Quasi-Elastic Scattering at MINERνA

SLAC Experimental Seminar

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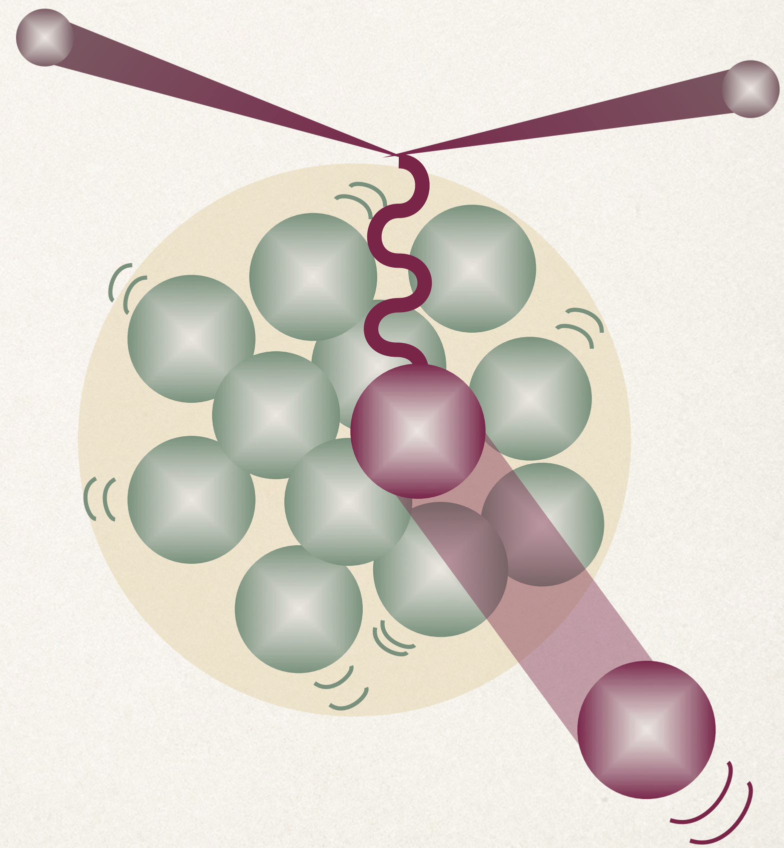
Outline

- Introduction
  - Motivation
  - Neutrino-Nucleus Scattering
  - Quasi-Elastic Scattering
- Experimental Apparatus
  - The NuMI Beamline
  - The MINERνA Detector
- First MINERνA Quasi-Elastic Analyses
- Conclusion

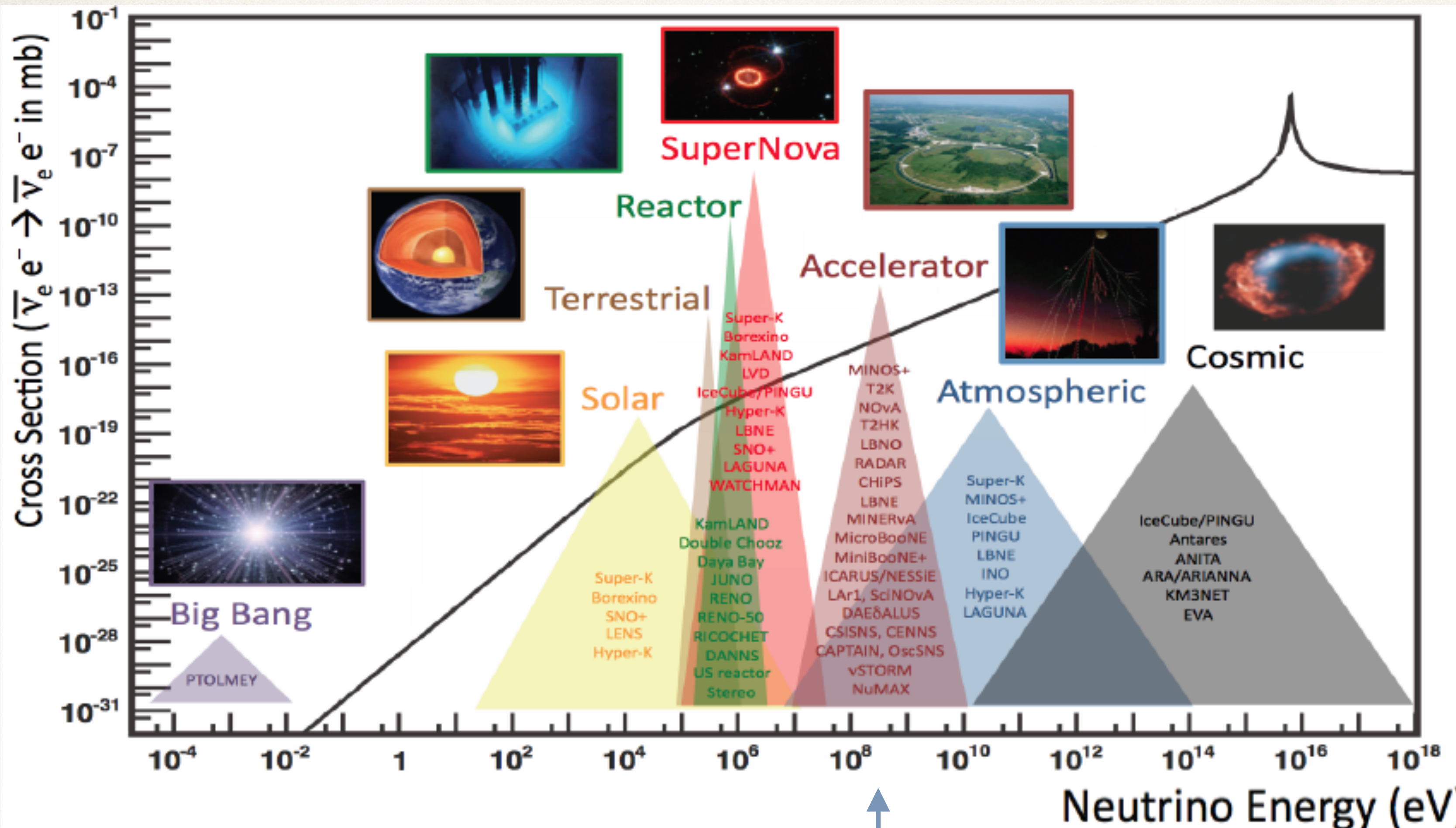
Introduction: Motivation

- This is a talk about measuring Neutrino-Nucleus scattering cross sections
- Why do we want to bother doing this?
- There are several answers to this question
  - But the one that gets me up in the morning…



Introduction: Motivation

- Knowledge of neutrino-nucleus scattering cross sections is crucial to the global neutrino physics program:



J.A. Formaggio and G.P. Zeller, Rev. Mod. Phys. 84 (2012), via Snowmass Neutrino WG Summary

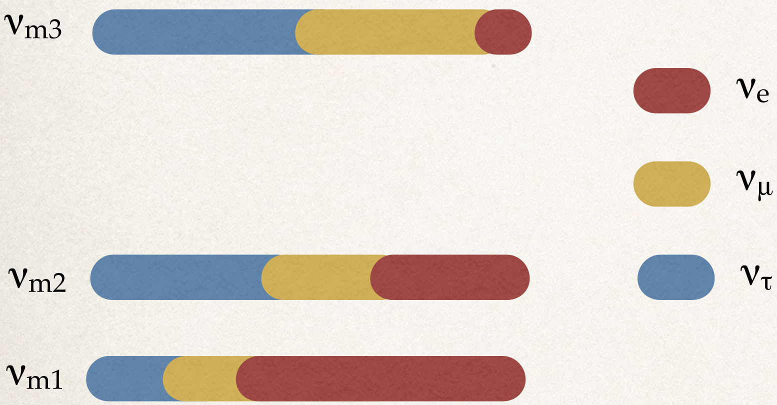
Cross sections are particularly important to the accelerator-based oscillation experiments in the few-GeV region.

An Example: LBNE

- LBNE: The Long Baseline Neutrino Experiment
  - Currently in development (DOE CD-1) to be the flagship accelerator-based experiment in the United States.
  - Neutrinos created at Fermilab will travel to a liquid Argon TPC detector in the Sanford Underground Research Facility (SURF) in South Dakota.
  - Marquee measurements: neutrino mass hierarchy and CP phase
    - Also: atmospheric neutrinos, proton decay, supernovas and more

Overview of Neutrino Mixing

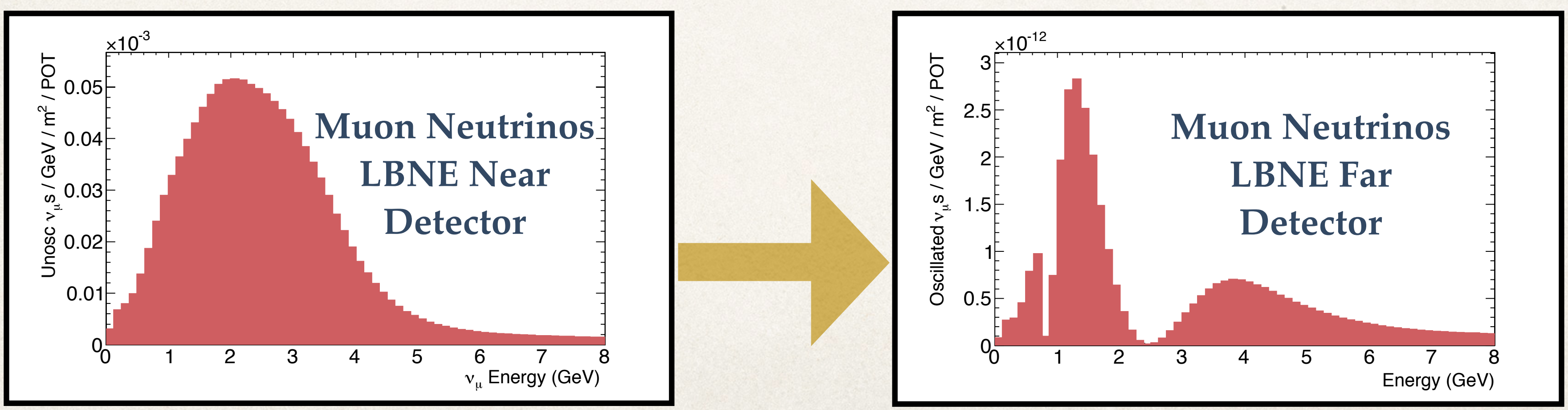
- Experiments such as LBNE study neutrino mixing:



Neutrino oscillations are possible because there are three different neutrino mass states, and each mass state is a different mixture of ν_e, ν_μ, and ν_τ

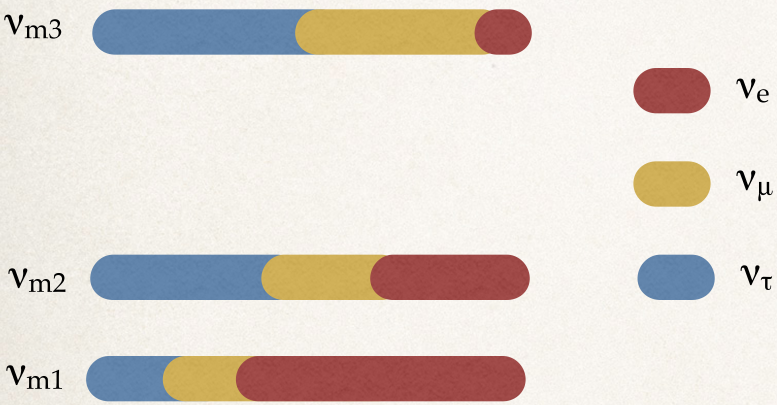
The flavor composition of a beam of neutrinos changes as the beam propagates through space

The mixing is a function of the neutrino's energy and the distance it has travelled.



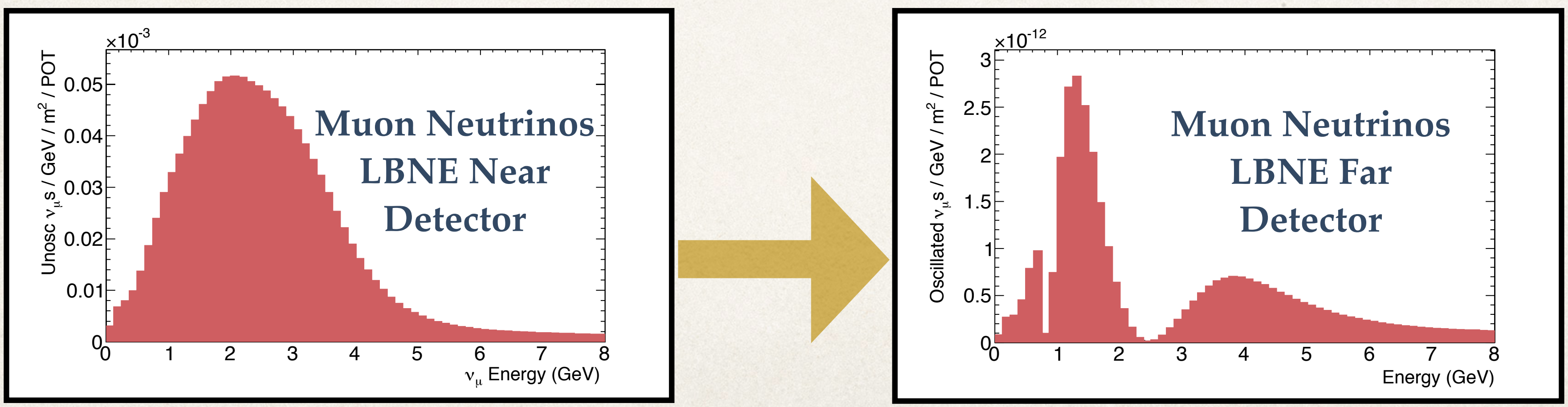
Overview of Neutrino Mixing

- Oscillation experiments are aimed at studying neutrino mixing:



$$P\left(\nu_\alpha \rightarrow \nu_\beta\right) = \sin^2\left(2\theta\right)\sin^2\left(\frac{1.27\Delta m_{ij}^2 L}{E}\right)$$

(A two-neutrino approximation)



Overview of Neutrino Mixing

- If you look up neutrino oscillation on Wikipedia:

Neutrino oscillation

From Wikipedia, the free encyclopedia

? This article includes a list of references, but **its sources remain unclear because it has insufficient inline citations**. Please help to improve this article by introducing more precise citations. *(April 2010)*

Neutrino oscillation is a quantum mechanical phenomenon predicted by Bruno Pontecorvo[1] whereby a neutrino created with a specific lepton flavor (electron, muon or tau) can later be measured to have a different flavor. The probability of measuring a particular flavor for a neutrino varies periodically as it propagates. Neutrino oscillation is of theoretical and experimental interest since observation of the phenomenon implies that the neutrino has a non-zero mass, which is not part of the original Standard Model of particle physics.

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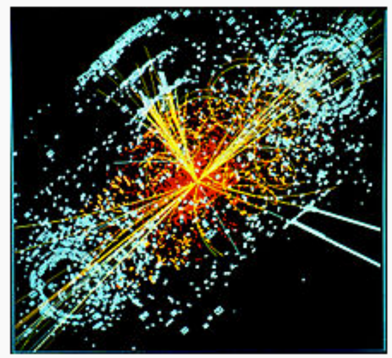
1 Observations
1.1 Solar neutrino oscillation
1.2 Atmospheric neutrino oscillation
1.3 Reactor neutrino oscillation
1.4 Beam neutrino oscillation
2 Theory
2.1 Pontecorvo–Maki–Nakagawa–Sakata matrix
2.2 Propagation and interference

Beyond the Standard Model



Simulated Large Hadron Collider CMS particle detector data depicting a Higgs boson produced by colliding protons decaying into hadron jets and electrons

Standard Model

A Higgs event in CMS
Very pretty, but not beyond the standard model!

In our LHC-obsessed world, it's important to remember that:

New physics was discovered years before the LHC turned on, in the form of neutrino oscillations

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Questions about Neutrino Mixing…

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

PMNS Matrix:
three mixing angles and one CP phase

$$\begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{13}s_{23}c_{12}e^{i\delta} & c_{23}c_{12} - s_{13}s_{23}s_{12}e^{i\delta} & c_{13}s_{23} \\ s_{23}s_{12} - s_{13}c_{23}c_{12}e^{i\delta} & -s_{23}c_{12} - s_{13}c_{23}s_{12}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

- What are the parameters of the mixing matrix?
  - What is the value of the CP-violating phase δ_{CP}?
  - Is θ_{23} maximal?
- Is the mass hierarchy normal or inverted — i.e. which neutrino is the lightest?
- Is the data consistent with this mixing model?

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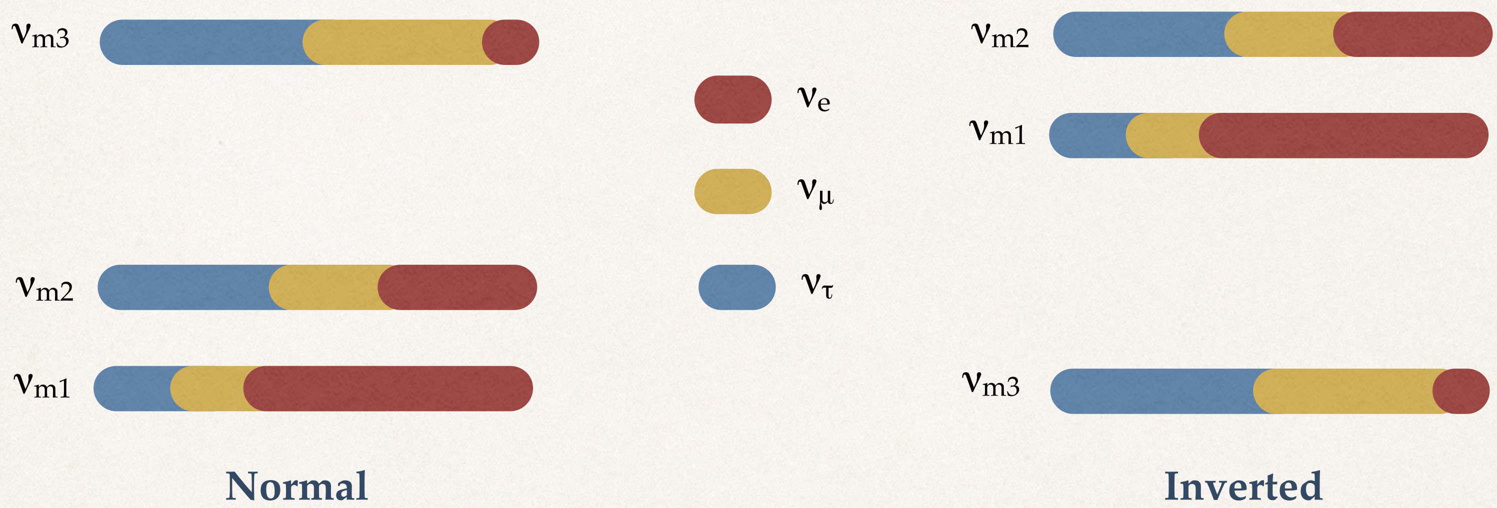
Questions about Neutrino Mixing…



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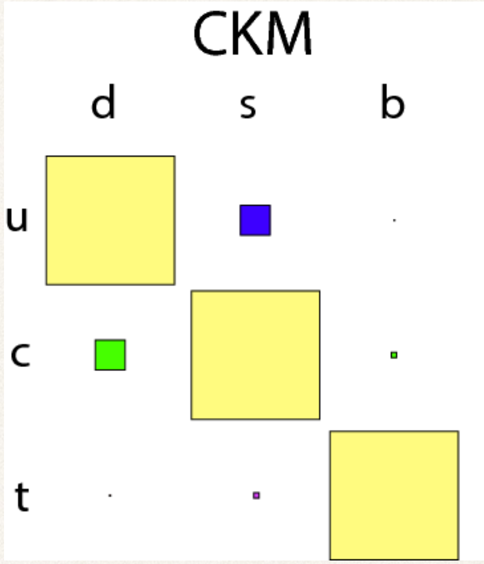
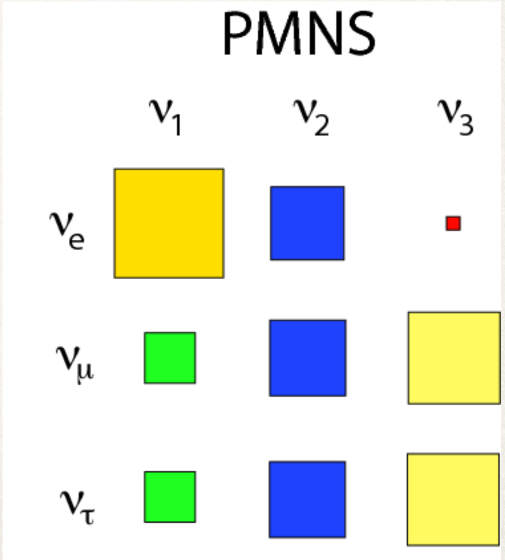
- Is the data consistent with this mixing model?

S. Stone arXiv:1212:6374

Questions about Neutrino Mixing

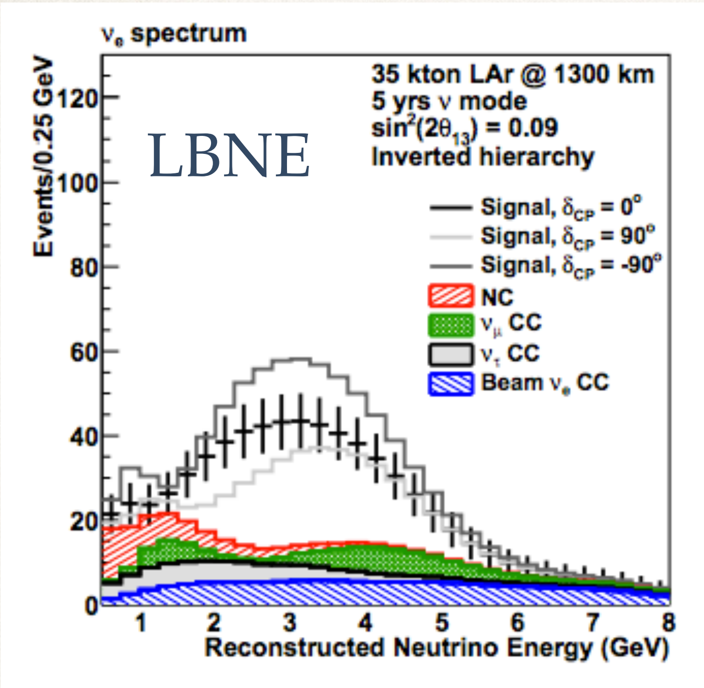
- We hope that answering those specific questions will lead to answers to bigger questions:
    - Does CP violation in the neutrino sector explain the matter/antimatter asymmetry of the universe?
    - Why is neutrino mixing so different than quark mixing?
        - Is there a new theory that explains both phenomena?
    - How do neutrinos acquire mass?
    - Are there one or more sterile neutrinos?
        - How do they impact our model of the universe?





How oscillation experiments work

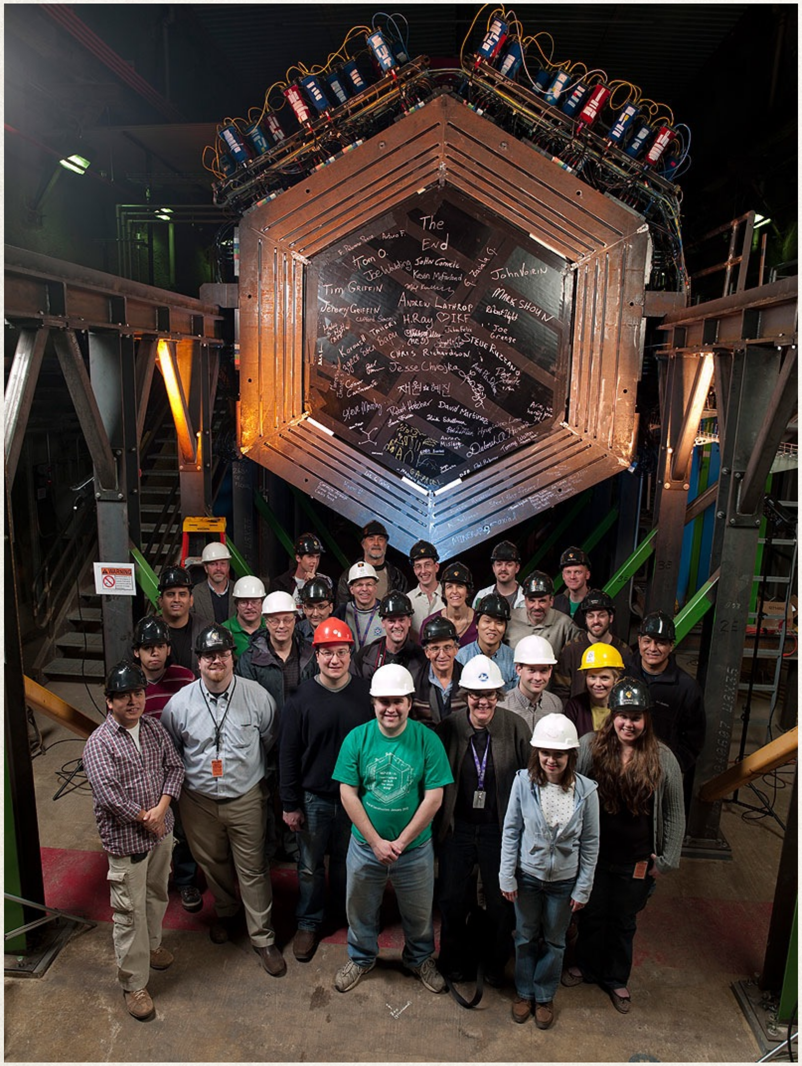
"Scientific Opportunities with the Long-Baseline Neutrino Experiment" Snowmass 2014



Large final state uncertainties would completely obscure the value of δ_{CP} for LBNE

- You produce a beam of neutrinos and let them propagate a long distance
  - Then you compare the observed neutrino spectra to predictions for different oscillation parameters
- The predictions **need many inputs from neutrino scattering experiments:**
  - The neutrino interaction **cross-sections as a function of energy** for signal and background channels
  - An accurate model of the **final state kinematics** of signal and background channels
    - Crucial for accurate neutrino energy reconstruction and for understanding efficiencies
  - Both of these must be understood for **the nuclei in the far detector**

Oscillation experiments need MINERνA!



The MINERνA detector was designed to provide these inputs. This talk details our first results.

- The predictions **need many inputs from neutrino scattering experiments:**
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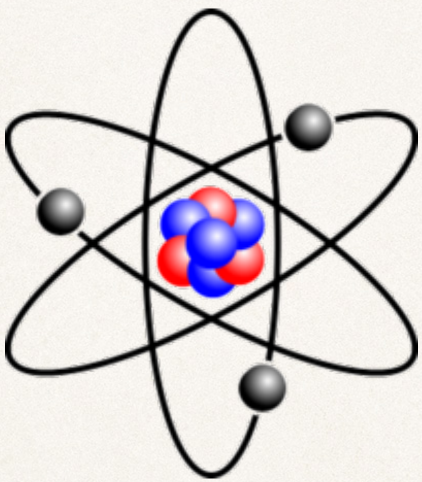
Overview of Neutrino-Nucleus Scattering

Or: what happens when a few-GeV neutrino interacts in a particle detector?

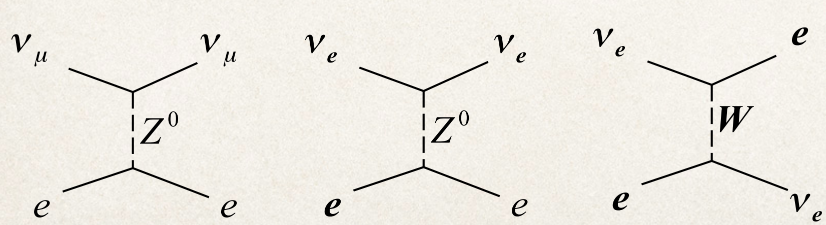
Neutrino Scattering

First a caveat…



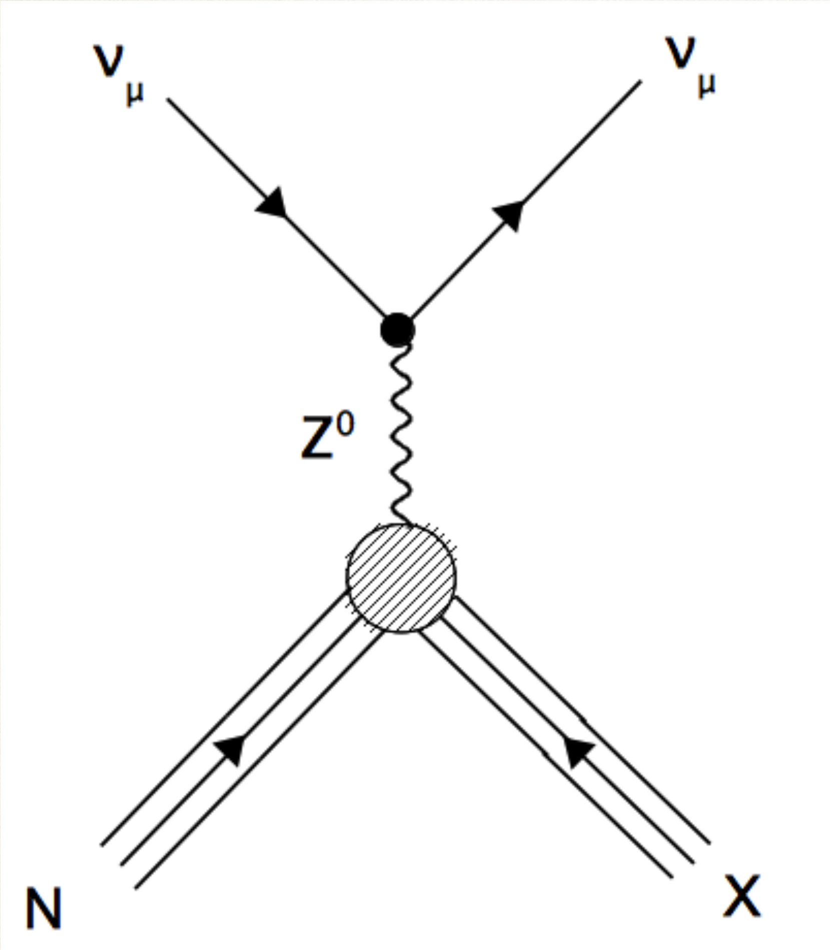
MINERνA will measure neutrino-electron scattering too!

Watch for a paper soon on neutrino-electron scattering:



- Neutrinos can interact with electrons or nuclei within particle detectors
- Interaction with a nucleon is ~2000 times more likely than interaction with an electron
- Usually, when we talk about neutrino scattering, we mean neutrino-nucleus scattering
  - That includes me throughout this talk
- Almost all accelerator-based neutrino scattering measurements are made with muon neutrinos
  - That also includes everything in this talk

Neutrino-Nucleus Scattering



Neutral Current

- Mediated by neutral boson
- Neutrino in initial and final state
  - Difficult to reconstruct kinematics → typically appear in oscillation measurements as backgrounds
  - Examples:

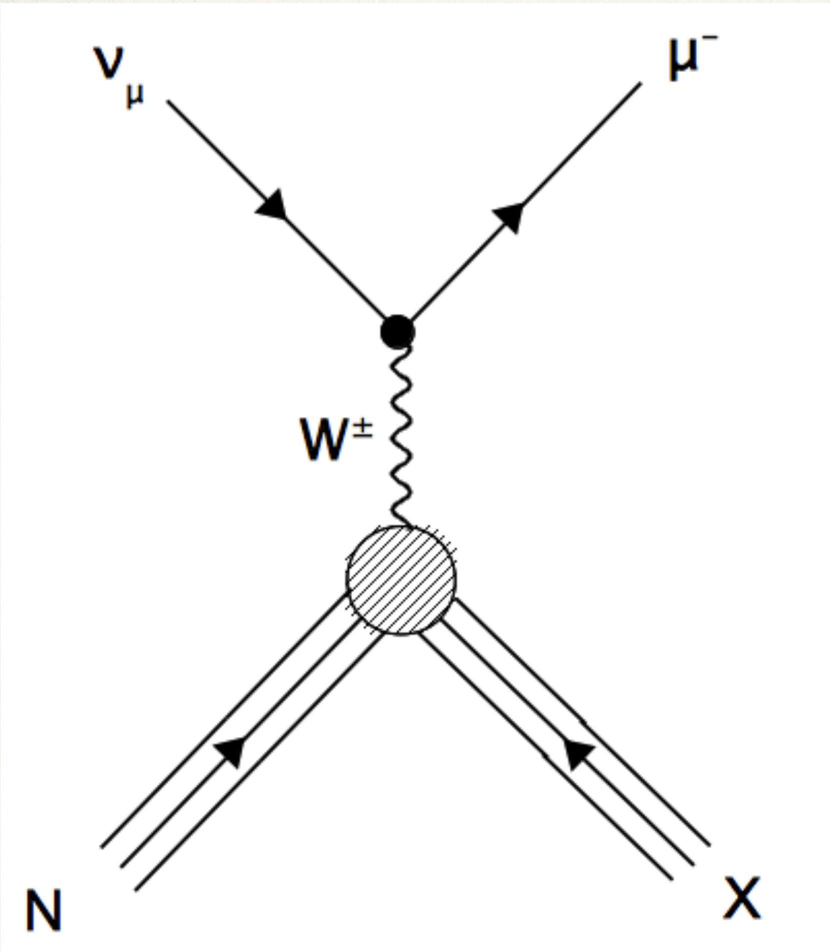
NC Elastic:

$\nu\, p \rightarrow \nu\, p$

NC π^0 production:

$\nu\, p \rightarrow \nu\, p\, \pi^0$

Neutrino-Nucleus Scattering



Charged Current

- Mediated by charged boson
- Charged lepton in final state
  - Easier kinematic reconstruction → typically used as signal channels in oscillation experiments
  - Examples:

Quasi-Elastic:

$\nu\, n \rightarrow l\, p$

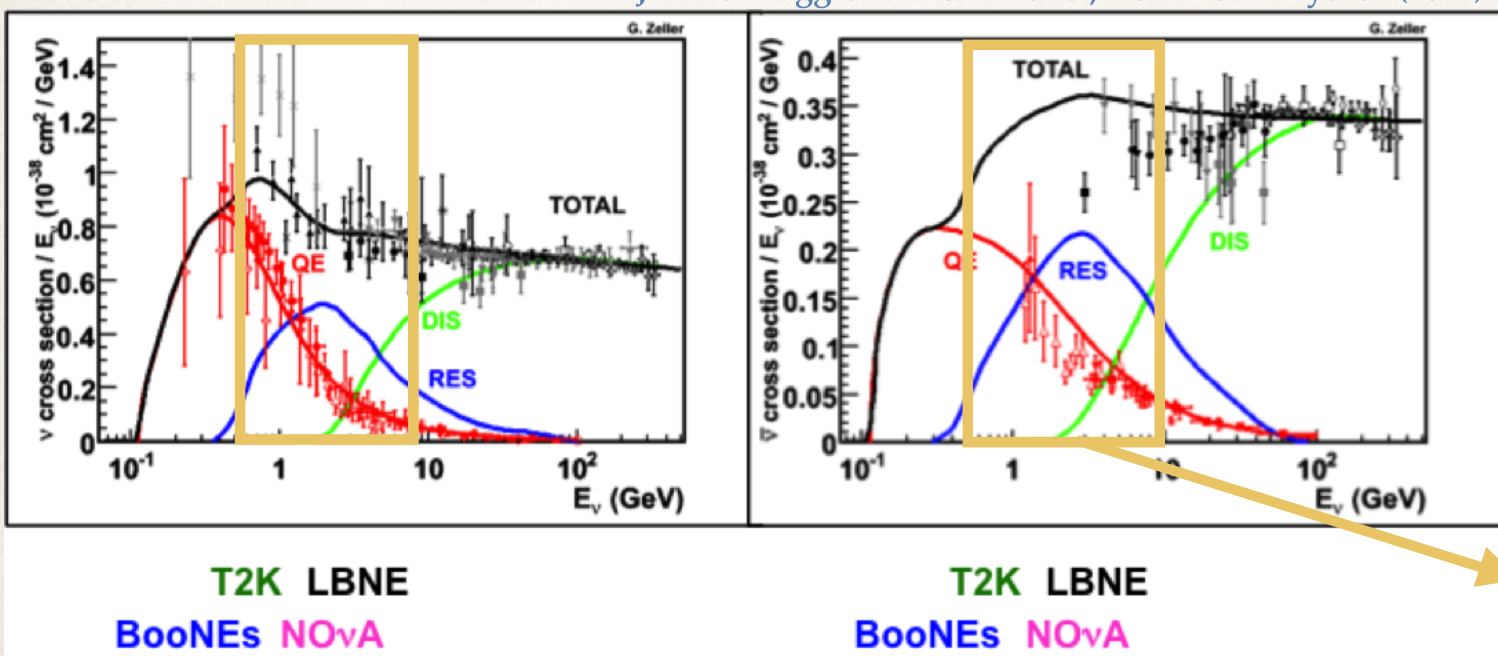
Pion Production:

$\nu\, p \rightarrow l\, p\, \pi$

Neutrino-Nucleus Scattering

Charged current cross-sections:

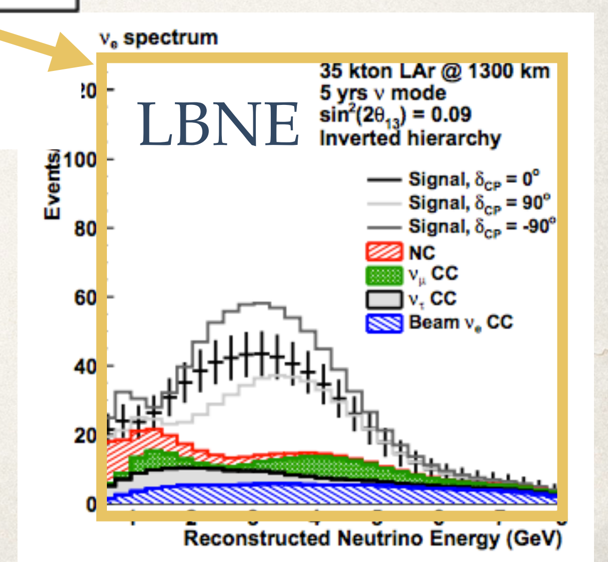
J.A. Formaggio and G.P. Zeller, Rev. Mod. Phys. 84 (2012)



QE:
Quasi-elastic Scattering

RES:
Pion Production

DIS:
Deep Inelastic Scattering



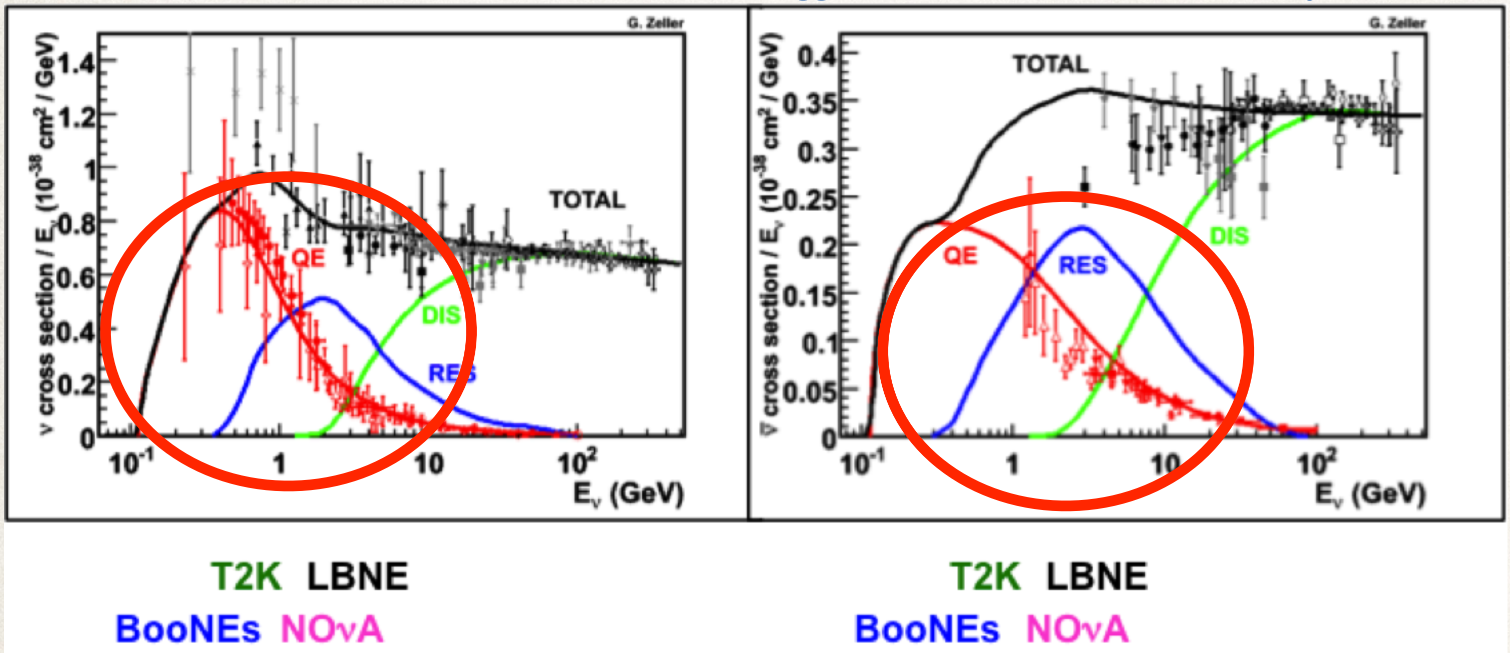
The dominant **interaction channel changes dramatically** over the region of interest to oscillation experiments

Nuclear effects are also maximal in this region.

Neutrino-Nucleus Scattering

Charged current cross-sections:

J.A. Formaggio and G.P. Zeller, Rev. Mod. Phys. 84 (2012)



QE:
Quasi-elastic Scattering

RES:
Pion Production

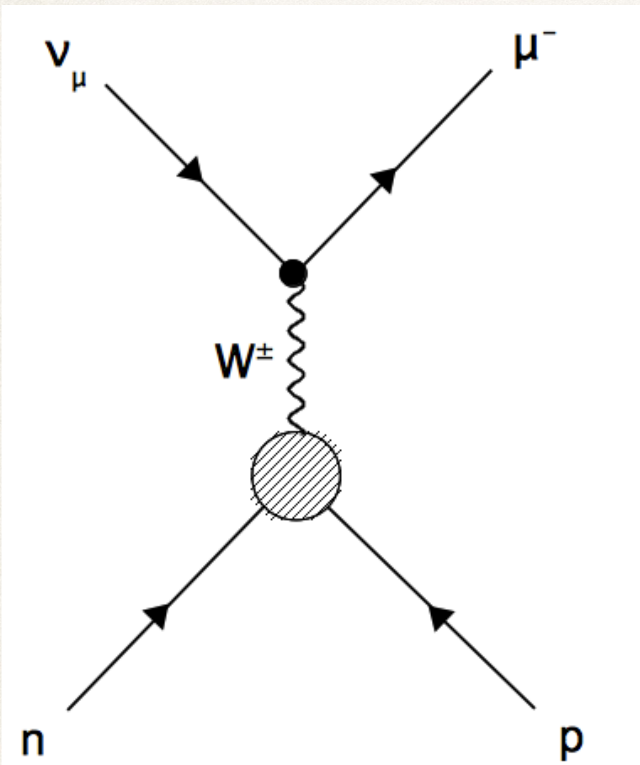
DIS:
Deep Inelastic Scattering

Understanding all of these channels is crucial to oscillation experiments.

Today, my focus is on quasi-elastic scattering of neutrinos and anti-neutrinos.

Quasi-Elastic Scattering

Neutrino-nucleon quasi-elastic scattering:



- Commonly used as a signal channel in oscillation measurements
  - Clean experimental signature
  - Identifies neutrino flavor
  - Kinematics can be reconstructed (assuming a nucleon at rest) using lepton measurement alone:

$$\nu_l + n \rightarrow l^- + p$$
$$\bar{\nu}_l + p \rightarrow l^+ + n$$

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

Q = Four momentum transferred to the nucleon → $Q_{QE}^2 = 2E_\nu^{QE}(E_\mu - p_\mu \cos\theta_\mu) - m_\mu^2$

Quasi-Elastic Scattering

Neutrino-nucleon quasi-elastic cross section:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}Q^2}_{QE}\begin{pmatrix}\nu_l n \to l^- p \\ \bar{\nu}_l p \to l^+ n\end{pmatrix} = \frac{M^2 G_F^2 \cos^2\theta_C}{8\pi E_\nu^2}\left\{A(Q^2) \mp B(Q^2)\frac{s-u}{M^2} + C(Q^2)\frac{(s-u)^2}{M^4}\right\}$$

C.H. Llewellyn Smith. Neutrino reactions at accelerator energies. Physics Reports, 3(5):261–379, June 1972.

- Sign on B term is negative for neutrinos, positive for antineutrinos
- G_F is the Fermi constant (1.17 x 10^{-5} GeV^{2})
- M is the average nucleon mass (939 MeV)
- θ_C is the Cabbibo angle ($\cos \theta_C = 0.9742$)
- s and u are Mandelstam variables
- E_ν is the incoming neutrino energy
- A, B and C are combinations of hadronic form factors….

