Neutrino Physics Results at MINERvA

Carrie McGivern

On behalf of the MINERvA Collaboration

University Of Pittsburgh

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mcgivern@fnal.gov

Outline

this is the way it's going to go...

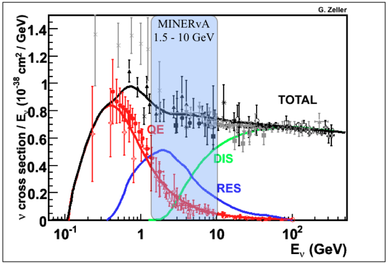
- Motivation
- NuMI Beam and the MINERvA Experiment
- Charged Current Quasi-Elastic (CCQE) Results - fresh off the presses
- Status of the CC Inclusive Pion analysis

Motivation

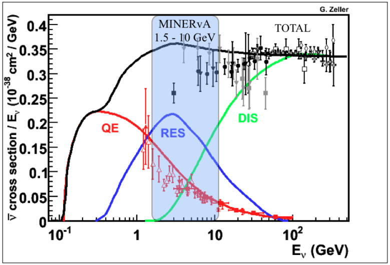
want are we trying to learn here?

- 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

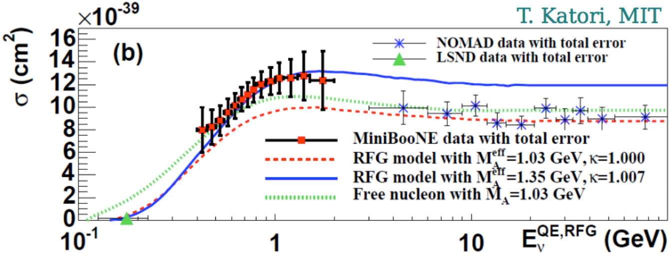


J.A. Formaggio and G.P. Zeller, Rev. Mod. Phys. 84, 1307-1341, 2012

Motivation

want 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



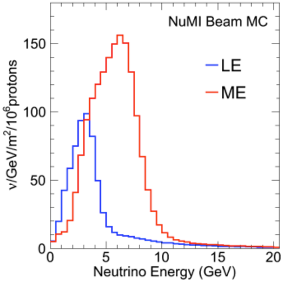
- Additionally, neutrinos make for a good weak-interaction probe of the nuclear structure

NuMI Beam

Neutrinos at the Main Injector

- 120 GeV proton beam from the Main Injector
- Average spill of 35×10^{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



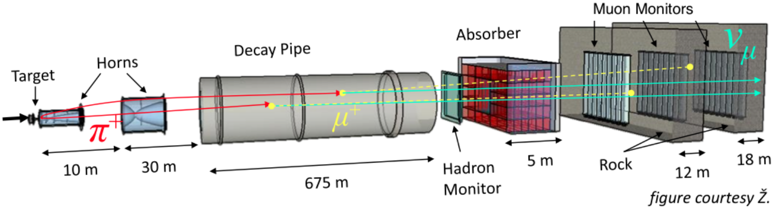
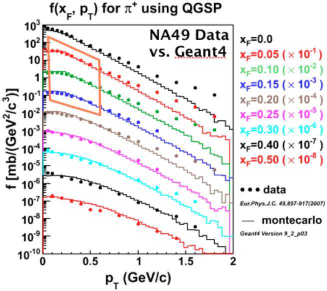


