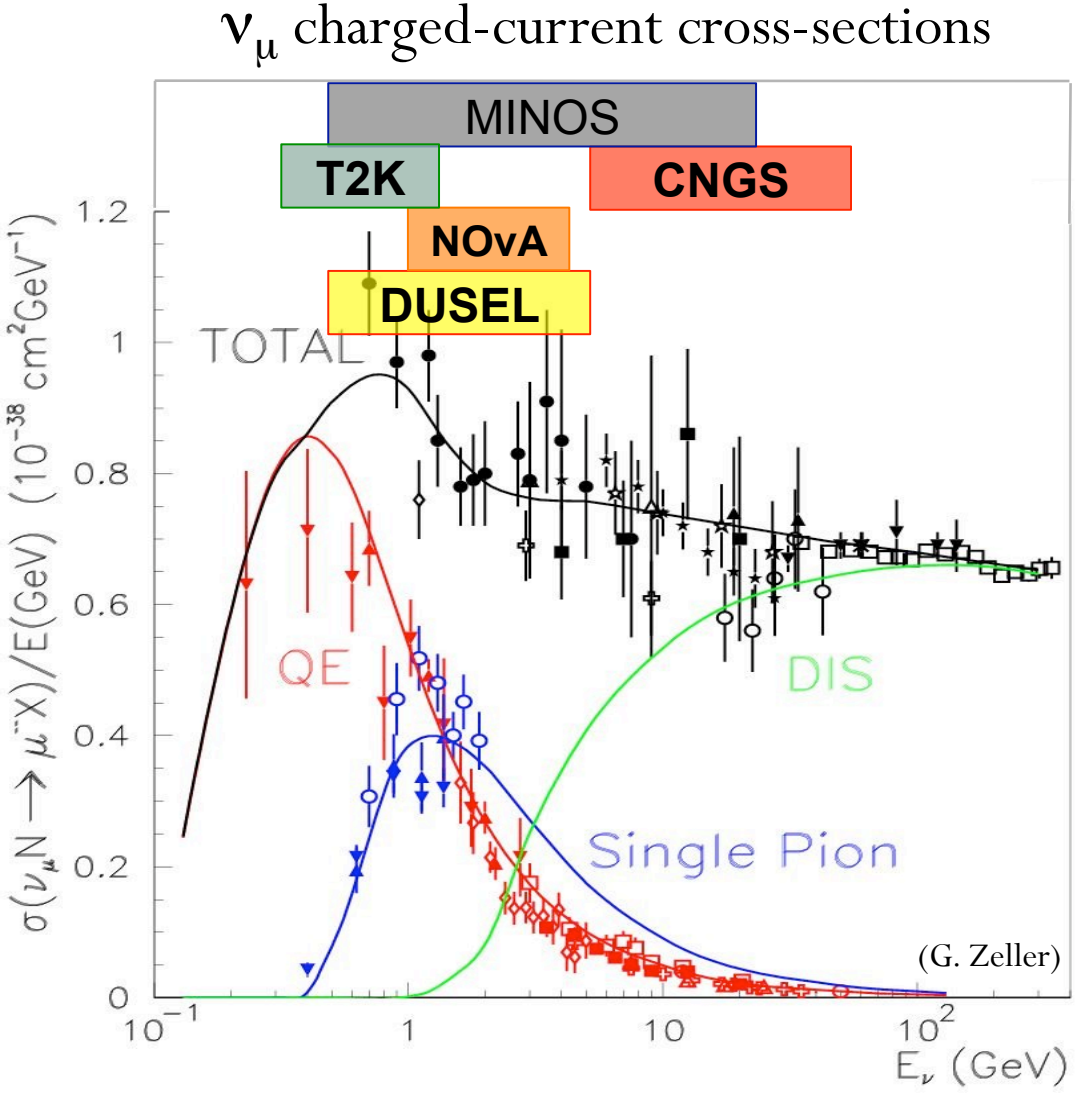
- Target Materials:
  - MINOS = Fe
  - CNGS = Pb, Ar
  - T2K = H_2O
  - NOvA = C
  - DUSEL = H_2O, Ar



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



Energies and Targets

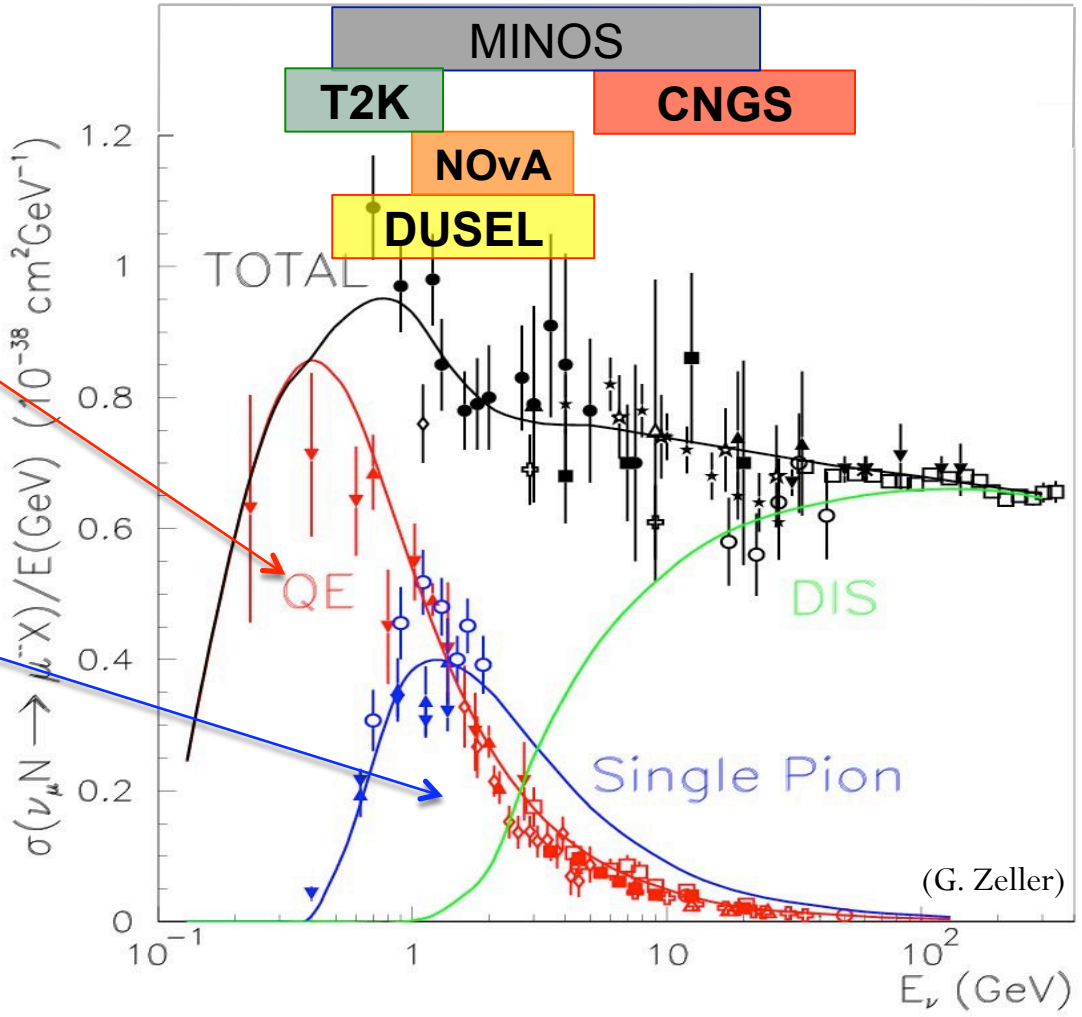
of the LBL oscillation experiments

Quasi-Elastic
signal channel in LBL oscillation experiments

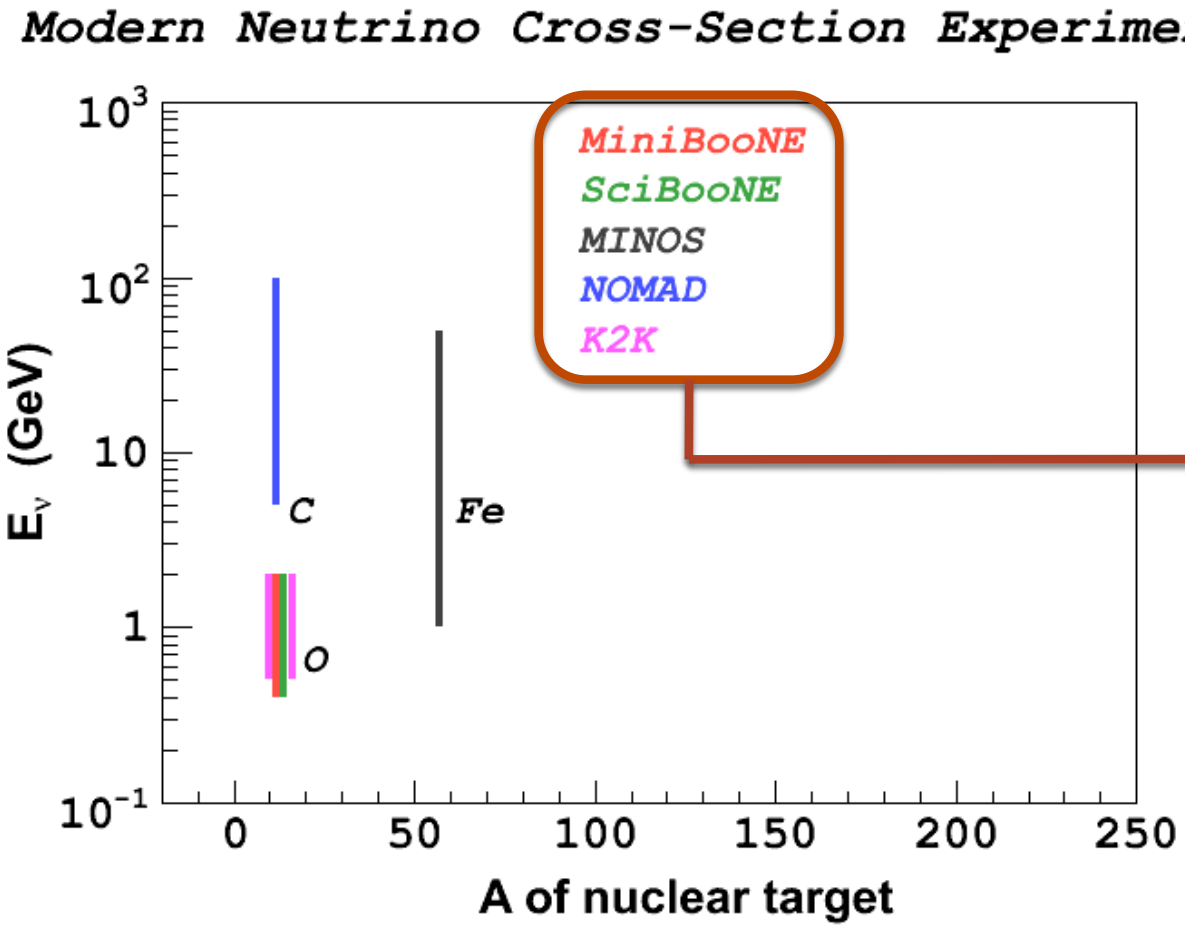
CC π^+
background for ν_μ disappearance

NC π^0
background for ν_e appearance

ν_μ charged-current cross-sections



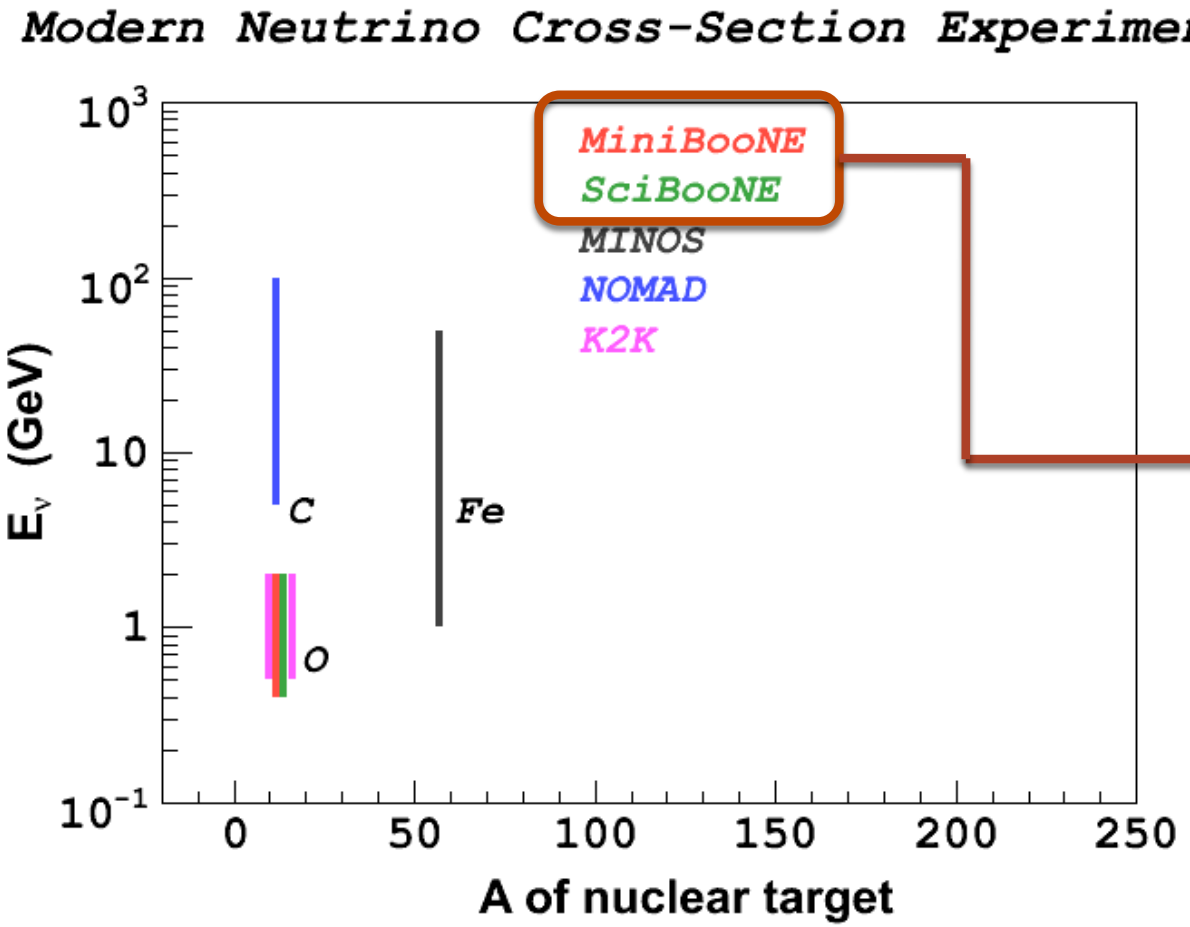
Energies and Targets



of the cross-section experiments

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

Energies and Targets

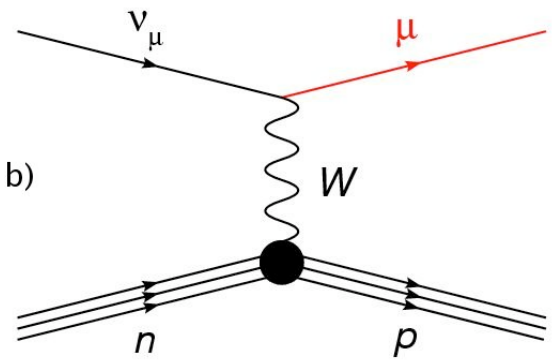


of the cross-section experiments

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

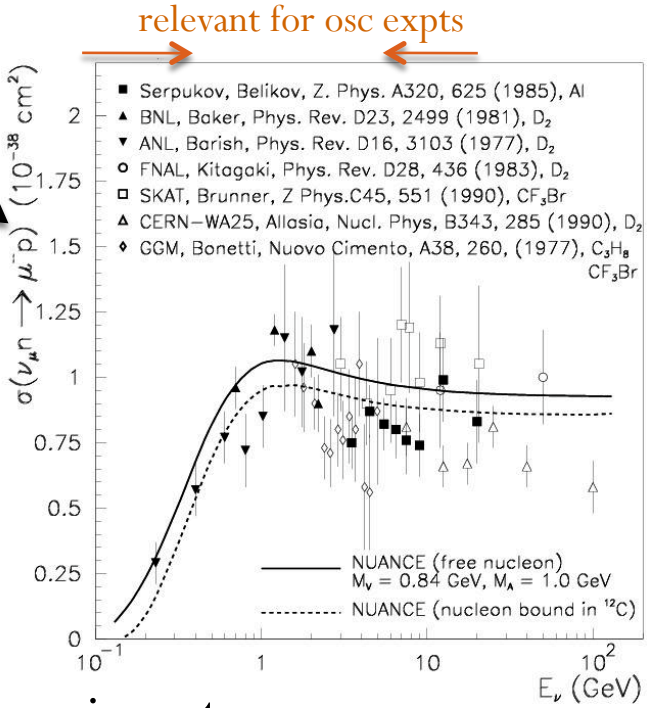


no /E(GeV)

~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

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

The Interactions (CCQE)

- Charged-Current Quasi-Elastic Scattering

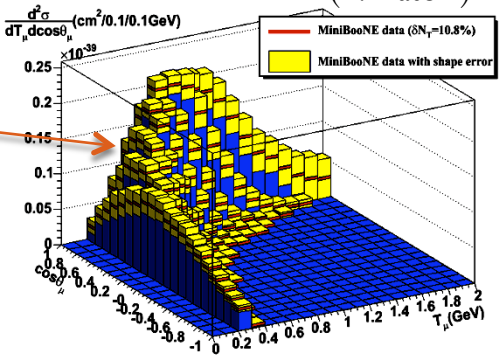
• 146,070 ν_μ QE events on carbon (76% purity)