Quasi-elastics are often described as "simple"…

Quasi-Elastic Scattering

Neutrino-nucleon quasi-elastic cross section:

$$A(Q^2) = \frac{m_\mu^2 + Q^2}{M^2}\left\{(1+\frac{Q^2}{4M^2})F_A^2 - (1-\frac{Q^2}{4M^2})F_1^2 + \frac{Q^2}{4M^2}(1-\frac{Q^2}{4M^2})(\xi F_2)^2 + \frac{Q^2}{M^2}Re(F_1^*\xi F_2) - \frac{Q^2}{M^2}(1+\frac{Q^2}{4M^2})(F_A^3)^2 - \frac{m_\mu^2}{4M^2}\left[|F_1+\xi F_2|^2 + |F_A + 2F_P|^2 - 4(1+\frac{Q^2}{4M^2})((F_V^3)^2 + F_P^2)\right]\right\}$$

$$B(Q^2) = \frac{Q^2}{M^2}Re\left[F_A^*(F_1+\xi F_2)\right] - \frac{m_\mu^2}{M^2}Re\left[(F_1 - \tau\xi F_2)F_V^{3*} - (F_A^* - \frac{Q^2}{2M^2}F_P)F_A^3)\right]$$

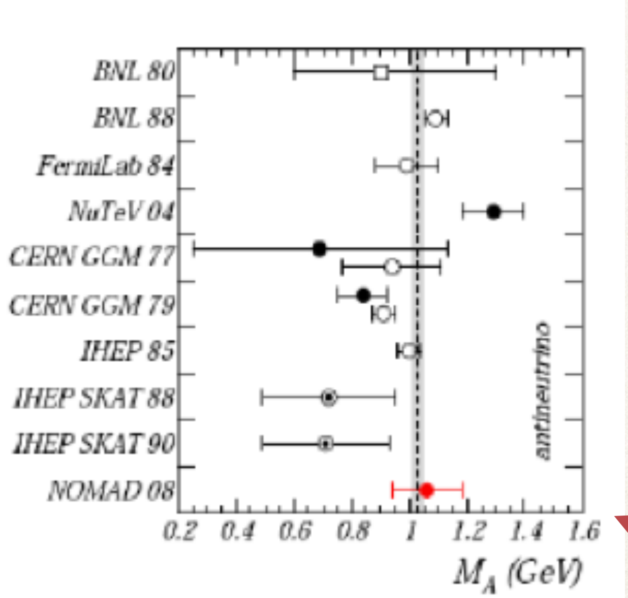
$$C(Q^2) = \frac{1}{4}\left\{F_A^2 + F_1^2 + \tau(\xi F_2)^2 + \frac{Q^2}{M^2}(F_A^3)^2\right\}$$

- Definitely not simple!
  - But actually just combinations of six form factors
    - Two vector (F_1 and F_2), an axial vector (F_A), a pseudoscalar (F_P), and two small second order terms (F_A^3 and F_V^3)

Quasi-Elastic Scattering

Neutrino-nucleon quasi-elastic cross section:

- All but the axial form factor are known from electron-nucleon scattering experiments
    - Only the F_A is most easily measured via neutrino scattering; it is typically approximated as a dipole:



from Lyubushkin, etal [NOMAD collab] Eur.Phys.J.C63:355-381,2009

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

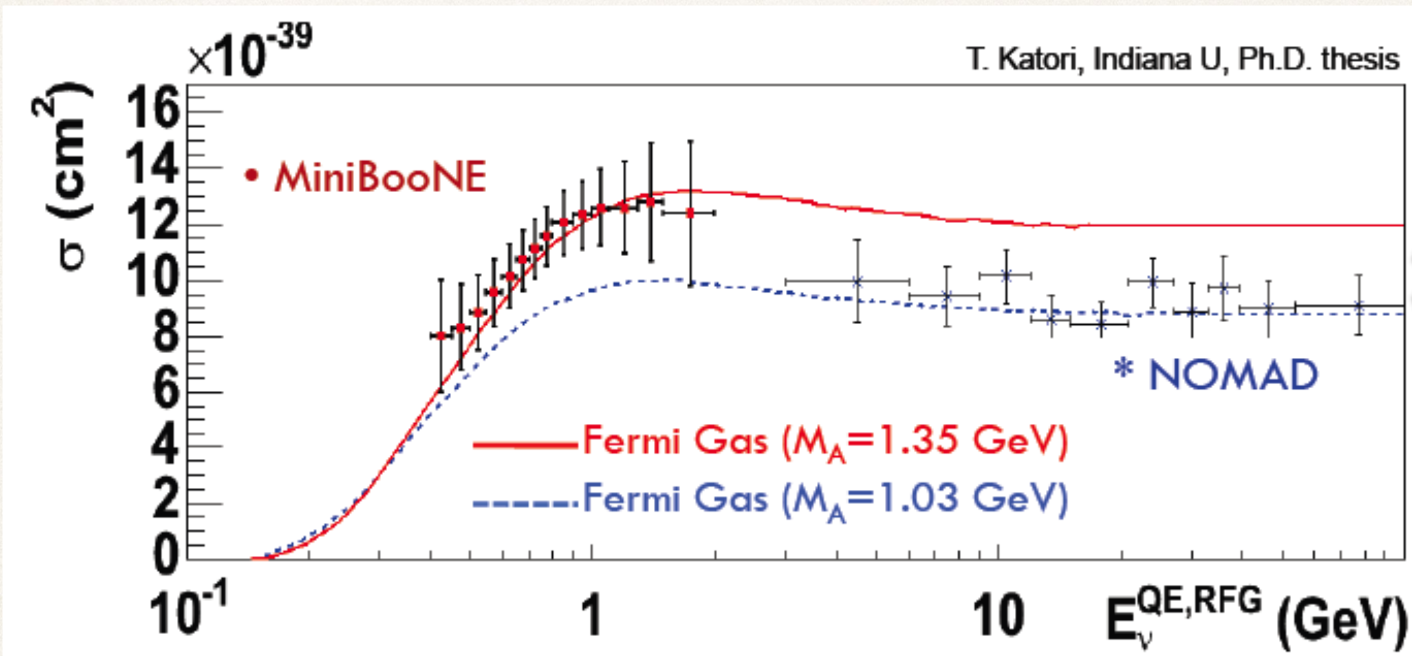
← Known from beta decay

We are left with only one unknown parameter in the quasi-elastic form factor, an axial mass. It modifies both the Q^2 shape and total cross-section.

M_A has been measured a lot, often in Deuterium bubble chambers; as of 2003, experiments agreed that M_A is ~ 1 GeV

Recent Measurements of M_A

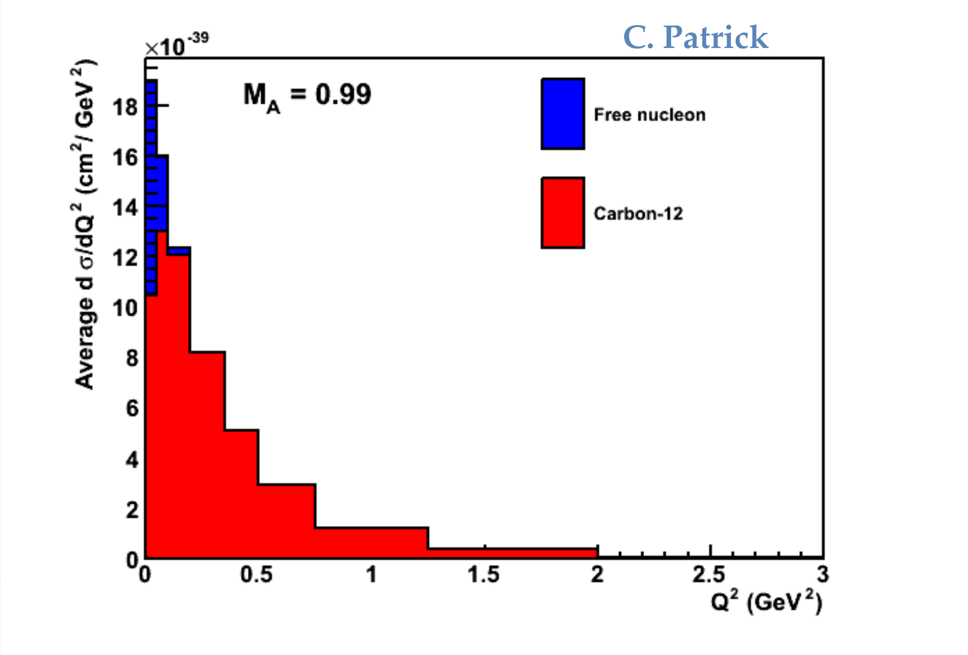
- The MiniBooNE experiment turned the view that quasi-elastics and M_A are well understood upside down:



The MiniBooNE data prefer a much larger axial mass than older experiments; this preference is supported by SciBooNE, K2K and MINOS

What’s Going On?

- One issue: everything I’ve told you so far applies to neutrino-nucleon scattering
- But modern neutrino detectors are made of heavy nuclei (which yield high event rates)
  - The nucleons within particle detectors are not free!



Some ways that the nucleus modifies the interactions:

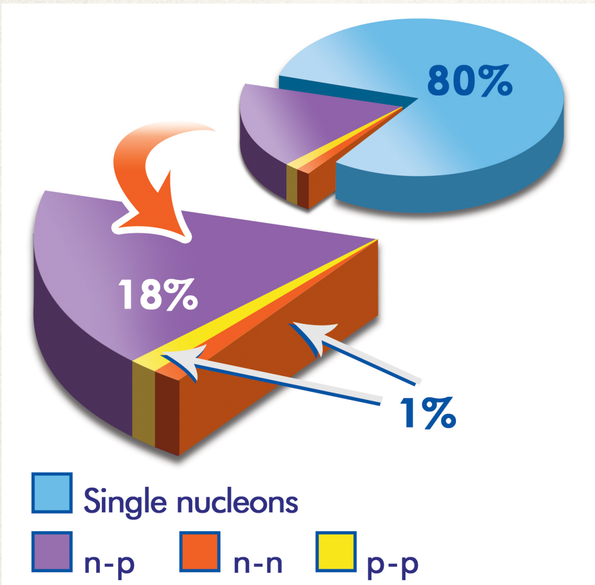
Pauli blocking reduces the cross-section at low Q^2

Final state particles can interact as they exit the nucleus

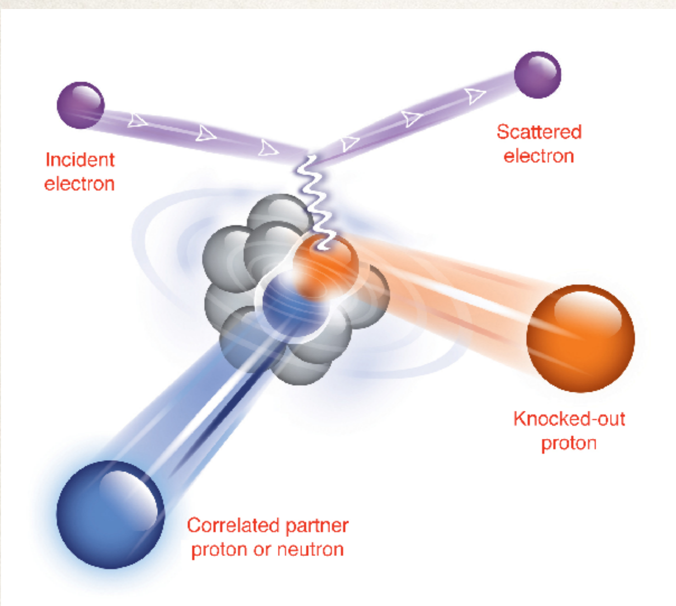
Initial state nucleons have Fermi momentum → smears final state kinematics

Neutrinos can interact with multi-nucleon bound states

Multi-Nucleon Bound States

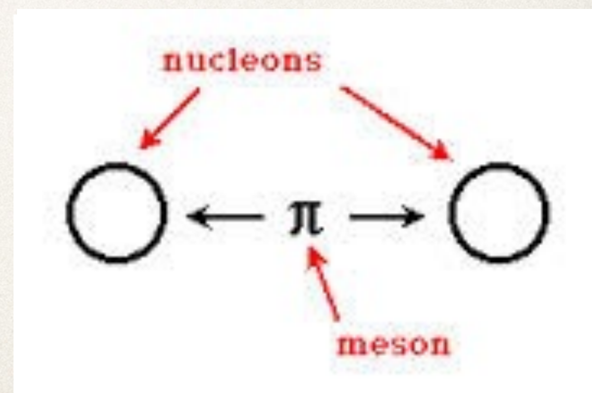


R. Rubedi et al., Science 320, 1476 (2008)

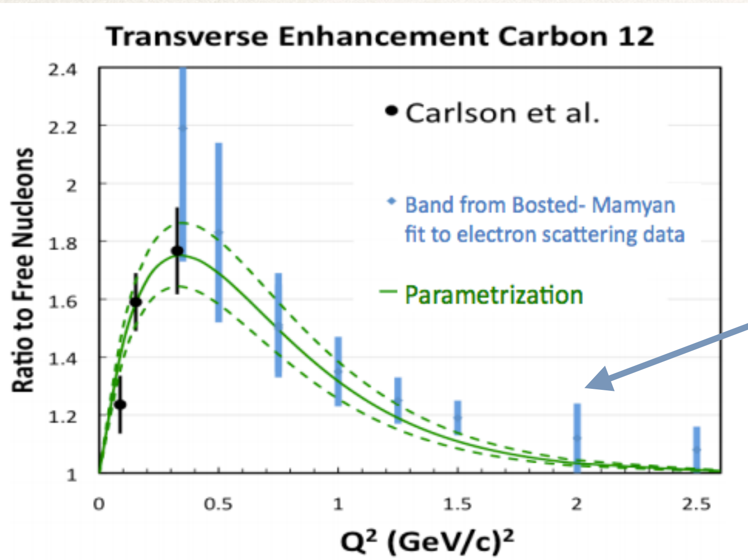


- We know from electron scattering that ~20% of nucleons are involved in **Short Range Correlations.**
- Neutrino interactions with other correlations known as **Meson Exchange Currents** have also been hypothesized.

The impact of nuclear correlations on quasi-elastic (and other) neutrino scattering is **not well understood**, but there are indications that their **effects are substantial.**

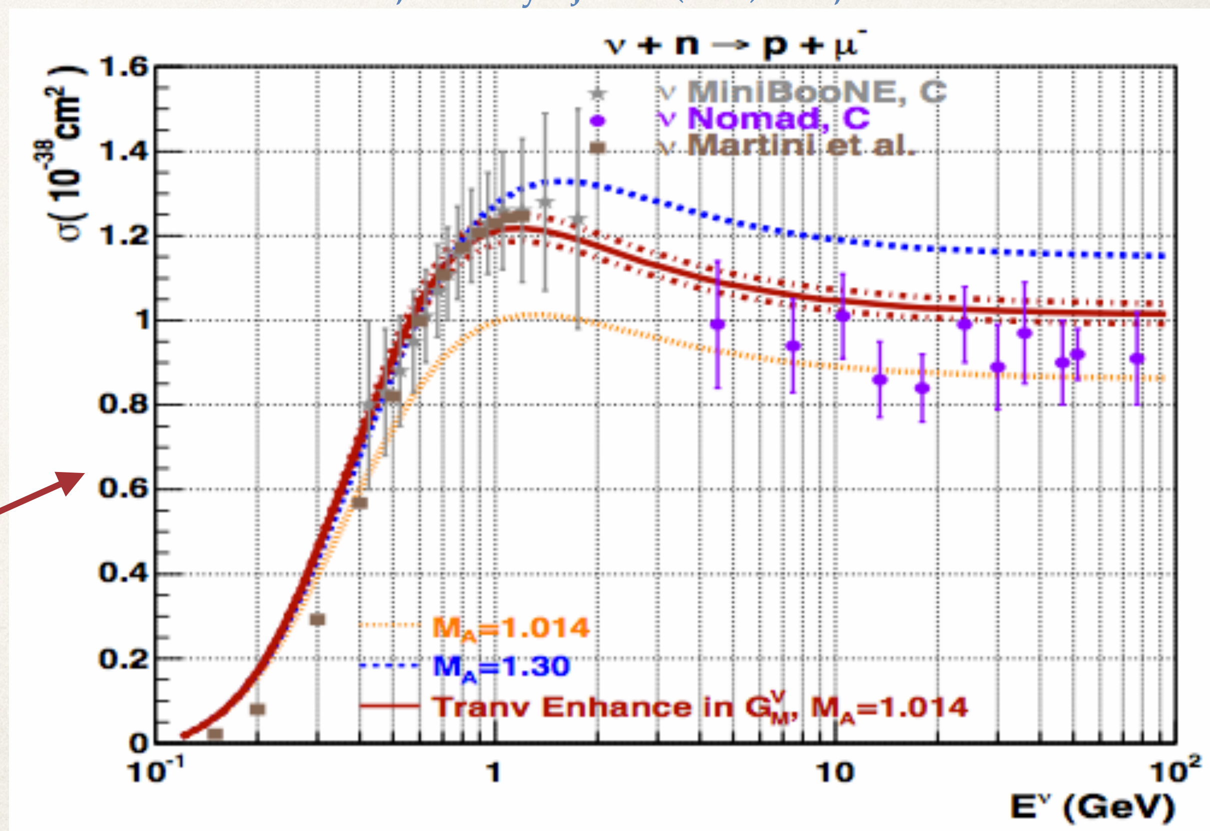


Experimental hits of MEC



- An enhancement of the transverse component of the quasi-elastic electron scattering cross section on Carbon is thought to be due to Meson Exchange Currents

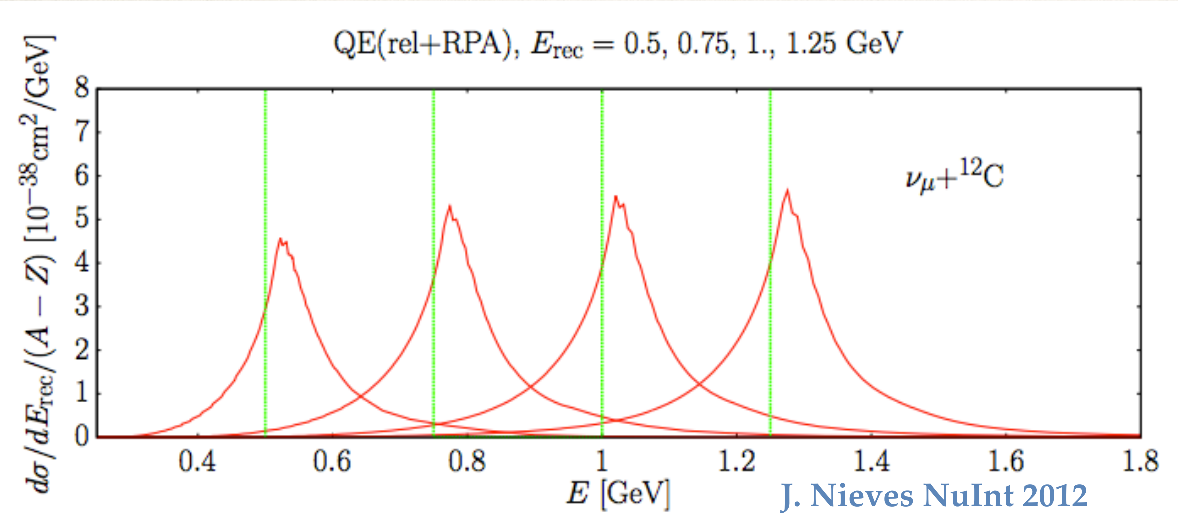
A. Bodek et al, Eur. Phys. J. C 71 (2011) 1726, arXiv:1106.0340



- This enhancement has been parameterized and used to predict a MEC contribution to neutrino scattering

- This transverse enhancement model (TEM) is a better fit to MiniBooNE and Nomad data than a modification of M_A

Impact of MEC on Oscillation Physics

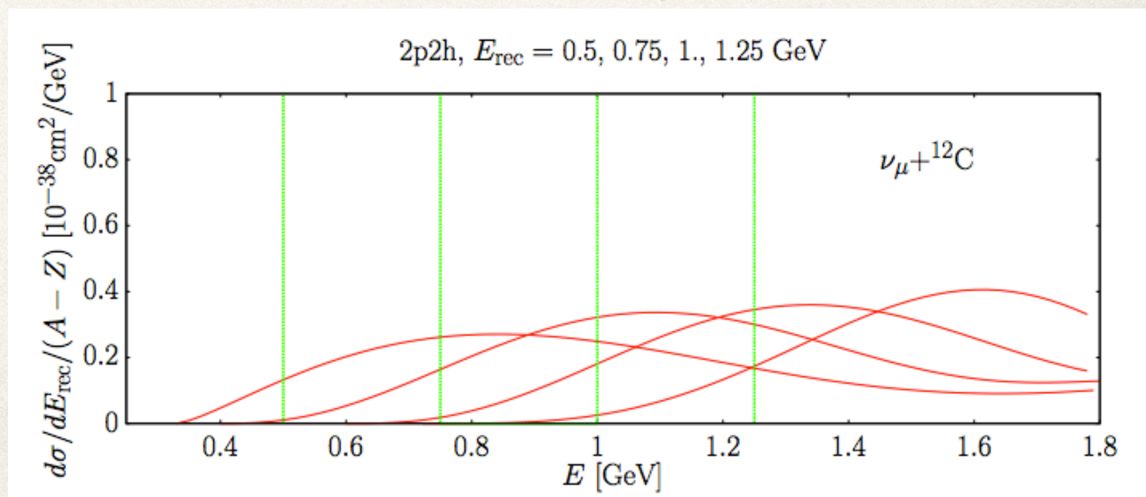


- Neutrino energy reconstructed assuming a quasi-elastic hypothesis is similar to true energy in standard quasi-elastic interactions

Reconstructed (green) and true (red) energy in traditional quasi-elastic scattering assuming perfect detector resolution

Reconstructed (green) and true (red) energy in Meson Exchange Current events assuming perfect detector resolution

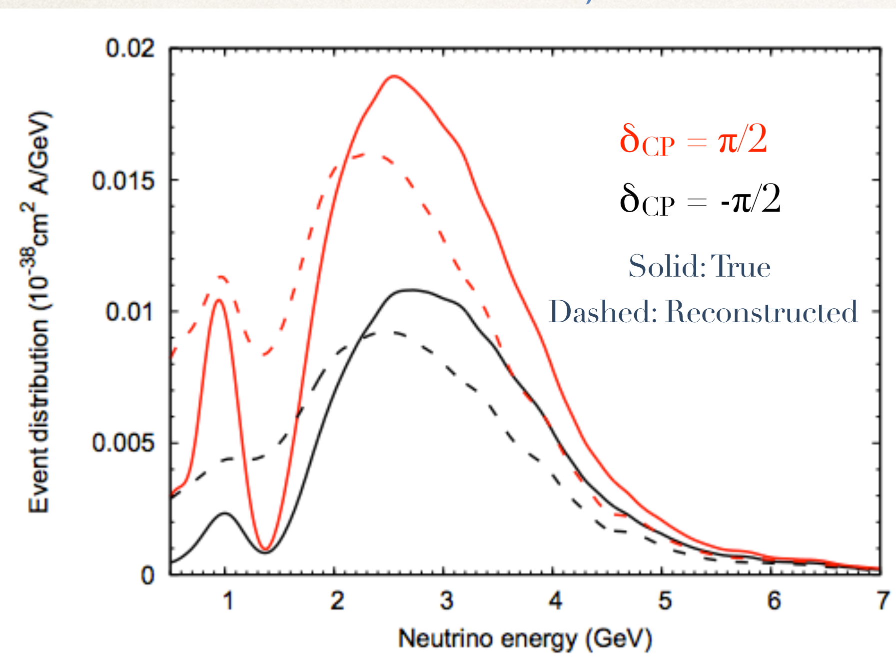
- Energy reconstruction using a quasi-elastic hypothesis does not work on MEC events.



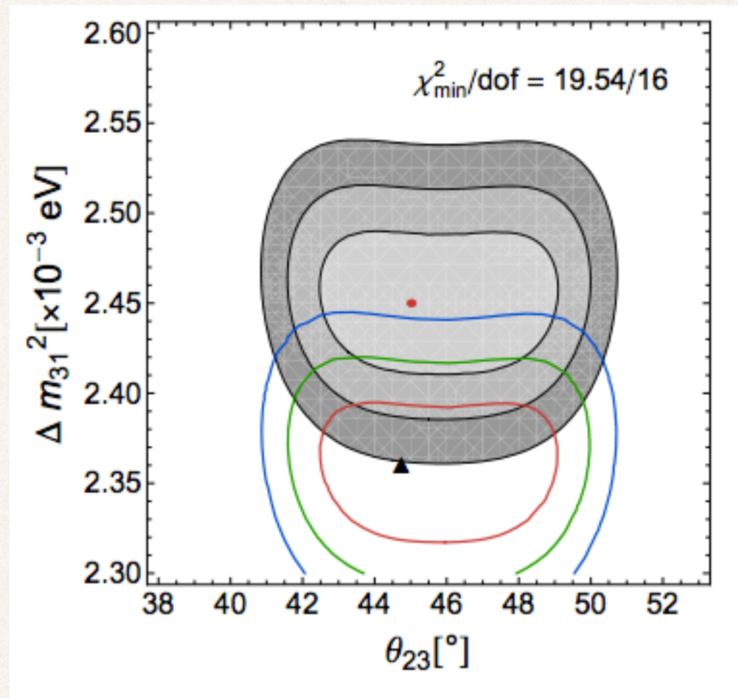
Impact of MEC on Oscillation Physics

This energy smearing has a big effect:

U Mosel et al, arXiv:1311.7288



P Coloma et al, arXiv:1311.4506



LBNE electron appearance spectrum is substantially distorted by MEC effects, especially below ~1.5 GeV

Simulations indicate that the presence of MEC shifts T2K muon disappearance results by ~3σ if not accounted for in fits.

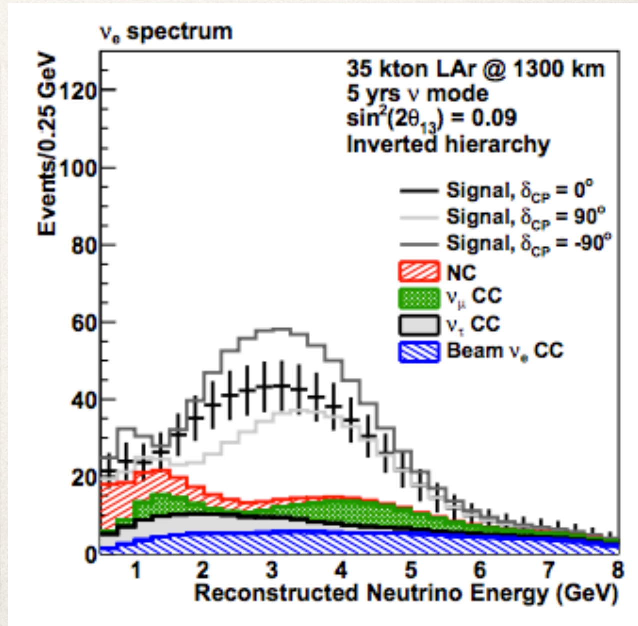
Summarizing the Quasi-Elastic Situation

- Understanding quasi-elastic interactions is **crucial for oscillation experiments**
- Scattering experiments have produced **contradictory cross section measurements** that indicate significant nuclear effects are present
- Theorists have postulated **QE-like processes** that would have big implications but have yet to be experimentally confirmed

Oscillation measurements are moving into a new era that will involve **high-precision measurements** and searches for **subtle effects** especially differences between **neutrinos and antineutrinos.**

A much clearer understanding of quasi-elastic interactions will be necessary for this next generation to succeed.

The MINERvA detector was designed to make this happen.

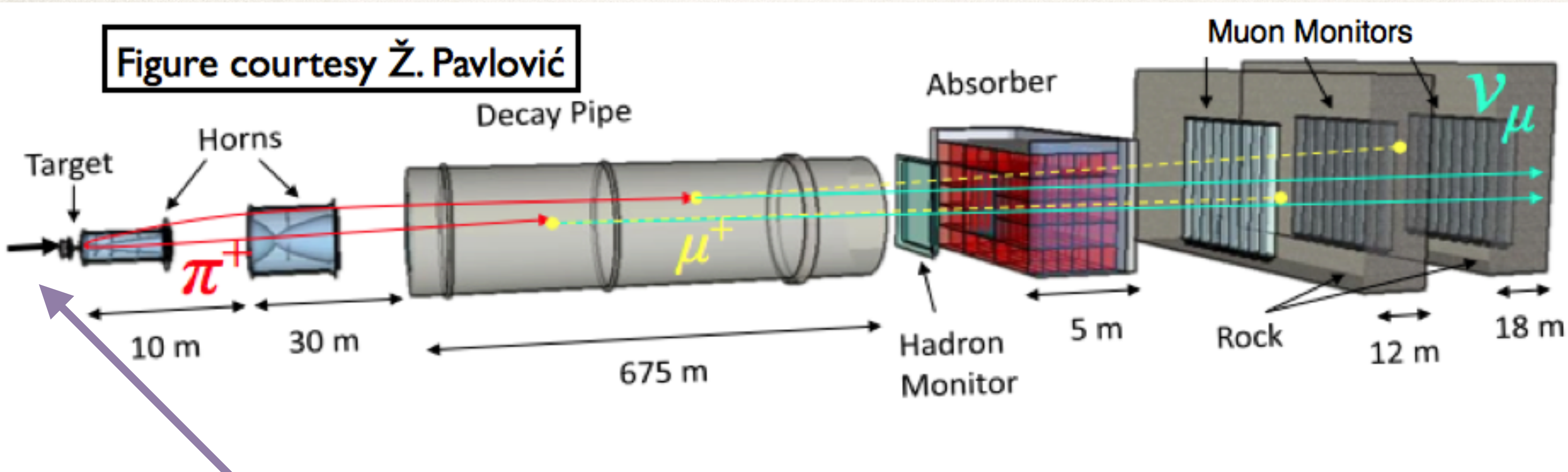


The NuMI Beamline

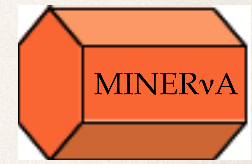
&

The MINERνA Detector

The NuMI Beamline



~210 m of rock

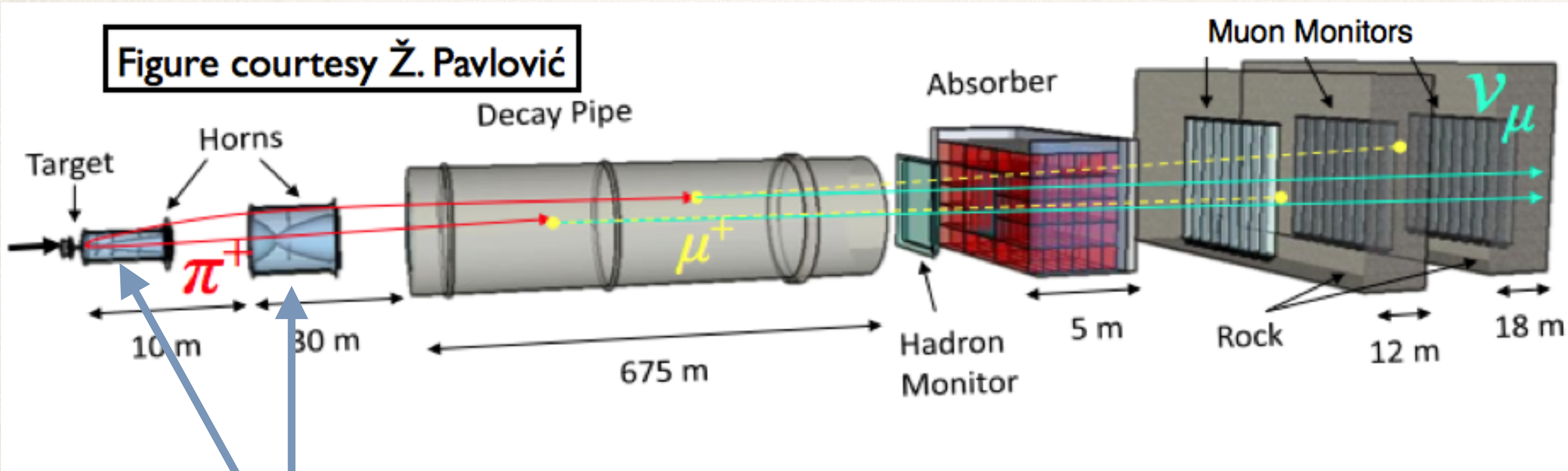


The NuMI neutrino beam starts with a 120 GeV proton beam from Fermilab's main injector

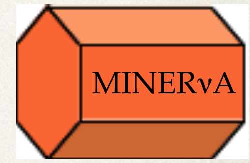
35e12 protons per "spill"
spill rate ~0.5 Hz

- Protons impinge on a graphite target, creating charged pions and kaons (among other things)

The NuMI Beamline



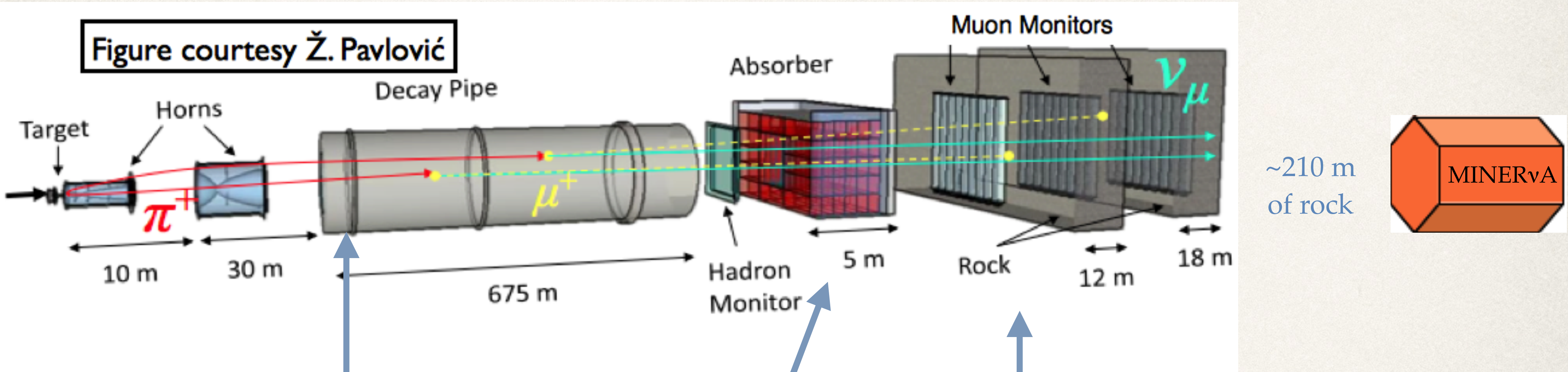
~210 m of rock



The pions and kaons are focused by a pair of horns.

- Horn current is 180 kA in nominal neutrino mode configuration, focusing positive pions
- Reversed to -180 kA to focus negative pions for anti-neutrino mode

The NuMI Beamline

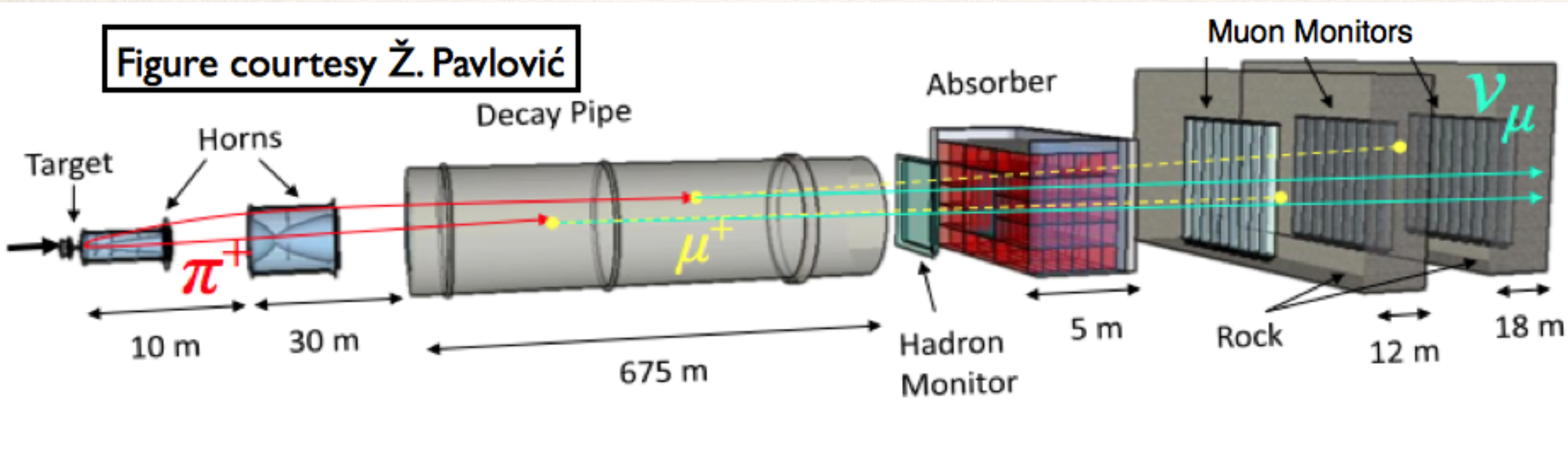


The pions and kaons decay in a 675 m decay pipe to produce muons and neutrinos (among other things)

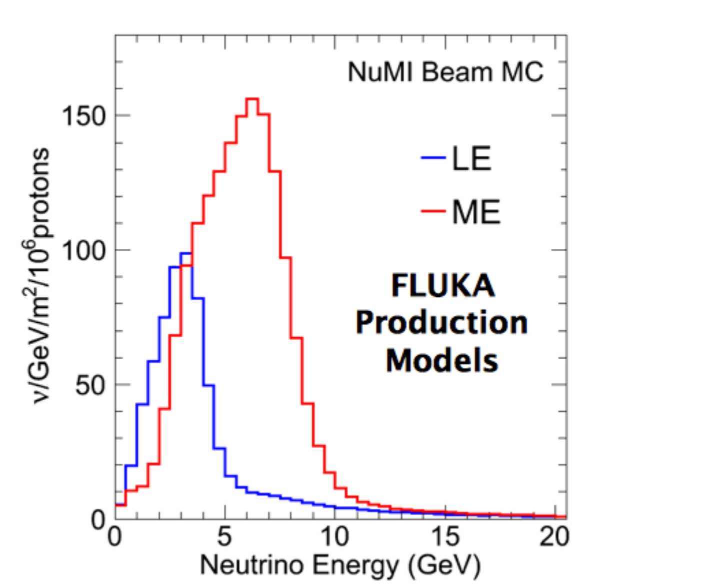
Muons are stopped (and monitored) in the rock downstream of the beam line

Everything but muons and neutrinos are stopped in a hadron absorber

The NuMI Beamline



~210 m of rock



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

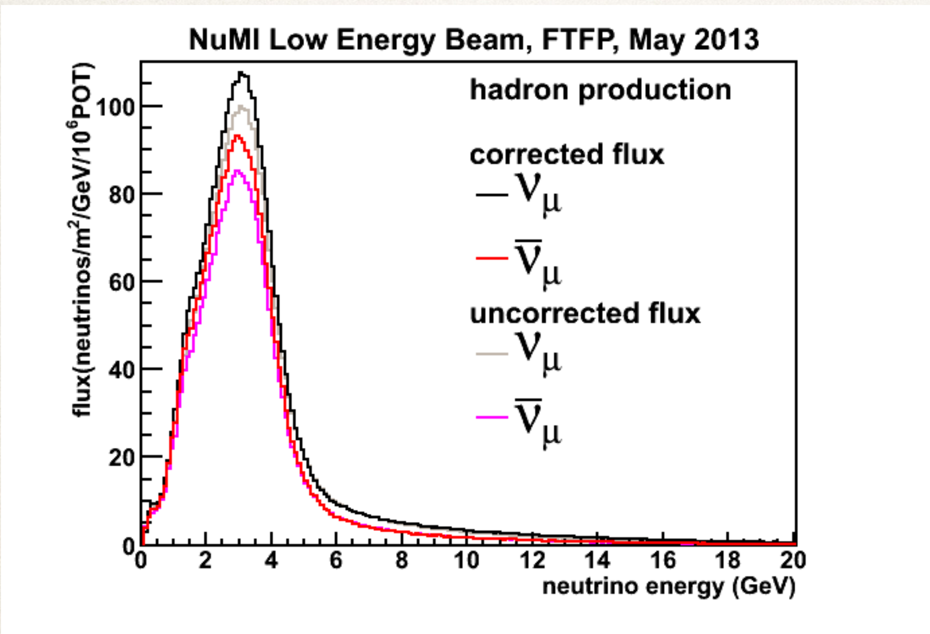
- Target/Horn spacing can be varied to produce different energy spectra
- My talk today focuses on the "Low Energy (LE)" data taken 2010-2012
- We are currently running in the "Medium (ME)" configuration of the NOvA era.

Neutrinos arrive at the MINERvA detector (along with the product of neutrino interactions in the rock).

The NuMI Beamline

“The Flux” = the energy spectrum of the neutrino beam

- Knowing both the normalization and the shape is crucial to neutrino experiments

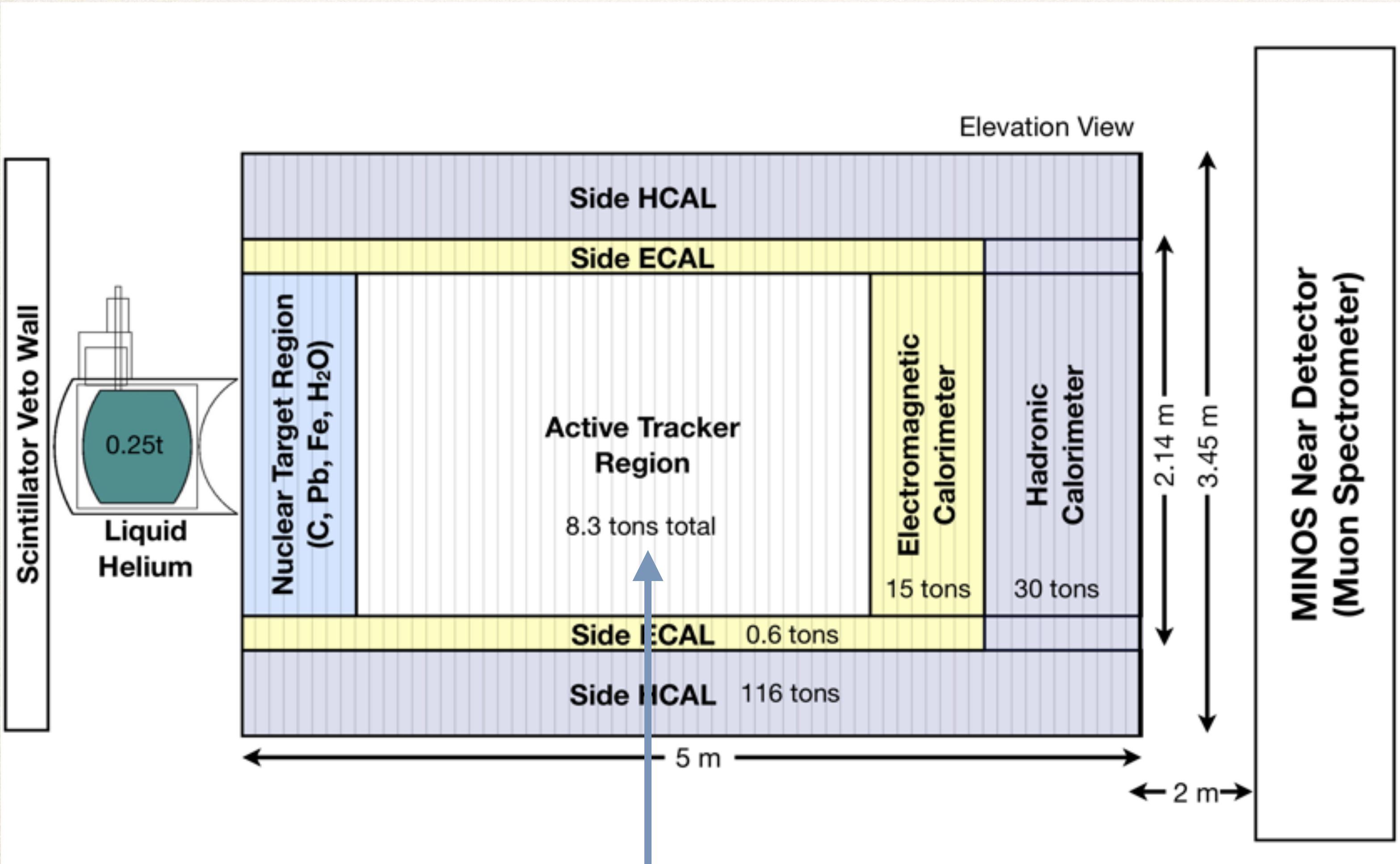


Our flux estimation starts with a Geant4-based simulation of the NuMI beam line.

We then reweight that simulation using NA49 pC → πX data where possible; a large portion of the flux remains unconstrained.

~10% uncertainty on the normalization of cross sections. This will improve in the future.

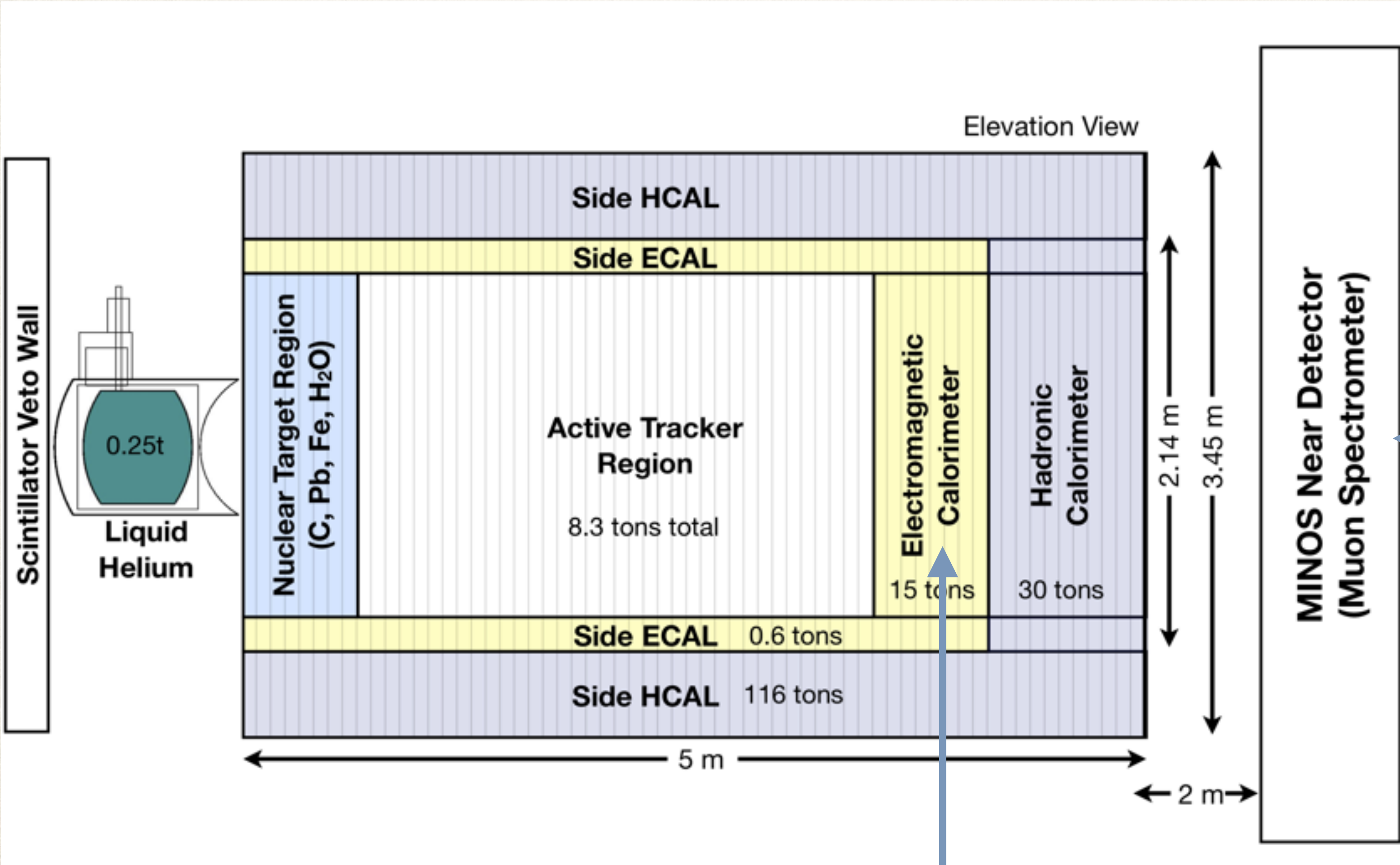
The MINERνA Detector



Tracker region composed of scintillator strips.
All of the interactions discussed in this talk happened here.

The MINERνA detector is made of 120 "modules" of varying composition.

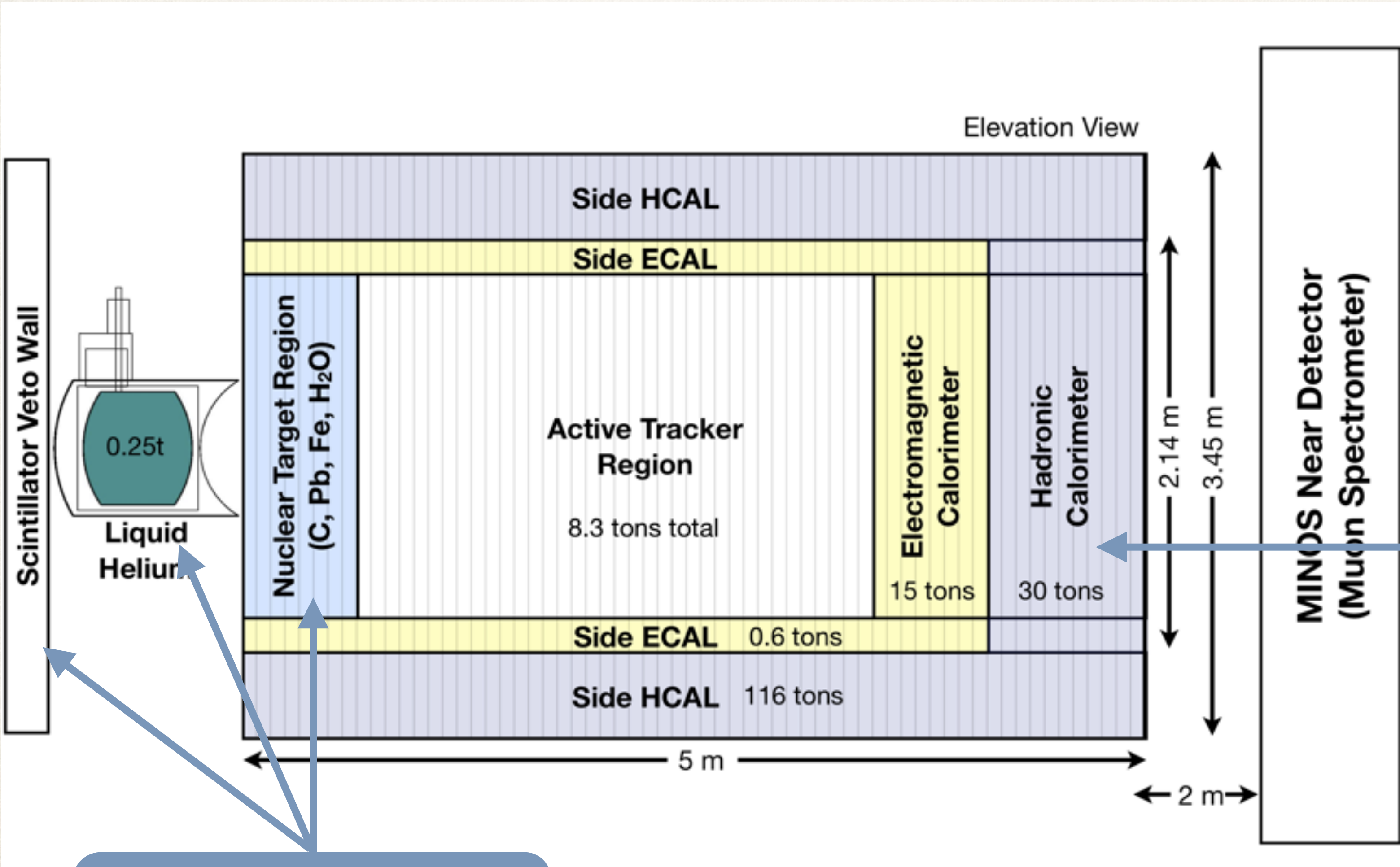
The MINERvA Detector



MINOS near detector: used to identify charge and energy of muons exiting MINERvA

EM Calorimeter is scintillator + lead. Used as part of calorimetric recoil measurements.

