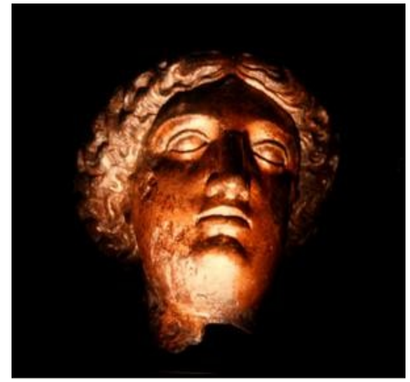


CCQE ANALYSES FROM MINERvA

NuFACT 2015 – August 10th

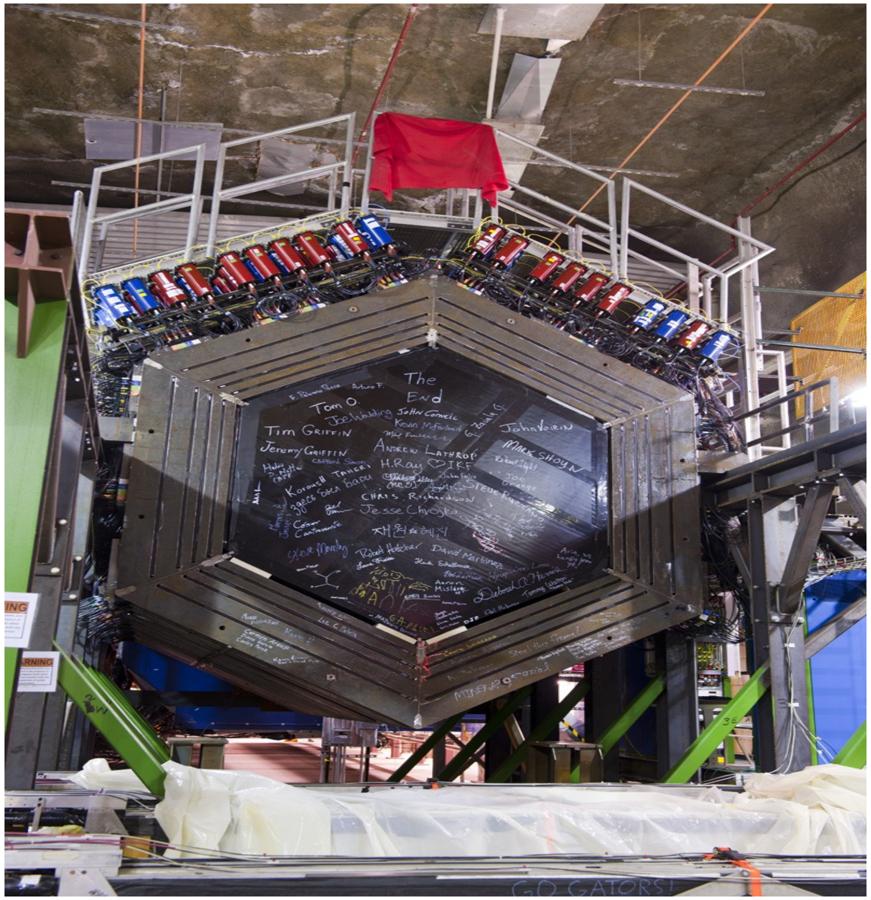
Anushree Ghosh – CBPF/Brazil

On behalf of the MINERvA Collaboration

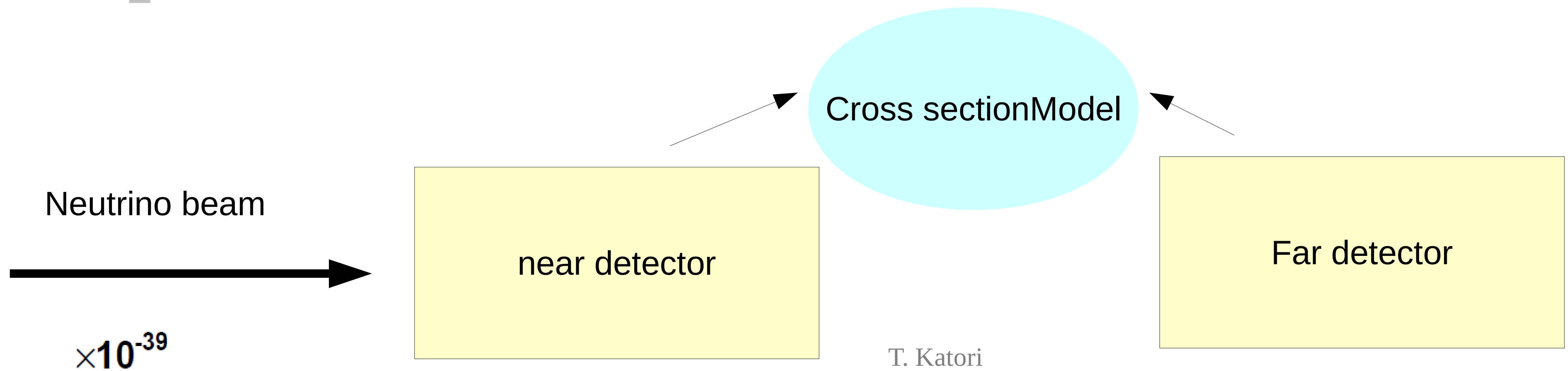
MINERvA Experiment

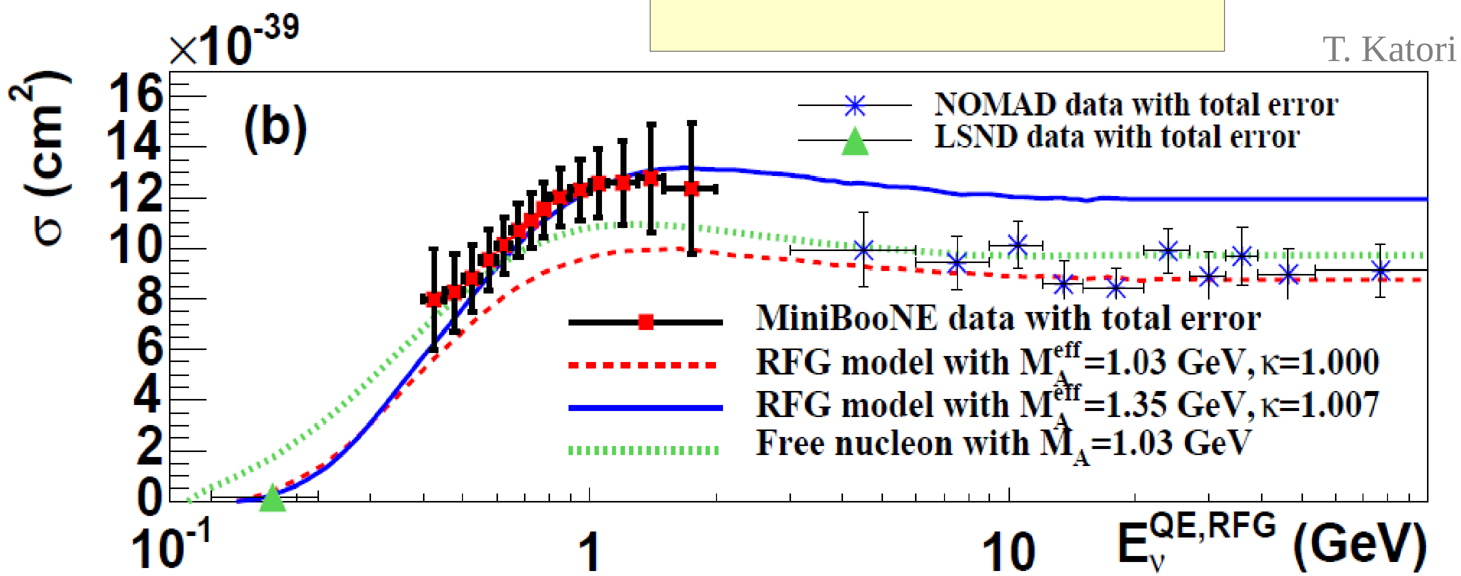
- **M**ain **IN**jector Expe**R**iment **v-A** is a dedicated neutrino nucleon cross section experiment situated in Fermilab's NuMI beam along with MINOS and NovA.

- MINERvA is able make a high precision cross seciton measurement and also is excellent for probing the structure of the nucleus, and its effects on neutrino scattering cross section.

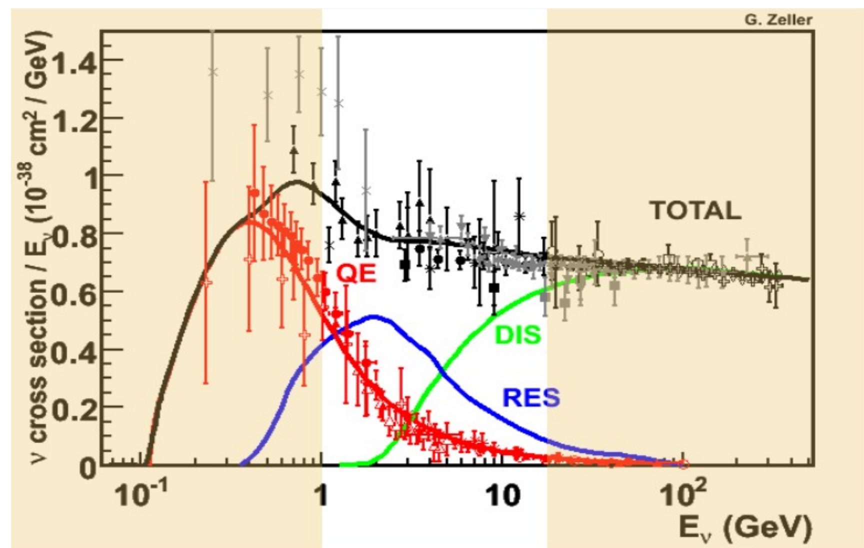


Importance of cross section measurement



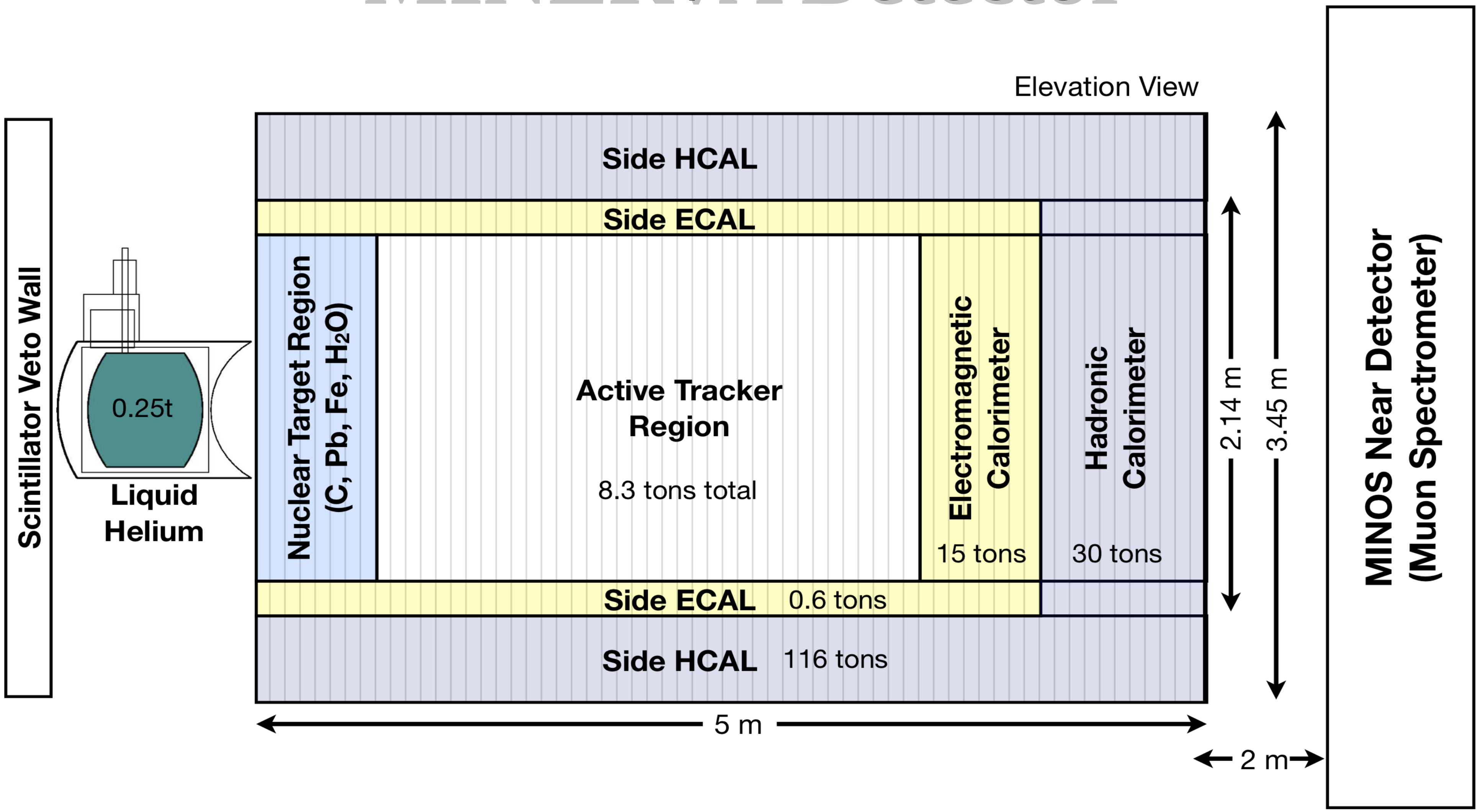


J.A. Formaggio and G.P. Zeller, Rev. Mod. Phys. 84, 1307-1341, 2012



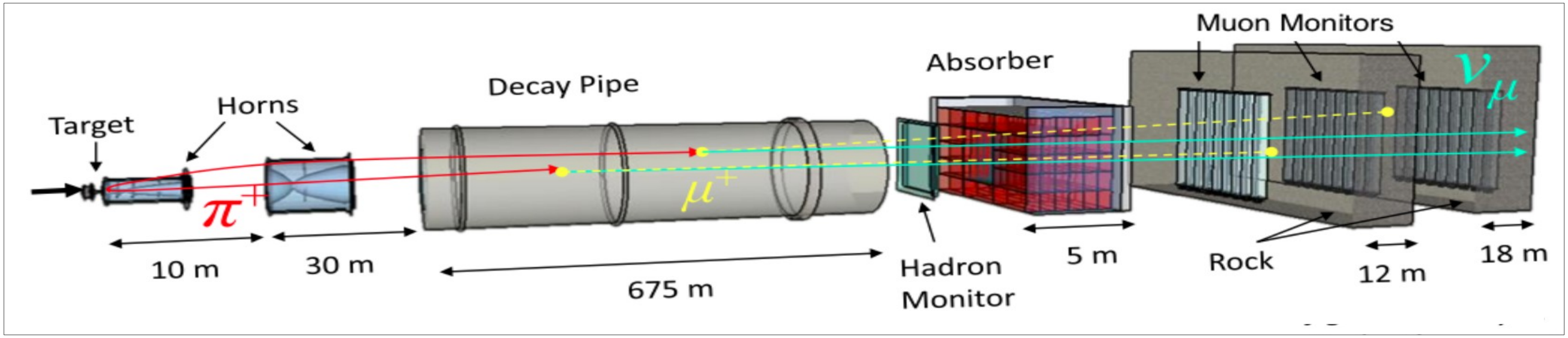
- Cross sections between 0.1-10 GeV important in the regime of oscillation experiments. MINERvA is able to provide such data.

MINERvA Detector

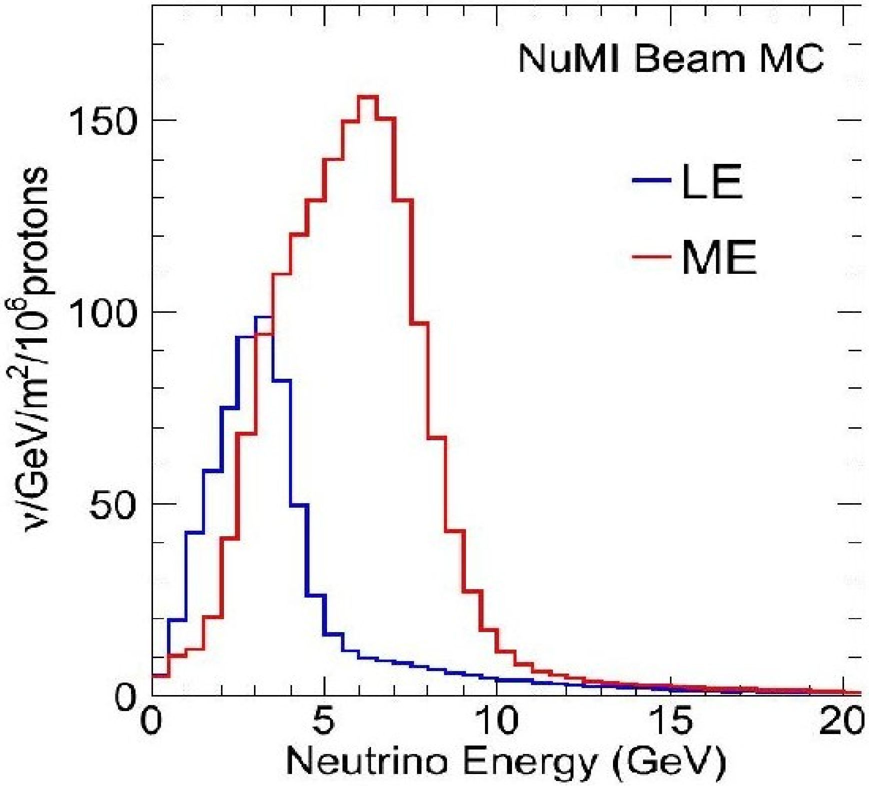


- 120 “modules” perpendicular to the beam direction, containing ~32k readout channels
- Finely-segmented scintillating central tracking region
- Nuclear targets(carbon, lead, iron, water), plastic (CH), EM and Hadronic calorimeter with additional lead and steel plates
- MINOS near detector is the muon spectrometer

NuMI Beam



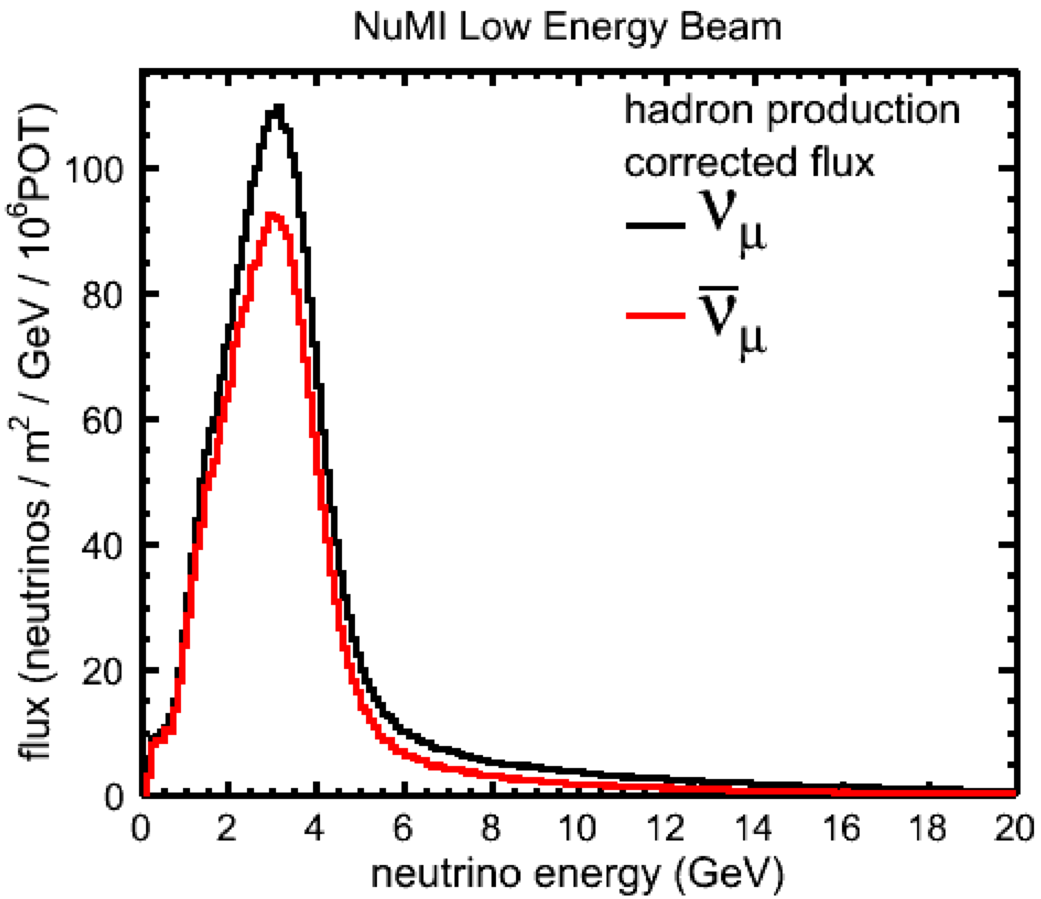
- 120 GeV proton beam from the Main Injector on carbon target
- Focus π+ and K+(or π- and K-) for ν_μ ($\bar{\nu}_\mu$) beam
- Neutrino beam energy increased by moving target and second horn



NuMI Beam: neutrino flux prediction

Neutrino flux is estimated from hadron production:

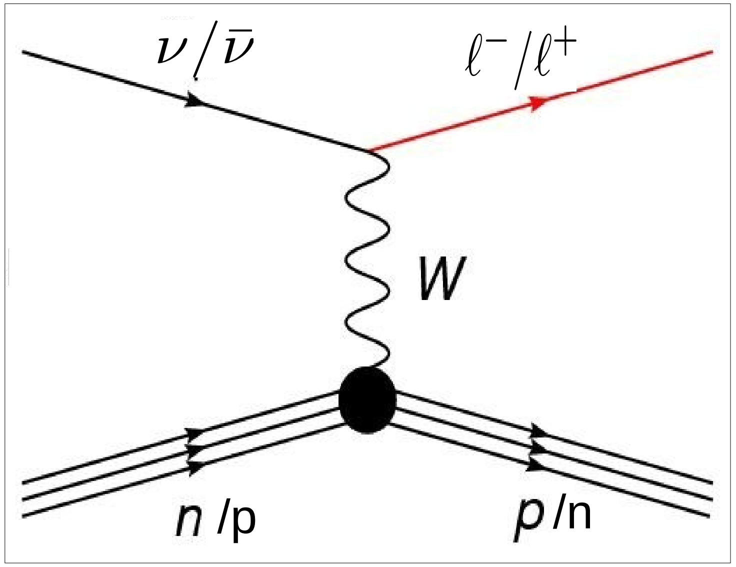
- First, flux is calculated by GEANT4 simulation
- Reweight the simulation to predict the NA49 Data. Then apply corrections to get 120 GeV proton energy.
- Uncertainties due to the NA49 data and hadron production models are included as systematics



Charge Current Quasi Elastic Scattering

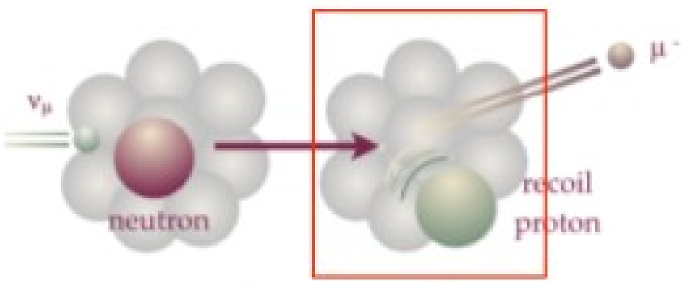
- Pure QE is defined as an event in which the primary interaction is quasi-elastic (regardless of final-state particles)

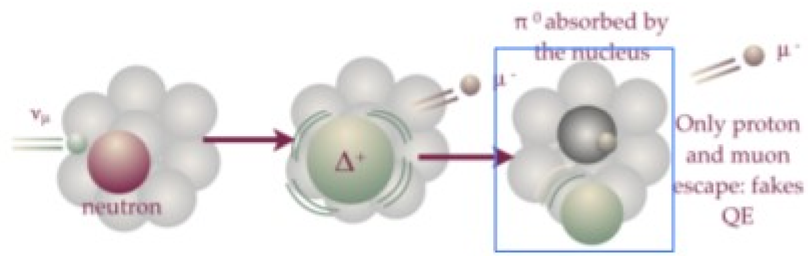
- QE-like are events with a CCQE signature outside the nucleus - with no final state pions. The difference is Final State Interactions (FSI)