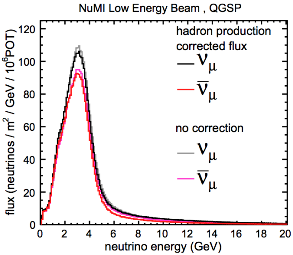
figure courtesy Ž. Pavlović

NuMI Beam

low energy (LE) beam flux

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

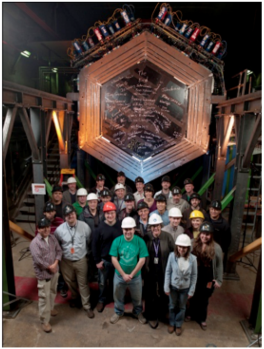




The Collaboration

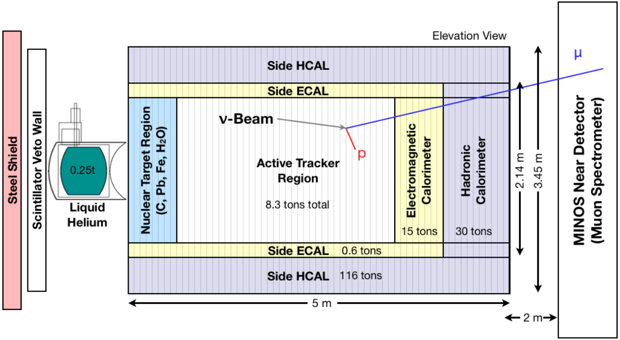
~80 collaborators from nuclear and particle physics

University of Athens
University of Texas at Austin
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. Col. Lib. Arts
Northwestern University
Otterbein University
Pontificia Universidad Catolica del Peru
University of Pittsburgh
University of Rochester
Rutgers University
Tufts University
University of California at Irvine
University of Minnesota at Duluth
Universidad Nacional de Ingeniería
Universidad Técnica Federico Santa María
William and Mary



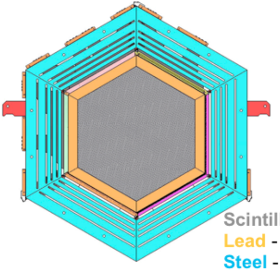
The Detector

- 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 spectometer

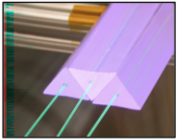


The Detector

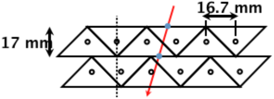
in more detail

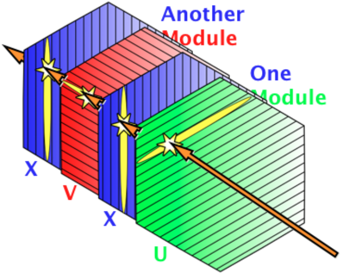


Scintillator - tracking
Lead - EM calorimetry
Steel - hadronic calorimetry

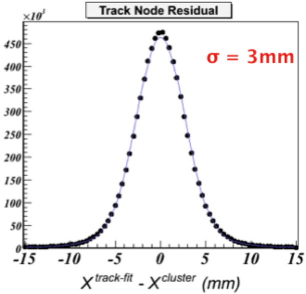


Extruded scintillator & wavelength shifting fibers.





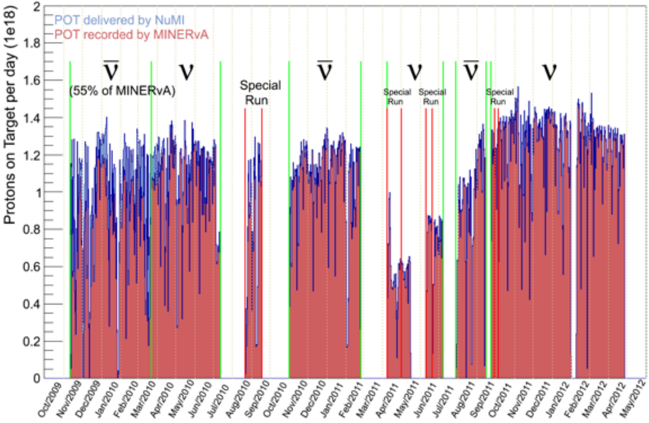
Charge sharing for improved position resolution (~3 mm) and alignment



Data Collected

big THANKS to the Accelerator Division at Fermilab!!

- 4.0x10^{20} POT in ν-mode
- 1.7x10^{20} POT in $\bar{\nu}$-mode



Charged Current Quasi-Elastic Results

Charged Current Quasi-Elastic Results

released just last week!

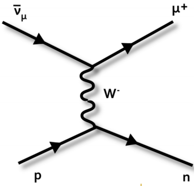
Signal

muon track and energy deposition (recoil) that is consistent with a neutron (proton)

...