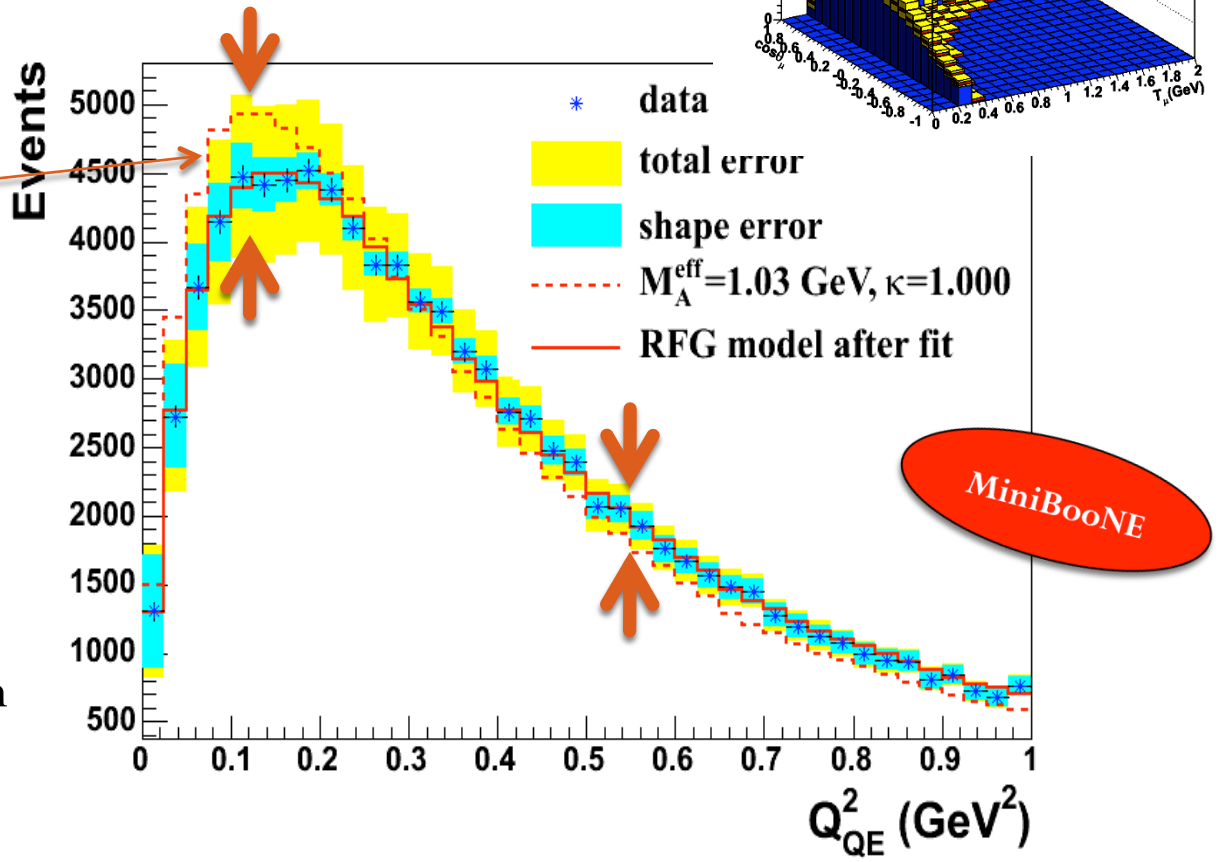
• Q^2 distribution is used to compare to default QE model used in event generator
  - deficit seen at lowest Q^2
  - excess at higher Q^2

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

(T. Katori)

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



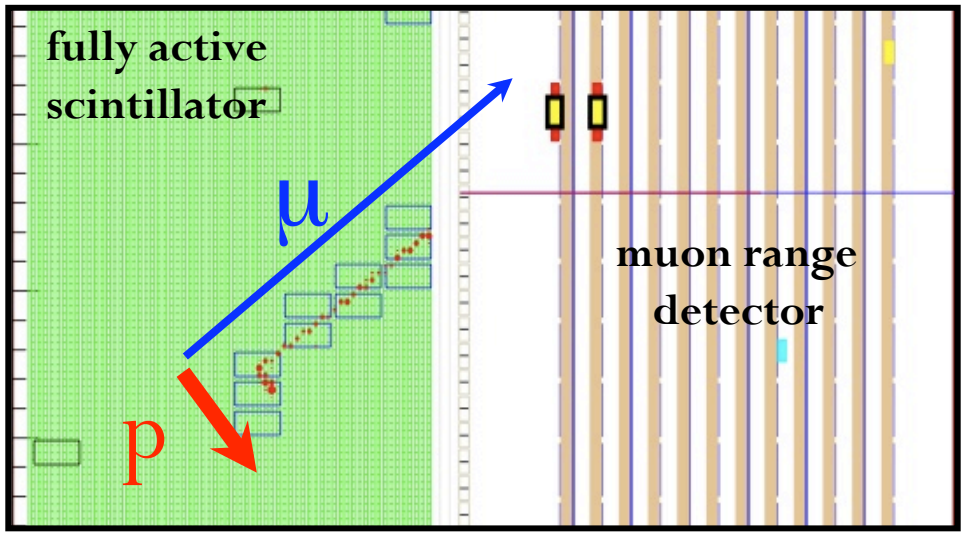


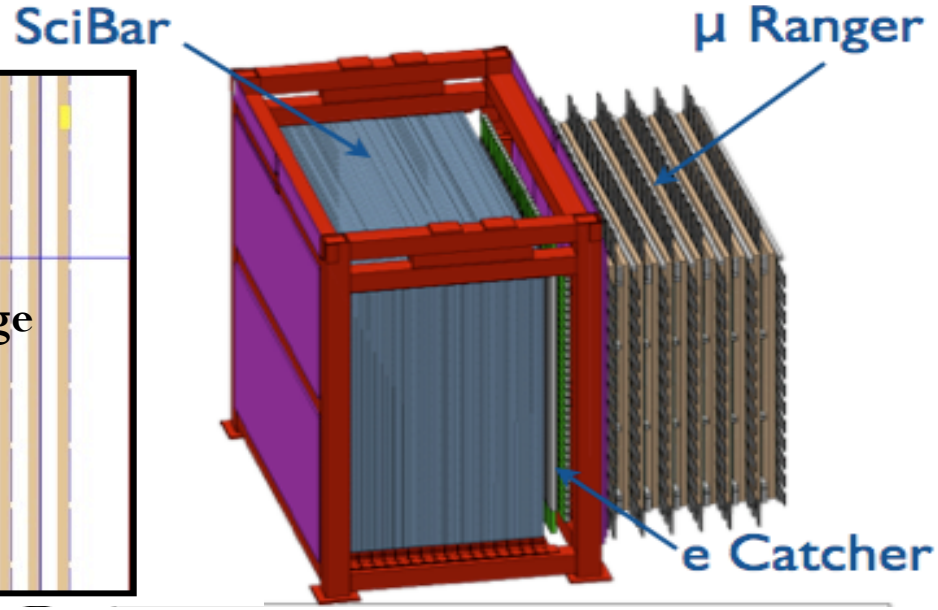
The Interactions (CCQE)

- Charged-Current Quasi-Elastic Scattering

SciBooNE

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





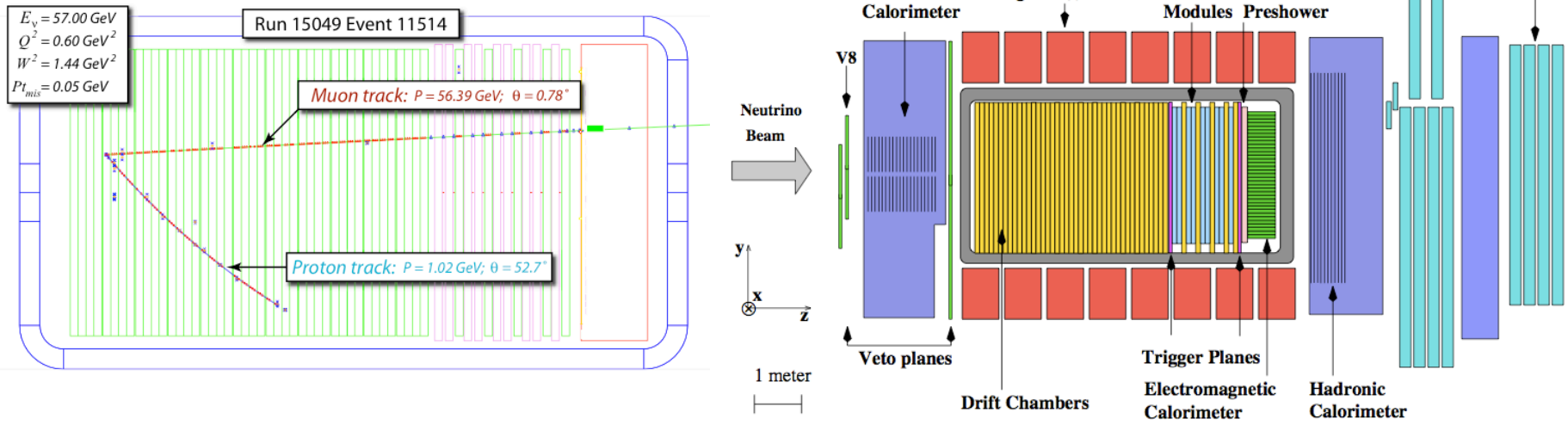
The Interactions (CCQE)

- Charged-Current Quasi-Elastic Scattering

NOMAD

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

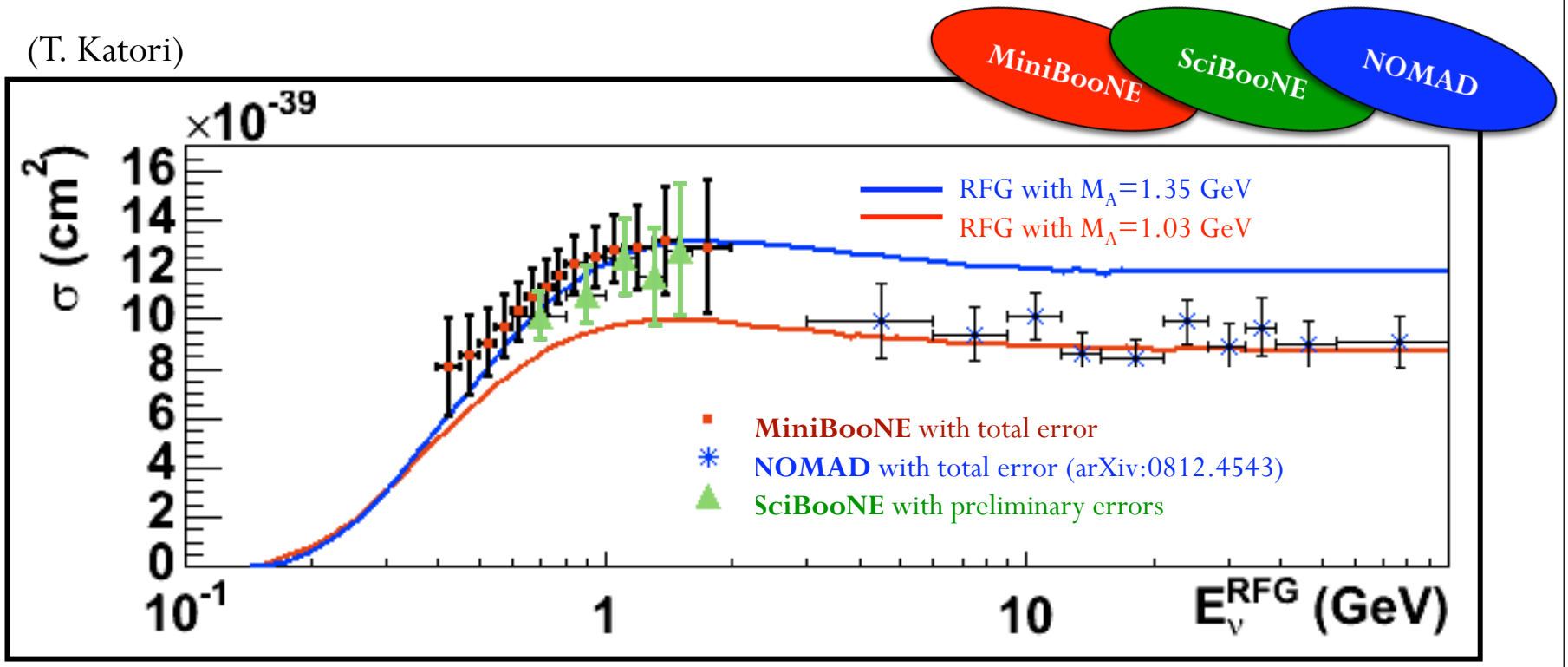
arXiv:0812.4543v3



The Interactions (CCQE)

- Charged-Current Quasi-Elastic Scattering

(T. Katori)



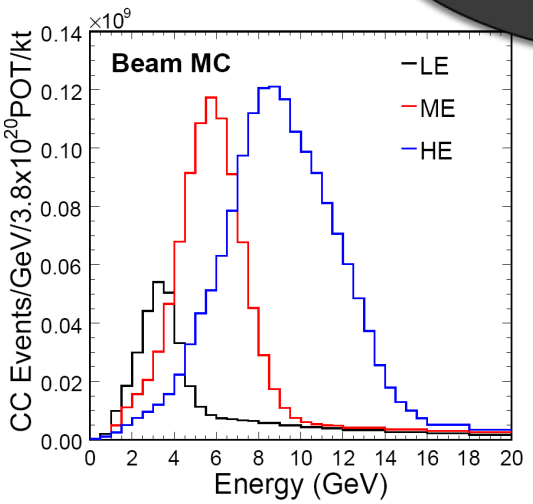
- MiniBooNE/SciBooNE in agreement, but tension with higher energy NOMAD results. All three on carbon. This is not understood.

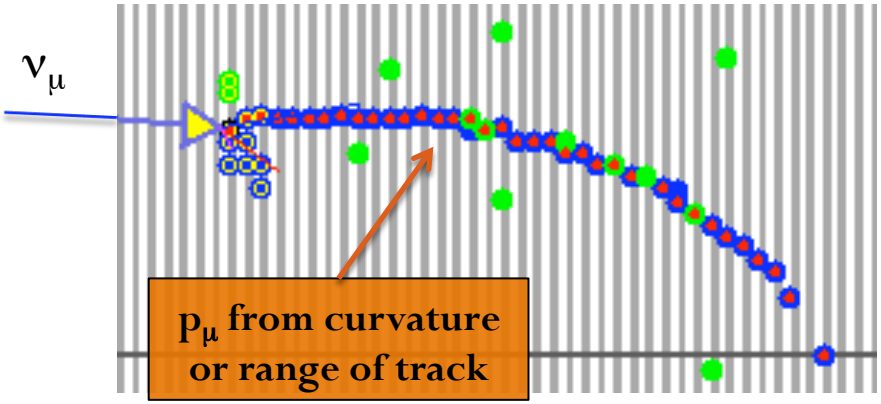
The Interactions (CCQE)

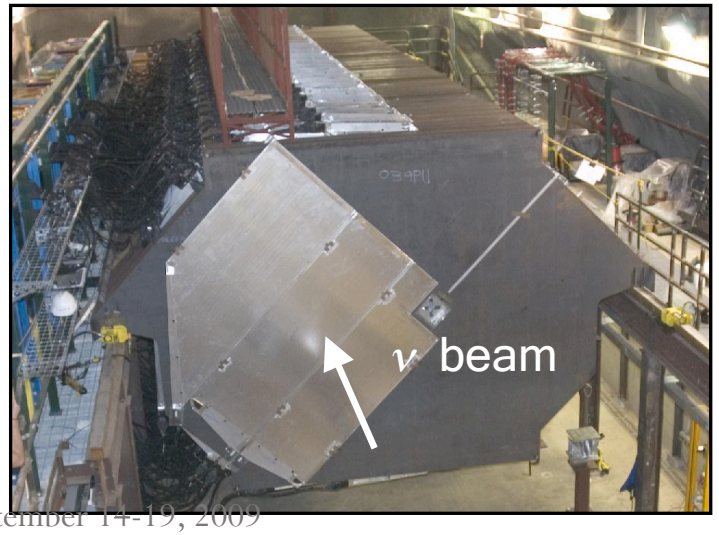
- Charged-Current Quasi-Elastic Scattering

MINOS

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







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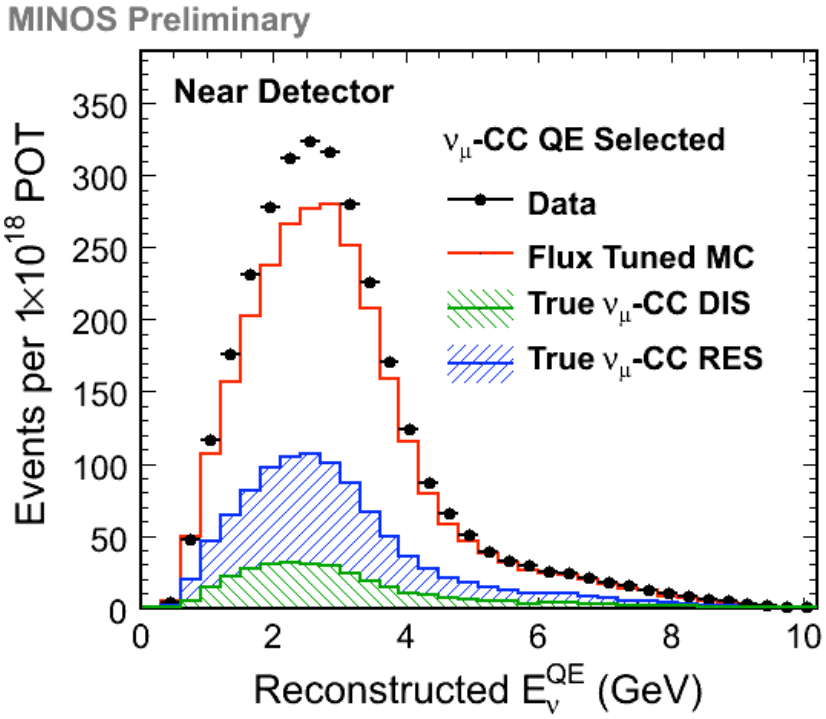