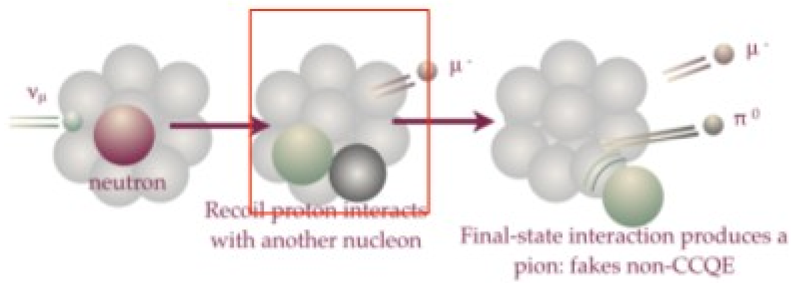
True-QE | **Not true QE**

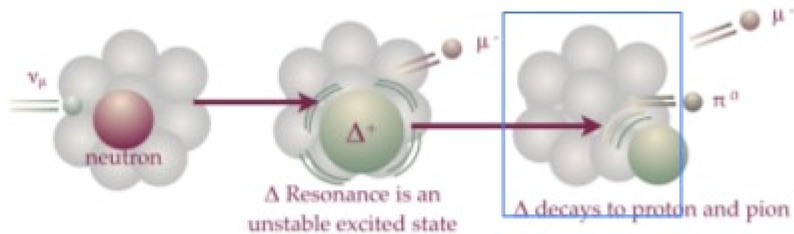
QE-like





Not QE-like

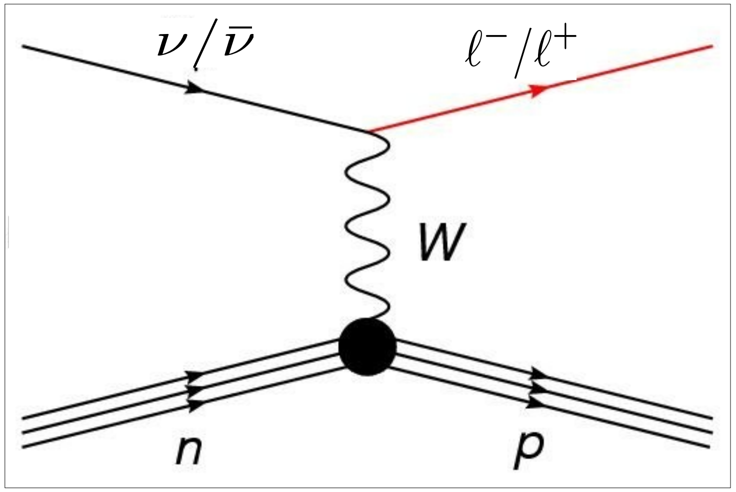




Plan of the talk

- Over view the CCQE result with muon kinematics
    - L. Fields, J. Chvojka et al. (MINERvA Collaboration), Measurement of Muon Antineutrino Quasielastic Scattering on a Hydrocarbon Target at Eν∼3.5 GeV, Phys. Rev. Lett. 111, 022501 (2013)
    - G. A. Fiorentini, D. W. Schmitz, P. A. Rodrigues et al. (MINERvA Collaboration), Measurement of Muon Neutrino Quasielastic Scattering on a Hydrocarbon Target at Eν∼3.5 GeV, Phys. Rev.Lett. 111, 022502 (2013)
- CCQE analysis with proton kinemtaics
    - T.Walton et al. (MINERvA Collaboration), Measurement of muon plus proton final states in νμ Interactions on Hydrocarbon at average Eν of 4.2 GeV, Phys. Rev. D91, 071301 (2015).
- New results on CCQE Electron neutrino Analysis
- Upcoming CCQE analyses

Event Kinematics with lepton side



- For pure QE events, we can reconstruct the neutrino energy and 4 momentum transfer, Q^2 , from just the lepton kinematics:
- Assuming bound nucleon at rest, Reconstructed Q^2_{QE} is given by

$$Q^2_{QE} = -m_l^2 + 2E_\nu^{QE}(E_l - \sqrt{E_l^2 - m_l^2}cos\theta_l)$$

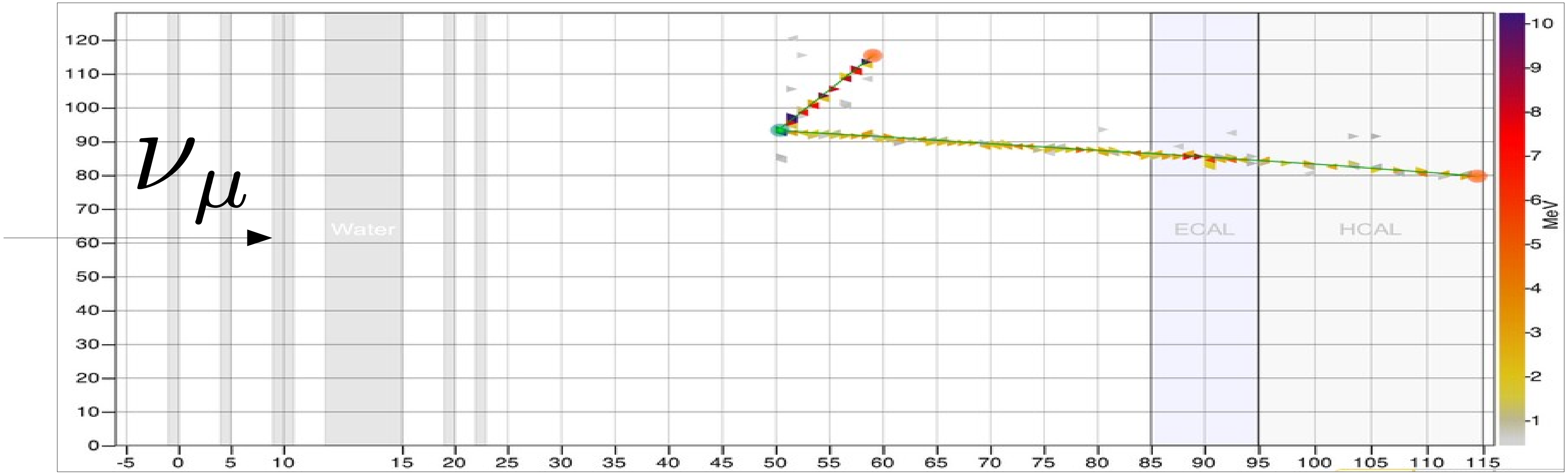
- We cut on reconstructed neutrino energy: $1.5 < E_\nu^{QE} < 10$GeV

$$E_\nu^{QE} = \frac{2(M_n - E_B)E_l - [(M_n - E_B)^2 + m_l^2 - M_p^2]}{2[M_n - E_B - E_l + p_l cos\theta_l]}$$

M_n, M_p = neutron, proton mass
E_B = nuclear binding energy
m_l, E_l, θ_l = mass, energy, angle of final state lepton

- Note: For QE-like events (like delta production followed by pion absorption), the above formulae give incorrect result.

Quasi-elastic scattering with muon kinematics



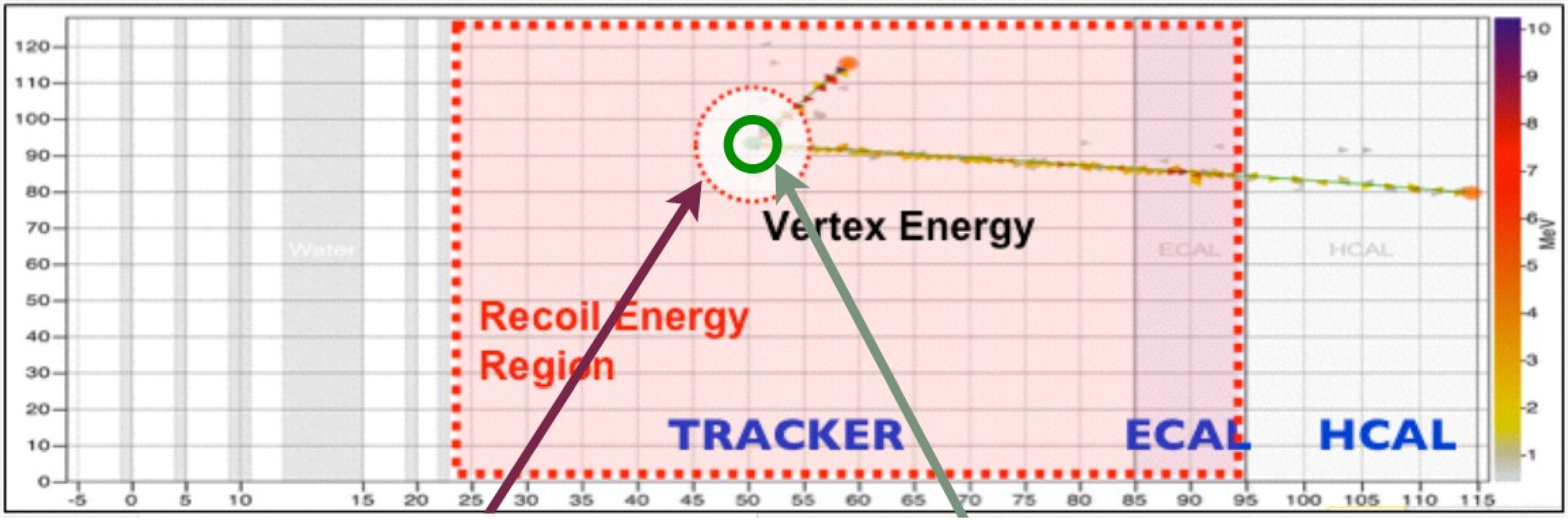
Neutrino mode

- MINOS-matched μ − track
- Reconstructed vertex in central fiducial Volume
- maximum 2 isolated energy showers outside of vertex region

Anti-Neutrino mode

- MINOS-matched μ + track
- Reconstructed vertex in central fiducial volume
- Maximum 1 isolated energy shower outside of vertex region
- No track other than muon

CCQE Event Selection: Recoil Energy



Exclude vertex region:
30 g/cm2 for neutrino mode
Contains < 225 MeV protons

Antineutrino mode
exclude 10 g/cm2
Contains < 120 MeV protons

- Backgrounds typically contain pions, which will deposit energy in the detector
- A cut is therefore made on the total calorimetrically-corrected recoil energy
- The energy is summed over the region shown
- The area around the vertex is excluded, as it is suspected that nuclear effects could lead to additional low-energy nucleons in this area, even in CCQE events

Cross section Calulation

Unfolding: reconstructed muon kinematics to true muon kinematics

Background constrained by data

$$\left(\frac{d\sigma}{dQ^2_{QE}}\right)_i = \frac{1}{T_n \Phi_\nu} \frac{1}{\Delta Q^2_{QE}} \frac{\sum_j U_j \left(N_j^{data} - N_j^{bkjd}\right)}{\epsilon_i}$$

Differential cross-section vs 4 momentum transferred to nucleon

Target number

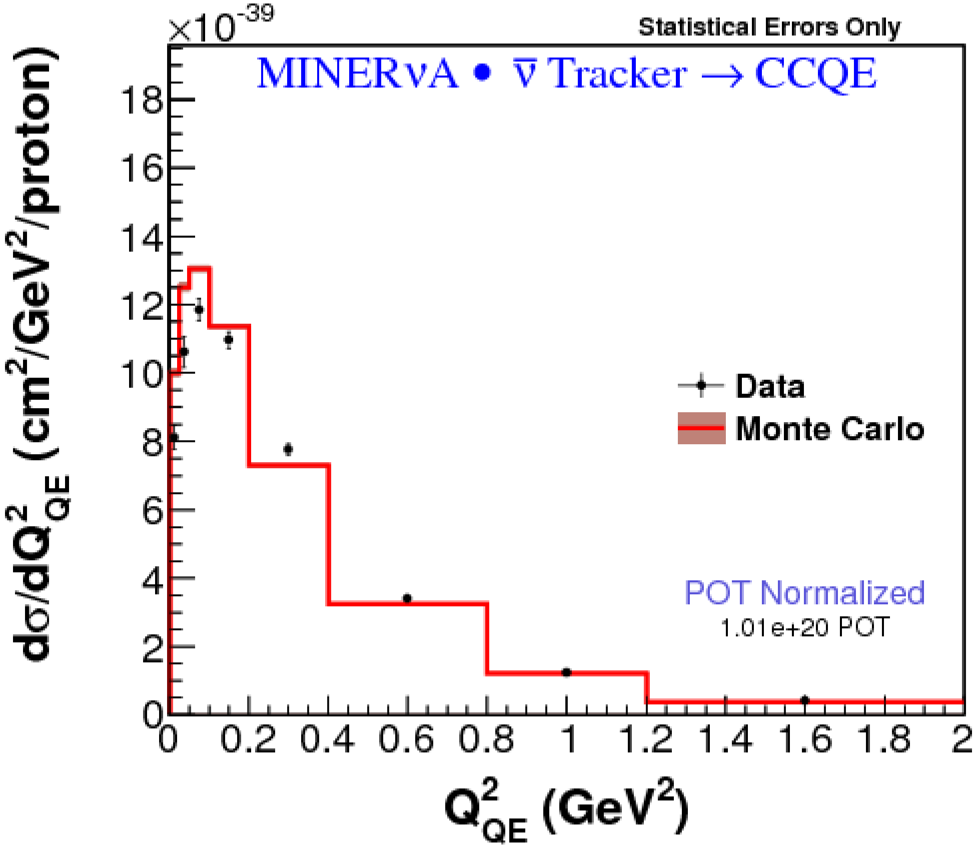
Predicted flux

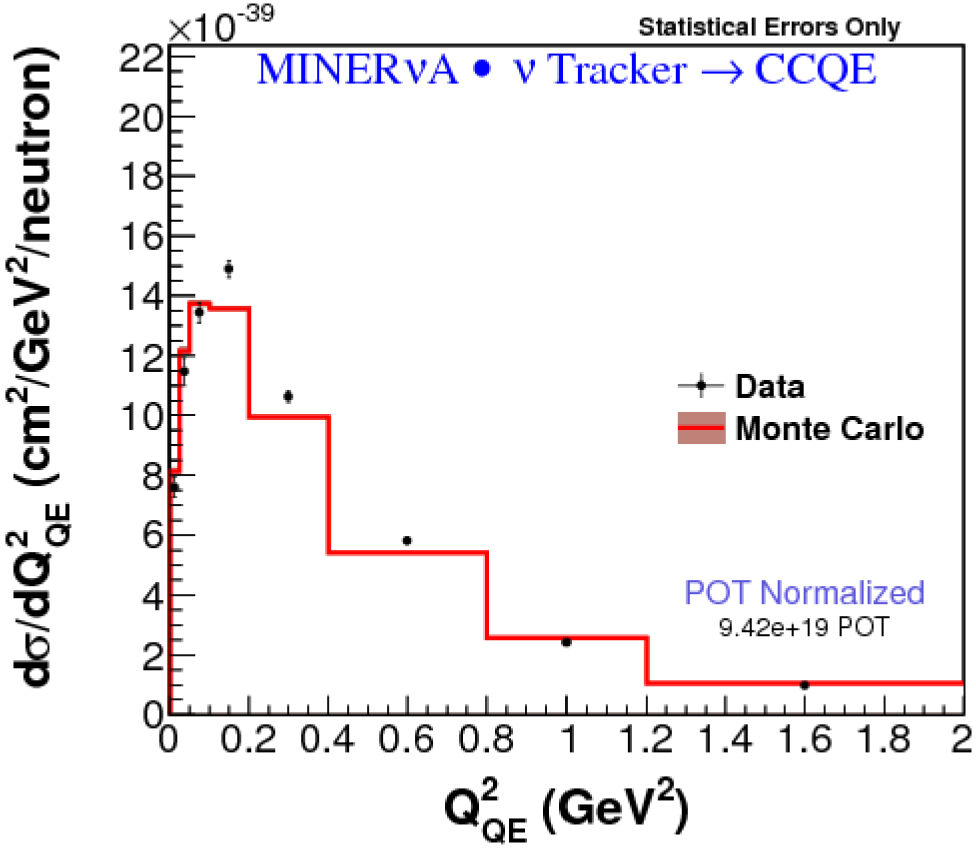
Bin size

Reconstruction efficiency X detector acceptance

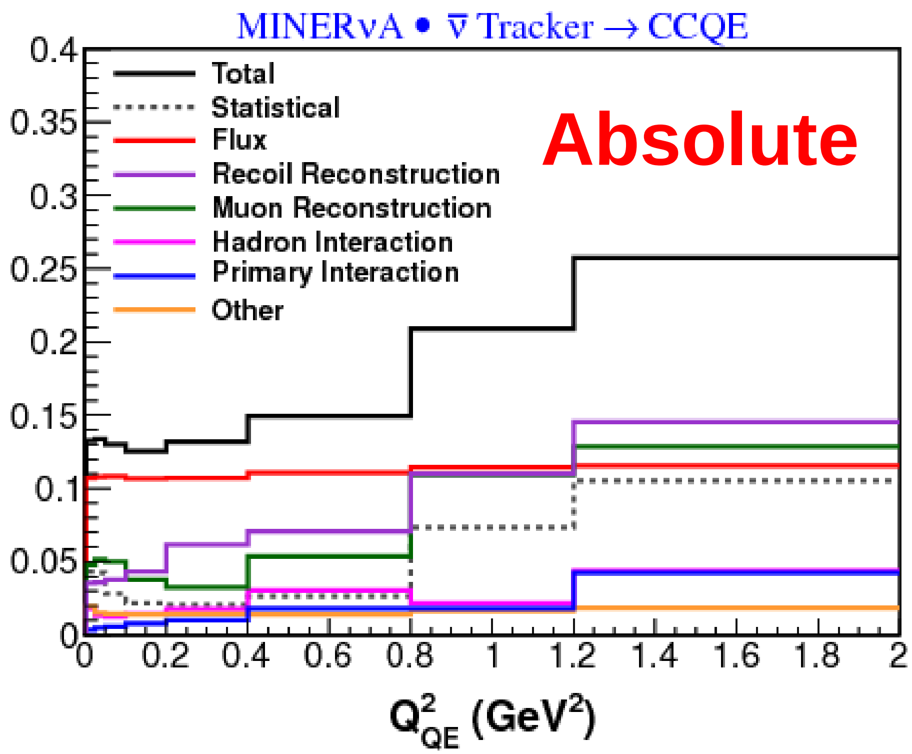
Differential cross section distribution

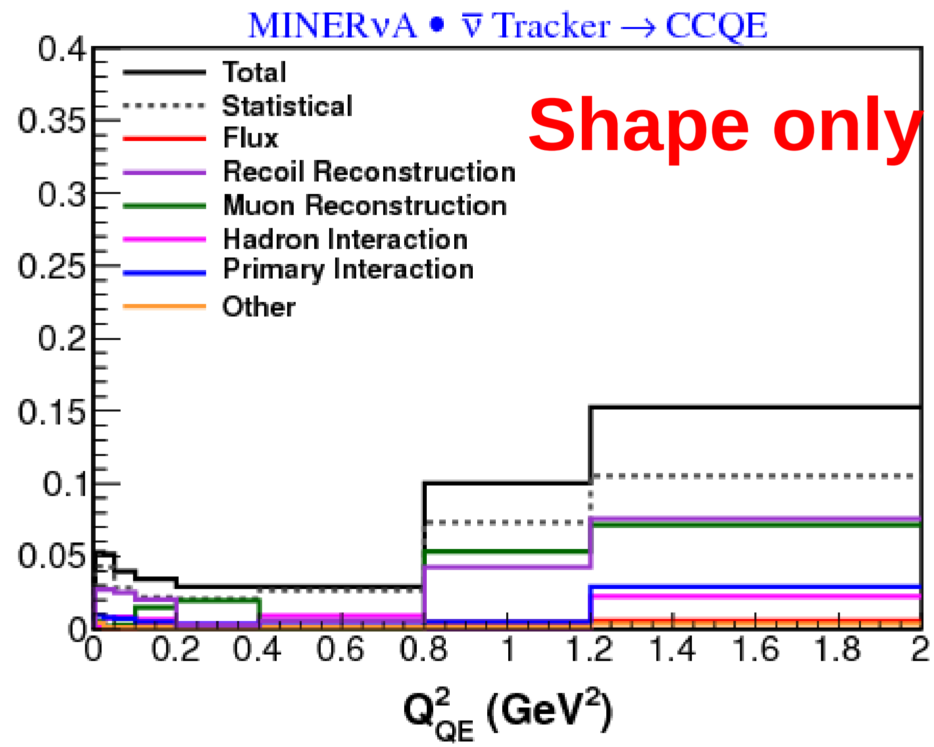
- Substract backgrounds:we use data to estimate our backgrounds by performing a fraction fit of simulated signal and background recoil energy distributions from our Monte Carlo, Q^2_{QE} bins
- Unfolding: We use four iterations of a Bayesian unfolding method
- Apply efficiency x acceptance corrections to the MC and data





Error Summary:Anti-Neutrino Mode





- Flux dominates the absolute uncertainty but largely cancels in the shape
- Statistical uncertainties dominate the shape distribution

Flux uncertainty

statistical uncertainty

Recoil reconstruction

Total uncertainty

Nuclear Models

- **Relativistic Fermi Gas (RFG**) :Popular model is relatively easy to implement, modeling independent particles in a potential generated by the rest of the nucleus
  R. Smith and E. Moniz, Nucl.Phys. B43, 605 (1972); A. Bodek, S. Avvakumov, R. Bradford, and H. S. Budd, J.Phys.Conf.Ser. 110, 082004 (2008) ;K. S. Kuzmin, V. V. Lyubushkin, and V. A. Naumov, Eur.Phys.J. C54, 517 (2008)

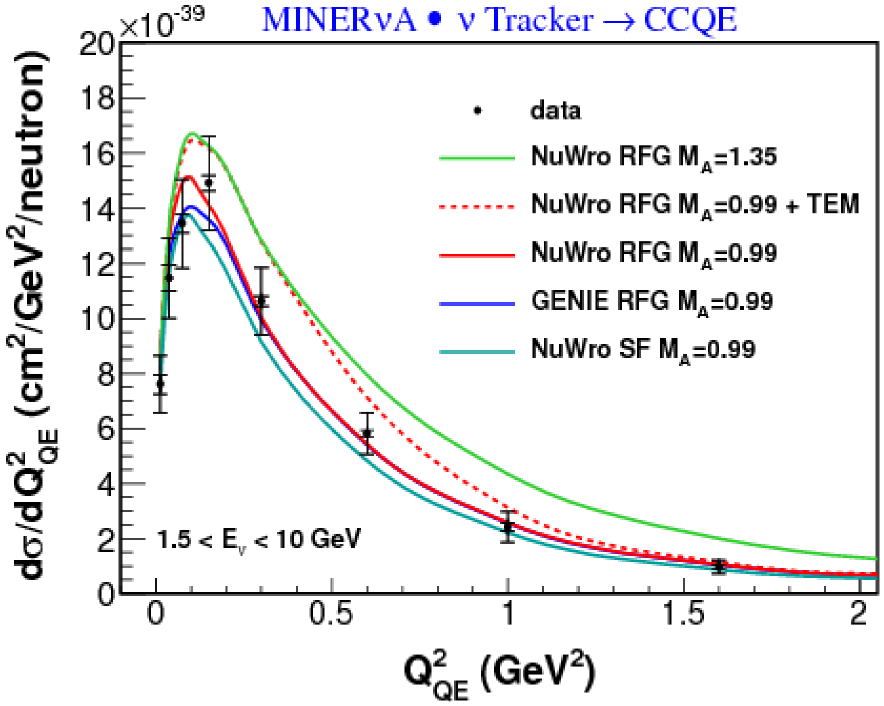
- **Local Fermi Gas (LFG)**: Fermi momentum and binding energy are a function of position in the nucleus AK. S. Kuzmin, V. V. Lyubushkin, and V. A. Naumov, Eur.Phys.J. C54, 517 (2008)

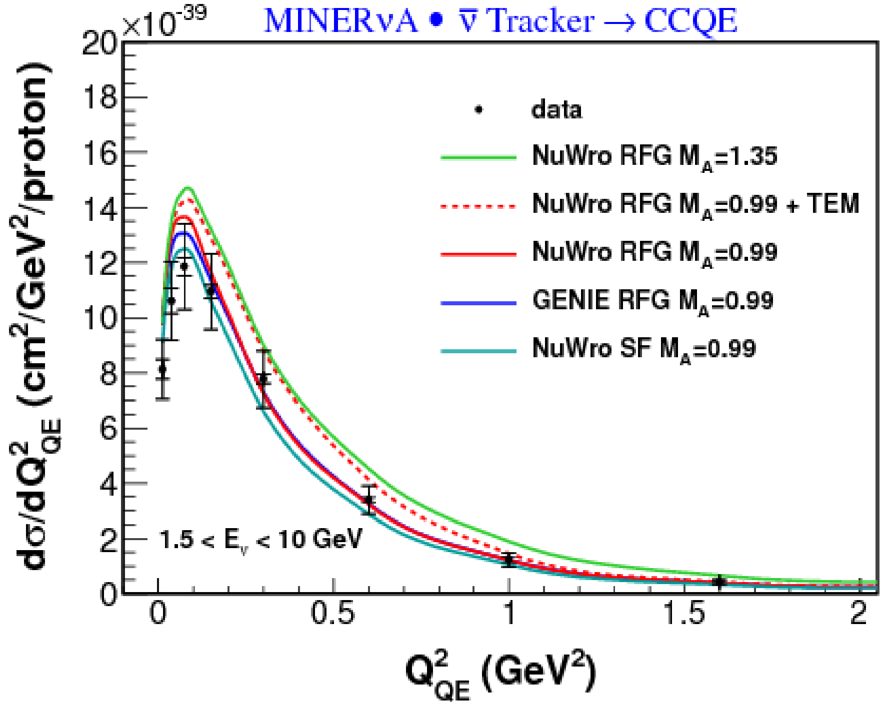
- **Spectral functions (SF):** takes correlations into account when calculating initial-state momenta and removal energies O. Benhar, A. Fabrocini, S. Fantoni, and I. Sick, Nucl.Phys. A579, 493 (1994)