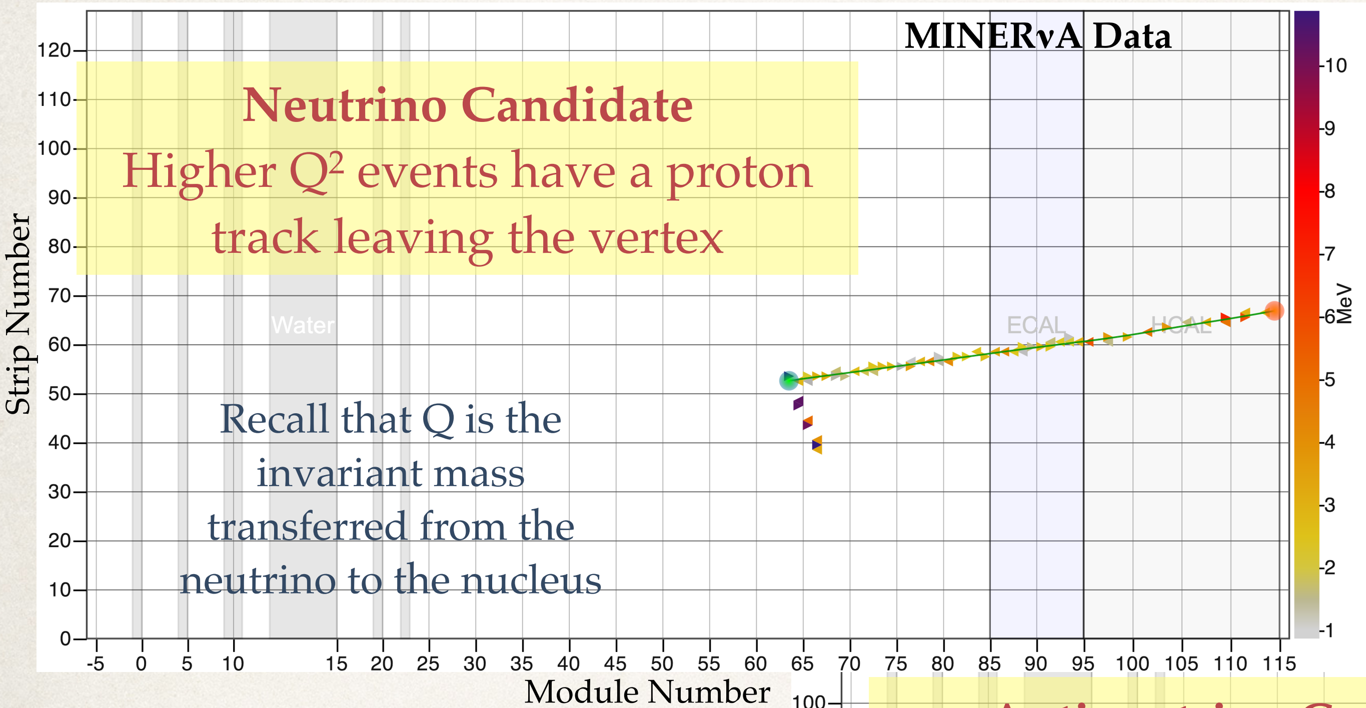
The MINERνA Detector

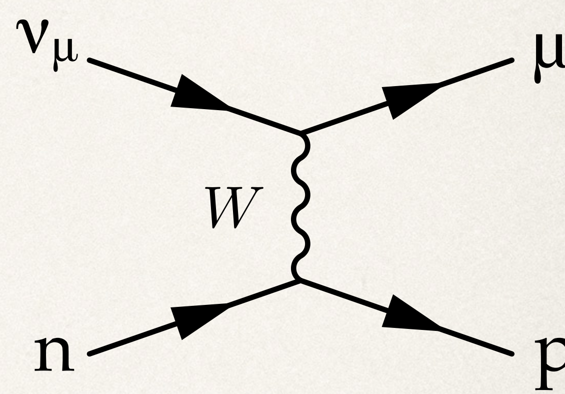


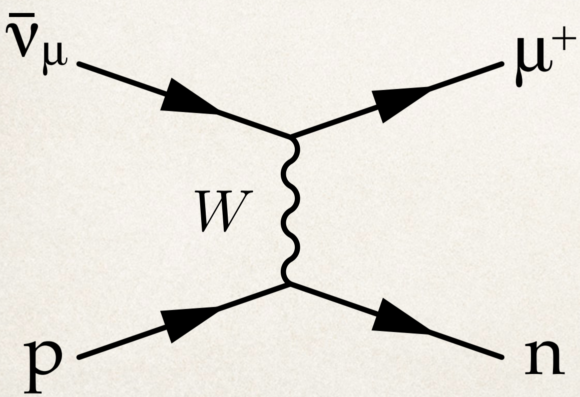
HCAL is scintillator and iron; also not used in the results discussed in this talk

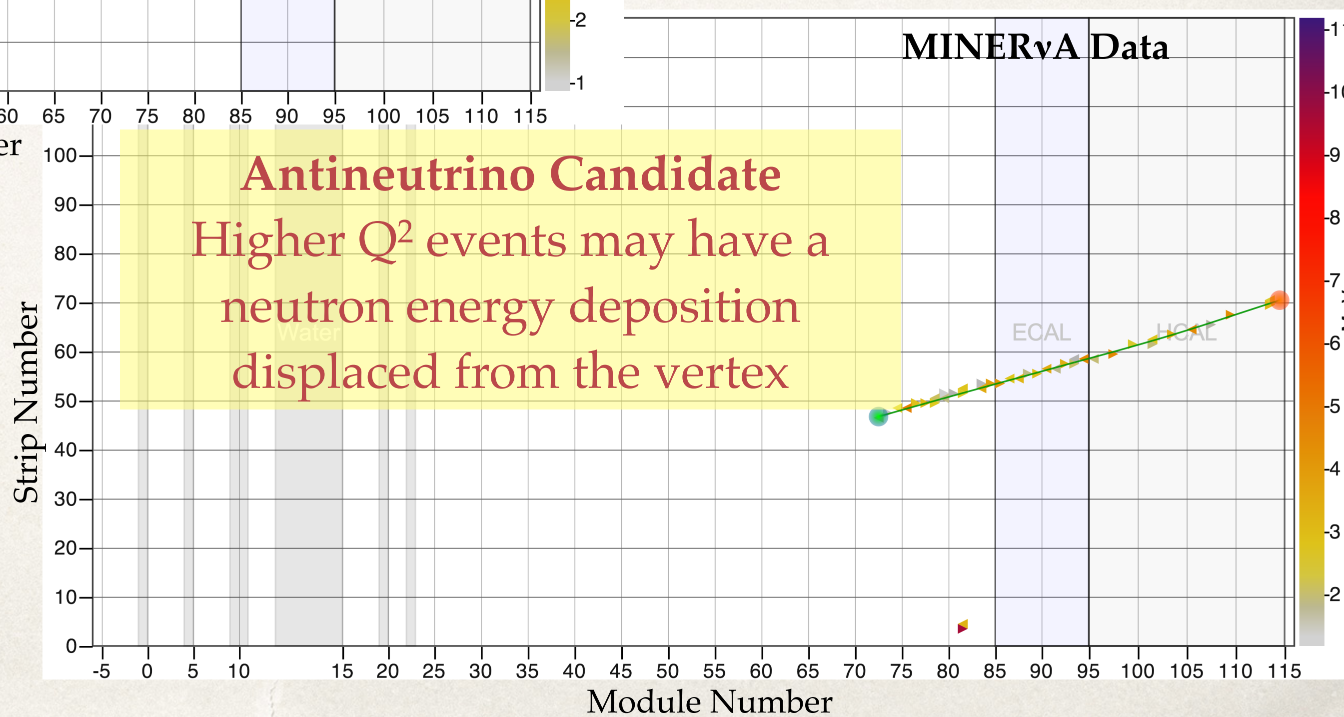
Passive targets and veto wall will be used to compare cross sections across different nuclei in the future, but are not used in today's work.

What QE Looks Like In MINERνA

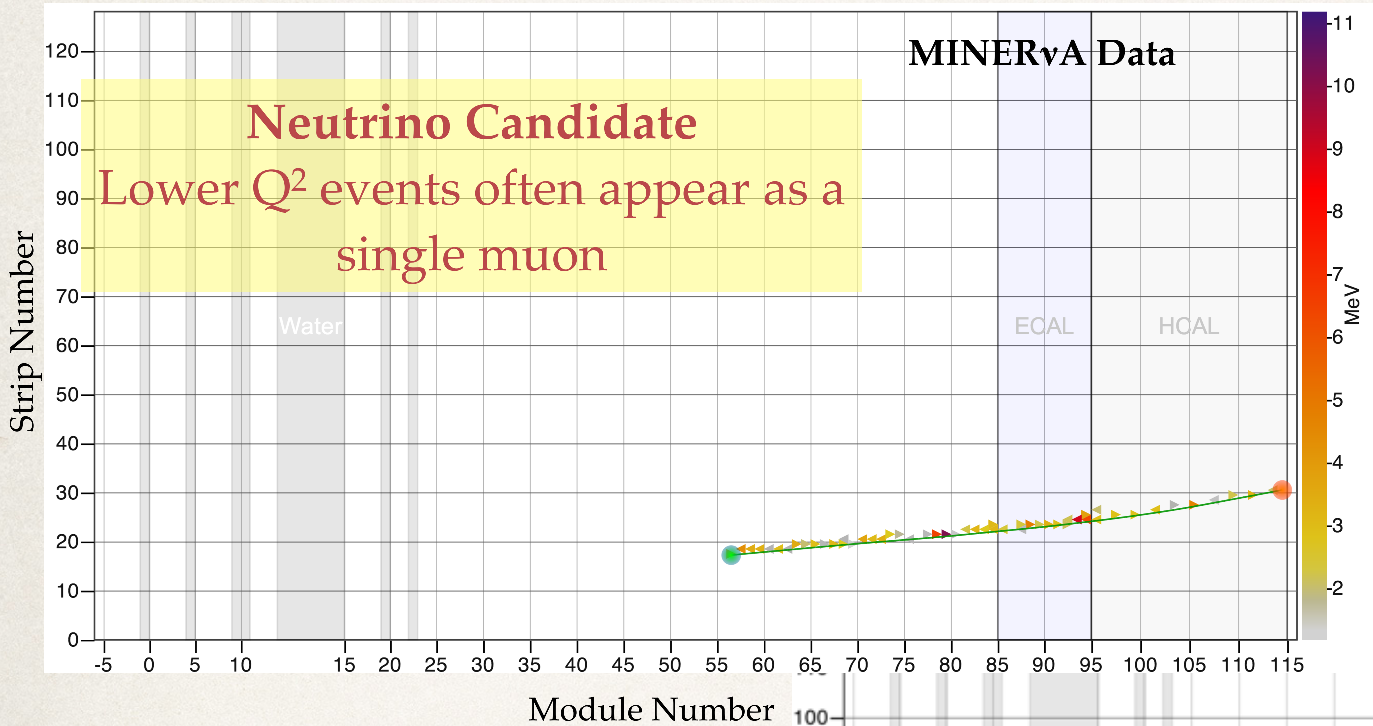


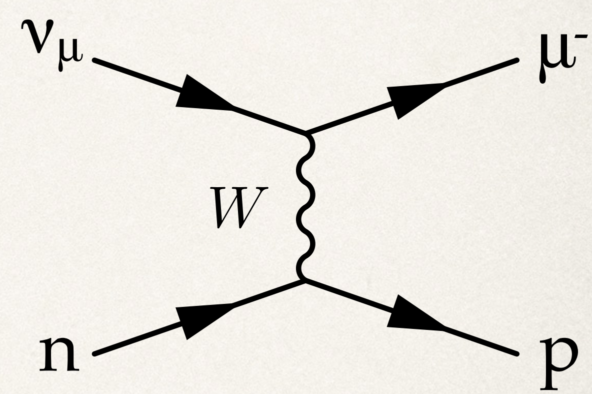


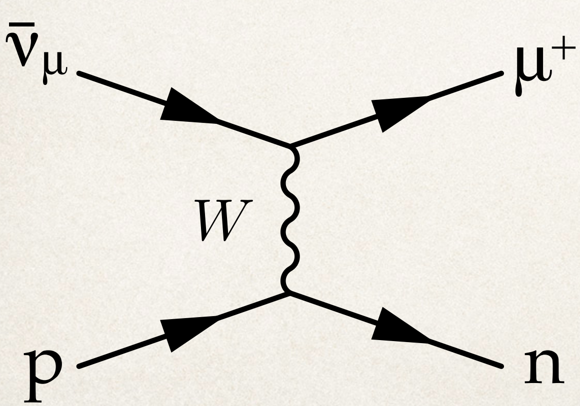


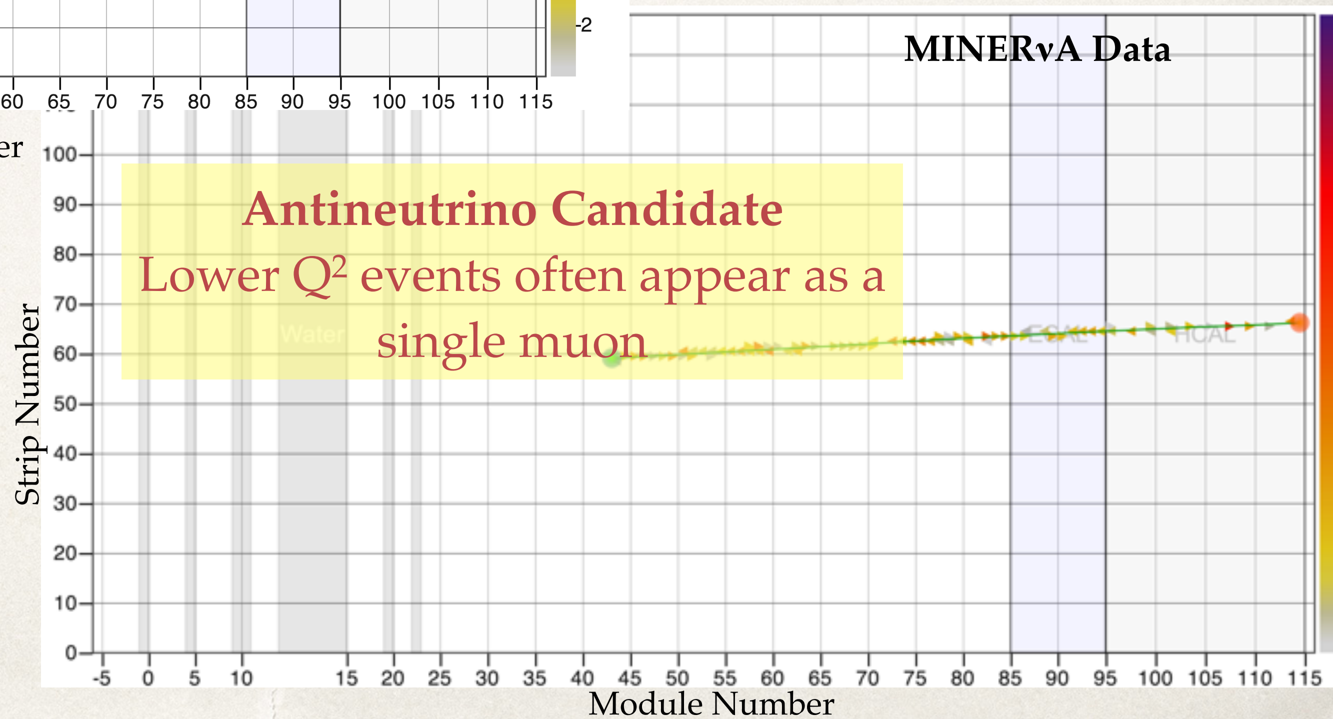


What QE Looks Like In MINERνA

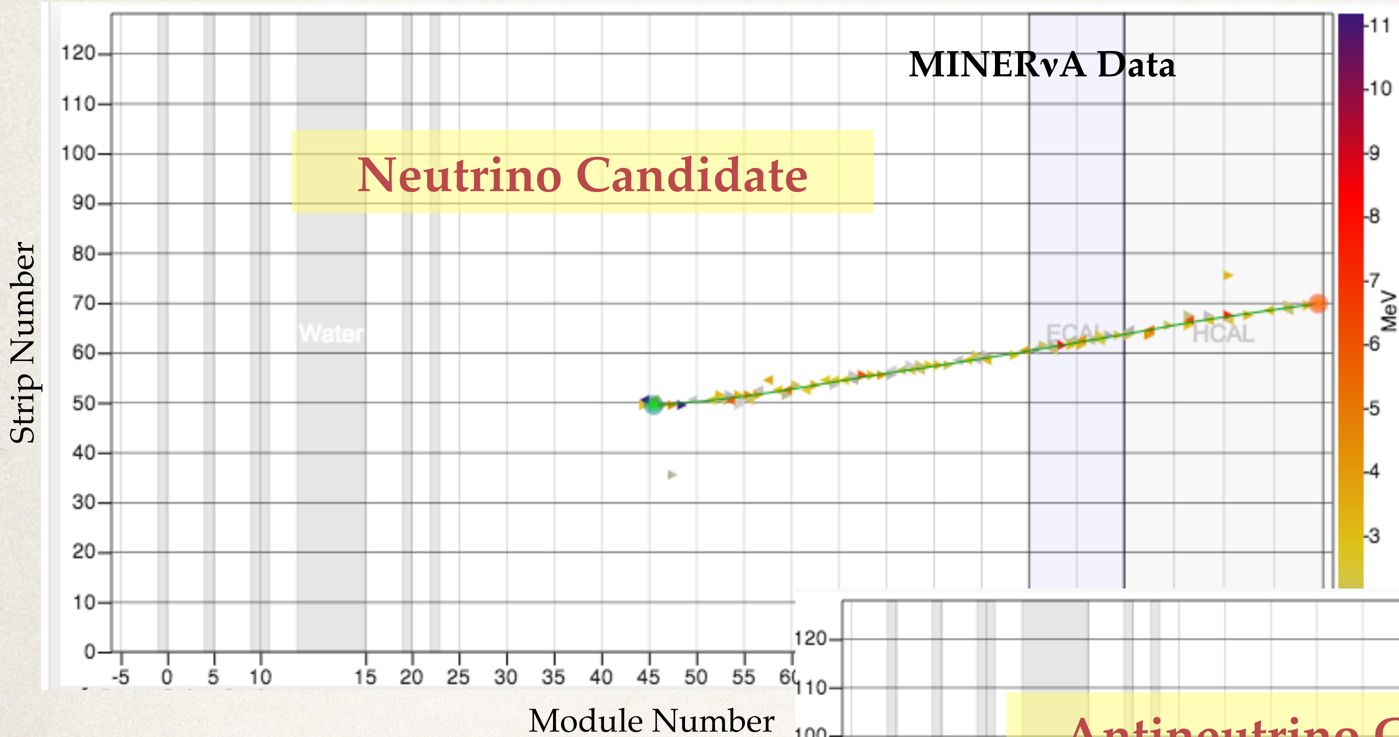






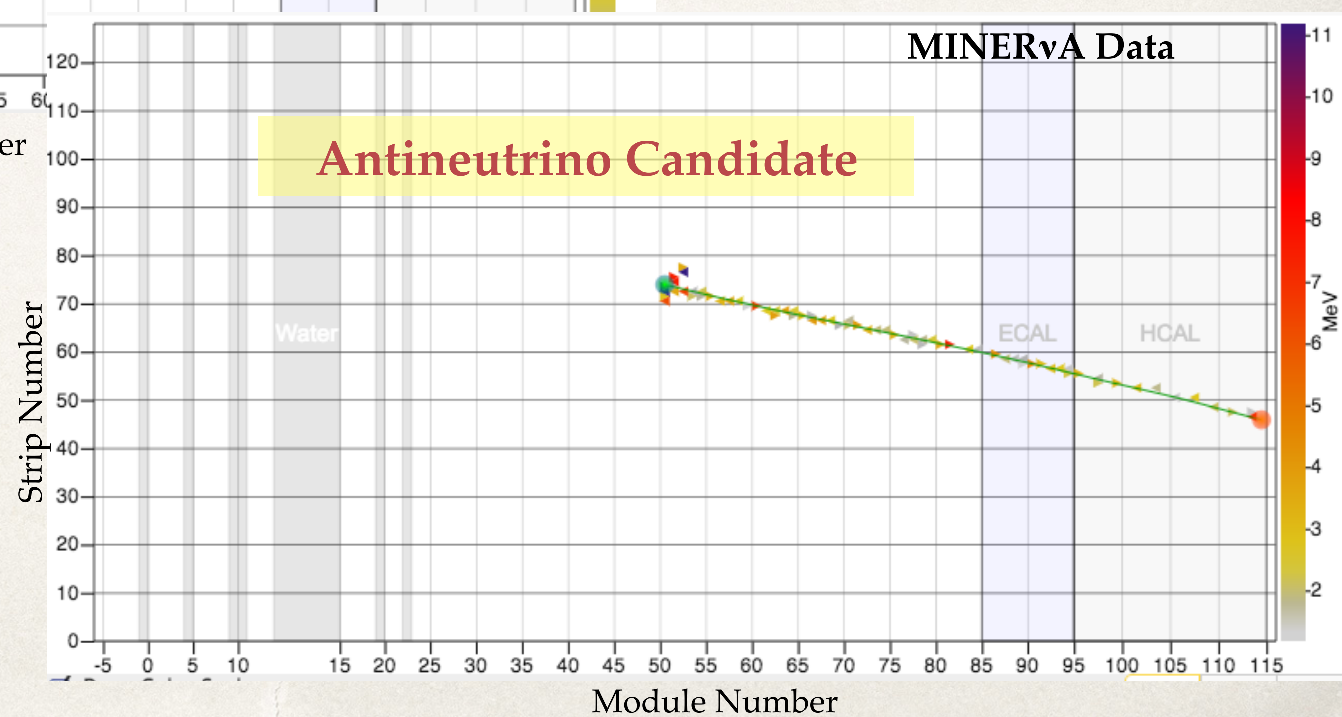


What QE Looks Like In MINERνA

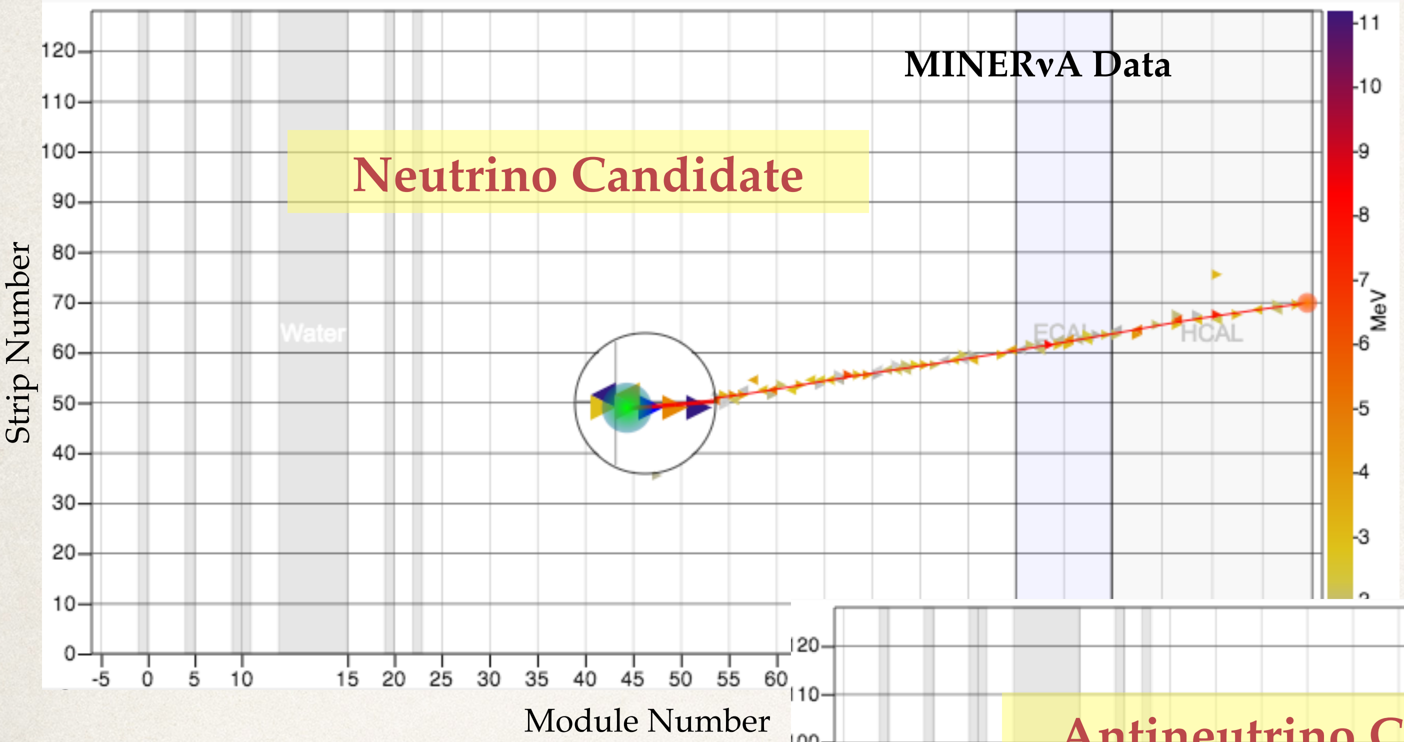


Candidates in both modes can have significant amounts of vertex activity from FSI and other nuclear effects

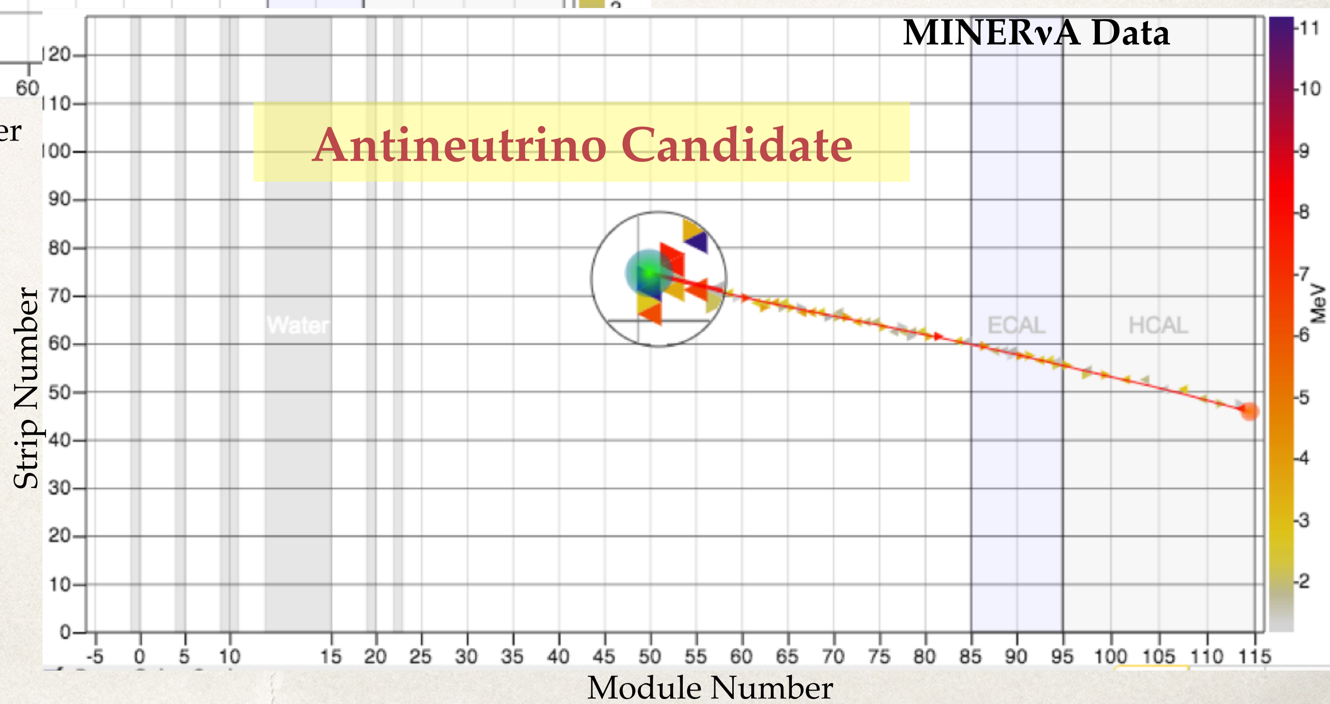
Both analyses I'll discuss today take steps to minimize our sensitivity to energy near the vertex, which we expect to be poorly simulated



What QE Looks Like In MINERνA

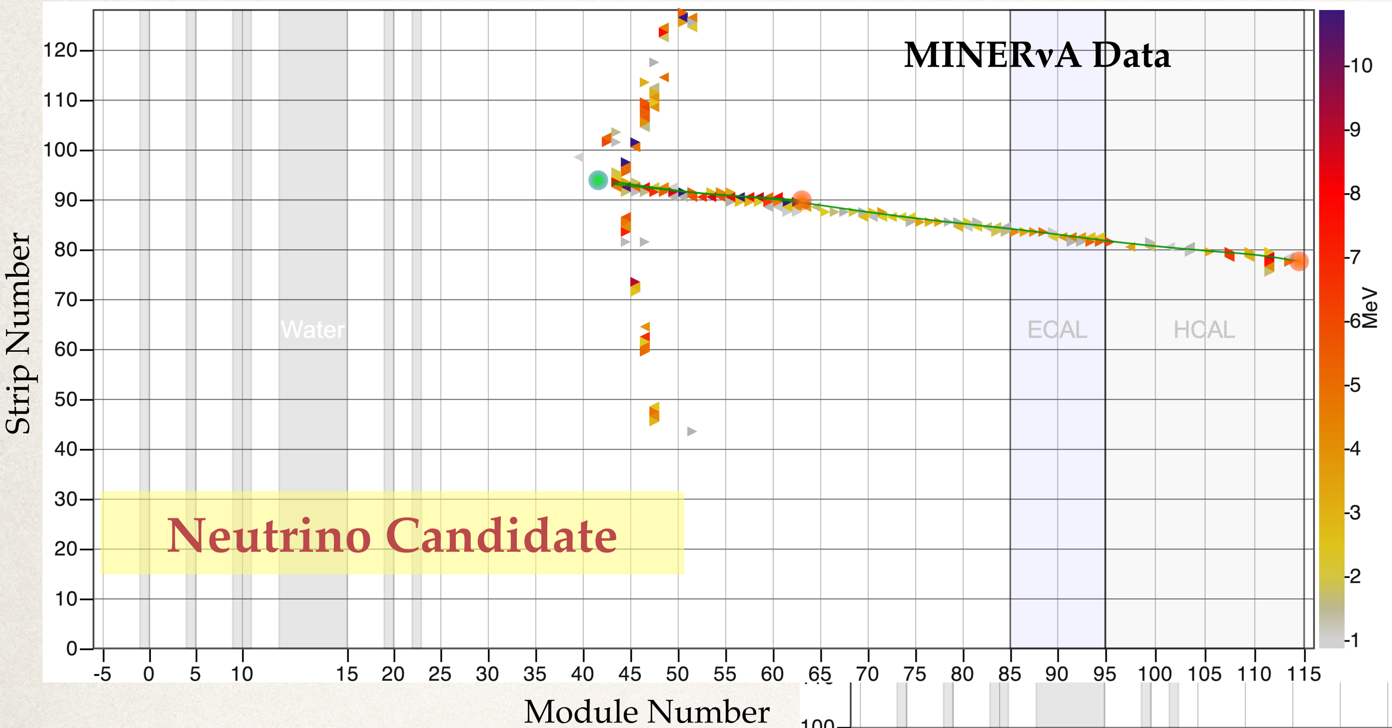


Candidates in both modes can have significant amounts of vertex activity from FSI and other nuclear effects

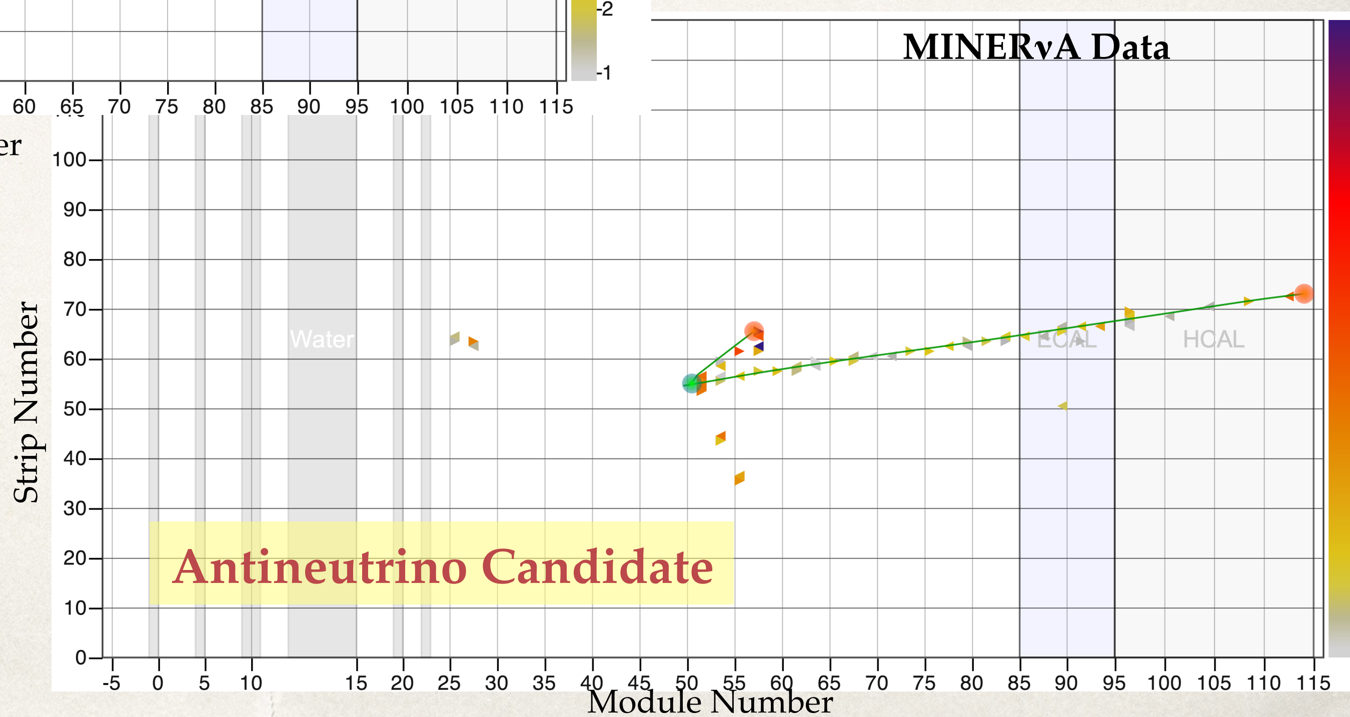


Both analyses I'll discuss today take steps to minimize our sensitivity to energy near the vertex, which we expect to be poorly simulated

What Non-QE Looks Like In MINERνA



Backgrounds usually involve pions and generally have significantly more recoil activity than quasi-elastics



MINERνA Quasi-Elastic Analyses

Analysis Introduction

Laura Fields
http://www.facebook.com/laurajfields?ref=tn_tnmn

PHYSICAL REVIEW LETTERS

week ending
12 JULY 2013

Measurement of Muon Antineutrino Quasielastic Scattering on a Hydrocarbon Target at $E_\nu \sim 3.5$ GeV

PRL **111,** 022502 (2013)

PHYSICAL REVIEW LETTERS

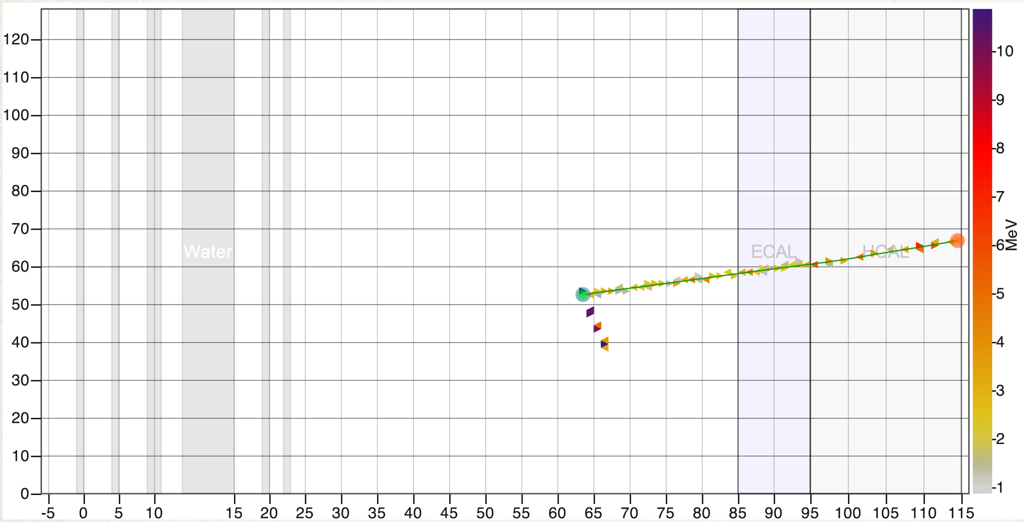
week ending
12 JULY 2013

Measurement of Muon Neutrino Quasielastic Scattering on a Hydrocarbon Target at $E_\nu \sim 3.5$ GeV

G. A. Fiorentini,[1] D. W. Schmitz,[2,3] P. A. Rodrigues,[4] L. Aliaga,[5,6] O. Altinok,[7] B. Baldin,[3] A. Baumbaugh,[3]
A. Bodek,[4] D. Boehnlein,[3] S. Boyd,[8] R. Bradford,[4] W. K. Brooks,[9] H. Budd,[4] A. Butkevich,[10]

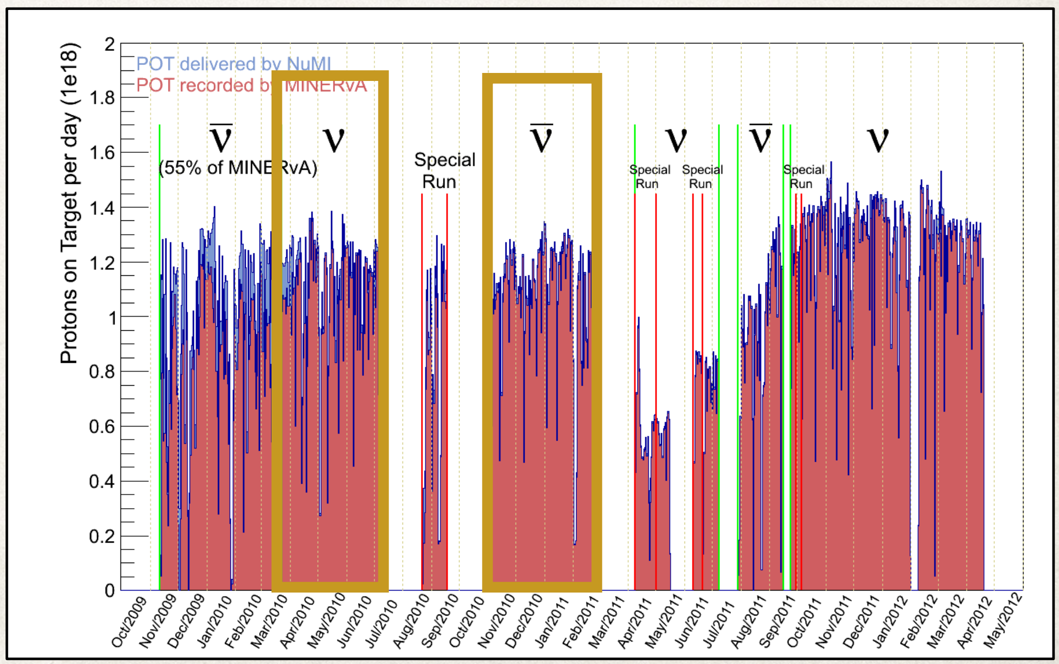
- MINERνA's first two physics results were published this past summer
- Two studies of quasi-elastic scattering in neutrino and anti-neutrino-mode data
- I led both of these analysis; was particularly involved in the antineutrino analysis

Analysis Introduction



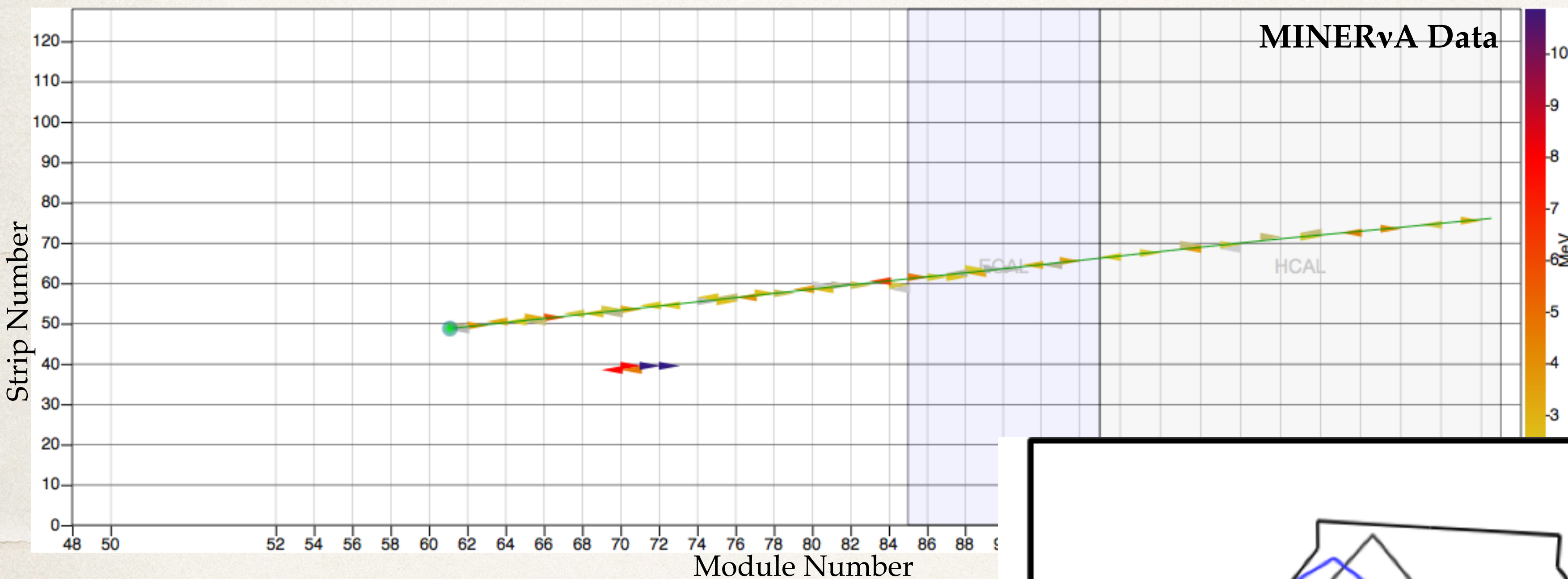
- Uses very simple reconstruction technique
- Reconstructs muon only
- Vetoes backgrounds by looking requiring small amounts of non-muon energy.
- Goal: look for evidence of nuclear effects hinted at by MiniBooNE data.

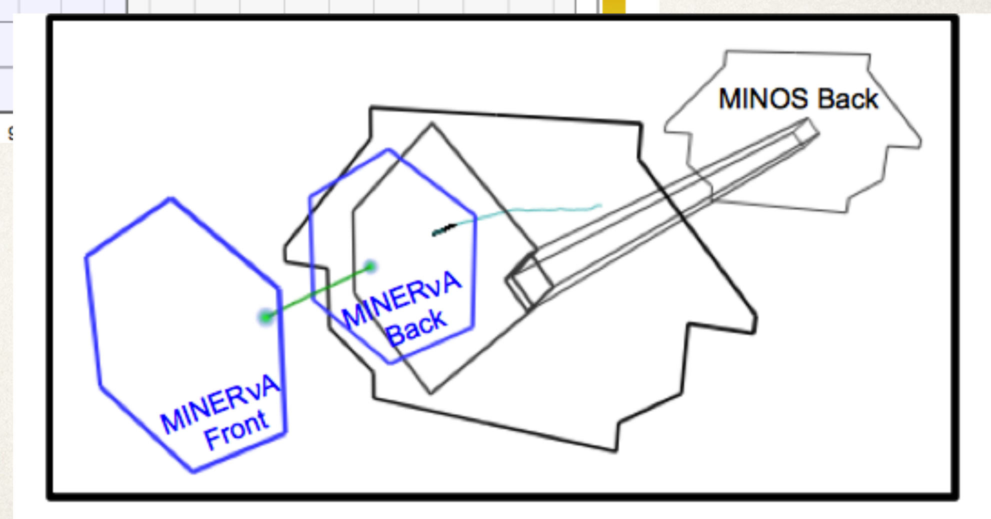
- Both analyses use ~1e20 POT taken at the beginning of MINERνA's low energy run
- More statistics to come in both modes; much more in neutrino mode.



Quasi-Elastic Reconstruction

To reconstruct quasi-elastic events:





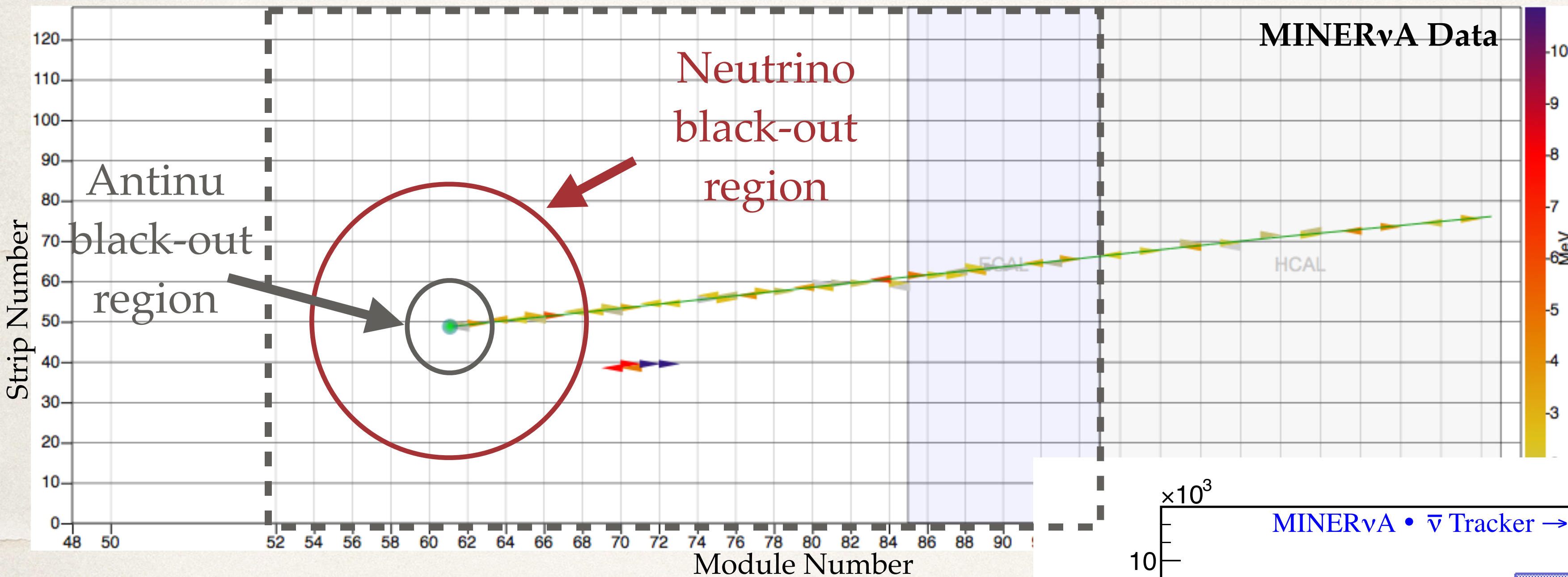
We start by reconstructing muons that are matched into the MINOS detector.

