Prospects and Progress of the Charged-Current Quasi-Elastic(-Like) Cross Section Measurements at MINERvA

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On behalf of the MINERvA Collaboration

9th International Workshop on Neutrino-Nucleus Interactions in the Few-GeV Region: NuInt14

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Outline

just going to jump right in...

Analyses being presented :

- Neutrino Charged-Current Quasi-Elastic-Like (CCQE-Like)
  $\rightarrow$ protons, protons, protons
- Double Differential Neutrino Charged-Current Quasi-Elastic
  $\rightarrow$ muons, muons, muons

Neutrino Charged-Current Quasi-Elastic-Like Analysis

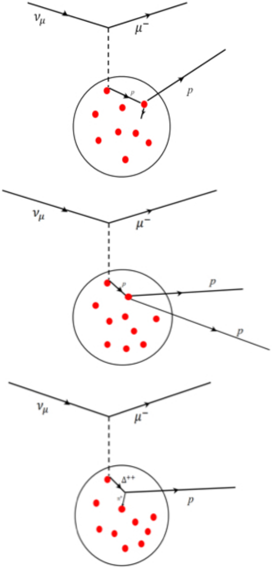
Quasi-Elastic Scattering

By using both muon and hadron kinematic variables, we have more information available in an effort to decouple nuclear effects from Final State Interactions (FSI)

$\rightarrow$ Model sensitivities differ given various observables, which can strongly affect the reconstructed neutrino energy

Defining Quasi-Elastic-Like

- (top) FSI alter the kinematic distributions of the recoil nucleon
- (middle) FSI can produce many nucleons in the final state
- (bottom) Non-QE scattering processes that look QE-like



Defining Quasi-Elastic-Like

how it differs from the quasi-elastic definition

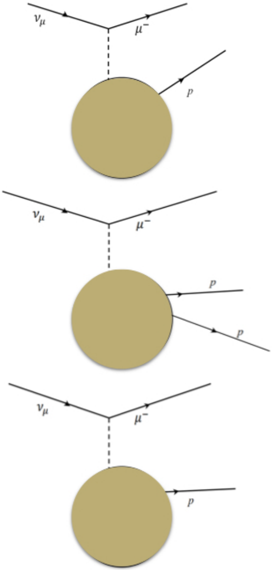
Want to remove dependence on neutrino scattering modeling

$\rightarrow$ just focus on what comes out

Signal definition :

- one negatively charged muon
- at least one proton with momentum greater than 450 MeV/c
  (due to tracking threshold)
- no pions

Selection criteria is as follows...

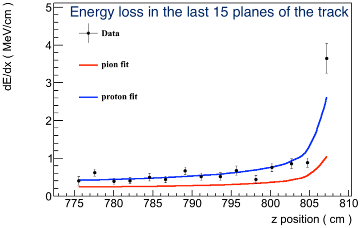


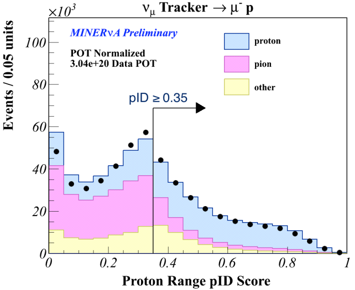
Proton Track Identification

distinguishing a proton from a pion

$\rightarrow$ Require all hadron tracks to look like range out protons

- Fit each hadron track energy loss (dE/dx) profile to standard proton and pion energy loss fit templates
- Use χ^2/d.o.f. for both fits to give a particle identification (pID) score and particle momentum
- Require pID score ≥ 0.35

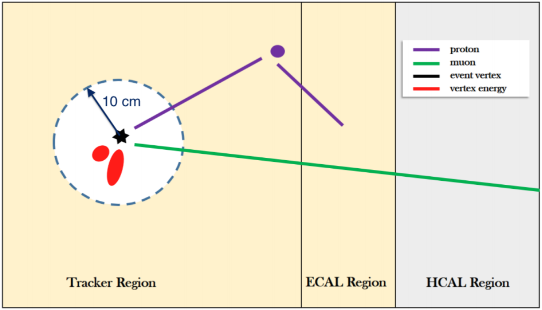




Remove Unattached Energy

define a topological observable : unattached visible energy

- Large amounts of extra energy, not associated with the muon or proton, usually comes from untracked particles



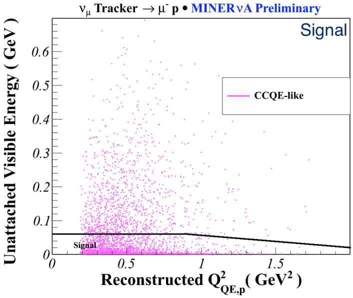
- Plot this versus the 4-momentum transfer QE scattering from a nucleon at rest, using proton kinematics ($Q^2_{QE,p}$), and define a signal region

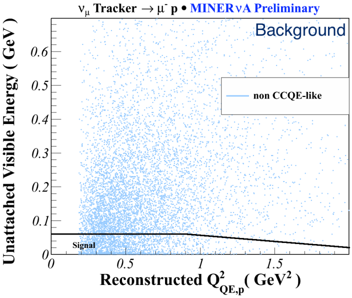
Remove Unattached Energy
define the signal region