- **TEM(transverse enhancement model):** parameterizes an enhancement seen in electron-nucleus scattering data, by modifying the magnetic form-factor. A. Bodek, H. Budd, and M.Christy, Eur.Phys.J. C71, 1726 (2011)

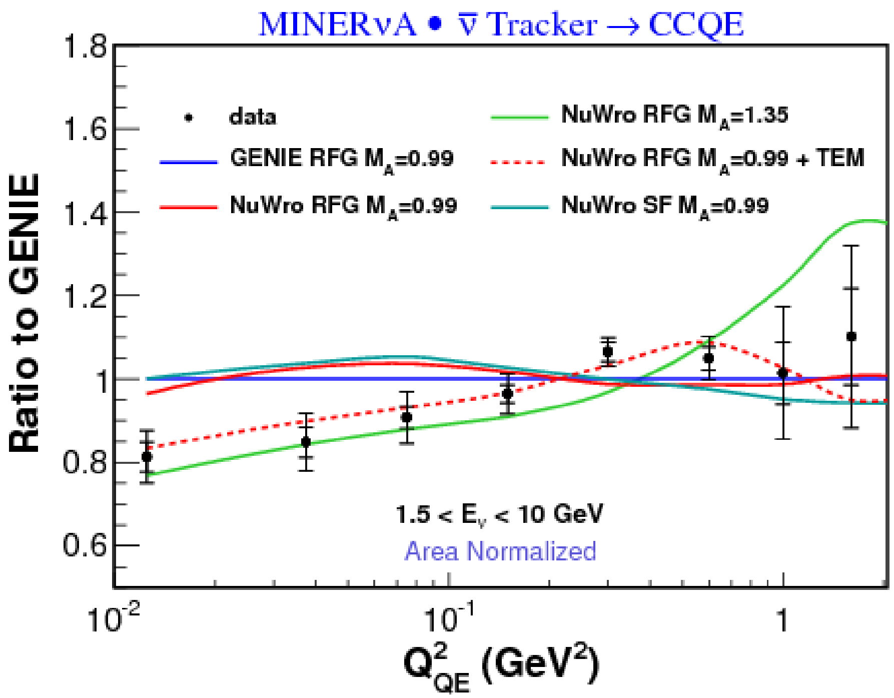
- The Nieves model includes **meson-exchange current (MEC)** diagrams.
  J. Nieves, I. Ruiz Simo and M. J. Vicente Vacas, Phys. Rev. C 83 (2011) 045501

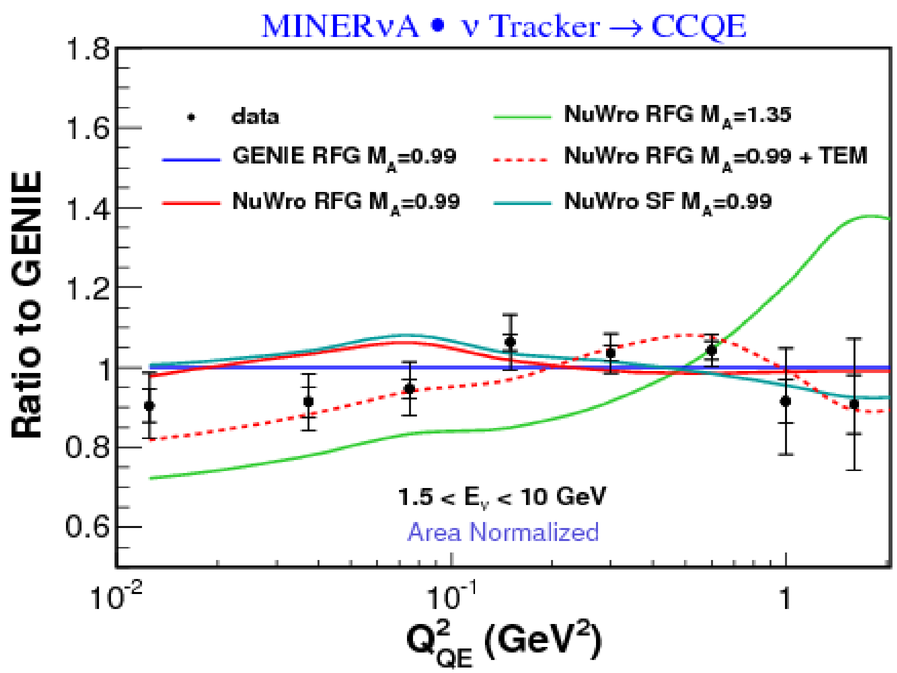
Cross section: Model Comparison





Compared data to **GENIE RFG** C.Andreopoulos, et al., NIM 288A, 614, 87 (2010) and **NuWro** T. Golan, C. Juszczak and J.T. Sobczyk, Phys. Rev. C86, 015505 (2012) nuclear models





The results favour RFG with M_A=0.99+TEM suggesting initial-state nucleon-nucleon correlations

CCQE ANALYSIS WITH PROTON KINEMATICS

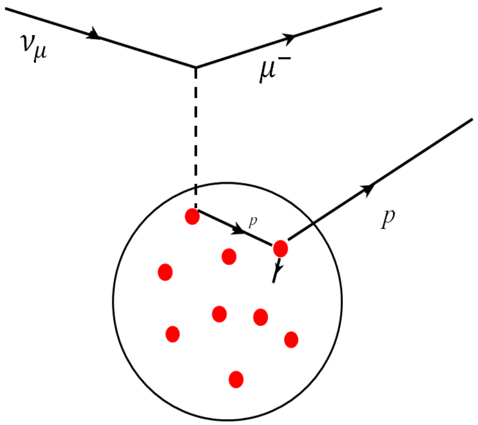
Event Kinematics with hadron side

- Instead of muon kinematics, we can we reconstruct 4 momentum transfer, Q^2, from the kinematics of the stopping proton :

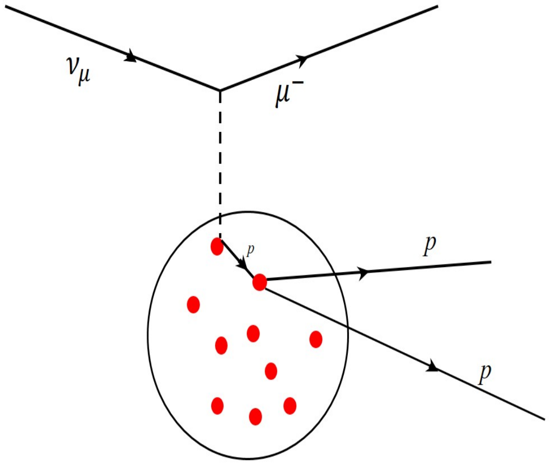
$$Q^2_{QE,p} = (M_n - E_b)^2 - M_p^2 + 2(M_n - E_b)(T_p + M_p - M_n + E_b)$$

$M_{n,p}$ = neutron, proton mass, T_p =proton KE, E_b =binding energy

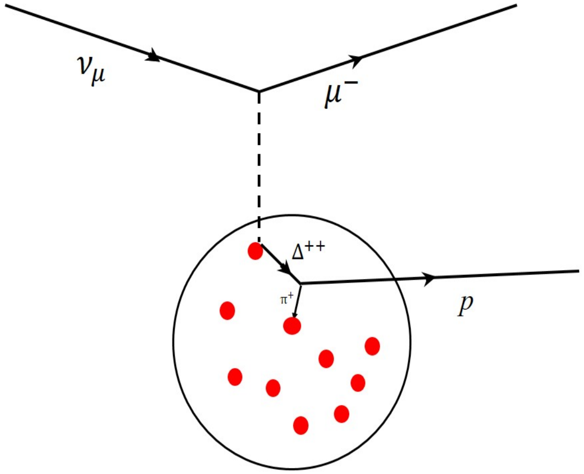
- Protons can undergo final-state interactions, so this is particularly sensitive to FSI modeling.



FSI alter the kinematic distributions of the recoil nucleon

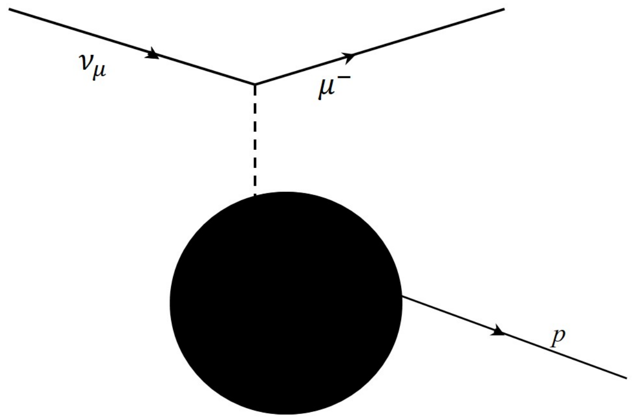


FSI can produce many nucleons in the final state



Non-QE scattering processes that look QE-like

Defining CCQE-like events



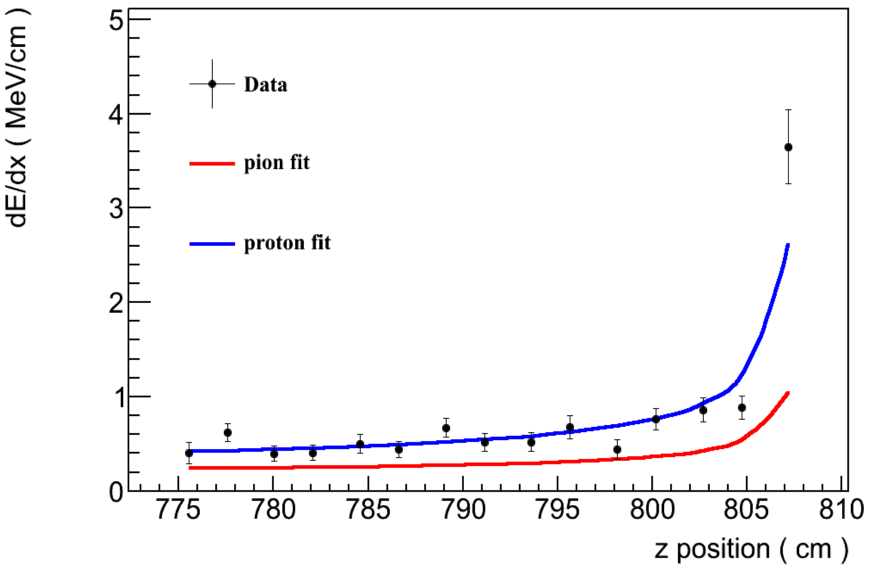
focus on what comes out

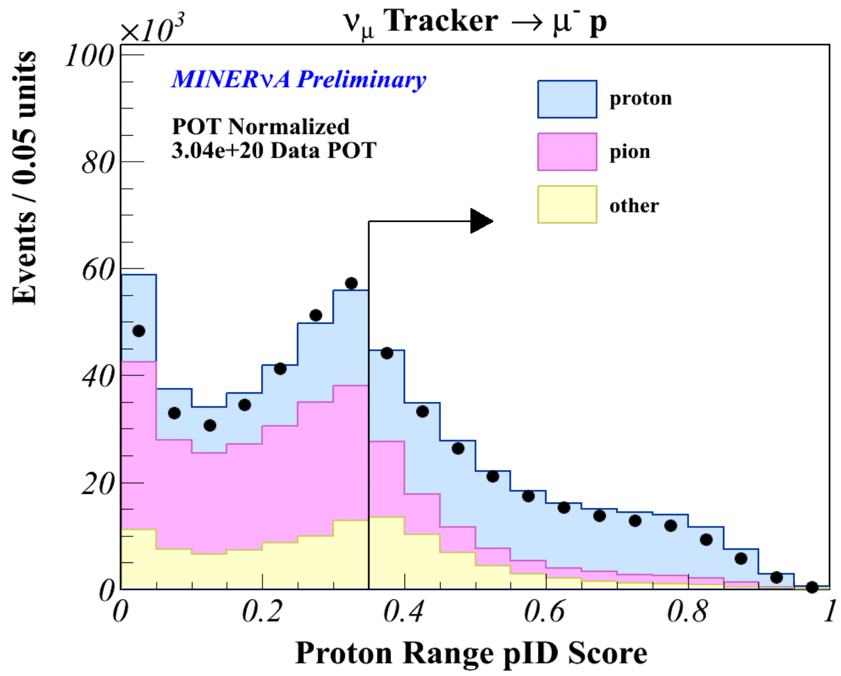
Signal definition:

- one negatively charged muon
- at least one proton with momentum greater than 450 MeV/c
- No mesons

Event Selection

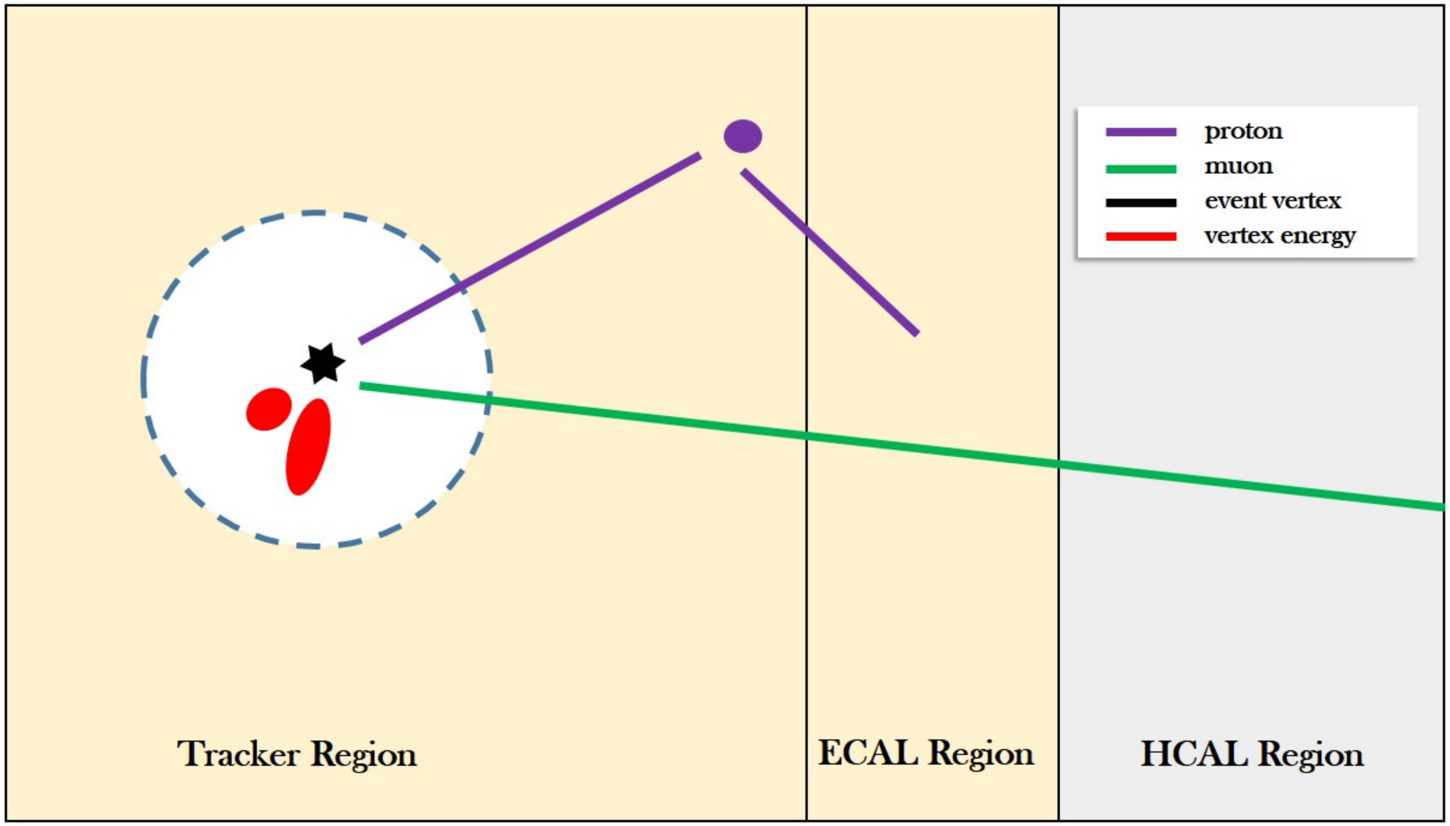
- Require all hadron tracks to look like range out protons
- Fit each hadron track energy loss (dE/dx) profile to standard proton and pion energy loss fit templates
- Use χ^2 /d.o.f. for both fits to give a particle
- identification (pID) score and particle momentum





Event Selection

Remove unattached energy



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

Michel electron veto

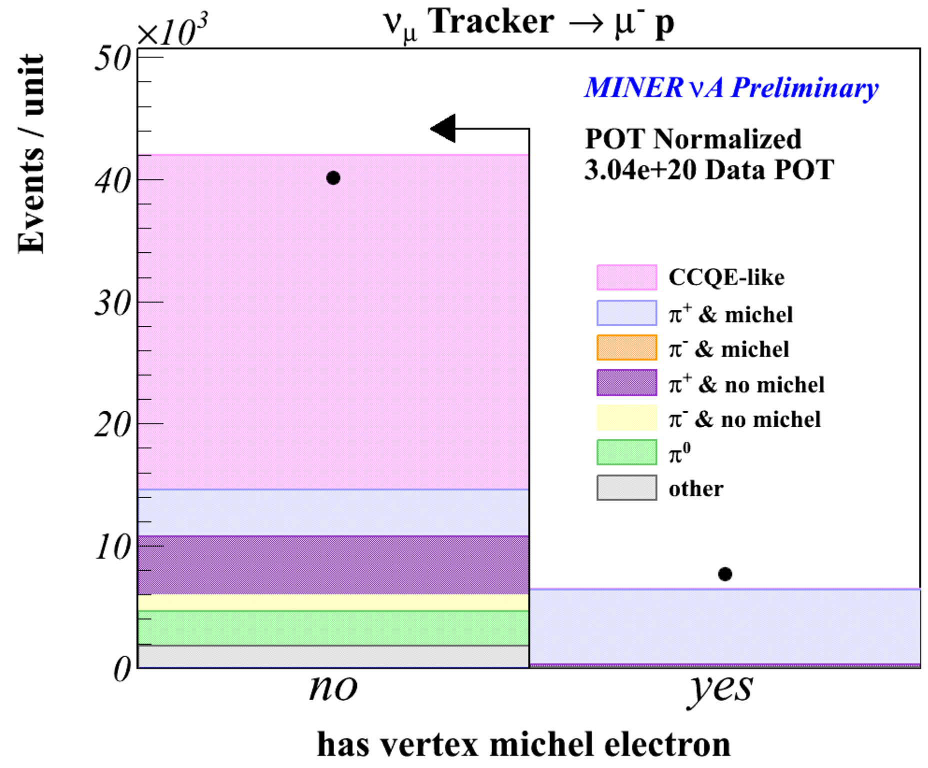
removes events with soft pions. Those are usually resonance production events

- $\pi^{\pm} \rightarrow \mu^{\pm} + \bar{\nu}_{\mu} (\nu_{\mu})$
- Dominant decay modes of the muons are:

$$\mu^{-} \rightarrow e^{-} \bar{\nu}_{e} \nu_{\mu}$$

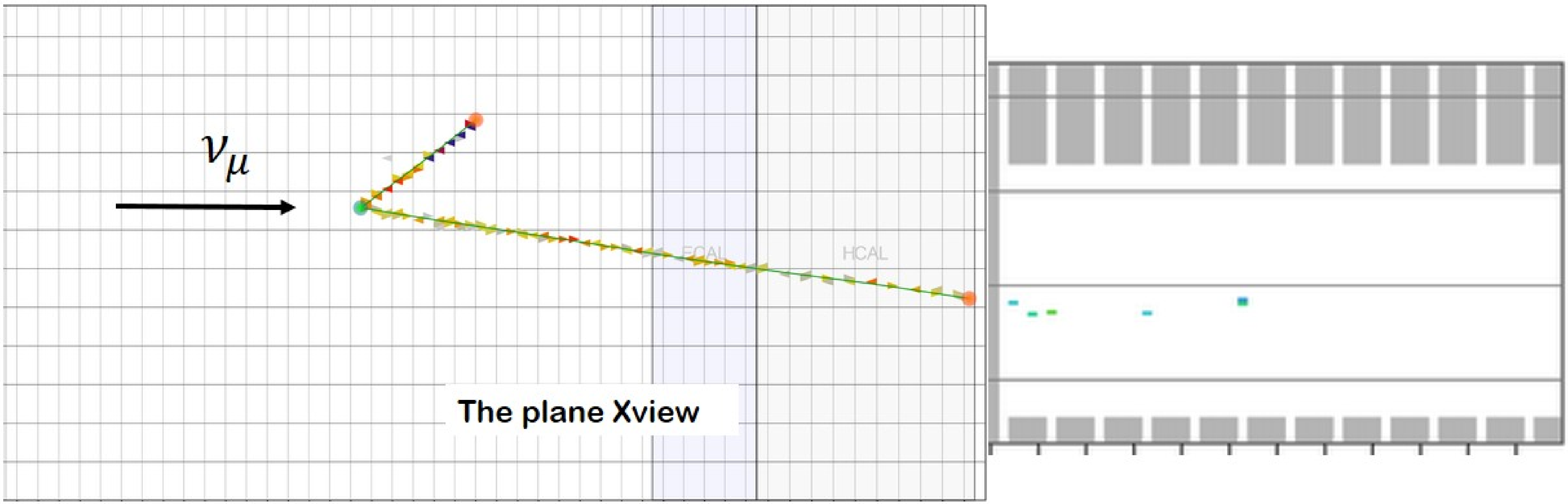
$$\mu^{+} \rightarrow e^{+} \nu_{e} \bar{\nu}_{\mu}$$

- Electrons/positrons produced from the muon decay are called Michel electrons



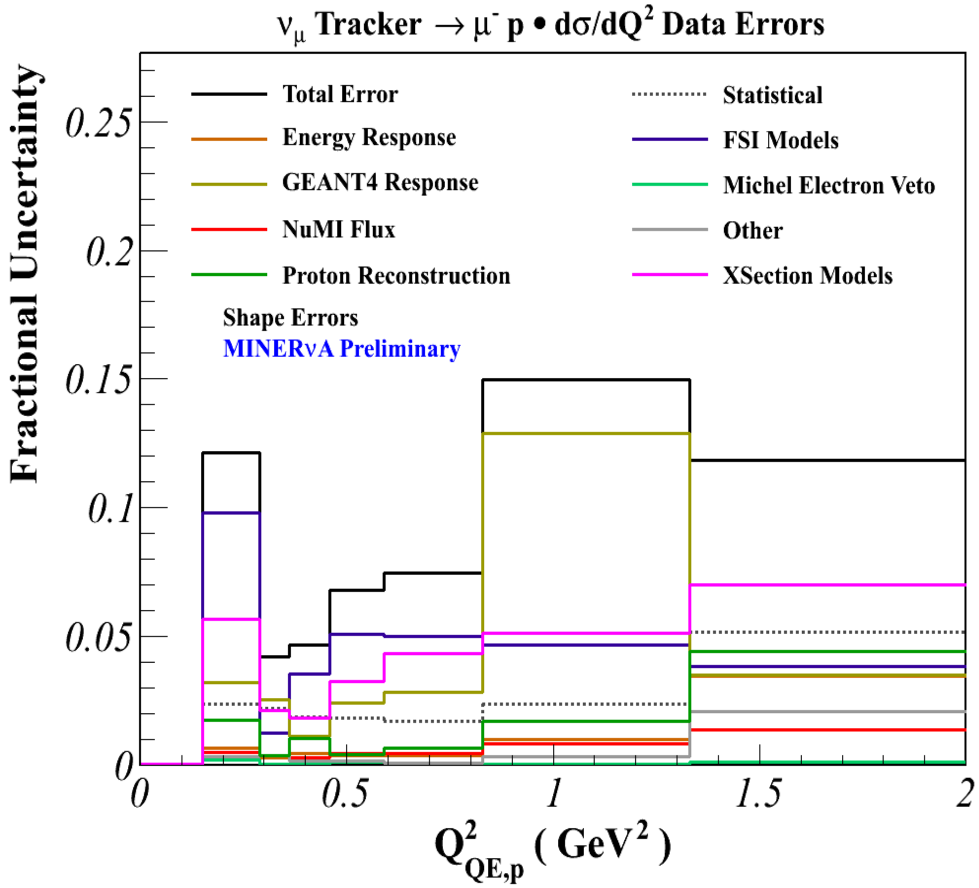
Event Selection

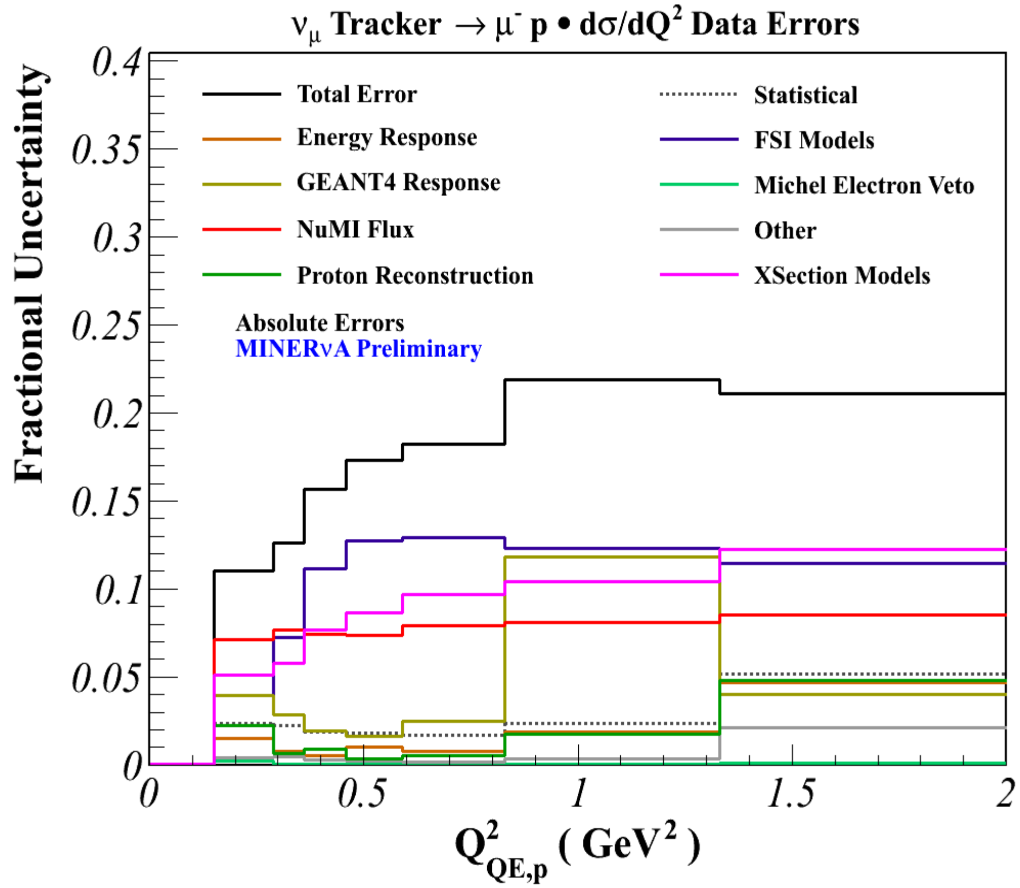
Selection of Muon events:



Look for muons that exit the tracker and are:
- matched to a track in MINOS (52.7%)
- matched to hits in MINOS (7.9%)
- matched to hits in the side HCAL region (27.5%)
- NOT matched to MINOS or the side HCAL (11.8%)

Systematic errors



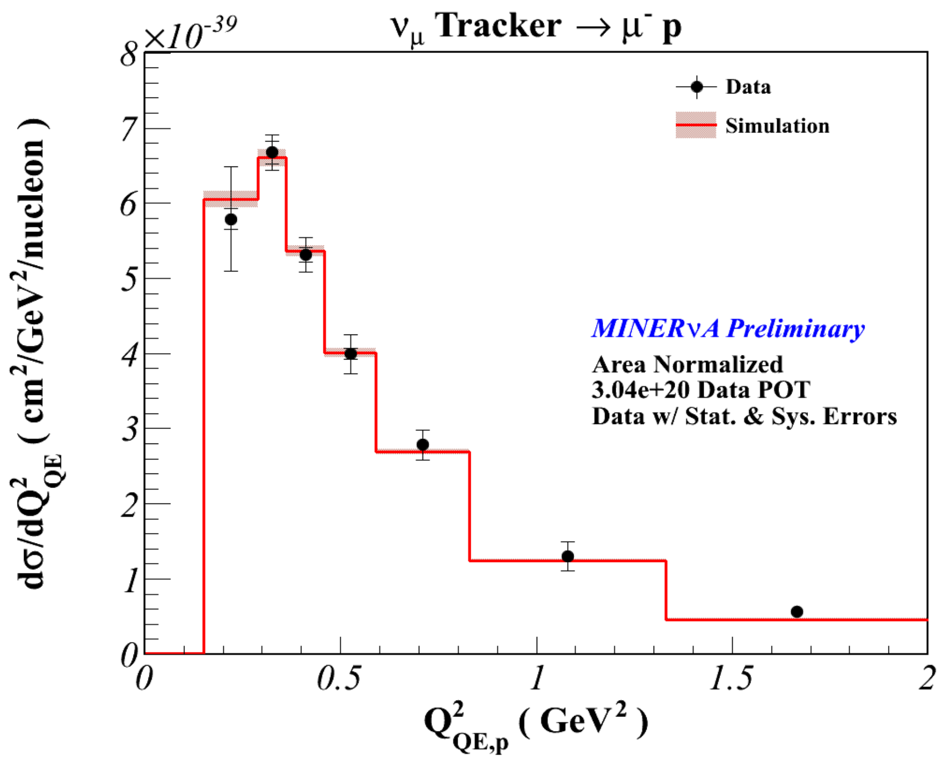


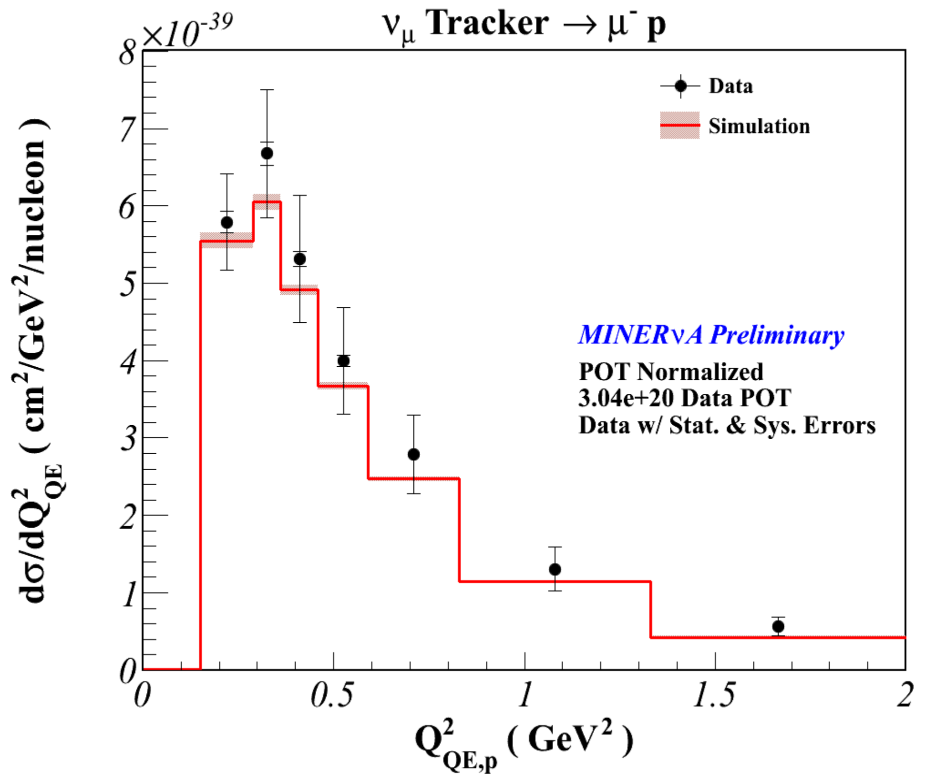
- Neutrino Interaction Models
- FSI Interaction Models
- Neutrino Flux
- Geant4 Modeling
- Michel Veto
- Proton Detector Response

Other

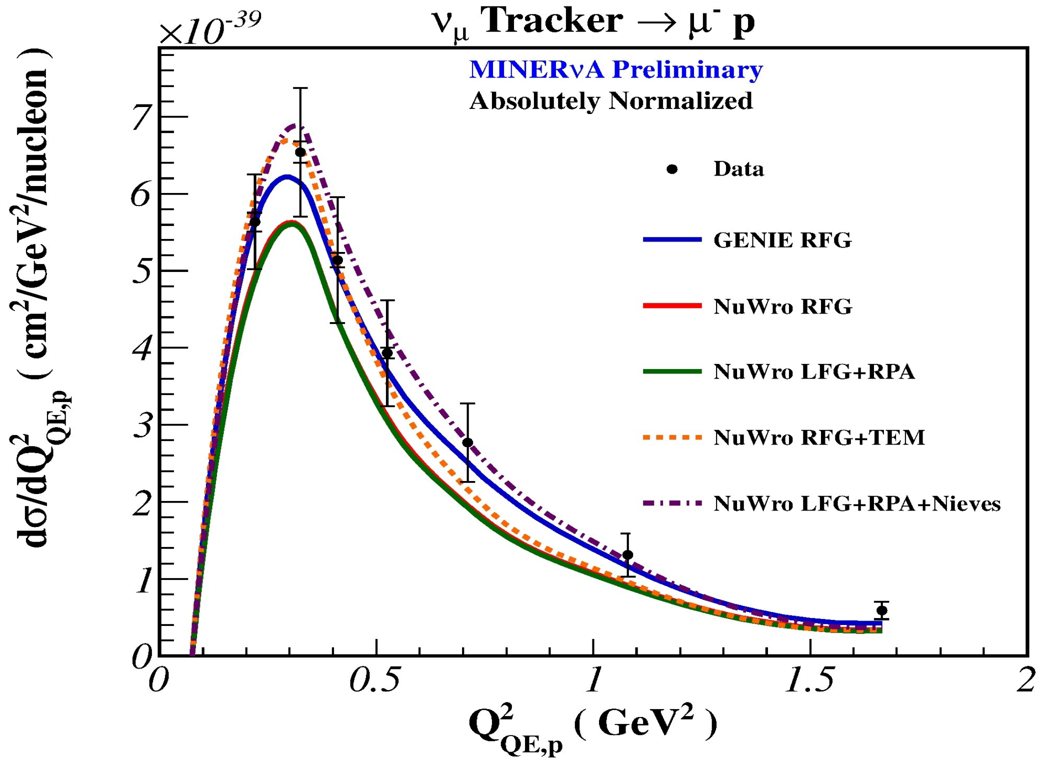
Primary contributions to total systematic uncertainty

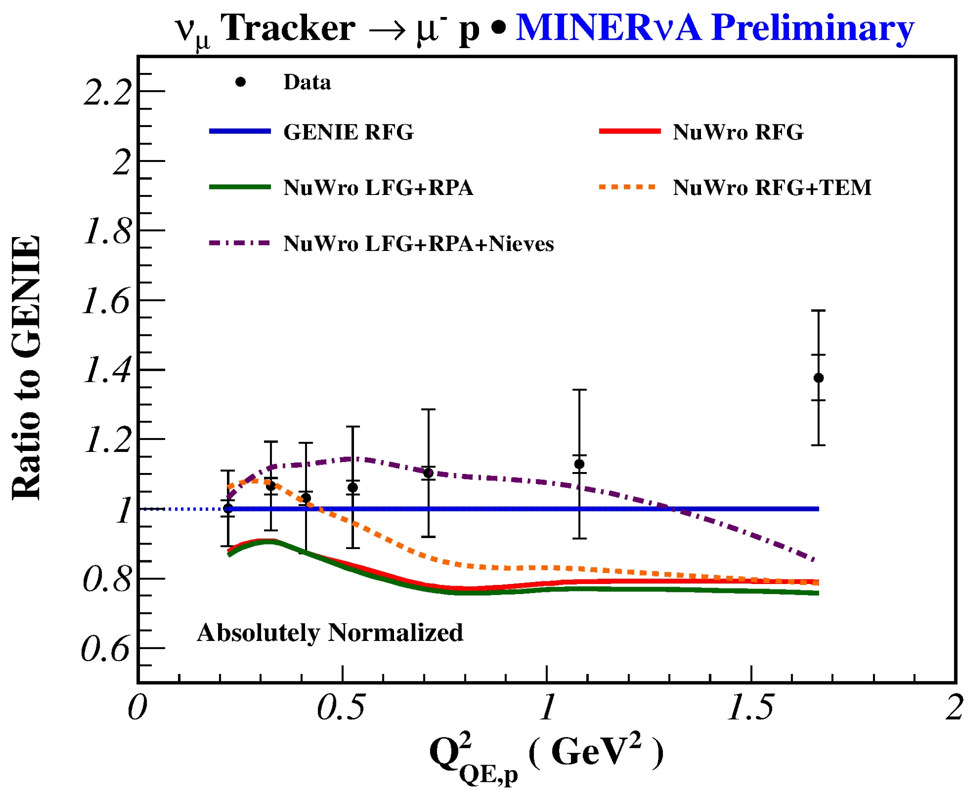
Differential Cross-section Distributions





Compare to cross section models





Quasi-elastic analysis from the hadron vertex (proton) favors the straightforward GENIE RFG model

This in contrast to the RFG + transverse enhanced model for the analysis from one track anlysis

CCQE ANALYSIS WITH ELECTRON NEUTRINO SCATTERING

Inputs Electron neutrino appearance measurements

accelerator ν_μ
Beams typically have an intrinsic ~1% ν_e component

$$N_{FD}(E_\nu) = \Phi_{\nu_\mu} \times P_{\nu_\mu \to \nu_e}(E_\nu) \times \sigma_{\nu_e}(E_\nu) \times R(E_\nu, E_{visible}) + \Phi_{\nu_e}\,\sigma_{\nu_e}$$

Observed events at far detector

beam flux predictin

Oscillation probability

ν_e cross section

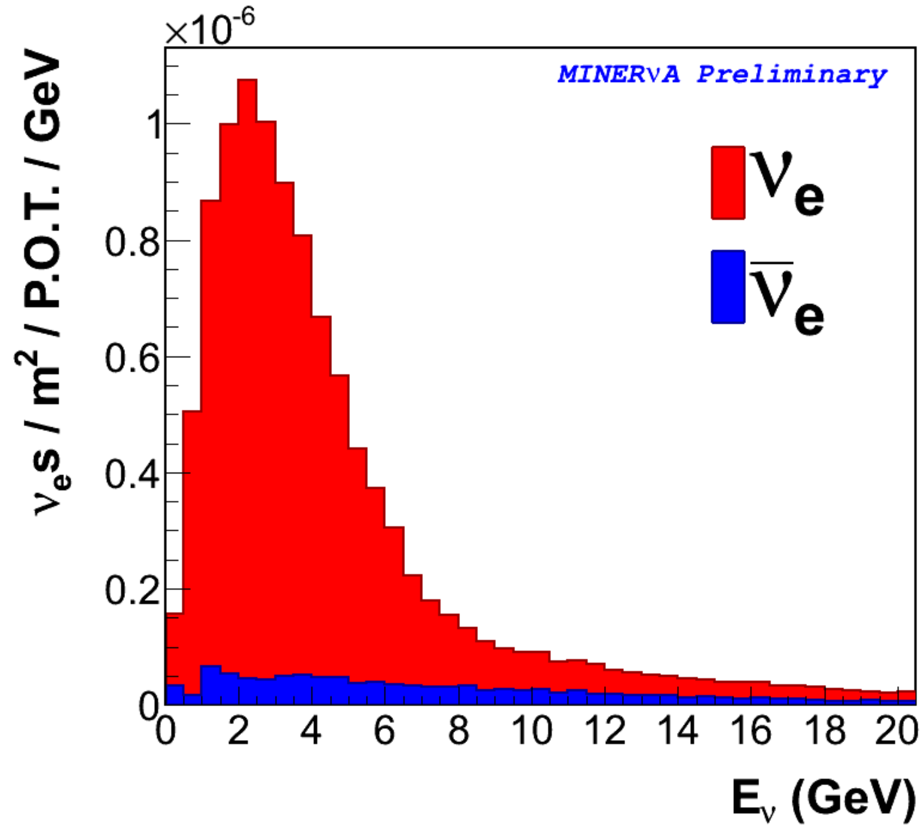
Detector effects

Precise oscillation measurements needs precise measurement of ν_e cross section

Signal definition

$$\pi^+ \rightarrow \nu_\mu \mu^+$$
$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$

Electron neutrinos from beam muon decay.
About 10% $\bar{\nu}_e$. MINERνA is not magnetized... so e^+ looks like e^-



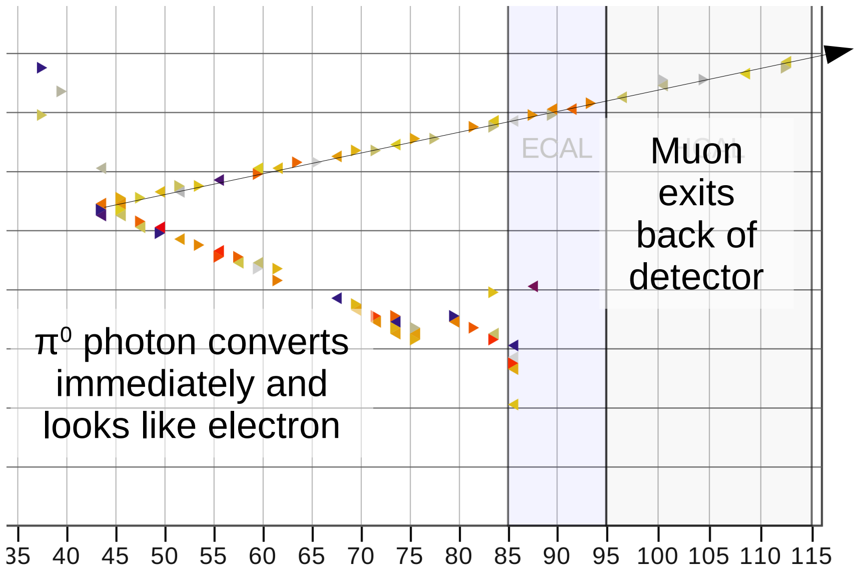
Signal:

- Exactly one lepton, either electron or positron
- Any number of nucleons (proton or neutron)
- No mesons, no baryons

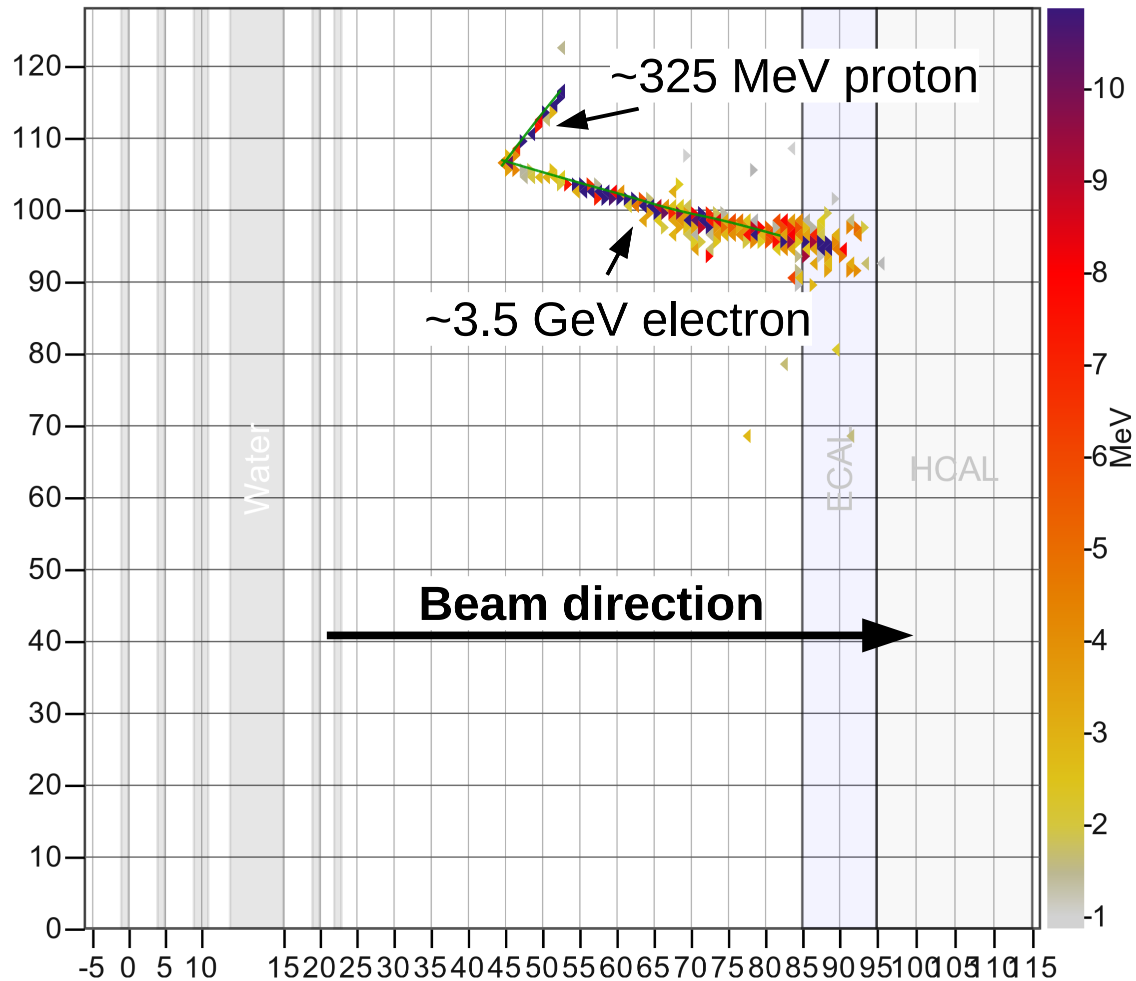
Event Selection

Signal events:

- One (or more) reconstructed track(s) (>85% of $e^{\pm}$ in inner detector region begin with track due to low-Z material)
- No obvious muons ;
  - No tracks exiting back of the detector
  - No Michel electron candidates
- Candidate must contain a reconstructed cone object of angle 7.5^{0} ,originating in the fiducial volume, which is identified as candidate EM cascade by multivariate PID classifier



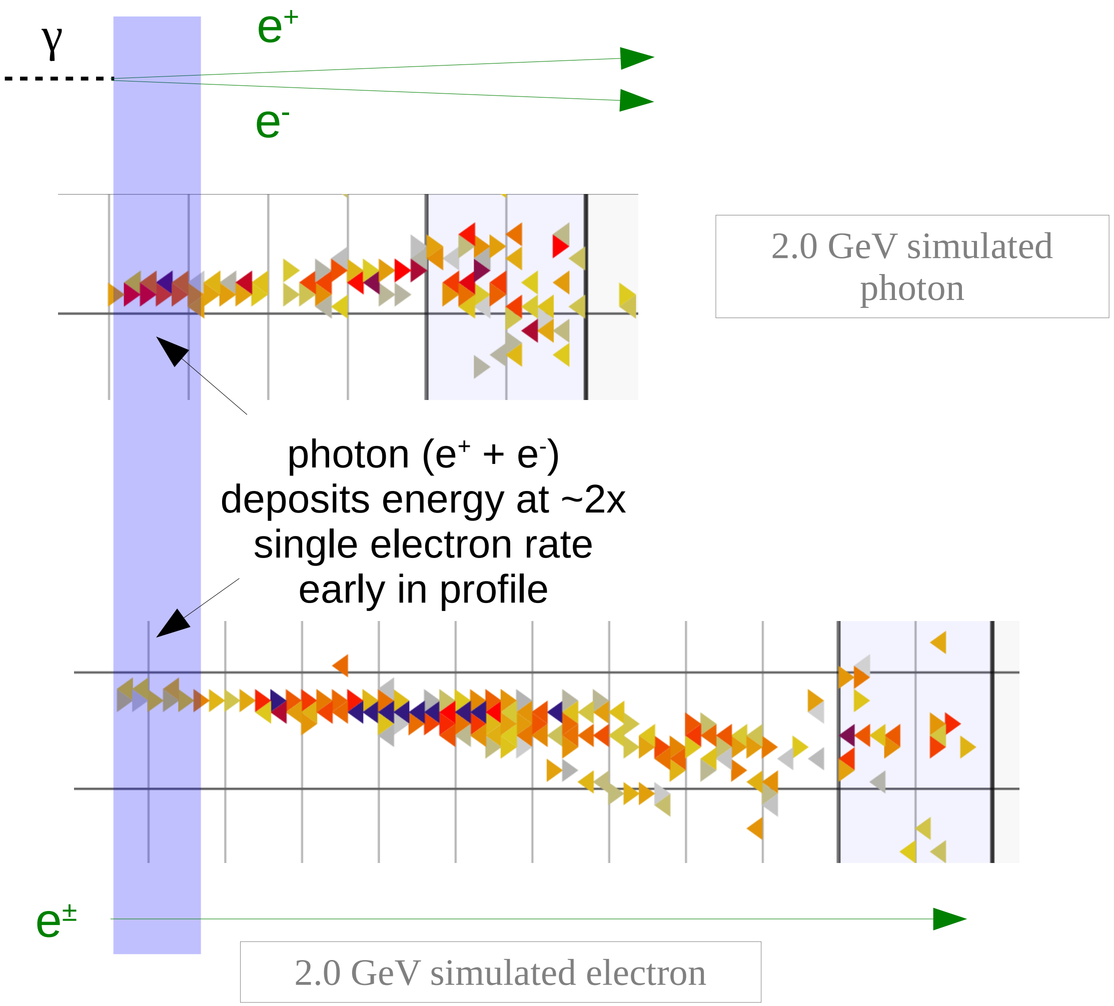
Simulated background rejected by muon cuts

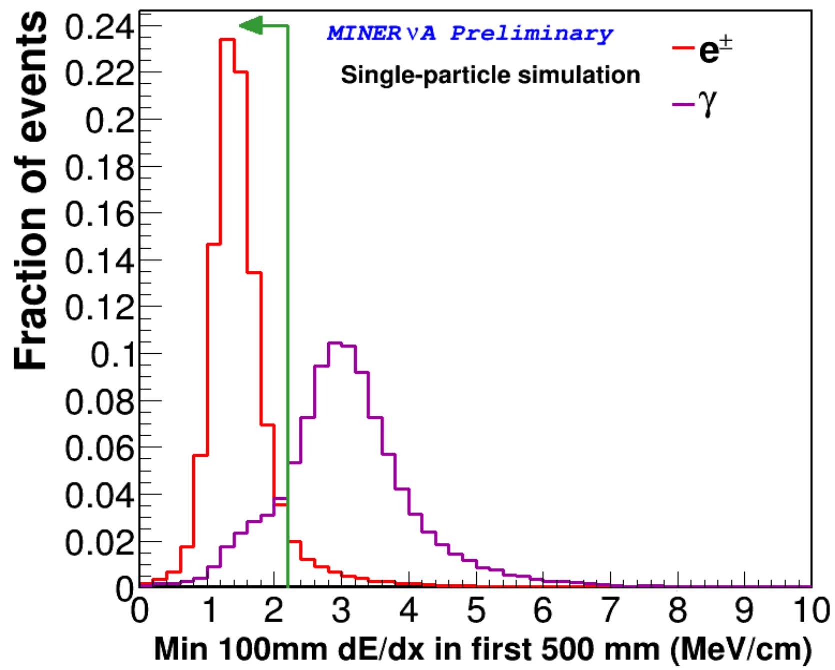


Event display of simulated ~4 GeV ν_e interaction in MINERvA

Event Selection

Photon rejection



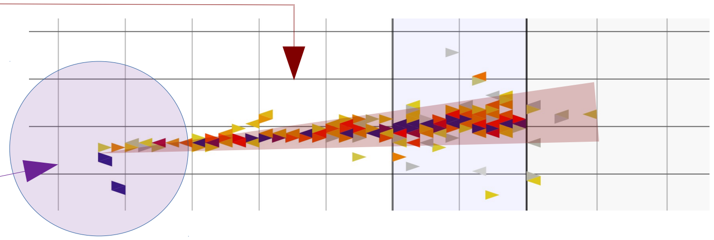


We seperate e+ and e- from photon by cutting events in which the energy deposition at the upstream end of the cone is consistent with two particle rather than one.

