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Muon Neutrino CCQE at MINERvA

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NuINT 2015, University of Osaka

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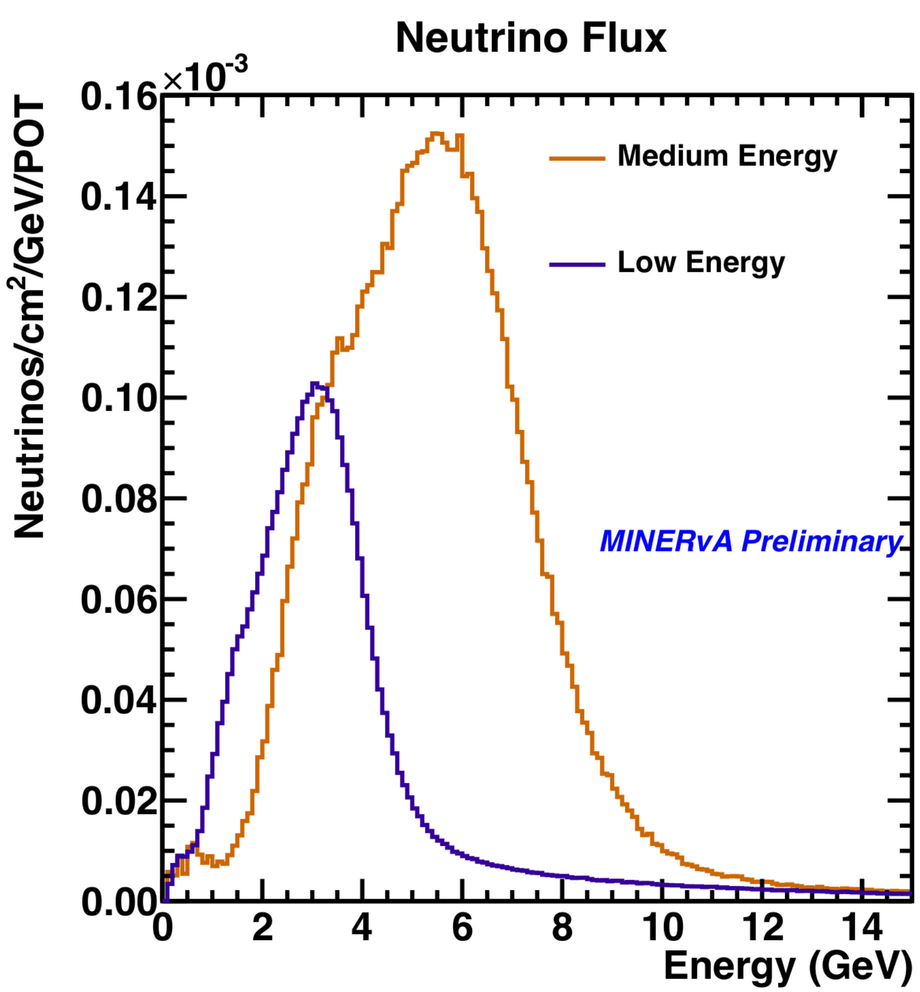
Introduction

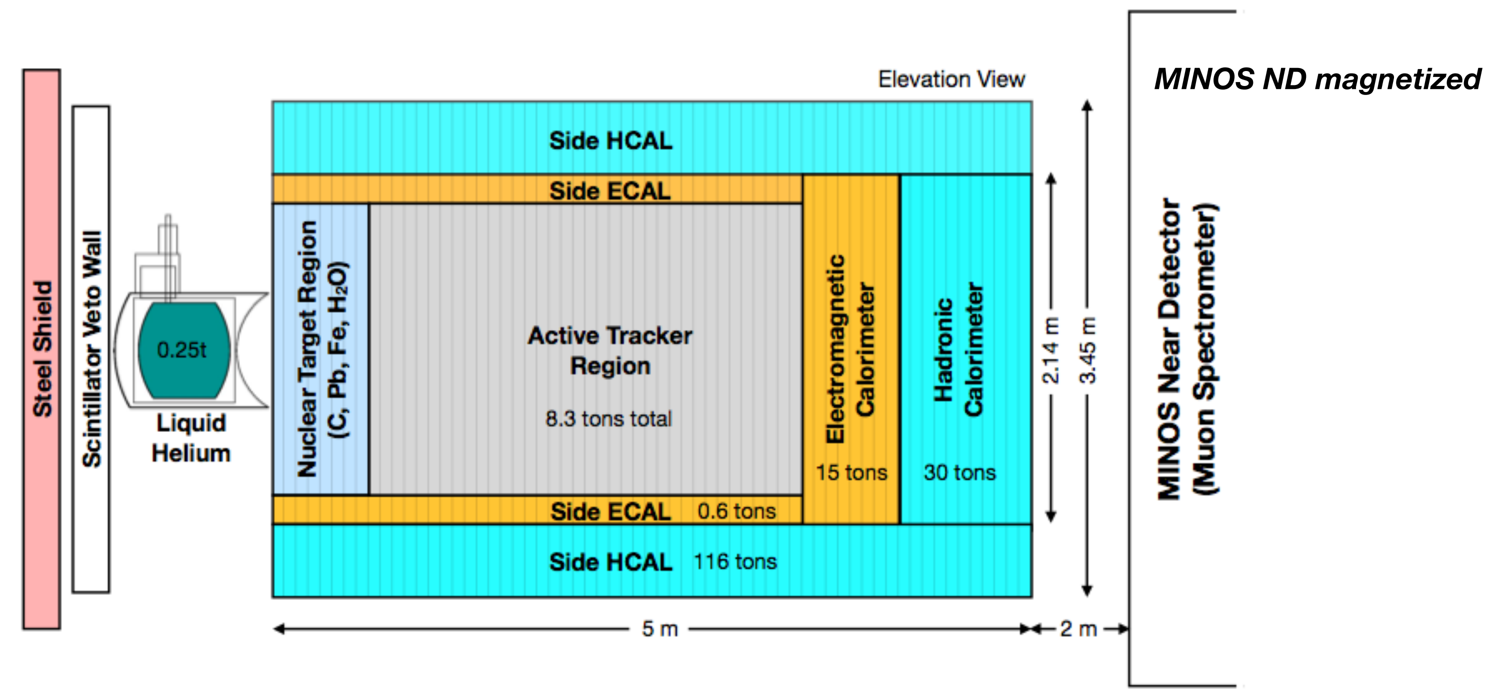
- We have a rich program for muon neutrino charged current quasi-elastic scattering (CCQE) in MINERvA
- Updates to the previous CCQE results with the new flux
- We have several analyses in progress:
  - Study of final state interactions (FSI) using muon plus protons with CCQE-like events for neutrinos
  - Double differential cross sections for neutrinos and antineutrinos
  - Starting to analyze the new medium energy neutrino beam
- Other CCQE talk from MINERvA:
  νe CCQE results by J. Wolcott, Identification of nuclear effects at low momentum transfer by P. Rodrigues

MINERvA Experiment

- MINERvA uses the NuMI beam



- Fine-grained scintillator surrounded by calorimeters



Design, calibration, and performance of the MINERvA detector

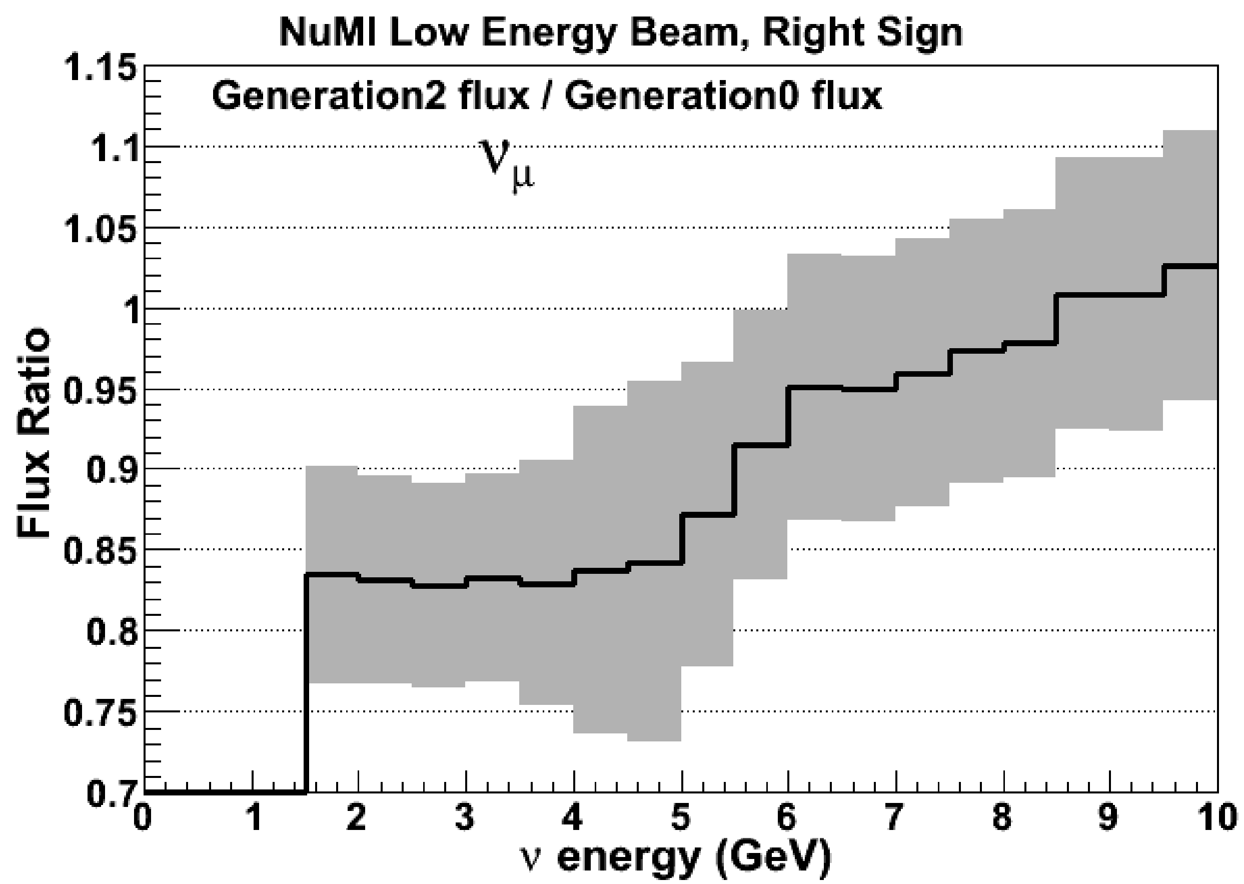
Nuclear Inst. and Methods in Physics Research, A, Volume 743, 11 April 2014, Pages 130-159

Currently running with medium energy spectrum

CCQE Measurements and the new Flux

- We have a new flux with improvements, main changes to beamline geometry and updates to the simulation (simulation has been constrained to hadron production data)

- Comparison of the new vs old flux for neutrinos (old flux=flux from 2013 publication)



Systematic uncertainties for the new flux are smaller

- An updated flux version from 2013 flux was used for the analyses shown in this talk, for details about the flux see Tomasz's talk from yesterday

Method to update the CCQE Measurements

- The differential cross section was measured using

$$\frac{d\sigma}{dQ^2}_i = \frac{(N_i - B_i)}{T\sum_j \Phi_j \epsilon_{ij}}$$

- Changes in the flux produces changes in the cross section

$$\frac{d\sigma}{dQ^2}_i^{new} = \frac{(N_i - B_i)}{T\sum_j \Phi_j^{new} \epsilon_{ij}} = \frac{d\sigma}{dQ^2}_i^{old} \frac{\sum_j \Phi_j^{old} \epsilon_{ij}}{\sum_j \Phi_j^{new} \epsilon_{ij}}$$