Backgrounds : non-CCQE $\bar{\nu}$ interactions, ν interactions with a mis-reconstructed charge, and rock muons that originate from outside of the detector

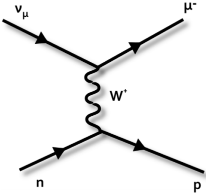
arXiv:1305.2234 [hep-ex]



$$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$$

- Nov. 2010 - Feb. 2011
- Uses 1.01 x 10^{20} POT

arXiv:1305.2243 [hep-ex]



$$\nu_\mu + n \rightarrow \mu^- + p$$

- Mar. 2010 - Jul. 2010
- Uses 9.42 x 10^{19} POT

IceCube Particle Astrophysics Symposium 2013

C.L. McGivern

Outline

Motivation

NuMI Beam

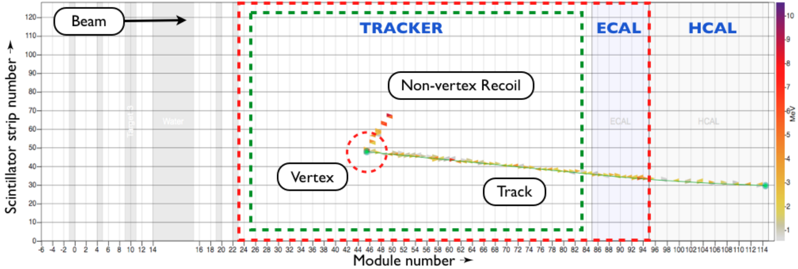
MINERvA Experiment

CCQE Results

CCIncPion Status

Conclusion

CCQE Event Selection



Anti-Neutrinos

- MINOS-matched μ^+ track
- Reconstructed vertex in central fiducial volume
- $\leq$ 1 isolated energy shower outside of vertex region (10 cm)
- Reconstructed Q^2_{QE}-dependent recoil energy cut that excludes the vertex region

$\rightarrow$ 16,467 events, 54% efficiency, 77% purity

Neutrinos

- MINOS-matched μ^- track
- Reconstructed vertex in central fiducial volume
- $\leq$ 2 isolated energy showers outside of vertex region (30 cm)
- Reconstructed Q^2_{QE}-dependent recoil energy cut that excludes the vertex region

$\rightarrow$ 29,620 events, 47% efficiency, 49% purity

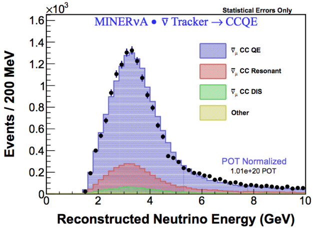
CCQE Kinematic Distributions

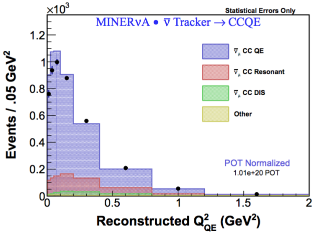
anti-neutrino reconstructed E_ν^{QE} and Q^2_{QE} distributions

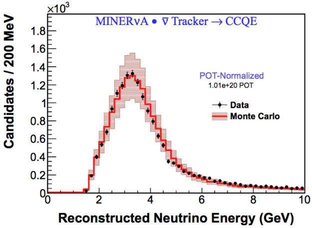
Assume a bound nucleon at rest with a fixed binding energy (E_b)

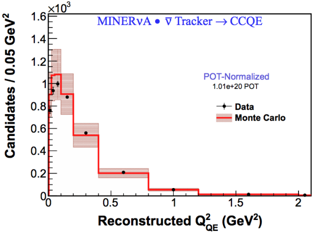
$$E_\nu^{QE} = \frac{m_n - (m_p - E_b)^2 - m_\mu^2 + 2(m_p - E_b)E_\mu}{2(m_p - E_b - E_\mu + p_\mu cos(\theta_\mu))}$$

$$Q^2_{QE} = 2E_\nu^{QE}(E_\mu - p_\mu cos(\theta_\mu)) - m_\mu^2$$









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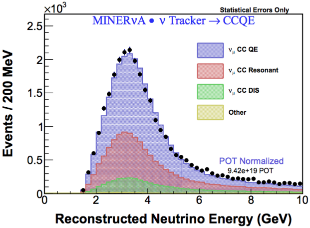
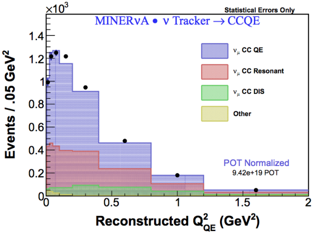
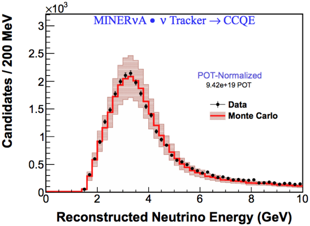
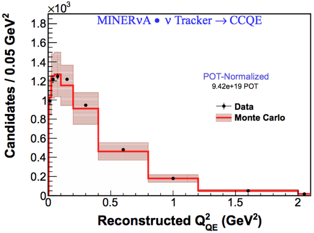