Antineutrino candidates must have positive charge; neutrino candidates must have negative charge.

This excludes muons at low energies and high angles from this sample; they will be recovered in future analyses.

Quasi-Elastic Reconstruction

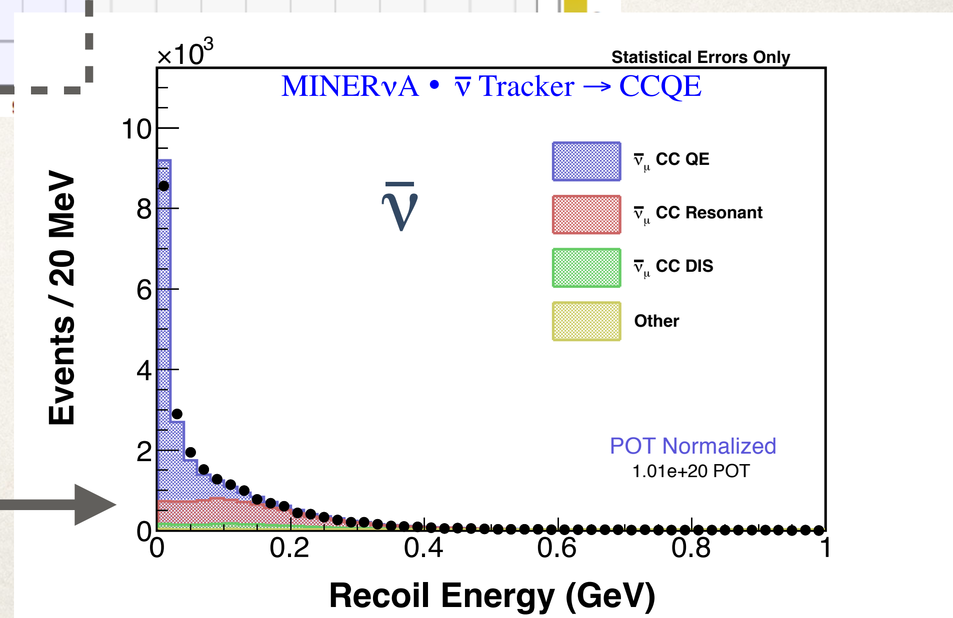
First, we consider the total recoil energy:



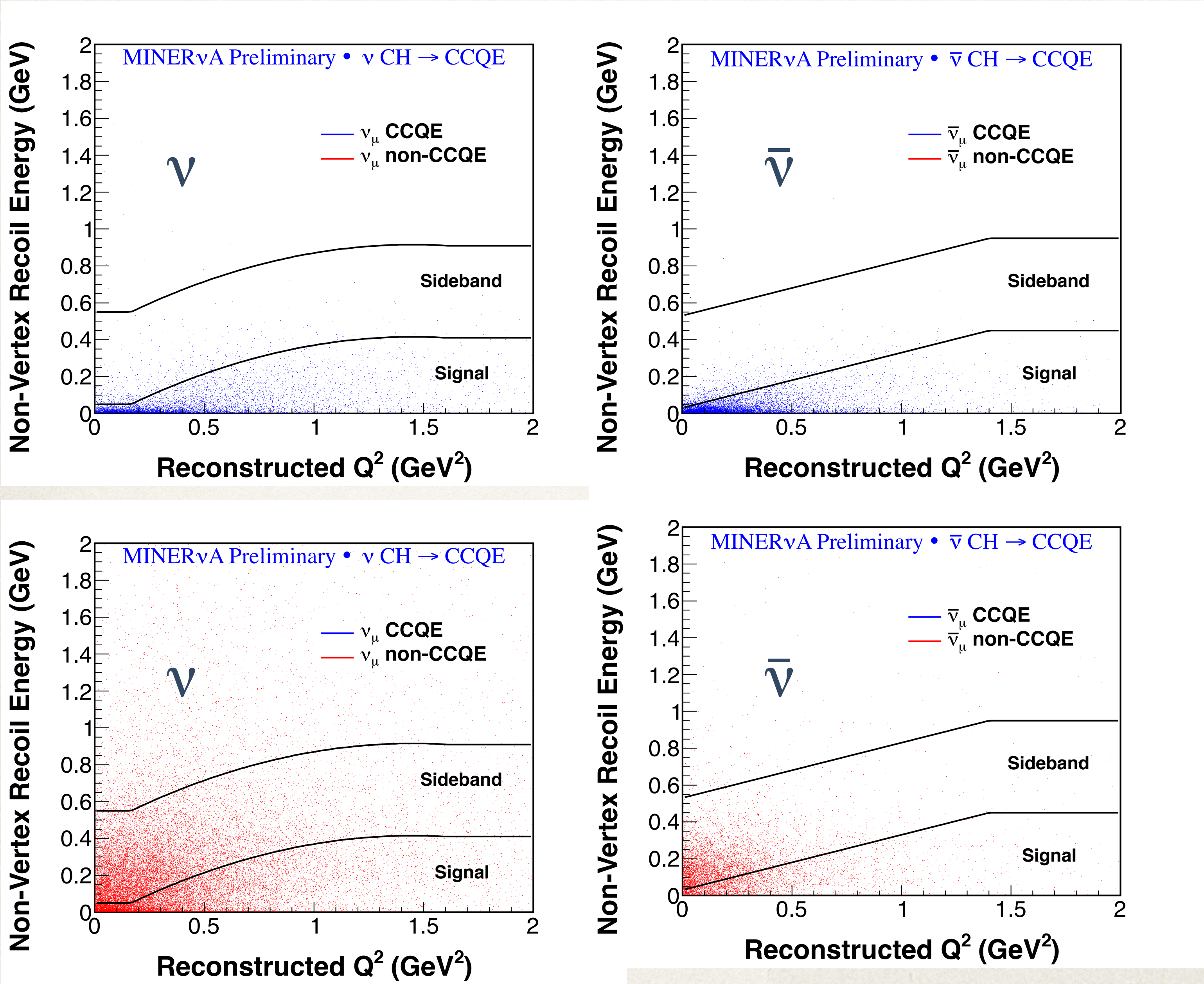
We sum all non-muon energy in the tracker and ECAL

We exclude a 10/30 cm radius around the vertex, as well as very low energy hits and PMT crosstalk hits.

Typically low for CCQE and higher for backgrounds

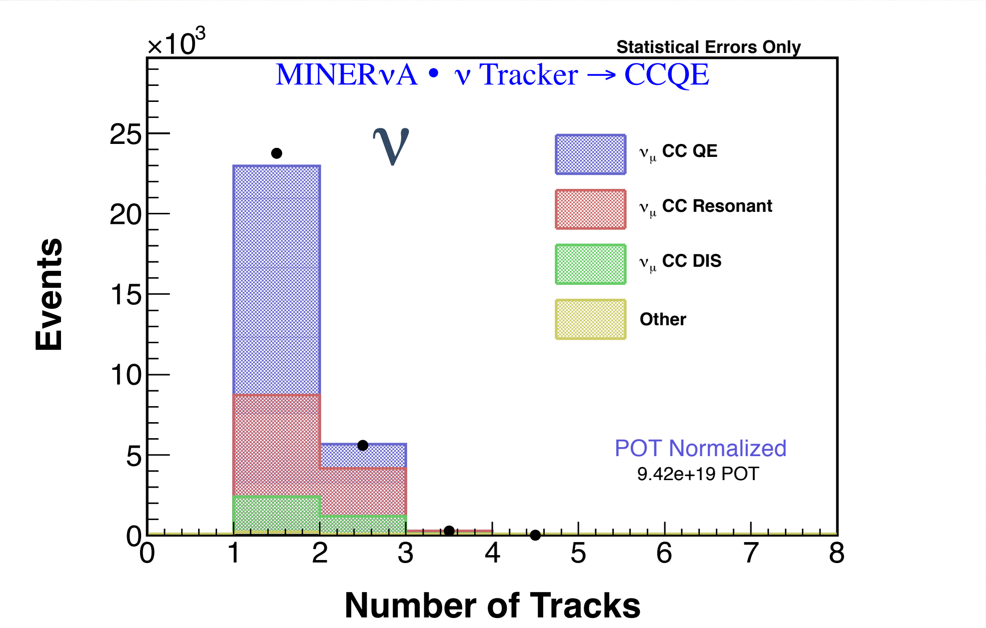


Quasi-Elastic Reconstruction

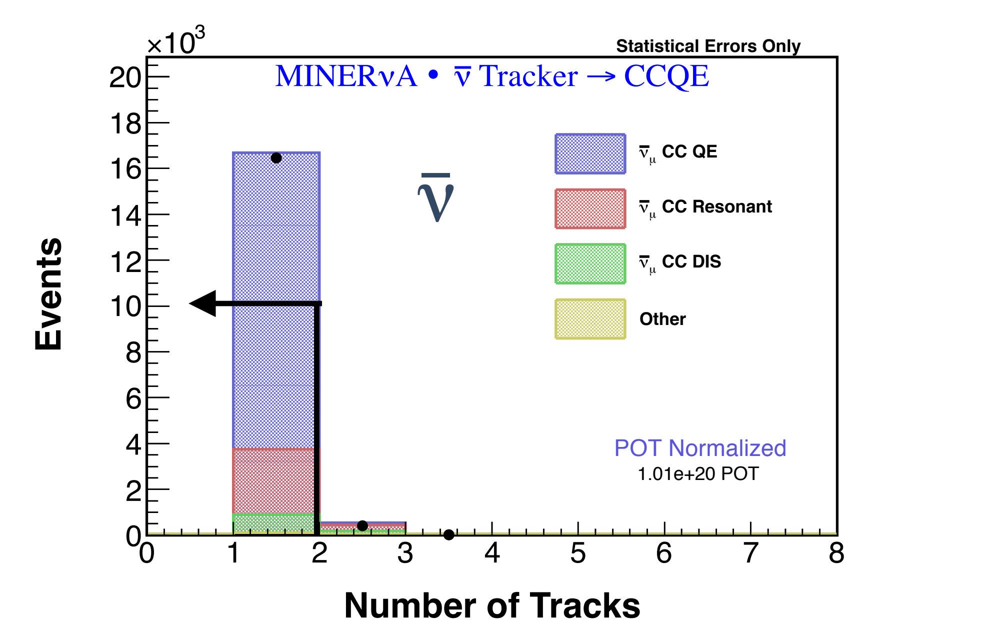


The value of the total recoil cut varies with Q^2 — tight at low Q^2 and quite loose at high Q^2

Quasi-Elastic Reconstruction



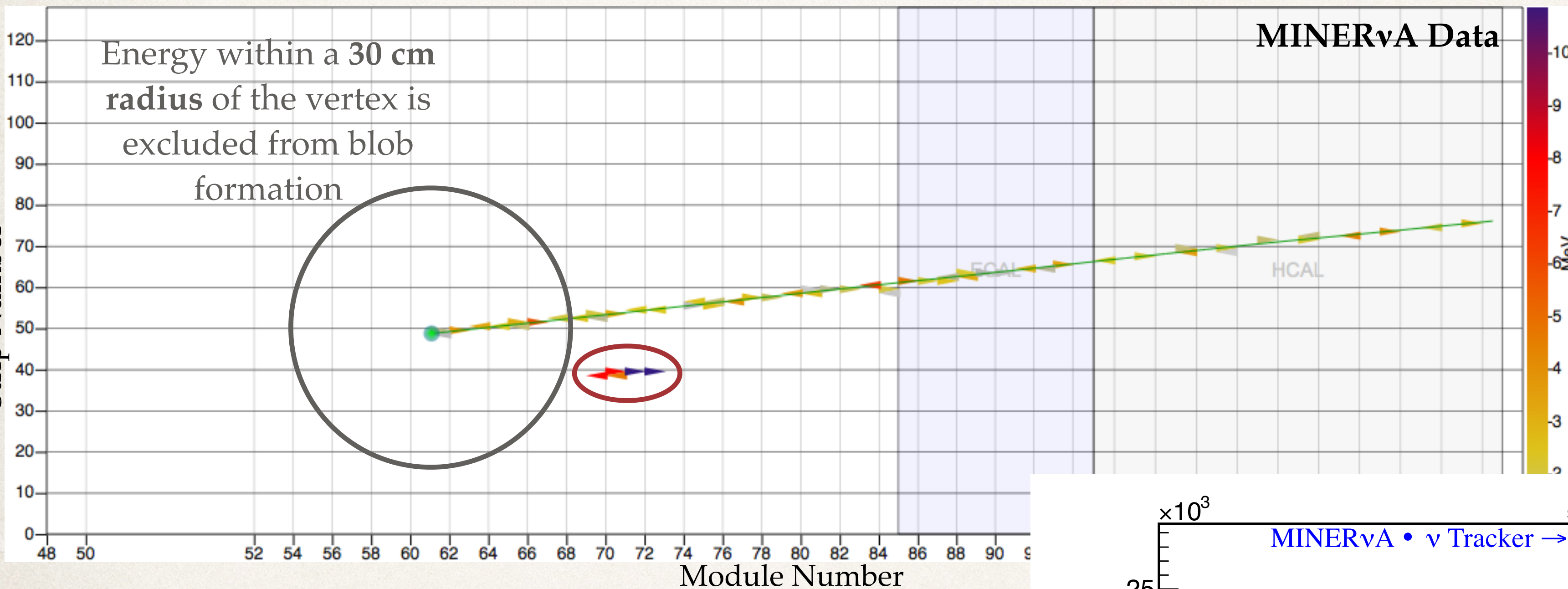
- For neutrino candidates, we make no requirement on the number of tracks
- The proton may or may not have created a track

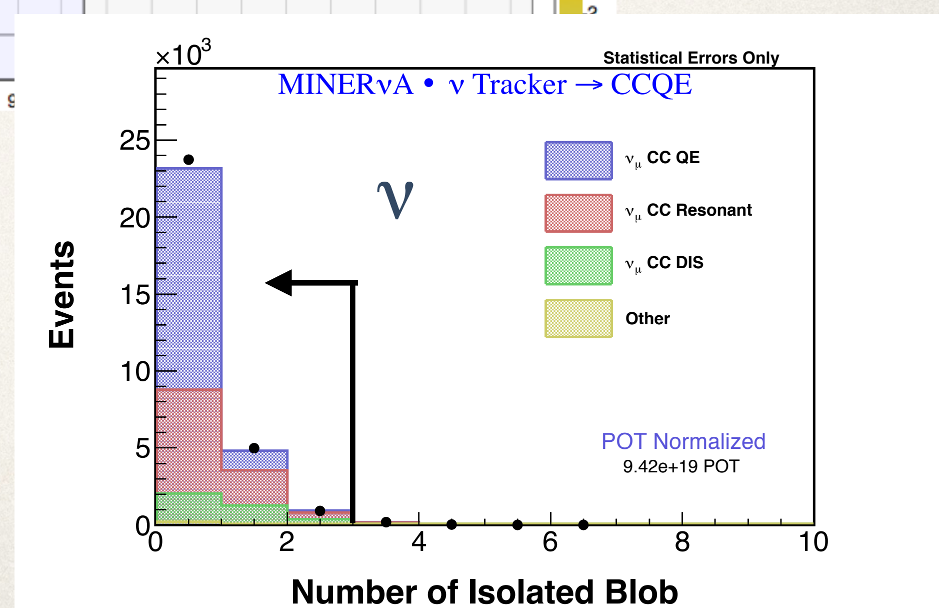


- For anti-neutrino candidates, we require no additional tracks leaving the vertex (other than the muon)
- Neutrons from true CCQE generally do not create a track

Quasi-Elastic Reconstruction

We additionally count the number of "blobs":





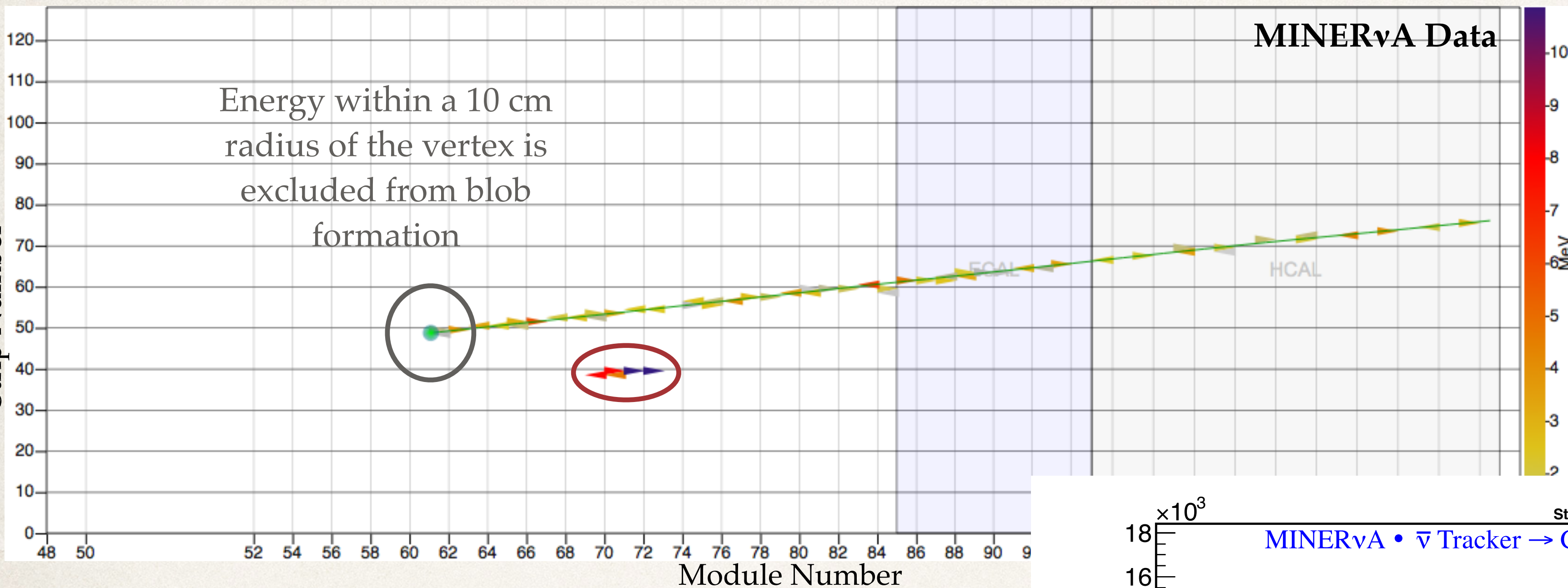
"Blob" = an isolated energy deposition

For **neutrino candidates**, we require **no more than two isolated energy depositions**.

The proton in true quasi-elastics can leave multiple depositions.

Quasi-Elastic Reconstruction

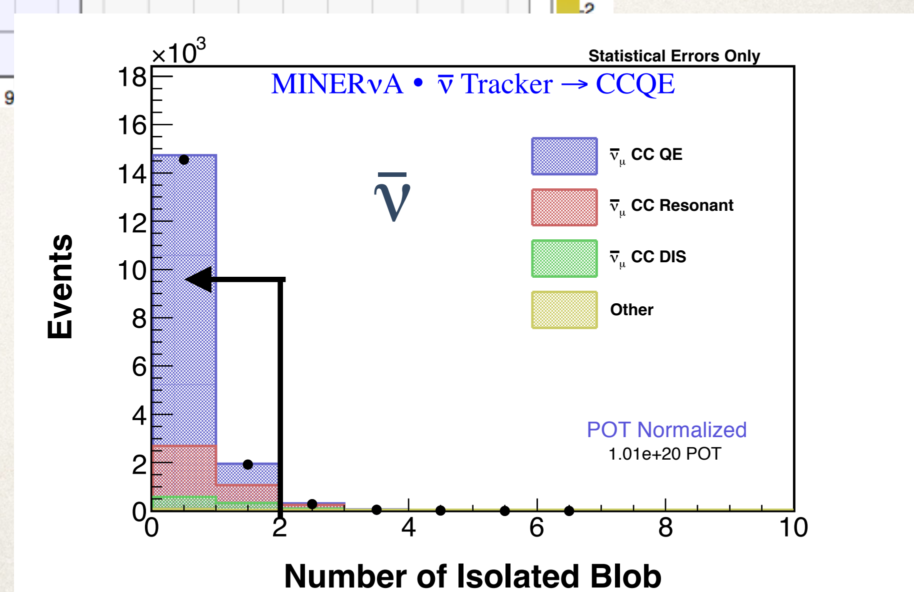
We additionally count the number of “blobs”:



“Blob” = an isolated energy deposition

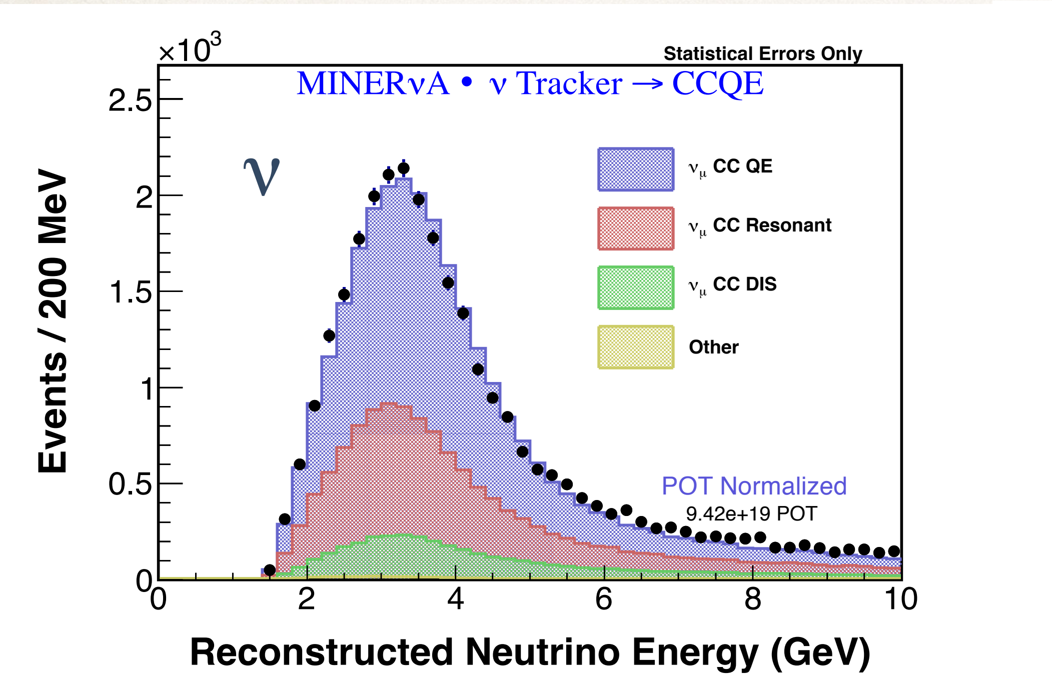
For antineutrino candidates, we require no more than one isolated energy deposition.

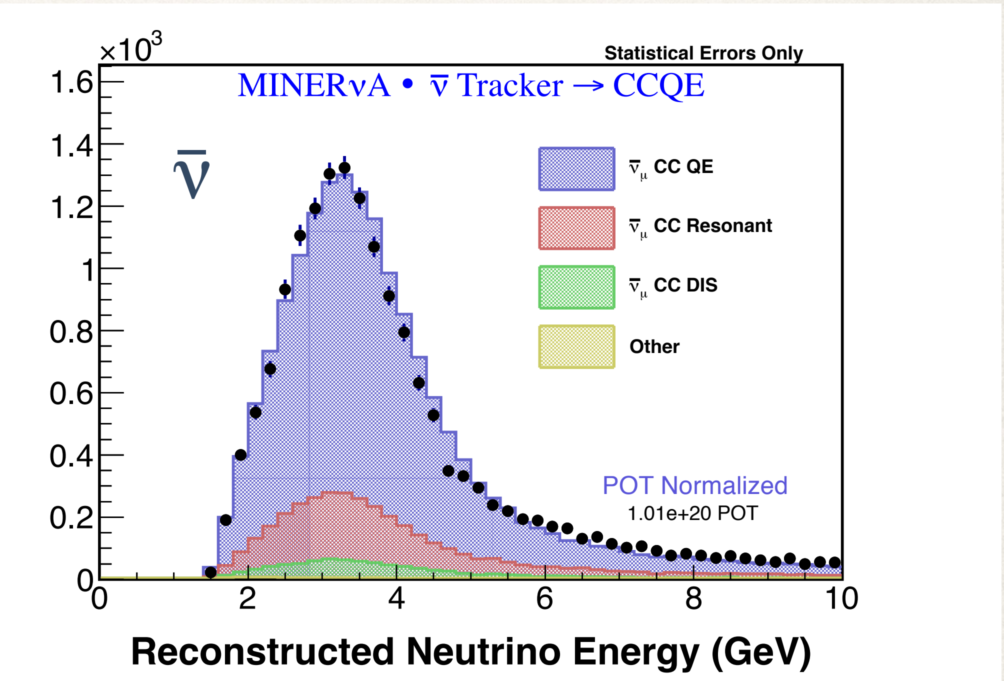
The neutron in true quasi-elastics typically leaves at most one energy deposition.



Neutrino Energy in The Final Samples

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



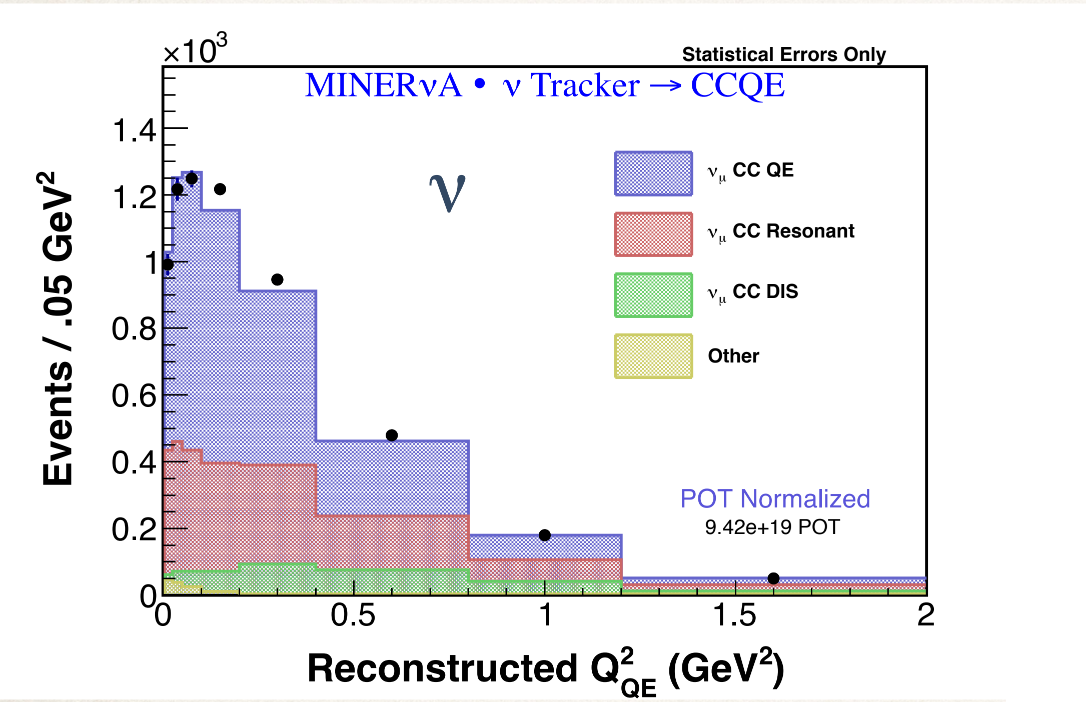


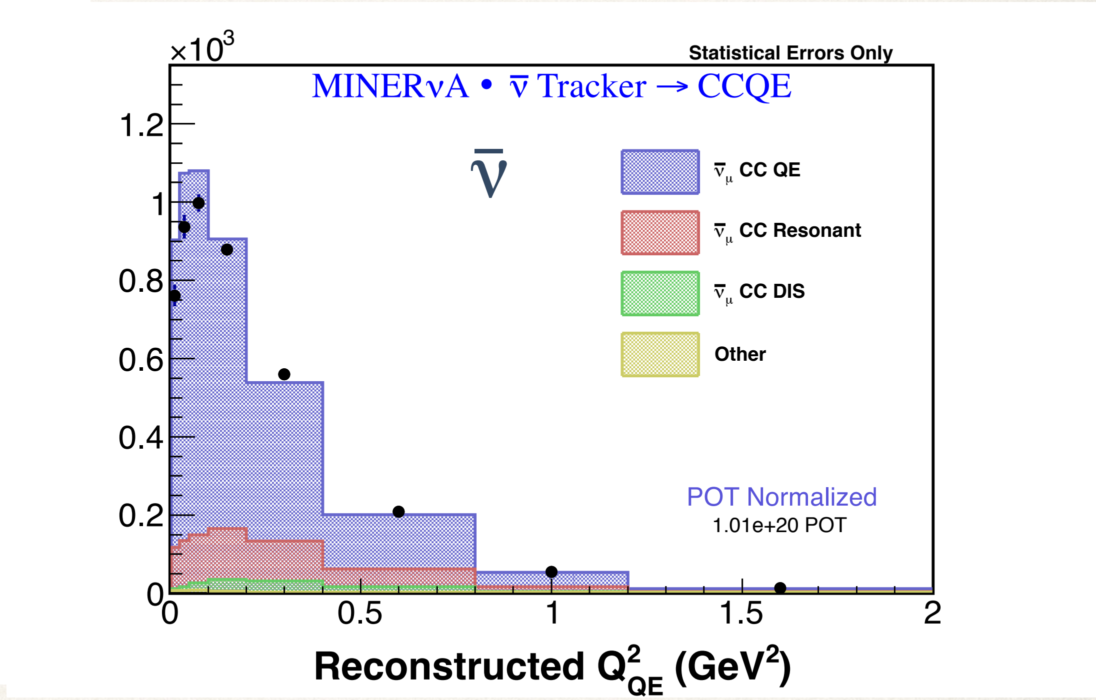
29,620 events
47% efficiency
49% purity

16,467 events
54% efficiency
77% purity

Q^2 in the Final Samples

Q^2 in the final samples: $Q^2 = 2E_\nu(E_\mu - p_\mu \cos\theta_\mu) - m_\mu^2$





29,620 events
47% efficiency
49% purity

16,467 events
54% efficiency
77% purity

How Do We Turn This Into A Cross Section?

- For now, we want to measure the *differential* cross section dσ/dQ2
    - Both the normalization and shape of this distribution can be used to study nuclear effects
    - The shape is insensitive to our (currently large) flux uncertainties

$$\left(\frac{d\sigma}{dQ^2_{\mathrm{QE}}}\right)_i = \frac{\sum_j \left(M_{ij}\left(N_{\mathrm{data},j} - N^{\mathrm{bkgd}}_{\mathrm{data},j}\right)\right)}{\epsilon_i \left(\Phi T\right) \Delta Q^2_{\mathrm{QE},i}}$$

Differential cross section for a given Q2 bin

Unfolding Matrix

The number of events we observe

Background estimate

Efficiency

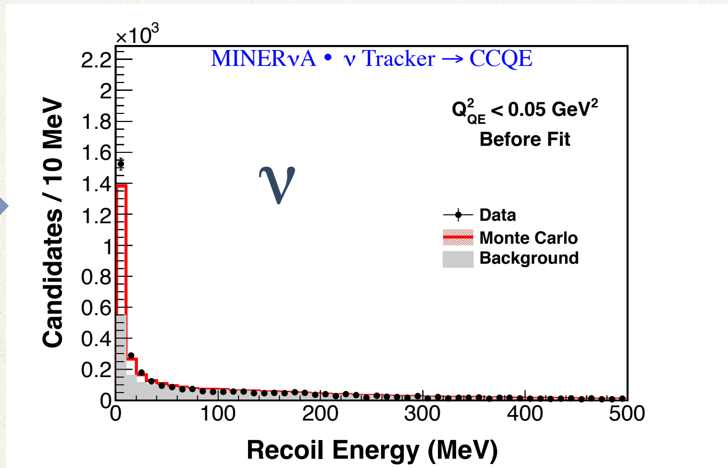
Neutrino flux

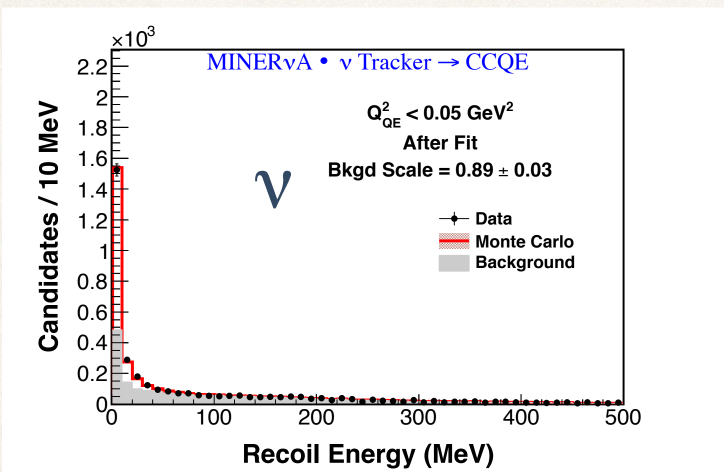
Number of target nucleons in MINERνA

Bin Width

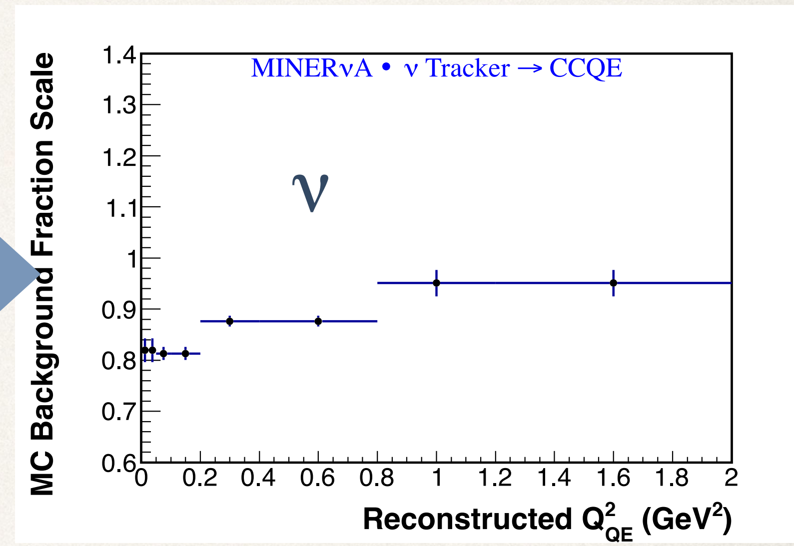
Background Estimation

Backgrounds are estimated via fits to recoil distributions





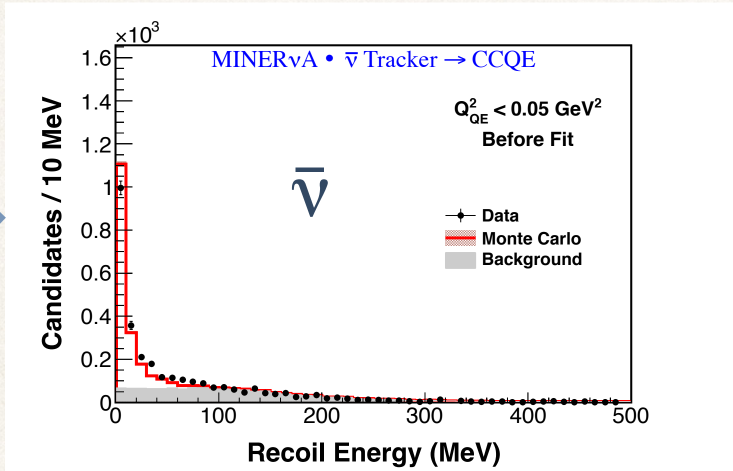
Neutrino

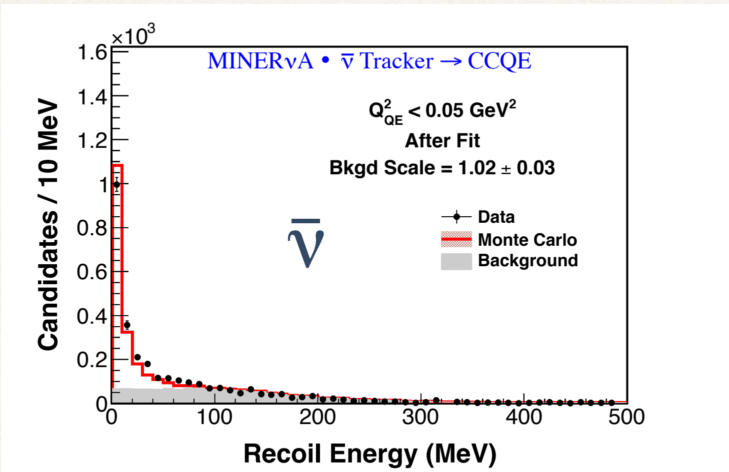


$$\left(\frac{d\sigma}{dQ^2_{\mathrm{QE}}}\right)_i = \frac{\sum_j \left(M_{ij}\left(N_{\mathrm{data},j} - N^{\mathrm{bkgd}}_{\mathrm{data},j}\right)\right)}{\epsilon_i \left(\Phi T\right) \Delta Q^2_{\mathrm{QE},i}}$$

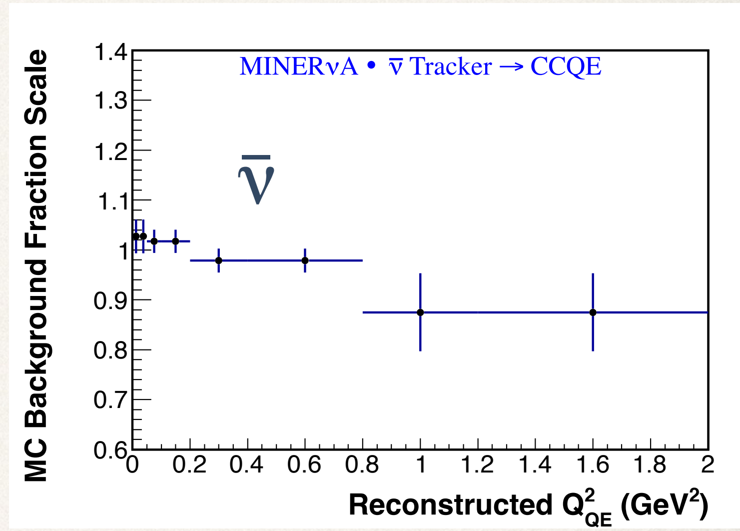
Background Estimation

Backgrounds are estimated via fits to recoil distributions





Antineutrino

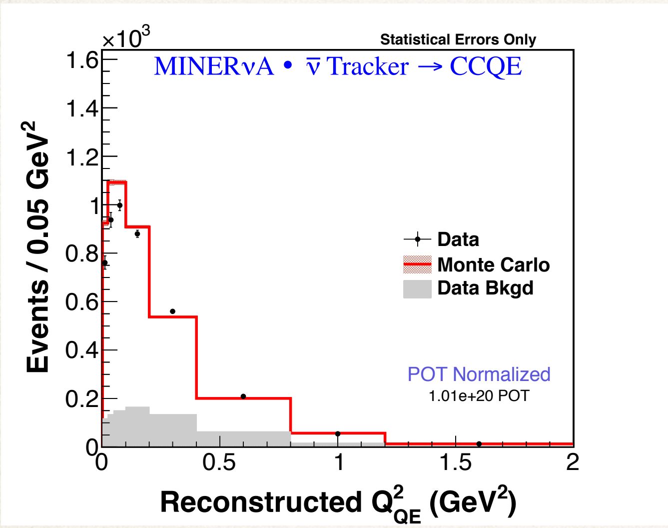


$$\left(\frac{d\sigma}{dQ^2_{\rm QE}}\right)_i = \frac{\sum_j \left(M_{ij}\left(N_{{\rm data},j} - N^{\rm bkgd}_{{\rm data},j}\right)\right)}{\epsilon_i\left(\Phi T\right)\Delta Q^2_{{\rm QE},i}}$$

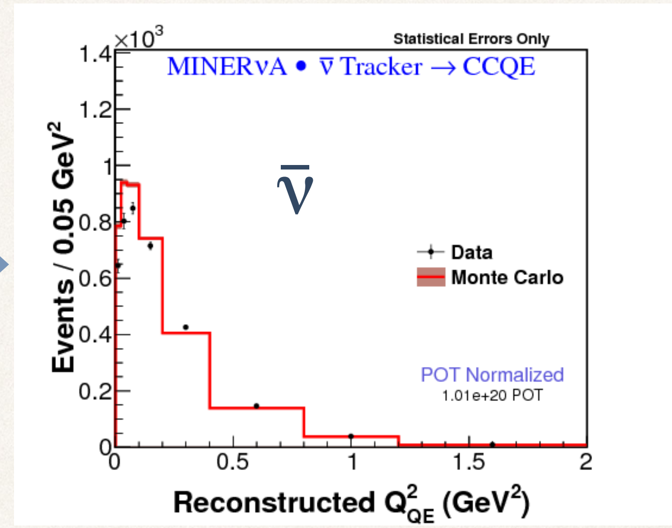
Unfolding

We unfold for detector smearing (not nuclear effects):

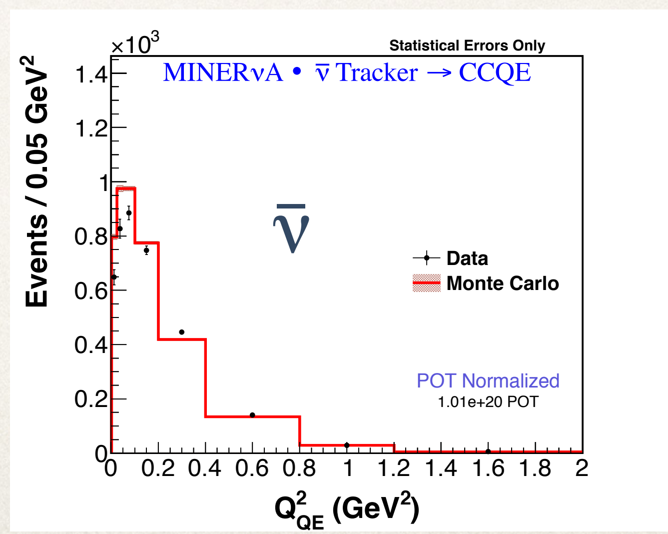
Antineutrino



Background Subtraction



Unfolding



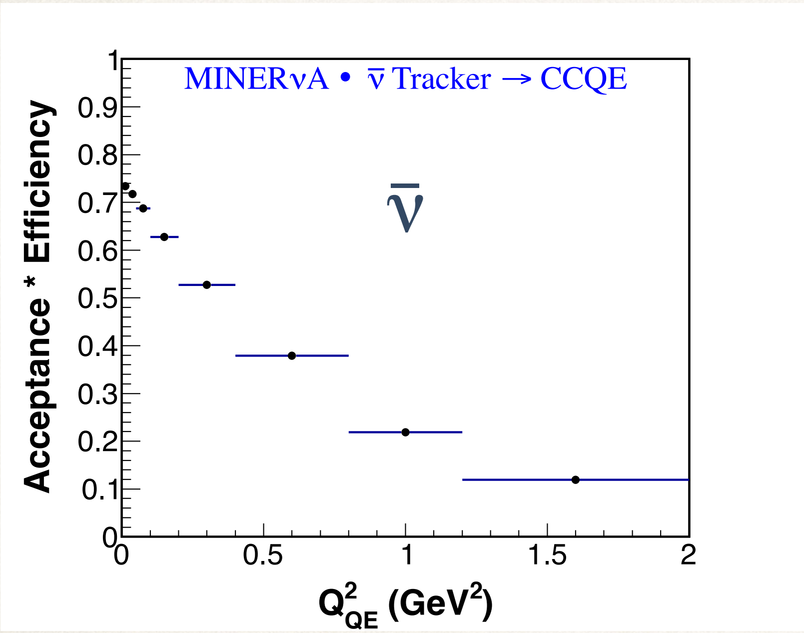
$$\left(\frac{d\sigma}{dQ^2_{\mathrm{QE}}}\right)_i = \frac{\sum_j \left(M_{ij}\left(N_{\mathrm{data},j} - N^{\mathrm{bkgd}}_{\mathrm{data},j}\right)\right)}{\epsilon_i\,(\Phi T)\,\Delta Q^2_{\mathrm{QE},i}}$$

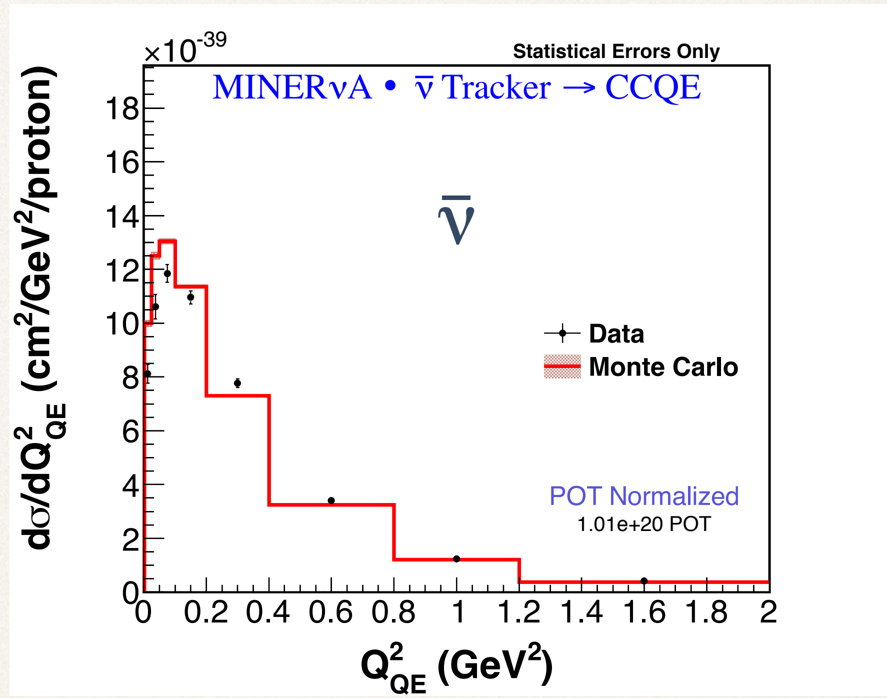
This analysis uses the iterative Bayesian unfolding technique with four iterations.