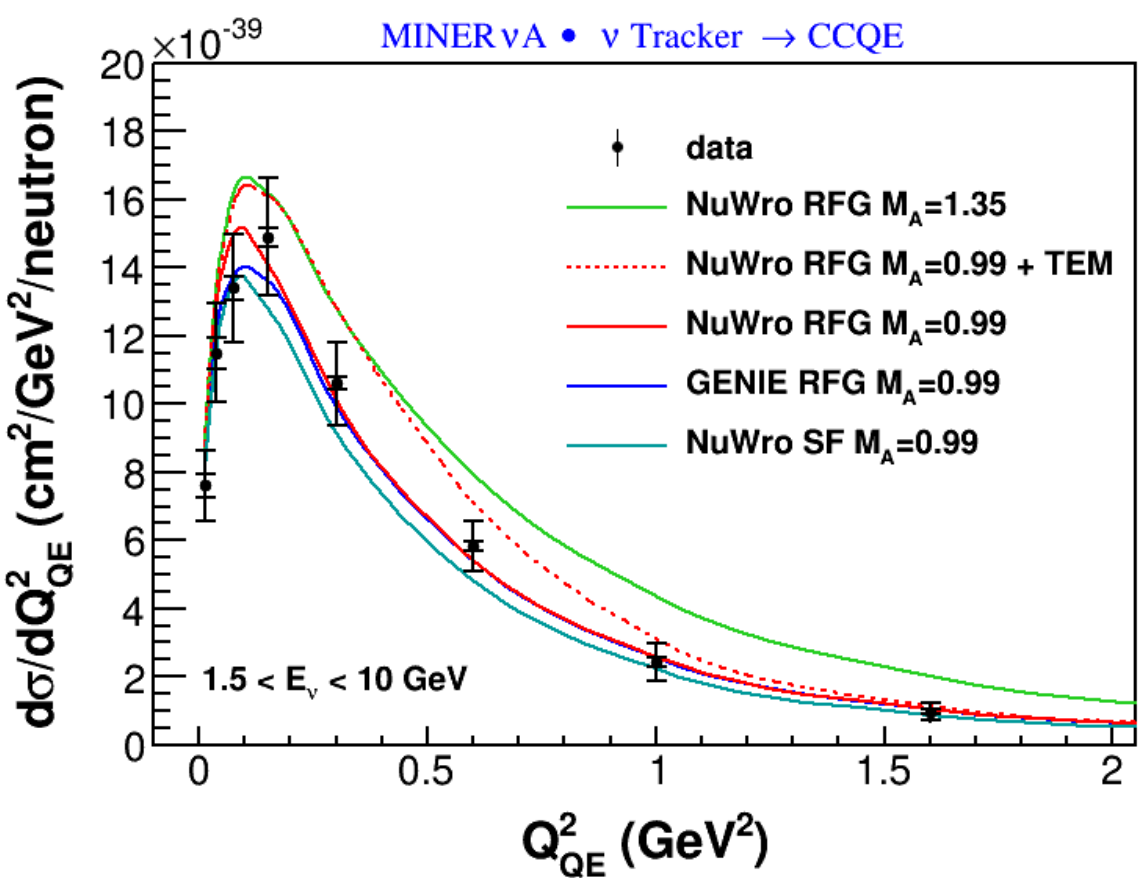
- We estimate factors like $\sum_j \Phi_j \epsilon_{ij}$ by taking the number of signal events for a given true flux bin and reconstructed Q^2 bin from the simulation

- Updates to the data only, change in the MC predictions should be small since the $d\sigma/dQ^2$ varies by <25% over the entire region of our acceptance flux, with the bulk of the change occurring below the flux peak

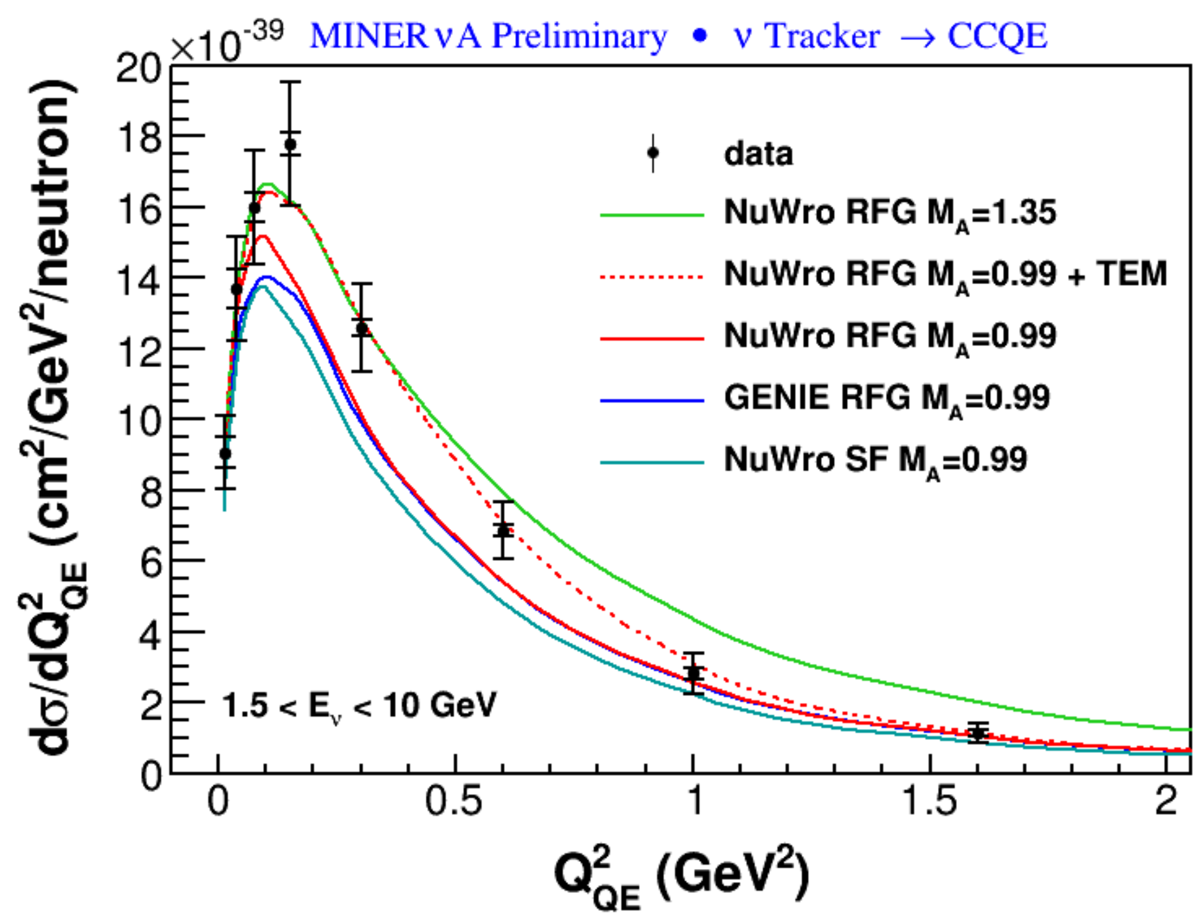
- Updates to the MC are underway

Single Differential Cross Section for Neutrinos

Phys. Rev. Lett. 111, 022501 (2013)



2013 Measurement with updated flux

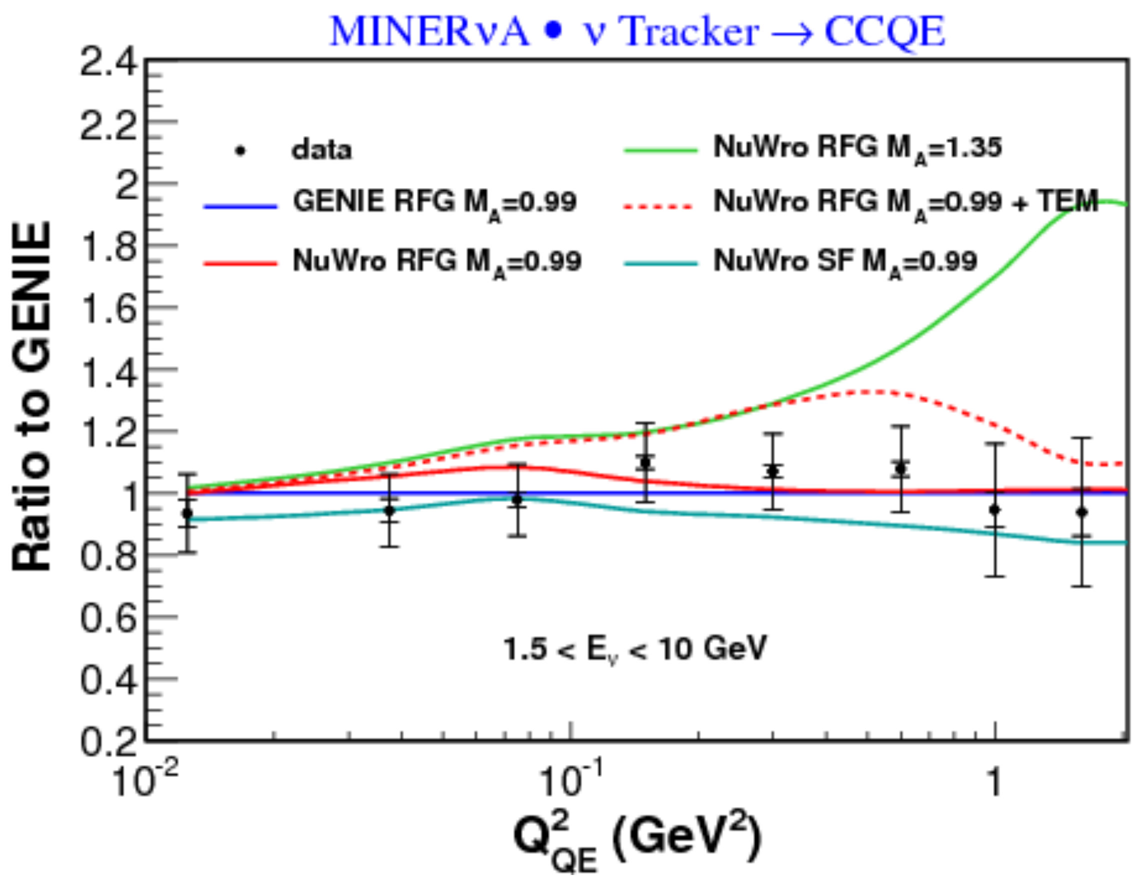


- Different event generators: GENIE and NuWro[+]
- Models:
  - Relativistic Fermi Gas (RFG), M_A=0.99GeV/c^2 (Model used by event generators) *
  - Relativistic Fermi Gas (RFG), M_A=1.35 GeV/c^2 (Higher MA motivated by recent measurements)**
  - Nuclear Spectral Function (SF), M_A=0.99 GeV/c^2 (More realistic model of the nucleon momentum) ***
  - Transverse Enhancement Model (TEM), M_A=0.99 GeV/c^2 (Empirical model tuned to electron-nucleon scattering data) ****

+ T. Golan, C. Juszczak, and J Sobczyk Phys.Rev. C85 (2012)
** R. Smith and E. Moniz, Nucl. Phys. B43, 605 (1972)*
***A. A. Agular-Arevalo, et al., Phys. Rev. D 81, 092005 (2010)*
**** O. Benhar, A. Fabrocini, S. Fanton, and I. Sick, Nucl. Phys. A579, 493 (1994)*
**** A. Bodek, H. Budd, and M. Christy, Eur.Phys.J. C71, 1726 (2011)