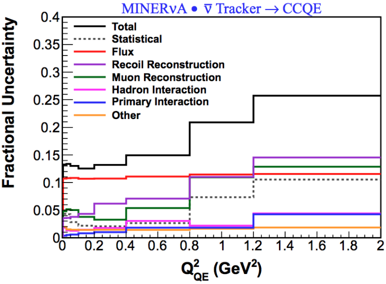


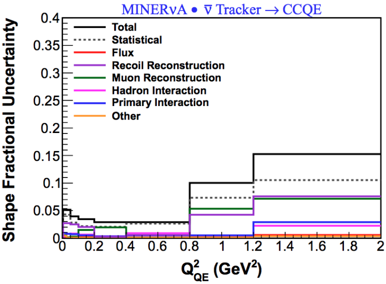


CCQE Systematic Uncertainties

anti-neutrino

- 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. neutrino flux)





Leading systematics due to neutrino flux, recoil reconstruction, muon reconstruction, hadron interaction, and ν interaction model

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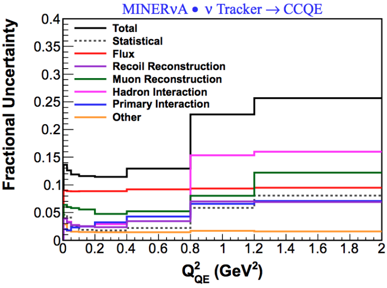
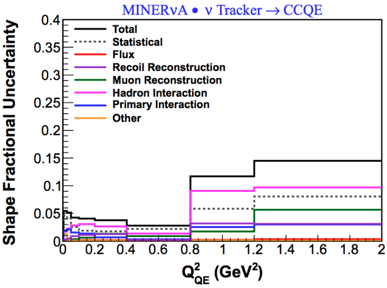




Leading systematics due to neutrino flux, recoil reconstruction, muon reconstruction, hadron interaction, and ν interaction model

CCQE Differential Cross Section

in bins of Q^2_{QE}

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

not to "generator Q²"

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

reco μ kinematics → true μ kinematics

backgrounds constrained by data

$$\left(\frac{d\sigma}{dQ^2_{QE}}\right)_i = \frac{1}{\Phi T}\frac{1}{\Delta Q^2_{QE}}\frac{\sum_j U_{ij}\left(N_{data,j} - N_{bg,j}\right)}{\varepsilon_i}$$

flux, targets

bin size

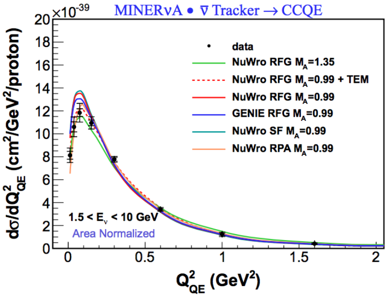
muon eff constrained with data;

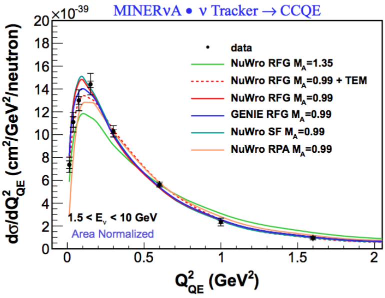
recoil eff uses MC away from vertex

Courtesy of D. Schmitz

CCQE Differential Cross Section

- Subtract background by fitting recoil energy distribution in bins of Q^2_{QE} to MC shape background templates
- Unfold the reconstructed Q^2_{QE} to estimate the true distribution
- Apply efficiency x acceptance corrections to the MC