Acceptance Correction

Unfolded distributions are corrected for efficiency, flux and target number

Antineutrino

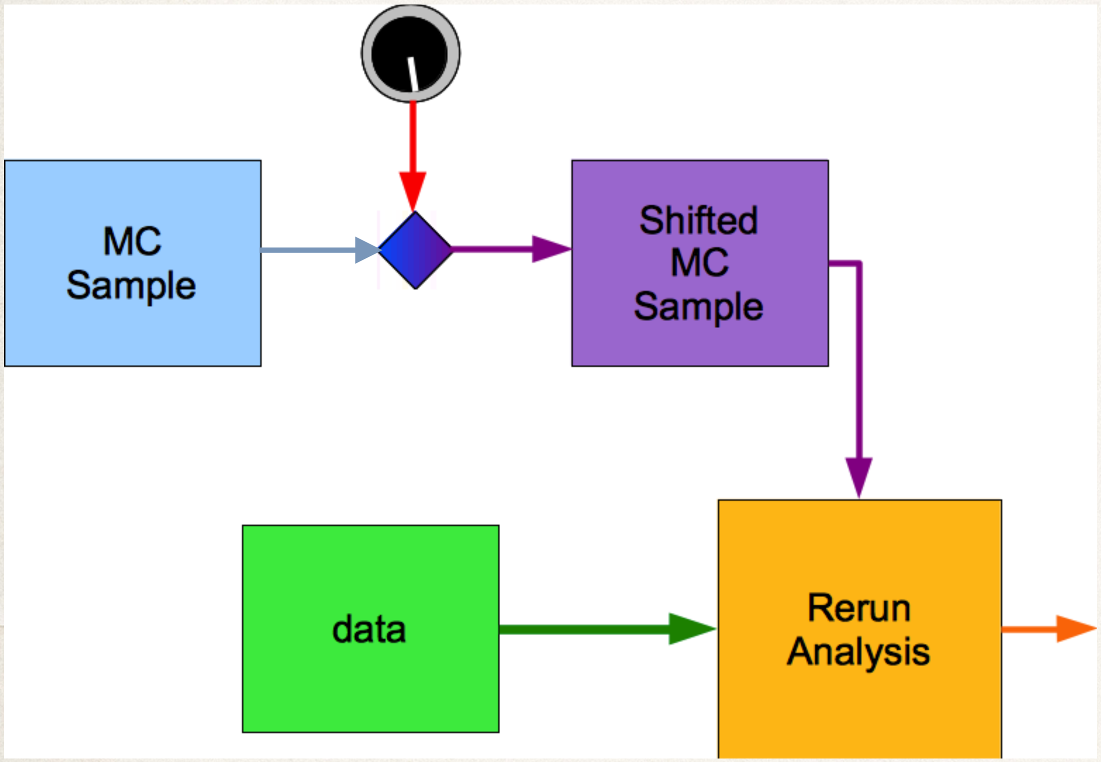




$$\left(\frac{d\sigma}{dQ^2_{\mathrm{QE}}}\right)_i = \frac{\sum_j \left(M_{ij}\left(N_{\mathrm{data},j} - N^{\mathrm{bkgd}}_{\mathrm{data},j}\right)\right)}{\epsilon_i \left(\Phi T\right) \Delta Q^2_{\mathrm{QE},i}}$$

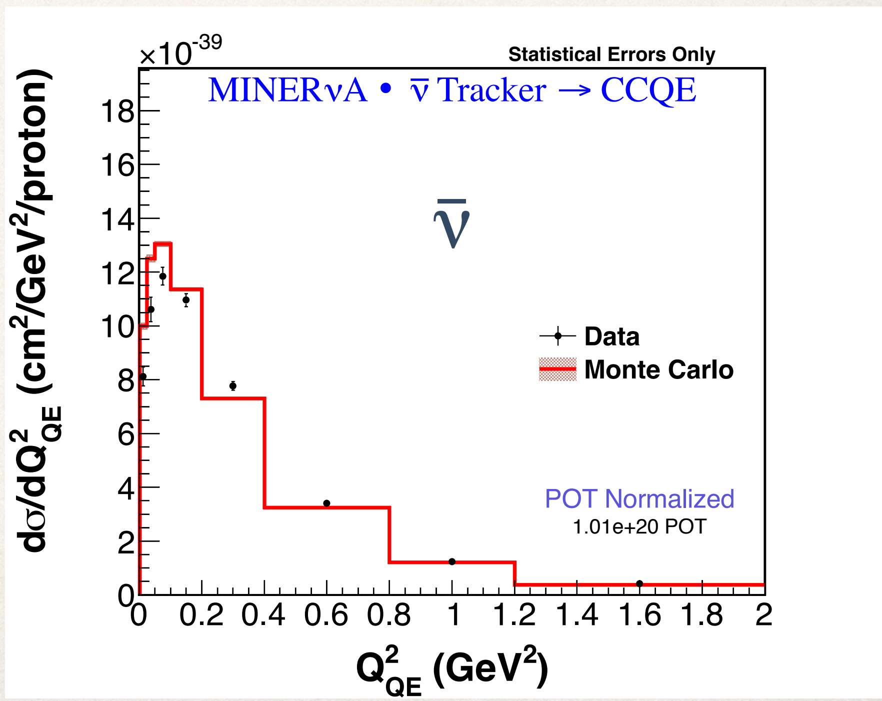
Before we dwell on this, let's look at some systematic uncertainties…

Systematic Uncertainties



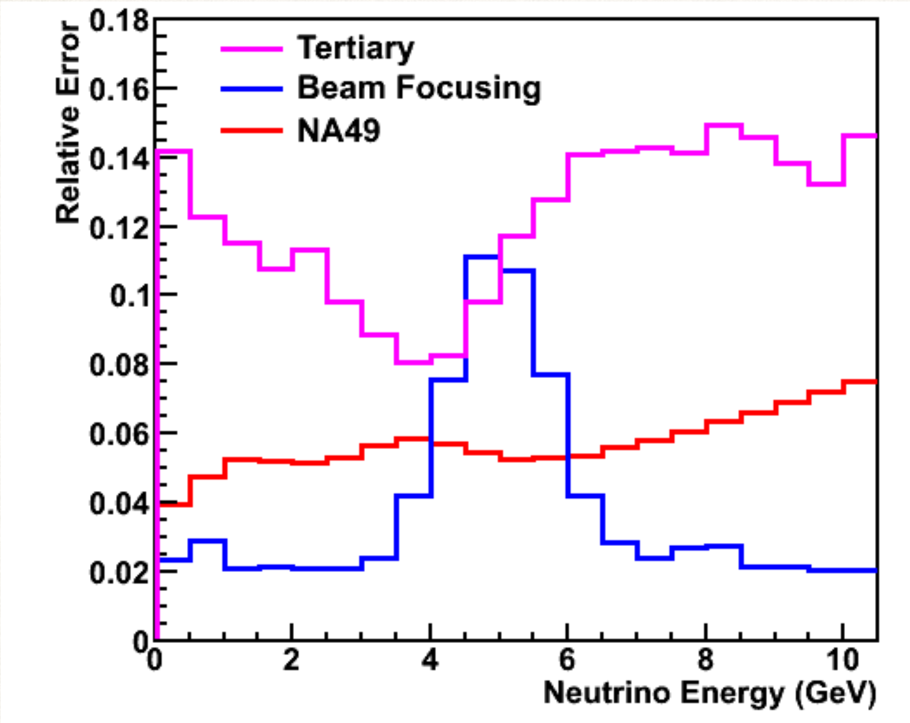
Uncertainty comes from difference between standard and shifted results (or average of the difference in the case of more than one shift)

Shifted result



Systematic Uncertainties

An example: Flux uncertainties come from three sources



- **NA49: Statistical and systematic errors, applied to events that are NA49 constrained.**
- **Tertiary: Estimated from hadron production model spread; applied to non-NA49 constrained events.**
- **Beam Focusing: Uncertainties due to e.g. horn currents, originally estimated by MINOS; applied to all events**

The flux estimation is varied within these uncertainties and cross sections are recalculated; the resulting change in cross section is taken as a systematic uncertainty.

Flux uncertainties are the largest uncertainty on the absolute differential cross sections, but are a negligible component of uncertainty on the Q^2 shape.

Systematic Uncertainties

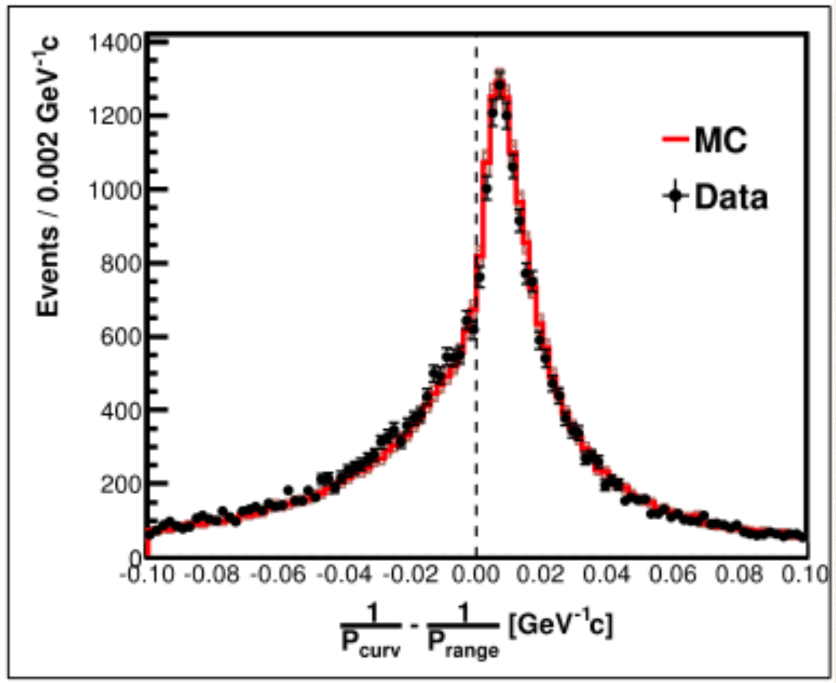
Another example: muon energy scale, also from three sources

Muon momentum scale uncertainties

MINOS range:
- ±2% for all p_μ

MINOS curvature:
- ±2.1% for p_μ < 1.0 GeV/c
- ±3.3% for p_μ > 1.0 GeV/c

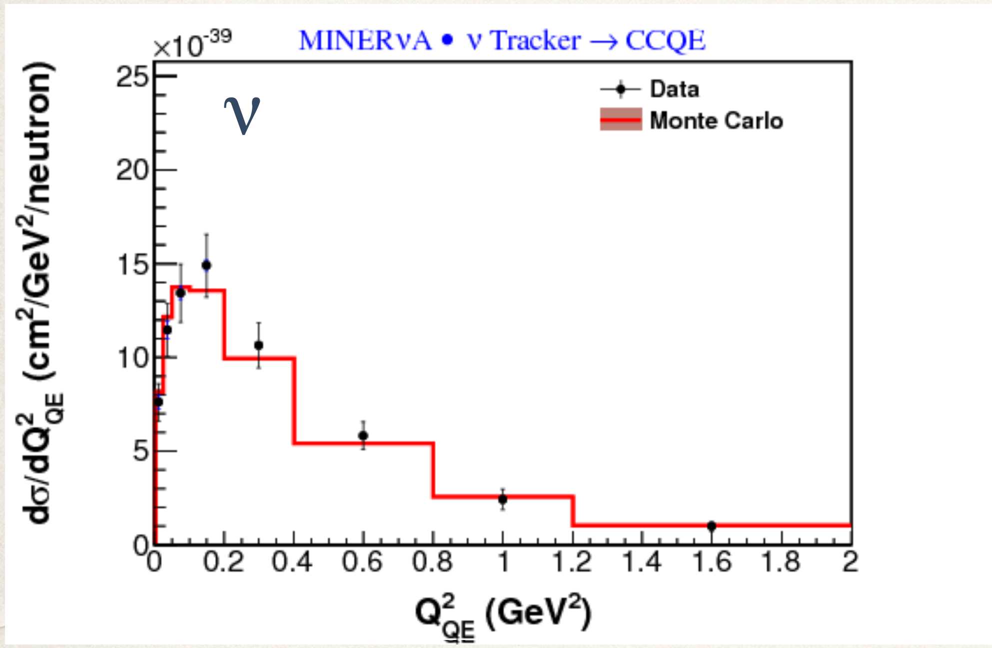
MINERvA
- ±11 MeV (mass model)
- ±30 MeV (dE/dx)

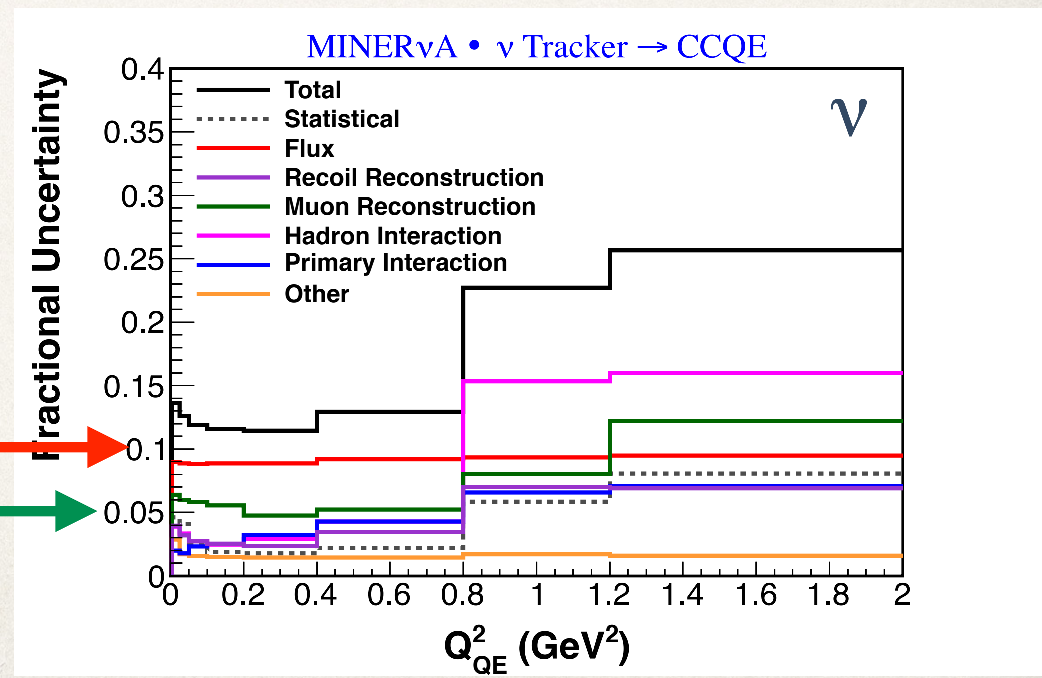


- Muon momenta are shifted within these uncertainties and the cross sections are recalculated; the resulting differences are taken as an uncertainty.
- Muon energy scale uncertainties are a significant component o the uncertainty on the Q2 shape.

Systematic Uncertainties

Summary of all systematic uncertainties (neutrino)



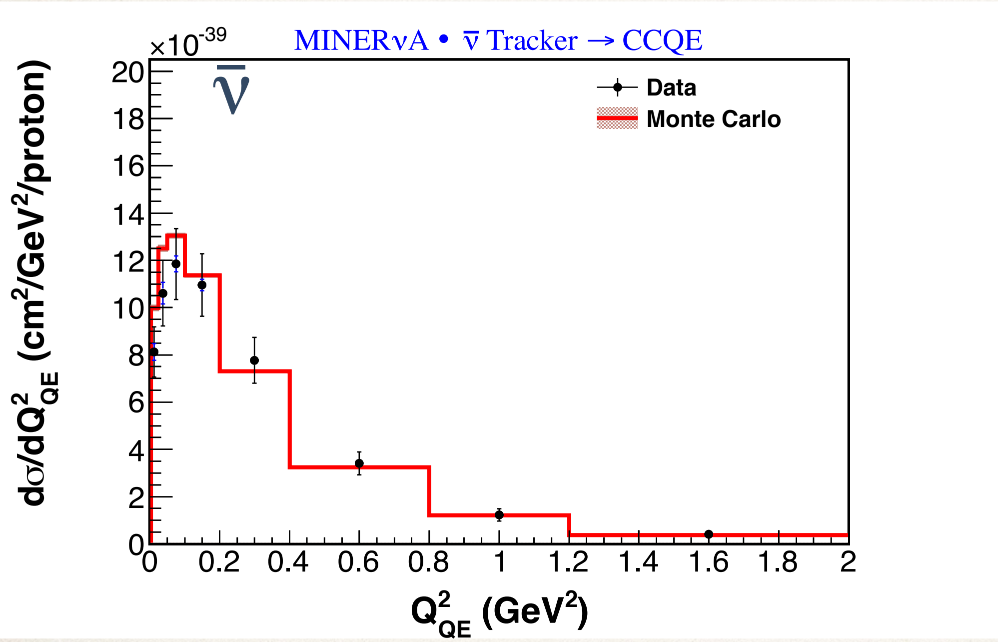


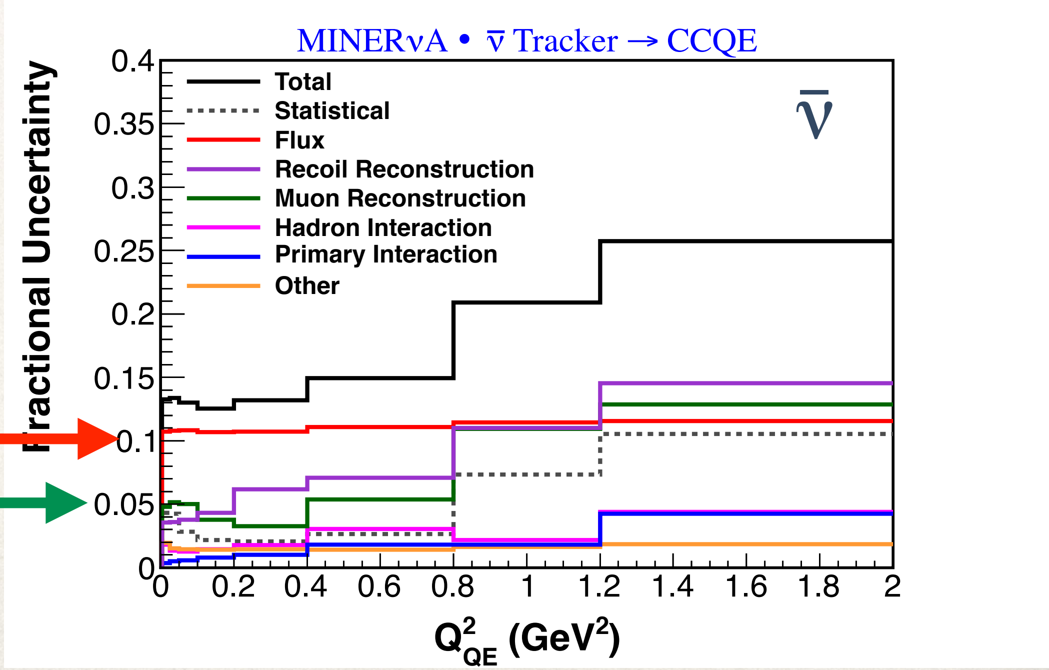
Flux uncertainties

Muon reconstruction uncertainties

Systematic Uncertainties

Summary of all systematic uncertainties (antineutrino)

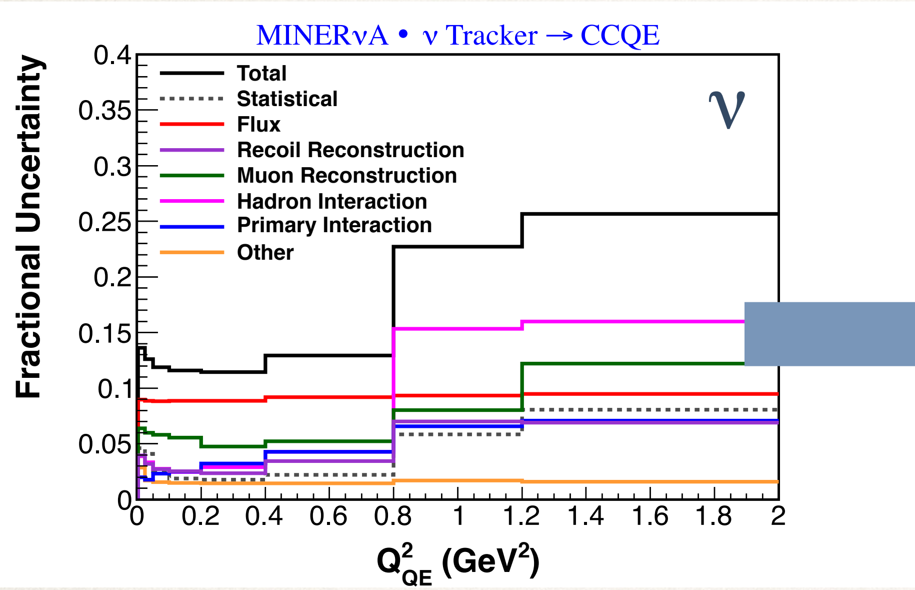


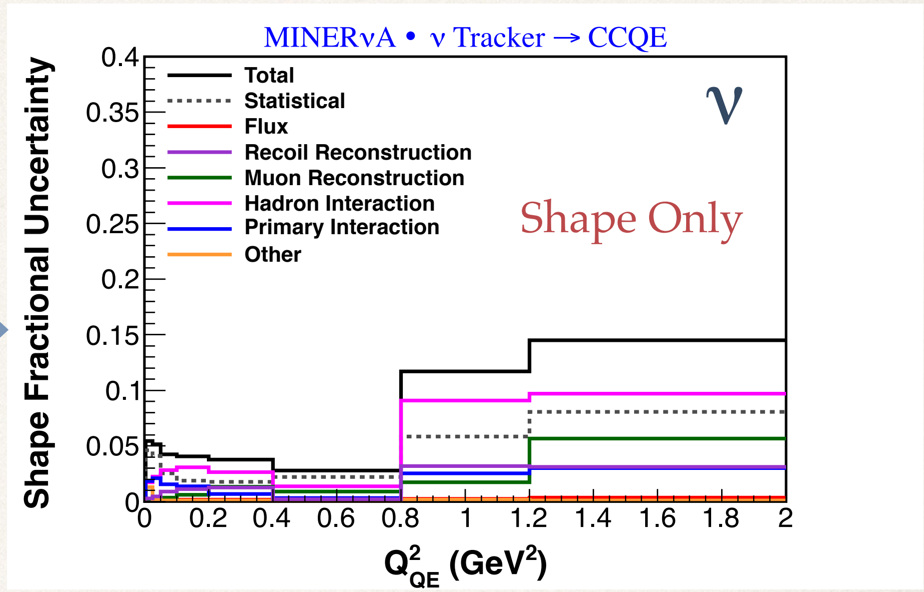


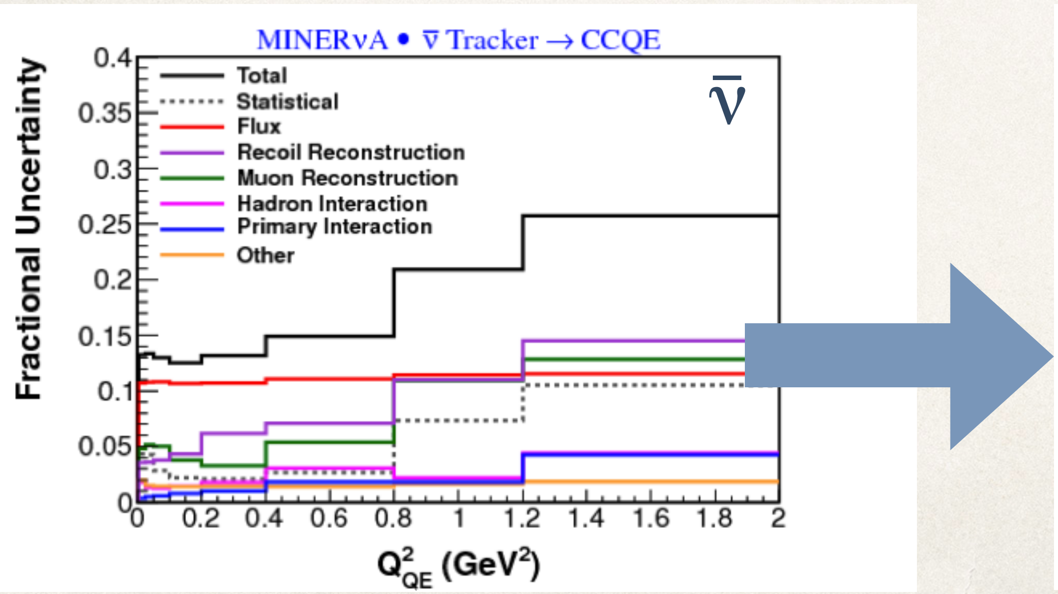
Flux uncertainties

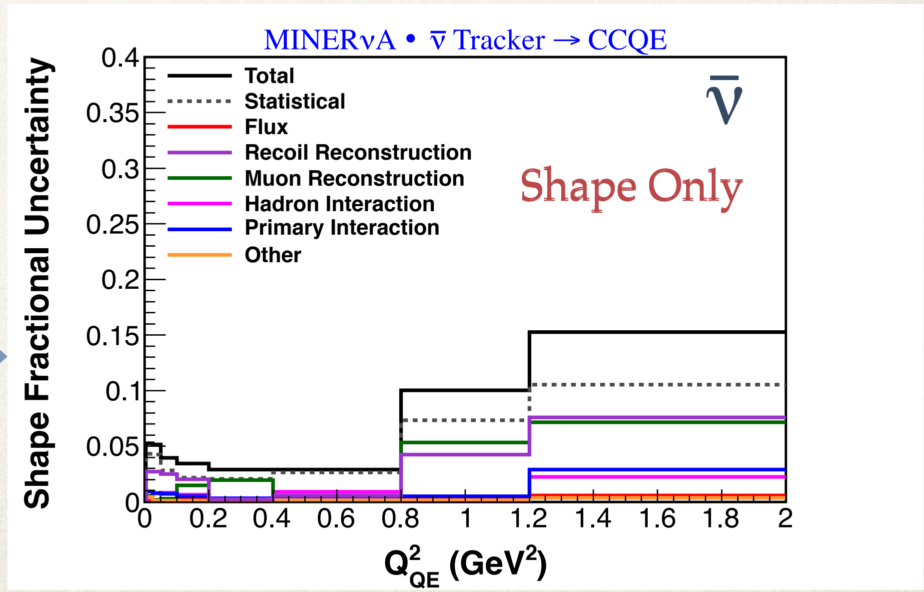
Muon reconstruction uncertainties

Shape versus Absolute Uncertainties

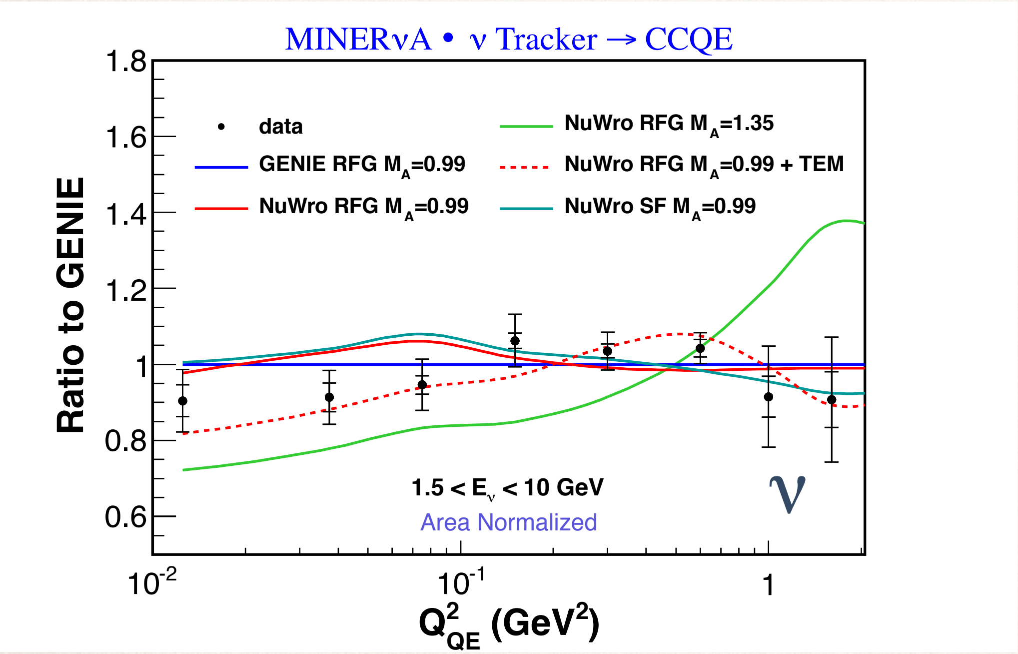






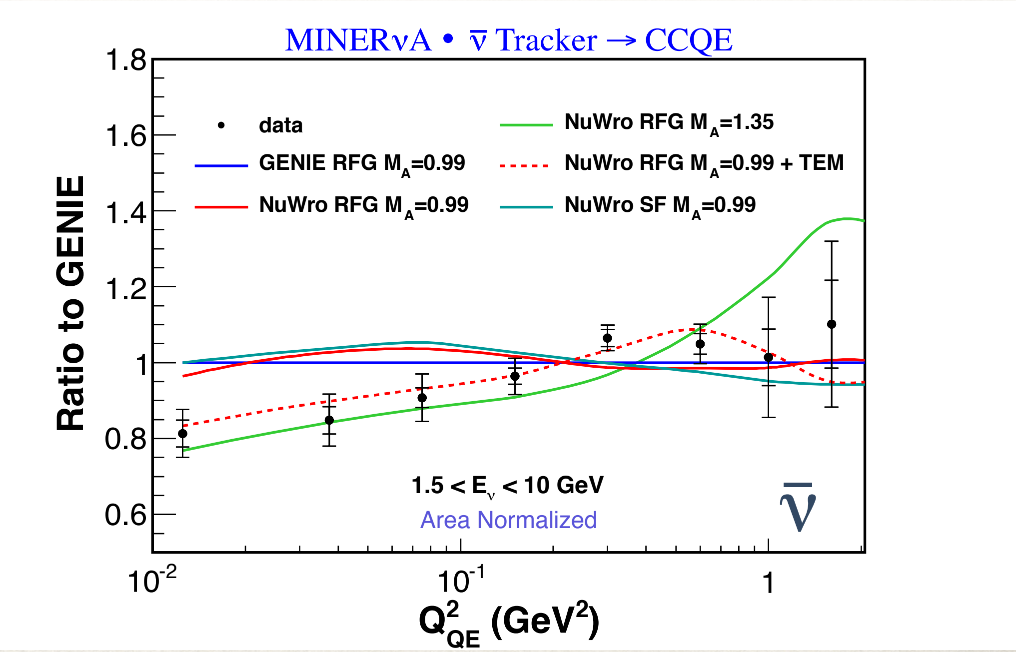


Shape Comparison with Models



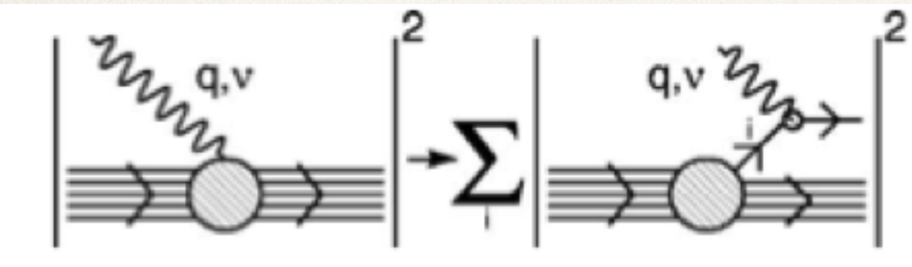
- Here all models and data have been normalized to the **same total rate.**
- And we've plotted **the ratio to our nominal GENIE simulation**.

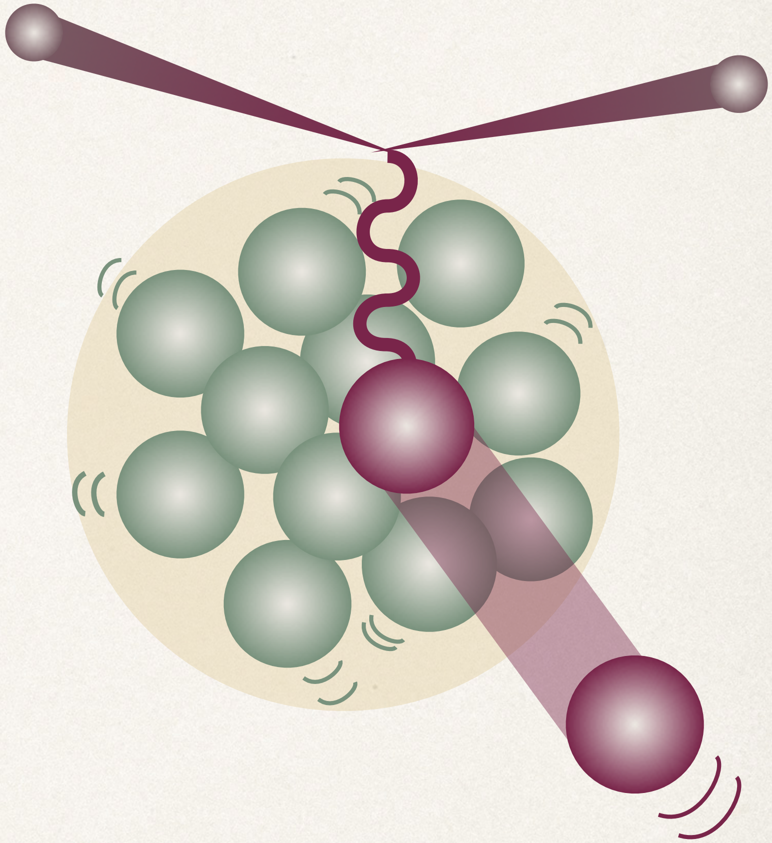
The blue and red lines are two different implementations of **standard quasi-elastic scattering with M_A = 0.99 GeV and using the Fermi Gas Model** of the nucleus with no multi-nucleon effects



The Fermi Gas Model

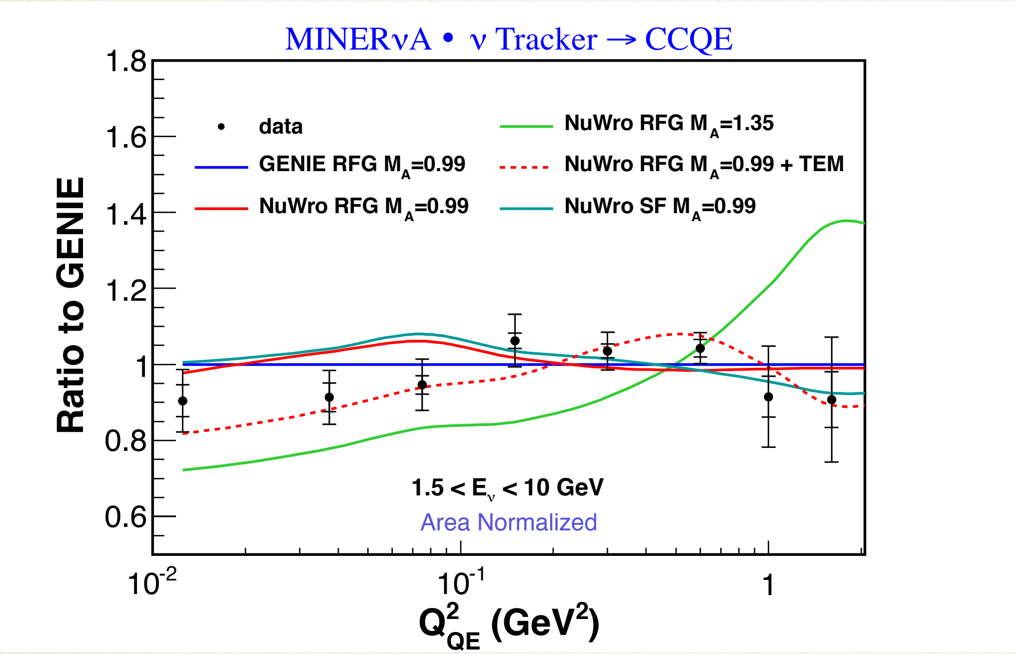
- Many event generators assume a Relativistic Fermi Gas (RFG) model of the nucleus
  - "Impulse Approximation": neutrinos scatter off of individual nucleons → total cross section is an **incoherent sum over nucleons** in the nucleus
  - Initial state nucleons are assigned **a momentum and binding energy**
  - **Pauli-blocking** implemented via a momentum cutoff





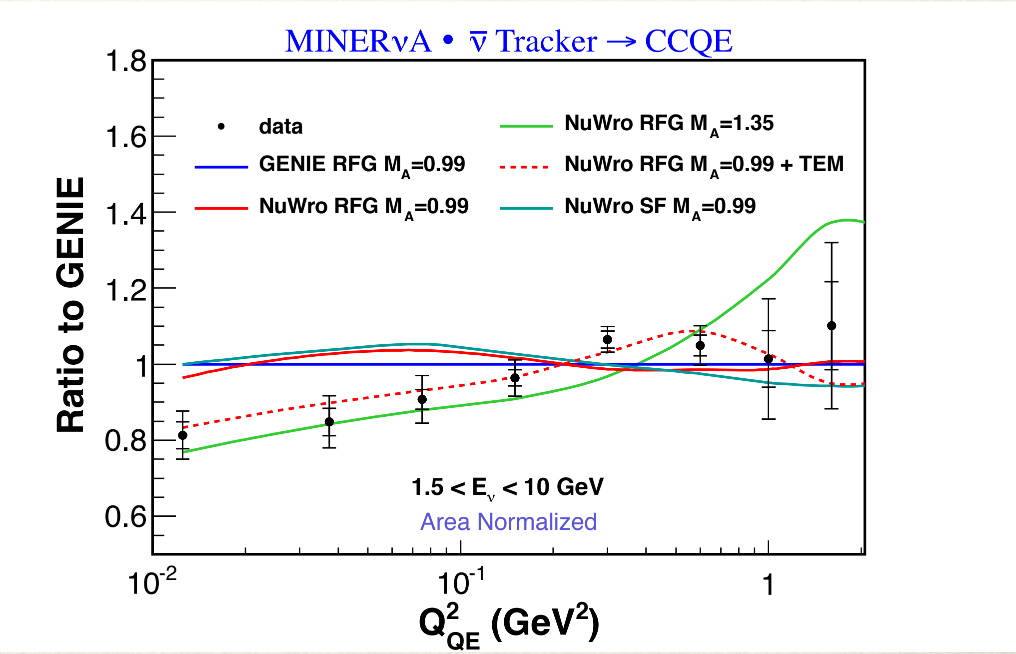
In both generators considered here, **nucleon correlations are minimally included** — the initial state nucleon momentum is modified, but secondary nucleons and cross section enhancements are not.

Shape Comparison with Models

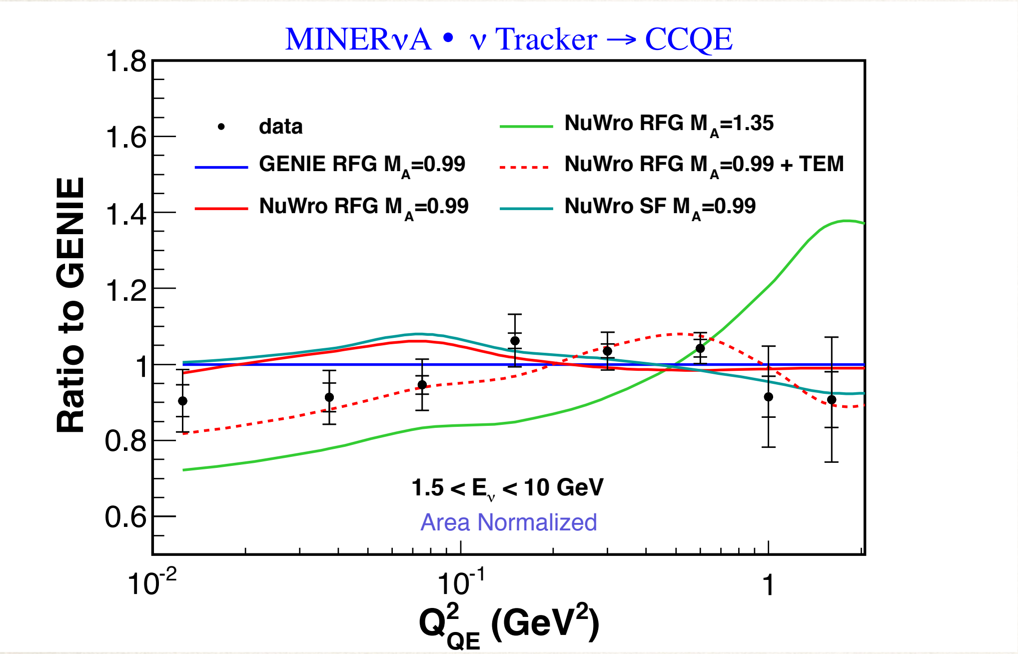


- Here all models and data have been normalized to the **same total rate.**
- And we've plotted **the ratio to our nominal GENIE simulation**.

The turquoise line uses the standard M_A = 0.99, but uses an alternate spectral function-based nuclear model (also no multi-nucleon effects)

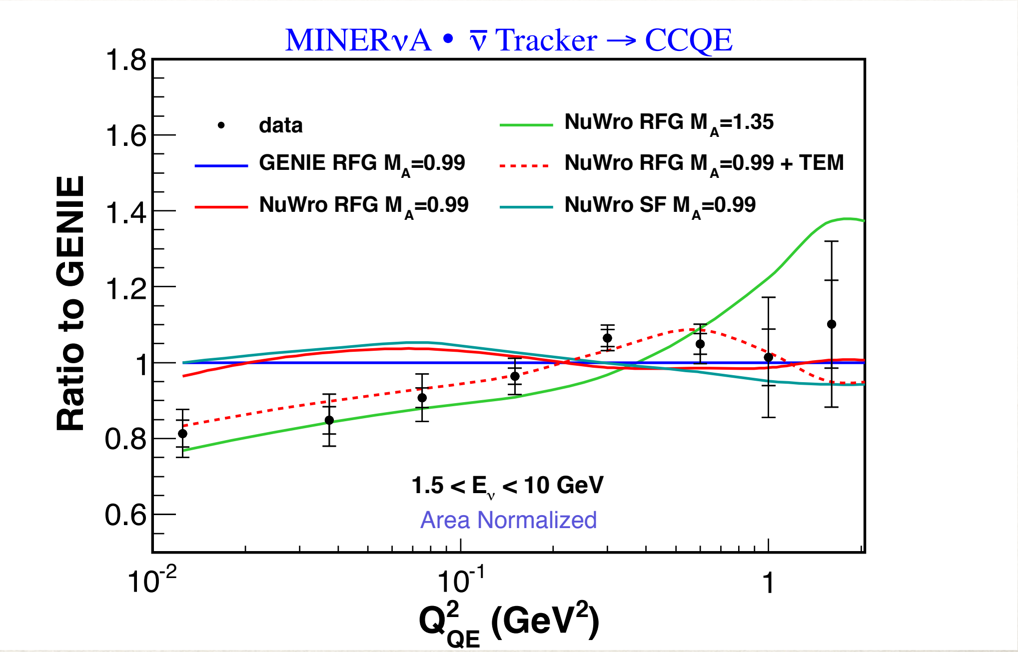


Shape Comparison with Models

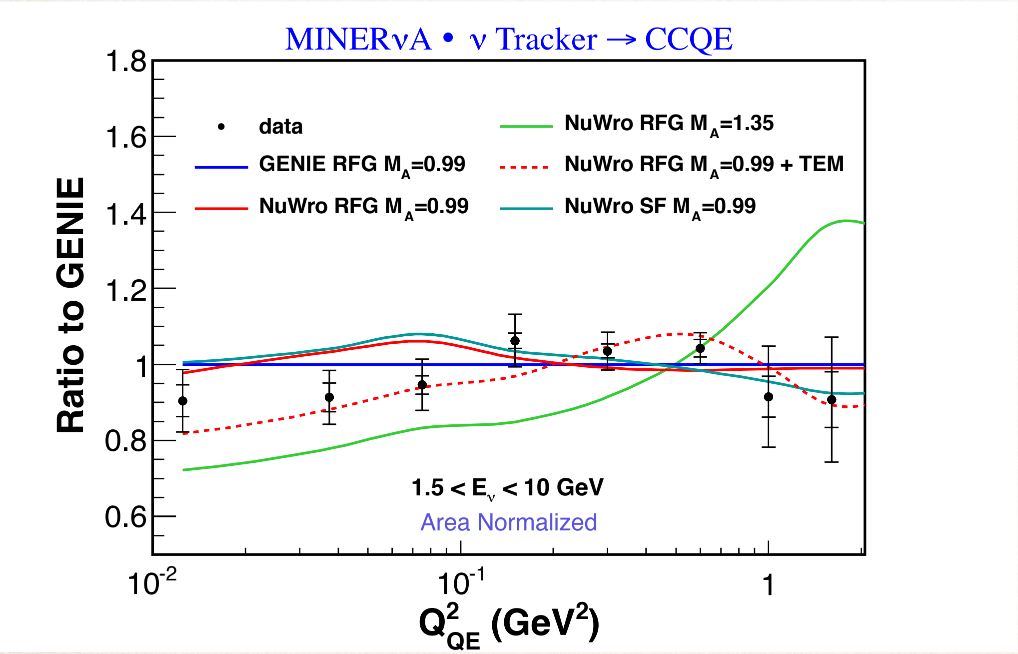


- Here all models and data have been normalized to the **same total rate.**
- And we've plotted **the ratio to our nominal GENIE simulation**.

The green line assumes the Fermi Gas nuclear model but uses a quasi-elastic axial mass of 1.35 (the value preferred by MiniBooNE) with no multi-nucleon effects

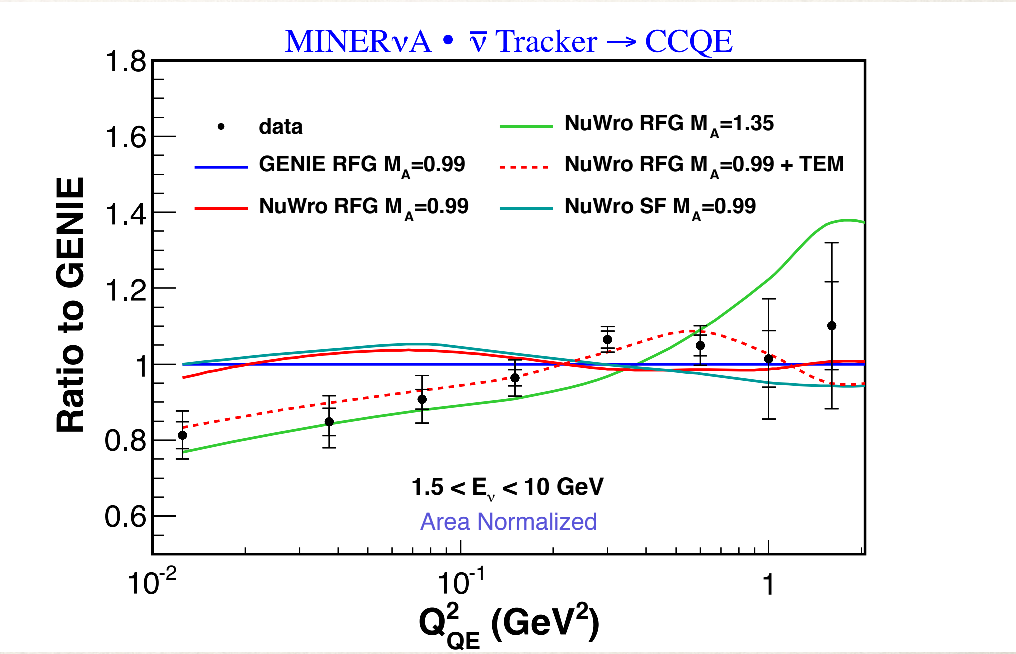


Shape Comparison with Models



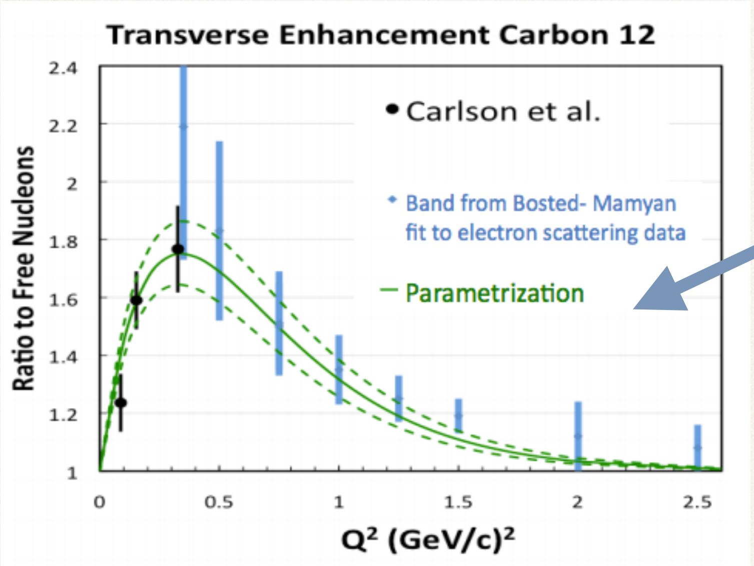
- Here all models and data have been normalized to the **same total rate.**
- And we've plotted **the ratio to our nominal GENIE simulation**.