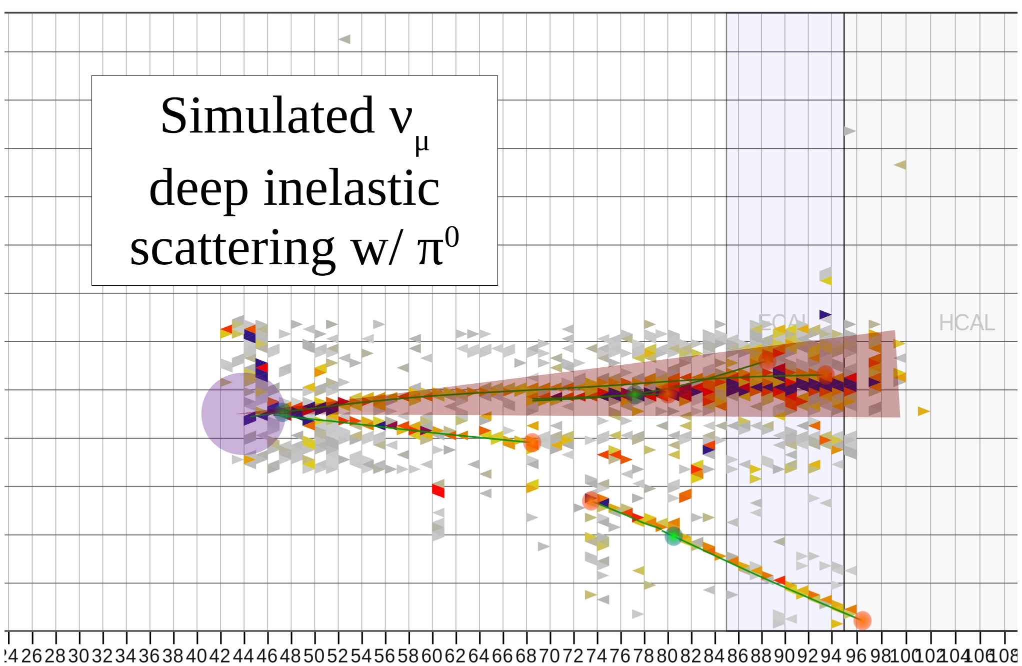
Event Selection

Quasi-elastic-like topology selection

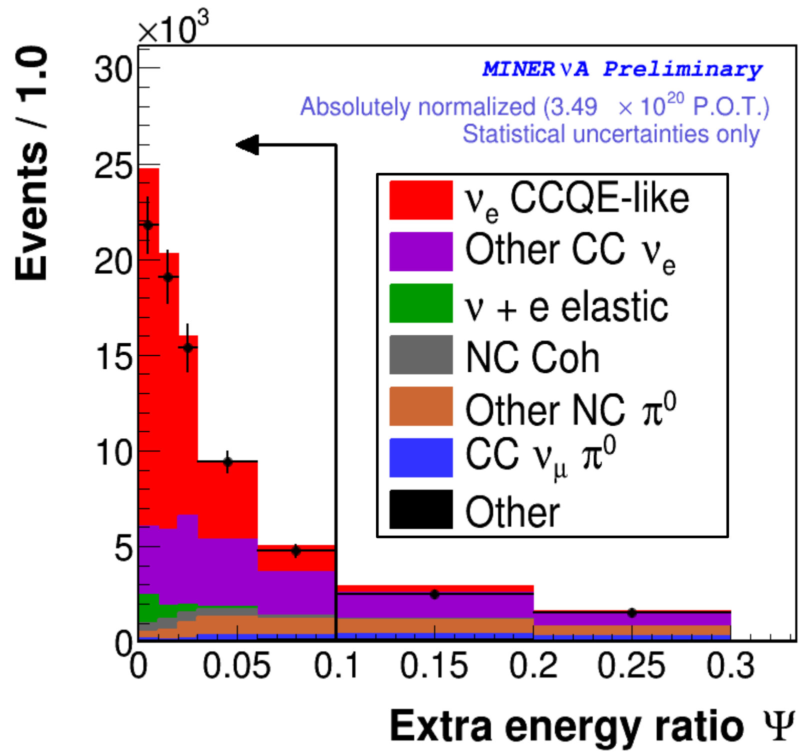
Anything not within a 7.5° electron cone or a vertex activity region of 30 cm radius or tracked as a proton is "extra energy."



Simulated ν_e CCQE

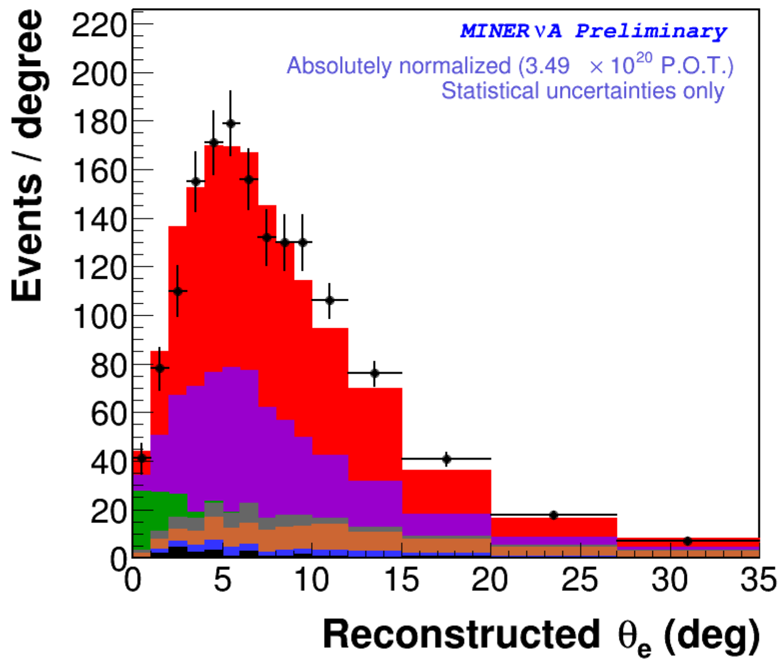


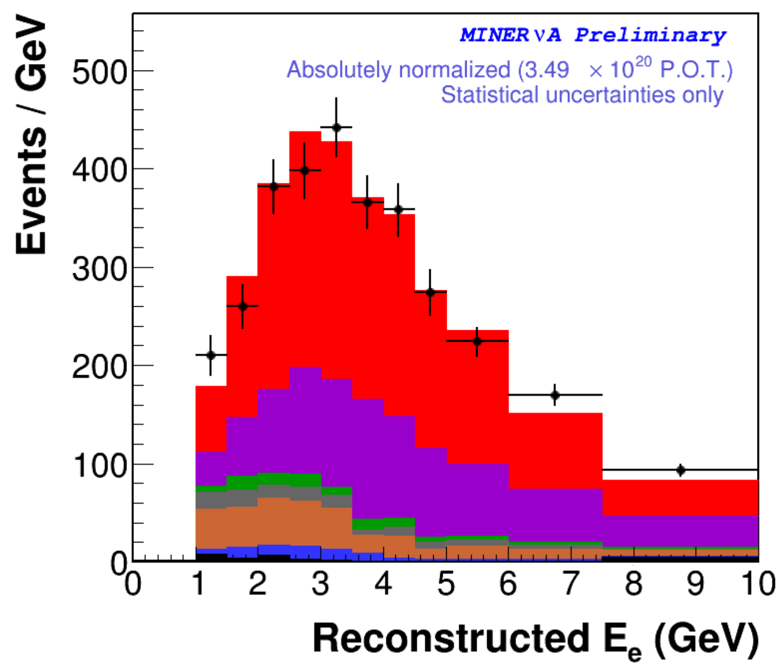
Simulated ν_μ deep inelastic scattering w/ π^0

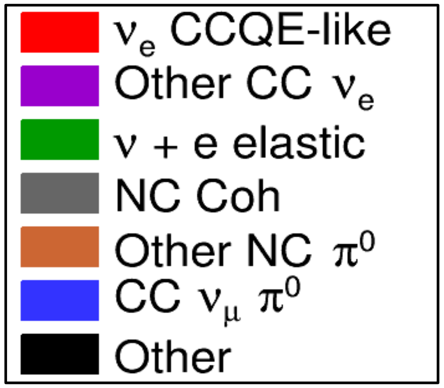


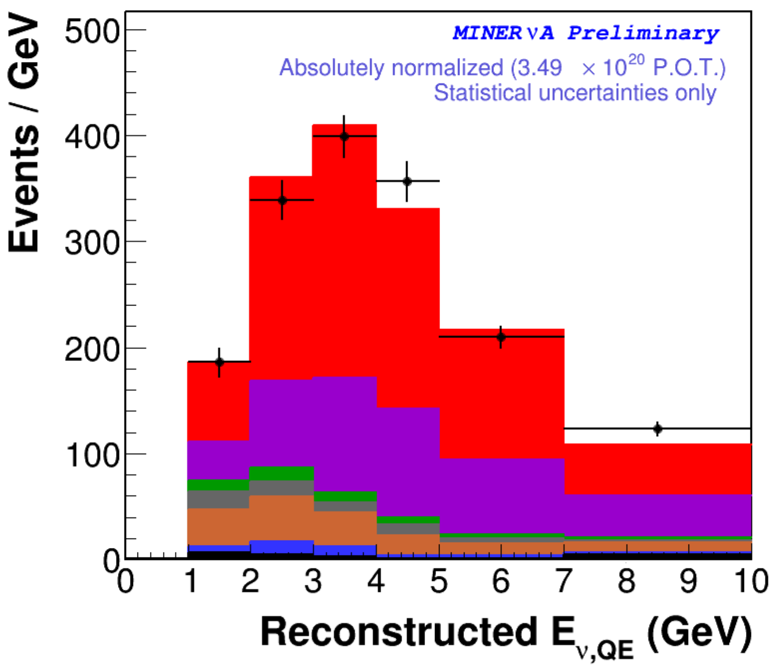
Extra energy $$\psi = \frac{E_{extra}}{E_{cone}}$$

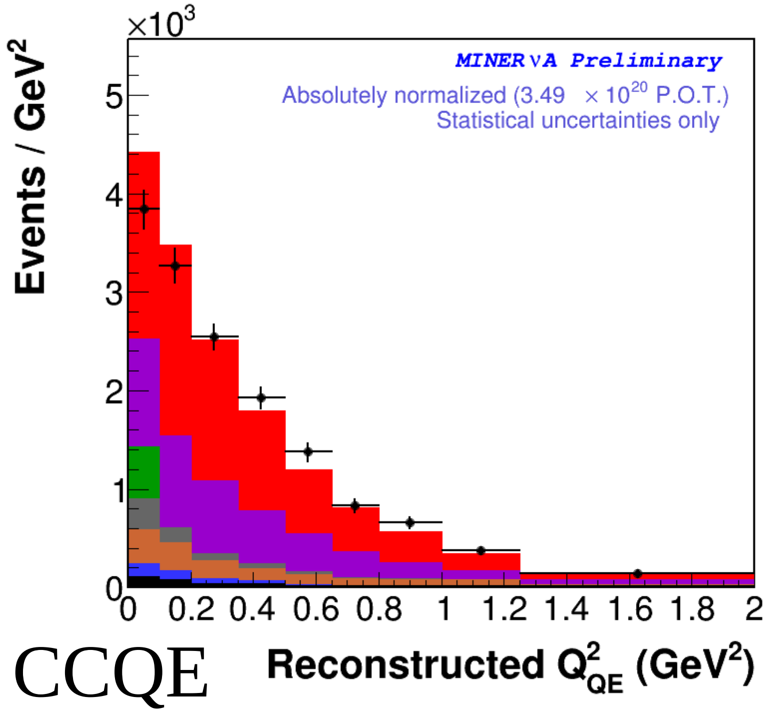
Selected events







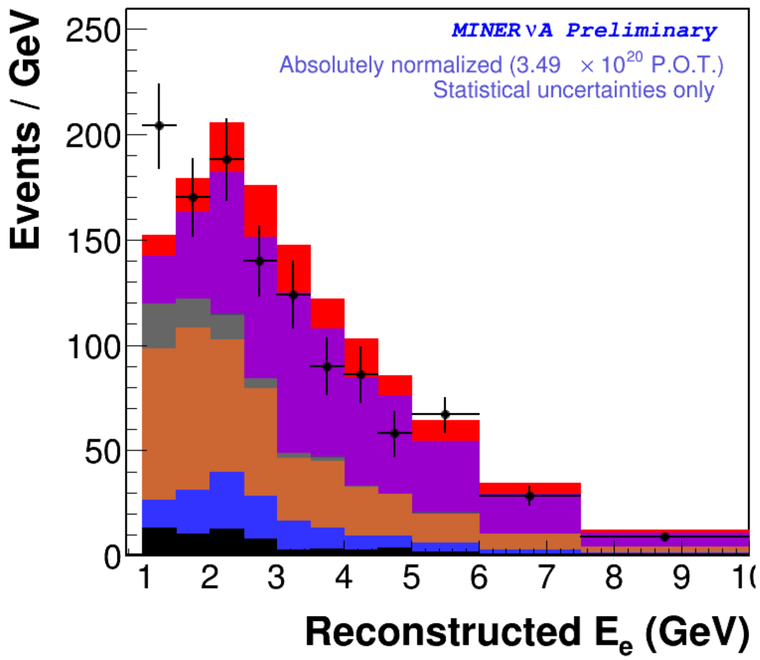




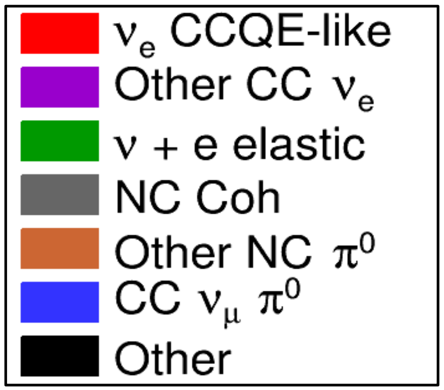
Sample: 52.1% ν_e CCQE

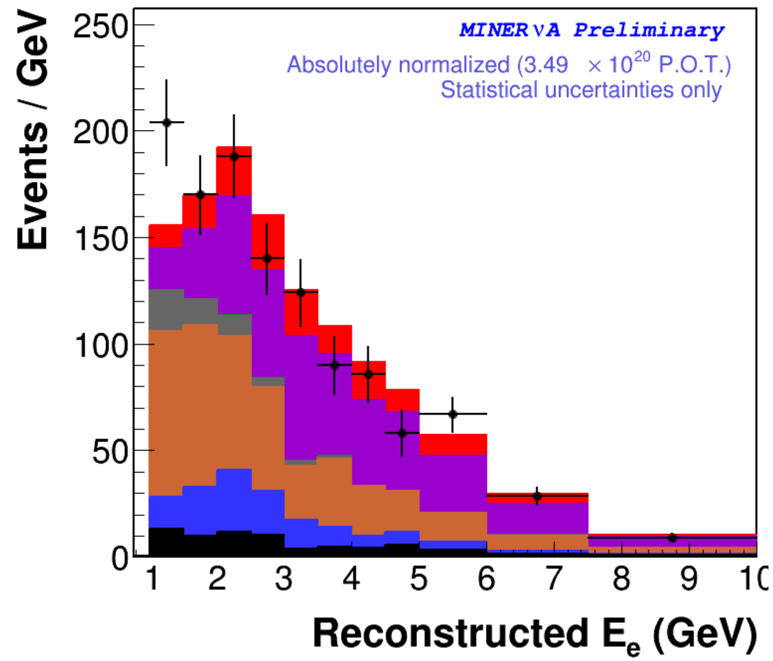
Constraing backgrounds

Normalizations of backgrounds are constrained using sidebands in Michel match, extra energy



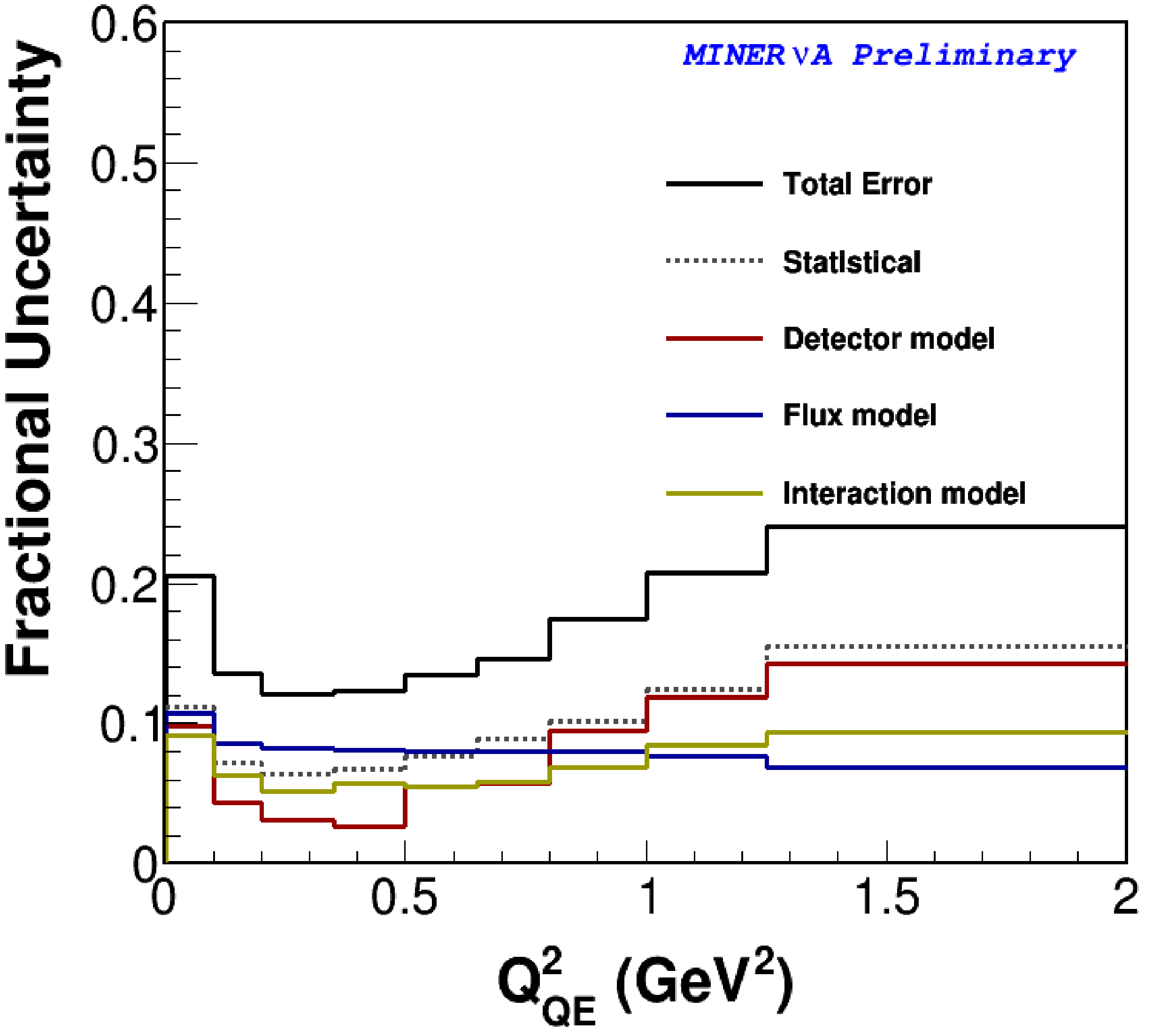
Extra energy sideband
(before fit)



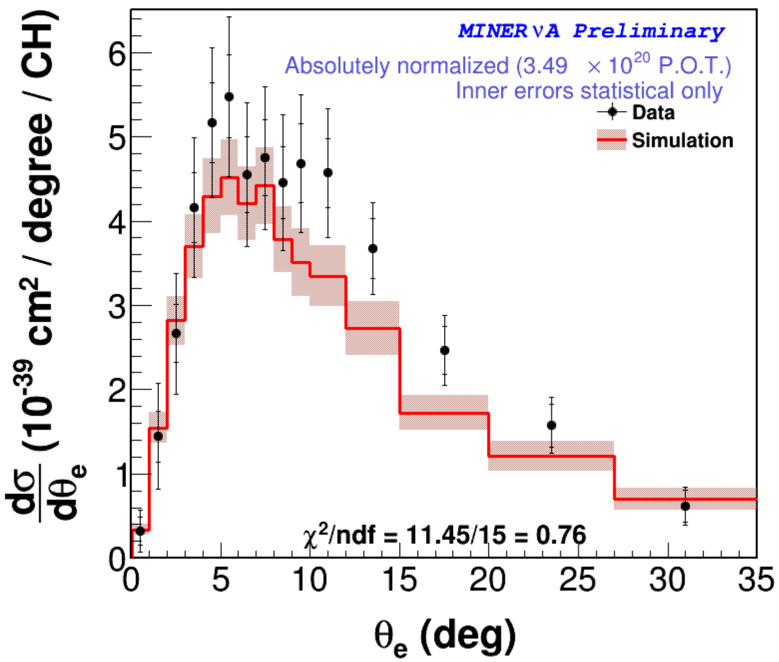


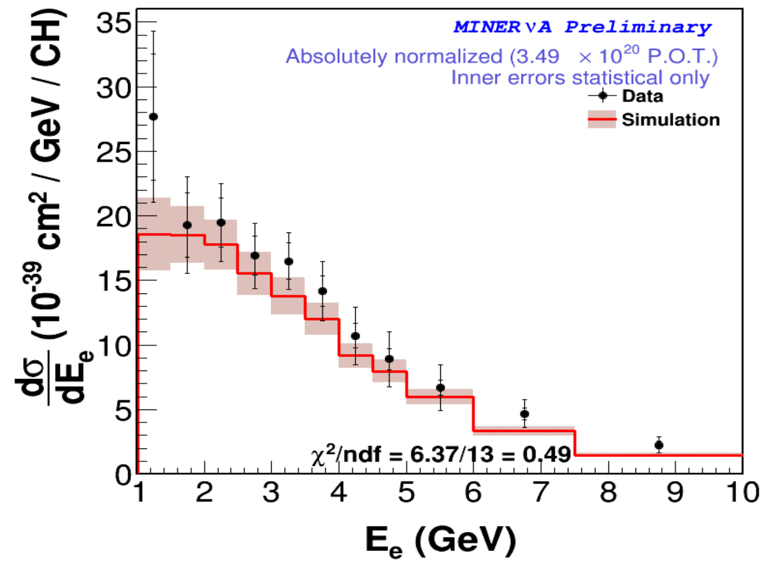
Extra energy sideband
(after fit)