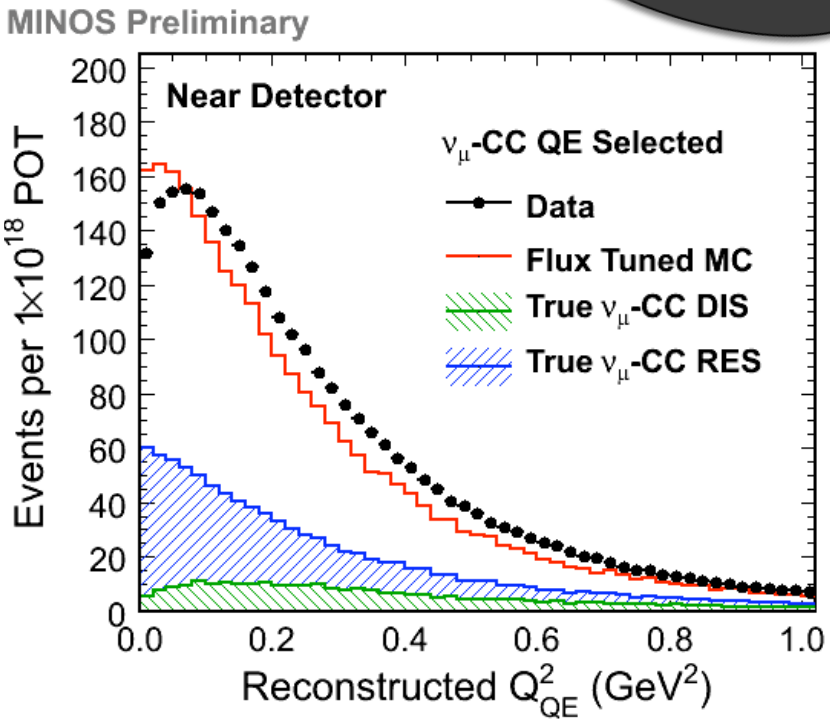

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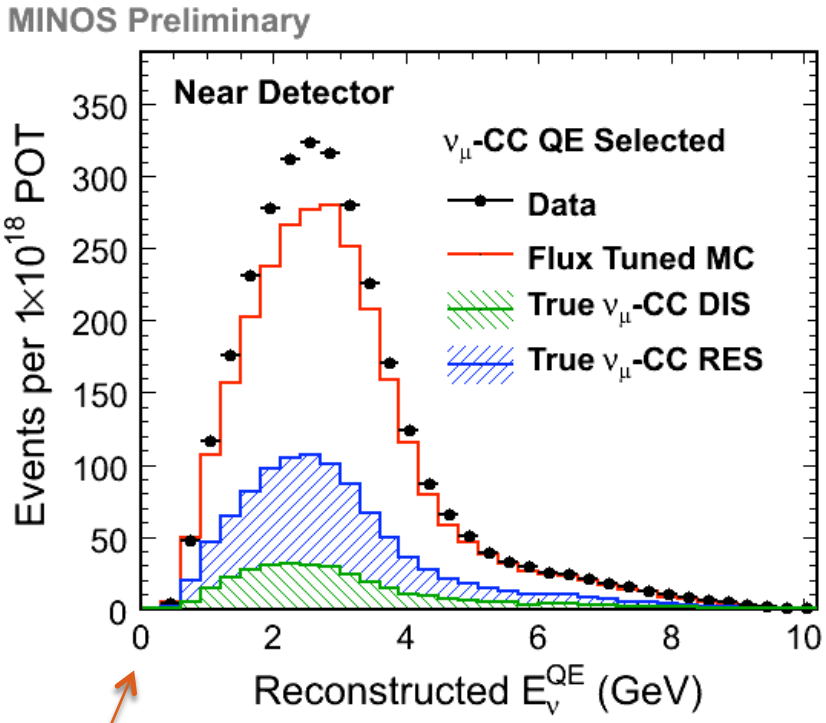
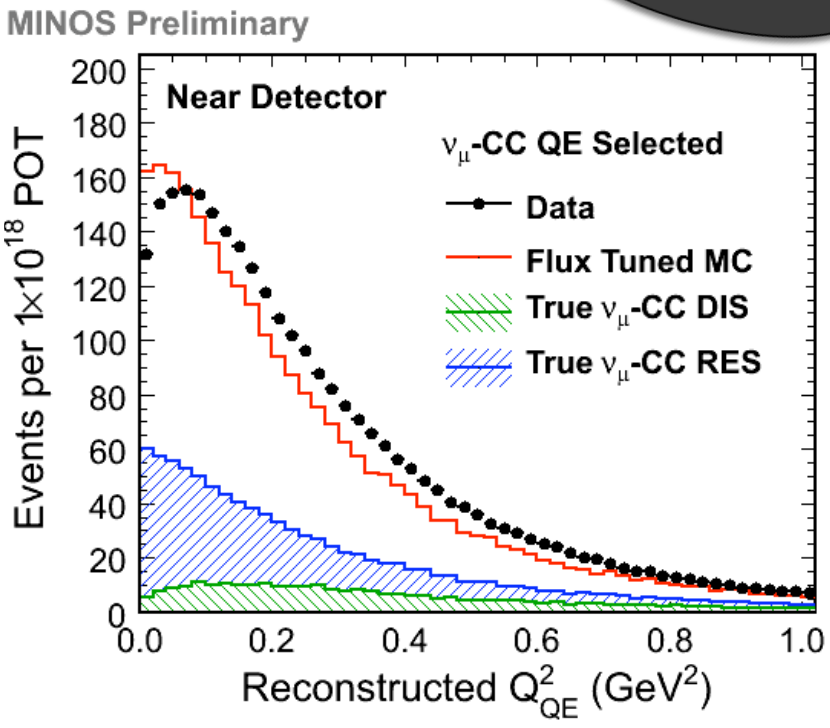


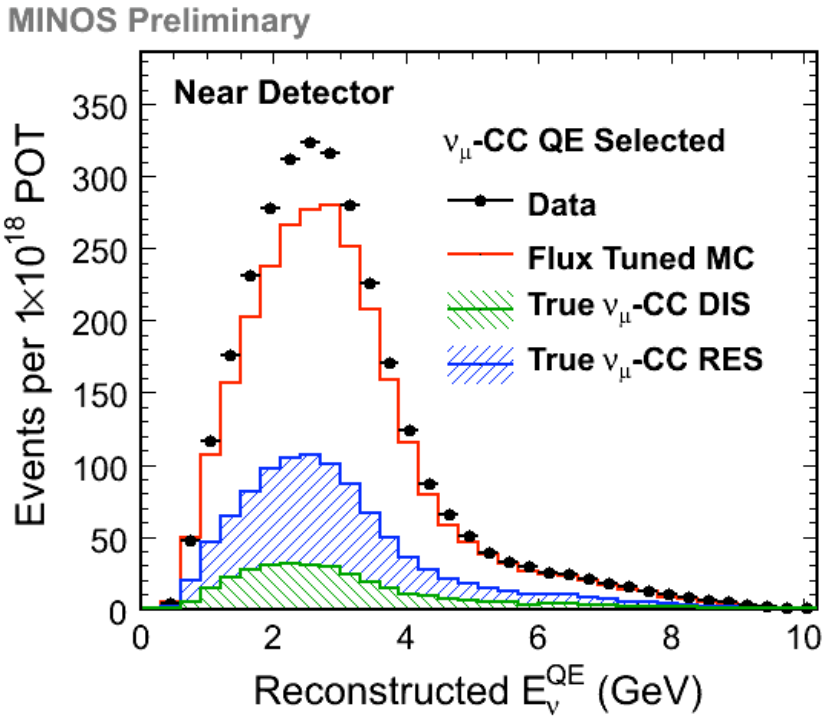


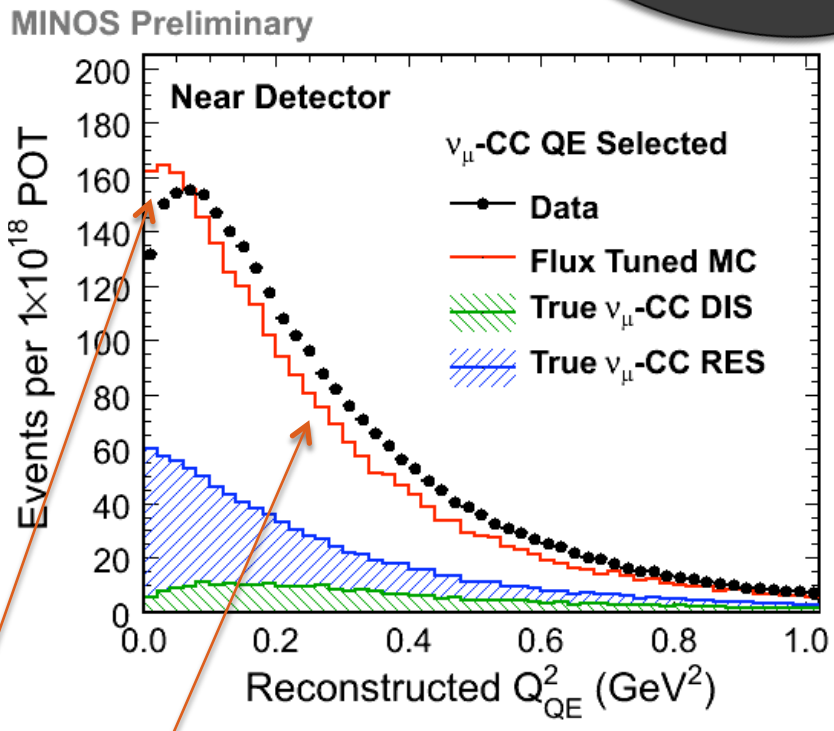
- Similar E_ν excess to those seen in Sci/MiniBooNE data

The Interactions (CCQE)

- Charged-Current Quasi-Elastic Scattering

MINOS



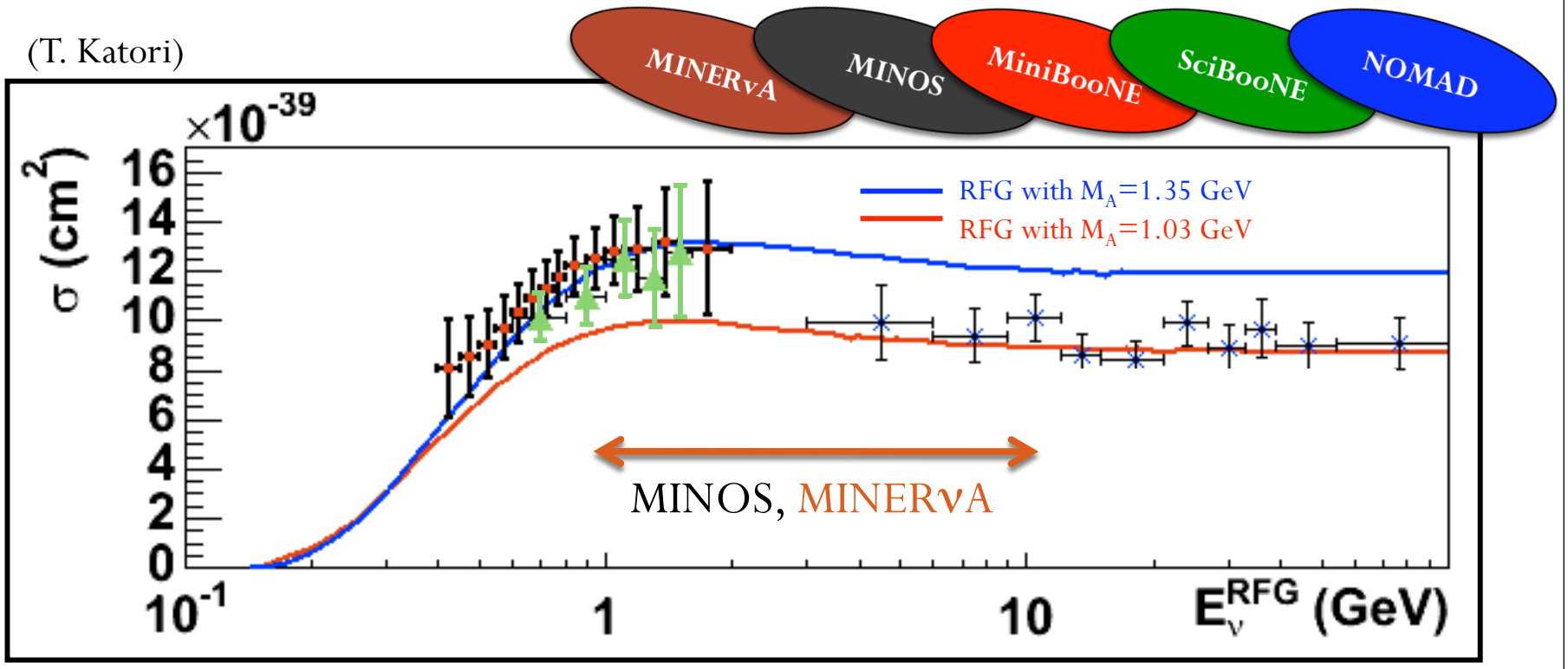


- Similar Q^2 shape disagreements to those seen in MiniBooNE data, but at higher energies and on iron instead of carbon

The Interactions (CCQE)

- Charged-Current Quasi-Elastic Scattering

(T. Katori)

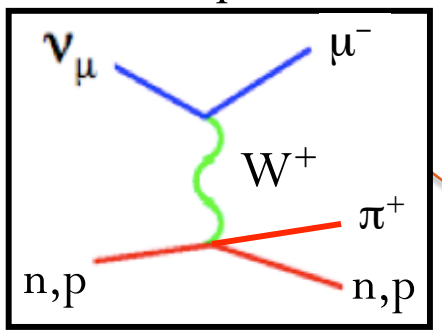


It is important to have data points from
MINOS and MINERvA to fill in this region

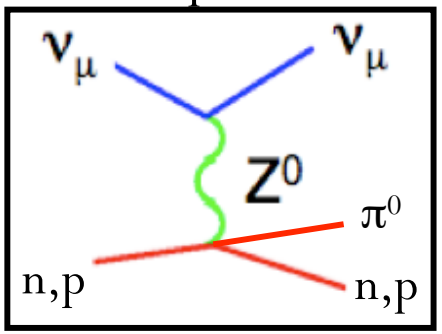
The Interactions (CC/NC π)

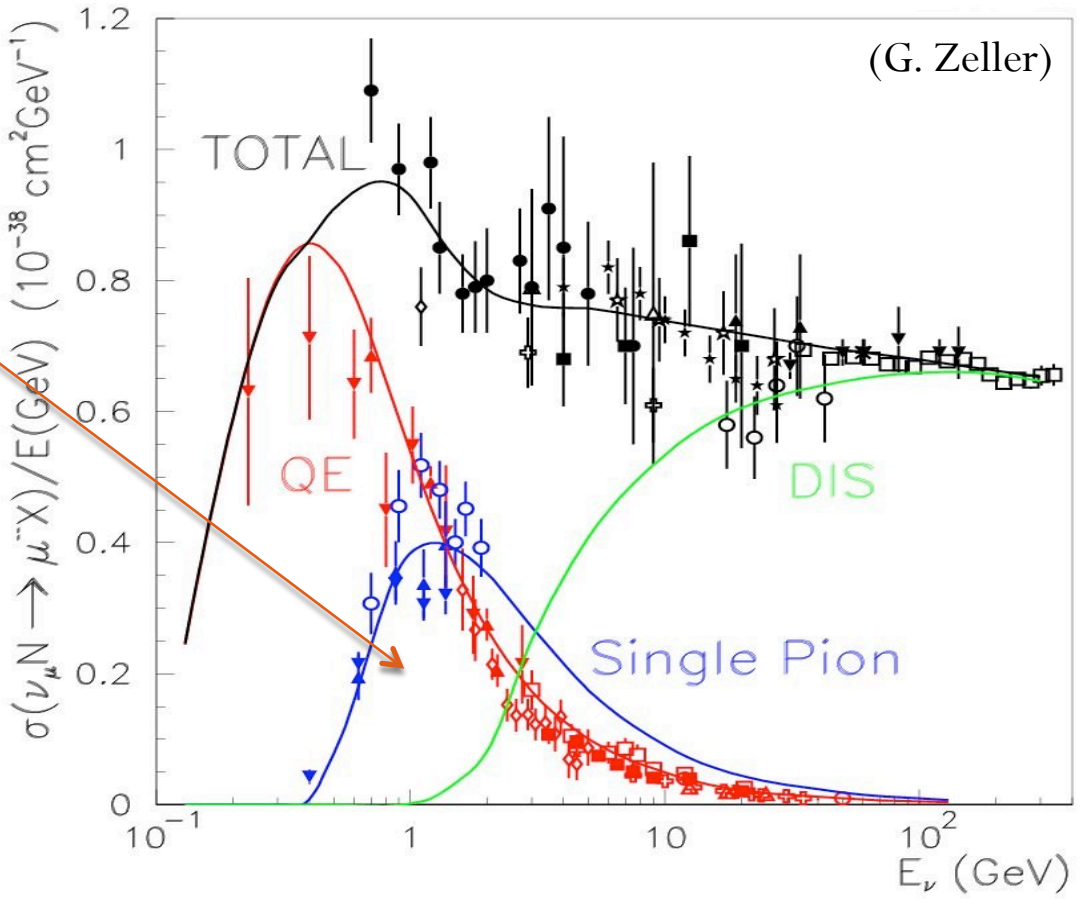
- Single Pion Production

CC π^+/π^0 production



NC π^0 production

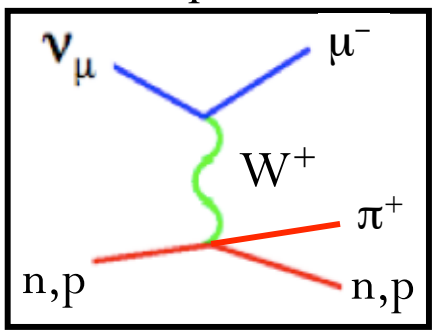


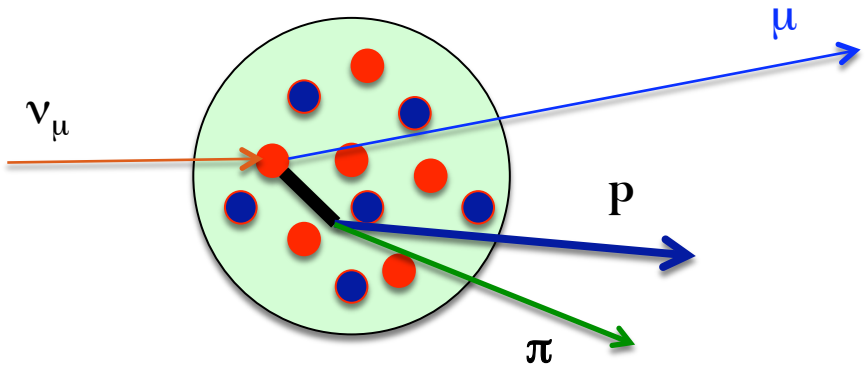


The Interactions (CC π^+)

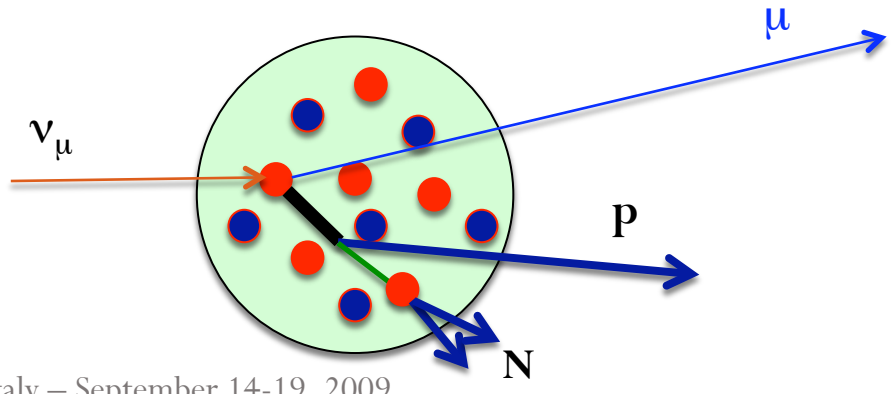
- Single Pion Production

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…

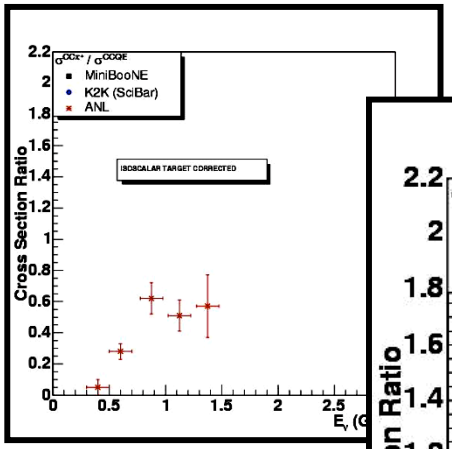


The Interactions (CC π^+)