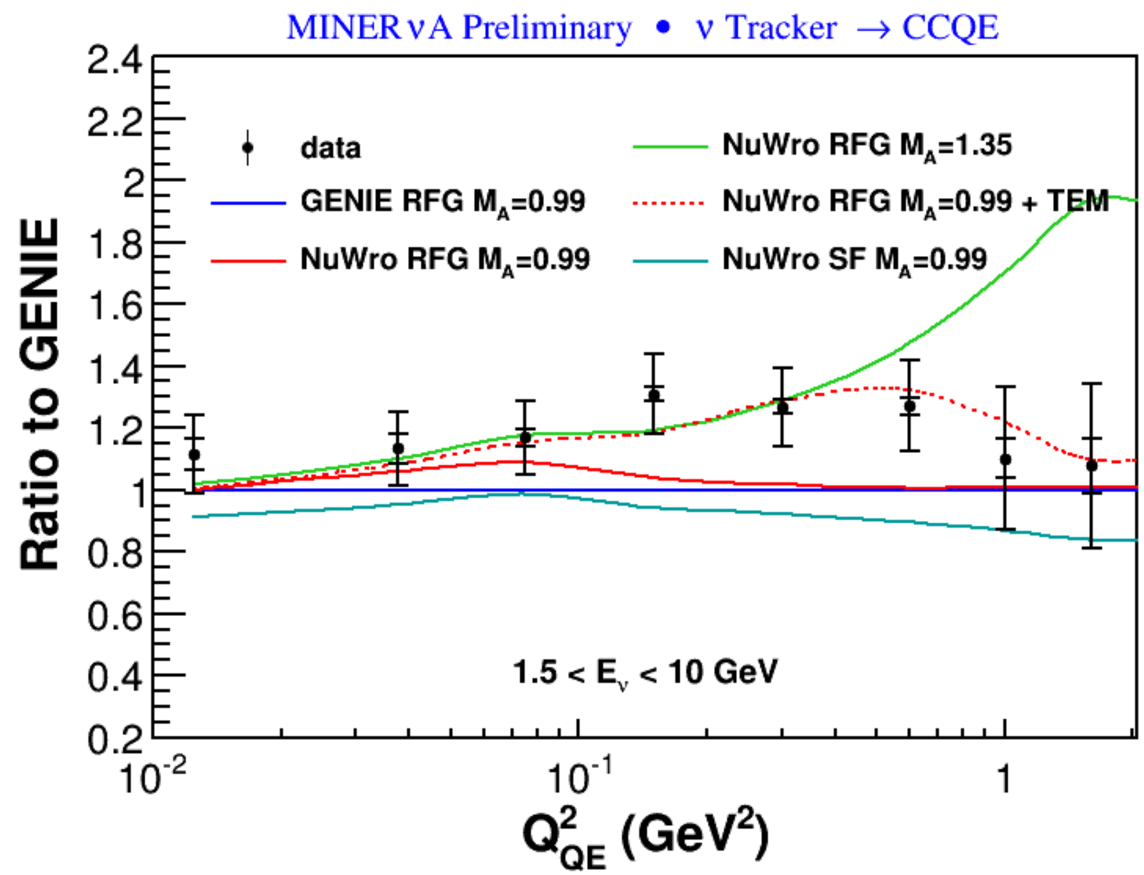
Single Differential Cross Section Ratios

Phys. Rev. Lett. 111, 022501 (2013)



Total cross section:
0.93±0.01(stat)±0.11(syst)x10^{-38}cm^2/neutron

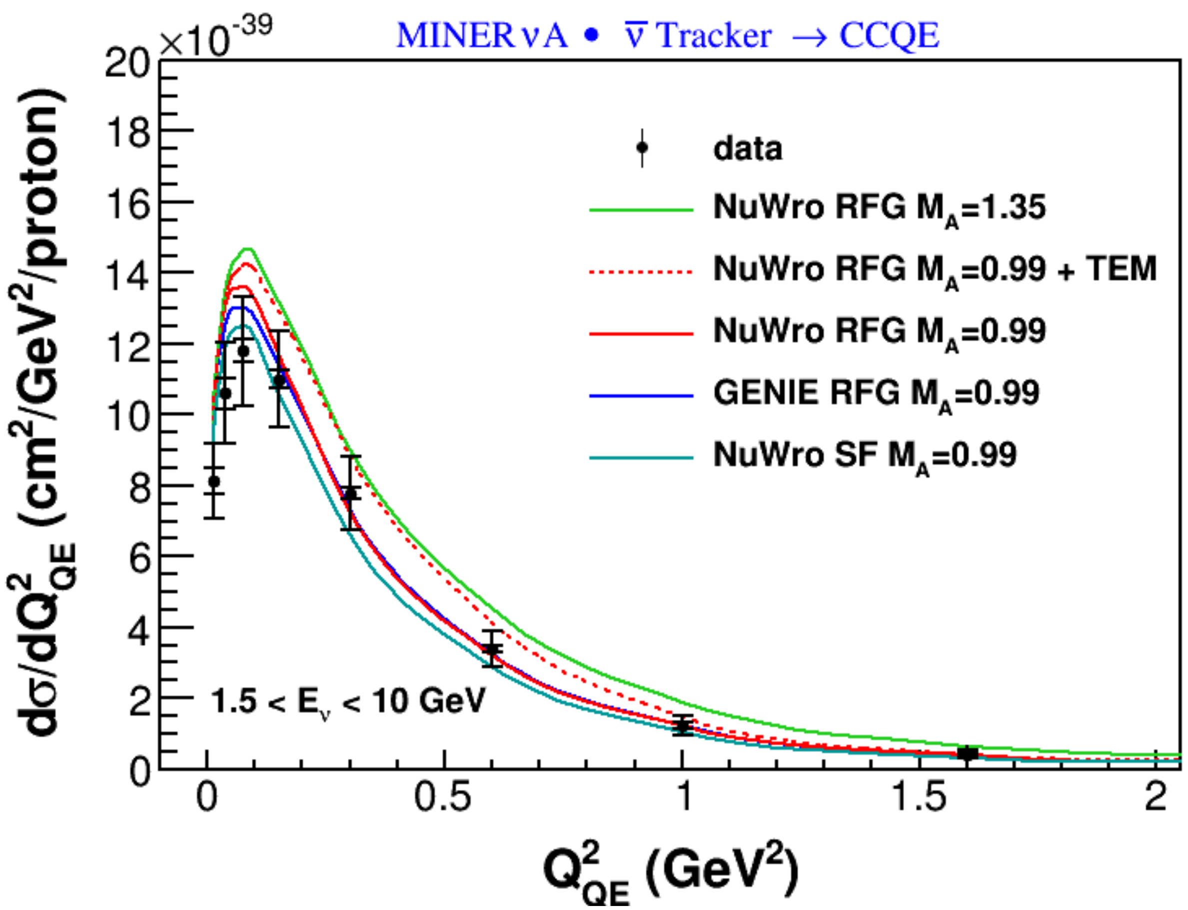
2013 Measurement with updated flux



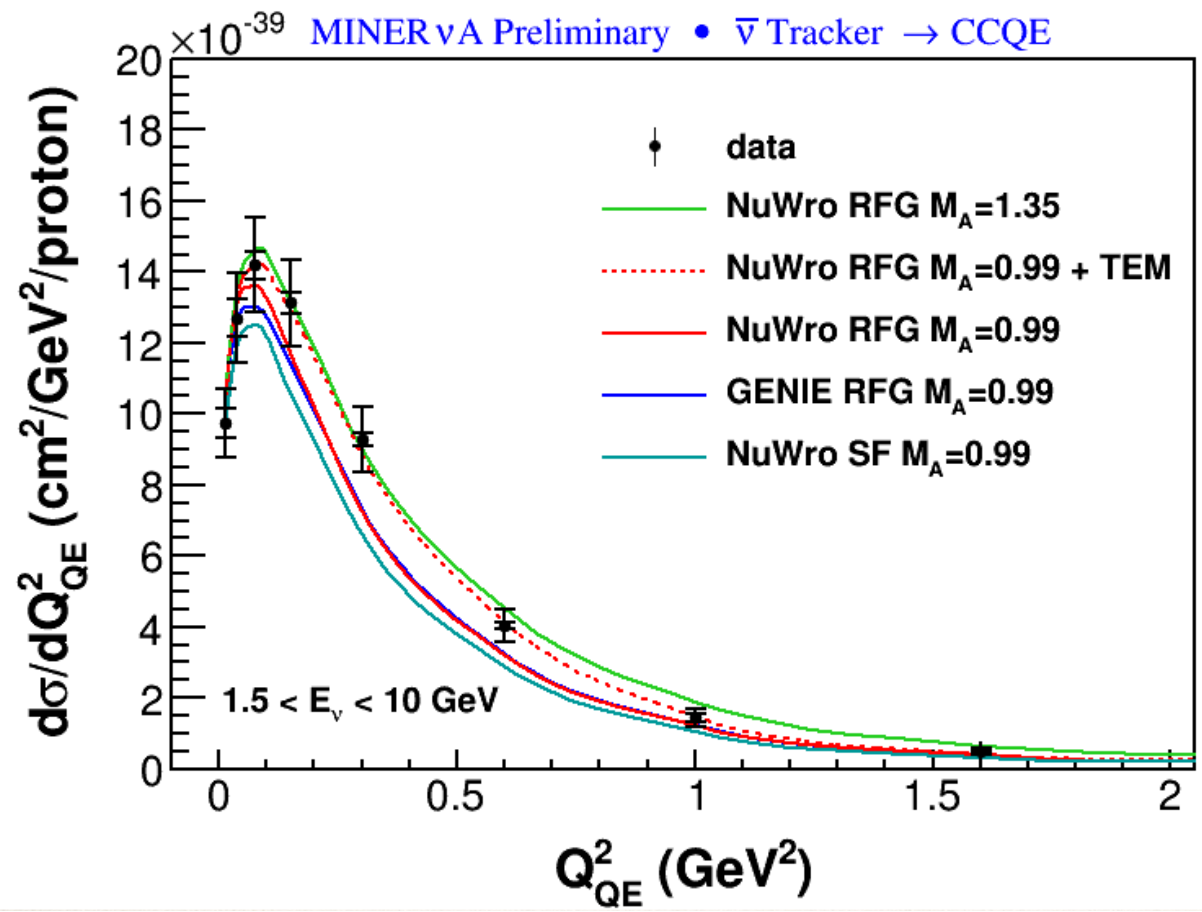
Total cross section:
1.10±0.01(stat)±0.13(syst)x10^{-38}cm^2/neutron

Single Differential Cross Section for AntiNeutrinos

Phys. Rev. Lett. 111, 022502 (2013)