- Use leading proton kinematics to reconstruct Q^2
- Use QE hypothesis
- Assume scattering from a free neutron at rest

$$Q^2_{QE,p} = (M')^2 - M_p^2 + 2M'(T_p + M_p - M')$$

where $M' = M_n + E_{binding}$



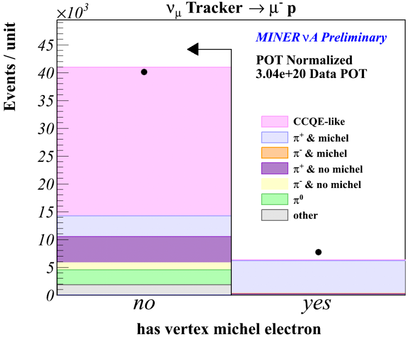


Michel Electron Veto

removes events with soft pions (below tracking threshold)

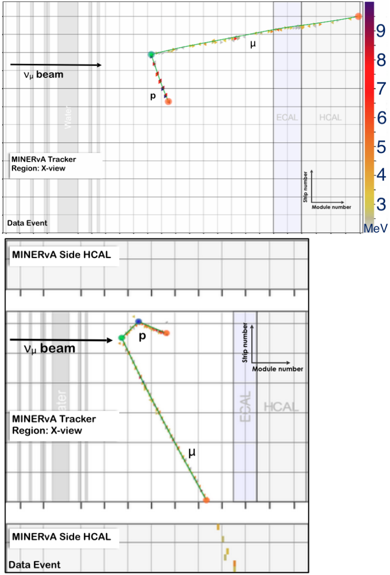
$$
\begin{array}{lll}
\pi^- & \rightarrow & \mu^- + \nu_\mu \\
\mu^- & \rightarrow & e^- \bar{\nu}_e \nu_\mu
\end{array}
\qquad
\begin{array}{lll}
\pi^+ & \rightarrow & \mu^+ + \bar{\nu}_\mu \\
\mu^+ & \rightarrow & e^+ \nu_e \bar{\nu}_\mu
\end{array}
$$

- Veto events with a Michel electron found near the vertex or the track endpoint
- Removes low energy pions that stop and decay in the detector



Which Muons to Keep?

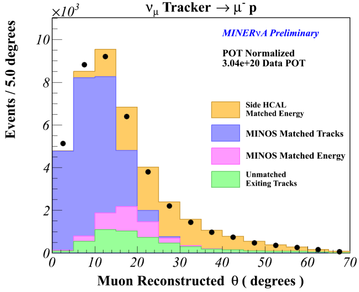
all of them!

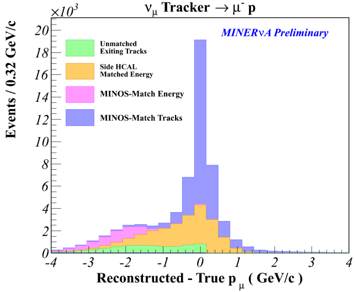


Look for muons that exit the tracker and are

- matched to a track in MINOS (52.7%)
- matched to hits in MINOS (7.9%)
- matched to hits in the side HCAL region (27.5%)
- NOT matched to MINOS or the side HCAL (11.8%)

Muon Acceptance
and consequences



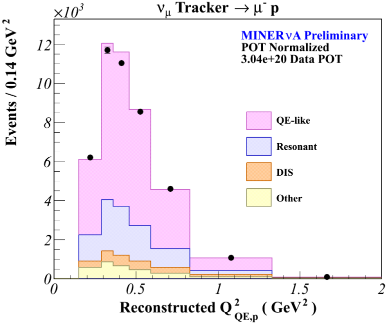


The θ_μ acceptance is increased, but due to poor energy reconstruction for non-matched tracks, we can't use muon kinematics to reconstruct event kinematics (i.e. Q^2_{QE})

$\Rightarrow$ Use the proton!!

CCQE-Like Candidates

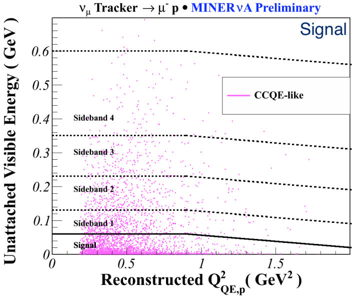
- Using the complete Low Energy (LE) neutrino dataset
- 40,102 candidate data events
    - 72.3% QE
    - 23.9% Resonant
    - 3.80% DIS (Deep Inelastic Scattering) + Other

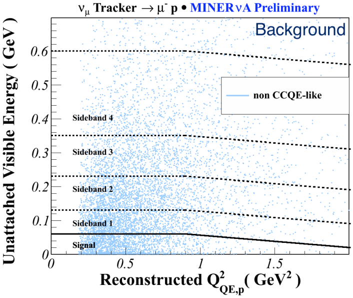


Background Subtraction

use data to tune the background - step 1

- Create 4 sidebands outside of signal region - separates the background into two components : Resonant (Δ^{++} produces a pion) and DIS+Others
- Use a multi-sideband procedure to obtain the "two component" background scales