GENIE: www.genie.org, NIM **A614, 87 (2010)**

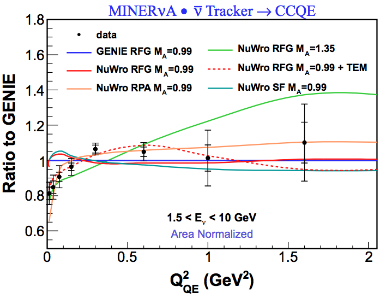
NuWro: Acta Phys. Polon. **B40, 2507 (2009)**

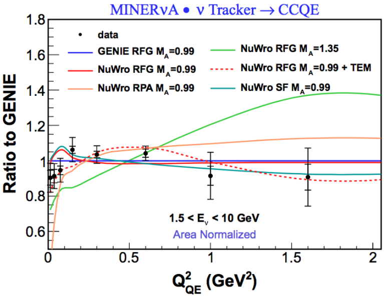
TEM = "Transverse Enhancement Model", A. Bodek, *et al.*, *Eur. Phys. J.* **C71 1726 (2011)**

CCQE Differential Cross Section

ratio compared to GENIE

Consistent with the RFG $M_A = 0.99$ + TEM model





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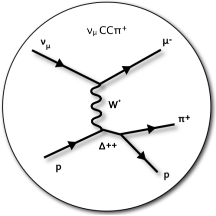
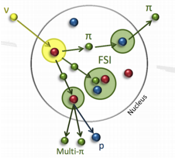
Charged Current Inclusive Pion Status

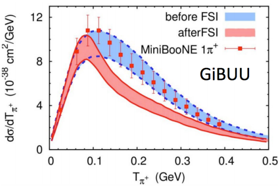
Charged Current Inclusive Pion Status

$$\nu_\mu A \rightarrow \mu^- \pi^\pm X A'$$
$$\bar{\nu}_\mu A \rightarrow \mu^+ \pi^\pm X A'$$



MiniBooNE does not favor models with final state interactions (FSI)





Event Selection

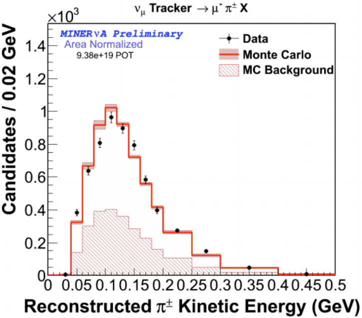
- Vertex is reconstructed in scintillator tracker fiducial volume
- MINOS-matched muon track with appropriate charge
- At least one hadron track from primary vertex, not matched to the muon track, and is consistent with a stopping pion

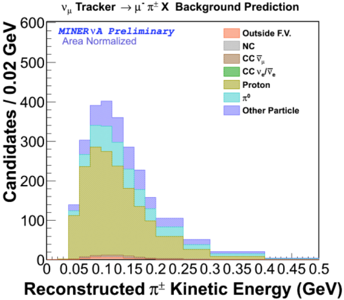
CC Inclusive Pion Status

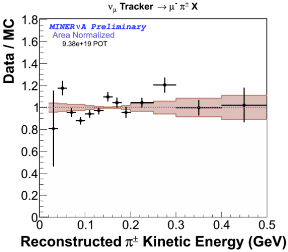
reconstructed pion energy distribution

Use 25% of available data

- Look at area normalized distributions to compare shapes, helps to reduce flux systematic errors







CC Inclusive Pion Status

reconstructed Q^2 and W$_{exp}$ distributions and what's next to come...

$$E_\nu = E_\mu + E_{recoil}$$

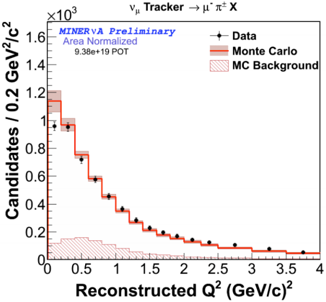
$$Q^2 = 2E_\nu(E_\mu - p_\mu cos(\theta_\mu)) - m_\mu^2$$

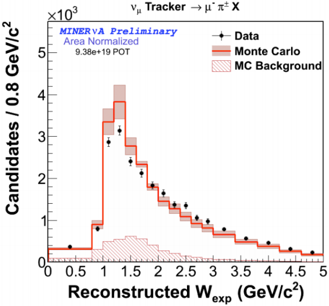
$$W_{exp} = -Q^2 + m_n^2 + 2m_n^2(E_{recoil})$$