2013 Measurement with updated flux



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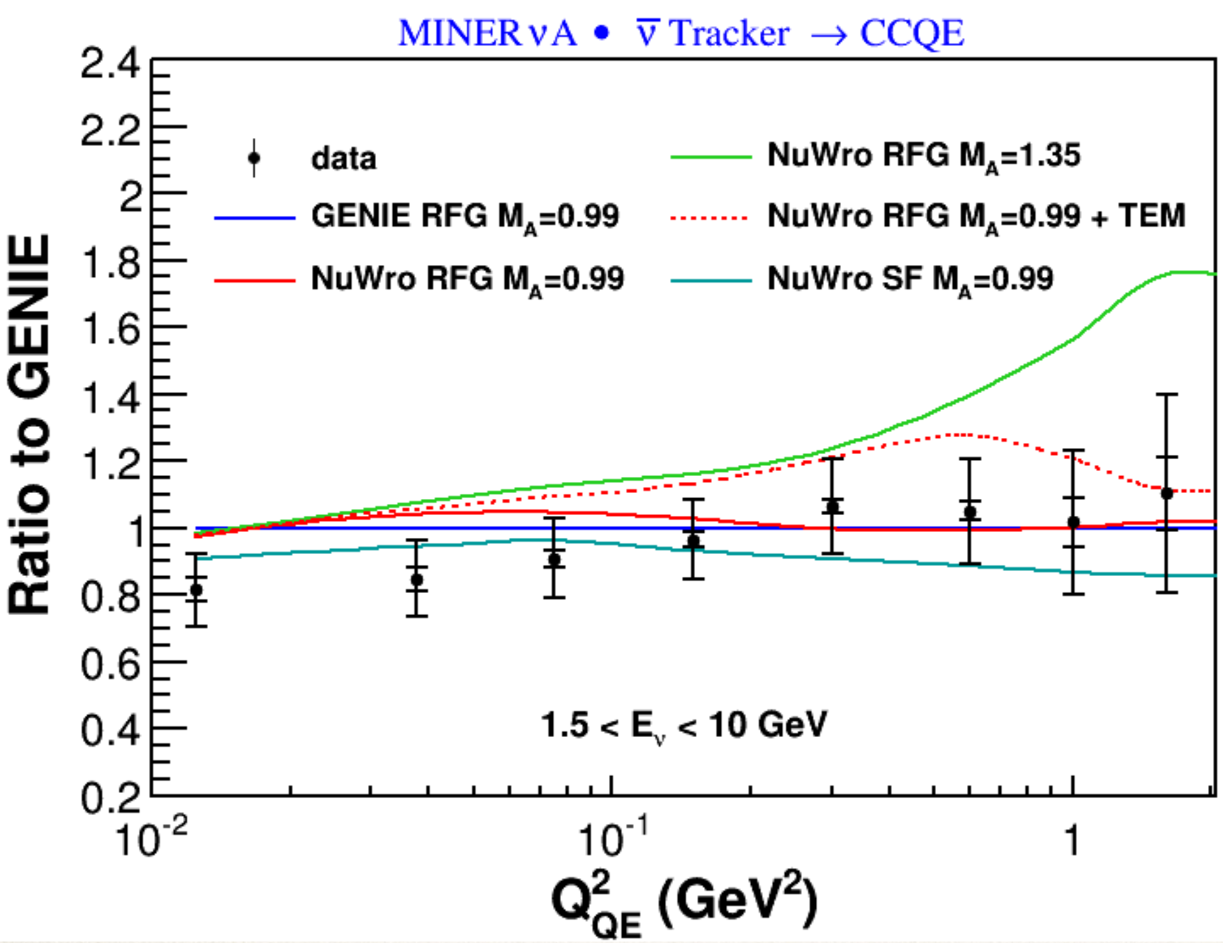
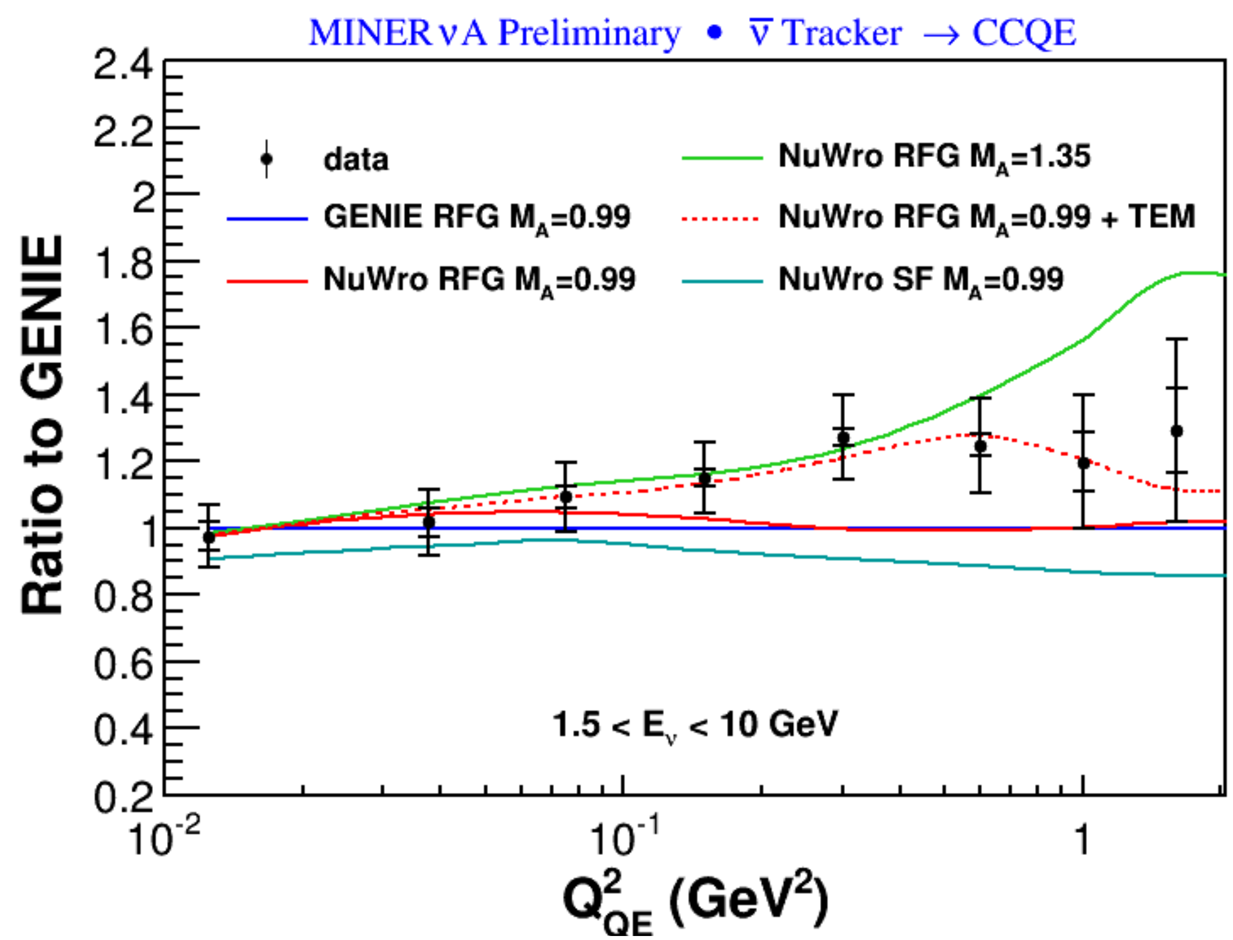
Single Differential Cross Section Ratios

Phys. Rev. Lett. 111, 022502 (2013)



Total cross section:
0.604±0.008(stat)±0.075(syst)x10^{-38}cm^2/neutron

2013 Measurement with updated flux



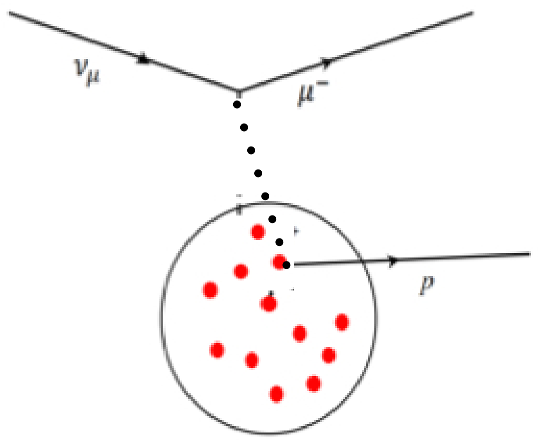
Total cross section:
0.719±0.010(stat)±0.089(syst)x10^{-38}cm^2/neutron

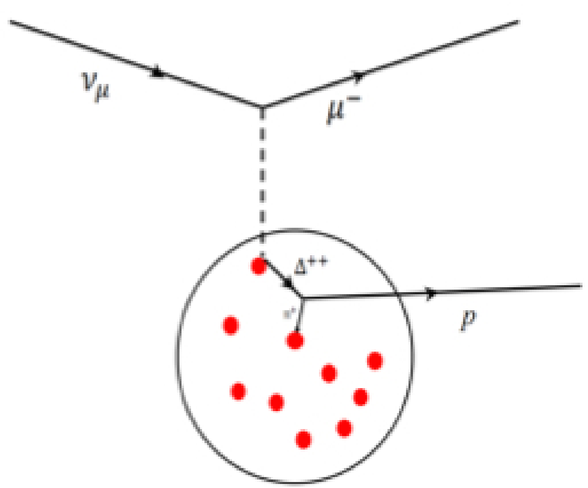
χ2 for ν and $\bar{\nu}$ and combined

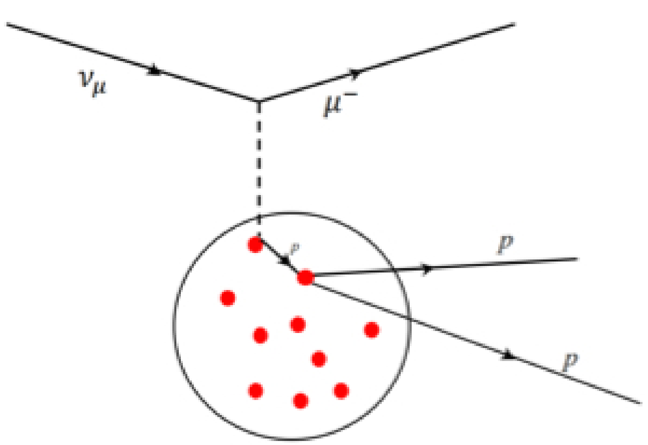
	Both Modes	Neutrinos	Antineutrinos
GENIE	40.5	27.6	24.0
$NuWro(M_A = 0.99)$	52.6	38.1	26.9
$NuWro(M_A = 1.35)$	56.8	50.9	25.4
$NuWro(M_A = 0.99)TEM$	26.8	21.1	7.6
$NuWro(M_A = 0.99)SLF$	44.8	39.5	27.8
$NuWro(M_A = 0.99)RPA$	101.8	109.8	39.6

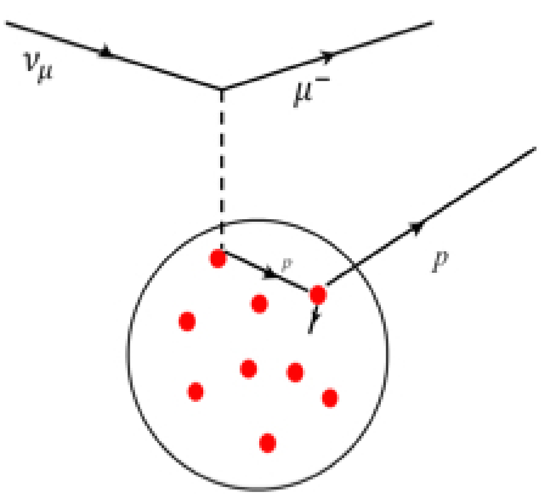
CCQE Signal Definitions

- **Old CCQE measurements:**
  - Signal is defined as an event in which the primary interaction is quasi-elastic (regardless of the final state particles)
  - Incoming (anti) neutrino energy between 1.5 and 10 GeV
- **New definition for future CCQE measurements:**
  - Signal is defined as CCQE-like, no pions in the final state
  - No cut on the neutrino energy
- **Why do we change the definitions?** CCQE-like is more clearly defined from an experimental point of view, depends less on the models









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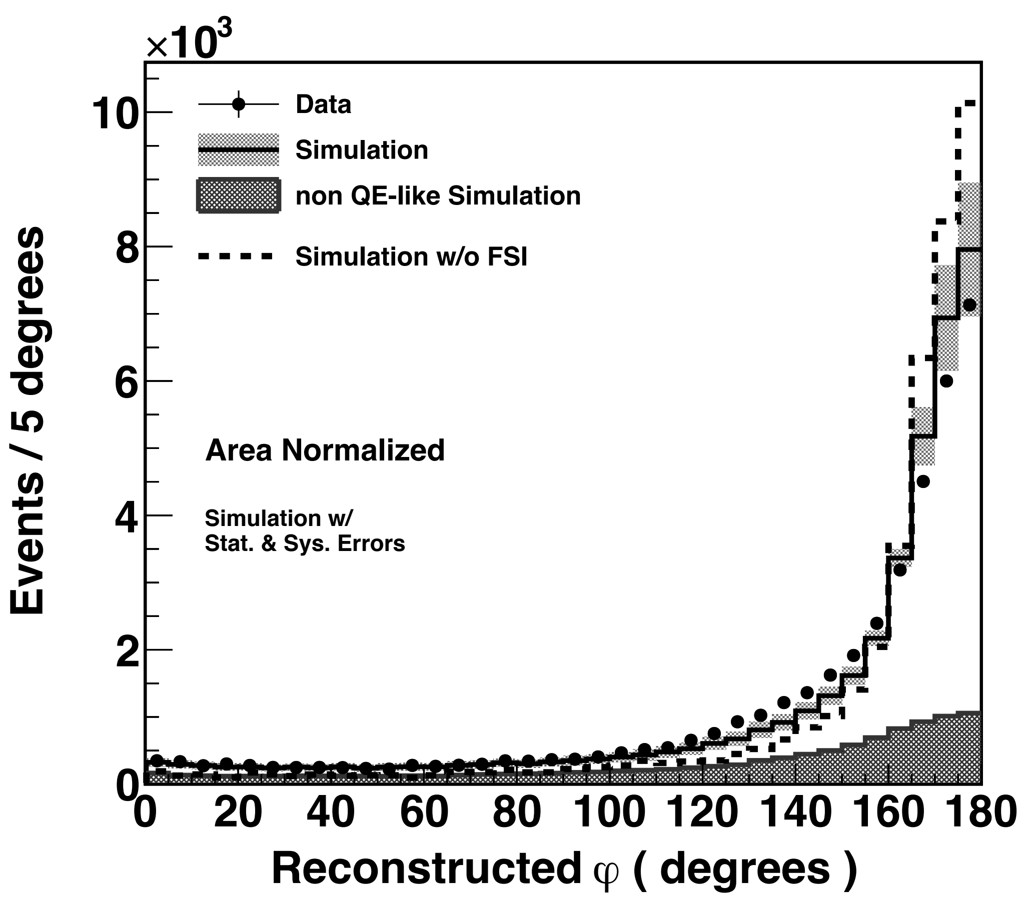
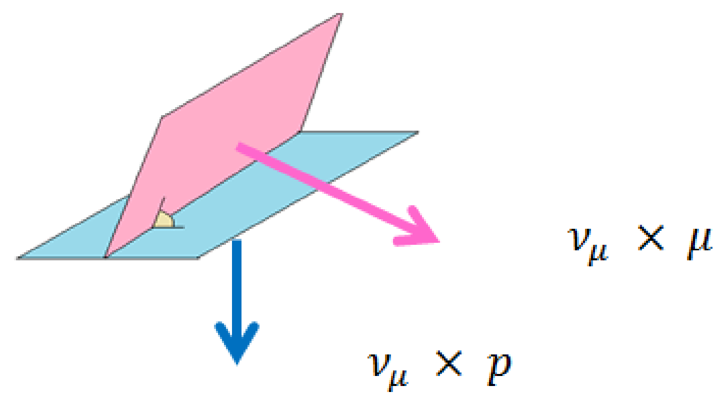
Studying Final State Interactions using CCQE-like