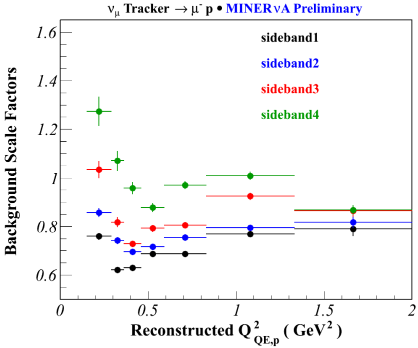




Background Subtraction

use data to tune the background - step 2

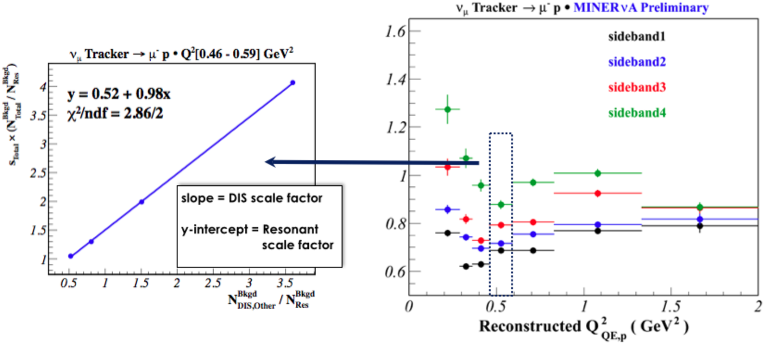
- Extract weights that force the data and simulation to match perfectly
- As you increment the sideband, further away from the signal region, note that
    - the fraction of signal events decreases
    - relative fraction of Resonant to DIS events decreases
    - agreement between data and simulation improves



Background Subtraction

use data to tune the background - step 3

- Fit each $Q^2_{QE,p}$ bin to a line
- Extract scale factors for the two background components simultaneously
    - we see the same linear progression in each $Q^2_{QE,p}$ bin

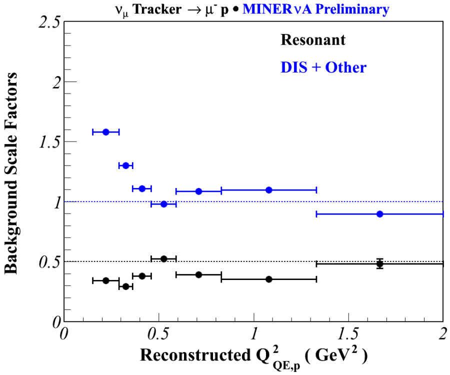


Courtesy of T. Walton

Background Subtraction

use data to tune the background

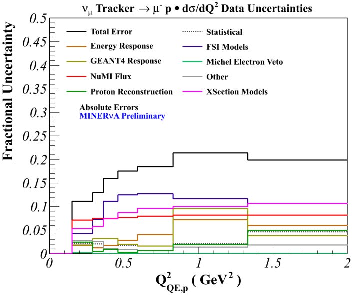
- Results show that GENIE overestimates resonant production
- Scale factors are a combination of the modeling of the neutrino primary interactions and the FSI

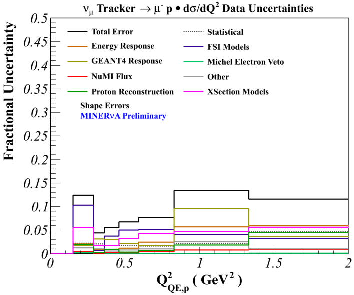


CCQE-Like Systematic Uncertainties

sources of uncertainty

- Estimate by varying systematic inputs within uncertainties and then rerun the analysis
- Look at shape of systematics to help reduce the impact of several uncertainties (i.e. NuMI Flux)





Leading systematics due to FSI Models, Cross Section Models, Geant4 Response, and Energy Response

CCQE-Like Differential Cross Section

in bins of $Q^2_{QE,p}$

not to "generator Q²"

$$Q^2_{QE} \rightarrow Q^2_{QE}$$

reco p kinematics — true p kinematics

Differential cross-section vs. 4-momentum transferred to nucleon

backgrounds constrained by data

$$\left(\frac{d\sigma}{dQ^2_{QE,p}}\right)_i = \frac{1}{\Phi T}\frac{1}{\Delta Q^2_{QE,p}}\frac{\Sigma_j U_{ij}\left(N_j^{data} - N_j^{bkg}\right)}{\epsilon_i}$$

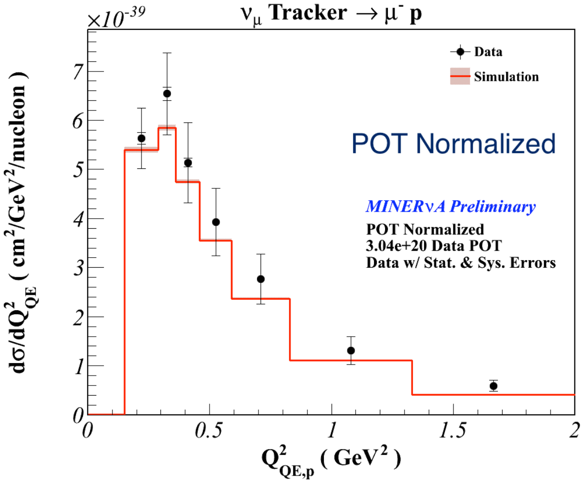
flux, targets

bin width

product of selection efficiency and acceptance

CCQE-Like Differential Cross Section

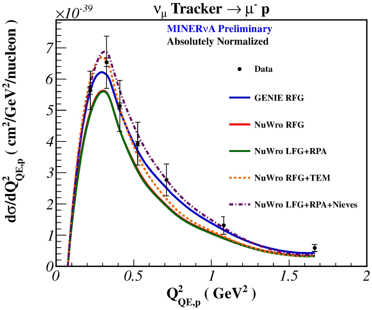
first EVER proton based CCQE-like cross section measurement!!