Resolution

$Q^2 \sim 25\%$

$W_{exp} \sim 10\%$





- Study pion identification to help reduce background further
- Use unfolding to apply detector resolution corrections and also apply efficiency corrections
- Estimate hadron reconstruction systematic uncertainties

Conclusion

- Currently putting a lot of effort into physics analyses
  - Charged current inclusive cross sections
  - Pion production cross sections
  - Inclusive cross section vs. various nuclei: He, C, O, Fe, Pb
  - Strangeness production cross sections
  - Structure functions
  - and much more...
- MINERvA will continue to run during the Nova-era medium energy beam
- Lots of exciting results to come!

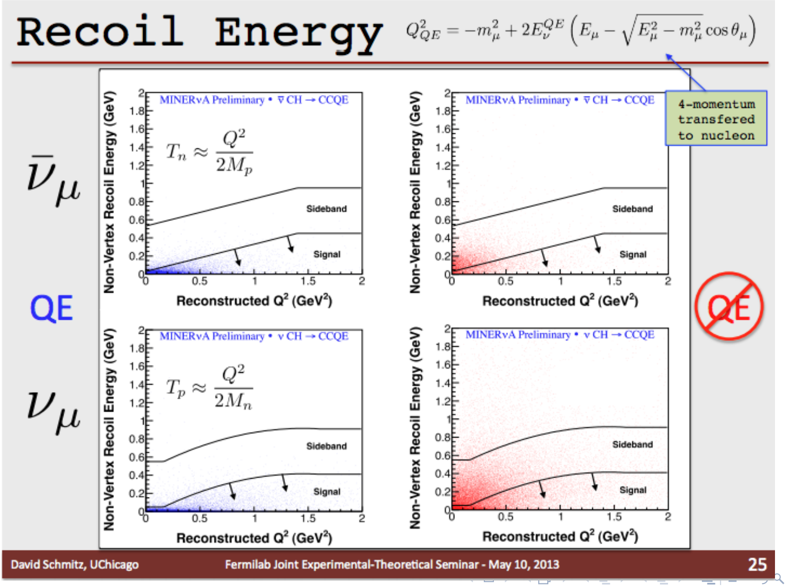
Backup Slides

Recoil Energy vs. Q^2_{QE}

IceCube Particle Astrophysics Symposium 2013

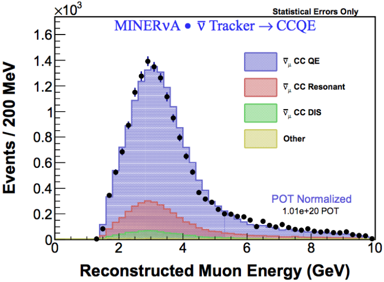
C.L. McGivern

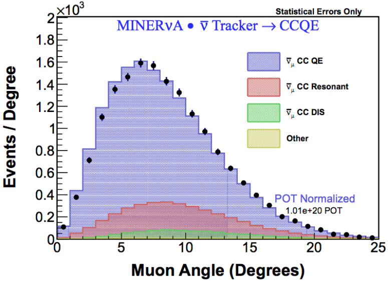
Backup Slides

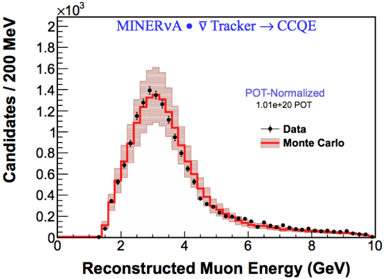


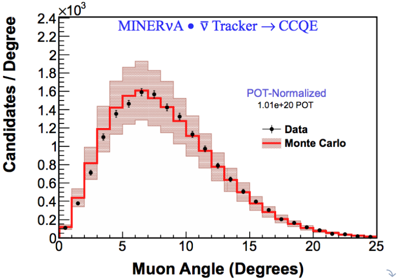
CCQE Kinematic Distributions