- We have a CCQE-like sample with selected protons and one muon, published early this year, Phys. Rev. D 91 (2015)
- We are studying the different regions of the coplanarity angle, the angle between the ν -muon and ν -proton planes
  - From 0 to 110˚, from 110˚ to 160˚, and from 160˚ to 180˚

coplanarity angle



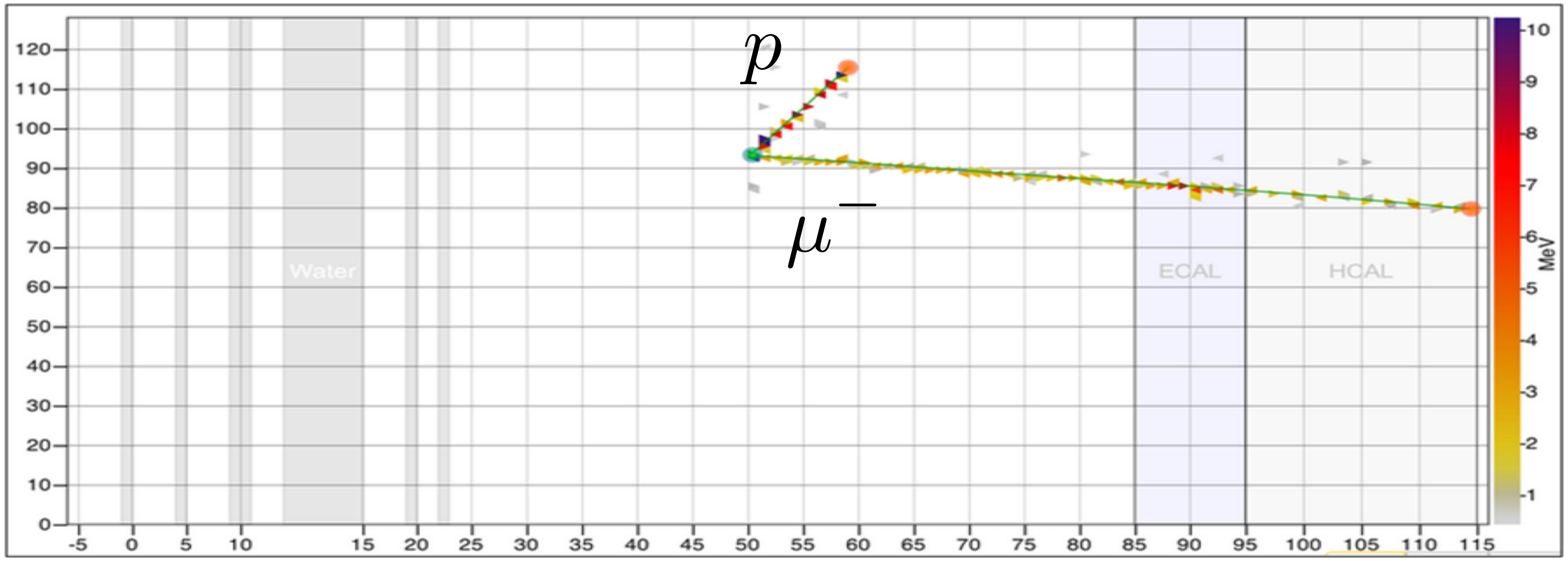
Phys. Rev. D 91 (2015) 7, 071301



$$\varphi = \cos^{-1}\left(\frac{(\hat{\mathbf{p}}_\nu \times \hat{\mathbf{p}}_\mu) \cdot (\hat{\mathbf{p}}_\nu \times \hat{\mathbf{p}}_p)}{|\hat{\mathbf{p}}_\nu \times \hat{\mathbf{p}}_\mu||\hat{\mathbf{p}}_\nu \times \hat{\mathbf{p}}_p|}\right)$$

Event Selection

- Select events with two or more tracks, where one track is the muon and the other tracks are protons
- Signal is defined as CC-QE like:
  - One negatively charged muon
  - At least one proton with momentum greater than 450 MeV/c
  - No pions



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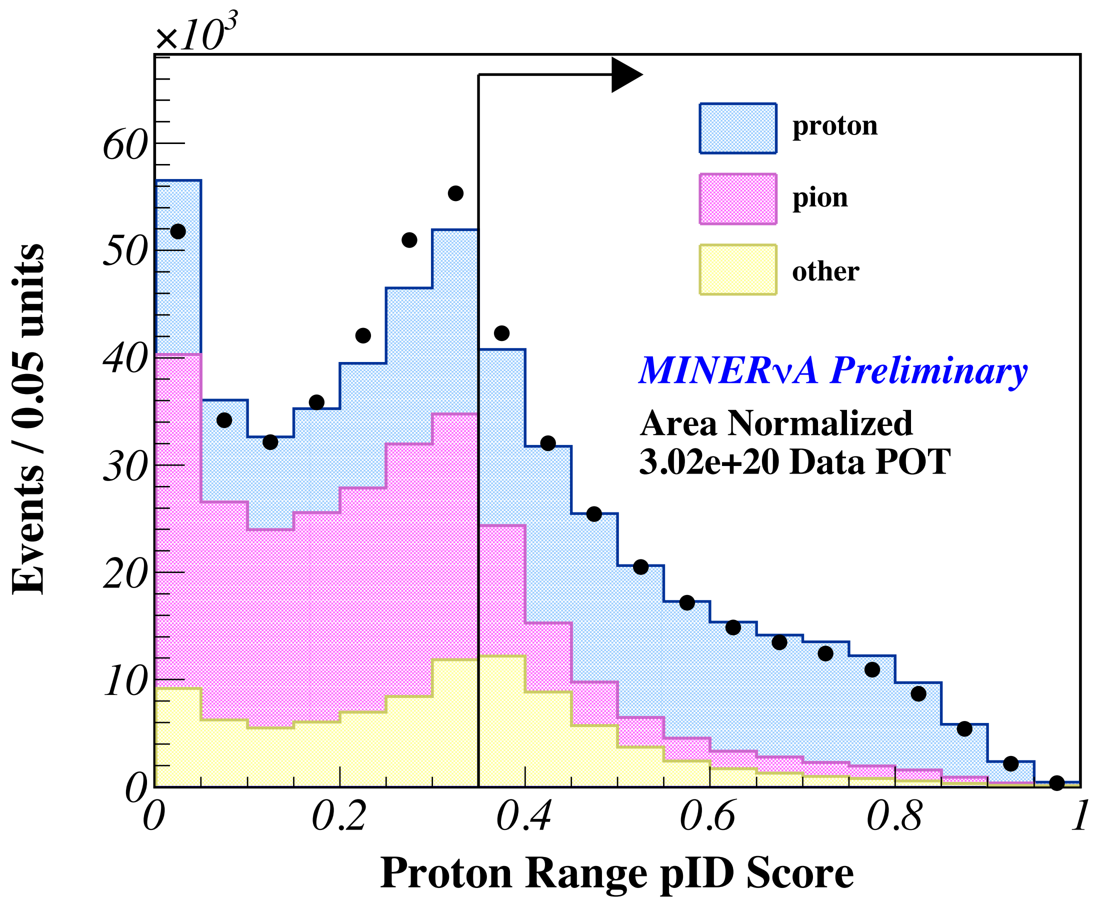
Identifying the Protons

- Requires the hadrons to look like protons
- Fit each hadron track energy loss, dE/dx profile, to standard proton and pion energy loss for templates
- Uses the chi2/d.o.f values from both the pion and proton fits to create a score and momentum, requires pID score >0.35



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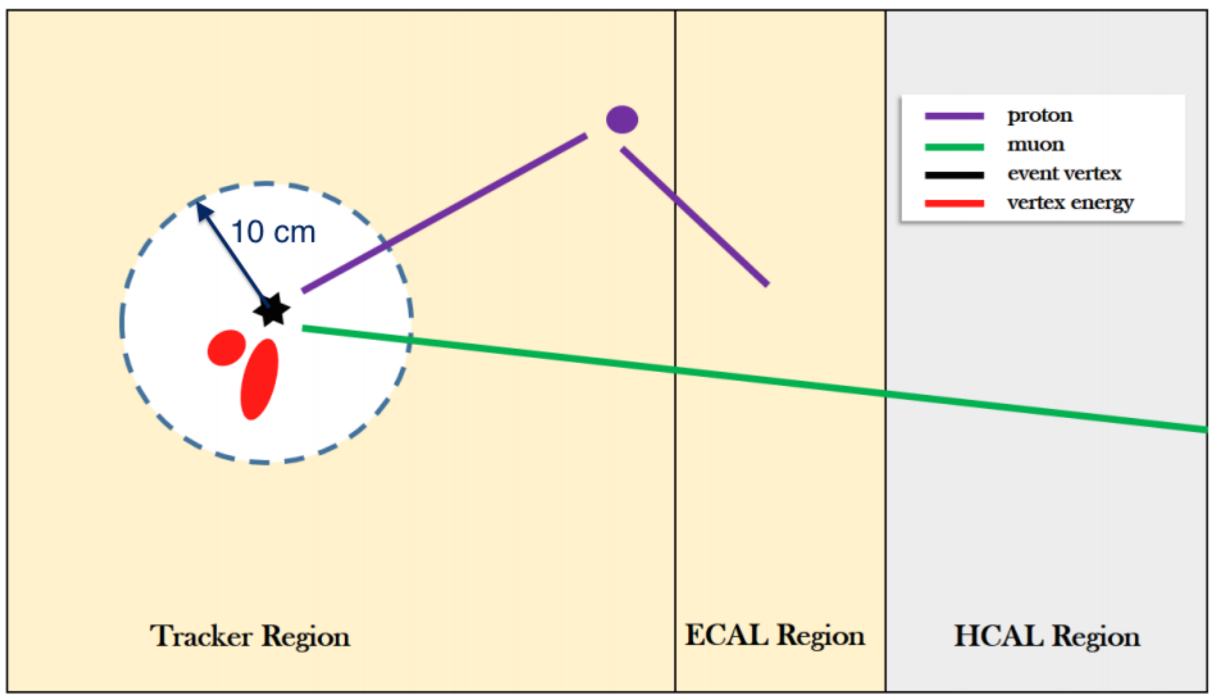
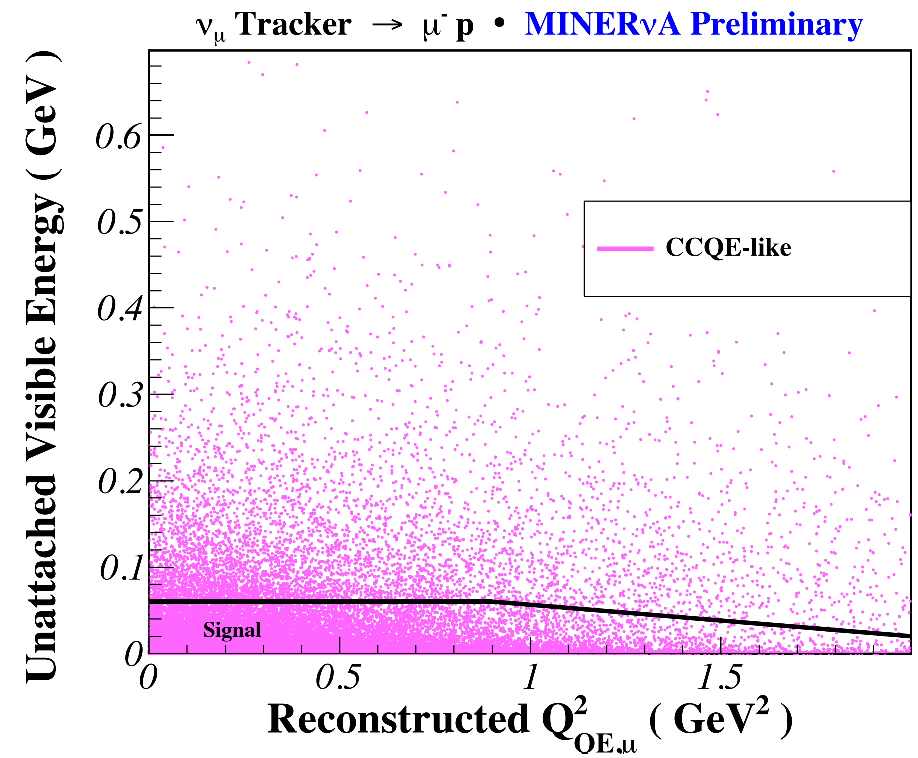
Removing Background Events