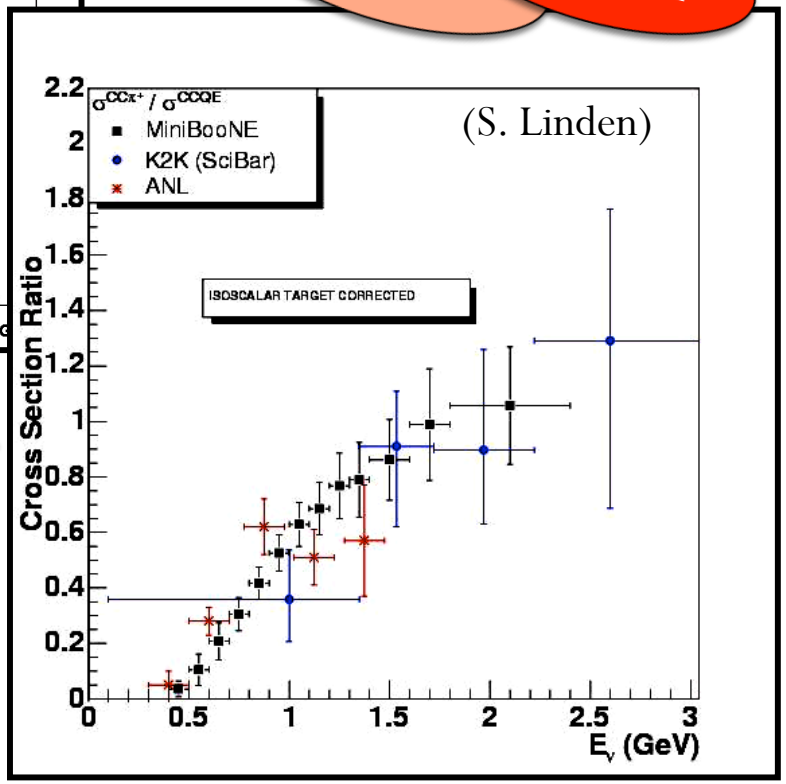
- Single Pion Production

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

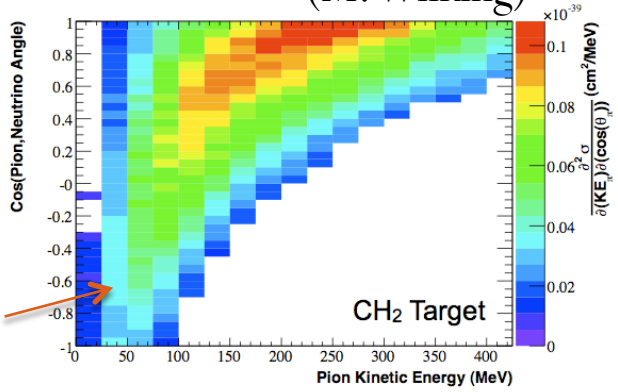
- 26 years between ANL and K2K/MiniBooNE results
- Cross-section ratio to CCQE
- Entering the realm of absolute differential cross-sections of π^+ production for the first time*



K2K MiniBooNE



(M. Wilking)



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

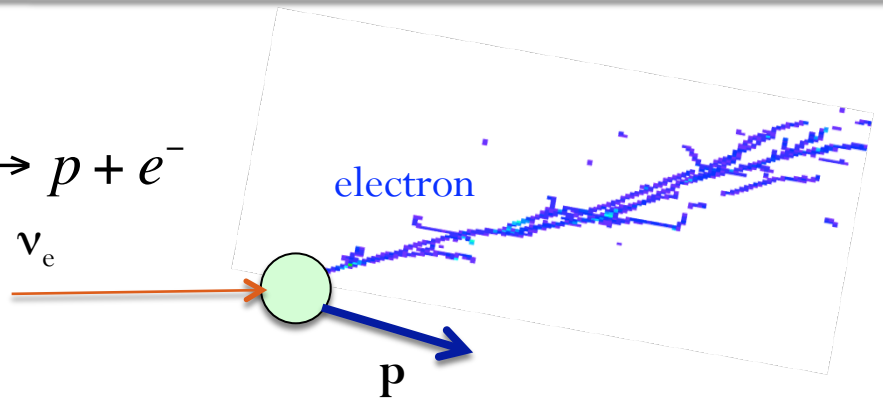
K2K: Phys. Rev. **D78**, 032003 (2008)

MiniBooNE: arXiv:0904.3159 [hep-ex]

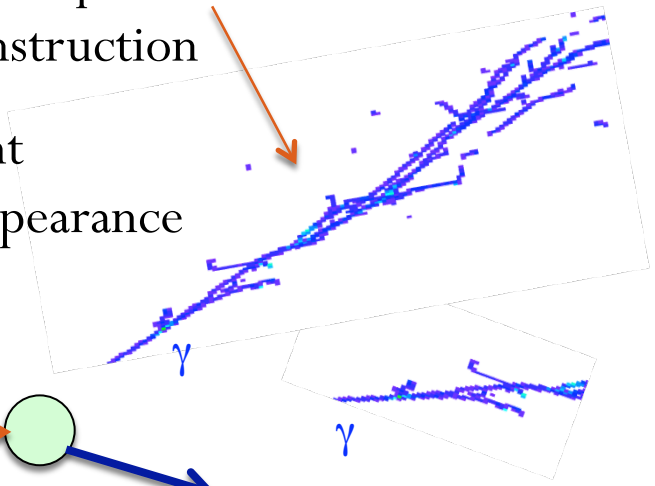
The Interactions (NC π^0)

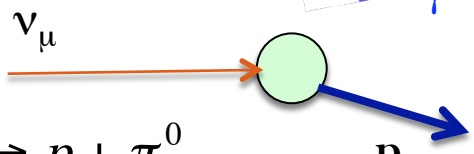
- Single Pion Production

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



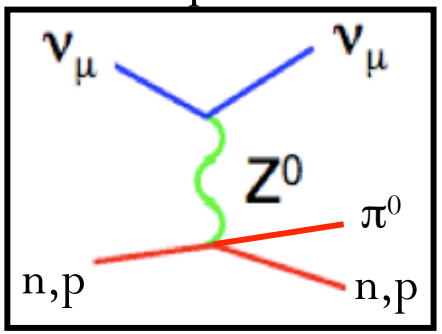
- Neutral pions create a reducible bkgd to ν_e CCQE if one photon is missed in event reconstruction
- miscount of important background in a ν_e appearance experiment





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

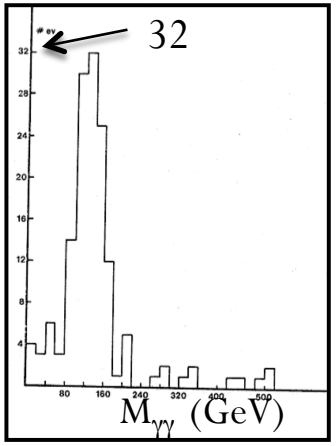
NC π^0 production

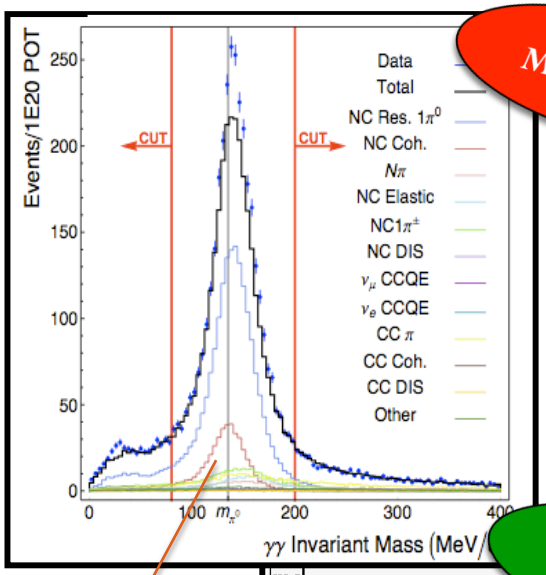


The Interactions (NC π^0)

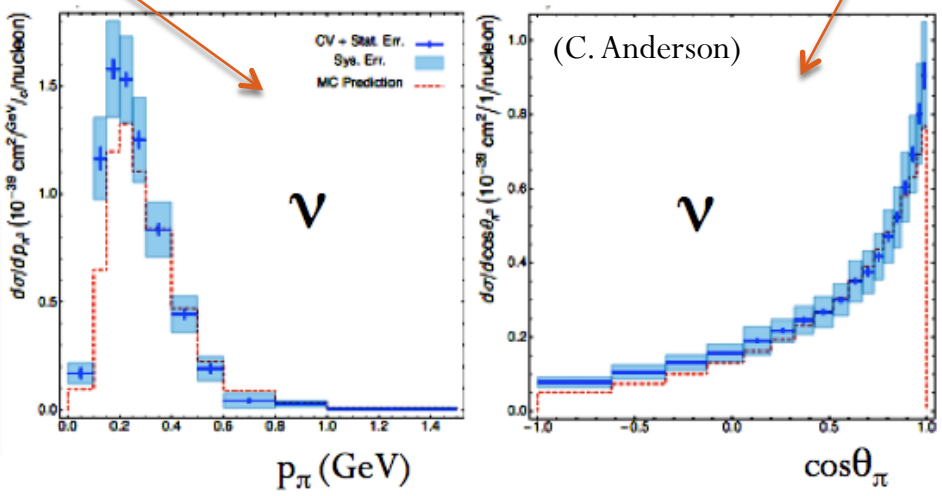
- Single Pion Production

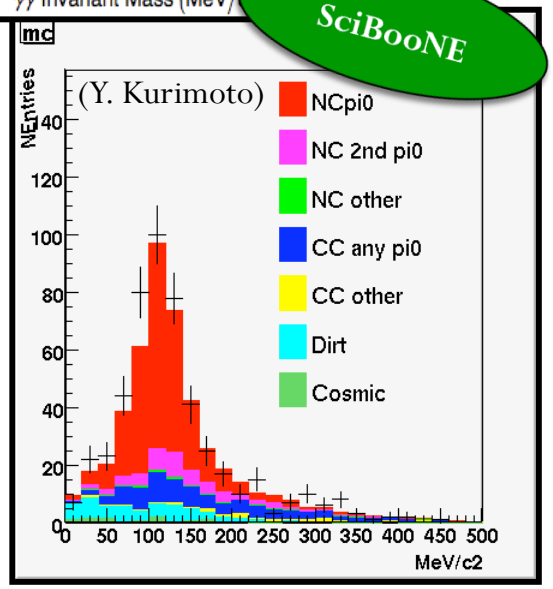
GGM, 240 NC π^0 events
Nucl. Phys. **B135**, 45 (1978)





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





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

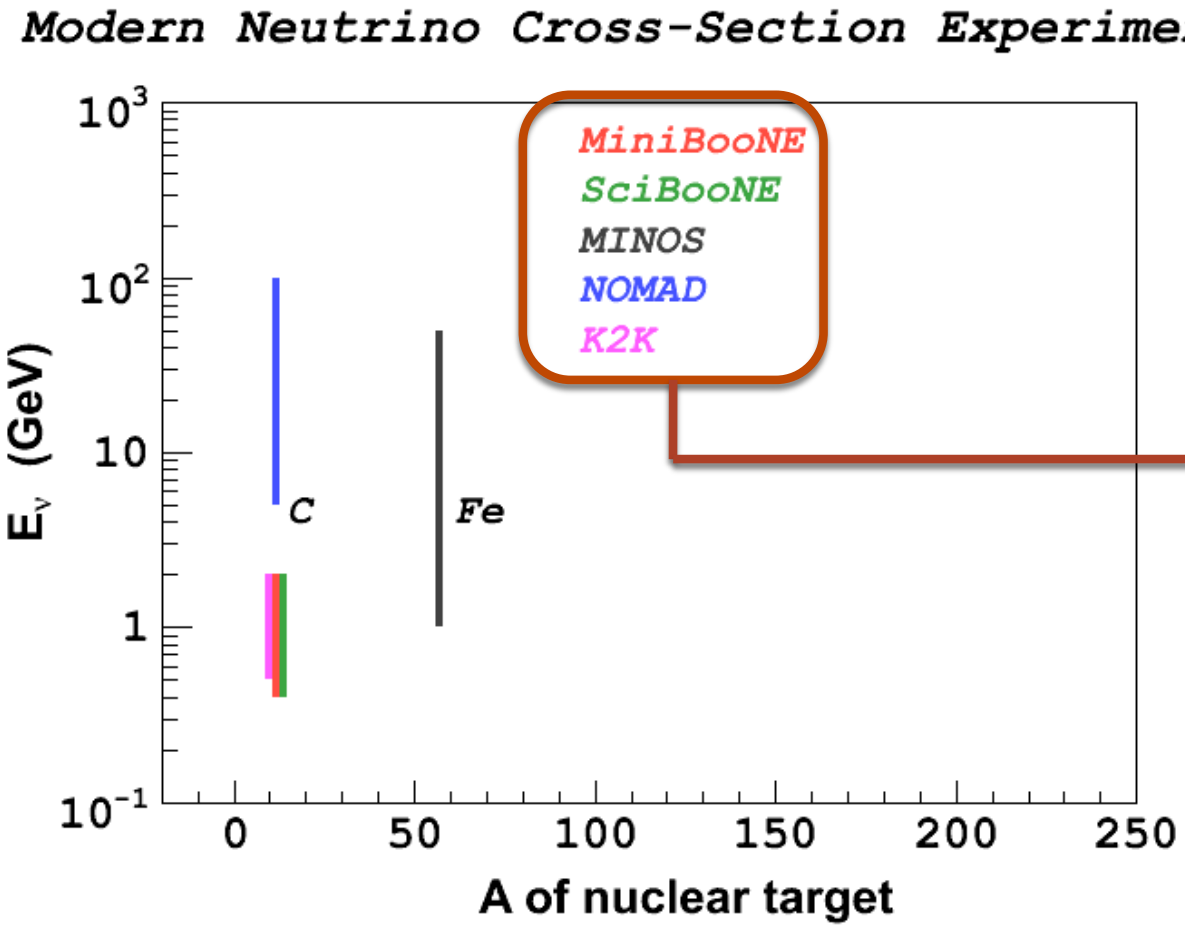
- High statistics CCQE samples show discrepancies with present MC predictions
- We are just now beginning to make real comparisons for other channels between binned data and MC predictions
  - CC π^+/π^0 production
  - NC elastic and NC π^0 production
  - CC/NC coherent interactions off the nucleus as 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
- MINERνA 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

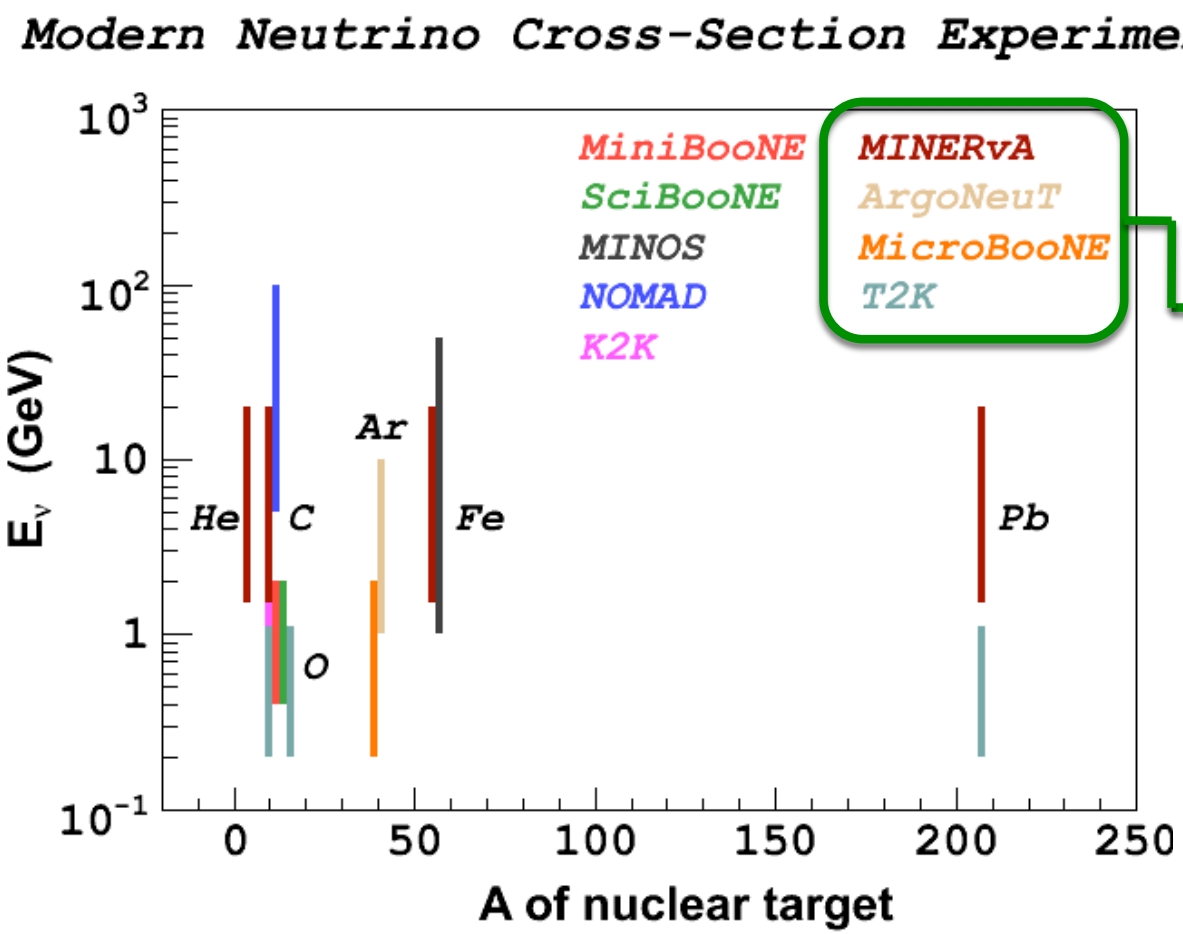
Energies and Targets



of the cross-section experiments

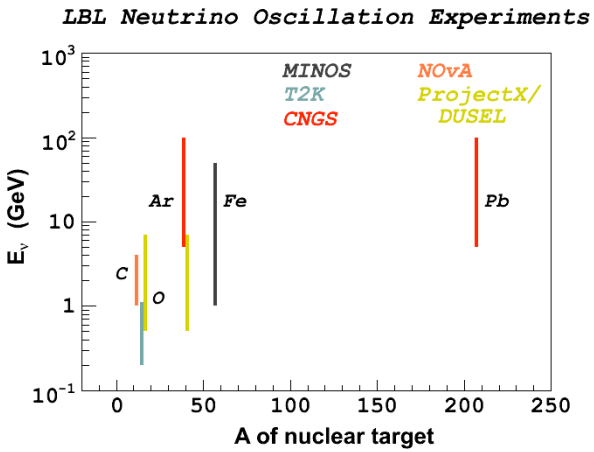
experiments with recent results and/or currently analyzing and publishing new cross-section data