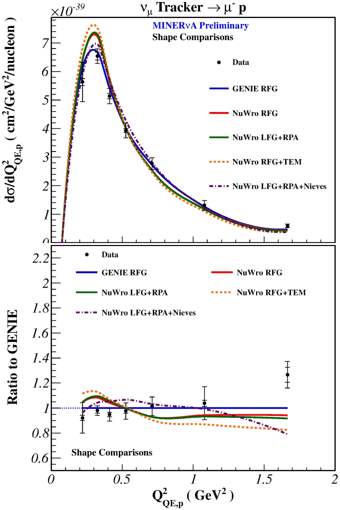


- Interpretating the results :
  - compare the total CCQE-like cross section to various models

Total CCQE Cross Section
consists of both QE and inelastic components

GENIE best describes the cross section measurement





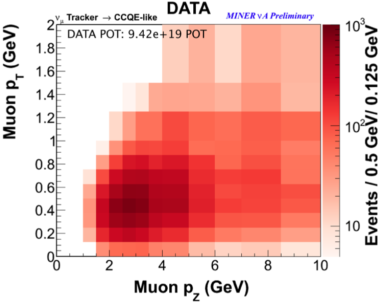
RFG = Relativistic Fermi Gas model
LFG = Local Fermi Gas model
GENIE: www.genie.org, NIM **A614**, 87 (2010)
NuWro: Acta Phys. Polon. **B40**, 2507 (2009)
TEM = "Transverse Enhancement Model",
A. Bodek, *et al.*, Eur. Phys. J. **C71** 1726 (2011)

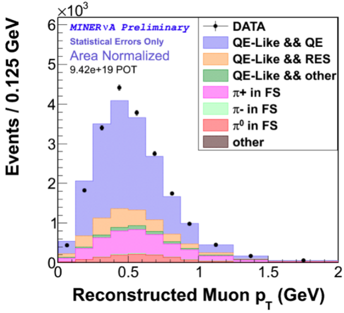
Double Differential Neutrino Charged-Current Quasi-Elastic Analysis

Double Differential ν CCQE Cross Section

using muon observables : p_T and p_z

- Complementary measurement to the published CCQE results
- Consider a QE-like topology to reduce model dependence and increase sample purity



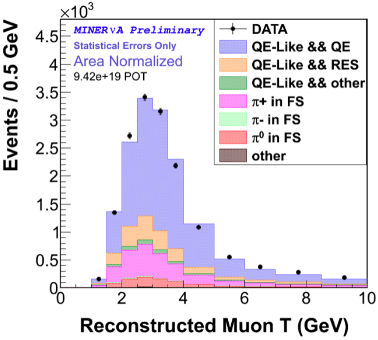


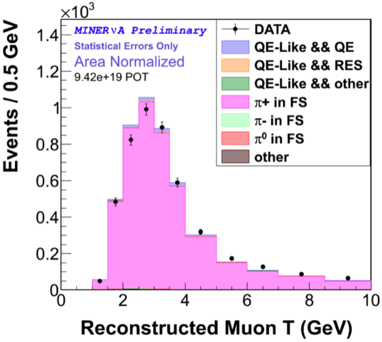
See good beam resolution in the parallel and perpendicular components of the muon momentum

Double Differential CCQE Cross Section

look at muon's kinetic energy : T

Not only use Michel electrons to remove pions near the vertex but also use a Michel background sample to constrain the charged pion background





Conclusion

what to look for next

- Currently putting a lot of effort into our CCQE analyses
  - in the $d\sigma/dQ^2_{QE,p}$ anaylsis, we have distributions with both proton+muon kinematics
    - how do we best use the comparison between muon and proton to constrain FSI effects?
    - your thoughts are welcome!
  - double differential $\bar{\nu}_\mu$ cross section measurement
  - cross section measurements using muon and proton observables in the nuclear targets region
  - use medium energy data to calculate the cross sections
- MINERvA continues to run during the NOvA-era medium energy beam
- Lots of exciting results to come!

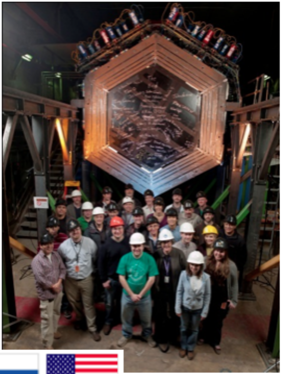
Thanks for listening!! Please also see the following NuInt talks being presented

- CCQE scattering cross sections and future analyses
  - see C. Patrick's talk and poster
- Charged current pion production cross section
  - see B. Eberly's talk
- Charged current coherent pion production cross section
  - see A. Mislivec's talk
- Inclusive cross section vs. various nuclei: He, C, O, Fe, Pb
  - see J. Mousseau's talk
- Strangeness production cross section
  - see C. Marshall's poster
- Importance of the Flux measurement
  - see D. Harris's talk

The Collaboration

$\sim$60 collaborators from nuclear and particle physics

University of California at Irvine
Centro Brasileiro de Pesquisas Físicas
University of Chicago
Fermilab
University of Florida
Université de Genève
Universidad de Guanajuato
Hampton University
Inst. Nucl. Reas. Moscow
Mass. College Liberal Arts
University of Minnesota at Duluth
Universidad Nacional de Ingeniería
Northwestern University
Otterbein University
Pontificia Universidad Catolica del Peru
University of Pittsburgh
University of Rochester
Rutgers, State University of New Jersey
Universidad Técnica Federico Santa María
Tufts University
William and Mary



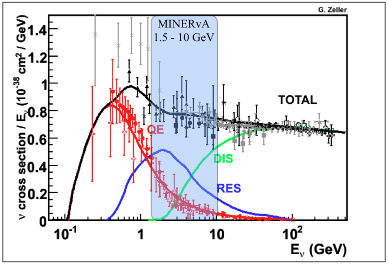
Backup Slides

Motivation

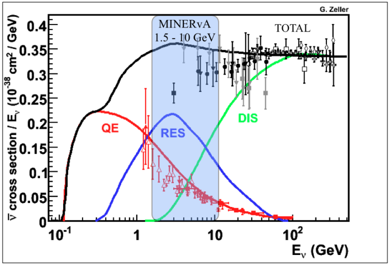
what are we trying to learn here?