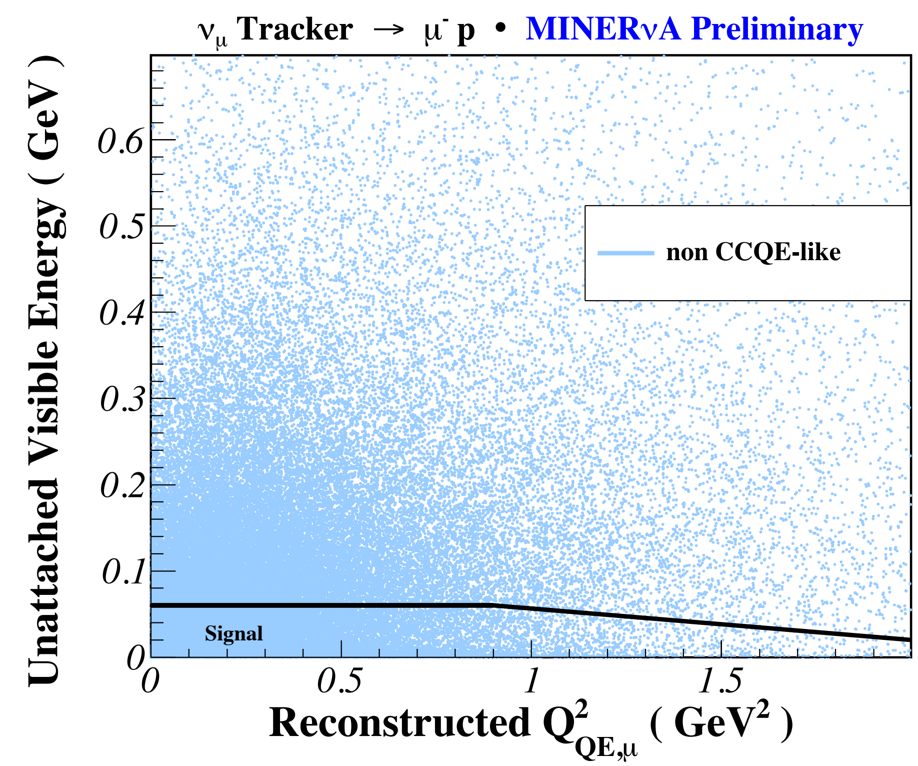
- Large amounts of extra energy, not associated with the muon or proton, usually come from untracked particles
- Define an unattached visible energy, energy outside 10 cm



- Requires the unattached energy versus the 4-momentum transfer QE scattering using the muon kinematics

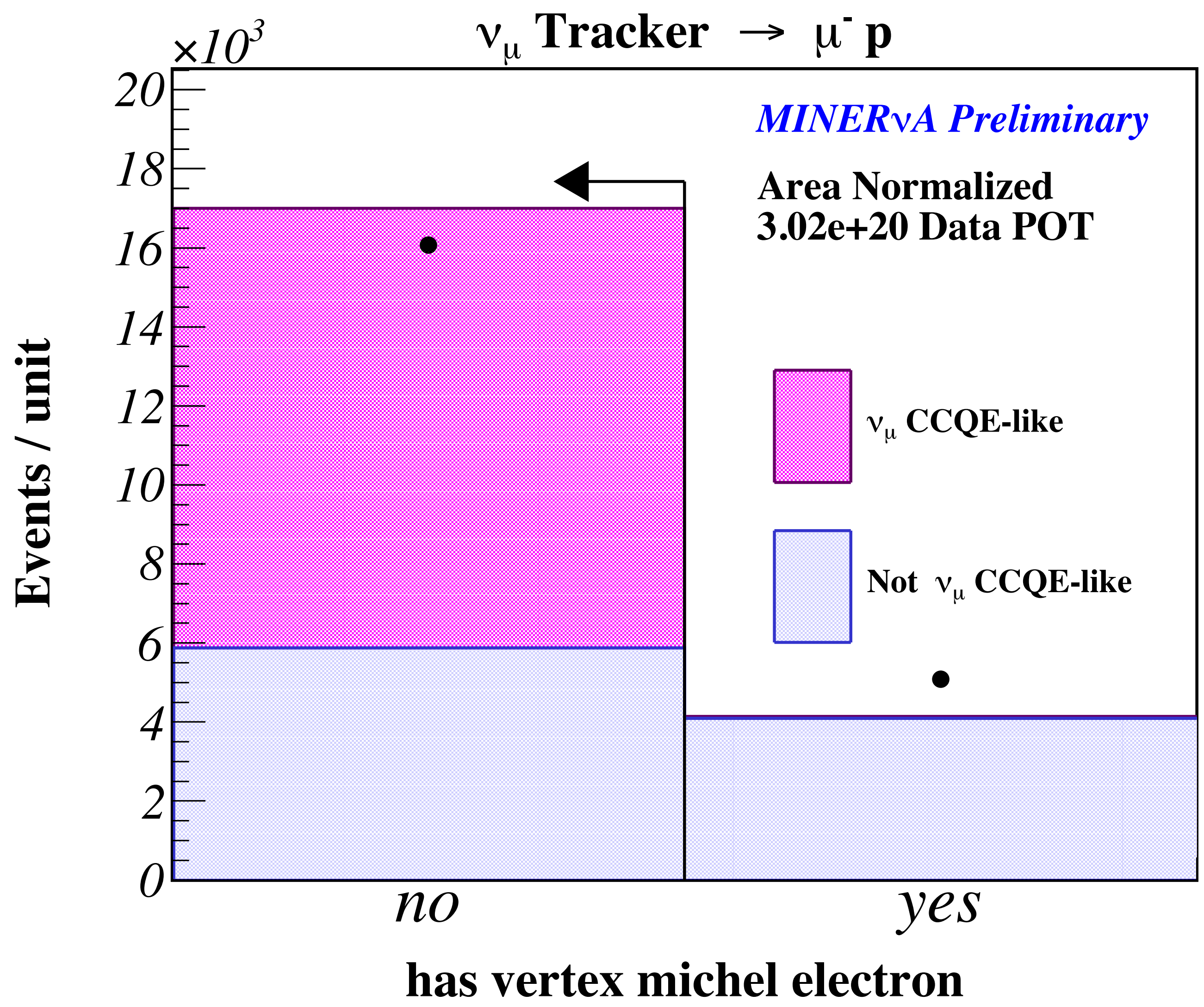
$$Q^2_{QE} = 2E_{\nu,QE}(E_\mu - p_\mu cos\theta_\mu) - m_\mu^2$$





Michel Electron Veto

- Removes the events with a Michel electron near the interaction vertex, events from low energy pions that stop and decay in the detector



$$\pi^{\mp} \rightarrow \mu^{\mp} + \nu_\mu(\bar{\nu}_\mu)$$

$$\mu^- \longrightarrow e^- \bar{\nu}_e \nu_\mu$$

$$\mu^+ \longrightarrow e^+ \nu_e \bar{\nu}_\mu$$

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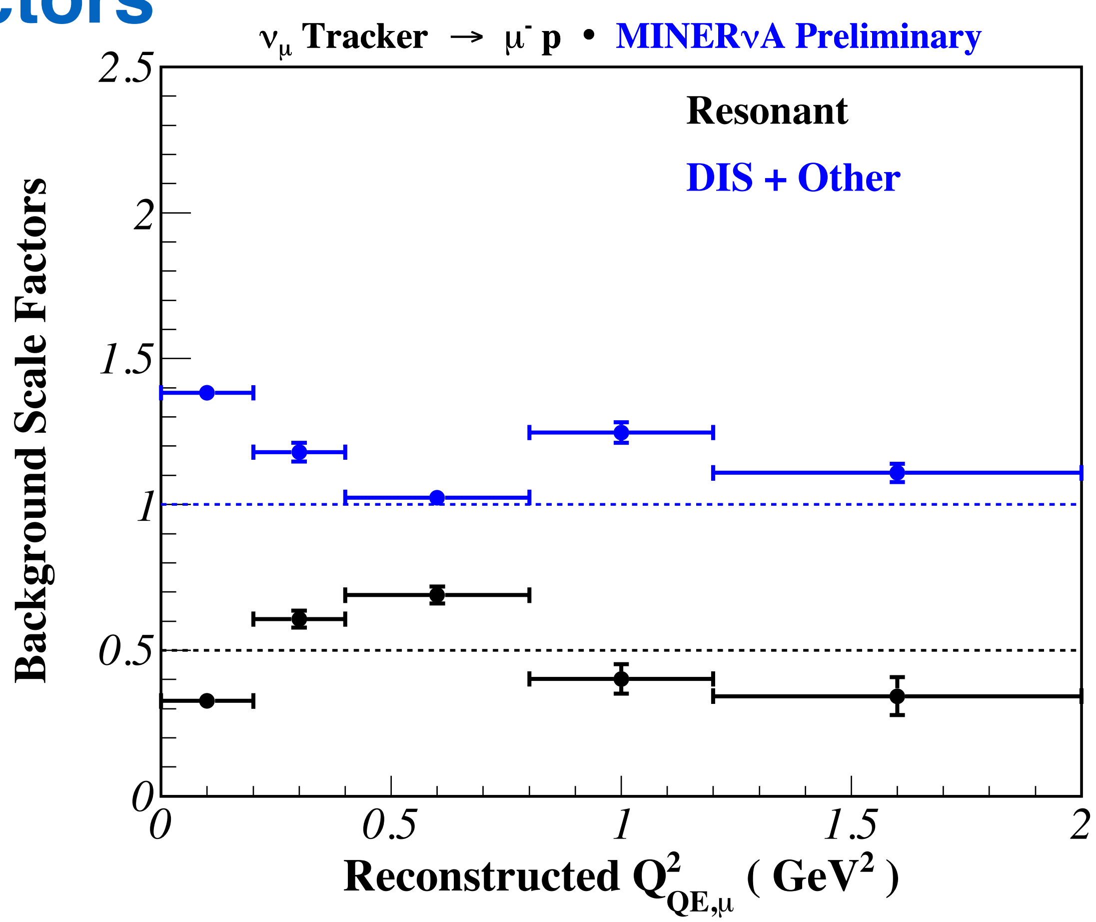
Tuning the Background

- Backgrounds are constrained using a multi-sideband technique
  - Use data to tune the background and select different sidebands outside the signal region
  - The fit extracts scale factors for Resonant and DIS plus other interactions