Energies and Targets



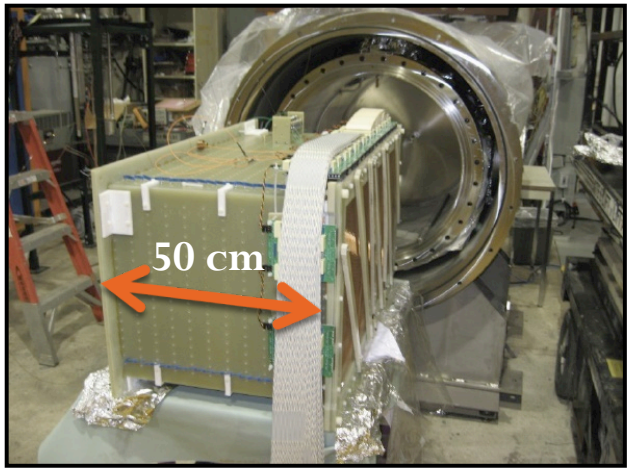
of the cross-section experiments

near future neutrino cross-section experiments

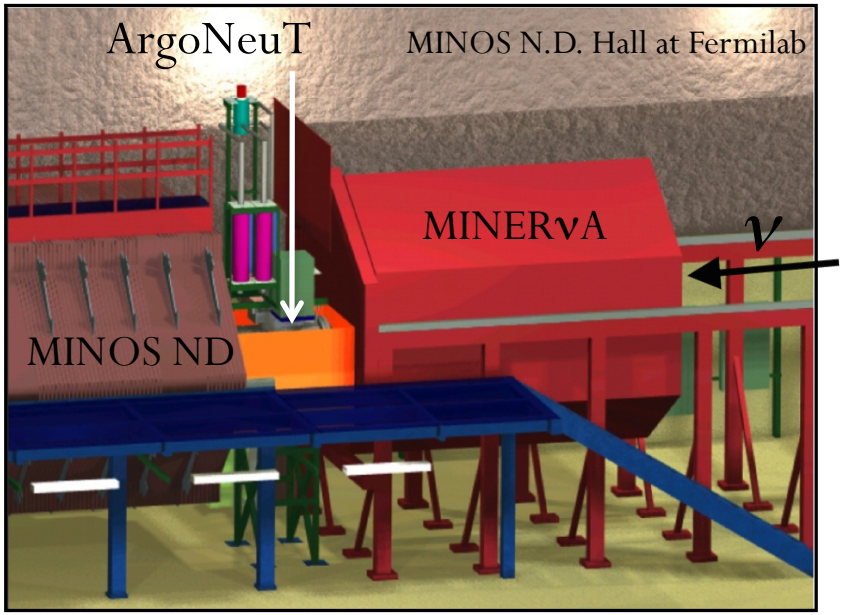


Liquid Argon

- ArgoNeuT
  - First Liquid Argon TPC to go in 'low-energy' neutrino beam, E_{peak} ~ 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

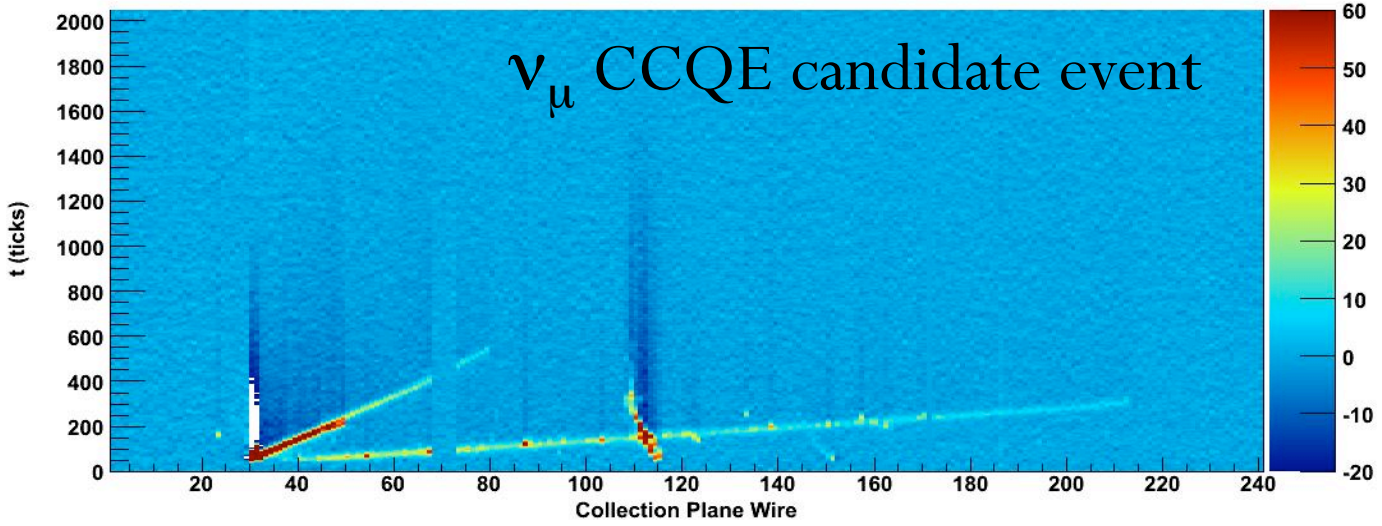


- LAr TPCs desirable for their 'bubble-chamber quality' events, e/γ ID, and low-energy threshold
- ArgoNeuT 170 L (0.3 t argon) Liquid Argon TPC
- Recorded neutrino data in the NuMI beam at Fermilab this spring

Liquid Argon

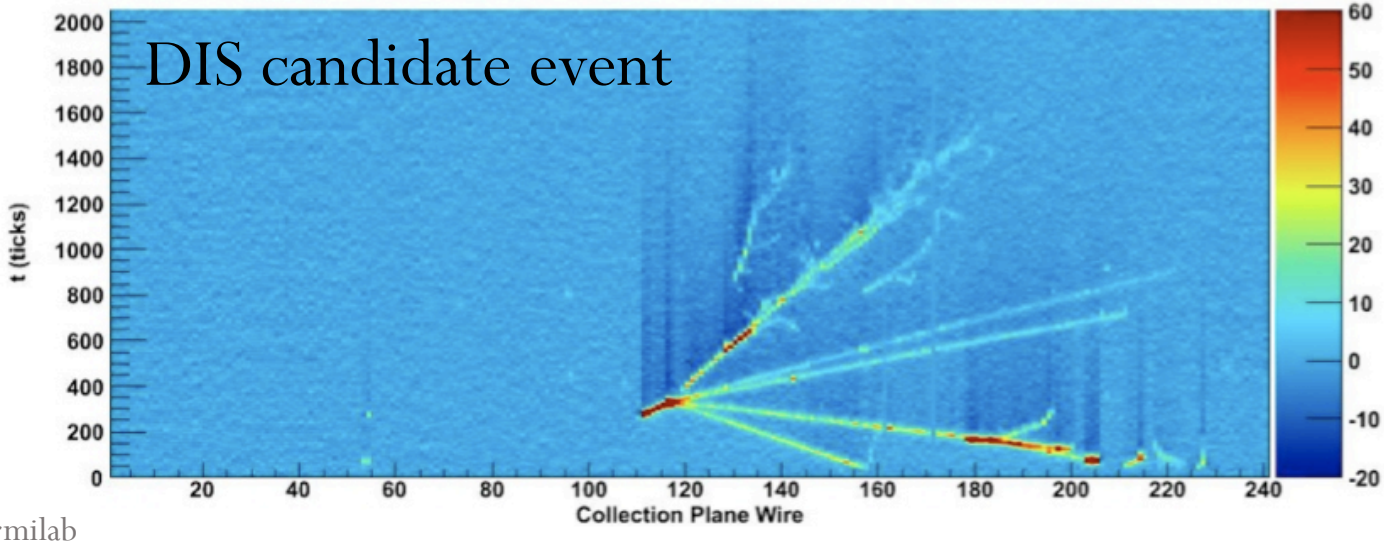
NuMI

Beam



NuMI

Beam

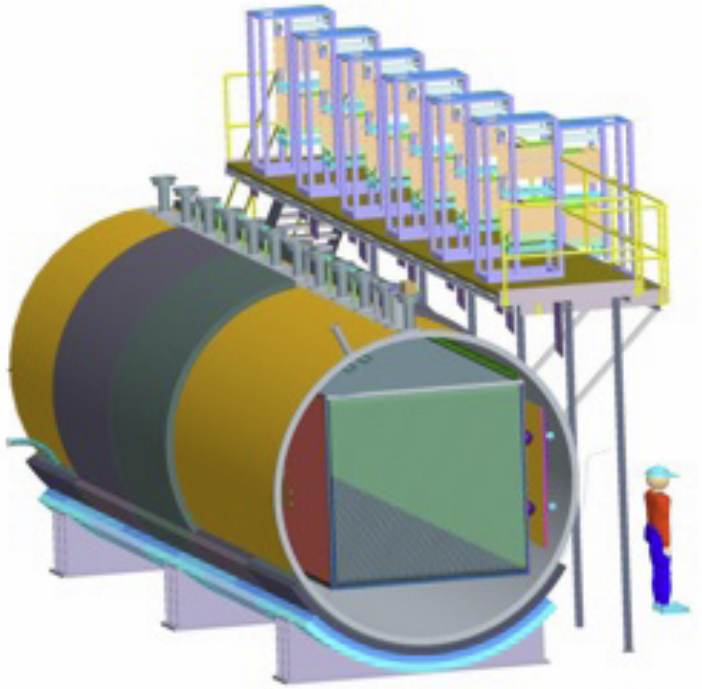


Liquid Argon

- 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^o	8k	3k
ν_e CCQE	0.4k	1.2k
POT	6×10^{20}	8×10^{20}

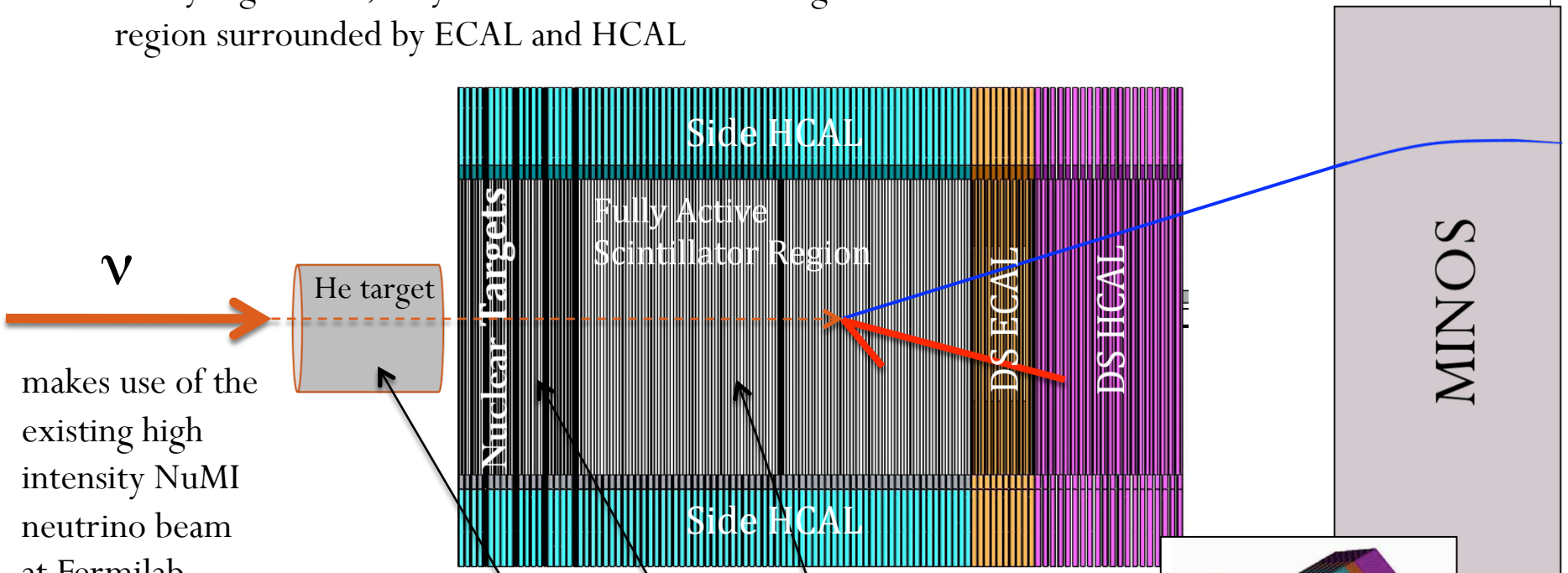
Expected Event Rates for MicroBooNE.



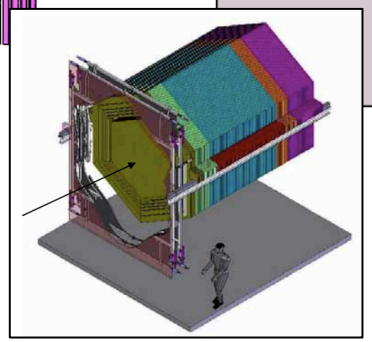
MINERνA

- MINERνA is a dedicated **neutrino-nucleus cross-section** experiment

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

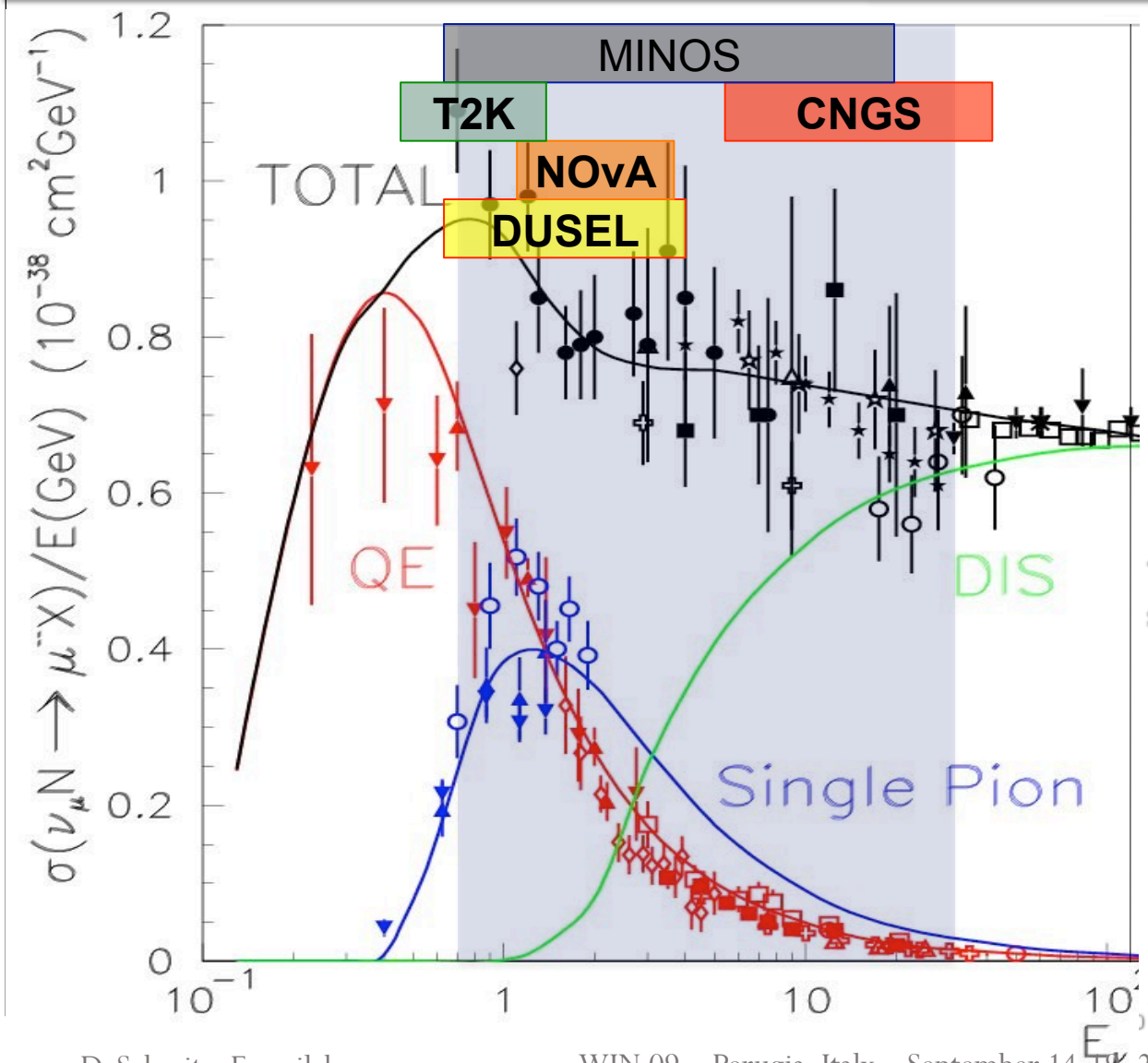


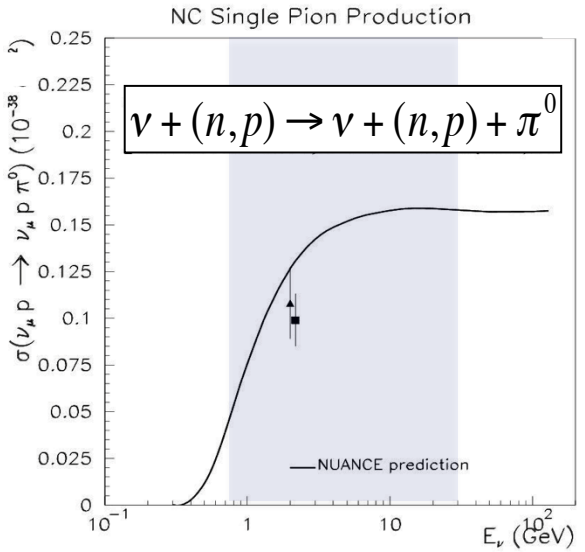
makes use of the existing high intensity NuMI neutrino beam at Fermilab