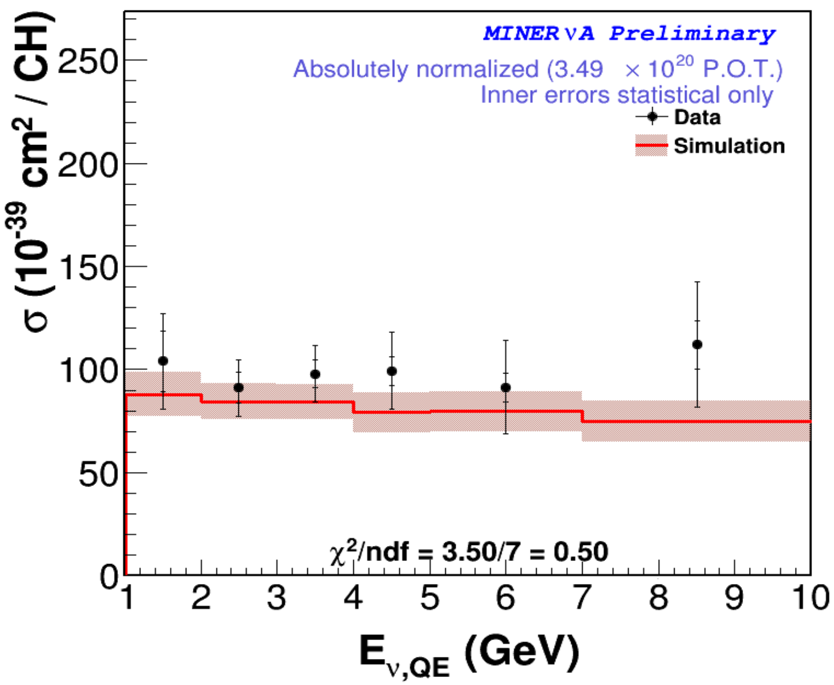
Uncertainty summary

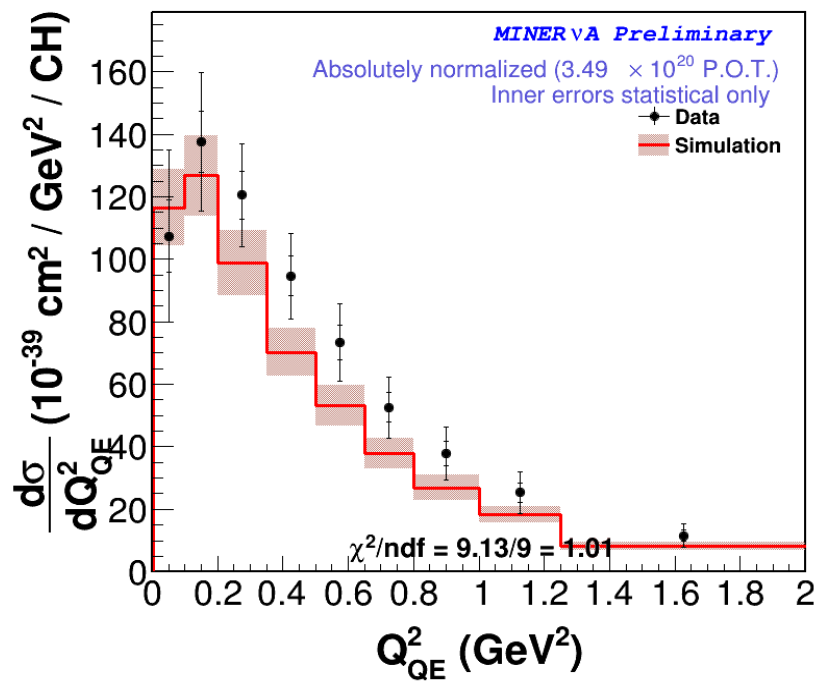


Cross-sections



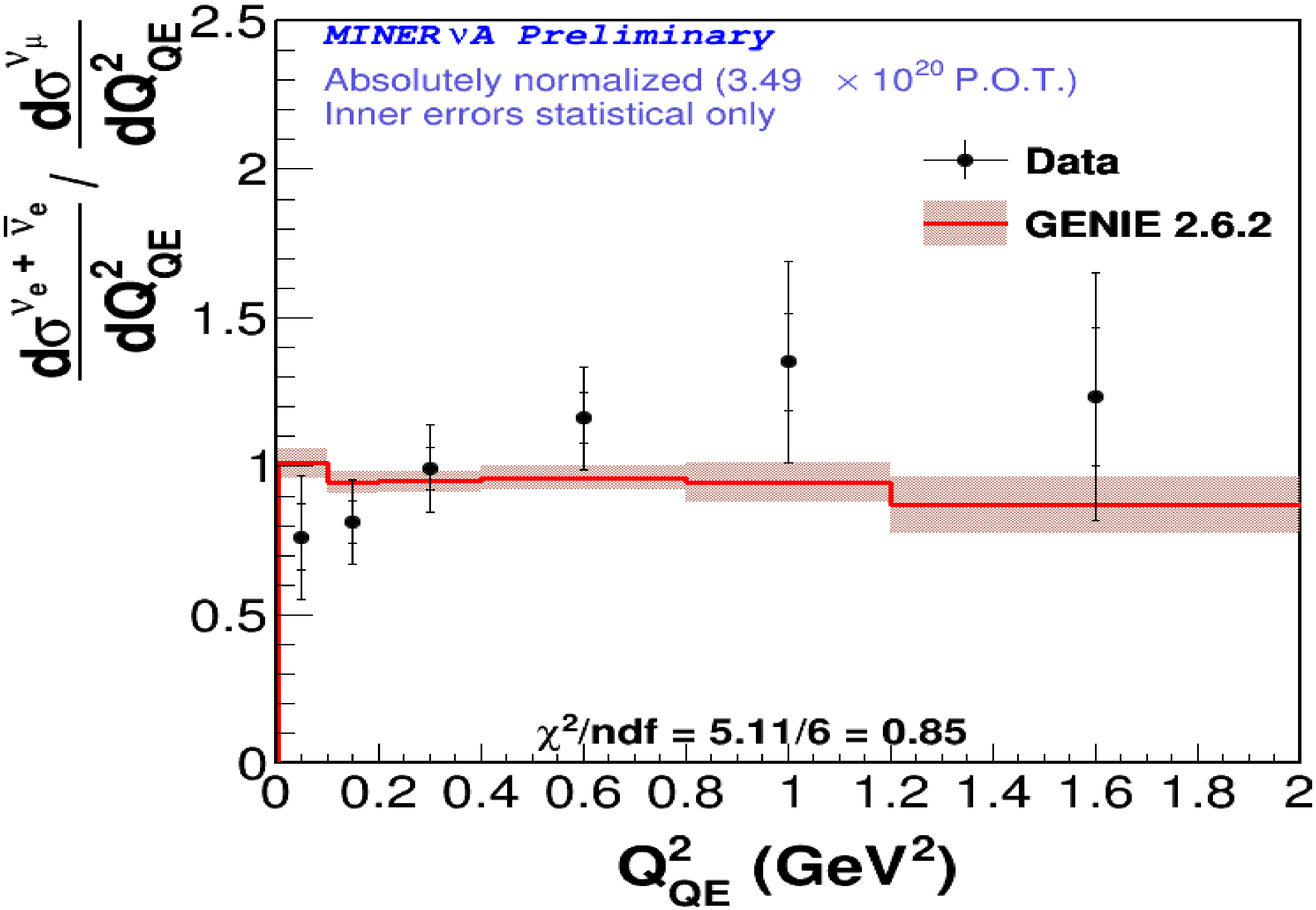






Measured cross-sections are consistent with the prediction from GENIE 2.6.2

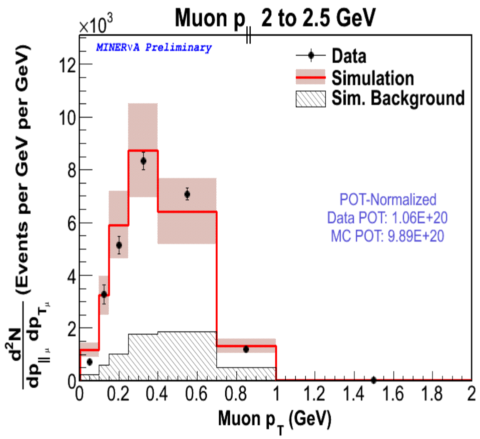
Comparison to ν_μ

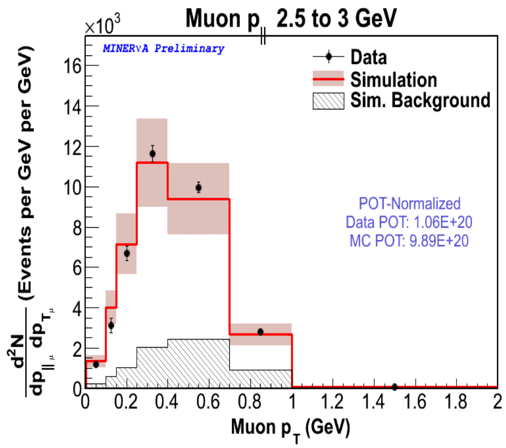


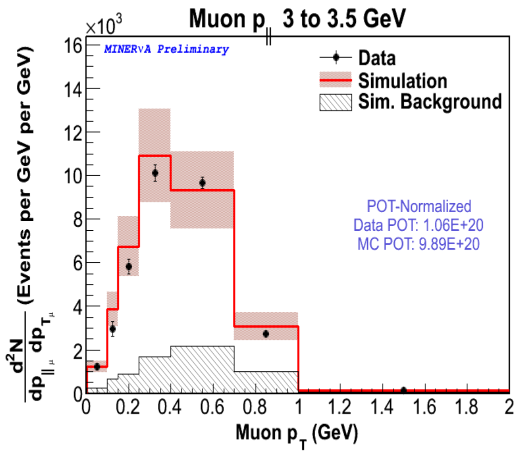
Result is consistent with lepton universality hypothesis (GENIE prediction)

CCQE DOUBLE DIFFERENTIAL CROSS SECTION

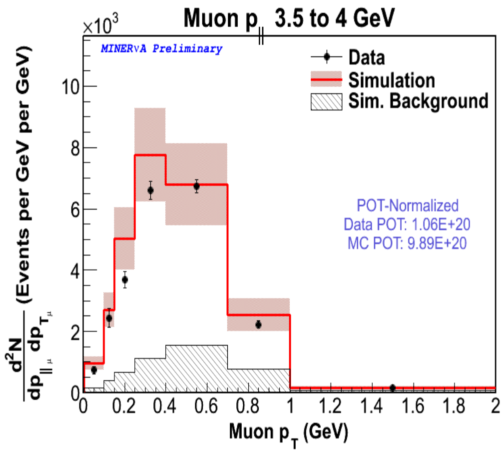
CCQE double differential cross seciton

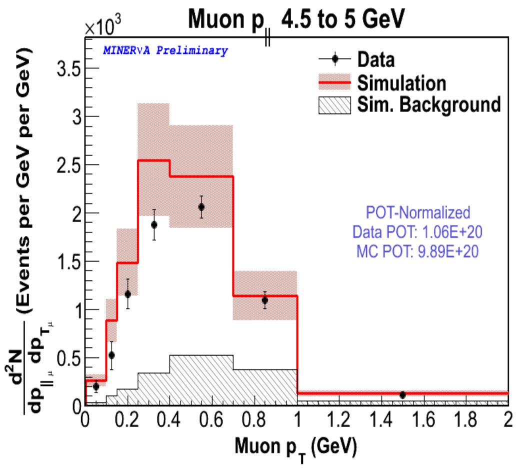


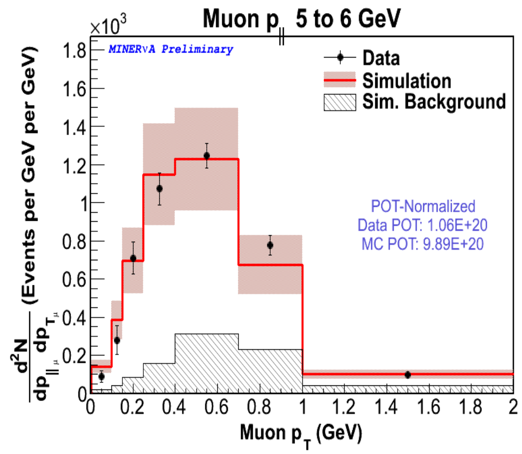




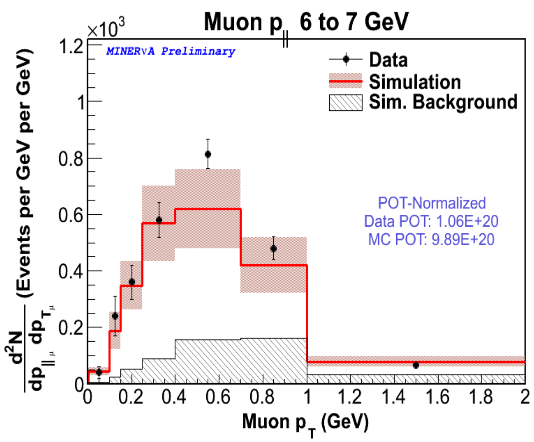
- Double-differential cross sections in measurable variables will provide extra information to help distinguish between models.







- The plots to the left are for the antineutrino CCQE sample.



- Plots show data and simulation event distributions vs. transverse muon momentum, in bins of longitudinal muon momentum
- Uncertainties on reconstruction and interaction model are shown on the simulation
- Reducing the uncertainty on the interaction model is a key goal of this study

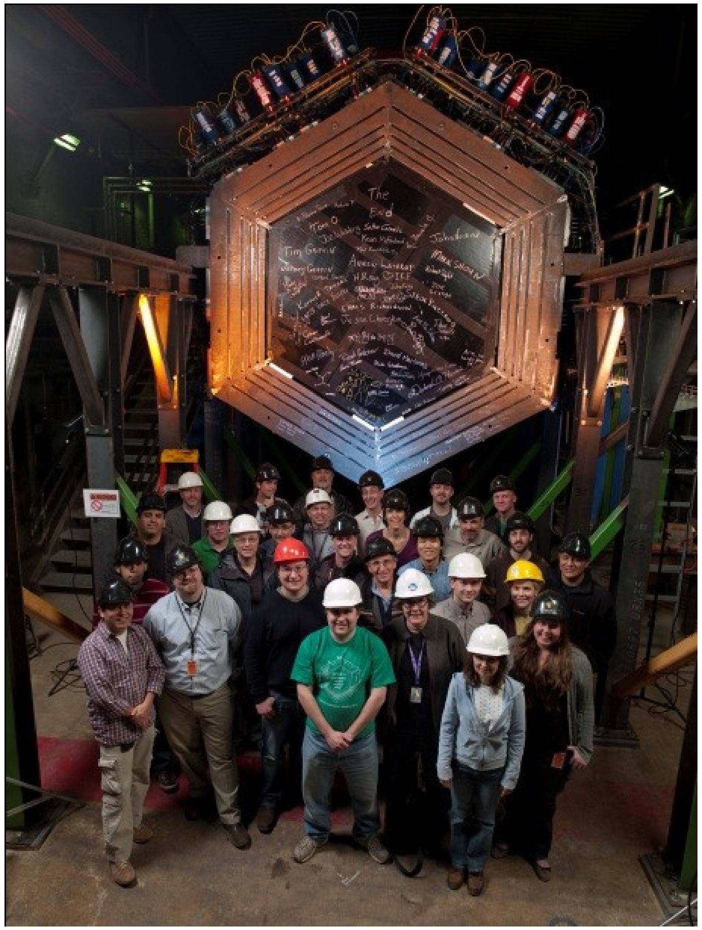
Upcoming analyses

- Neutrino-mode double differential cross section
- CCQE analysis with proton kinematics at different nuclear targets: Study the nuclear effects
- MINERvA continues to run during the NOvA-era medium energy beam. We will update the CCQE analyses with medium energy data.

Stay Tuned!

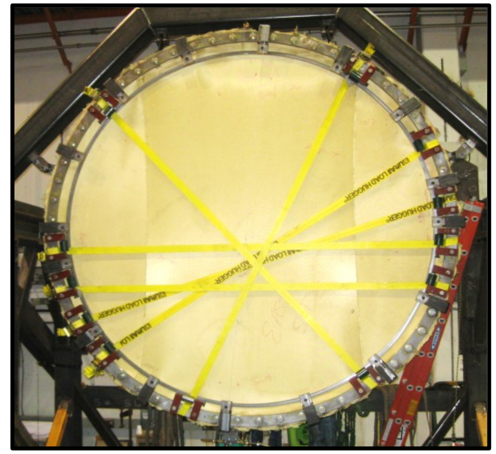
The MINERvA collaboration consists of ~65 Nuclear and Particle Physicists

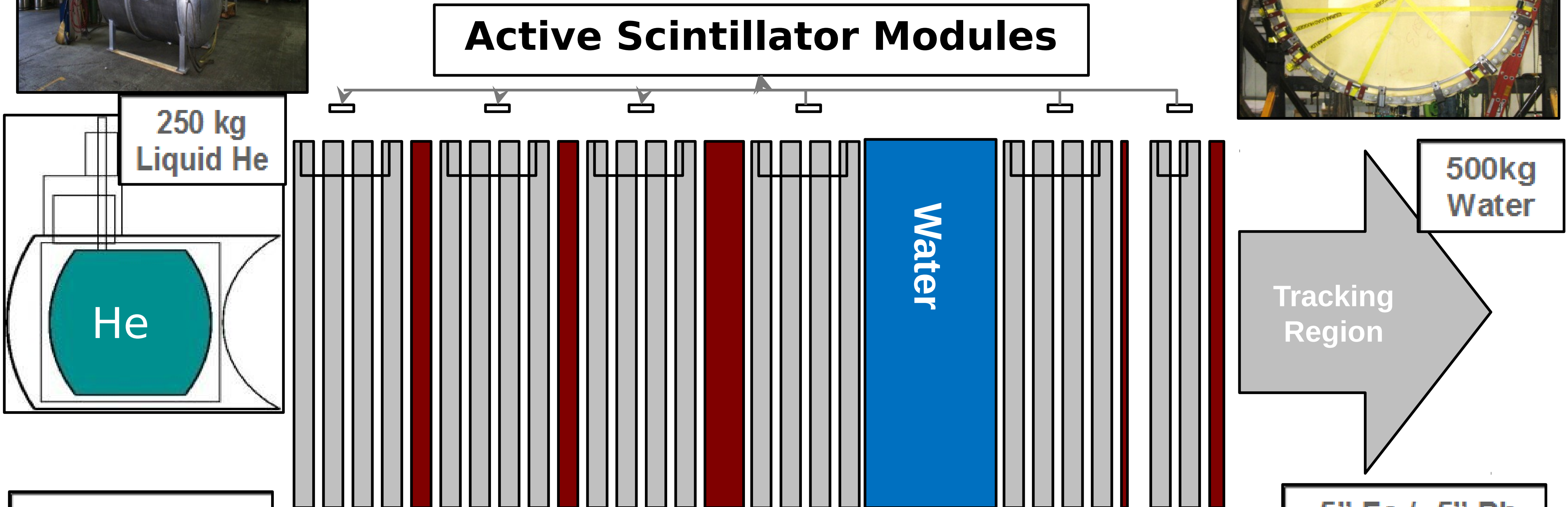
Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil
UC Irvine, Irvine, CA
University of Chicago, Chicago, IL
Fermi National Accelerator Laboratory, Batavia, IL
University of Florida, Gainsville, IL
Université de Genève, Genève, Switzerland
Universidad de Guanajuato, Ganajuato, Mexico
Hampton University, Hampton, VA
Mass. Col. Lib. Arts, North Adams, MA
University of Minnesota-Duluth, Duluth, MN
Northwestern University, Evanston, IL
Oregon State University, Portland, OR
Otterbein College, Westerville, aOH
University of Pittsburgh, Pittsburgh, PA
Pontificia Universidad Católica del Perú, Lima, Peru
University of Rochester, Rochester, NY
Rutgers University, Piscataway, NJ
Universidad Técnica Federico Santa María, Valparaiso, Chile
Tufts University; Medford, MA
Universidad Nacional de Ingeniería, Lima, Peru
College of William & Mary, Williamsburg, VA



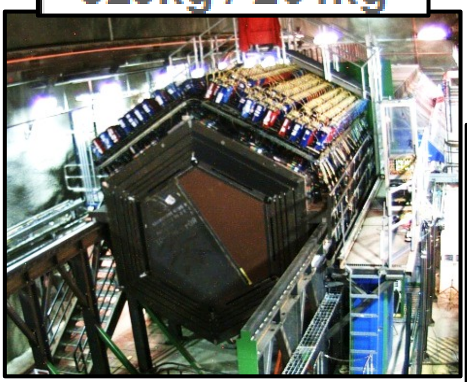
Backup

Nuclear Target Region

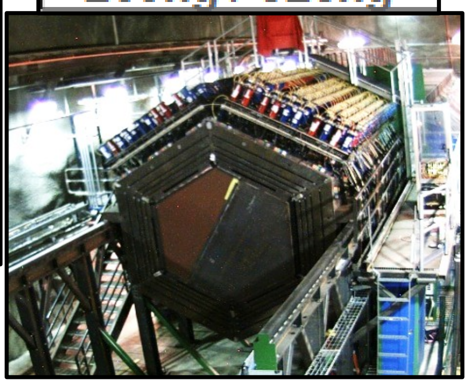




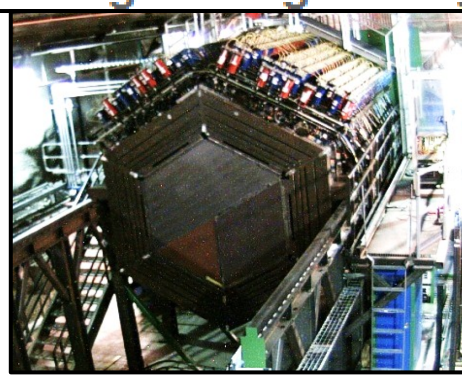
1” Fe / 1” Pb
323kg / 264kg



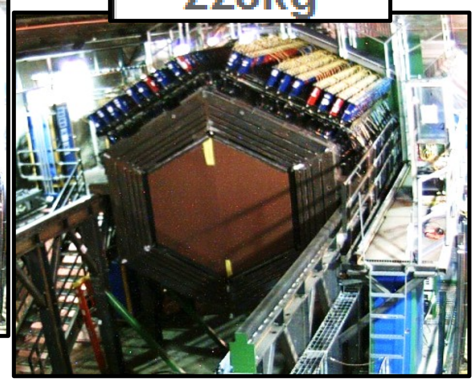
1” Pb / 1” Fe
266kg / 323kg



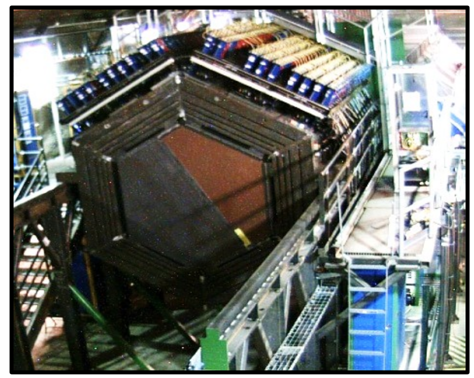
3” C / 1” Fe / 1” Pb
166kg / 169kg / 121kg



0.3” Pb
228kg



.5” Fe / .5” Pb
161kg/ 135kg



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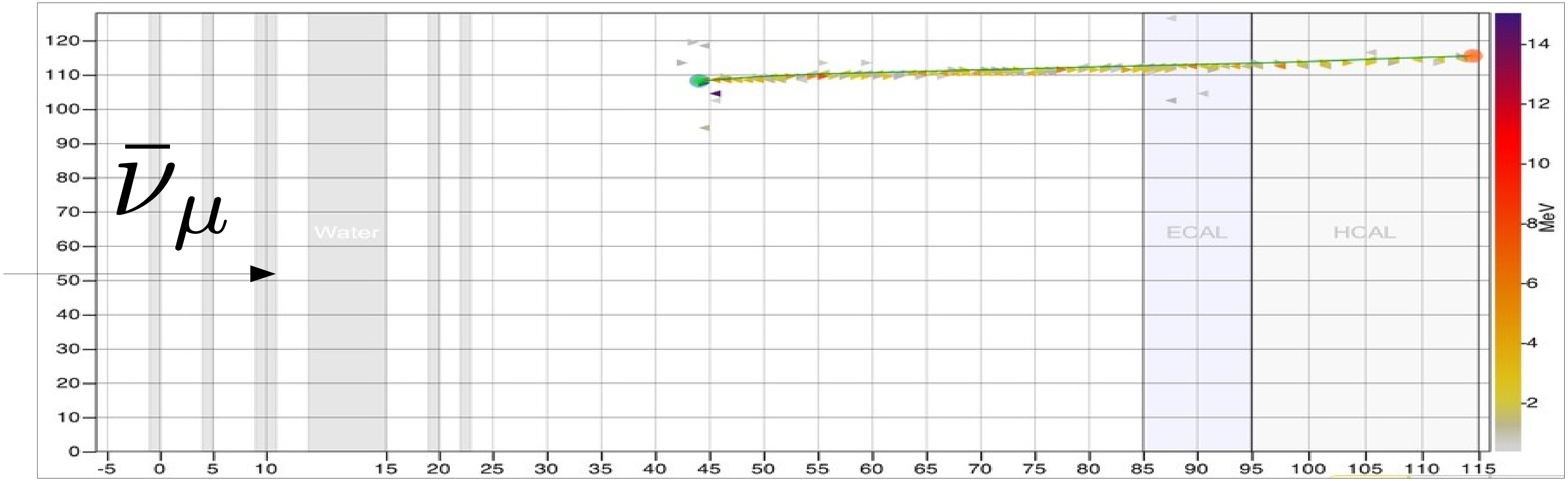
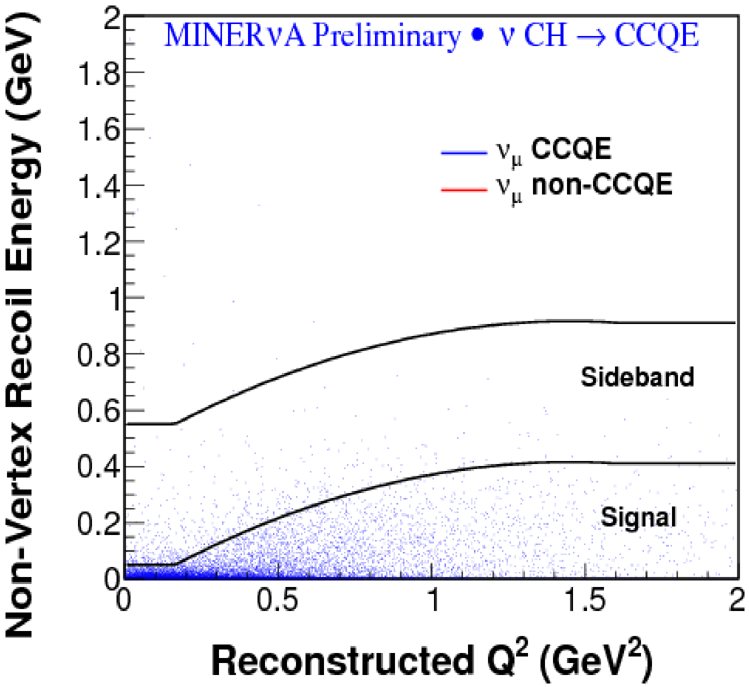
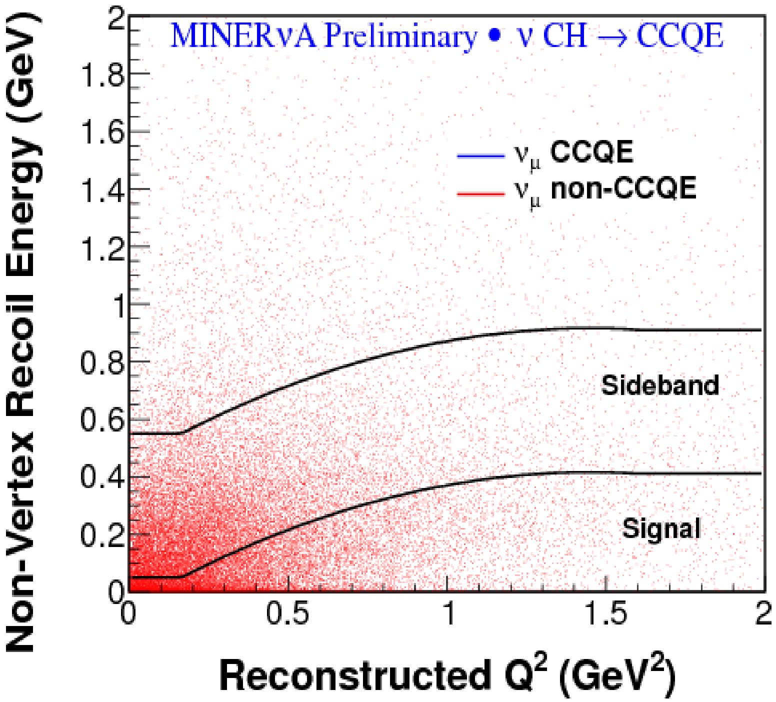
CCQE Event Selection: Anti-Neutrino Mode