Background Scale Factors



- GENIE overestimates the Resonant production

Definition of the Observables to study FSI

- Vertex energy inside a box of 20 cm
  - Excluding the energy of the muon
- Measured minus expected proton momentum

$$\Delta P = P_{measured} - P_{Expected}$$

where $P_{Expected}(E_\nu, E_\mu)$ is obtained from the muon kinematics

- Neutrino energy (proton, muon) minus neutrino energy from QE hypothesis $E_\nu - E_{\nu,QE}$

$$E_\nu = E_\mu + T_p + BE$$

BE=binding energy

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

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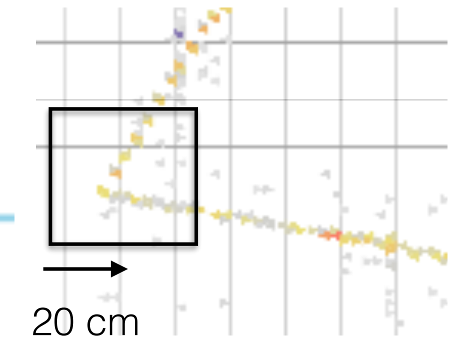
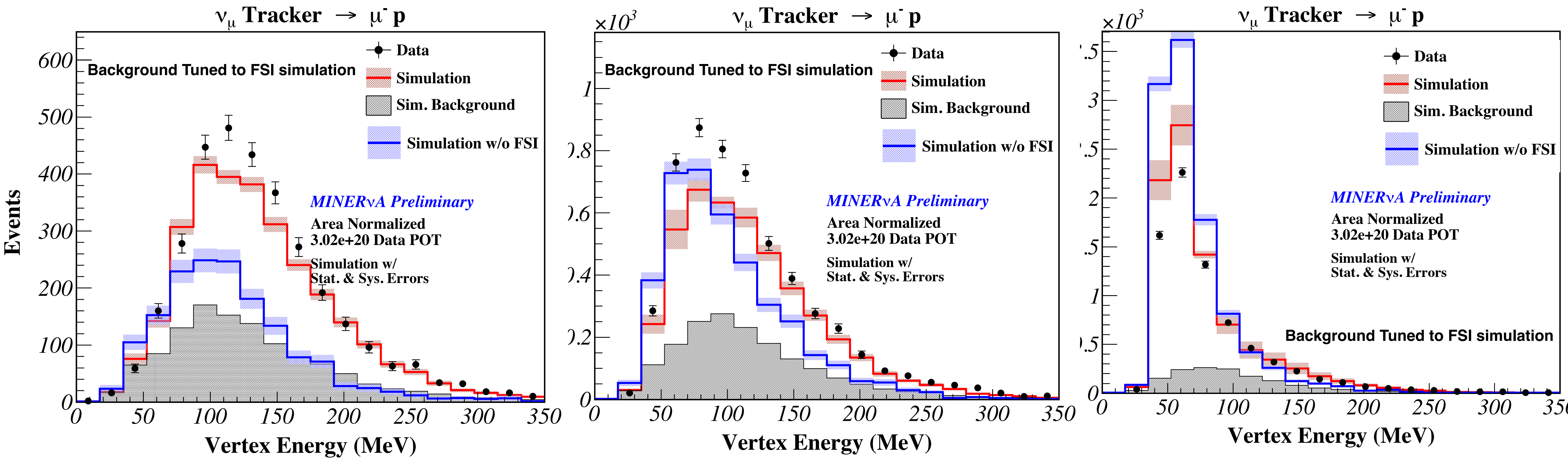
Vertex Energy



- Energy inside a box in slices of coplanarity angle, energy from the muon has been removed

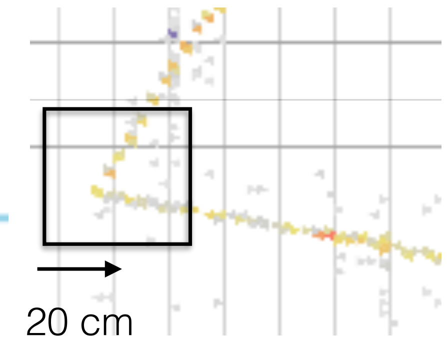


Distributions normalized to a common normalization for the entire φ range

$0 < \varphi < 110$ $110 < \varphi < 160$ $160 < \varphi < 180$

Background for FSI has been tuned and simulation w/o FSI has not been tuned

Vertex Energy



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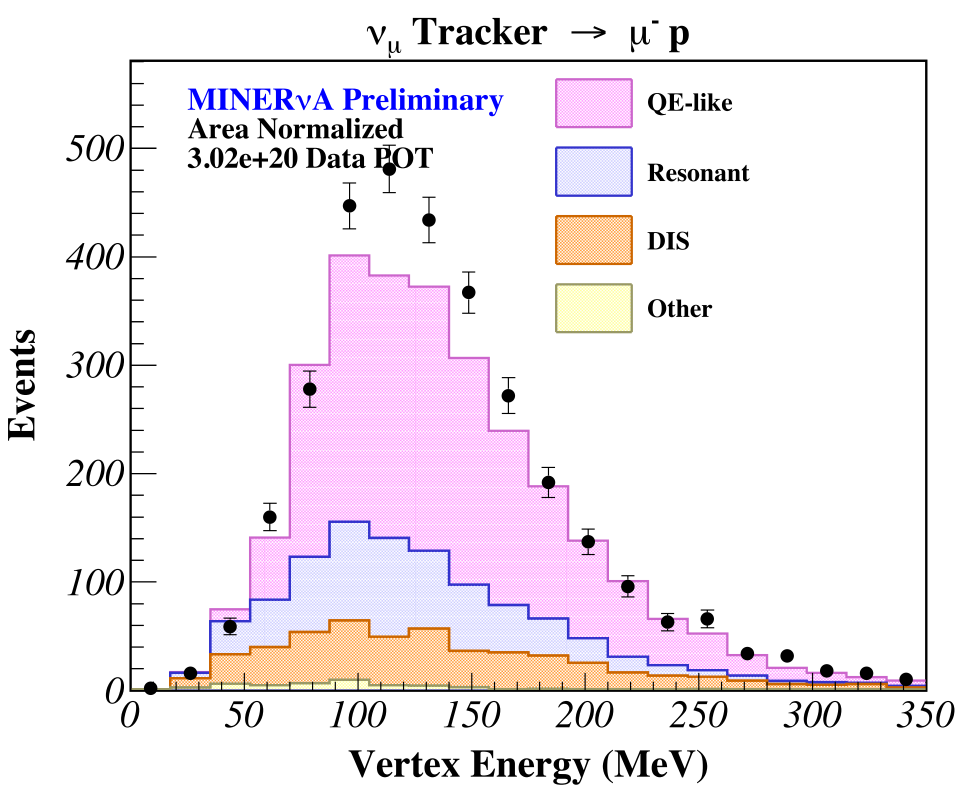
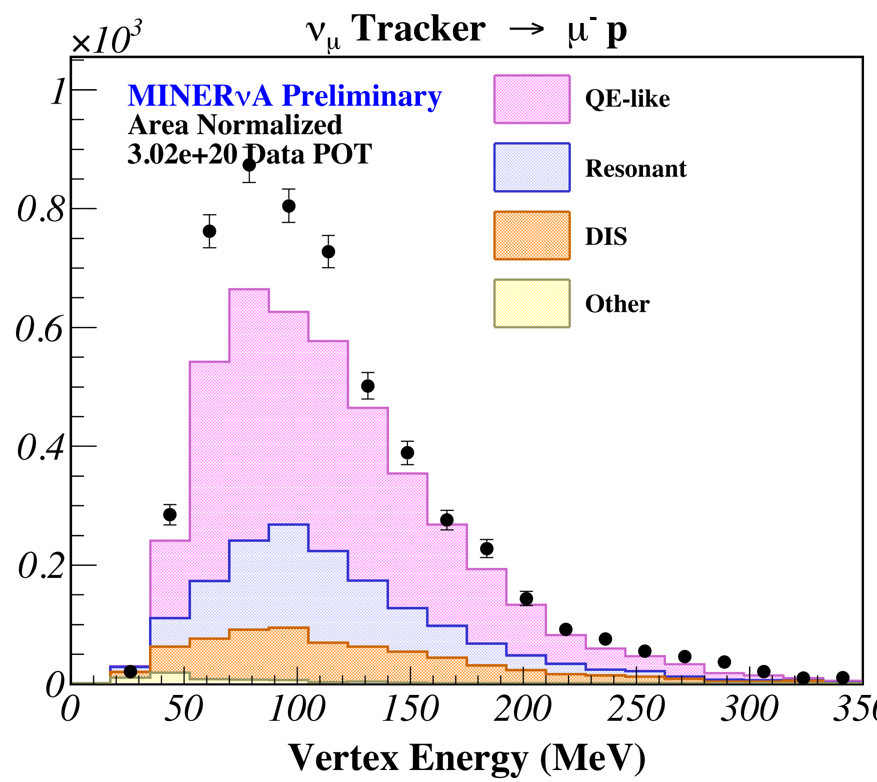
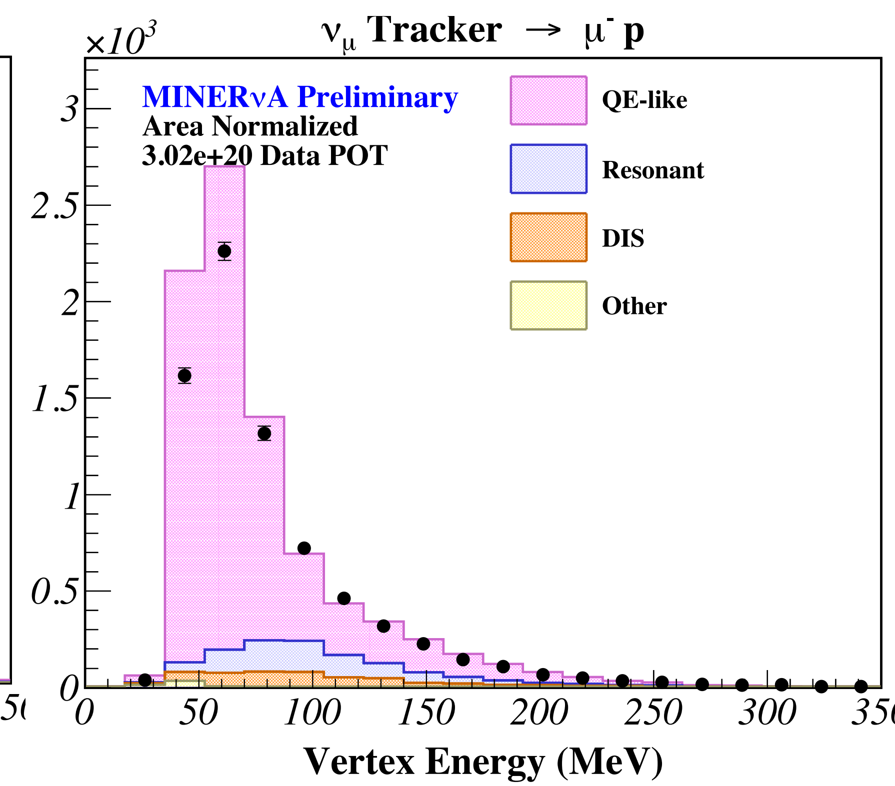
Background Tuned







Distributions normalized to a common normalization for the entire φ

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Background for FSI has been tuned

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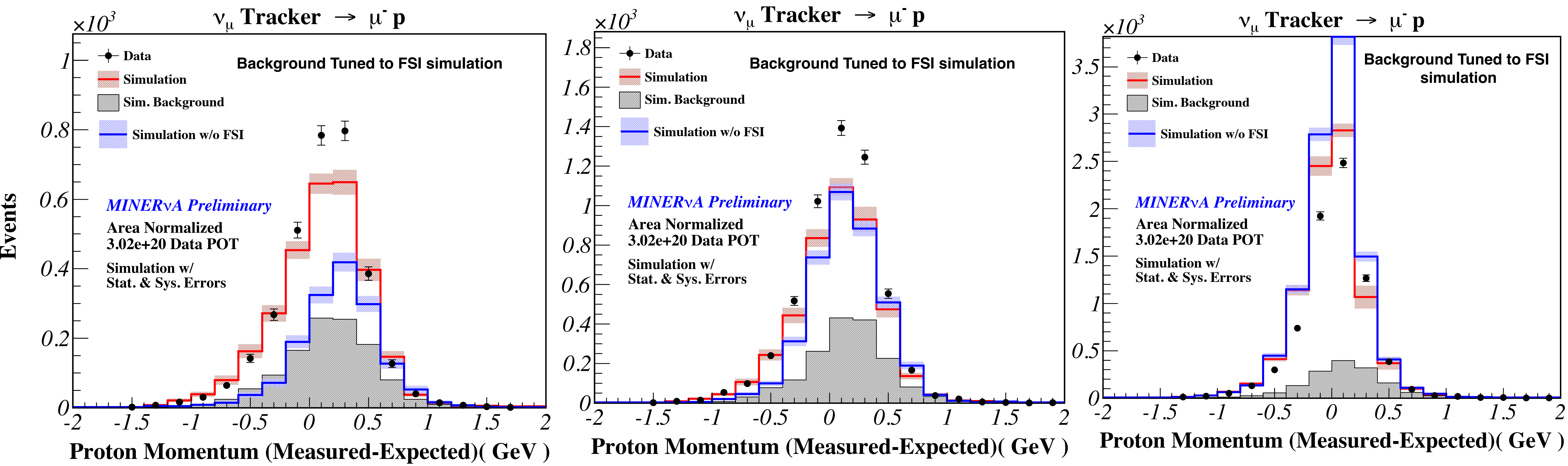
Measured-Expected Proton Momentum