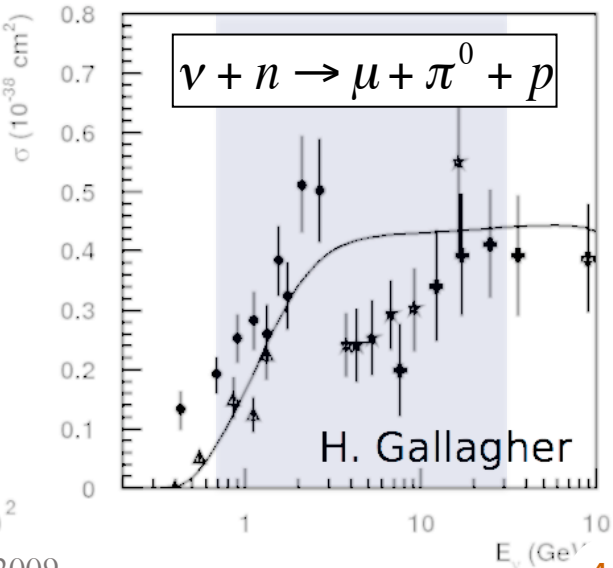


range of nuclear targets **(He, C, Fe, Pb, CH)** for study of **nuclear effects** in neutrino interactions

MINERνA Energy Range



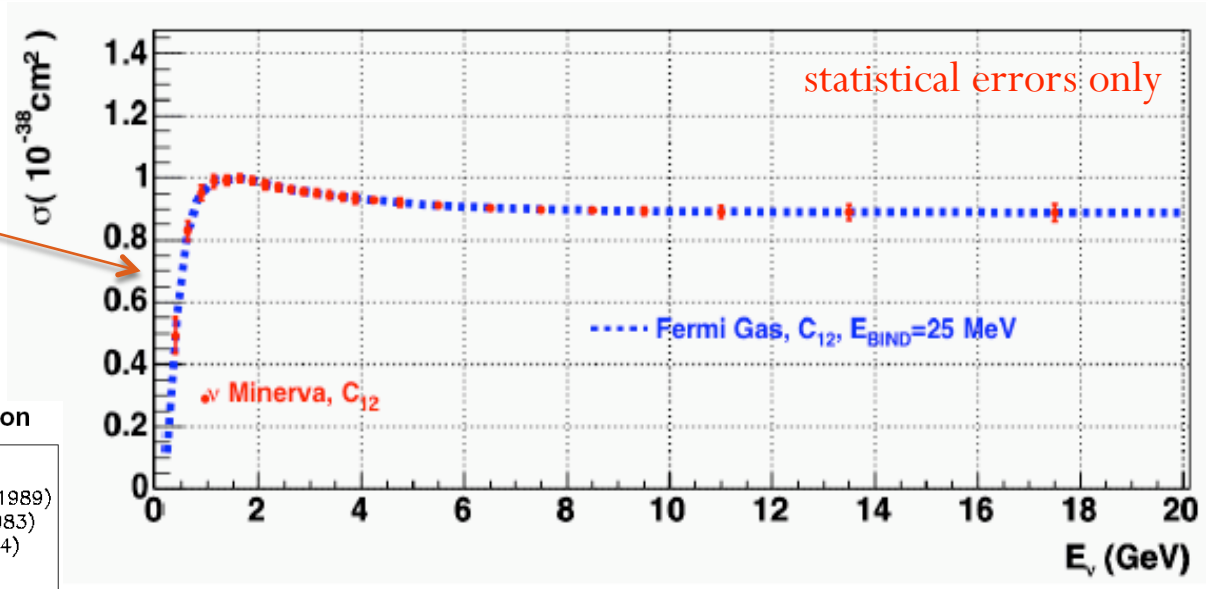


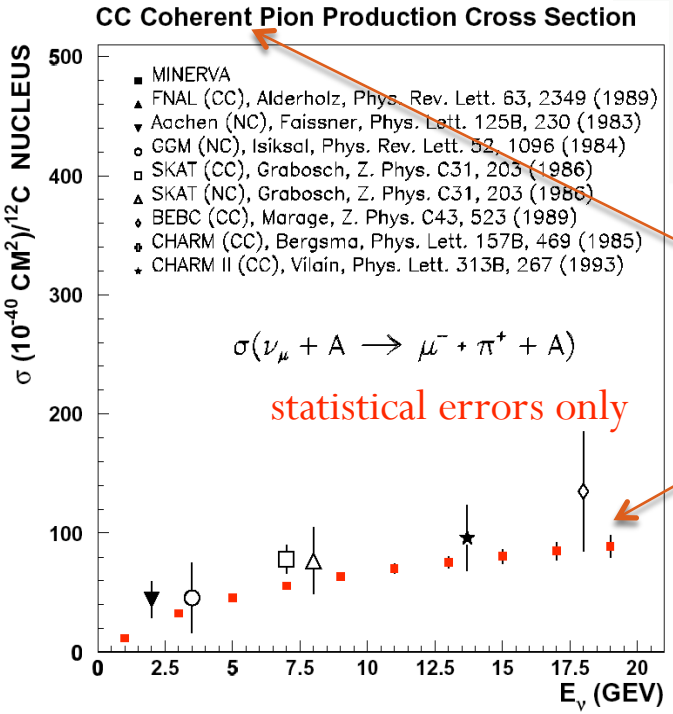


MINERνA Physics

- Some examples:

Expected CCQE results including efficiency estimates



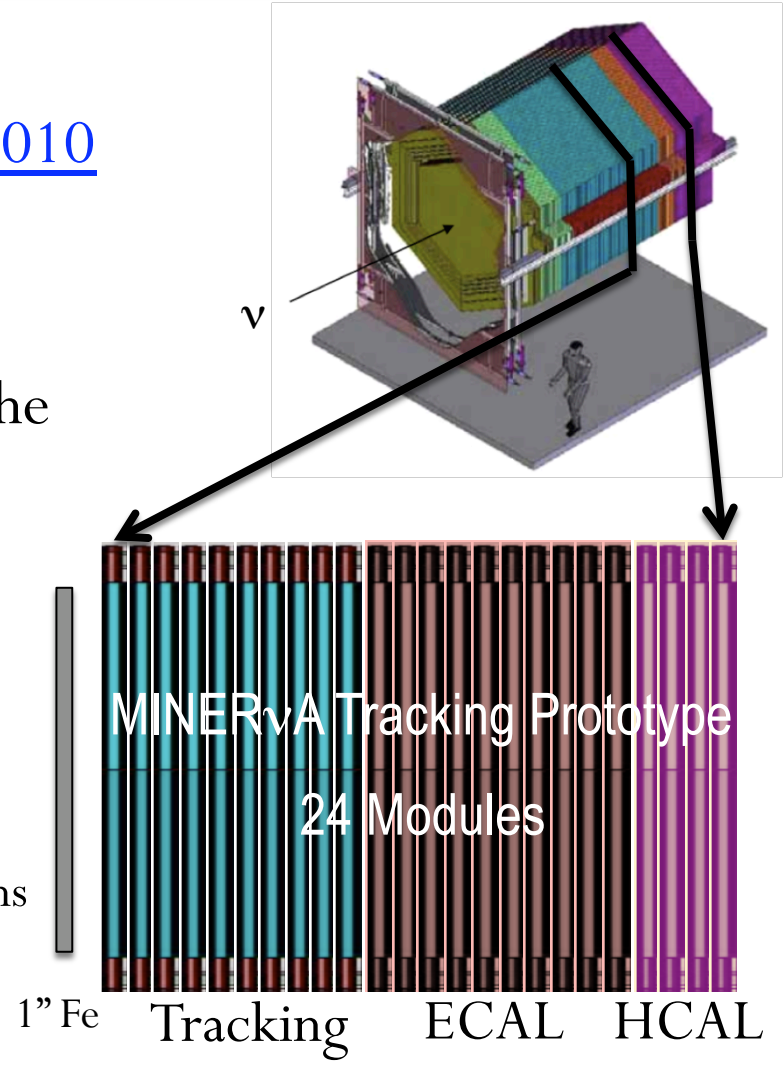


Coherent pion production occurs off the nucleus as a whole, leaving it in the ground state. Low rate.

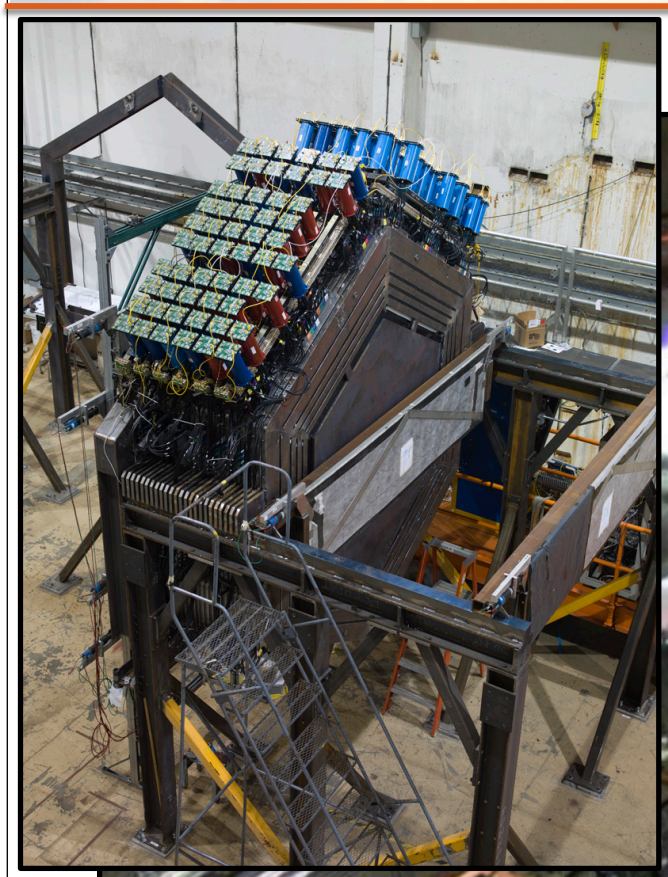
Note, MINERνA's nuclear targets allow the first measurement of the A-dependence of σ_{coh} across a wide A range

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



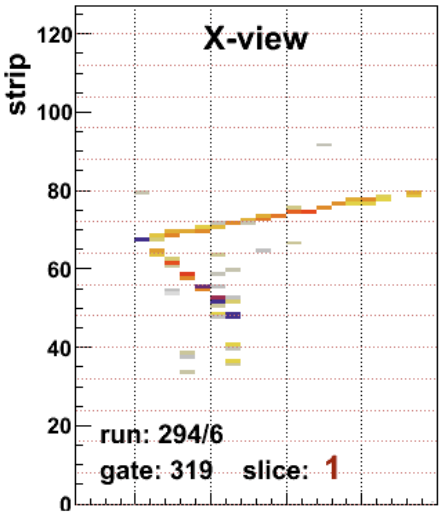
MINERνA Tracking Prototype



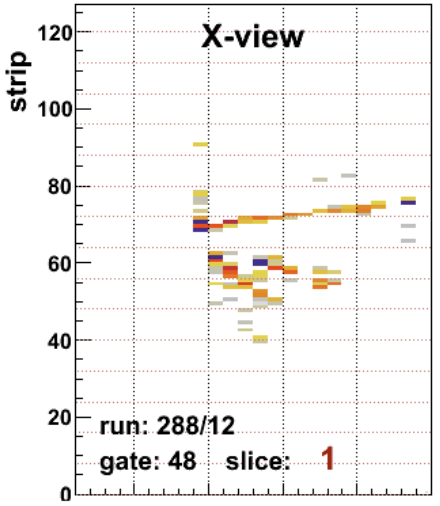
April – June, 2009

MINERνA Tracking Prototype

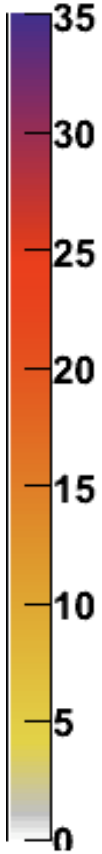
ν_μ CCQE candidate event



ν_μ CC π^0 candidate event



p.e. scale

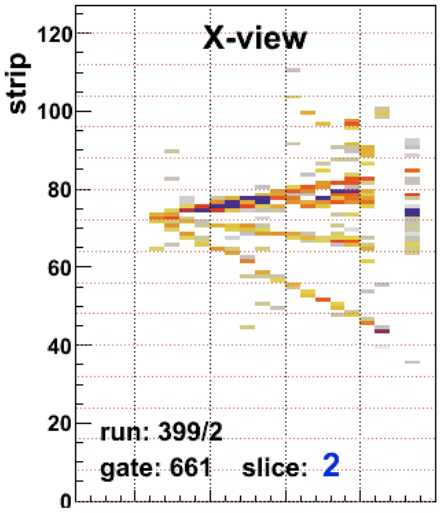


MINOS

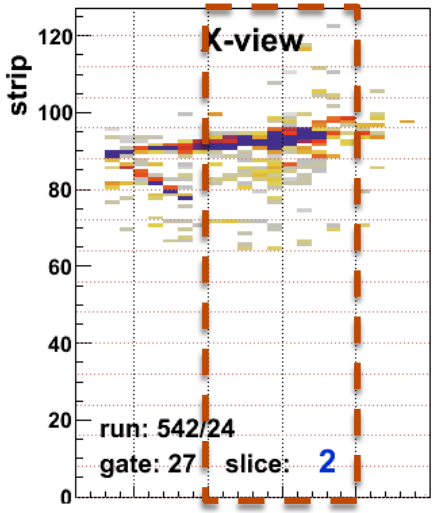
NuMI

Beam

Deep Inelastice candidate event

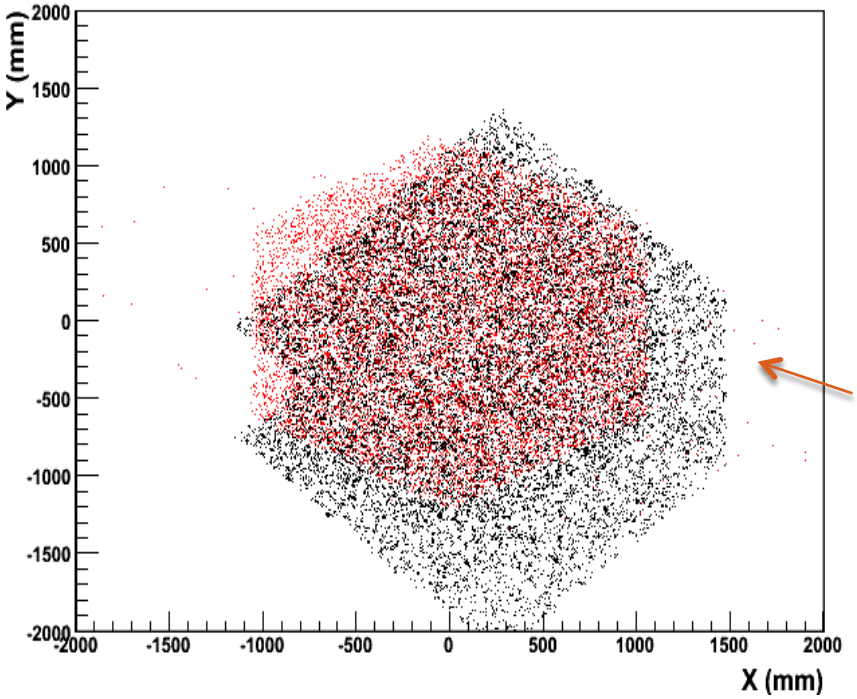


ν_e CCQE candidate event



ECAL

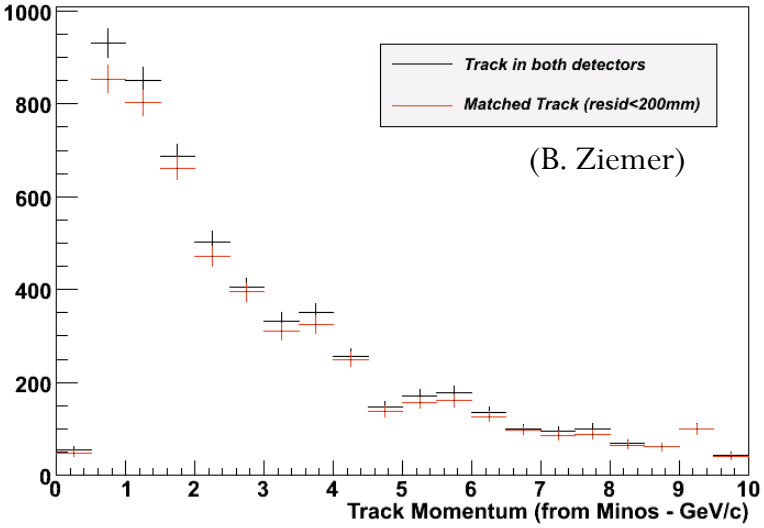
MINOS Works, too...



A unique kind of collaboration

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

All tracks in MINERνA (red) and MINOS (black) in MINERνA coordinate system



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

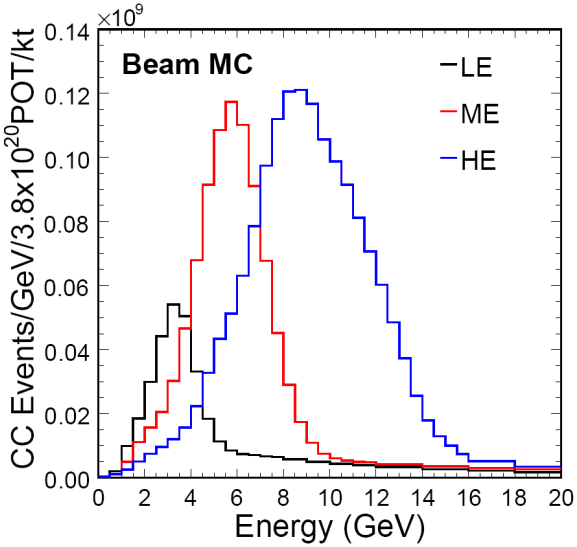
approximate fraction of those which are picked up by MINOS — 92% (for QE)

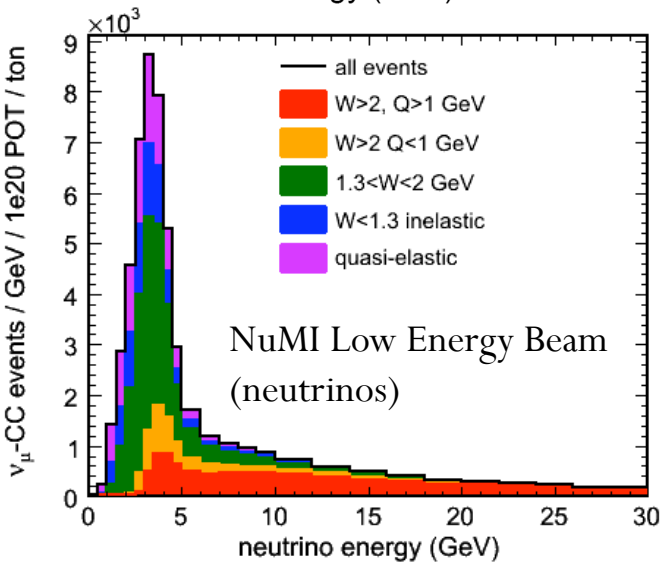
MINOS

MINERνA Physics Data

- Current Run Plan, beginning in early 2010
  - 4e20 POT low energy beam
  - 12e20 POT medium energy beam in NOνA 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, MINERνA, 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 '0 9

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.