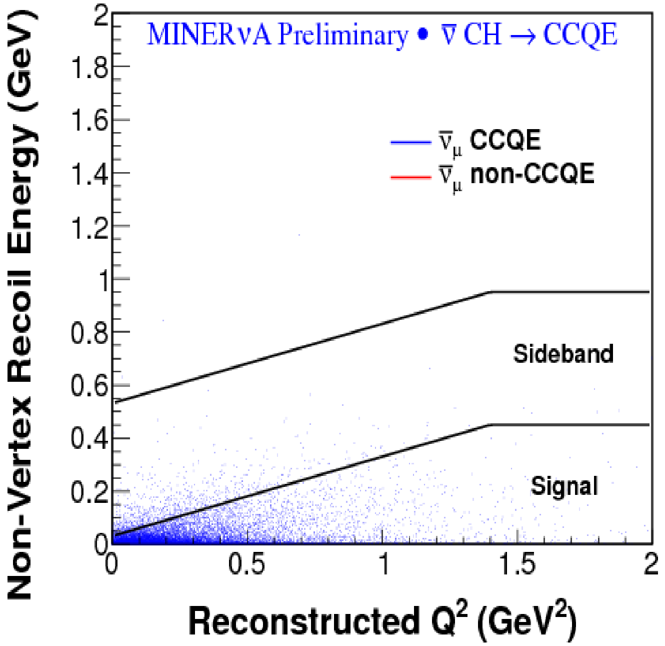
$$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$$

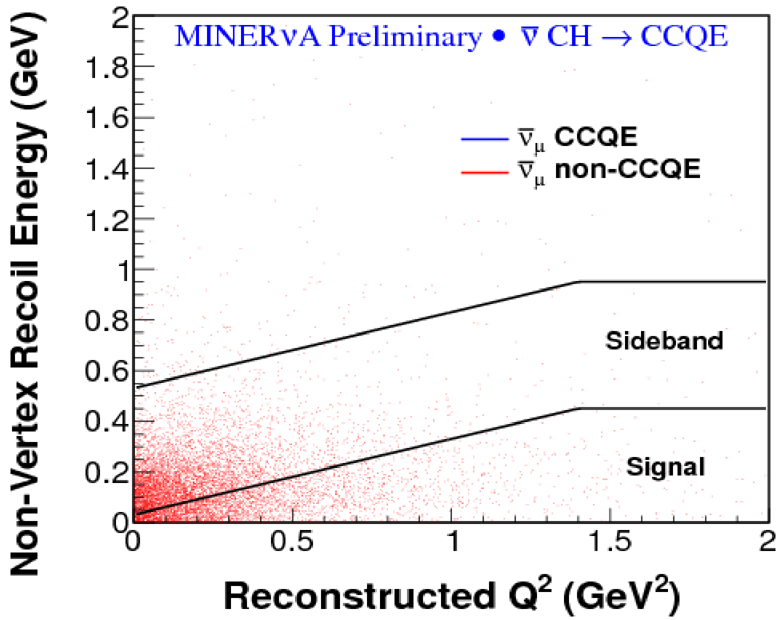
CCQE EVENT SELECTION





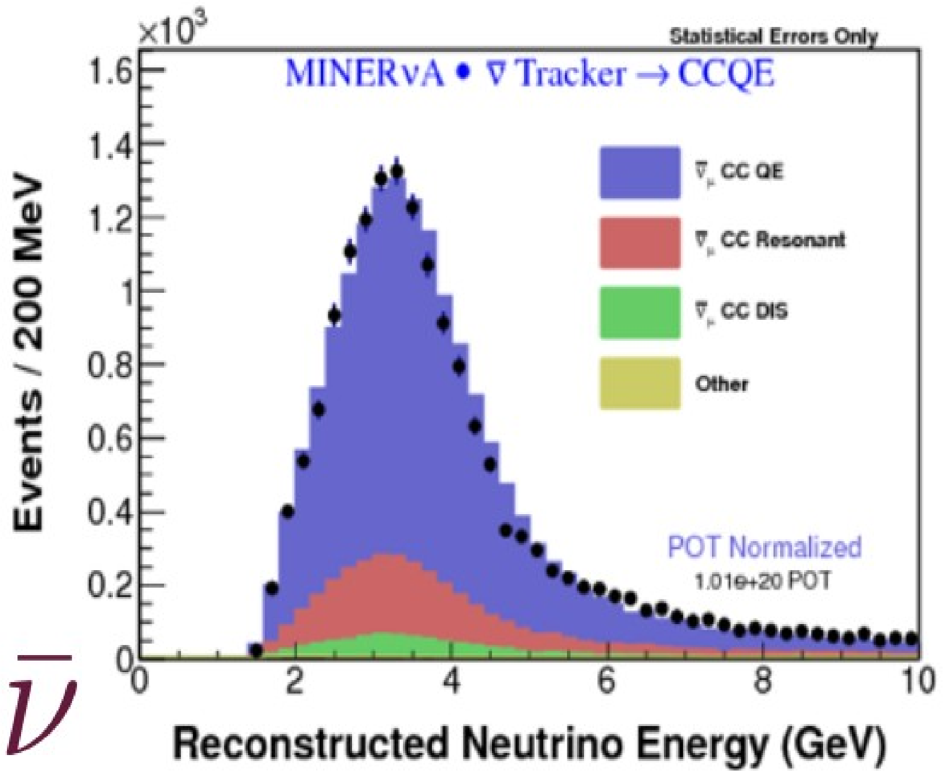
ν

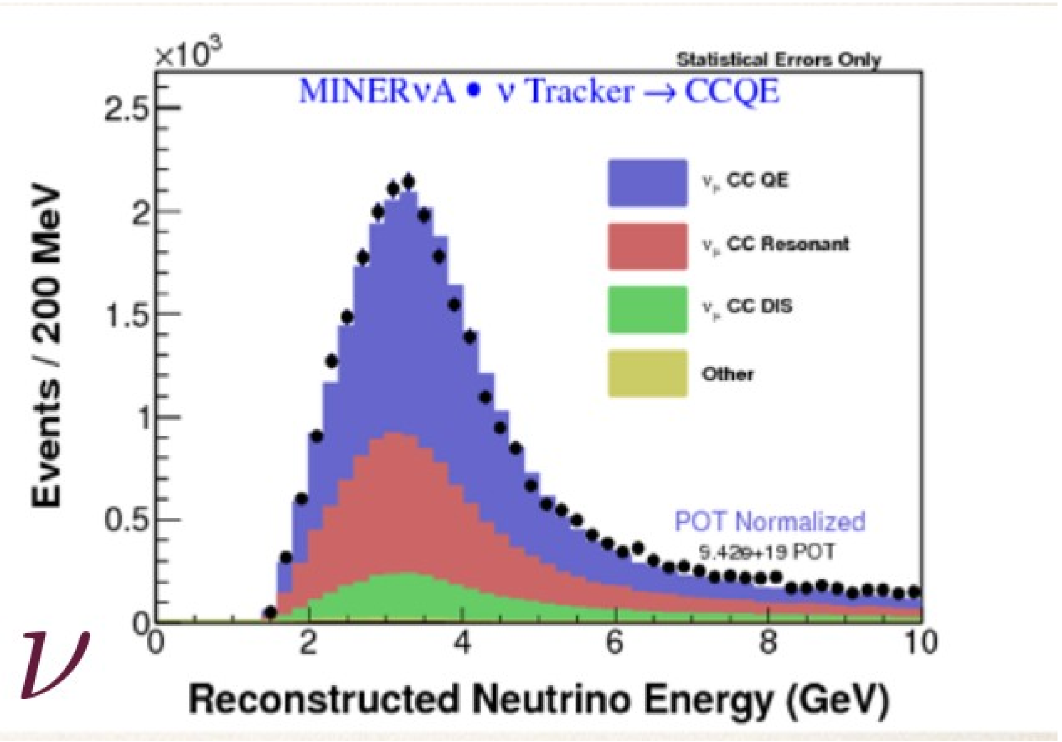




$\bar{\nu}$

Background Substraction

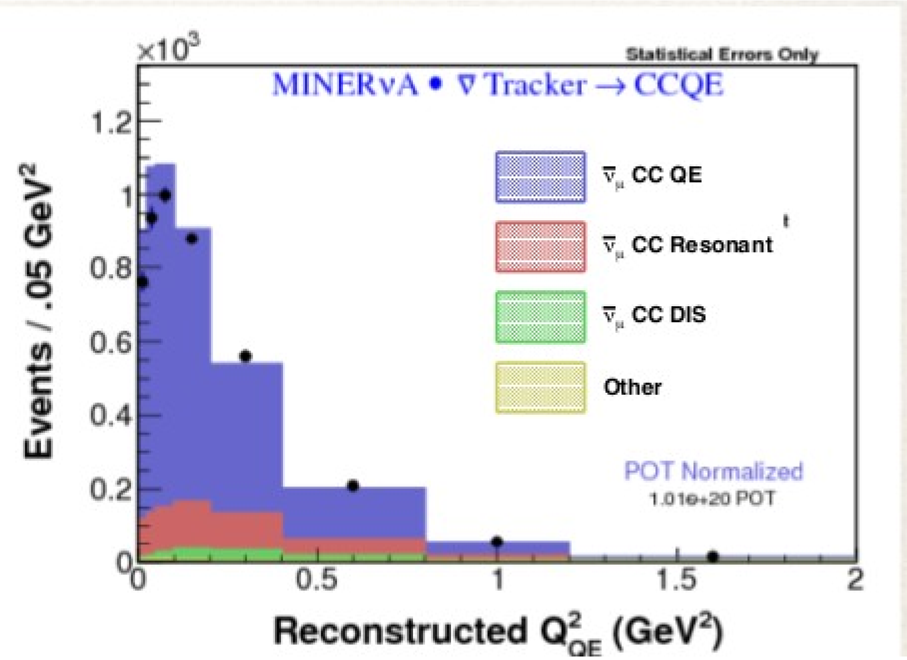




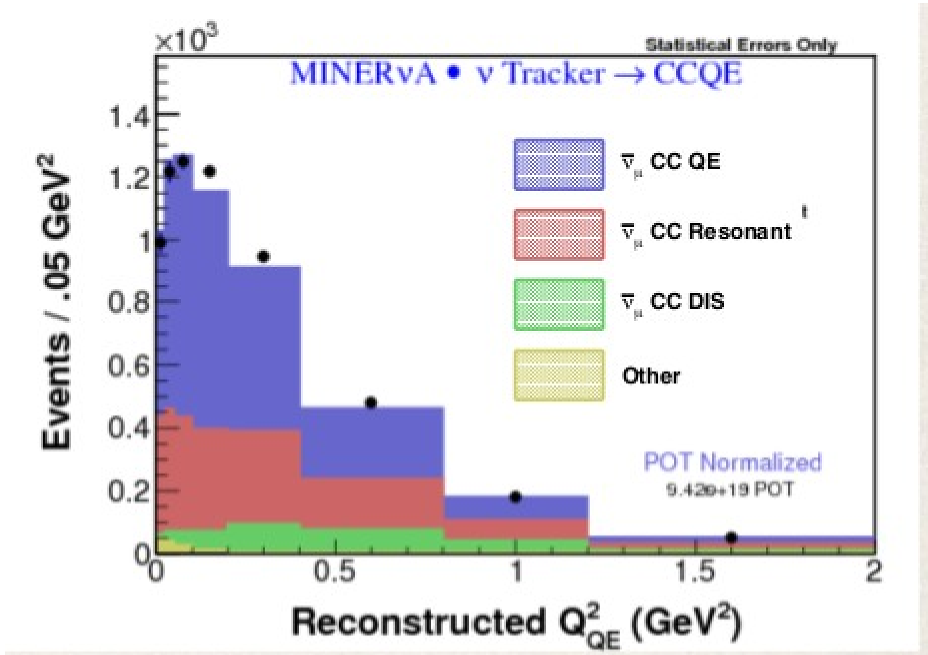
Backgrounds include events such as

- Quasi-elastic-like resonant events, where the pion is absorbed
- QE-like deep-inelastic scattering events
- Other DIS or resonant events which are not removed by our cuts

Reconstructed Q^2_{QE} Distribution



16,467 events, 54% efficiency, 77% purity



29,620 events, 47% efficiency, 49% purity

Assuming bound nucleon at rest, Reconstructed Q^2_{QE} is given by

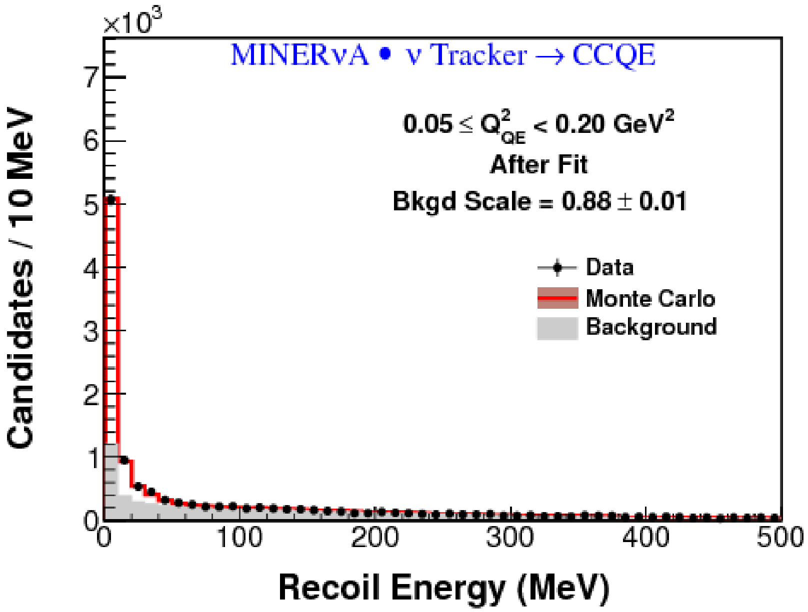
$$Q^2_{QE} = -m_l^2 + 2E_\nu^{QE}(E_l - \sqrt{E_l^2 - m_l^2}cos\theta_l)$$

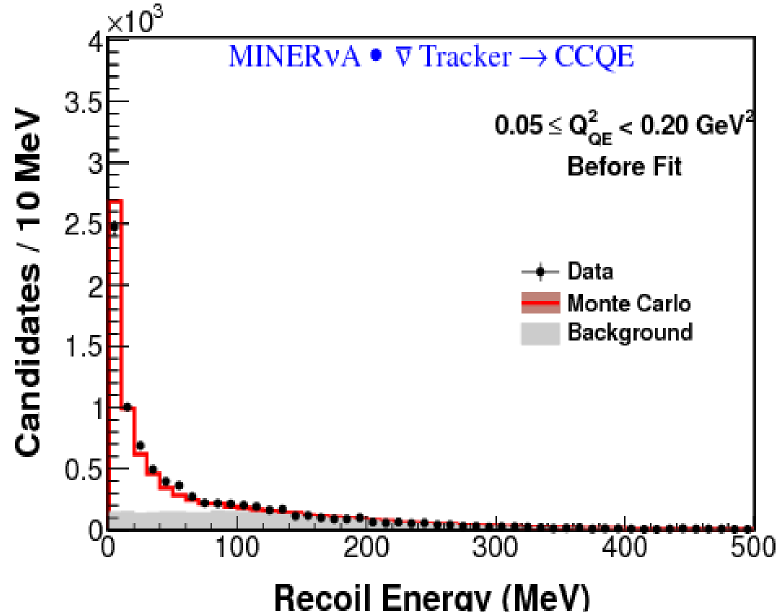
We cut on reconstructed neutrino energy:
$1.5 < E_\nu^{QE} < 10$GeV

$$E_\nu^{QE} = \frac{2(M_n - E_B)E_l - [(M_n - E_B)^2 + m_l^2 - M_p^2]}{2[M_n - E_B - E_l + p_l cos\theta_l]}$$

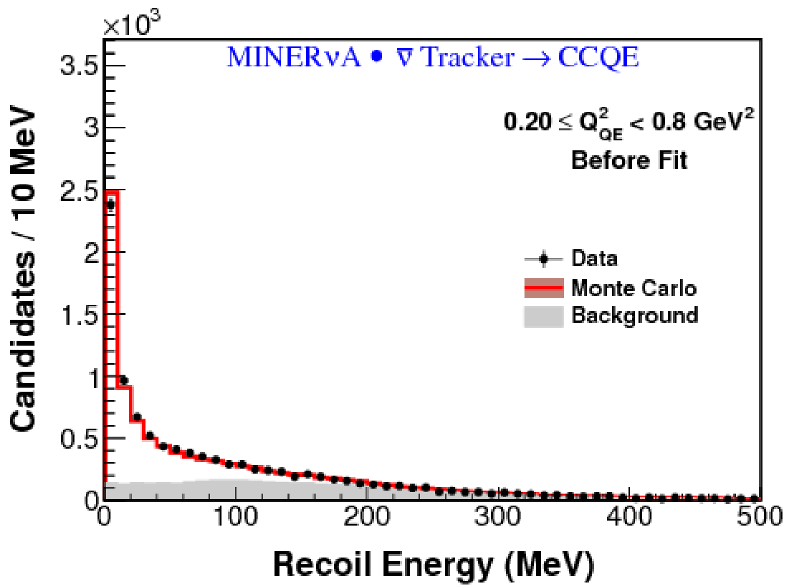
M_n, M_p = neutron, proton mass
E_B = nuclear binding energy
m_l, E_l, θ_l = mass, energy, angle of final state lepton

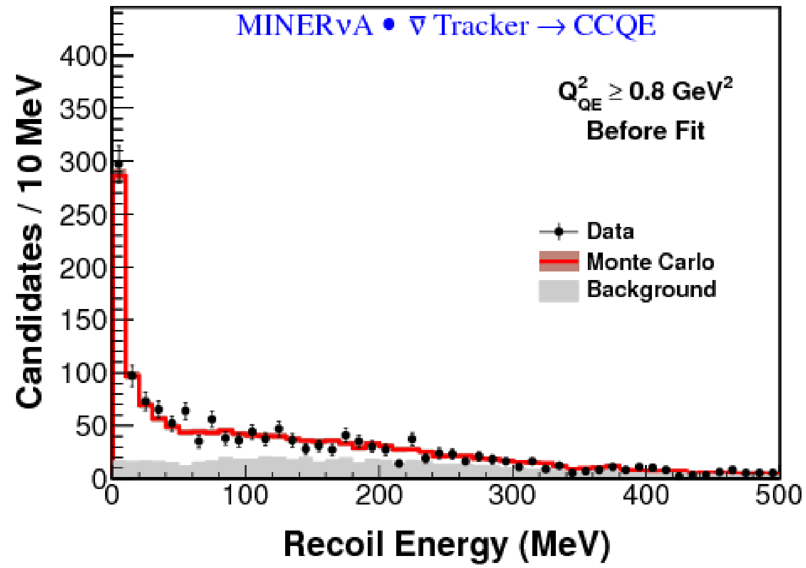
Background Substraction: Before





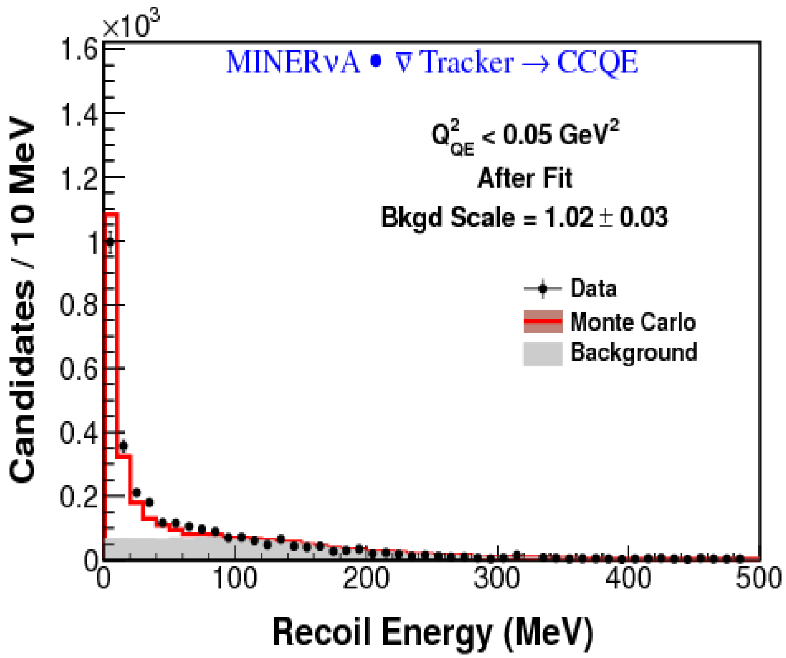
Anti-neutrino mode

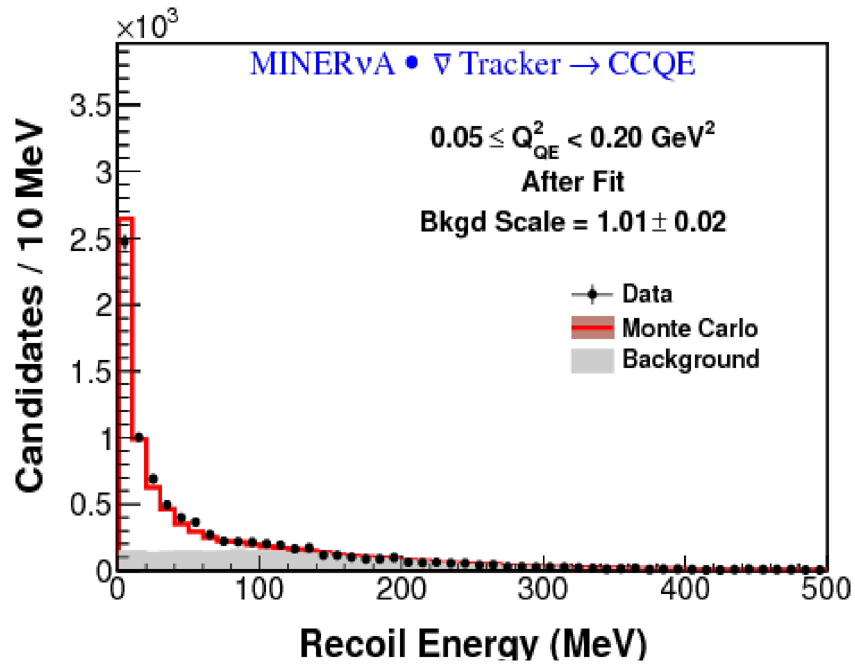




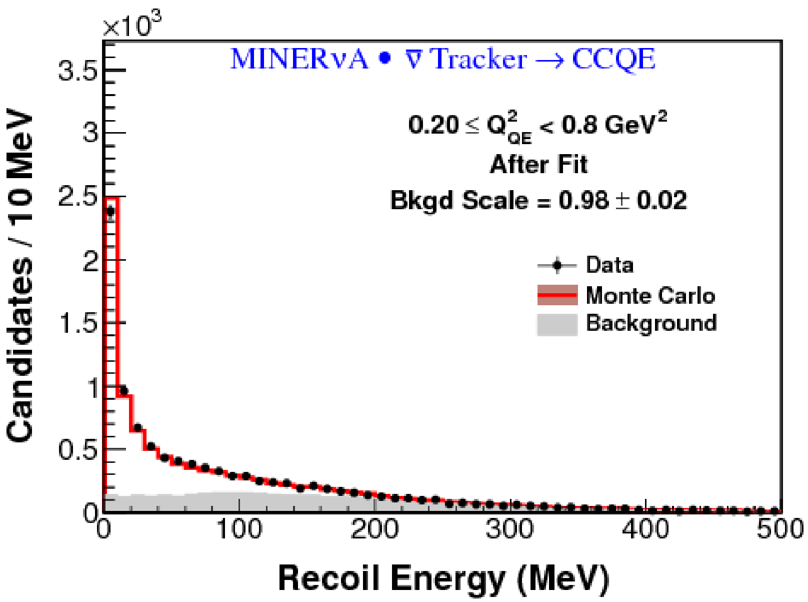
We use data to estimate our backgrounds by performing a fraction fit of simulated signal and background recoil energy distributions from our Monte Carlo, in each of 4 Q2 bins