- Main INjector ExpeRiment ν-A
  - measure the cross sections of neutrino-nucleus interactions
- Cross sections between 0.1-10 GeV not as well known, but important in the regime of oscillation experiments

Neutrinos



Anti-Neutrinos

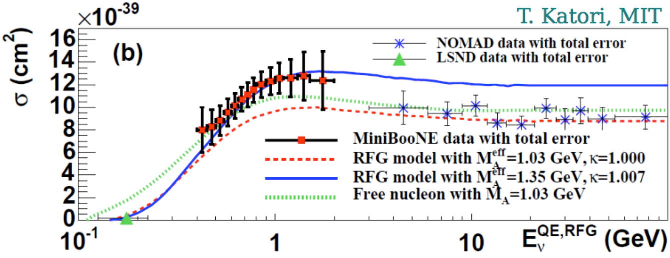


J.A. Formaggio and G.P. Zeller, Rev. Mod. Phys. 84, 1307-1341, 2012

Motivation

what are we trying to learn here?

- Do not understand the energy dependence in the CCQE cross section
  - MiniBooNE and SciBooNE disagree with the higher energy NOMAD data, MINERvA is in the energy range that can help resolve this discrepancy
  - Primary signal in the oscillation experiments



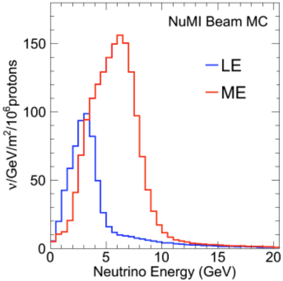
- Additionally, neutrinos make for a good weak-interaction probe of the nuclear structure

NuMI Beam

Neutrinos at the Main Injector

- 120 GeV proton beam from the Main Injector
- Average spill of 35x10^{12} Protons on Target (POT), with a beam power of 300-350 kW at $\sim$0.5 Hz
- Advantages - tunable beam
  - can change the energy of the beam by moving the target wrt the horns
  - neutrino or anti-neutrino beam mode depending on horn current

FLUKA: A. Ferrari, P.R. Sala, A. Fasso`, and J. Ranft, CERN-2005-10 (2005), INFN/TC_05/11, SLAC-R-773



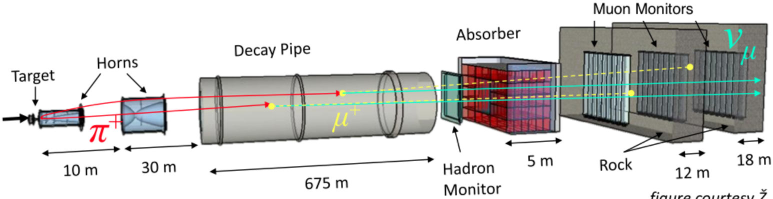
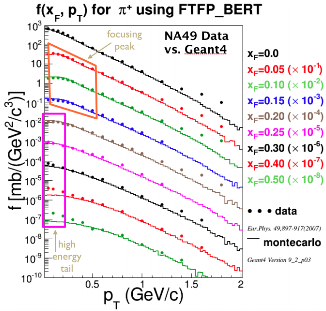


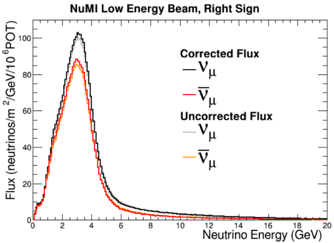
figure courtesy Ž. Pavlović

NuMI Beam

low energy (LE) beam flux

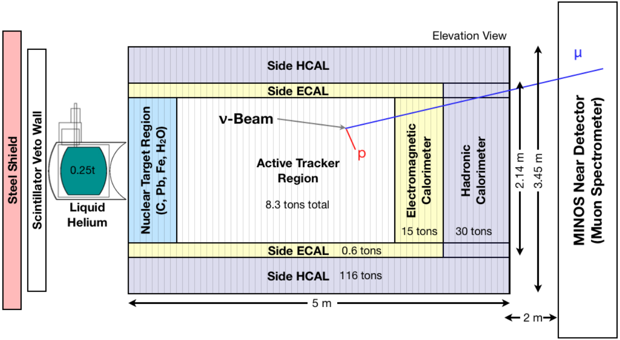
- Neutrino flux is estimated from hadron production
  - Monte Carlo (MC) is reweighted to match NA49 data ($pC \to \pi^+ X$)
  - Flux is then calculated using the GEANT4 simulator
  - Uncertainties due to the NA49 data and hadron production models are included as systematics