The dotted red line uses the standard M_A = 0.99 and the Fermi Gas nuclear model but adds QE-like interactions using the "Transverse Enhancement Model"



Transverse Enhancement Model

Transverse Enhancement Model:

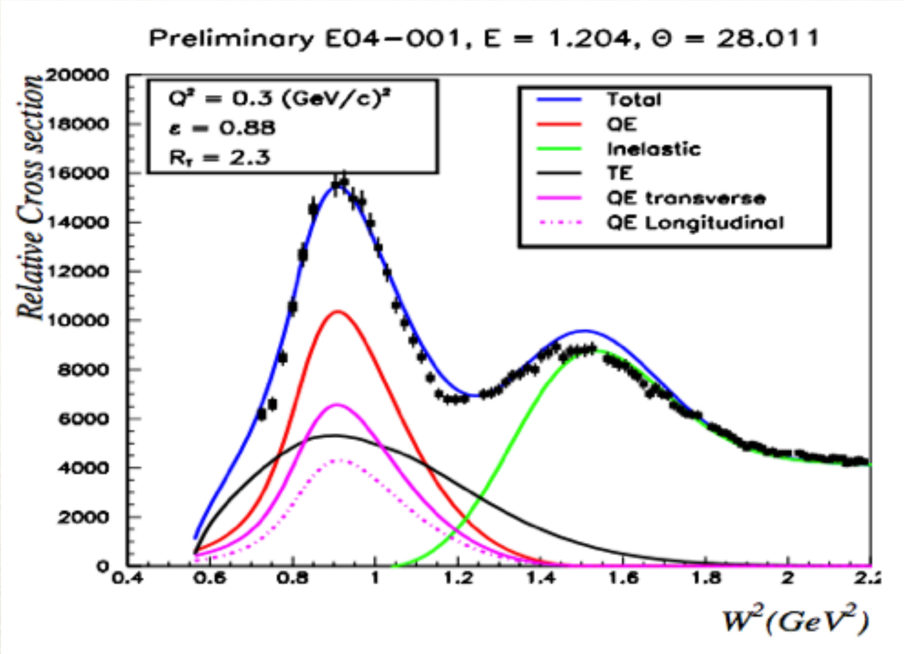


An empirical model

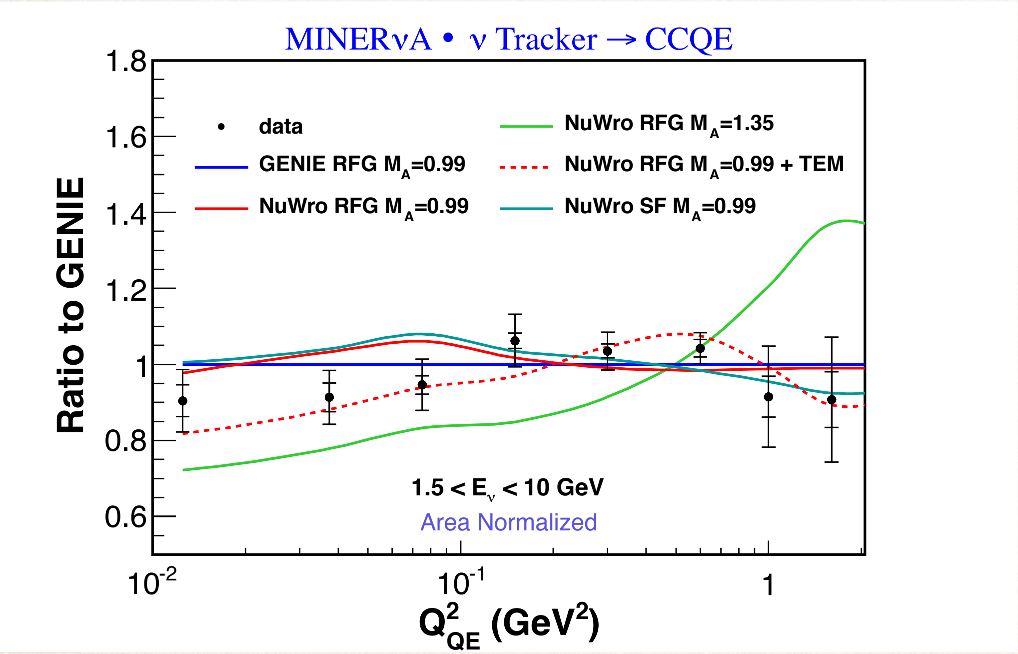
- Assumes enhancement of the transverse cross section in electron scattering modifies the magnetic form factor that appear in both electron and neutrino scattering

$$F_1(Q^2) = \frac{G_E + \tau G_M}{1+\tau} \qquad \xi F_2(Q^2) = \frac{G_M - G_E}{1+\tau}$$

Fits electron scattering data to extract parameters of form factor enhancement. The modified form factor is then applied to neutrino scattering.



Shape Comparison with Models



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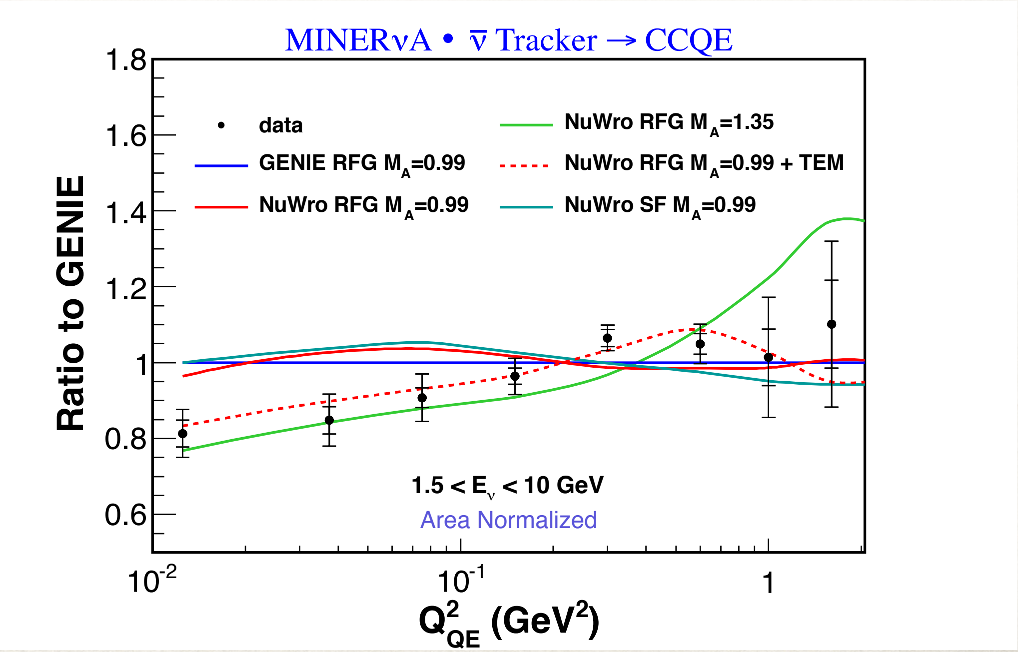


The dotted red line uses the standard M_A = 0.99 and the Fermi Gas nuclear model but adds QE-like interactions using the "Transverse Enhancement Model"

1-Track CCQE Analysis

Chisquares of model comparisons:

Antineutrino

NuWro Model	RFG	RFG +TEM	RFG	SF
M_A (GeV)	0.99	0.99	1.35	0.99
Rate χ^2/d.o.f.	2.64	1.06	2.90	2.14
Shape χ^2/d.o.f.	2.90	0.66	1.73	2.99

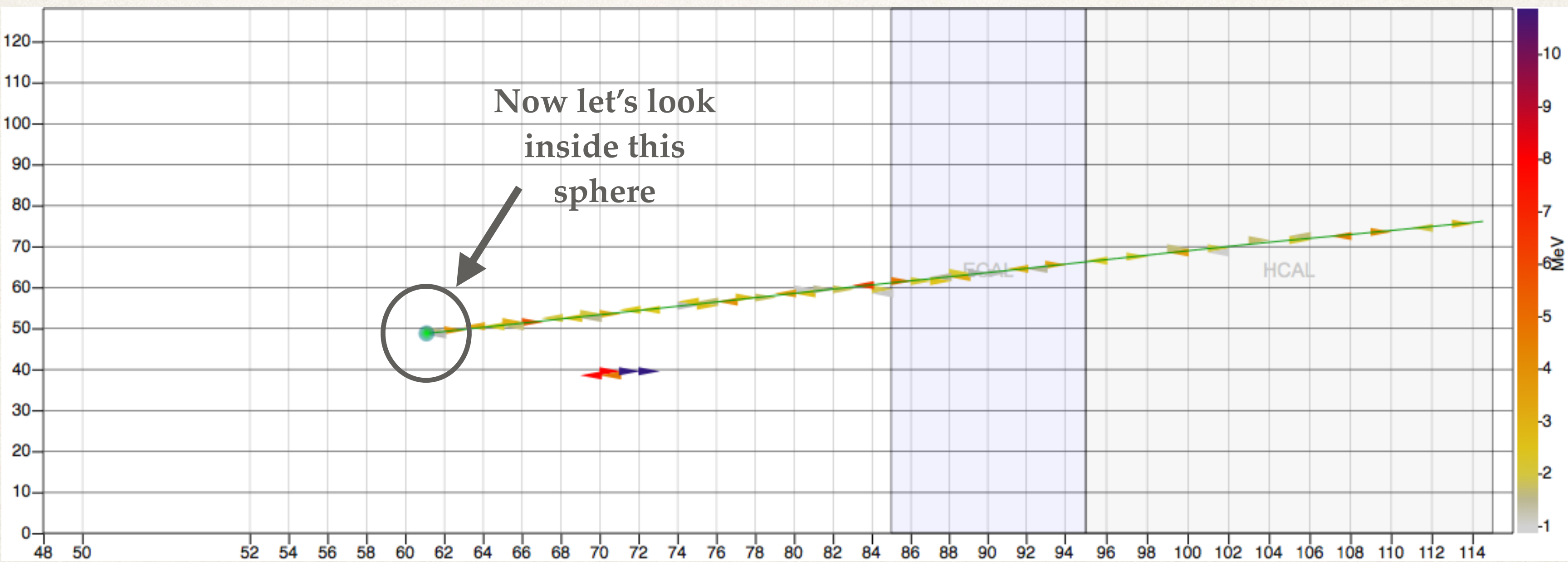
Neutrino

NuWro Model	RFG	RFG +TEM	RFG	SF
M_A (GeV/c^2)	0.99	0.99	1.35	0.99
Rate χ^2/d.o.f.	3.5	2.4	3.7	2.8
Shape χ^2/d.o.f.	4.1	1.7	2.1	3.8

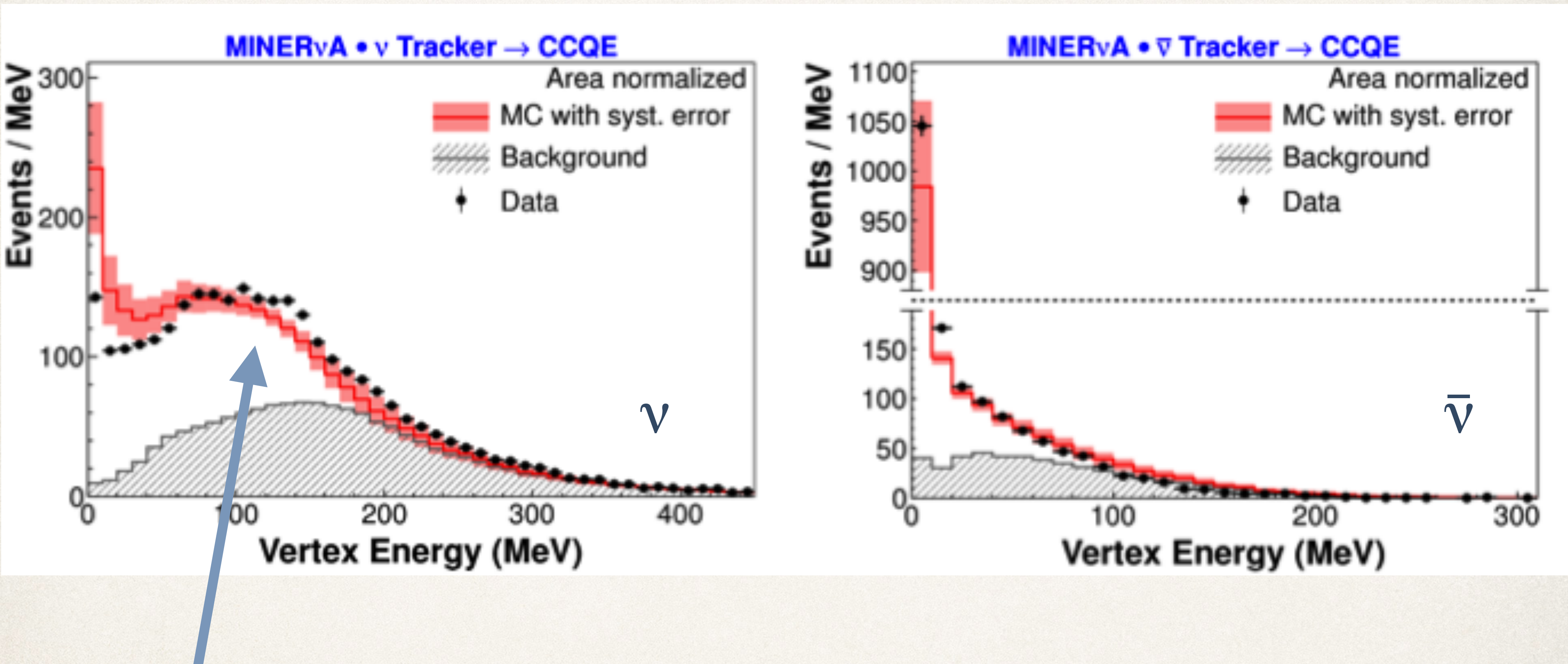
- **The data disfavor the Relativistic Fermi Gas Model.**
- **These data cannot discriminate between the spectral function and the Fermi Gas Model.**
- **Raising the axial mass to 1.35 does improve agreement versus MA = 0.99.**
- **The model most preferred by the data (RFG+TEM) is the transverse enhancement model**

Another Way of Studying Nuclear Effects

- Recall that we excluded a sphere around the vertex when making selection cuts.
  - Energy within a 10/30 cm sphere has not been used up to now in the analysis
- If there are unsimulated nuclear effects, we expect to see discrepancies between data and simulation in this region



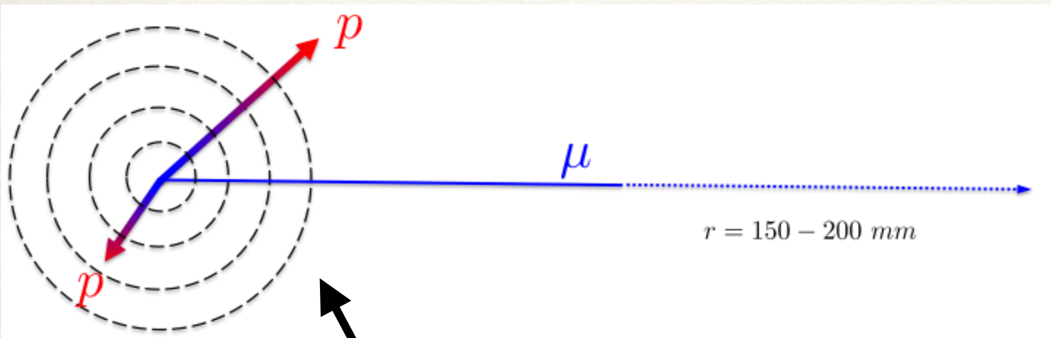
Vertex Energy



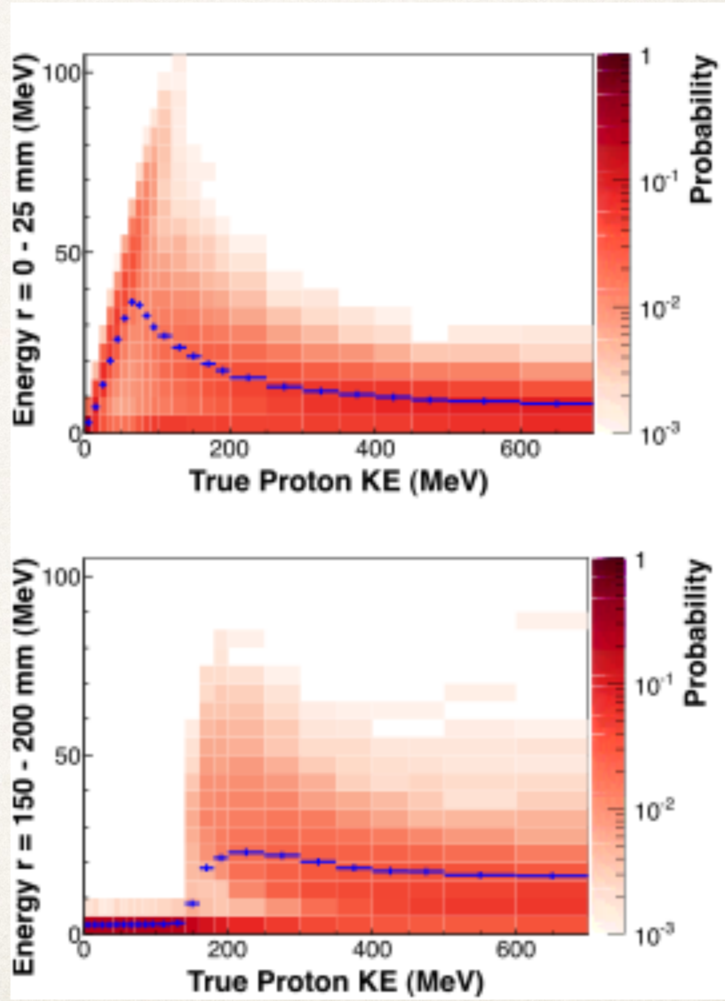
- The neutrino-mode data display a harder vertex energy spectrum than the simulation.
- **All systematics are included here, including FSI and hadron energy scale.**
- We don't know what's causing this excess energy. But let's hypothesize that it's extra hadrons…

Vertex Energy

Assuming that each event has one unsimulated additional proton:



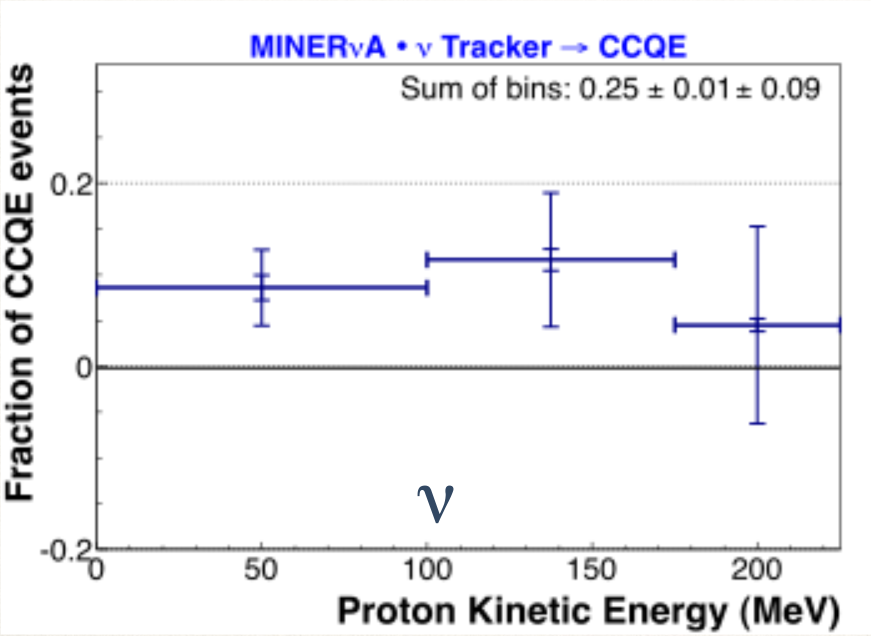
We look at the energy contained within annuli around the vertex.

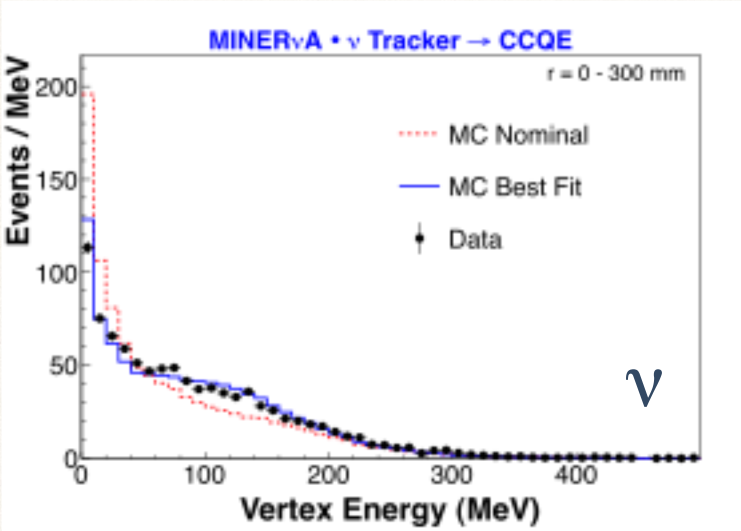


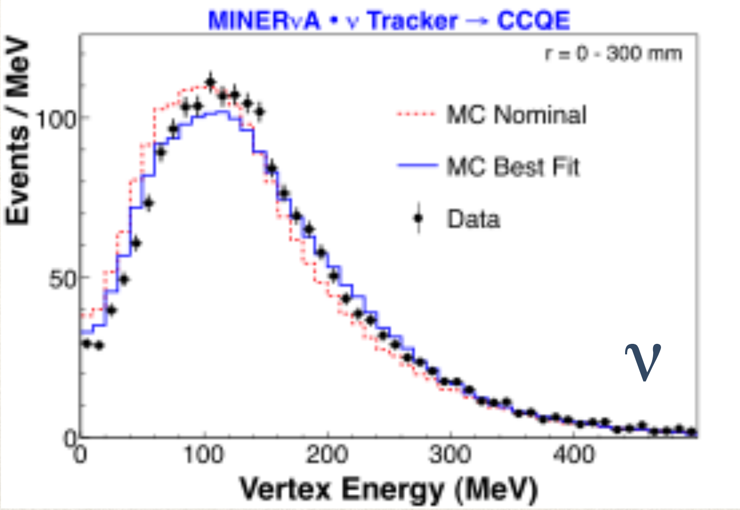
- We use the pattern of energy deposition near the vertex to estimate the most probable energy of the unsimulated proton.

Vertex Energy

Assuming that each event has one unsimulated proton:



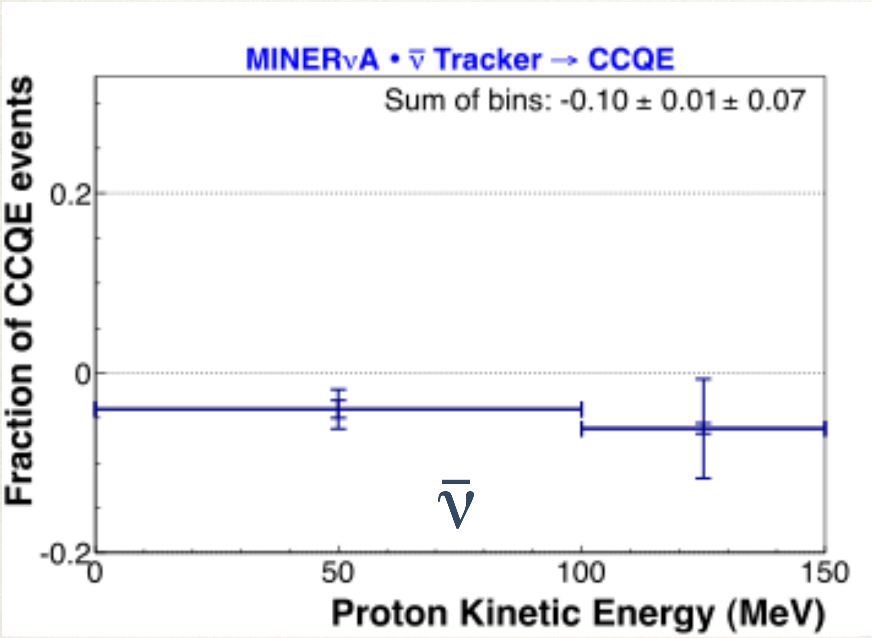


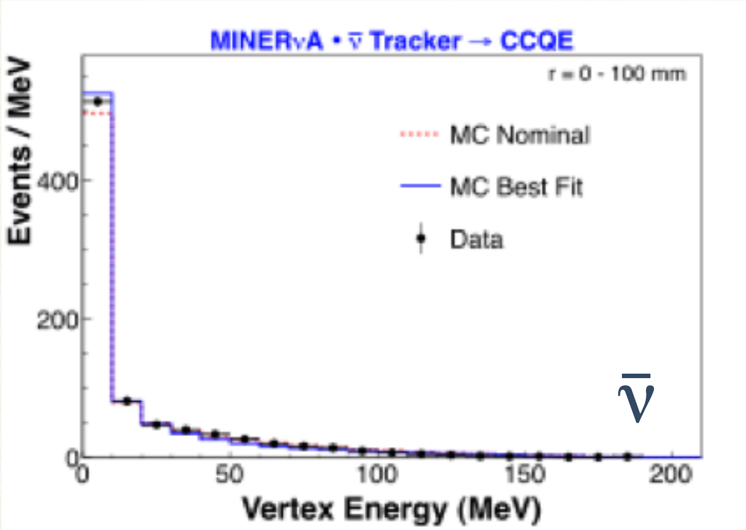


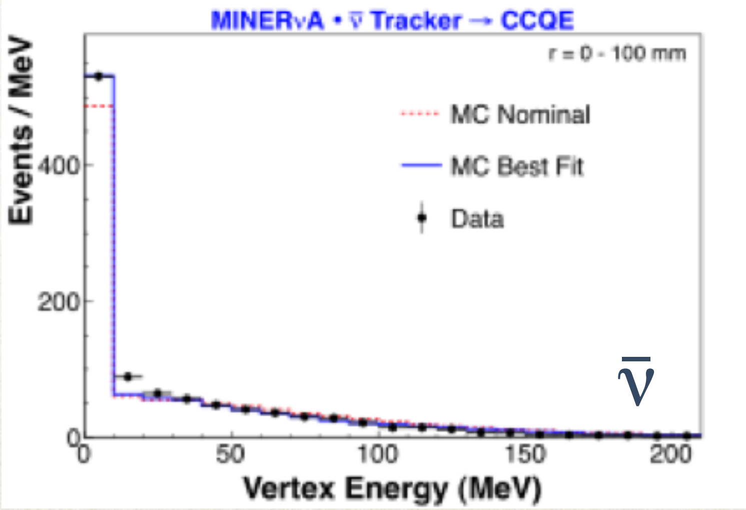
In the **neutrino-mode** analysis, we find improved agreement when we add a low energy (KE<225 MeV) proton to **(25 ± 9)**% of events

Vertex Energy

Assuming that each event has one unsimulated proton:







In the **antineutrino-mode** analysis, we find improved agreement when we **remove** a low energy (KE<225 MeV) proton from **(10 ± 7)**% of events

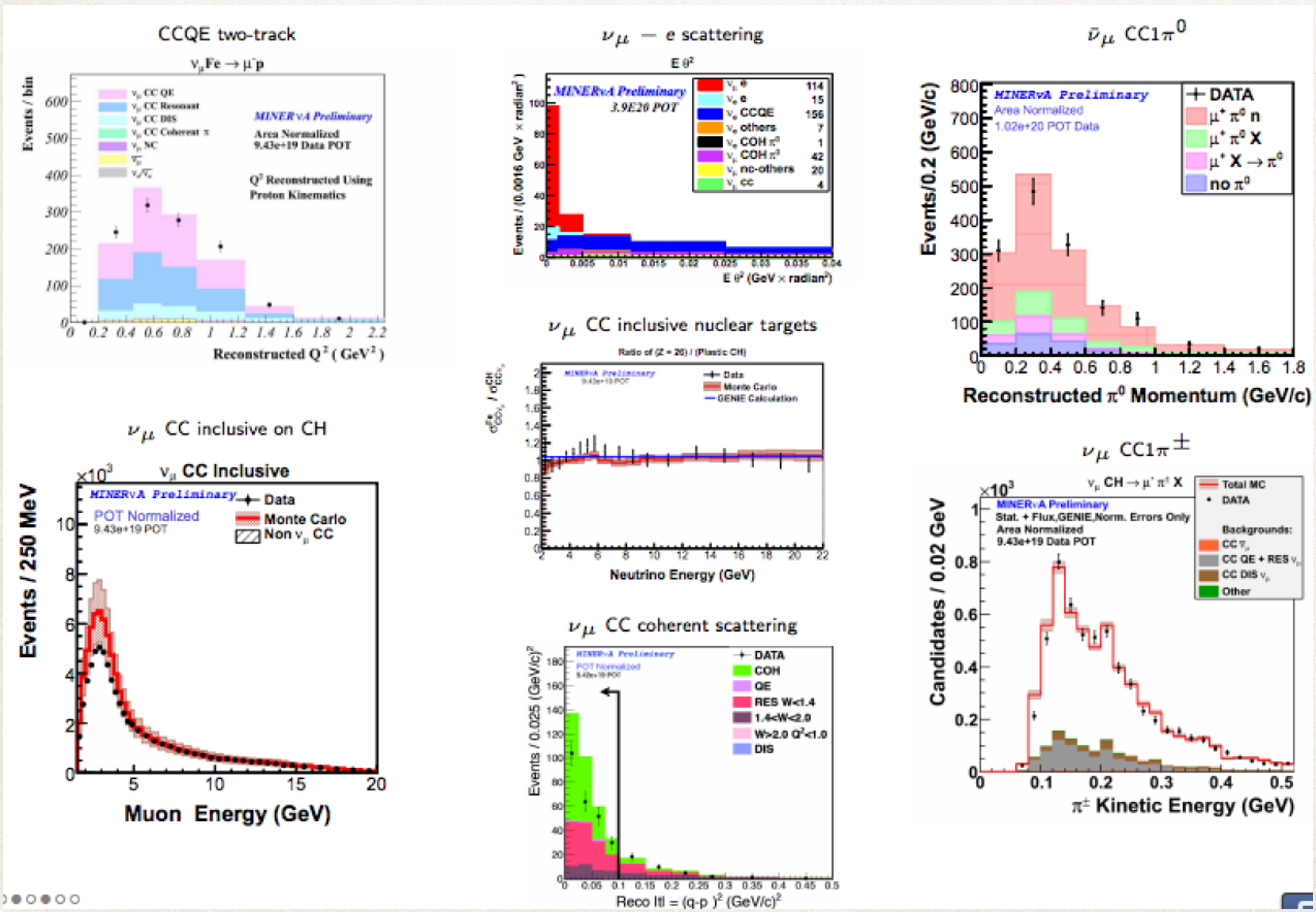
Vertex Energy

What does it all mean?

- Our cross section measurements favor a model that includes a **meson exchange current-like enhancement to the cross section**
- The vertex energy distributions are consistent with the presence of additional unsimulated protons in neutrino mode but not in antineutrino mode
  - This is what one would expect if the np correlations observed via electron scattering were contributing to the QE-like cross-section (this would lead to μpp final states in neutrino mode and μnn final states in antineutrino mode)
- We definitely see evidence of unsimulated effects that could have major ramifications for oscillation experiments
- Further study is needed to sort out exactly what we are seeing

Future Plans

- MINERνA has much future study planned:



- QE with full proton (or neutron) reconstruction.
- QE in the nuclear targets.
- QE ratio to CC inclusive
- ν_e QE scattering
- Many pion channels
- DIS/CC Inclusive
- Neutral Currents

Conclusion

- Precision understanding of neutrino-nuclear cross sections is essential to the next generation of oscillation analyses
- The MINERνA detector was designed to provide this
- The MINERνA collaboration recently published our first physics results
    - Companion neutrino and antineutrino analyses of charged-current quasi-elastic samples
    - We find evidence of unsimulated nuclear effects in vertex energy distributions, total cross-section and Q^2 shape.
- There is much more to come soon!

Thank You!

Backup

Backup Index

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- 86 Absolute Cross Sections
- 88 Correlations
- Cross sections for theta < 20 Degrees
- Absolute Background Scales
- Systematic Uncertainties
- QE vs QE-like
- Resolutions
- Flux
- More on the MINERvA Detector

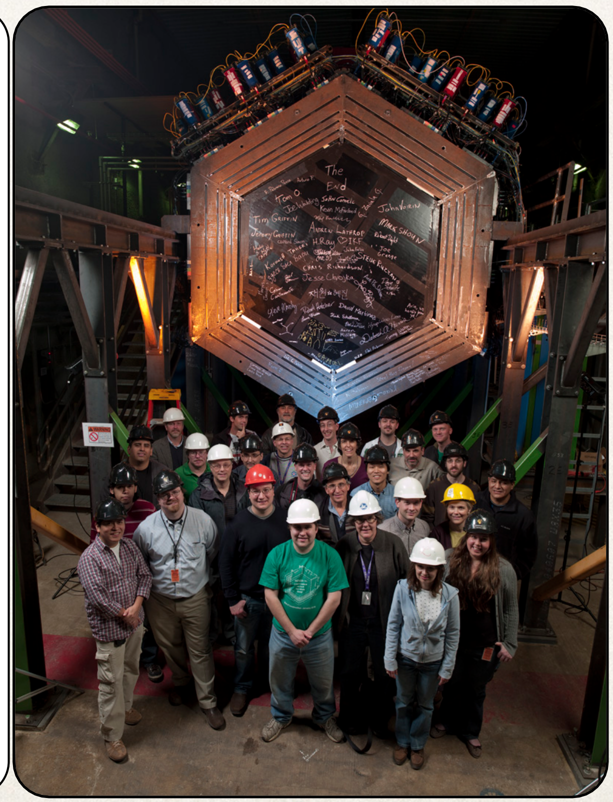
MINERνA Collaboration

MINERνA

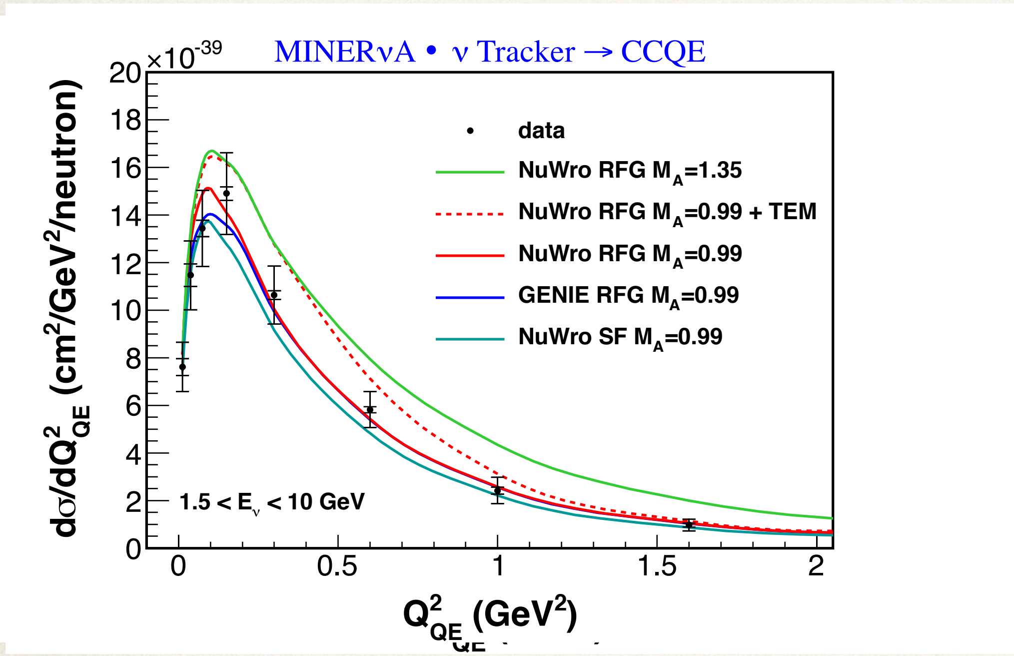
More than just a detector…

~80 collaborators from particle and nuclear physics

University of Athens
University of Texas at Austin
Centro Brasileiro de Pesquisas Físicas
Fermilab
University of Florida
Université de Genève
Universidad de Guanajuato
Hampton University
Inst. Nucl. Reas. Moscow
Mass. Col. Lib. Arts
Northwestern University
University of Chicago



Absolute Comparison with Models



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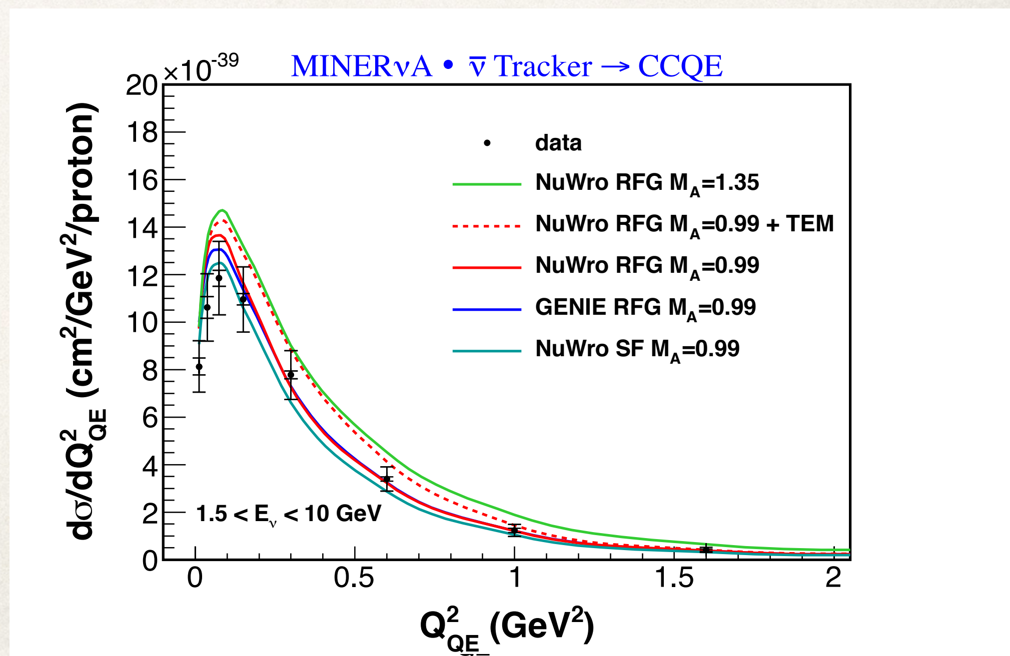

The dotted red line uses the standard $M_A = 0.99$ and the Fermi Gas nuclear model but adds QE-like interactions using the "Transverse Enhancement Model"

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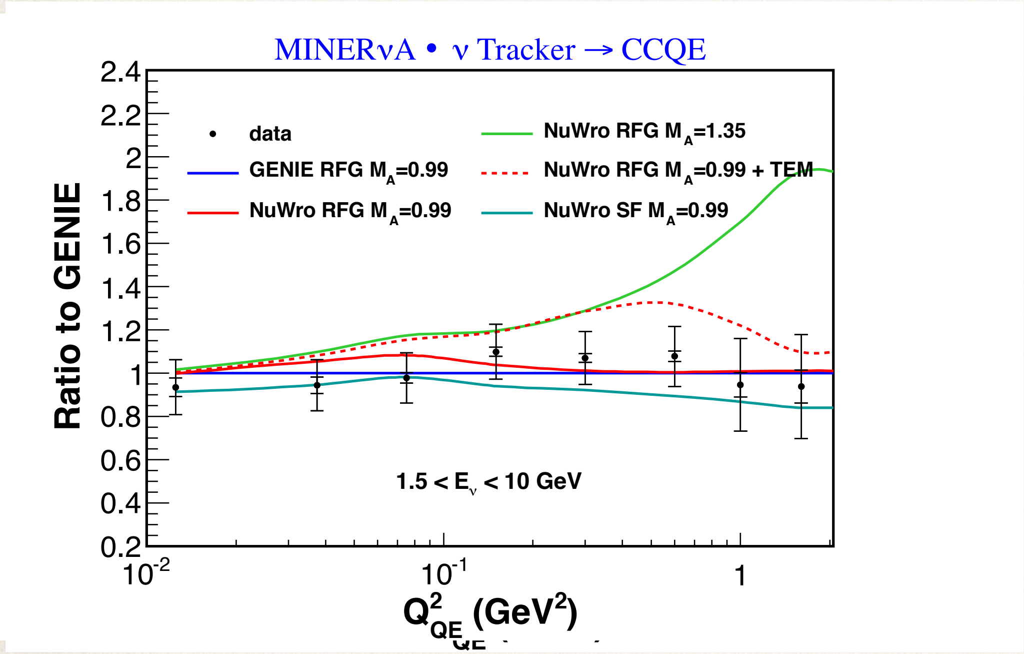

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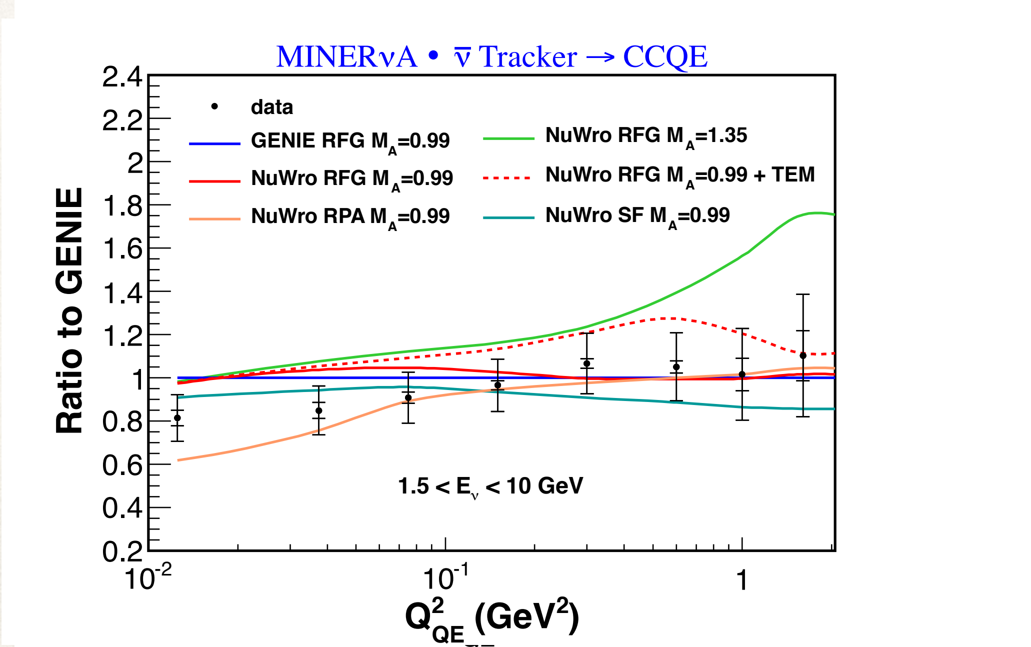
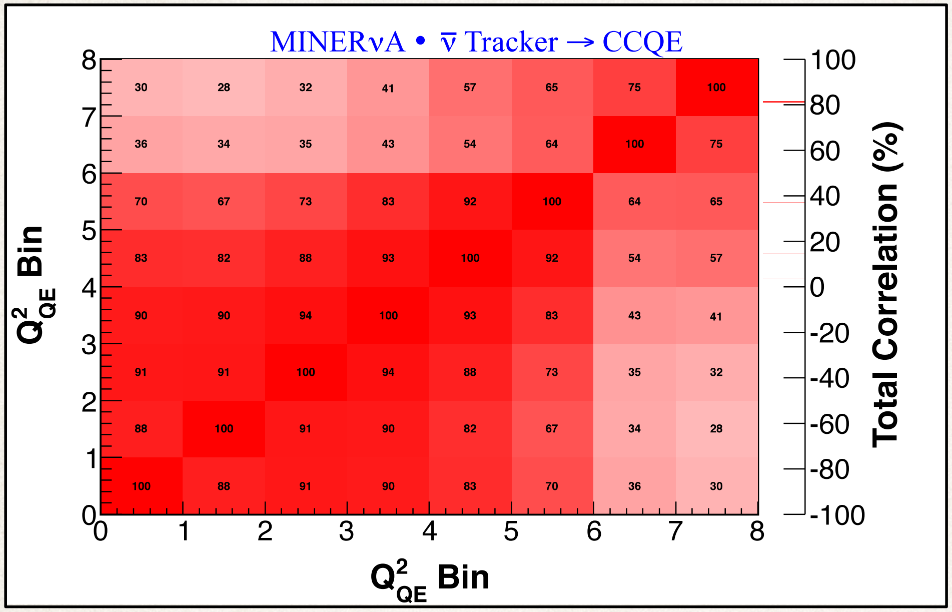
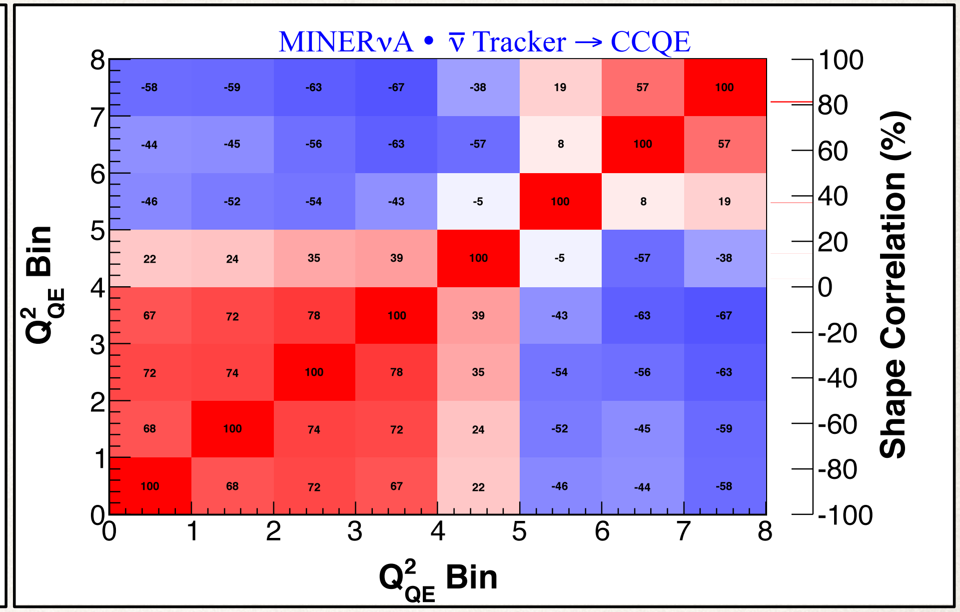
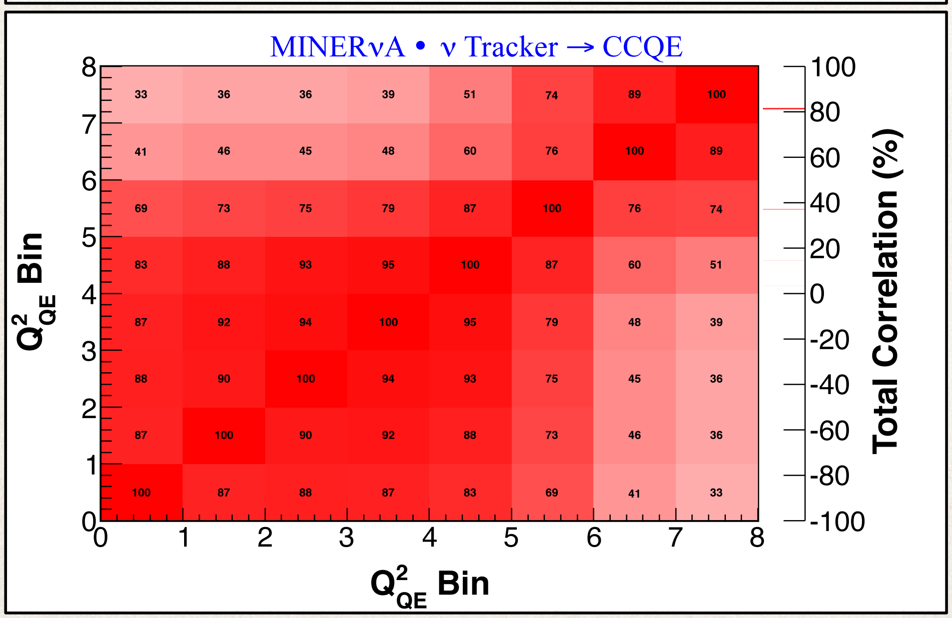
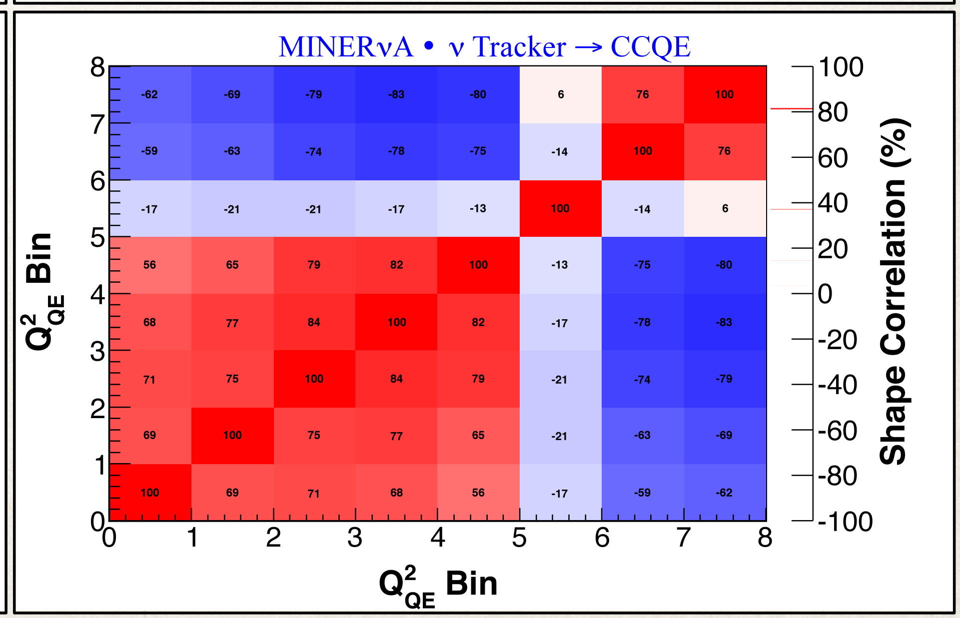