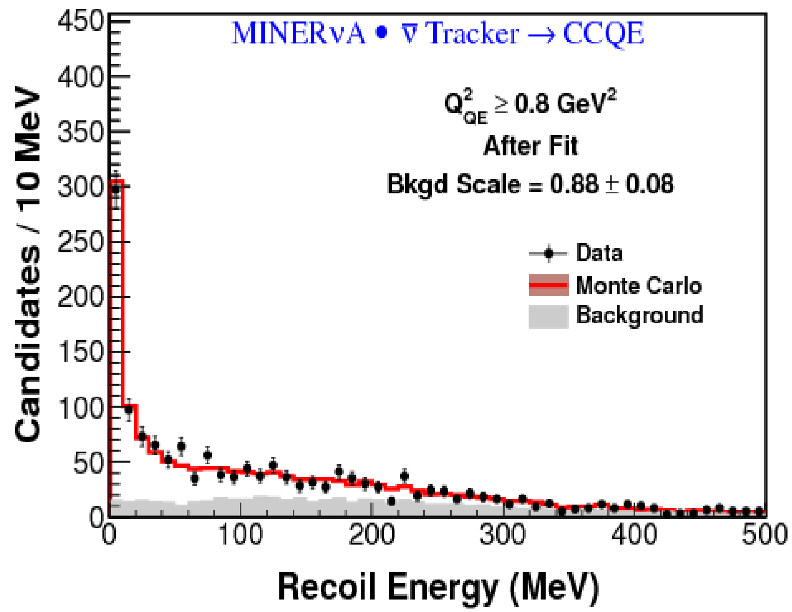
Background Substraction: After



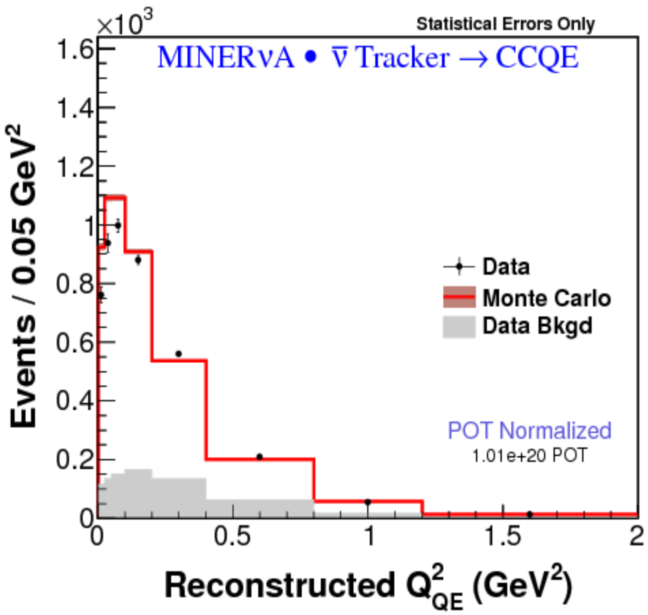


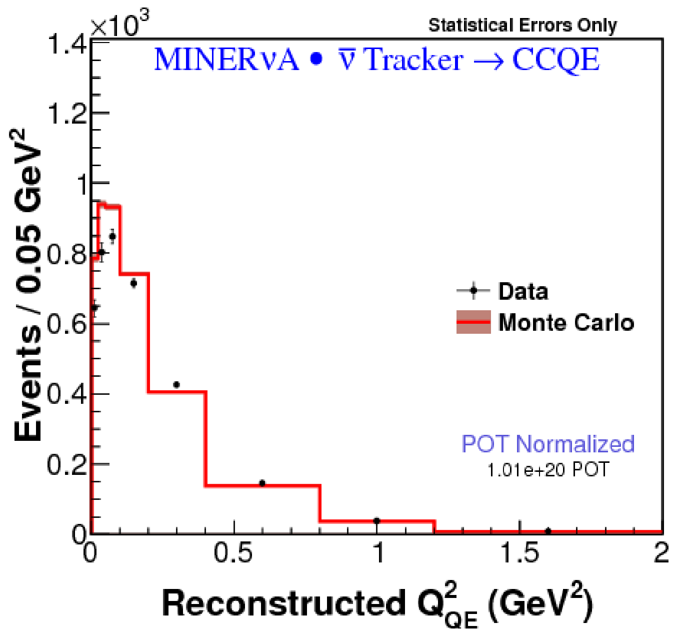
Anti-neutrino mode





Background substraction and Unfolding

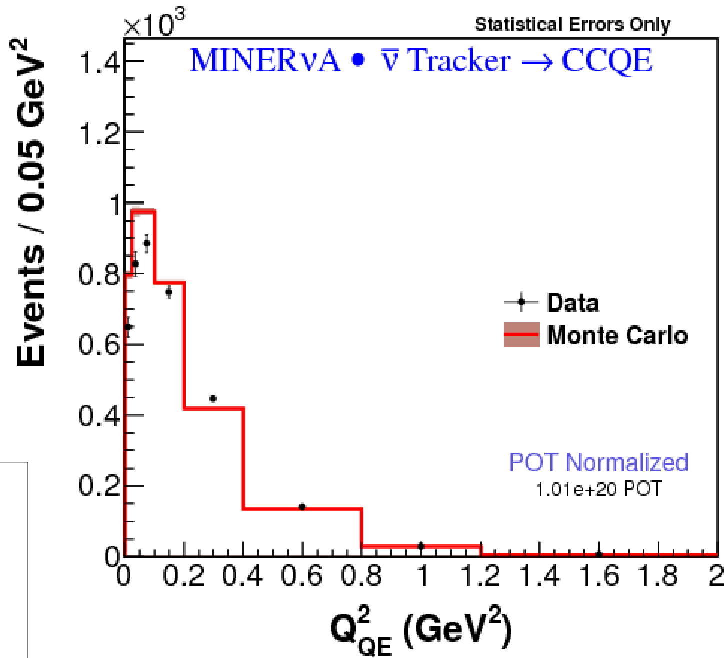




use data to estimate our backgrounds by performing a fraction fit of simulated signal and background recoil energy distributions from our Monte Carlo, in each of 4 Q2 bins

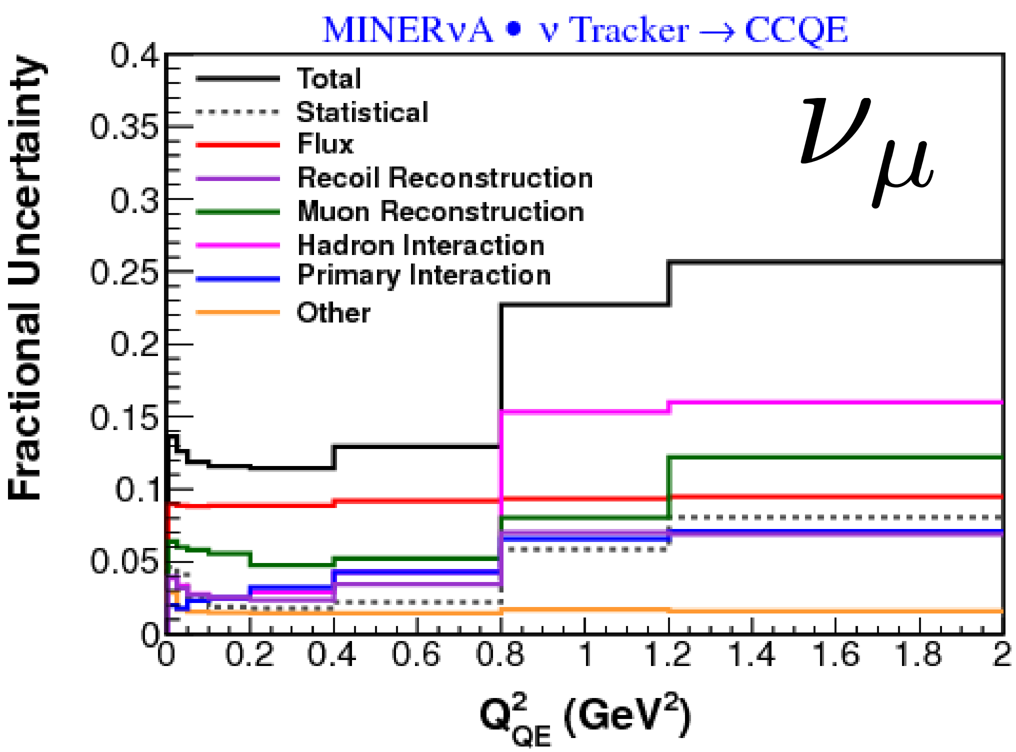
Backgrounds include events such as:

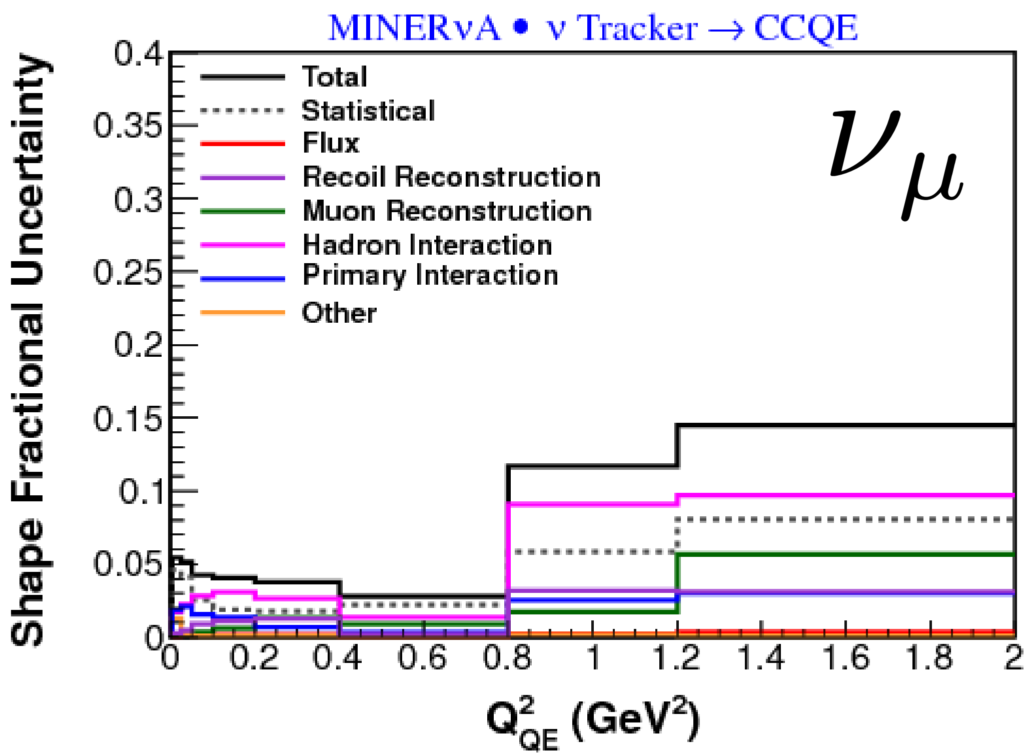
- QE-like resonant events, where the pion is absorbed
- QE-like deep-inelastic scattering events
- Other DIS or resonant events which are not removed by our cuts



- We use four iterations of a Bayesian unfolding method
- The unfolding maps reconstructed Q2QE to generated Q^2_{QE}

Error Summary:Neutrino Mode



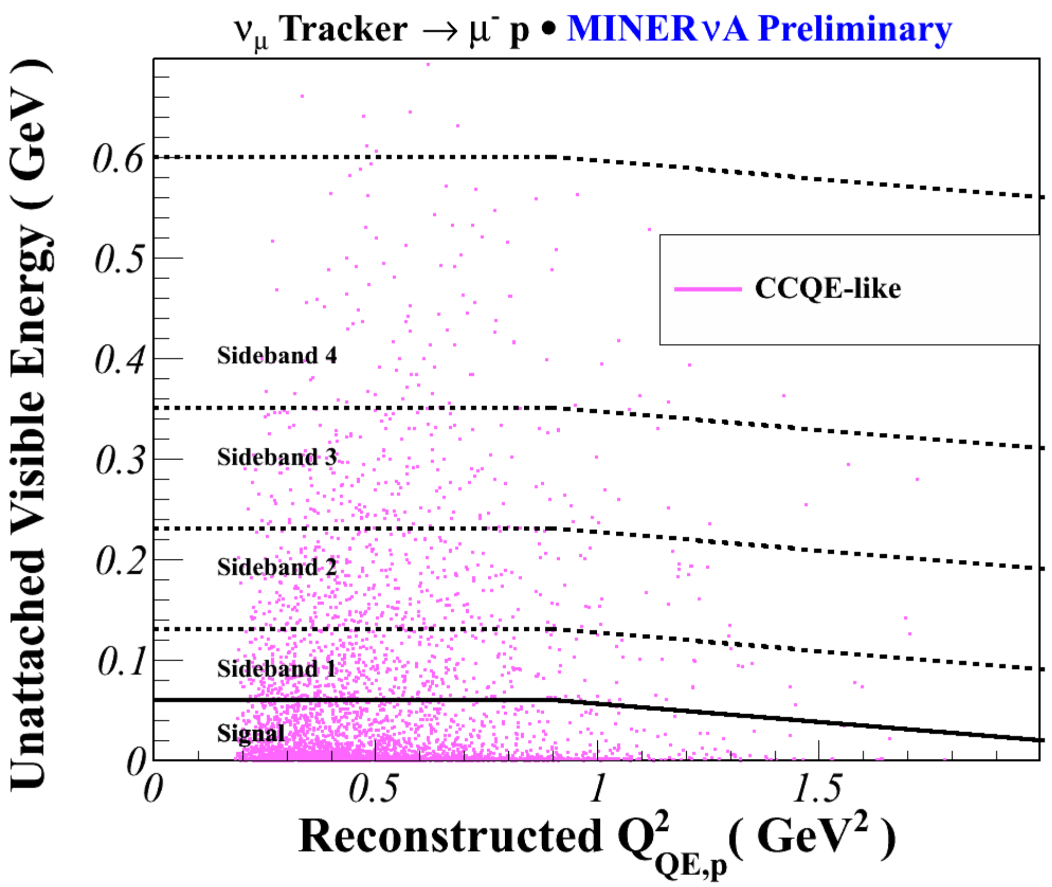


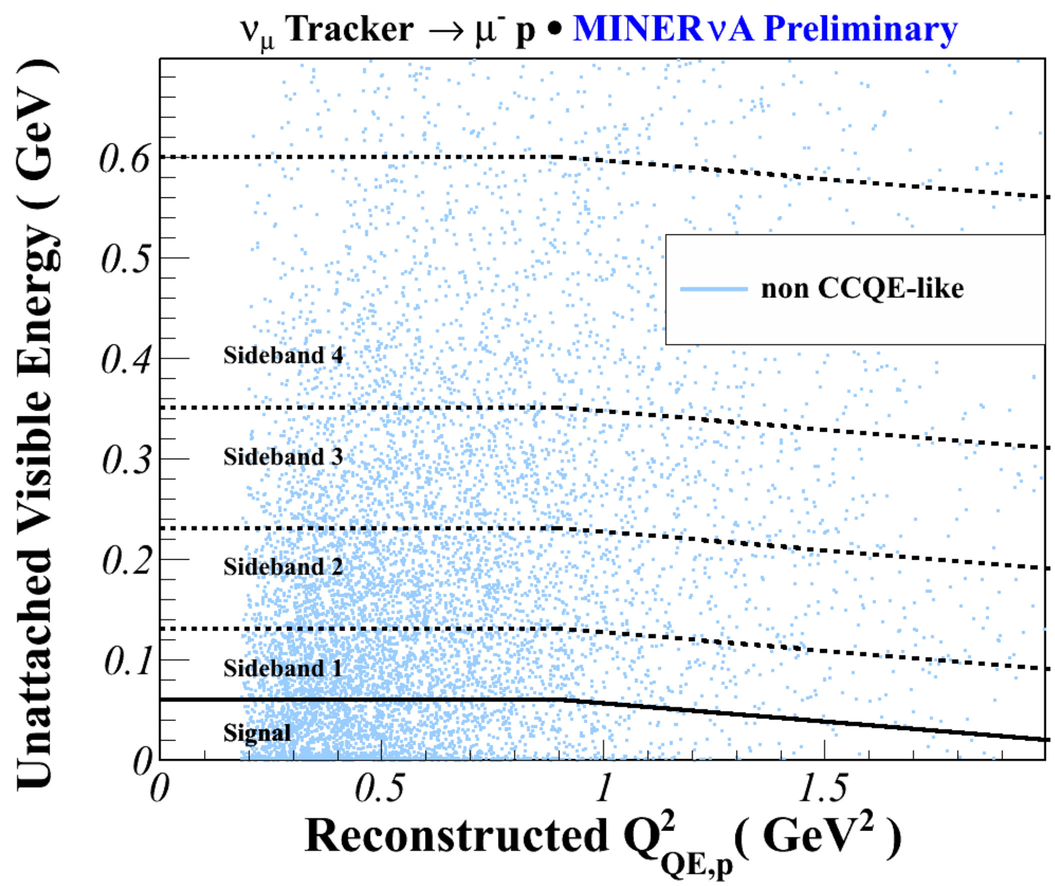
Absolute

Shape only

Background Substration

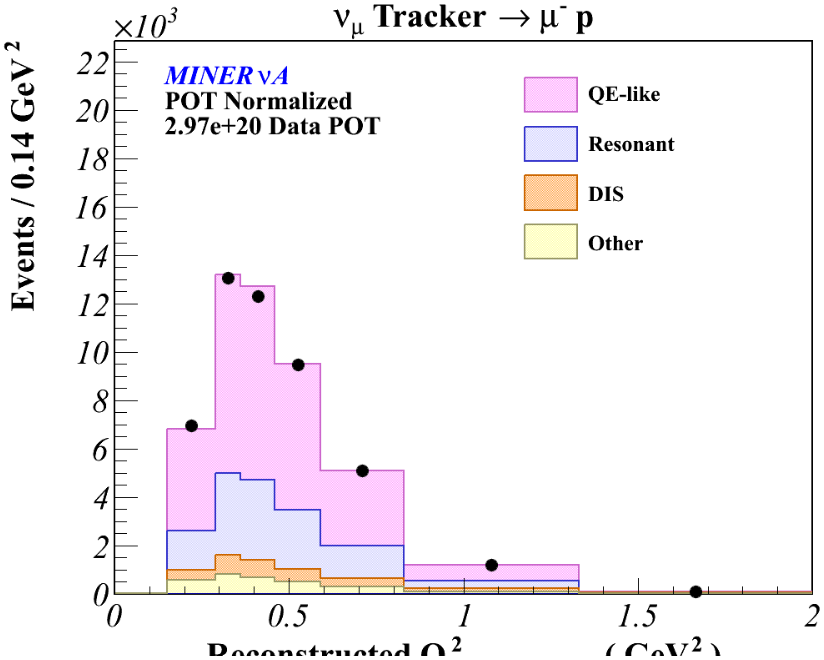
Sideband selection

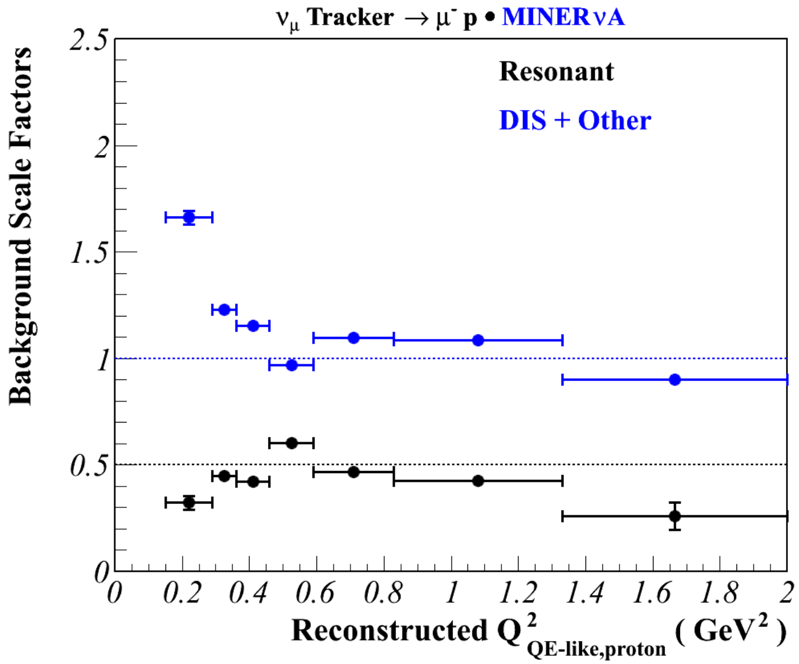




- Create 4 sidebands outside of signal region - separates the background into two components : Resonant (Δ ++ produces a pion) and DIS+Others
- Use a multi-sideband procedure to obtain the “two component” background scales

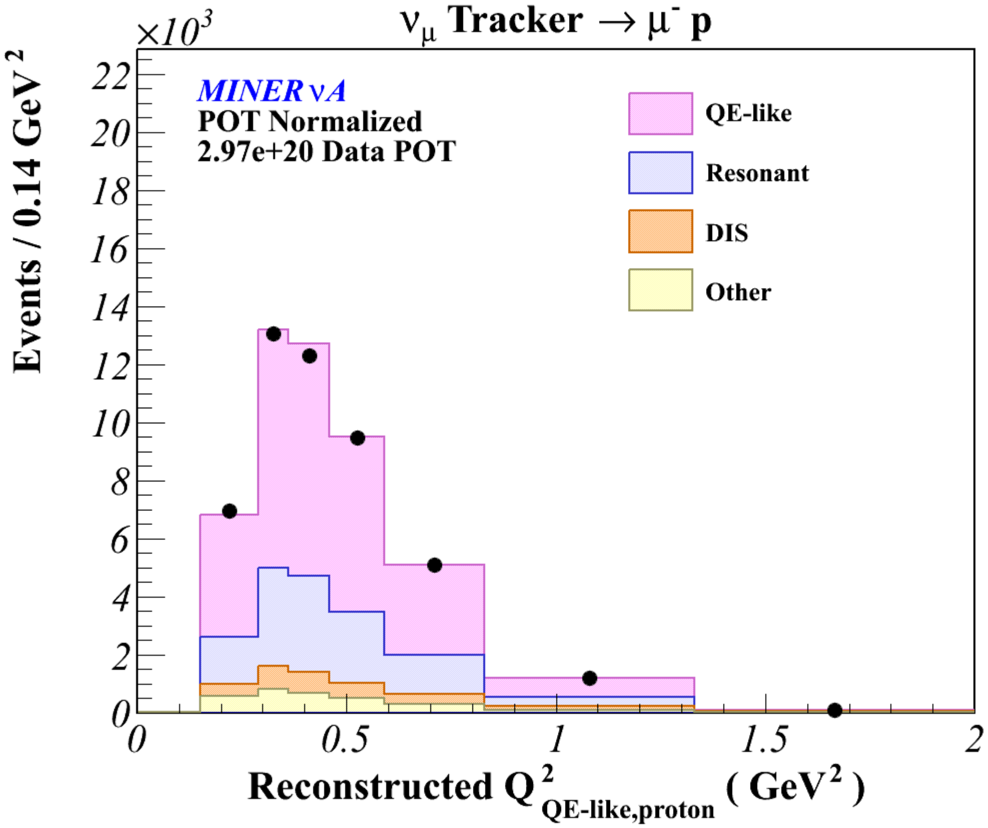
Background Subtraction





- Based on GENIE, majority of the backgrounds are from the Resonant and DIS productions.
- Use a data driven technique to constrain the two-component backgrounds.
  - *Resonant Production*
  - *DIS plus Other Production*
- Technique is a three step process, a multi-sideband bin-by-bin extrapolation procedure which extract scale factors to constrain the backgrounds.

CCQE-like candidates



40,102 candidate data events

The QE-like signal consists of:
QE = 71.7%
Res = 24.3%
DIS = 4.0%