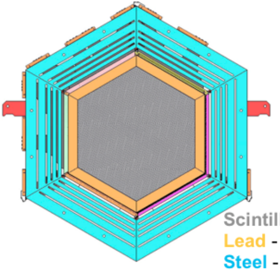
The Detector

- 120 “modules” perpendicular to the beam direction, containing ∼32k readout channels
- Finely-segmented scintillating central tracking region
- Nuclear targets, plastic (CH), EM and Hadronic calorimeter with additional lead and steel plates
- Minos near detector doubles as a muon spectrometer

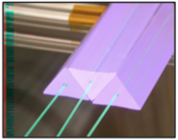


The Detector

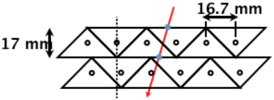
in more detail



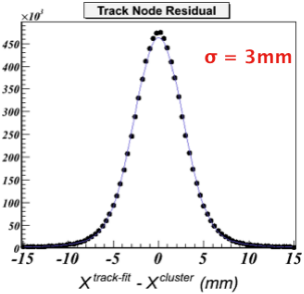
Scintillator - tracking
Lead - EM calorimetry
Steel - hadronic calorimetry

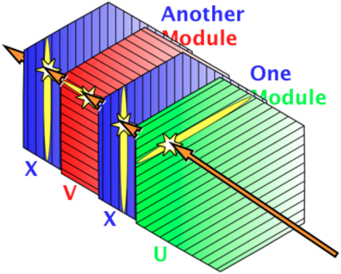


Extruded scintillator & wavelength shifting fibers.



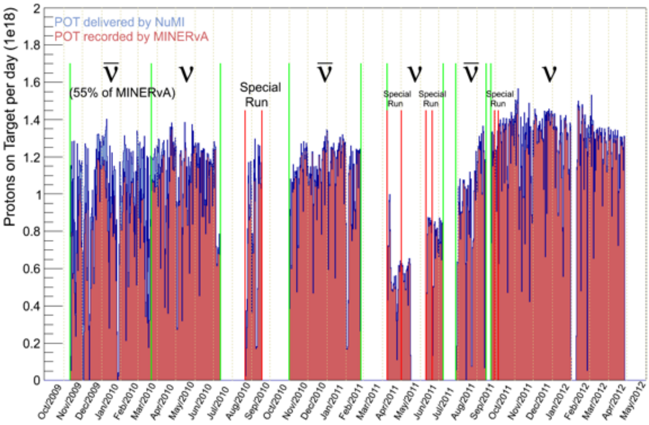
Charge sharing for improved position resolution (~3 mm) and alignment





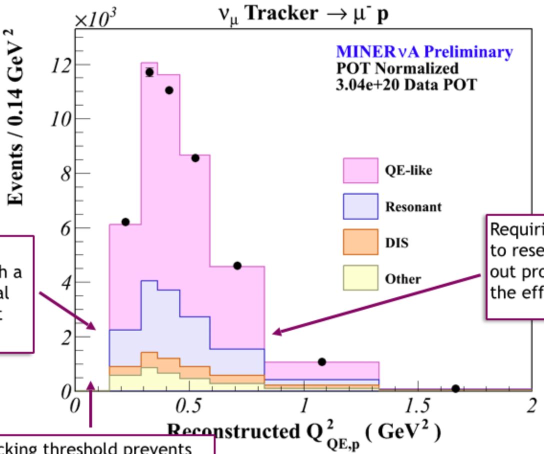
Data Collected
big THANKS to the Accelerator Division at Fermilab!!

- $4.0\mathrm{x}10^{20}$ POT in ν-mode
- $1.7\mathrm{x}10^{20}$ POT in $\bar{\nu}$-mode



CCQE-Like Candidates

courtesy of T. Walton, FNAL Exp./Theory Seminar, May 9, 2014



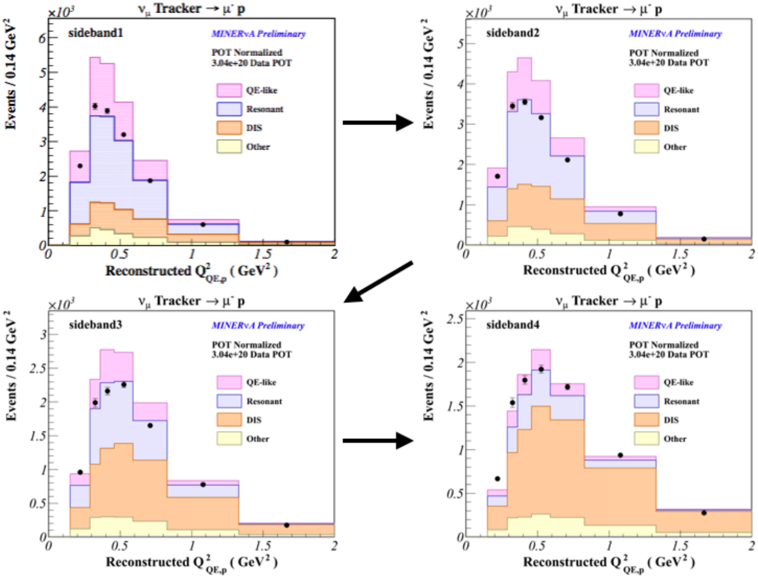
Resonant Production with a pion in the final state dominant background.

Requiring the hadron to resemble a range out proton → drop in the efficiency.

Tracking threshold prevents the reconstruction of events in the first bin.