anti-neutrino muon distributions



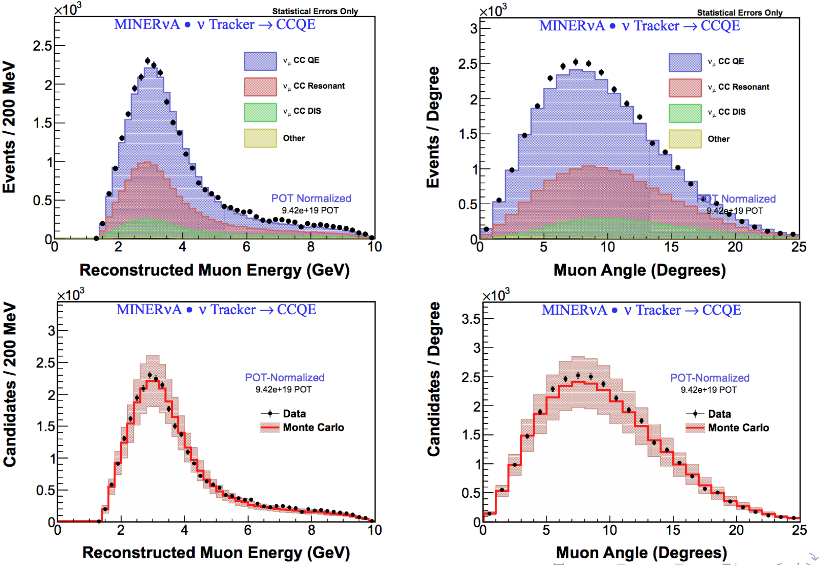




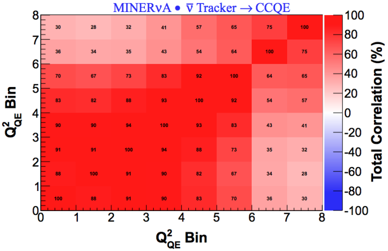


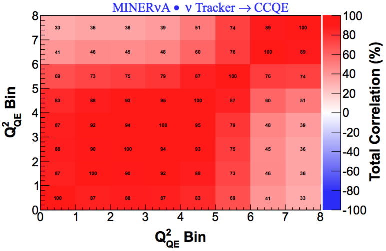
CCQE Kinematic Distributions

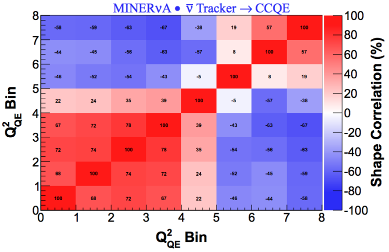
neutrino muon distributions

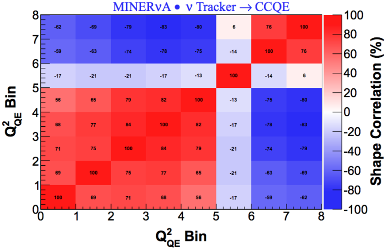


CCQE Systematic Uncertainty Correlation Matrices









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

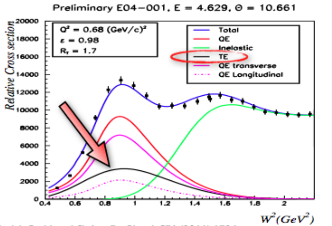
Bodek, Budd, Christy, Eur. Phys. J. C 71:1726 (2011), arXiv:1106.0340

Transverse Enhancement Model

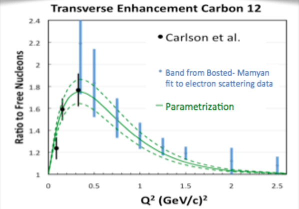
courtesy of G. Perdue, APS 2013 talk

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.

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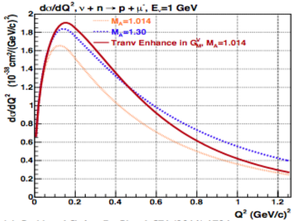
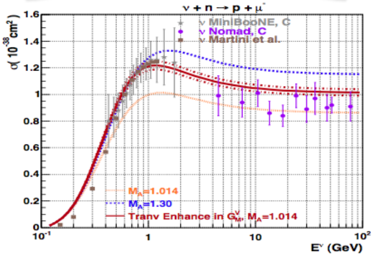
Transverse Enhancement Model

courtesy of G. Perdue, APS 2013 talk



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 $Q^2 < 0.6$ $(GeV/c)^2$.
- 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