Cross Section Correlations



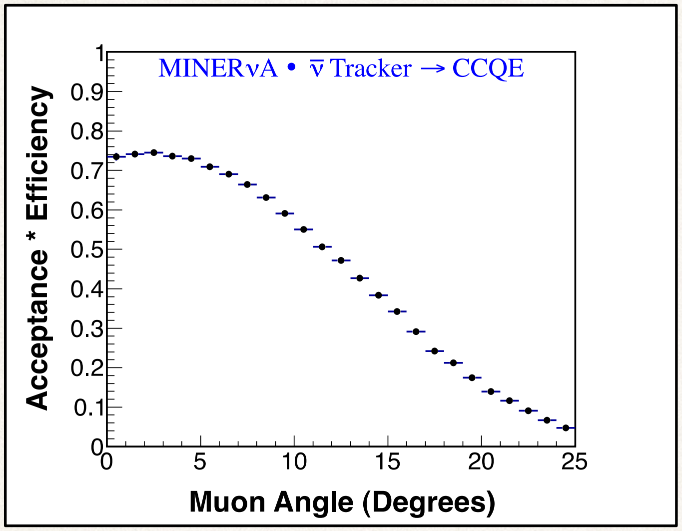


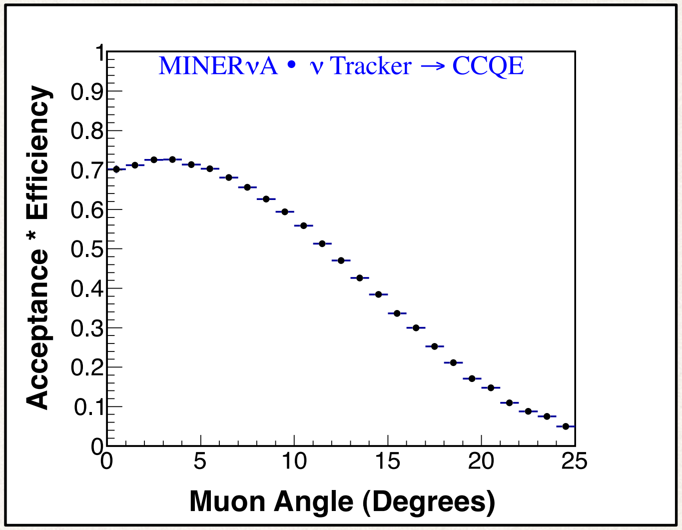




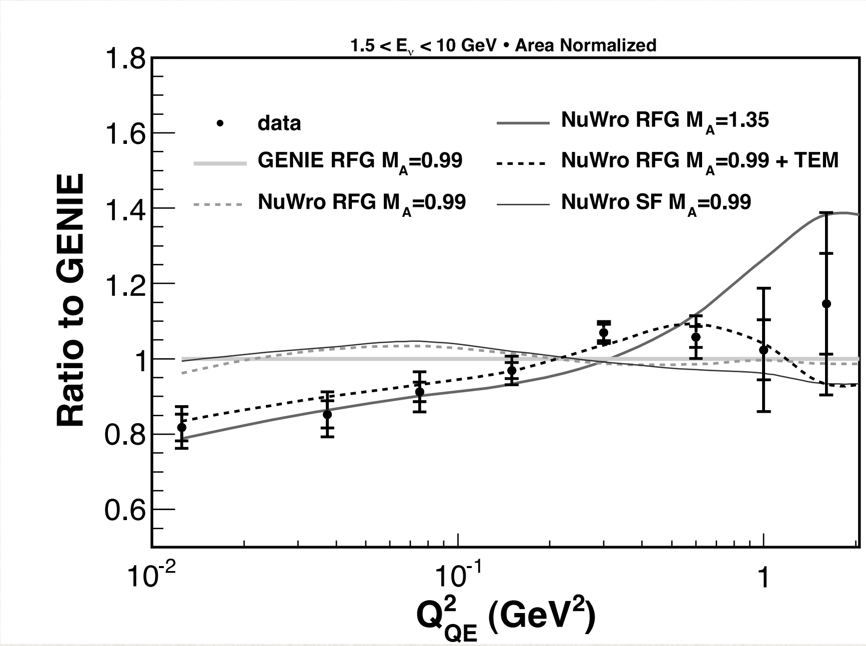
20 Degree Acceptance

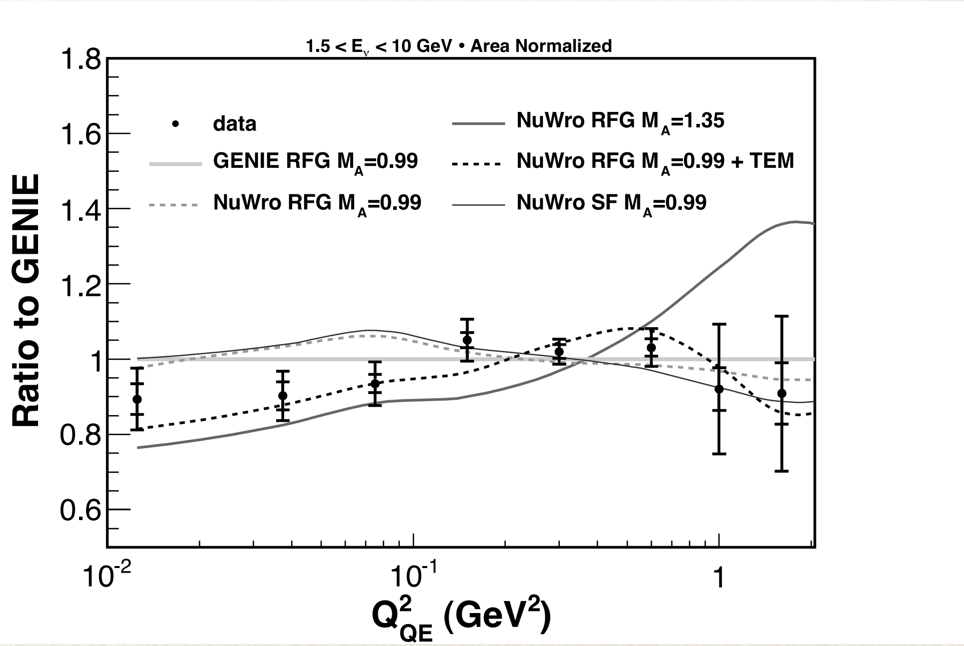
$\bar{\nu}_\mu$



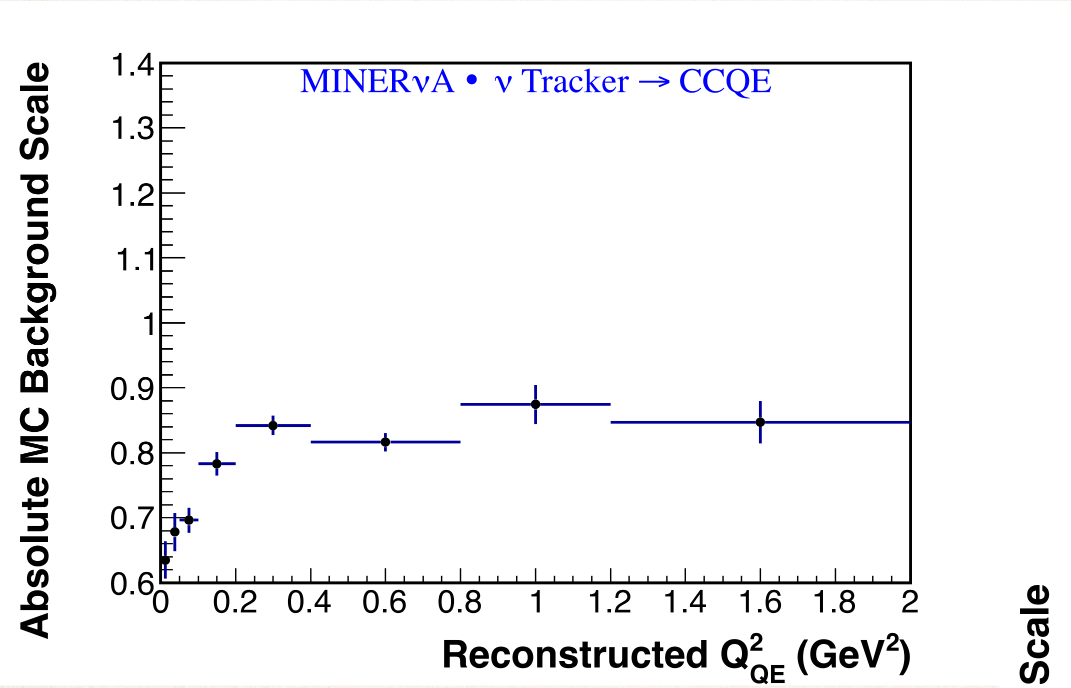


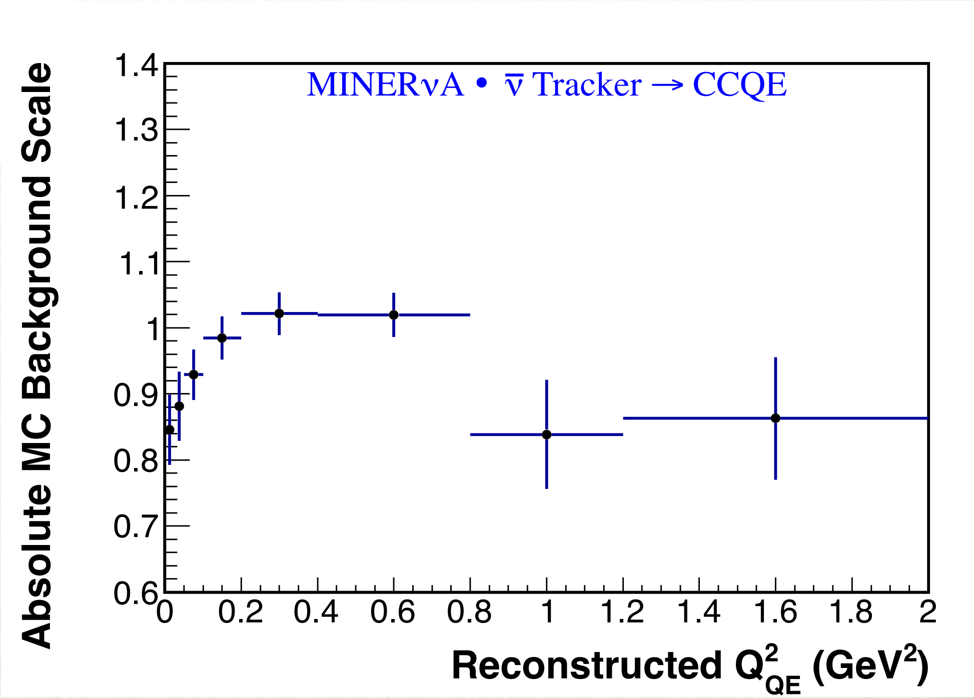
ν_μ





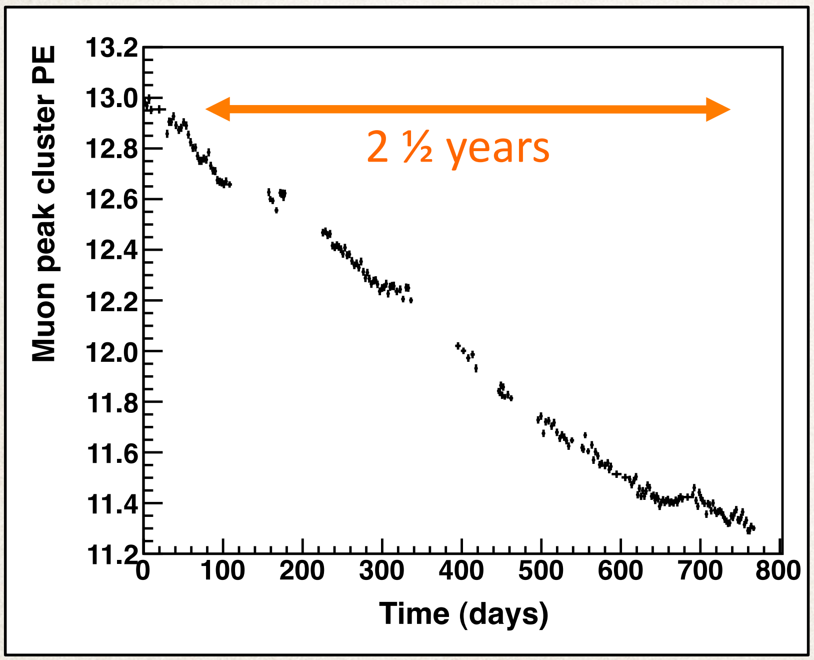
Absolute Background Scales

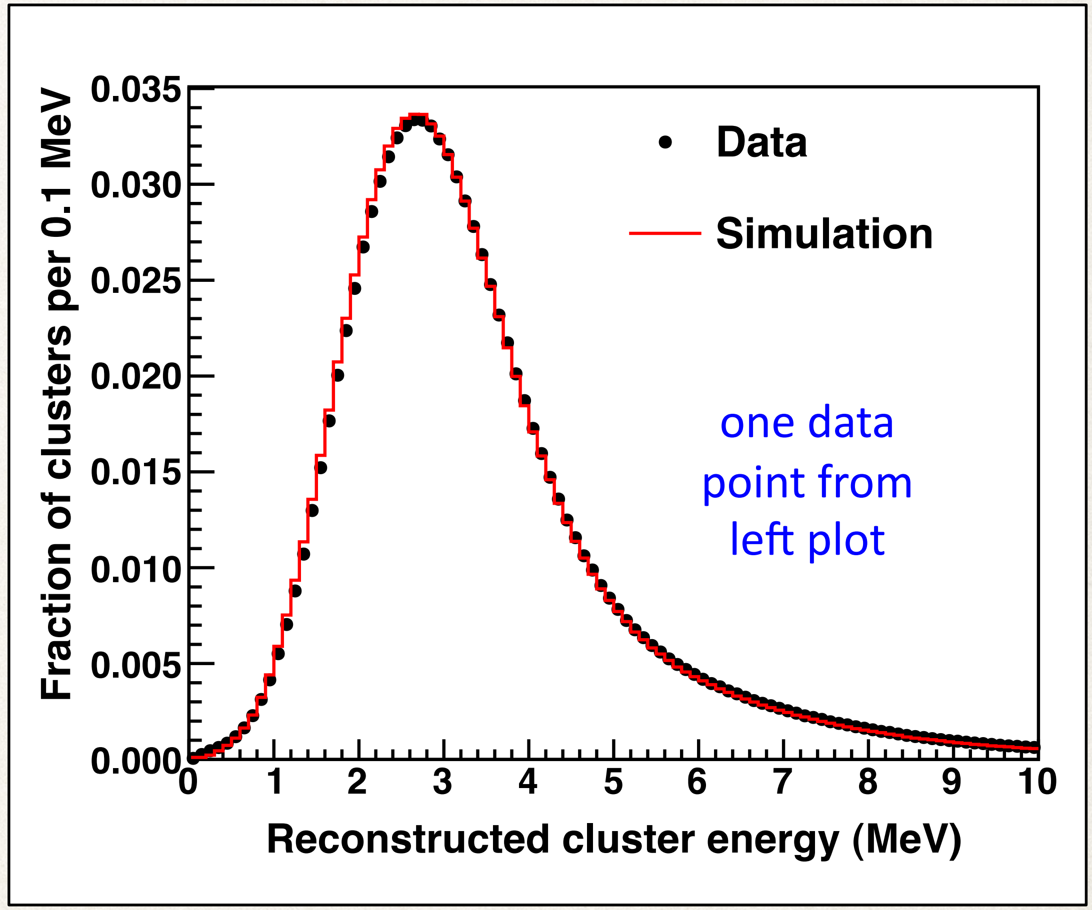




Systematic Uncertainties: Recoil Energy

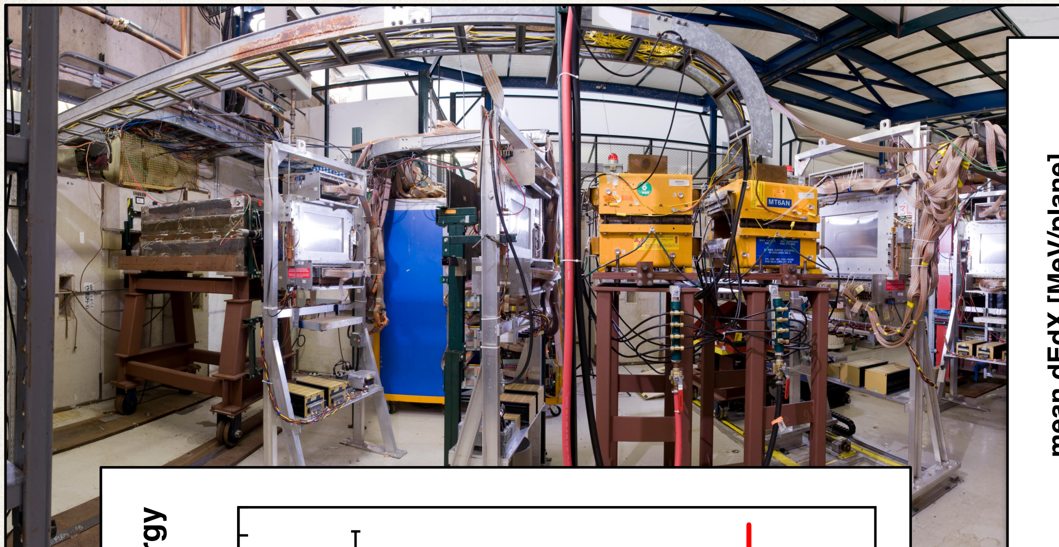
High statistics monitoring of the detector energy response with **"Rock Muons"**

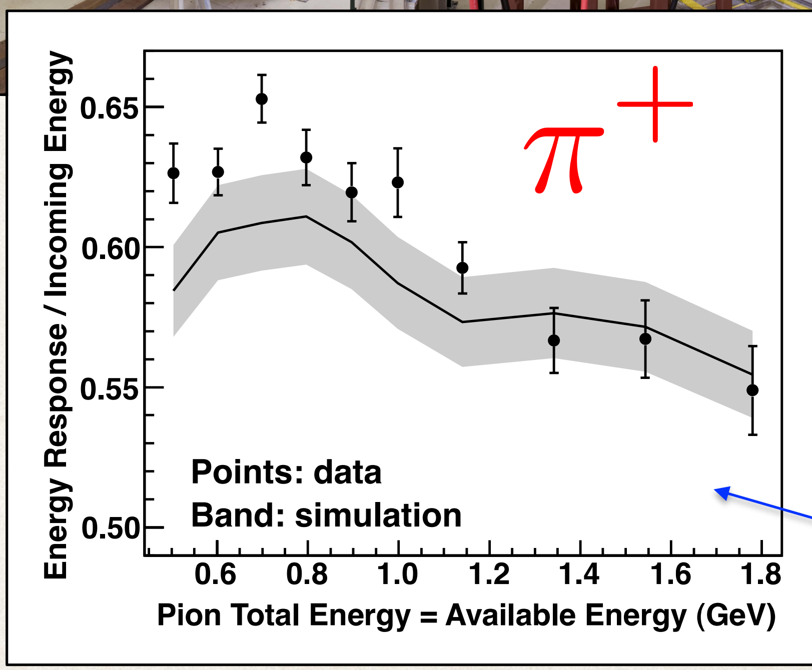


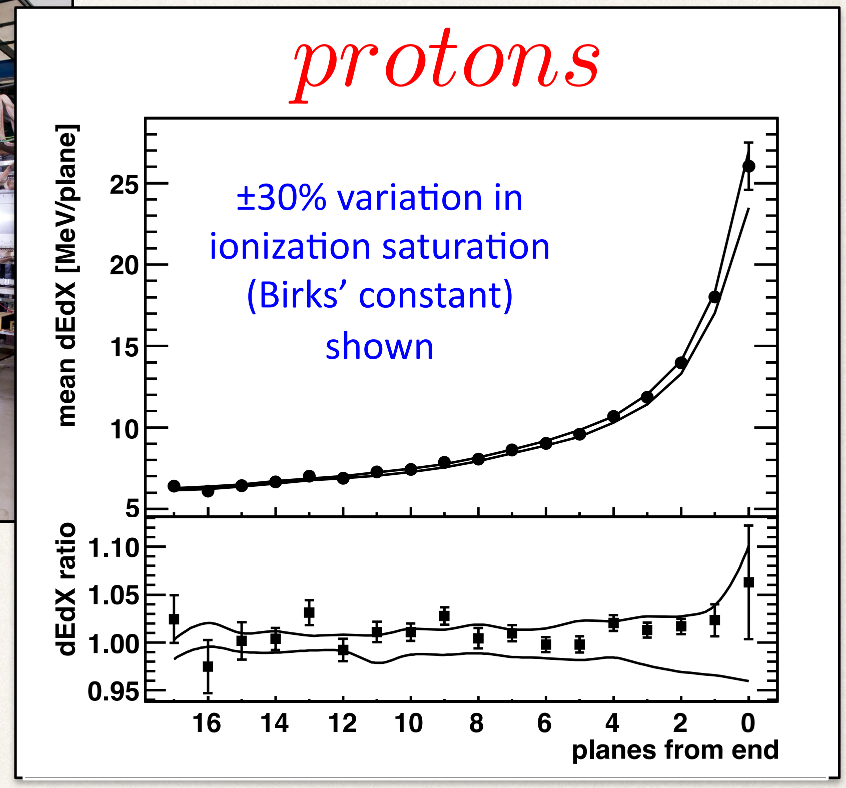


1 – 10 MeV mip hits

Systematic Uncertainties: Recoil Energy

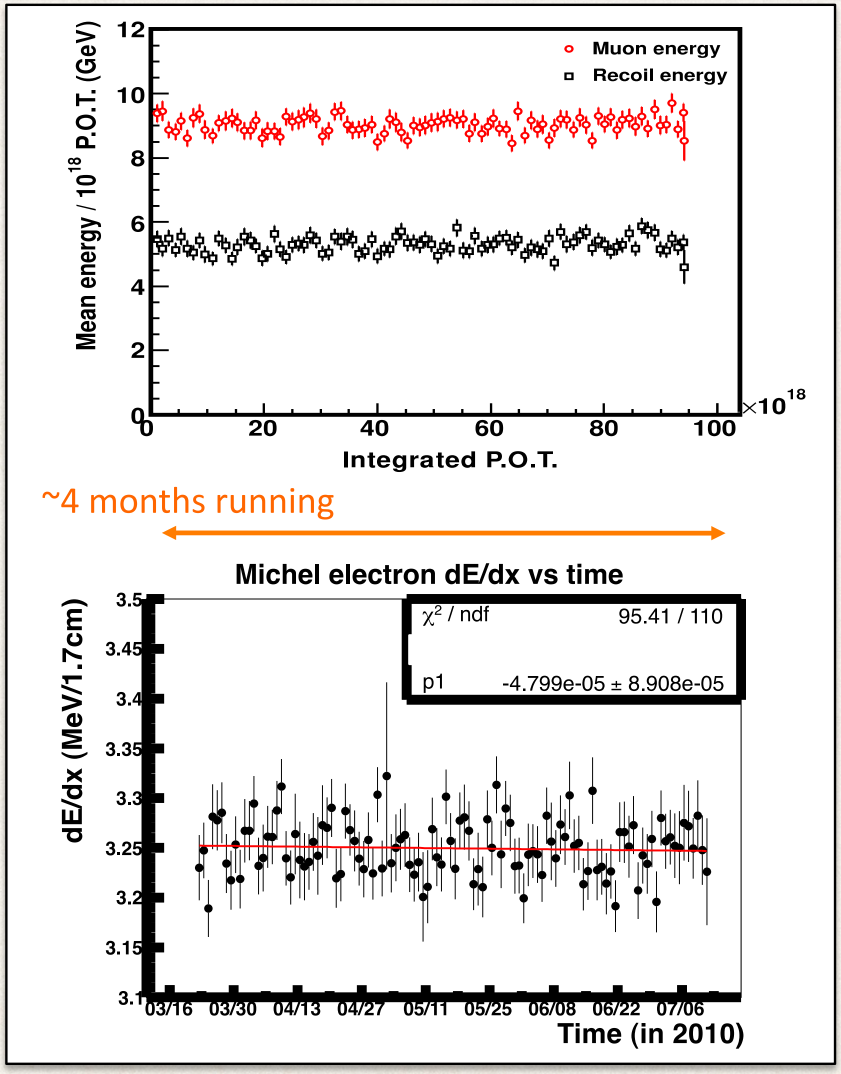






high-energy charged pion response uncertainty ≈ 5%

Systematic Uncertainties: Recoil Energy



Muons

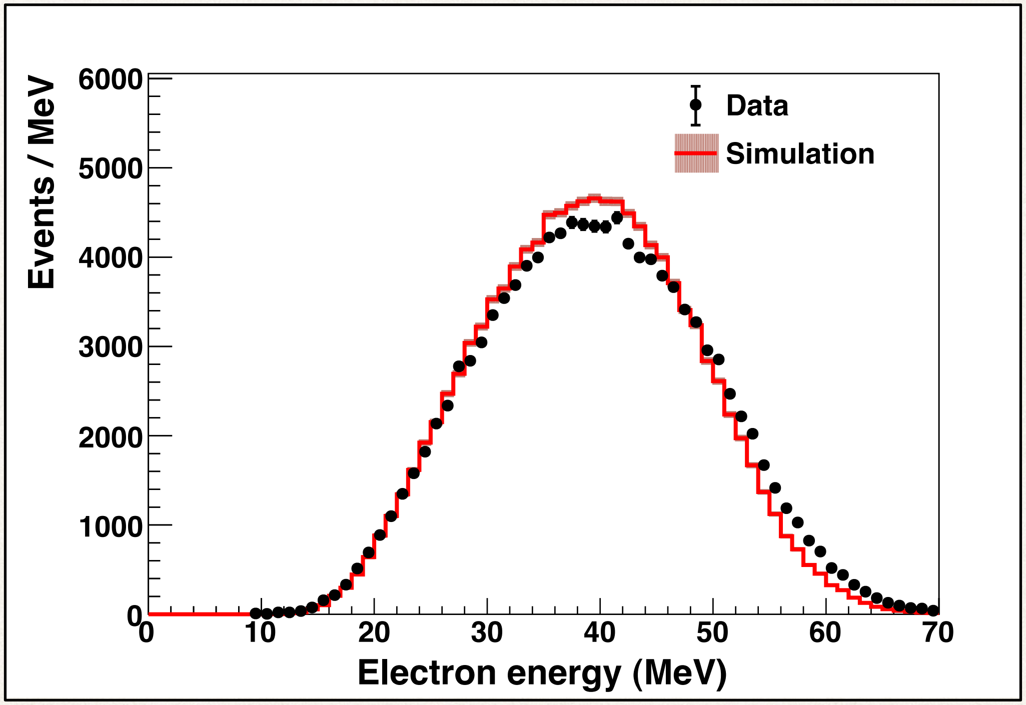
Recoil

Calibrated detector
very stable
at high and low
energy scales

Electron dE/dx

Systematic Uncertainties: Recoil Energy

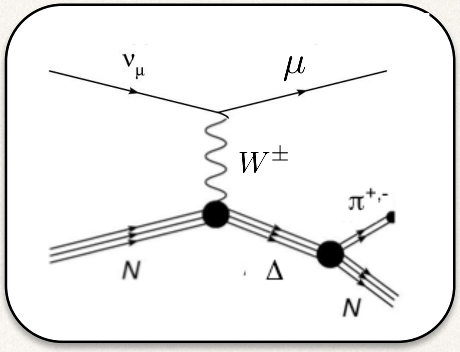
$20 - 60$ MeV electrons



electromagnetic response uncertainty ≈ 3%

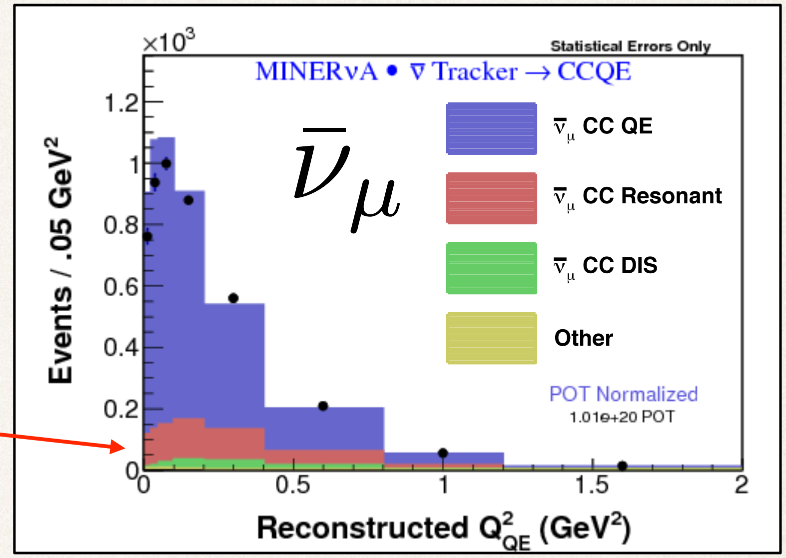
Systematic Uncertainties: Primary Interaction Model

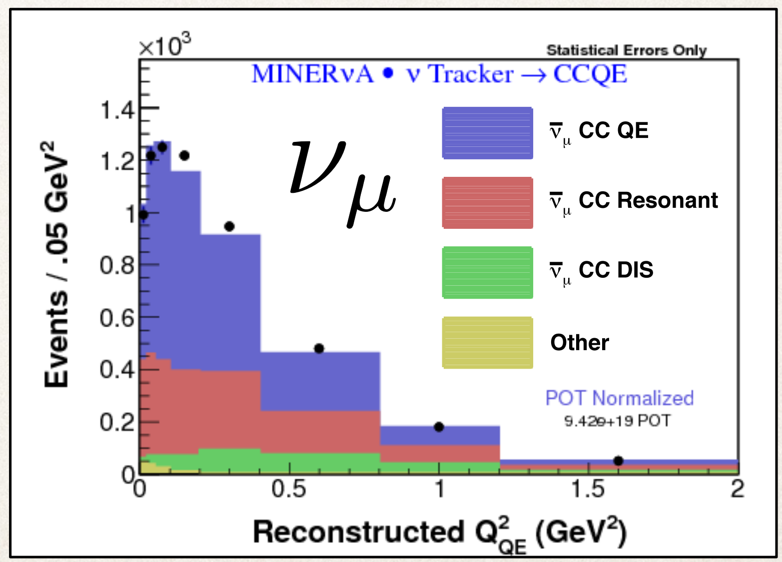
GENIE 2.6.2



- Main background from resonance production and decay to charged pions
  - Pion not tagged by recoil energy cut, OR
  - Pion absorbed in nucleus
- Rate constrained with data

Model parameter	uncertainty
CC resonance prod. normalization	±20%
Resonance model parameter (M_A)	±20%
Non-resonance pion production	±50%

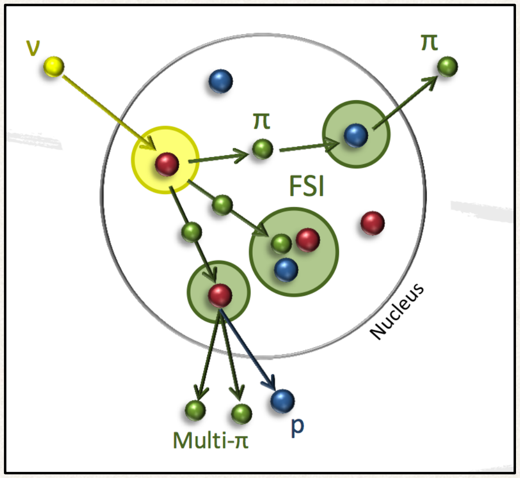


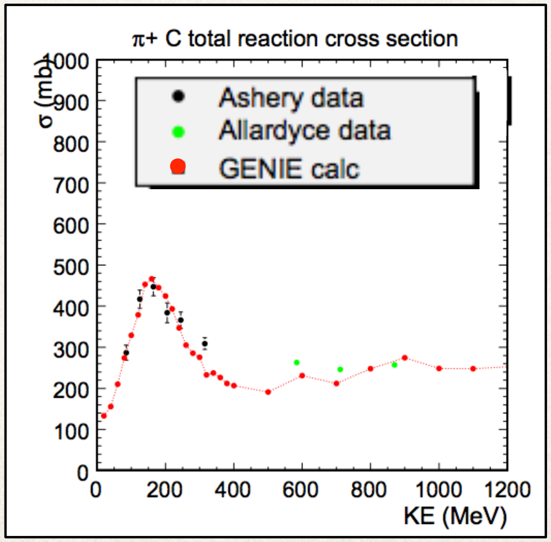


Systematic Uncertainties: Final State Interaction

- Another way the nuclear environment really complicates things
  - Final state different from interaction vertex
- Important part of neutrino event generators
  - Tune with external hadron data
  - Data comparisons inform systematics
- Crucial piece of any analysis

Model parameter	uncertainty
pion/nucleon mean path	±20%
pion/nucleon charge exchange	±50%
pion absorbtion	±30%
pion/nucleon inelastic cross-section	±40%
elastic cross sections	±10-30%





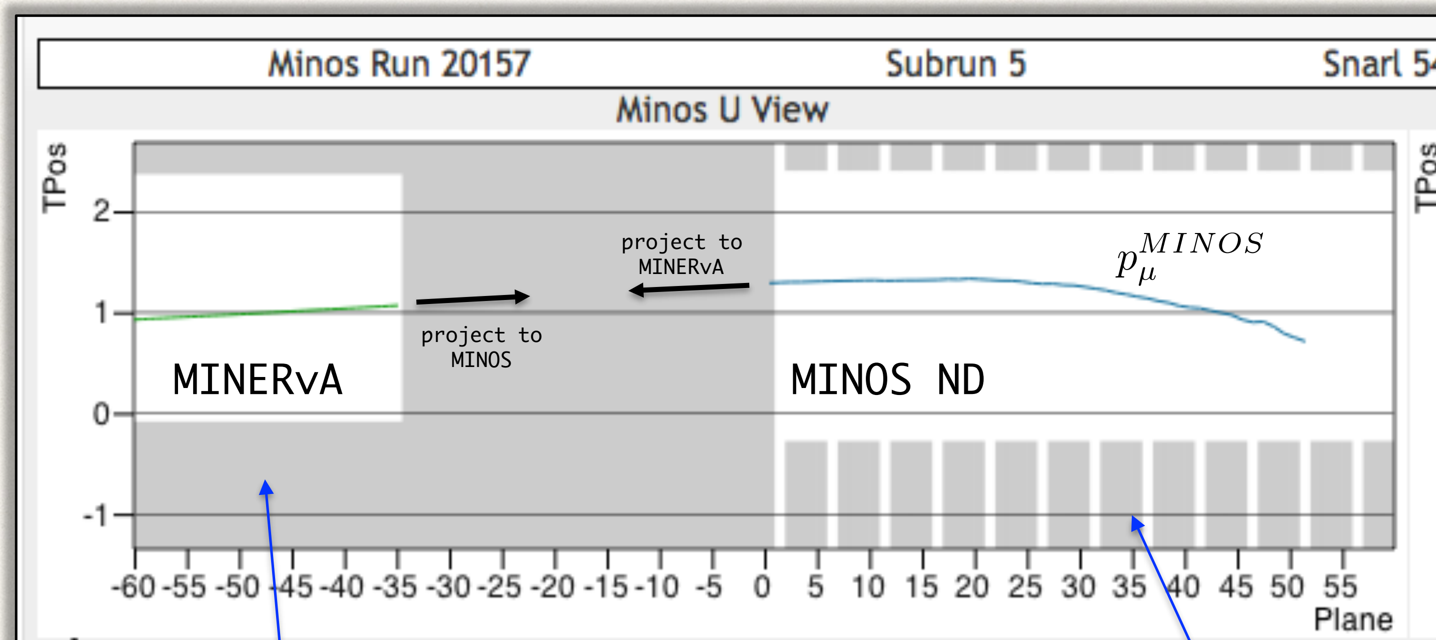
GENIE Physics Manual

Systematic Uncertainties: GENIE Summary

Uncertainty	GENIE Knob name	1 σ
M_A (Elastic Scattering)	MaNCEL	± 25%
Eta (Elastic scattering)	EtaNCEL	± 30%
M_A (CCQE Scattering)	MaCCQE	+25% −15%
CCQE Normalization	NormCCQE	+20% −15%
M_A (CCQE Scattering, shape only)	MaCCQEshape	± 10%
CCQE Vector Form factor model	VecFFCCQEshape	
CC Resonance Normalization	NormCCRES	± 20%
M_A (Resonance Production)	MaRES	± 20%
M_V (Resonance Production)	MvRES	± 10%
1pi production from $\nu p / \bar{\nu} n$ non-resonant interactions	Rvp1pi	± 50%
1pi production from $\nu n / \bar{\nu} p$ non-resonant interactions	Rvn1pi	± 50%
2pi production from $\nu p / \bar{\nu} n$ non-resonant interactions	Rvp2pi	± 50%
2pi production from $\nu n / \bar{\nu} p$ non-resonant interactions	Rvn2pi	± 50%
DIS CC Normalization	NormDISCC	??
Modfiy Pauli blocking (CCQE) at low Q^2	CCQEPauliSupViaKF	± 30%

Uncertainty	GENIE Knob name	1 σ
Pion mean free path	MFP_pi	± 20%
Nucleon mean free path	MFP_N	± 20%
Pion fates – absorption	FrAbs_pi	± 30%
Pion fates – charge exchange	FrCEx_pi	± 50%
Pion fates – Elastic	FrElas_pi	± 10%
Pion fates – Inelastic	FrInel_pi	± 40%
Pion fates – pion production	FrPiProd_pi	± 20%
Nucleon fates – charge exchange	FrCEx_N	± 50%
Nucleon fates – Elastic	FrElas_N	± 30%
Nucleon fates – Inelastic	FrInel_N	± 40%
Nucleon fates – absorption	FrAbs_N	± 20%
Nucleon fates – pion production	FrPiProd_N	± 20%
AGKY hadronization model – x_F distribution	AGKYxF1pi	± 20%
Delta decay angular distribution	Theta_Delta2Npi	On/off
Resonance decay branching ratio to photon	RDecBR1gamma	± 50%

Systematic Uncertainties: Tracking Efficiencies



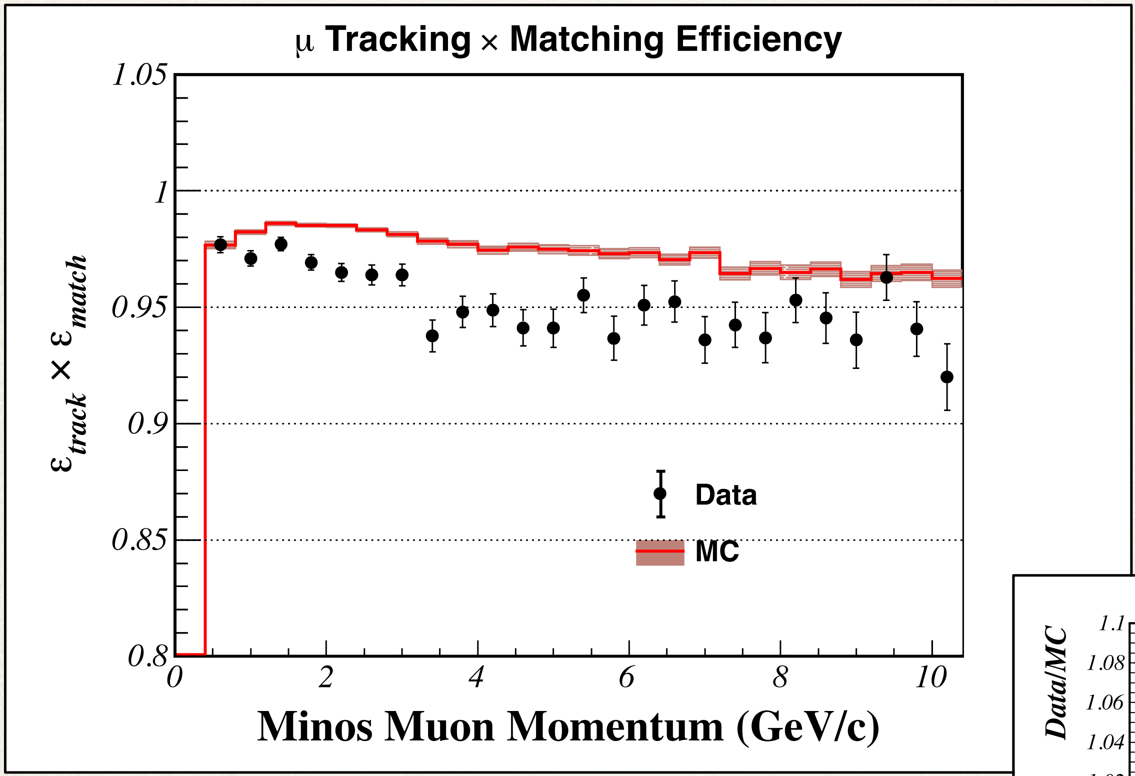
Affected by:

1. pile-up at high intensity
2. dead-time
3. large showers

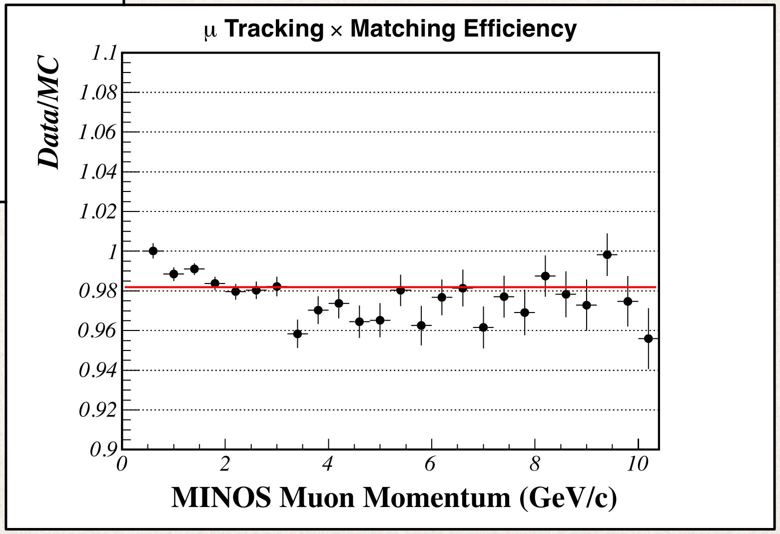
Affected by:

1. pile-up at high intensity, worse for shorter tracks (low energy)

Systematic Uncertainties: Tracking Efficiencies



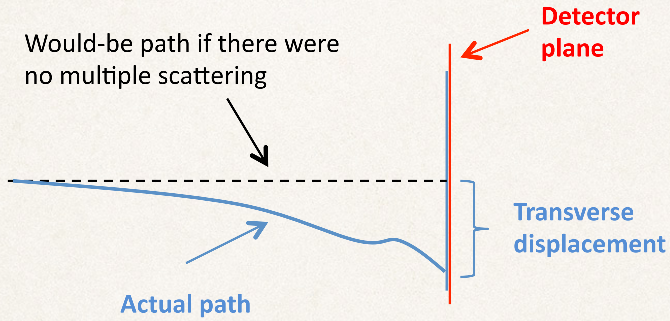
MINERvA muon tracking efficiency



Momentum provided by MINOS ND

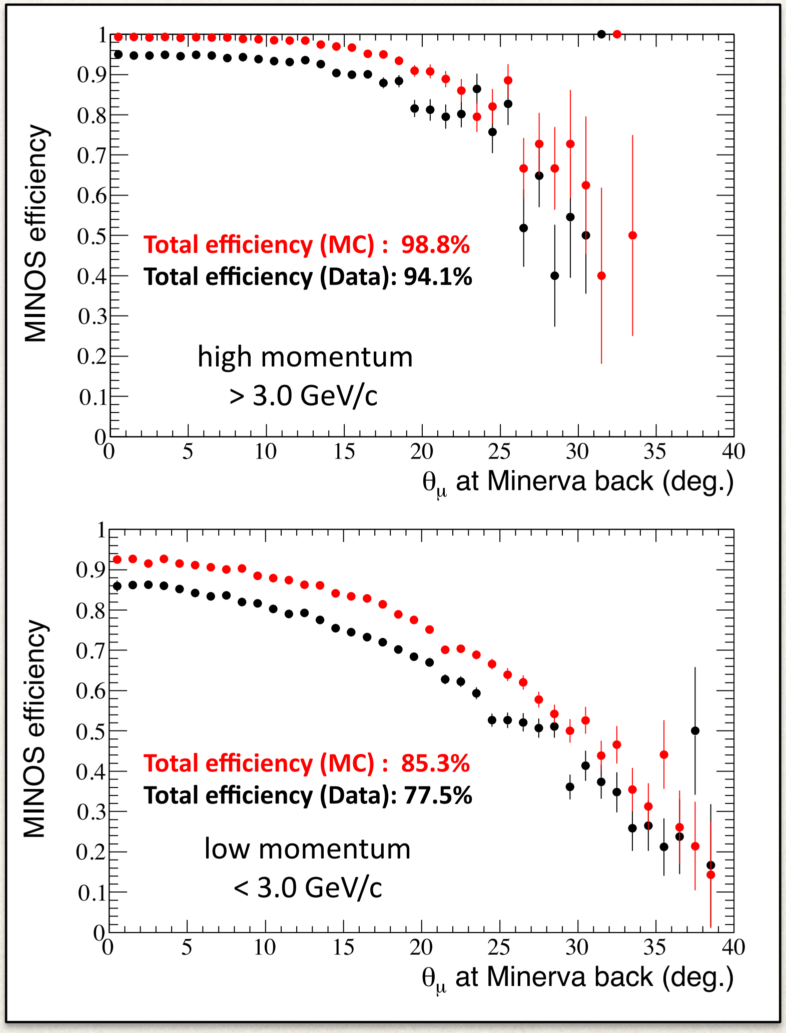
Systematic Uncertainties: Tracking Efficiencies

MINOS muon tracking efficiency



use scattering in MINERvA ECAL+HCAL to split into **high** and **low** momentum samples

Total Corrections	neutrinos	antineutrinos
p_μ < 3.0 GeV/c	(-10.1 ± 4.7) %	(-7.8 ± 3.4) %
p_μ > 3.0 GeV/c	(-6.7 ± 2.6) %	(-4.5 ± 1.9) %



Systematic Uncertainties: AntiNu Summary

Q^2_{QE} (GeV^2)	I	II	III	IV	V	VI	Total
$0.0 - 0.025$	0.05	0.04	0.00	0.02	0.11	0.02	0.13
$0.025 - 0.05$	0.05	0.04	0.01	0.01	0.11	0.02	0.13
$0.05 - 0.1$	0.05	0.04	0.01	0.01	0.11	0.01	0.13
$0.1 - 0.2$	0.04	0.04	0.01	0.01	0.11	0.01	0.12
$0.2 - 0.4$	0.03	0.06	0.01	0.02	0.11	0.01	0.13
$0.4 - 0.8$	0.05	0.07	0.02	0.03	0.11	0.01	0.15
$0.8 - 1.2$	0.11	0.11	0.02	0.02	0.11	0.02	0.20
$1.2 - 2.0$	0.13	0.15	0.04	0.04	0.12	0.02	0.23

TABLE I: Fractional systematic uncertainties on $d\sigma/dQ^2_{QE}$ associated with muon reconstruction (I), recoil reconstruction (II), neutrino interaction models (III), final state interactions (IV), flux (V) and other sources (VI). The final column shows the total fractional systematic uncertainty due to all sources.