Background Subtraction

use data to tune the background - step 2



CCQE-Like Systematic Uncertainties

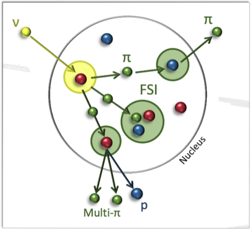
sources of uncertainty

- Neutrino flux
- Proton response
  - detector response of proton reconstruction
- Geant4 response
  - detector modeling of the hadron inelastic cross section
- Neutrino cross section models
- FSI models

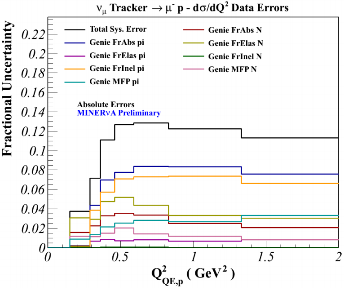
CCQE-Like Systematic Uncertainties

FSI modeling

- Applied as an efficiency correction
- The kinematic correlation modeling between the Resonant production of the proton and pion causes the GENIE pion production model uncertainties to become significant



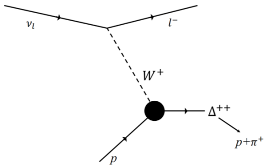
Model Parameter	Uncertainty
pion/nucleon mean path	±20%
pion/nucleon charge exchange	±50%
pion absorption	±30%
pion/nucleon inelastic cross section	±40%
elastic cross section	±10-30%



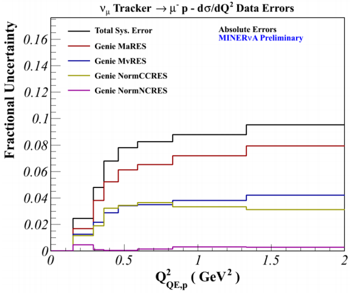
CCQE-Like Systematic Uncertainties

cross section modeling, using GENIE 2.6.2

- Primary background is from Resonant production
- Also applied as an efficiency correction

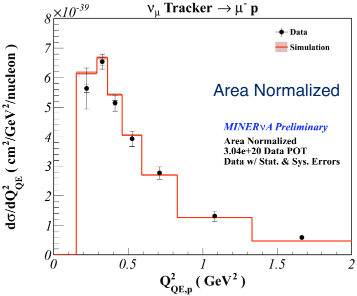


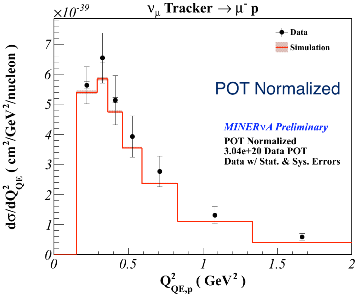
Model Parameter	Uncertainty
CC resonance production normalization	$\pm 20\%$
Resonance model parameter (M_A)	$\pm 20\%$
Non-resonance pion production	$\pm 50\%$



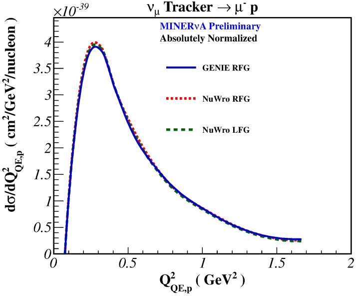
CCQE-Like Differential Cross Section

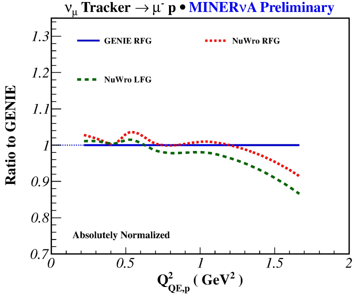
first EVER proton based CCQE-like cross section measurement!!





The differences between GENIE and NuWro are due to both the modeling of the momentum distribution of the initial state nucleons and FSI effects