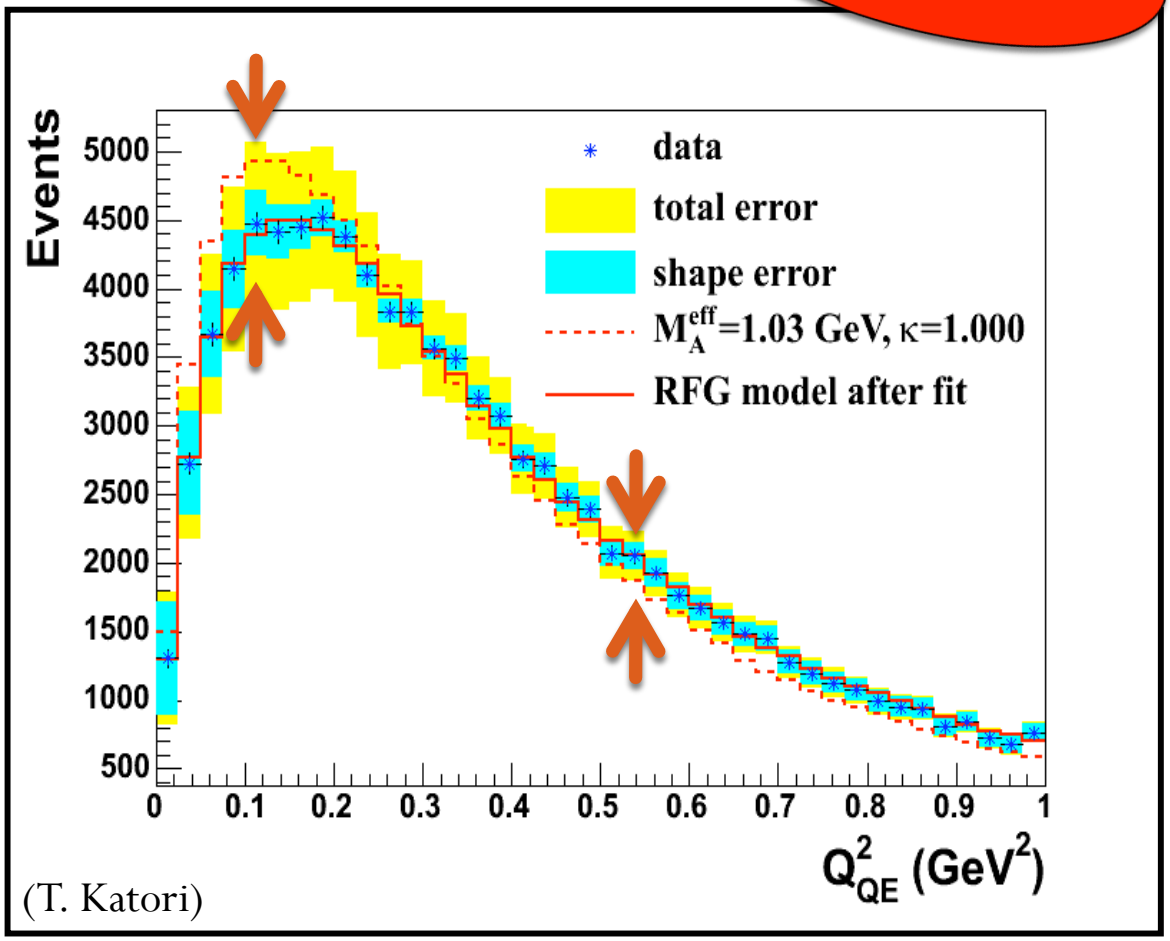
The Interactions (CCQE)

- Charged-Current Quasi-Elastic Scattering

MiniBooNE

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

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



(T. Katori)

The Interactions (CCQE)

SciBooNE

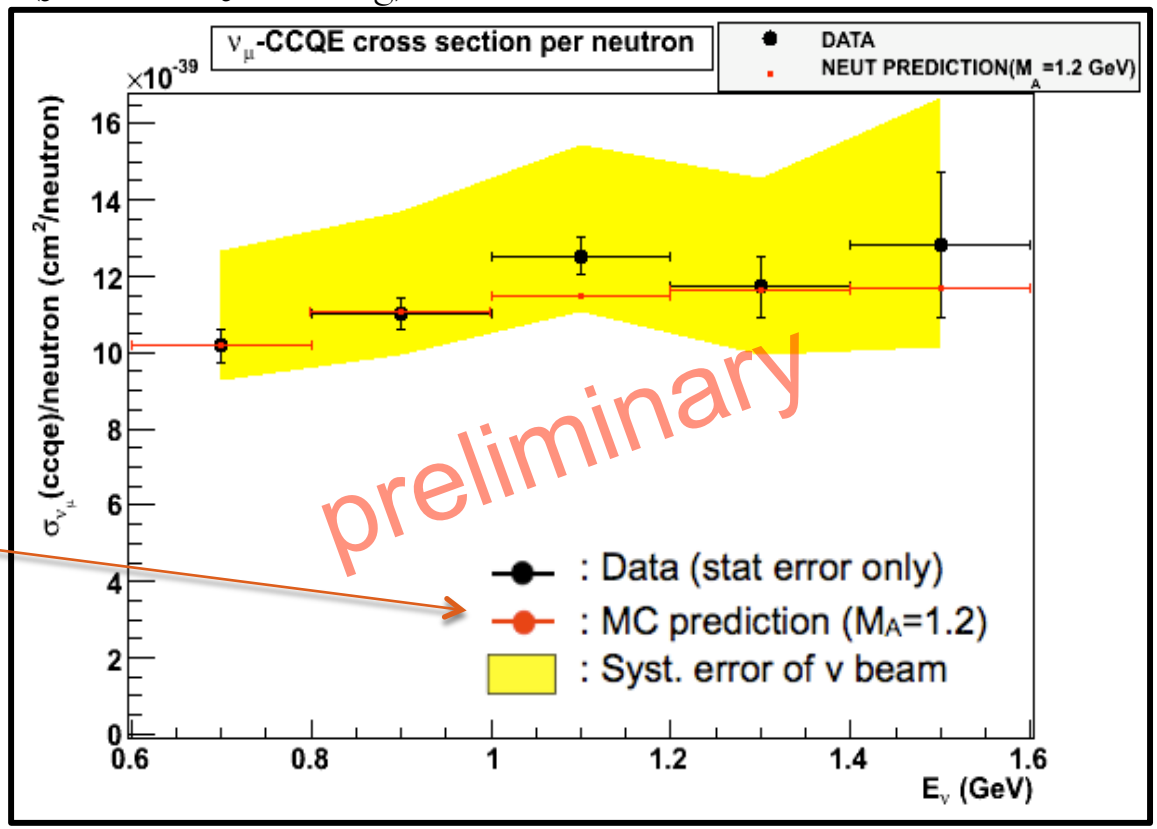
- Charged-Current Quasi-Elastic Scattering

• 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)

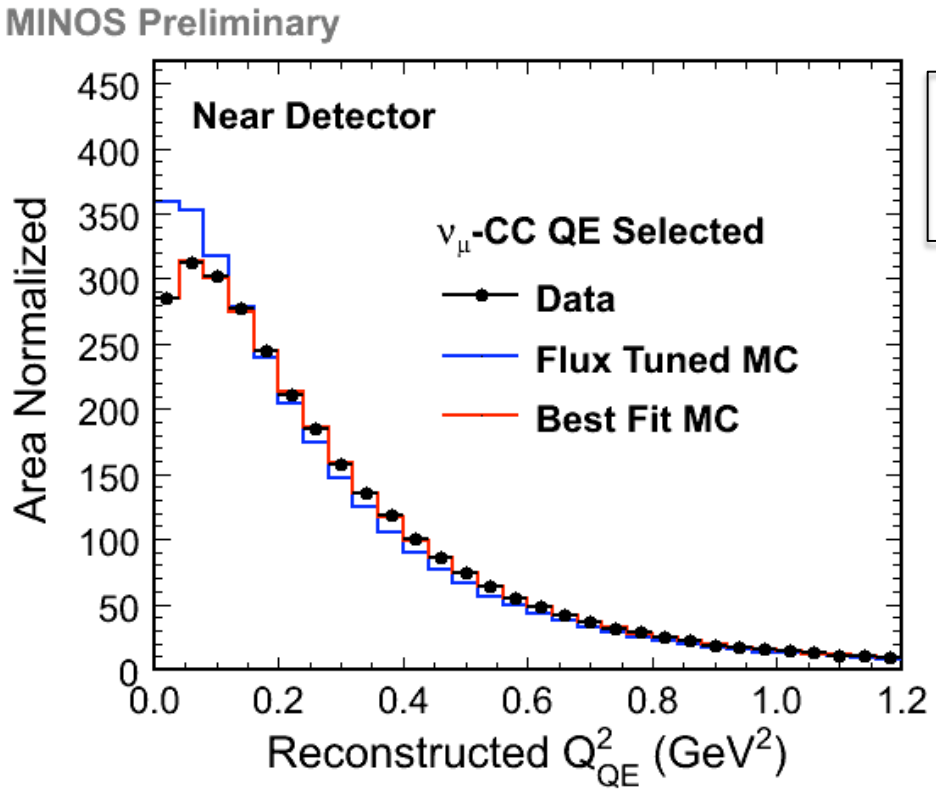
(J. Alcaraz, J. Walding)



The Interactions (CCQE)

MINOS

- Charged-Current Quasi-Elastic Scattering



MINOS Preliminary

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

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

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

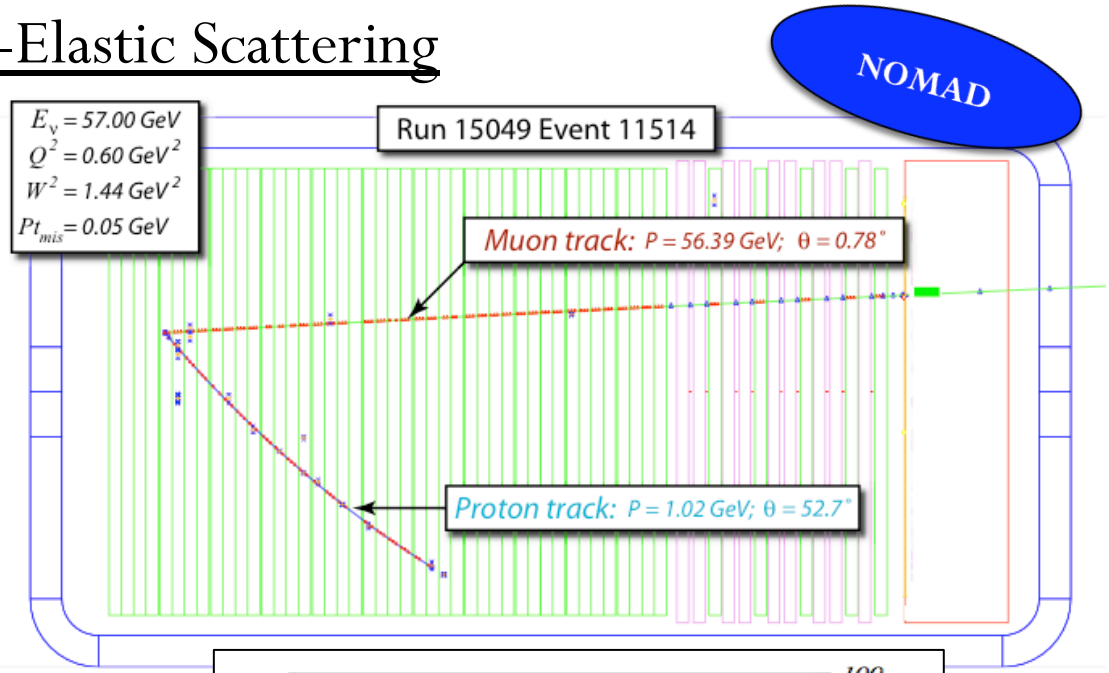
- no absolute cross-section values extracted yet – to come

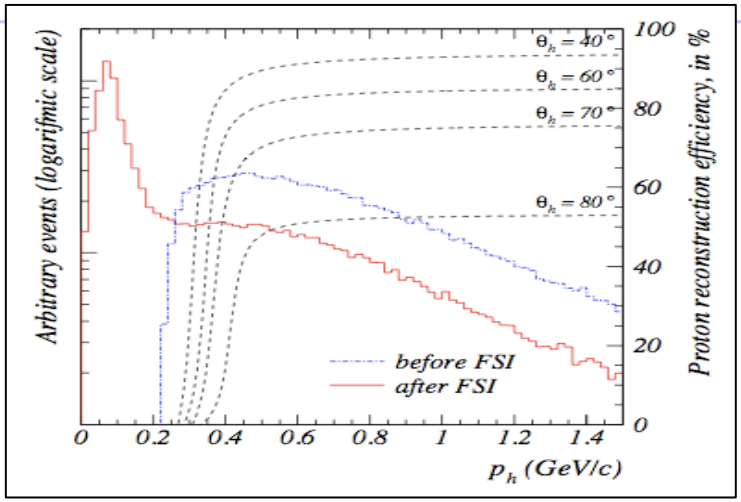
The Interactions (CCQE)

- Charged-Current Quasi-Elastic Scattering

• 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

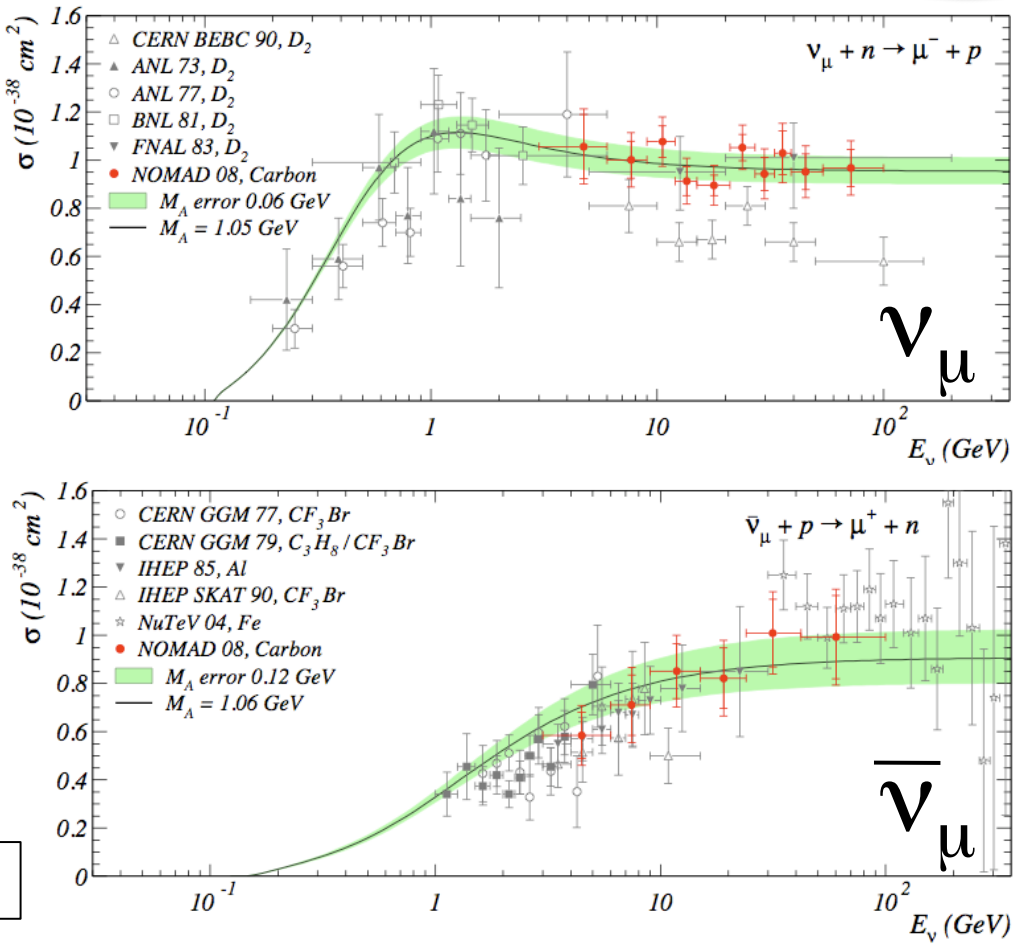
The Interactions (CCQE)

- Charged-Current Quasi-Elastic Scattering

NOMAD

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

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



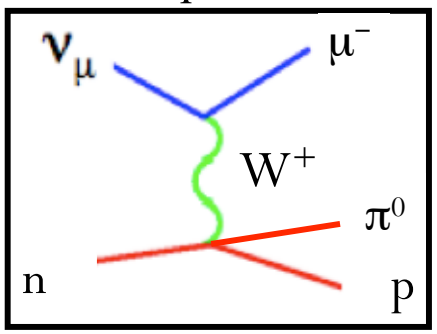
arXiv:0812.4543v3

The Interactions (CC π^0)

MiniBooNE

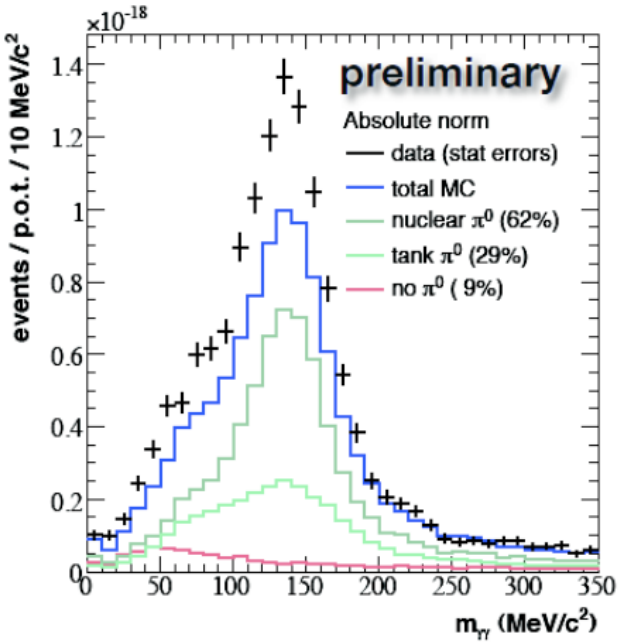
- Single Pion Production

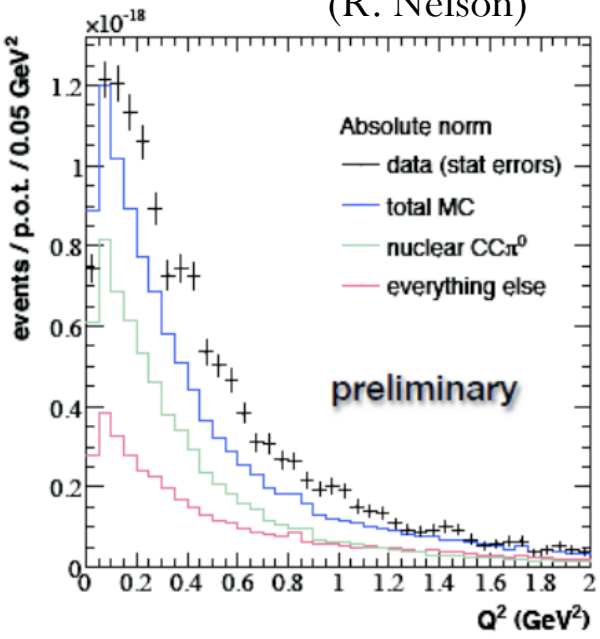
CC π^0 production



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

(R. Nelson)