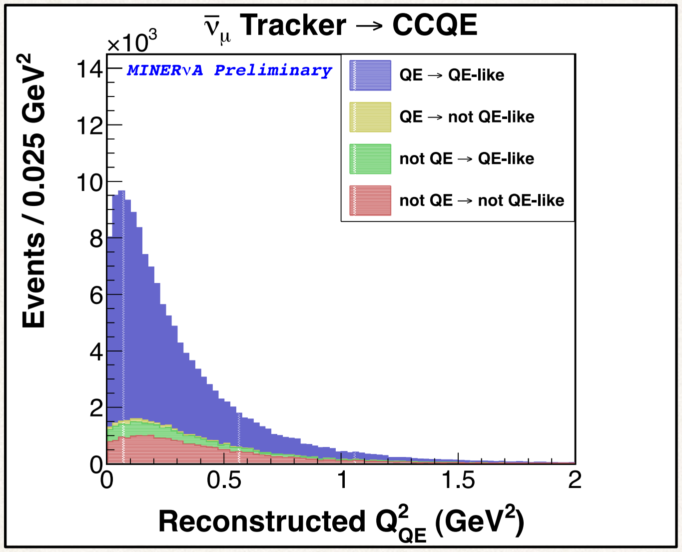
Systematic Uncertainties: Nu Summary

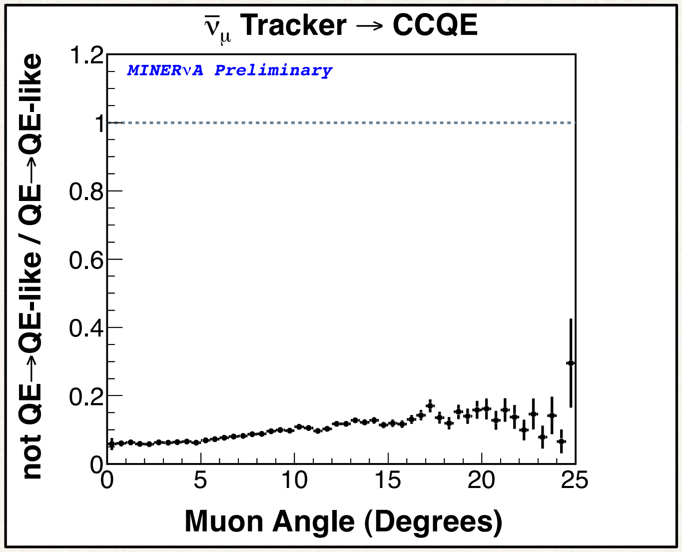
Q^2_{QE} (GeV^2)	I	II	III	IV	V	VI	Total
0.0 – 0.025	0.06	0.04	0.02	0.04	0.09	0.03	0.13
0.025 – 0.05	0.06	0.03	0.02	0.03	0.09	0.02	0.12
0.05 – 0.1	0.06	0.03	0.02	0.03	0.09	0.02	0.12
0.1 – 0.2	0.06	0.03	0.03	0.02	0.09	0.02	0.11
0.2 – 0.4	0.05	0.02	0.03	0.03	0.09	0.01	0.11
0.4 – 0.8	0.05	0.03	0.04	0.04	0.09	0.01	0.13
0.8 – 1.2	0.08	0.07	0.07	0.15	0.09	0.02	0.22
1.2 – 2.0	0.12	0.07	0.07	0.16	0.09	0.02	0.24

TABLE I: Fractional systematic uncertainties on $d\sigma/dQ^2_{QE}$ associated with (I) muon reconstruction, (II) recoil reconstruction, (III) neutrino interaction models, (IV) final state interactions, (V) flux and (VI) other sources. The rightmost column shows the total fractional systematic uncertainty due to all sources.

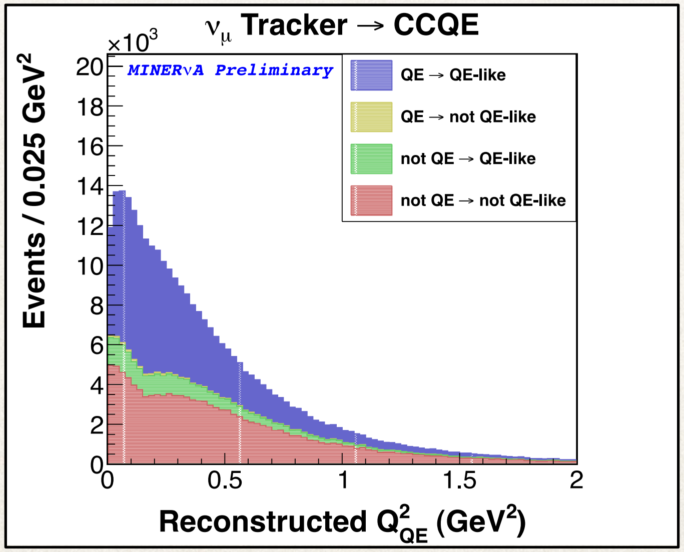
QE vs QE-like

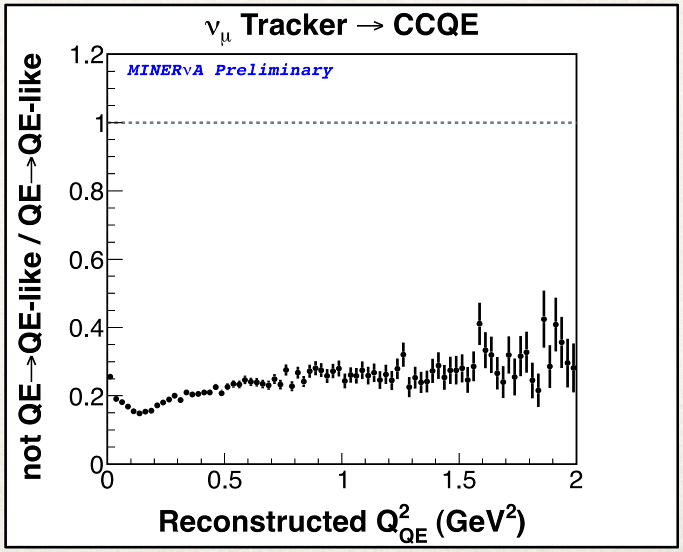
$\bar{\nu}_\mu$





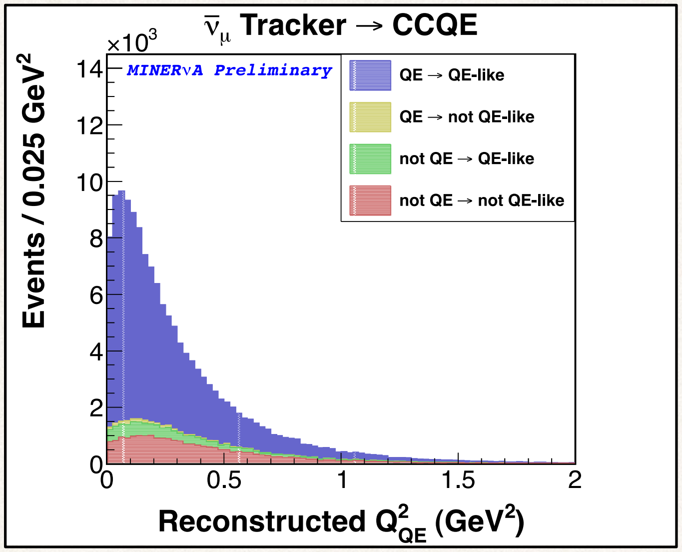
ν_μ

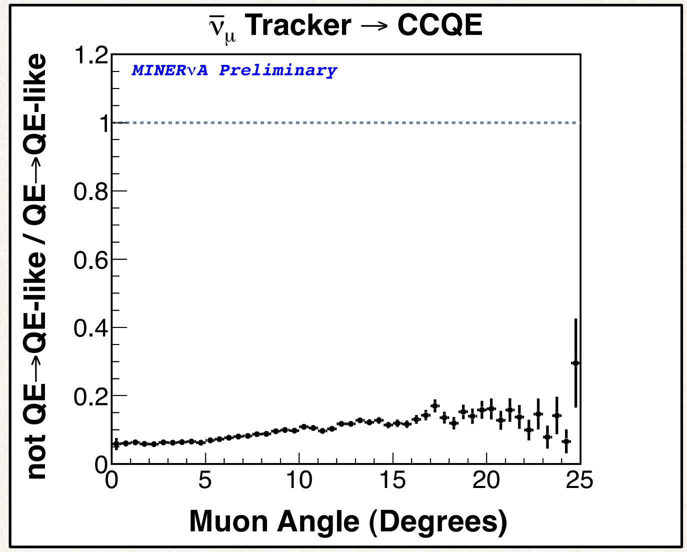




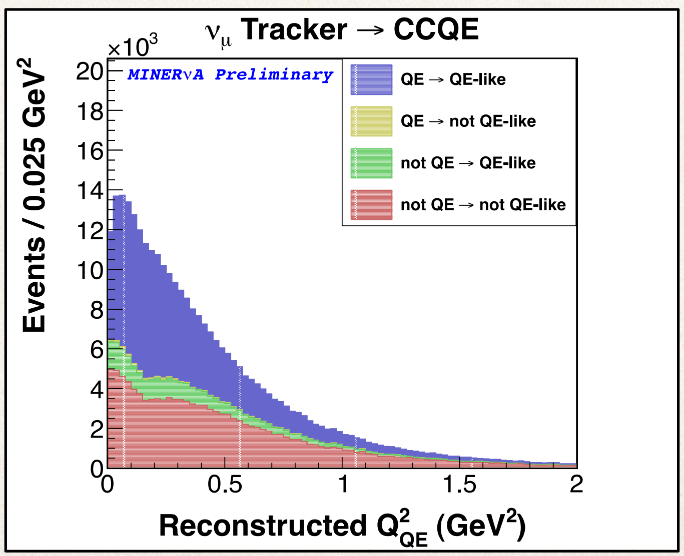
QE vs QE-like

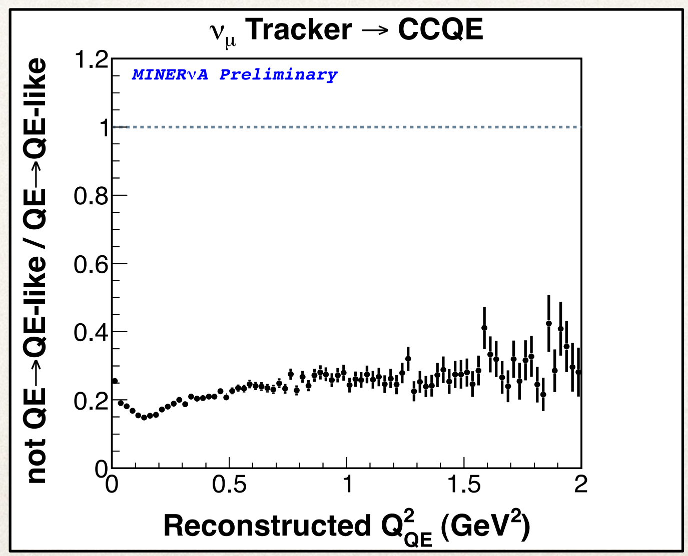
$\bar{\nu}_\mu$



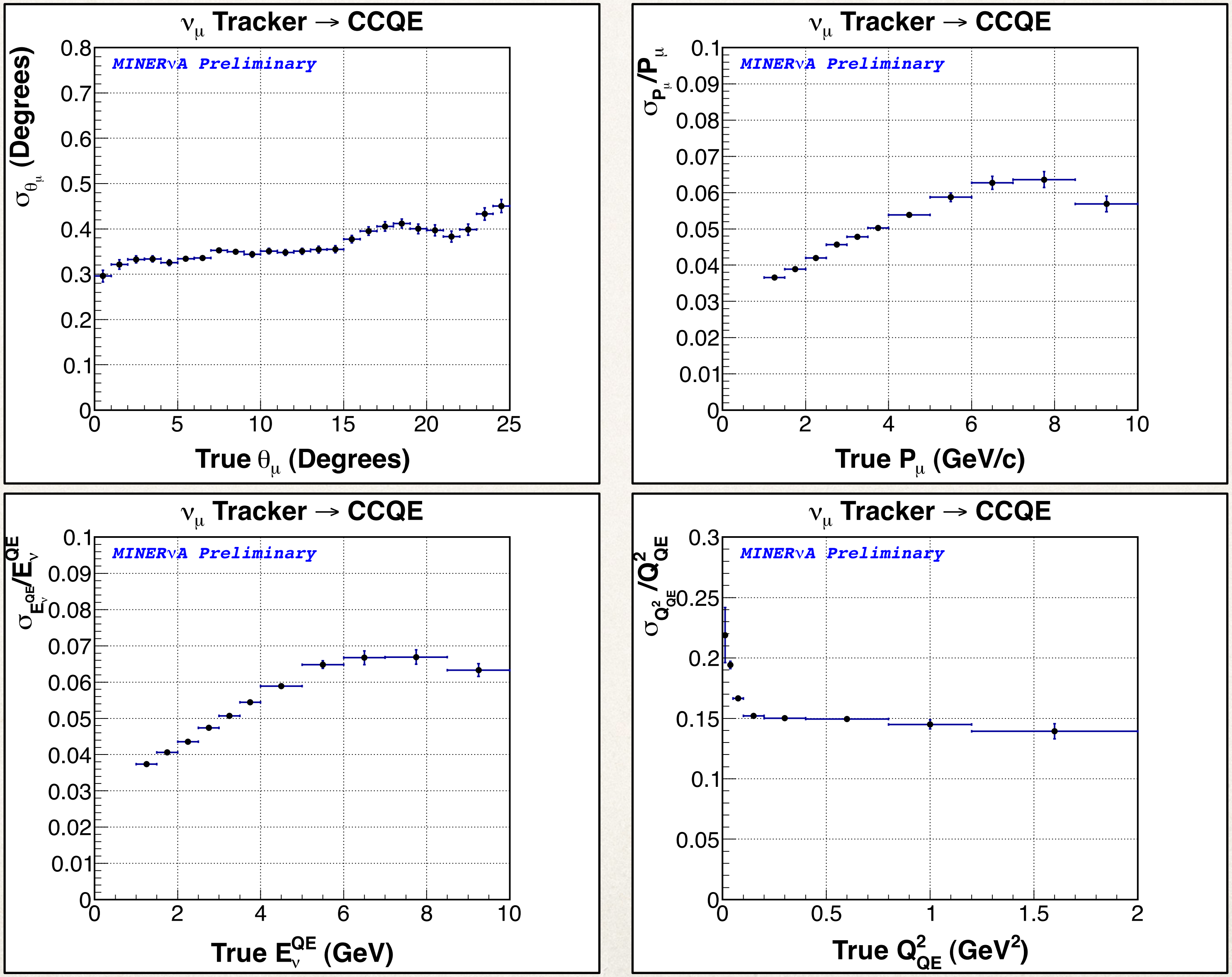


ν_μ

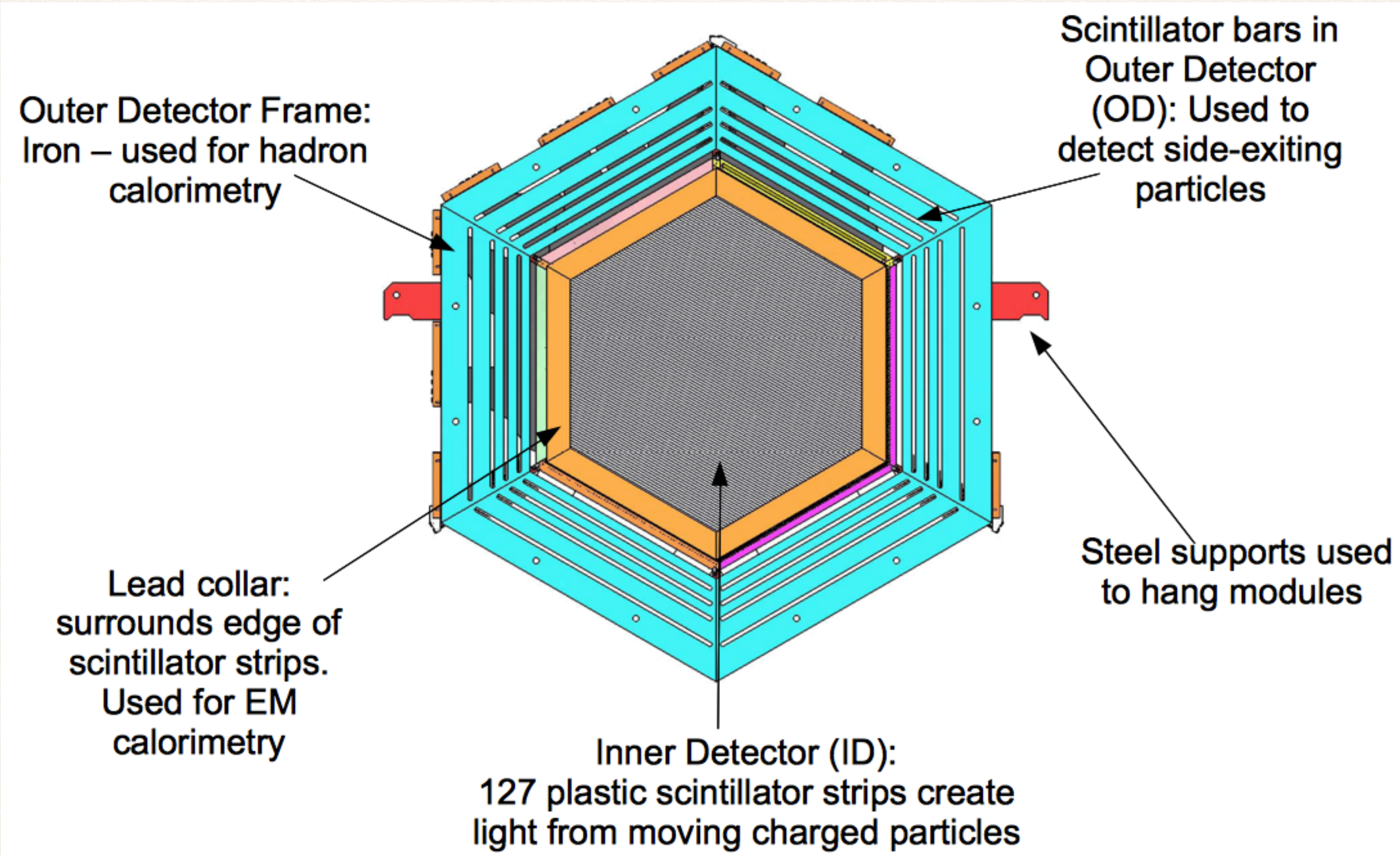




Resolutions



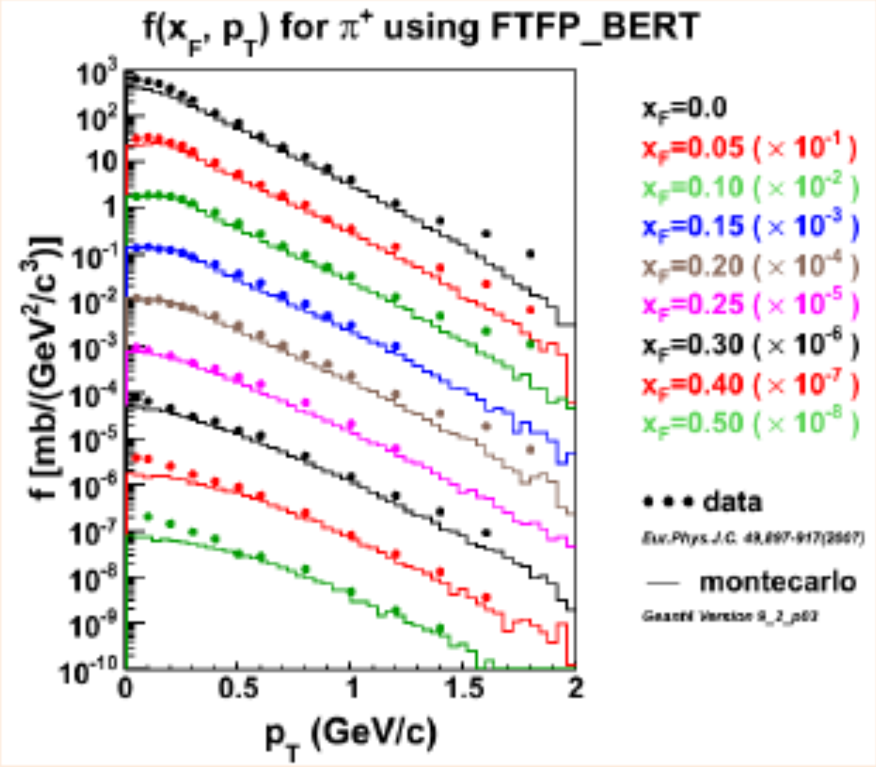
More on the MINERνA Detector

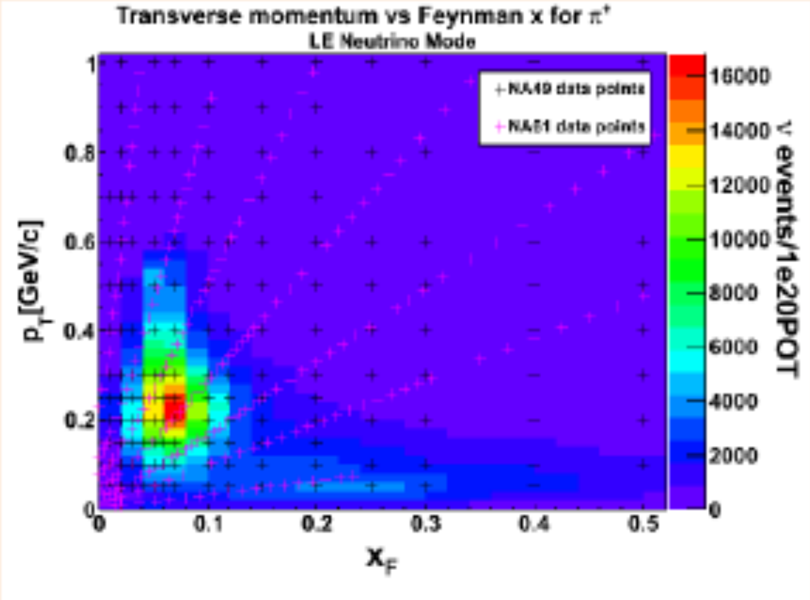


Flux: Current Constraints

Hadron Production: NA49

NA49, a hadron production Experiment at CERN, measured pion production with 158GeV protons on a thin graphite target. These data (plot at left) cover the relevant kinematics for the NuMI Beam (plot below)

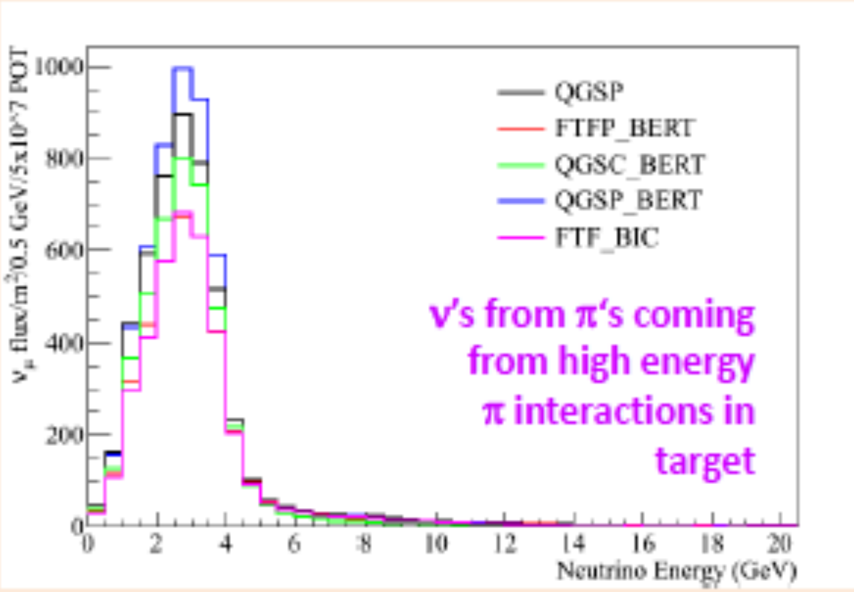


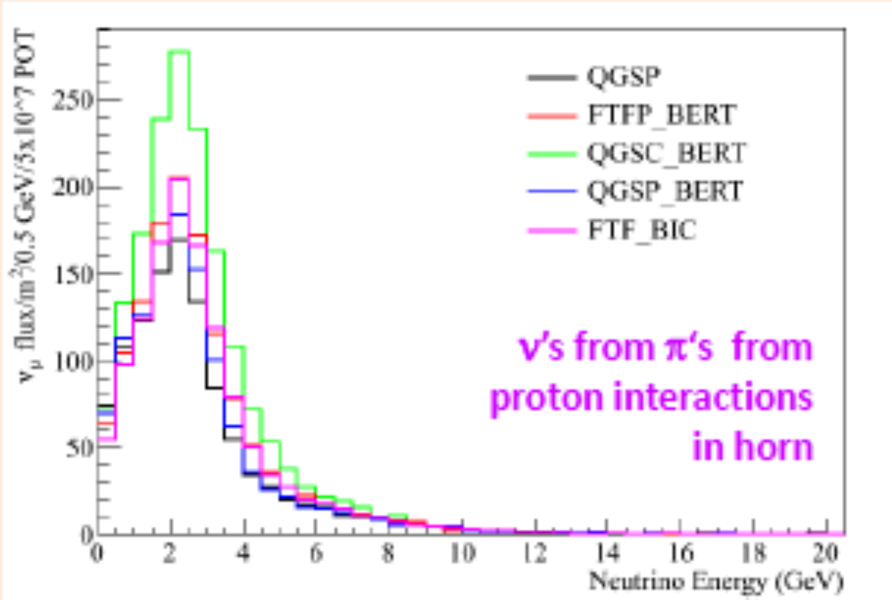


Flux: Current Constraints

Tertiary Production

Different hadron cascade models predict different neutrino fluxes from tertiary pion production, as shown in the two plots below: Note the 30% variations at the focusing peak

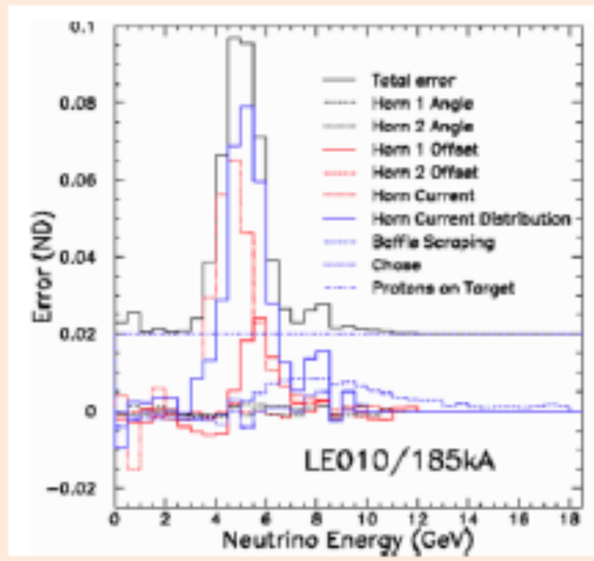




Flux: Current Constraints

Beam Focusing

Uncertainties in beamline alignment and horn magnetic field model are estimated to be small at most energies, but are significant (8%) at fall-off of focusing peak (see plot at right)

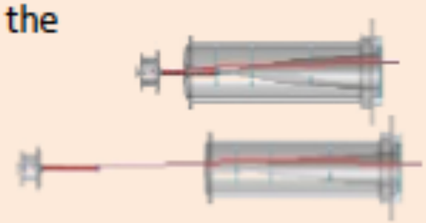


Z. Pavlovich, "Observation of disappearance of muon neutrinos in the NuMI beam", PhD thesis, UT Austin 2008

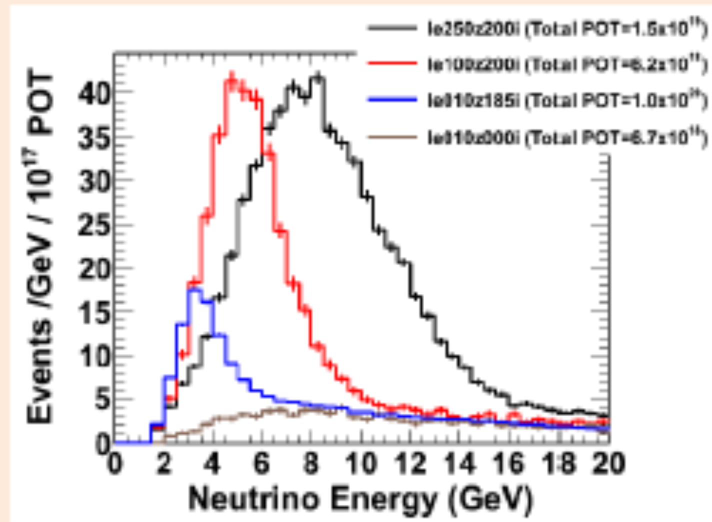
Flux: Future Constraints

Alternate ν Beam Constraints

The NuMI beamline is unique in that the distance between the target and first focusing horn can be changed with only a few days downtime.



By taking both neutrino and muon monitor data at several different target positions MINERvA will place additional constraints on the flux prediction. Figure at right shows spectra for 3 different target positions: nominal, 1m, and 2.5m from nominal, and for the case where the horn current was set to zero.



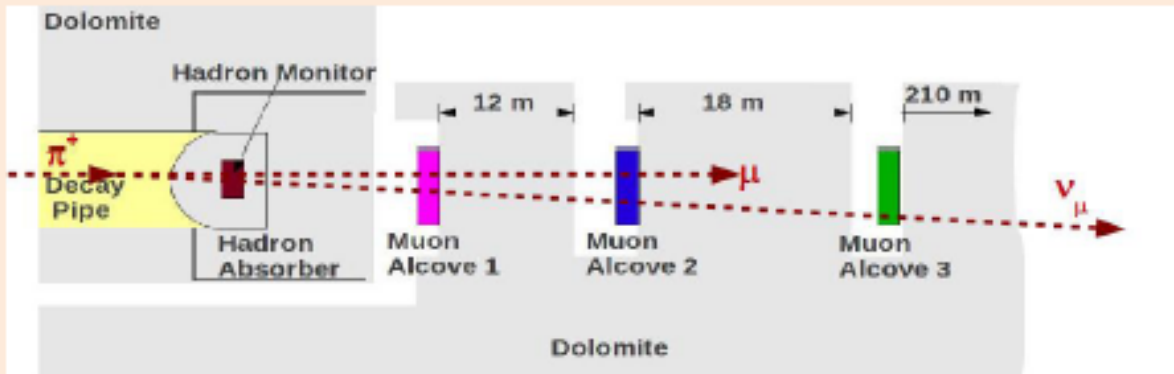
Flux: Future Constraints

Low-nu Flux Constraint:

$$\mathcal{N}(\nu < \nu_0) = C\Phi(E_\nu)\nu_0 \left[\mathcal{A} + \left(\frac{\nu_0}{E_\nu}\right)\mathcal{B} + \left(\frac{\nu_0}{E_\nu}\right)^2 \mathcal{C} + \mathcal{O}\left(\frac{\nu_0}{E_\nu}\right)^3\right],$$

Flux: Future Constraints

Constraints from Muon Monitors



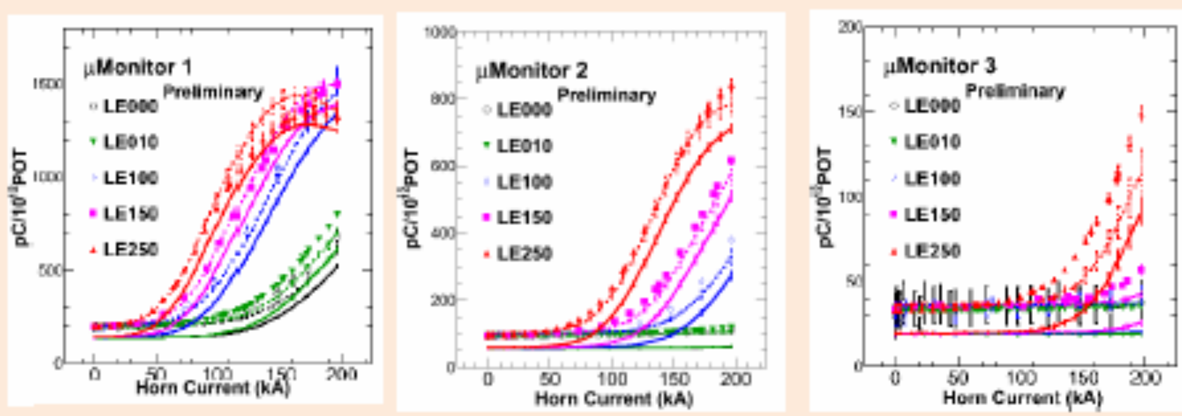
The three different muon monitors each see muons above different thresholds.

Muon Monitor 1: $E_{\mu,\pi} > 4.2$ GeV & $E_{\nu} > 1.8$ GeV

Muon Monitor 2: $E_{\mu,\pi} > 11$ GeV & $E_{\nu} > 4.7$ GeV

Muon Monitor 3: $E_{\mu,\pi} > 21$ GeV & $E_{\nu} > 9.0$ GeV

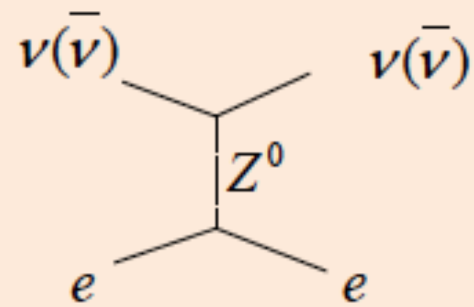
For three target positions, MINERvA took several beam pulses at different horn currents, from 0kA to 200kA. The muon rates in each muon monitor for each horn current will provide an additional cross-check of the flux model.



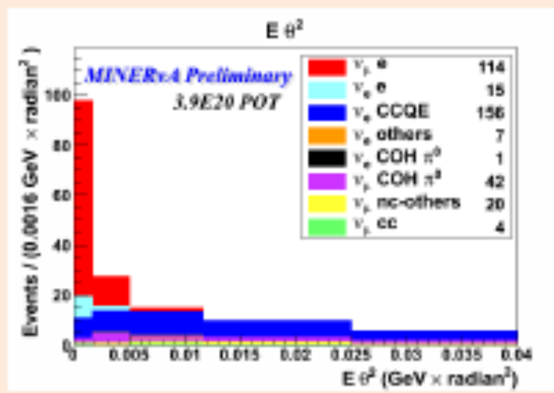
The challenge here is to predict and subtract the delta-ray and neutron backgrounds

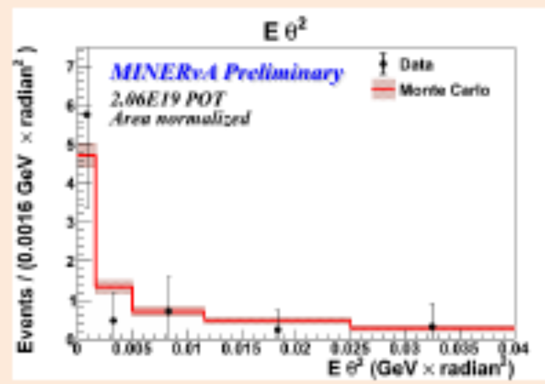
Flux: Future Constraints

Overall Rate Constraint: Neutrino-Electron Scattering



Simple final state and well understood cross-section provide overall flux constraint. Challenge is to isolate the signal from ne Charged current events: Eθ² provides discrimination, as shown at right. Estimated statistical precision for MINERvA LE Run: 10%
(Ref: J. Park, NuFact'12)

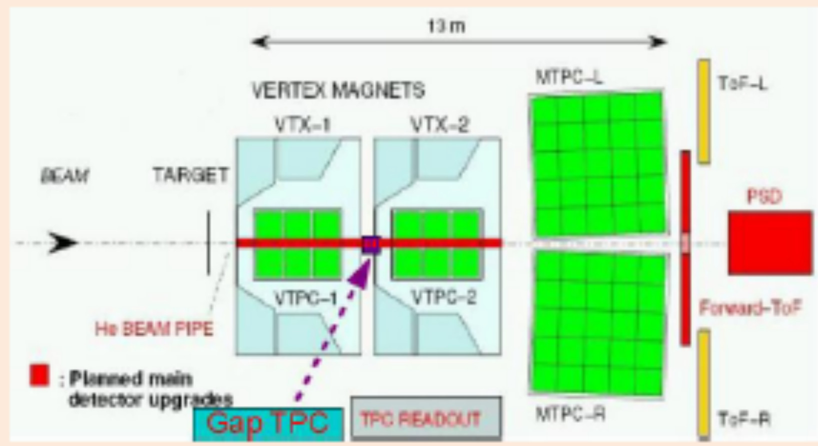




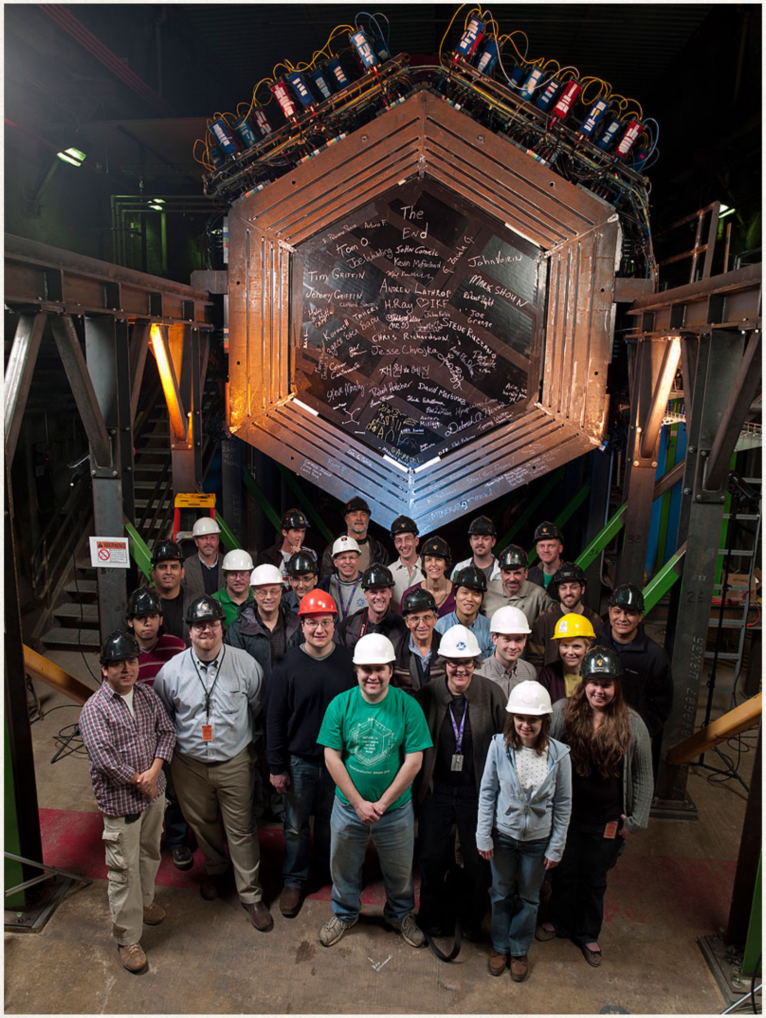
Flux: Future Constraints

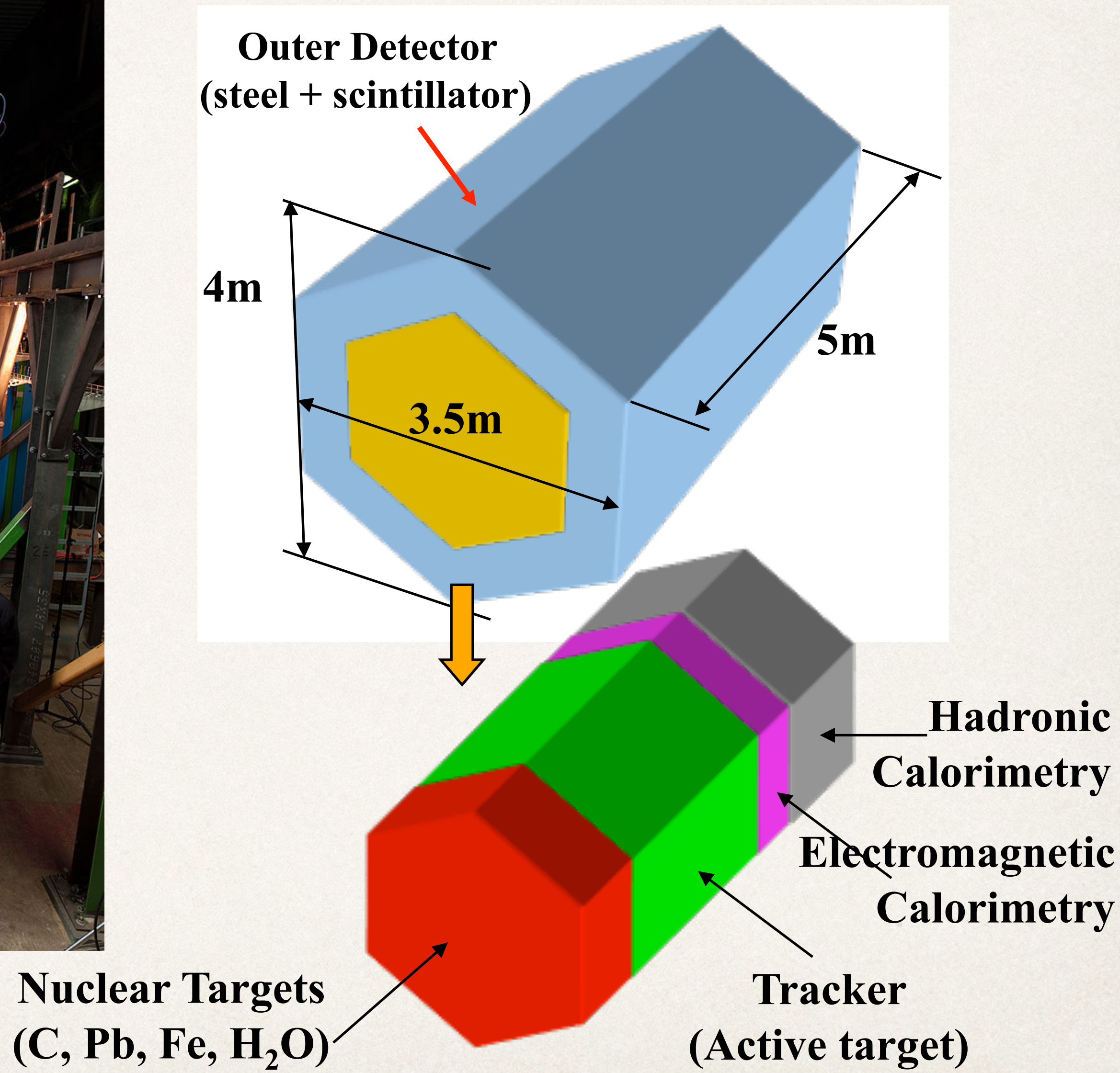
New Hadron Production Measurements: NA61

In order to improve its flux prediction, MINERvA (and other NuMI-based experiments and LBNE) are collaborating with NA61, a new hadron production experiment at CERN. Plans for taking data with 120GeV protons on a thick NuMI target are underway.

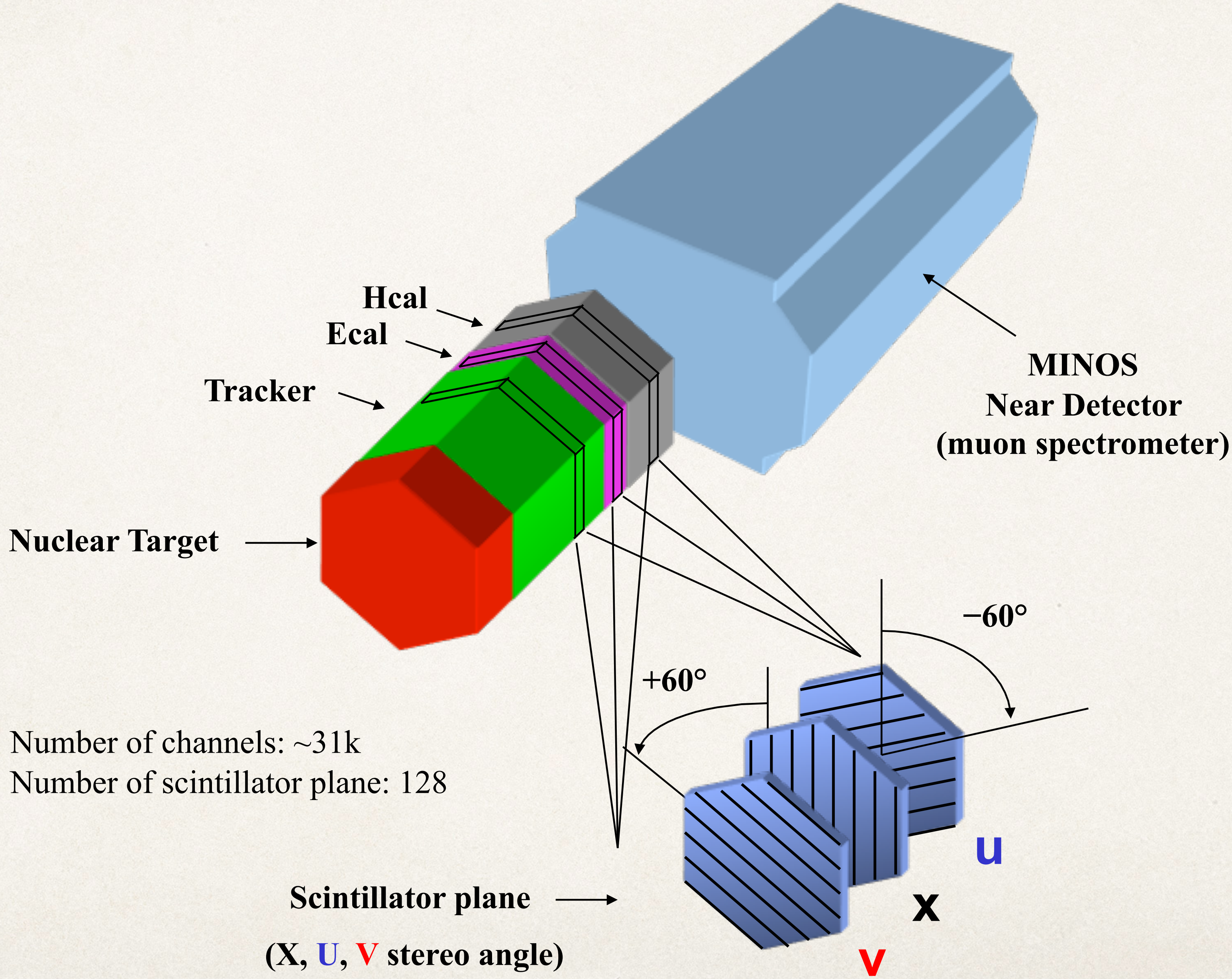


More on the MINERνA Detector





More on the MINERνA Detector



Number of channels: ~31k
Number of scintillator plane: 128