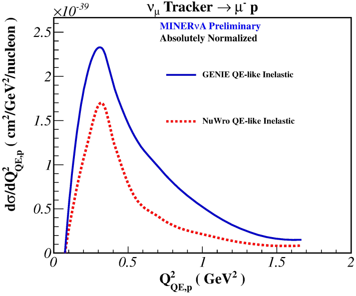


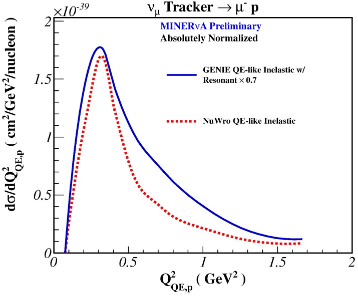


Inelastic Components of the Cross Section

modeled with GENIE vs. NuWro

Reduce the GENIE RFG resonant component by 30% to match NuWro peak

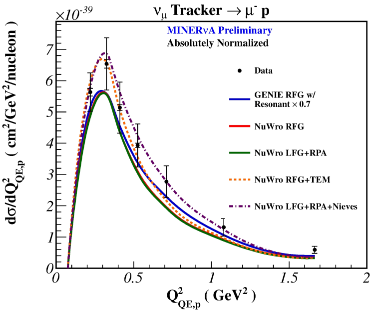


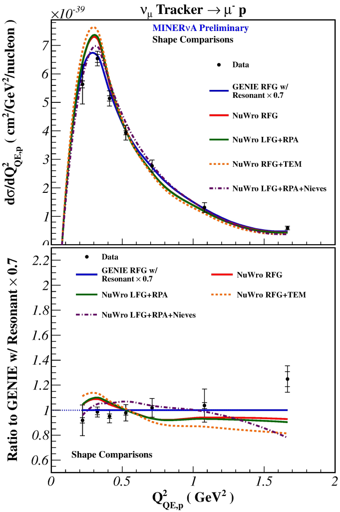


Total CCQE Cross Section

reduce GENIE RFG resonant component by 30%

GENIE still best describes the cross section measurement



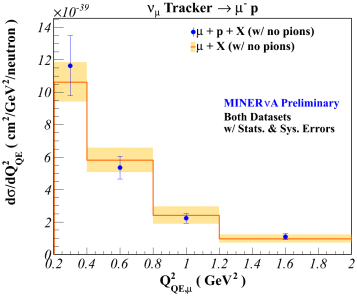


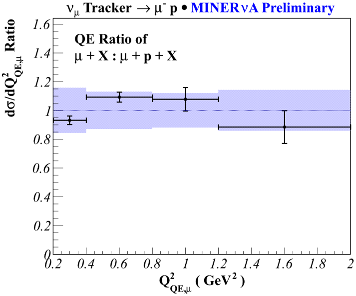
RFG = Relativistic Fermi Gas model
LFG = Local Fermi Gas model
GENIE: www.genie.org, NIM **A614**, 87 (2010)
NuWro: Acta Phys. Polon. **B40**, 2507 (2009)
TEM = "Transverse Enhancement Model",
A. Bodek, *et al.*, Eur. Phys. J. **C71** 1726 (2011)

Comparison to the CCQE Cross Section

$\mu + X$: ~3.0e20 Protons on Target (POT) vs. $\mu + p + X$: ~1.0e20 POT

- Use subsample of analysis (MINOS-matched muon tracks) with the CCQE signal definition
- The two measurements are consistent, despite the different treatment of the recoil system and background tuning procedure





- Common systematics do not cancel due to different software versions

Cross Section Models
for comparison

Interpretation #1: $d\sigma/dQ^2$ Shape

- Models that introduce nuclear correlations of various kinds ***tend to modify the QE cross-section as a function of Q^2*** (for a given ν energy spectrum)
- The models:
  - Relativistic Fermi Gas (RFG), M_A = 0.99 GeV/c^2
    - The canonical model in modern event generators used by all neutrino experiments
  - Relativistic Fermi Gas (RFG), M_A = 1.35 GeV/c^2
    - Motivated by recent measurements where this change was fairly successful at reproducing data
  - Nuclear Spectral Function (SF), M_A = 0.99 GeV/c^2
    - More realistic model of the nucleon momentum – energy relationship than standard RFG
  - Transverse Enhancement Model (TEM), M_A = 0.99 GeV/c^2
    - Empirical model which modifies the magnetic form factors of bound nucleons to reproduce an enhancement in the transverse cross-section observed in ***electron-nucleus scattering*** attributed to the presence of meson exchange currents (MEC) in the nucleus

Bodek, Budd, Christy, Eur. Phys. J. C 71:1726 (2011), arXiv:1106.0340

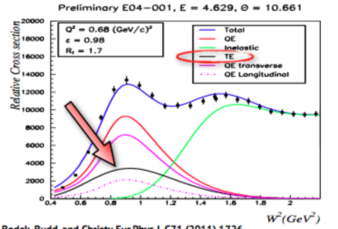
David Schmitz, UChicago   Fermilab Joint Experimental-Theoretical Seminar - May 10, 2013   42

Transverse Enhancement Model

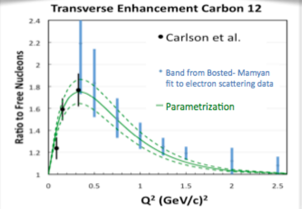
courtesy of G. Perdue, APS 2013 talk

Transverse Enhancement

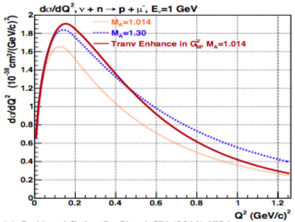
- The sort of model experimenters love - it may or may not be right, but it matches data (MiniBooNE - NOMAD).
  - Theorists often prefer being right to matching data. ☺
- Modify only vector magnetic form factors with e- scattering data - everything else is single free nucleon.
- e- scattering data suggests only the longitudinal portion of the QE x-section is ~universal free nucleon response function - the transverse component shows an enhancement relative to this approach.



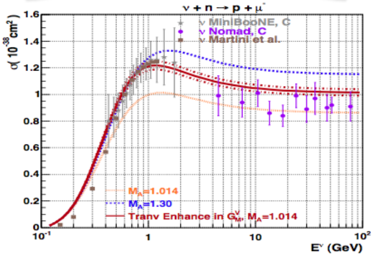
Bodek, Budd, and Christy Eur.Phys.J. C71 (2011) 1726



Fit to electron scattering data from JUPITER (JLab E04-001) to extract enhancement as a function of Q^2.



Bodek, Budd, and Christy Eur.Phys.J. C71 (2011) 1726



Bodek, Budd, and Christy Eur.Phys.J. C71 (2011) 1726

Transverse Enhancement

- $d\sigma/dQ^2$ w/ $M_A = 1.014$ GeV & TEM is very similar to the result for $M_A = 1.3$ GeV for $Q^2 < 0.6$ $(\text{GeV}/c)^2$.
- For high Q^2, the TEM contribution is small.
- Experiments at high energy often remove low Q^2 values from their M_A fits - predict an even lower M_A due to steep slope for $d\sigma/dQ^2$ at $M_A = 1.014$ GeV.

Gabriel N. Perdue 47 The University of Rochester