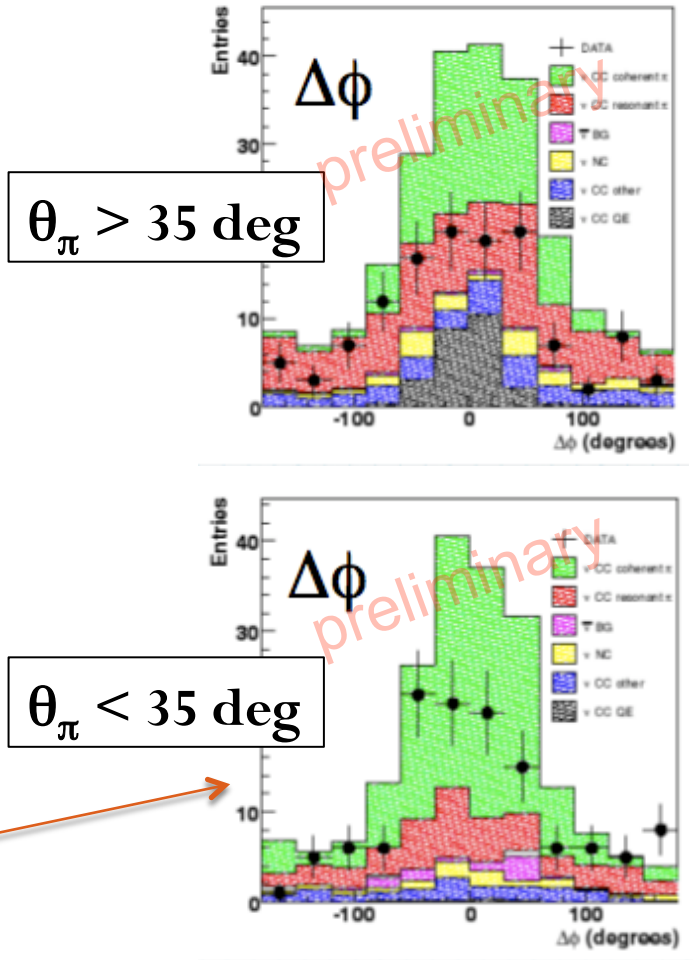




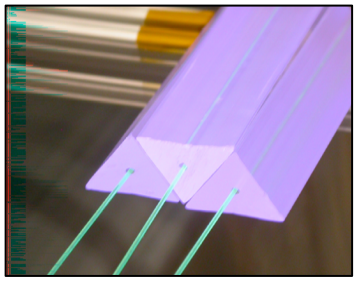
The Interactions (coherent)

- 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

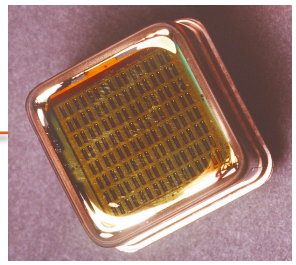


MINERνA Design

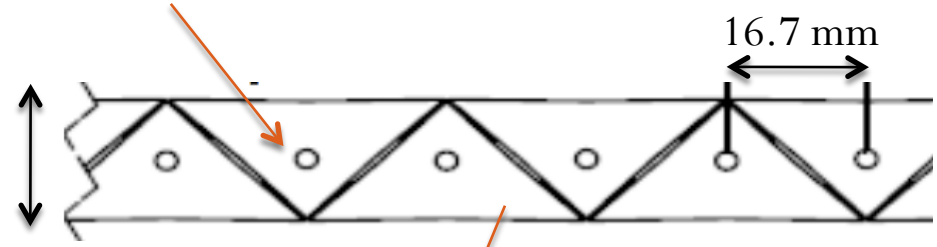


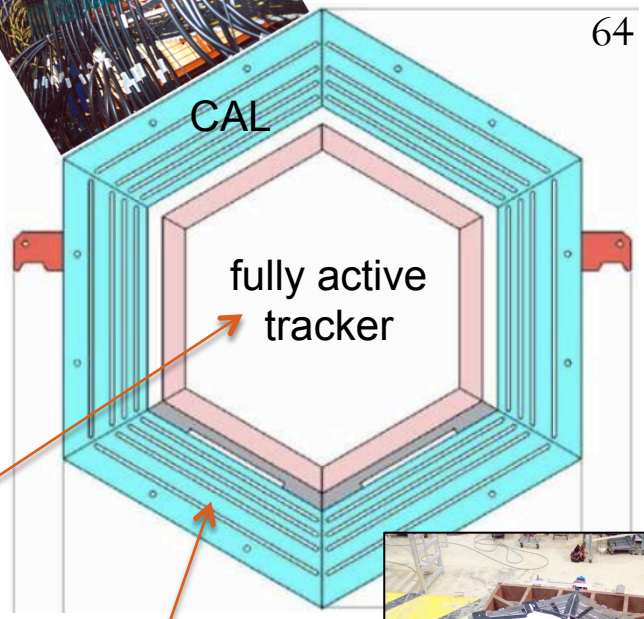
extruded plastic scintillator
+ wavelength shifting fibers

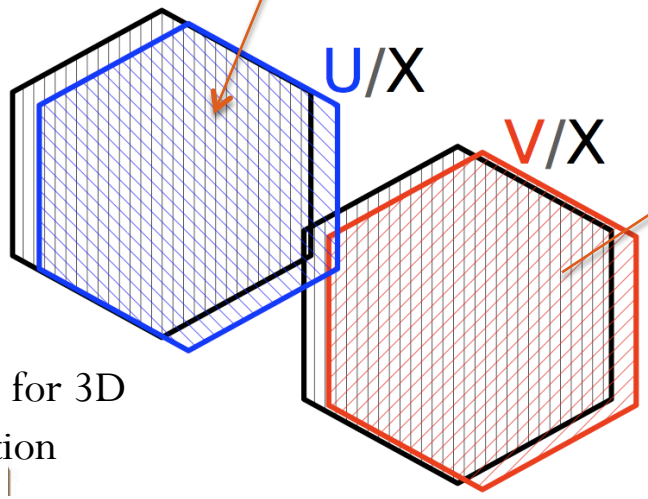
triangular geometry allows
charge sharing for better pos res.



64 anode
PMTs

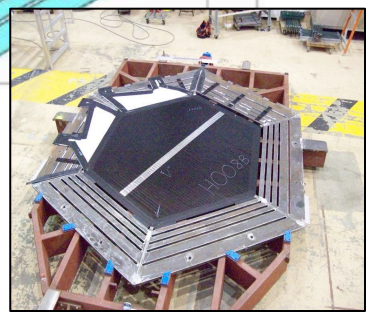






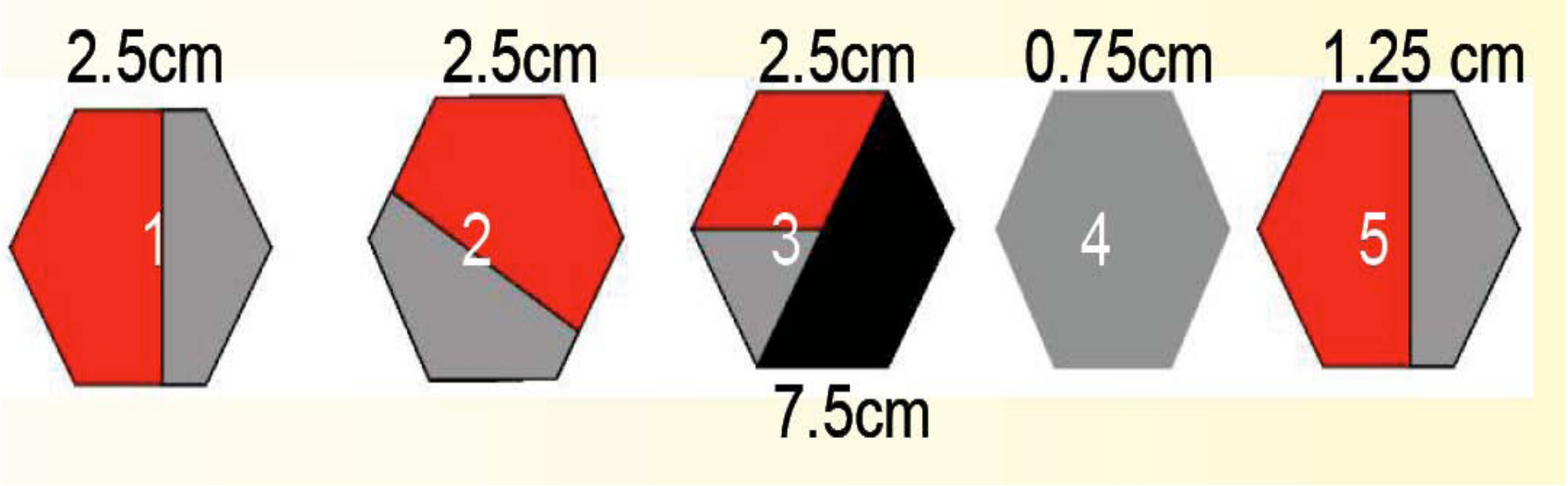
three views for 3D
reconstruction

iron outer detector
instumented for EM
calorimetry



MINERνA Nuclear Targets

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



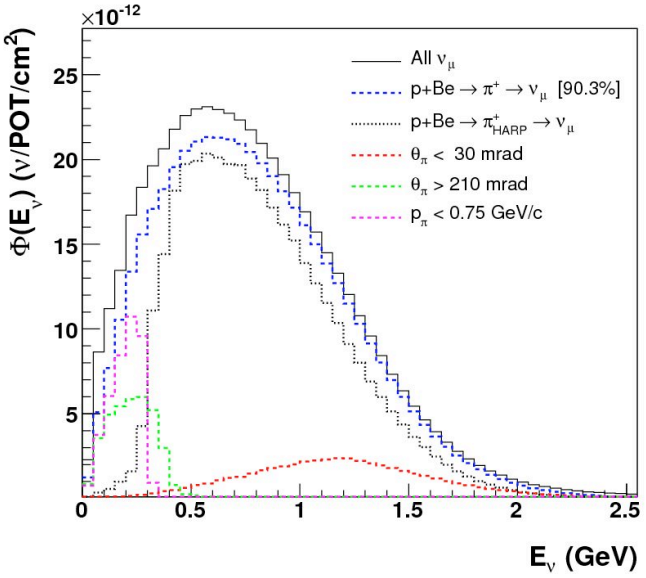
- First two targets: High statistics, compare lead and iron
- Third target: Compare lead, iron, and carbon with same detector geometry
- Last targets: Thin for low energy particle emission studies, high photon detection
- ^{4}He cryogenic target in front of detector

MINERνA Water Target

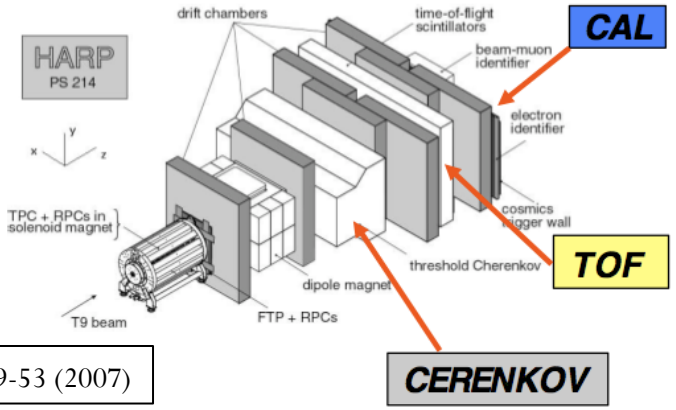
- People often ask, "Isn't water a pretty important nuclear target in neutrino physics?"
- And MINERνA has heard your calls…
- have been in contact with group at TRIUMP who built water "bags" for T2K
- working also with Fermilab engineers for ability to install this design and for a possible new design
- decision to be made very soon

HARP & the BNB Flux

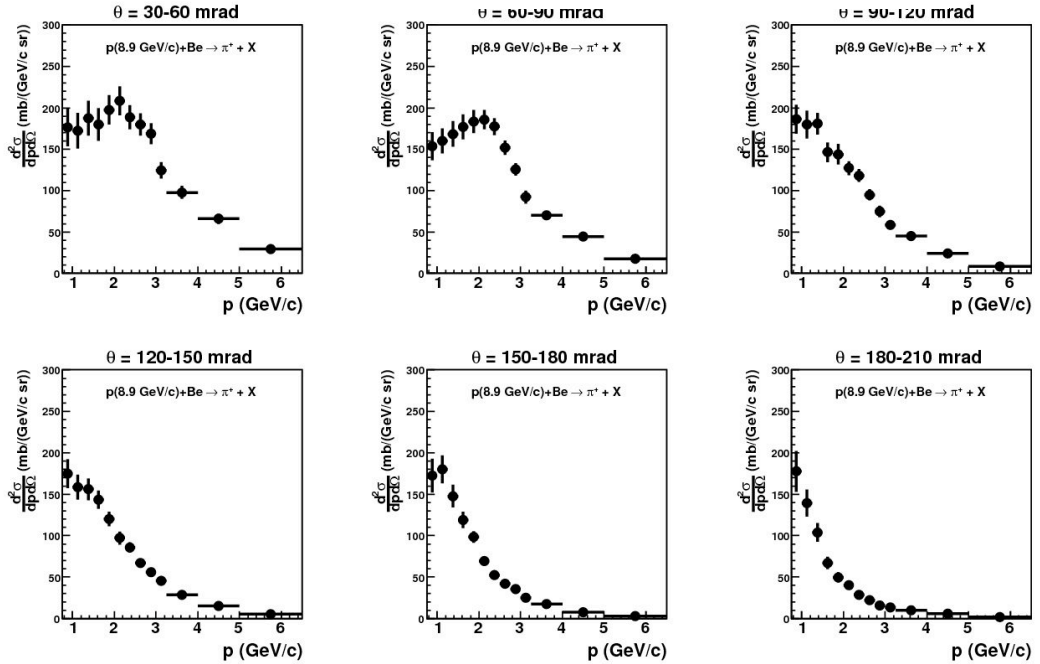
- MiniBooNE and SciBooNE both in Booster Neutrino Beam at Fermilab
  $E_\nu \sim 0.2 - 1.5$ GeV



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

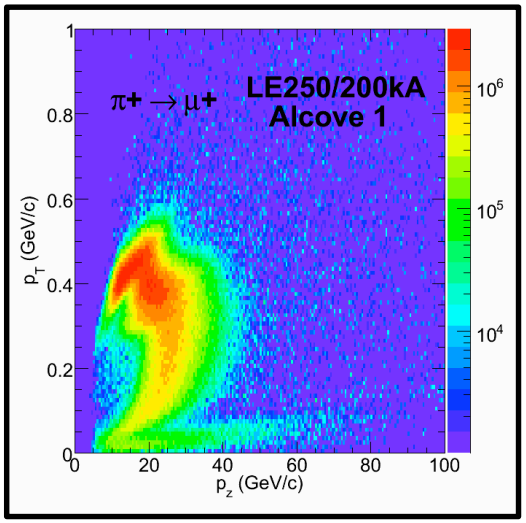


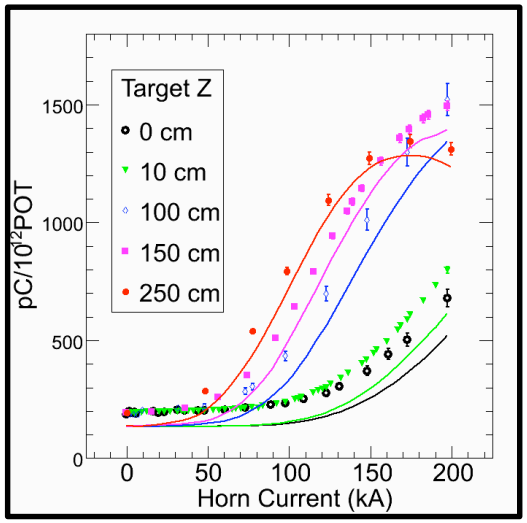
Euro. Phys. J C 52:29-53 (2007)

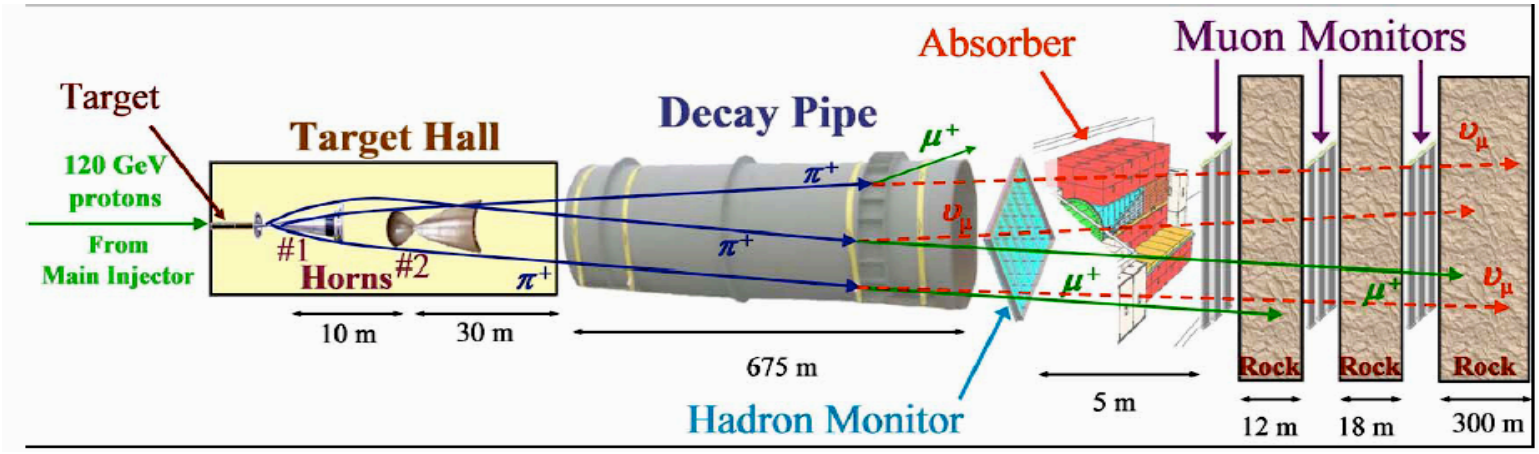


MINERνA & the NuMI Flux

- Goal to reach ~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







MINERνA & the NuMI Flux

- Goal to reach ~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