- The expected proton momentum is calculated using the muon kinematics in different bins of coplanarity angle



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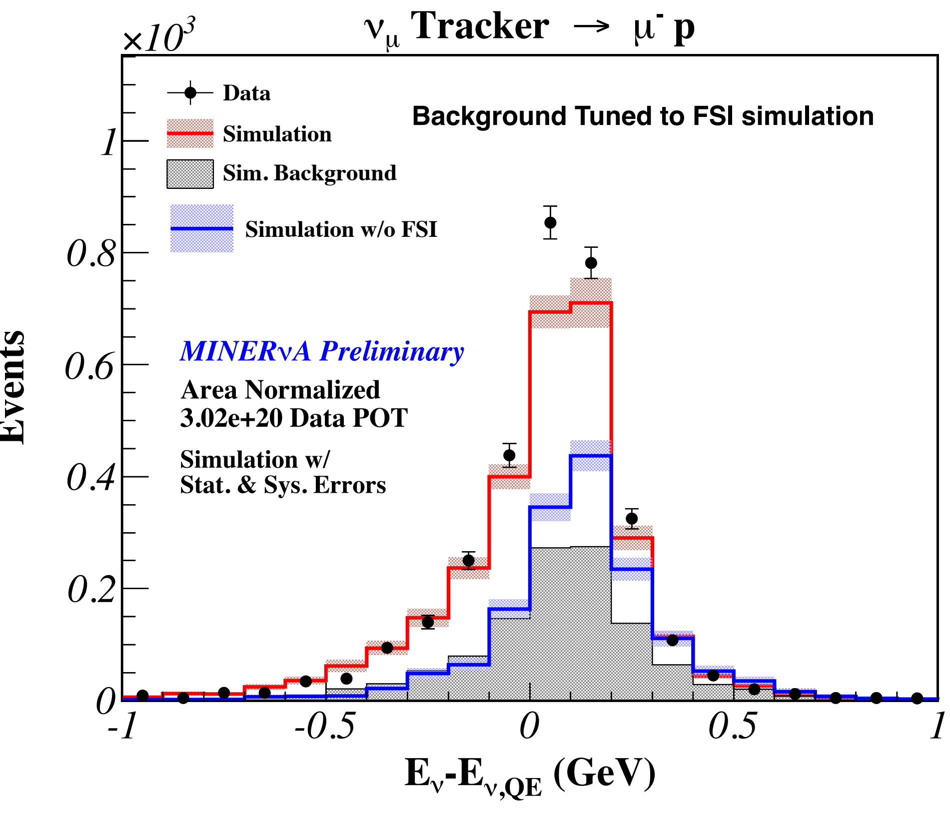
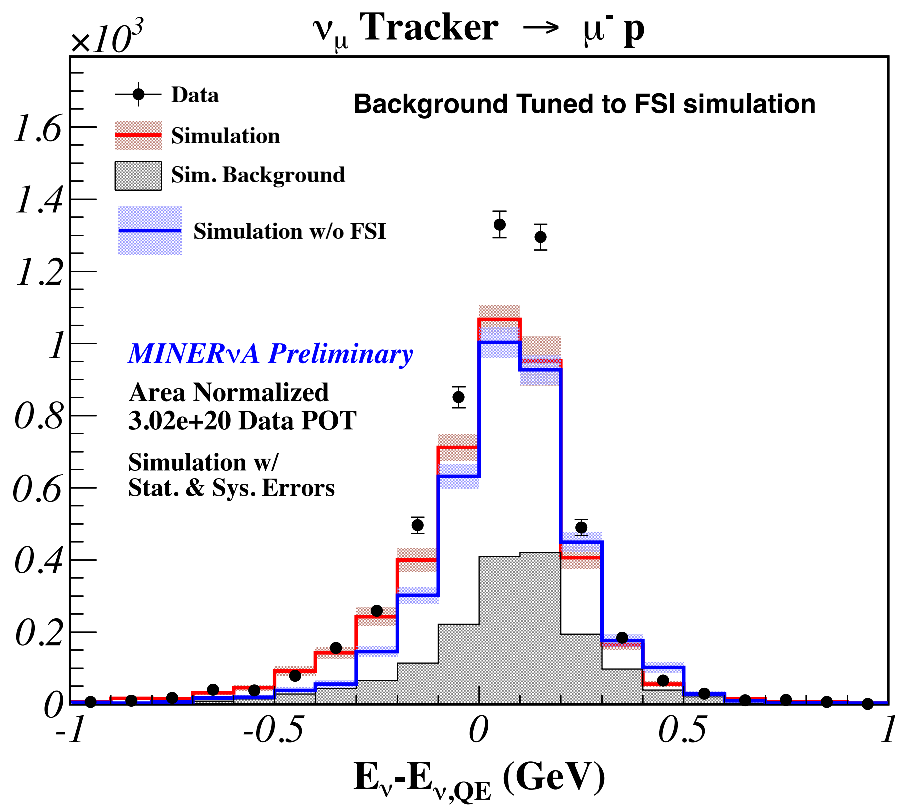
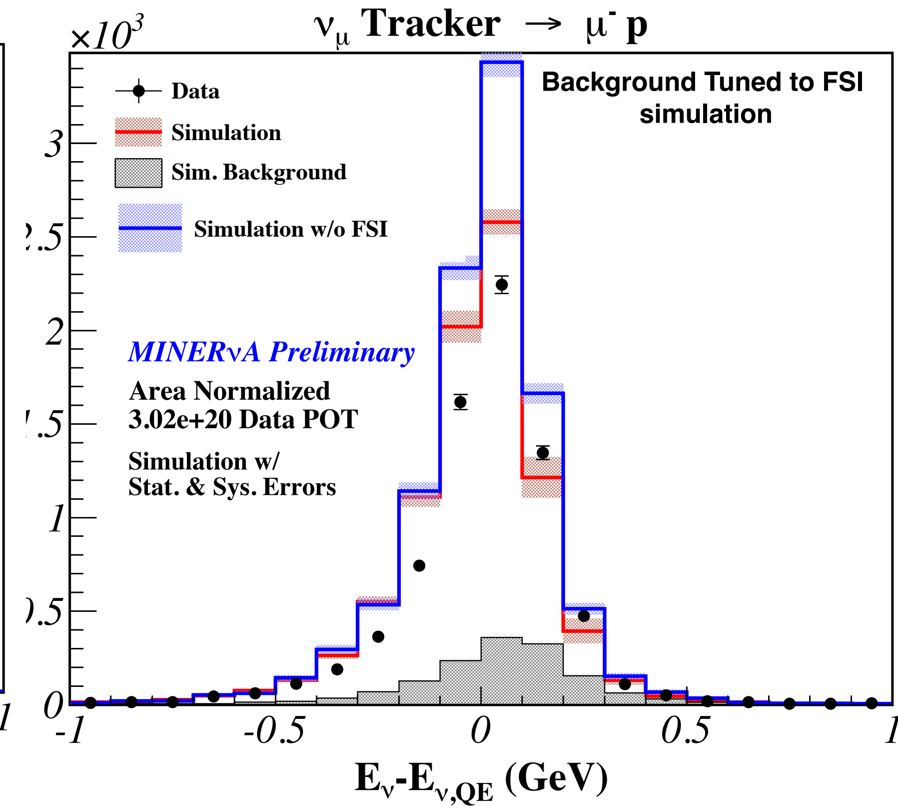
Neutrino Energy(proton+muon) - Neutrino from QE Hypothesis

- Neutrino energy prediction differences
  - E_ν is reconstructed using the muon and proton information
  - $E_{\nu,QE}$ is reconstructed using the QE hypothesis from muon angle and momentum







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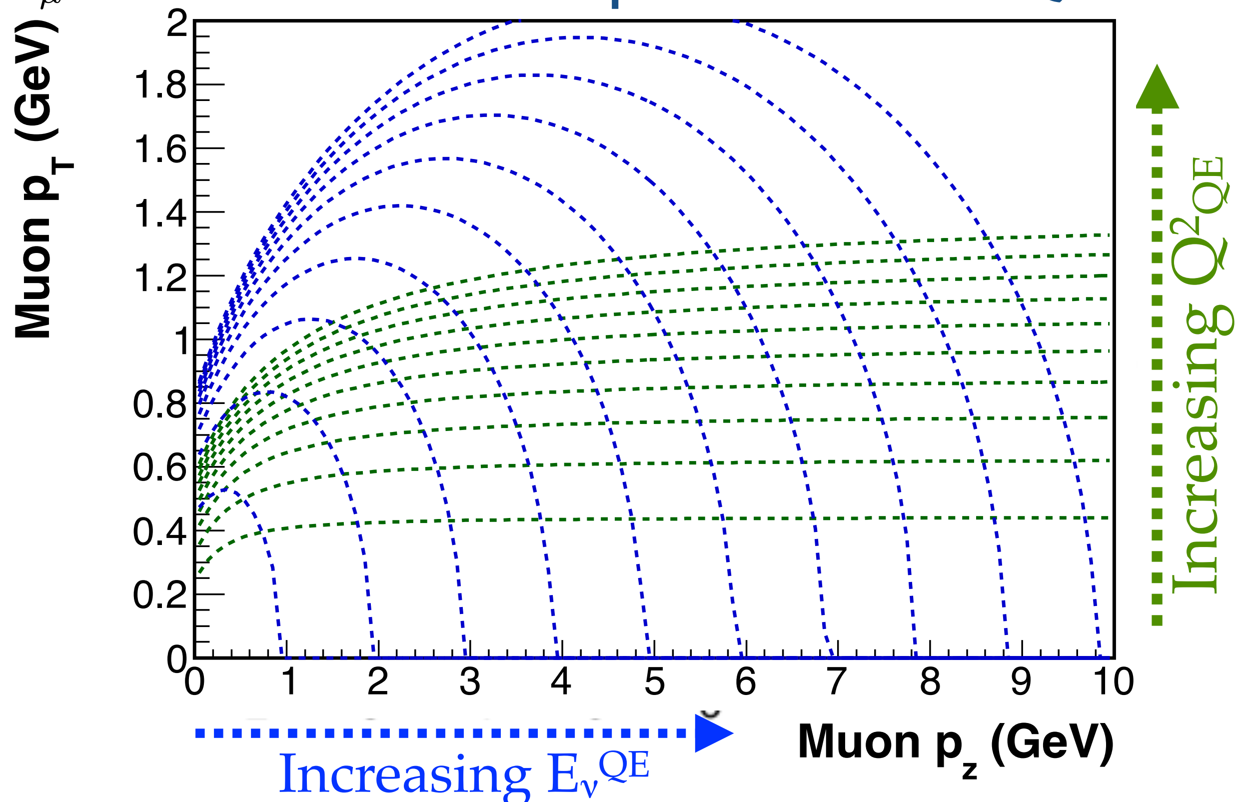
Double Differential Cross Sections

- Double differential cross sections for neutrinos and antineutrinos
- Muon longitudinal P_{Z_μ} and transverse momentum P_{T_μ} are measurable quantities

$$\frac{d^2\sigma}{dP_{T_\mu}dP_{Z_\mu}}$$

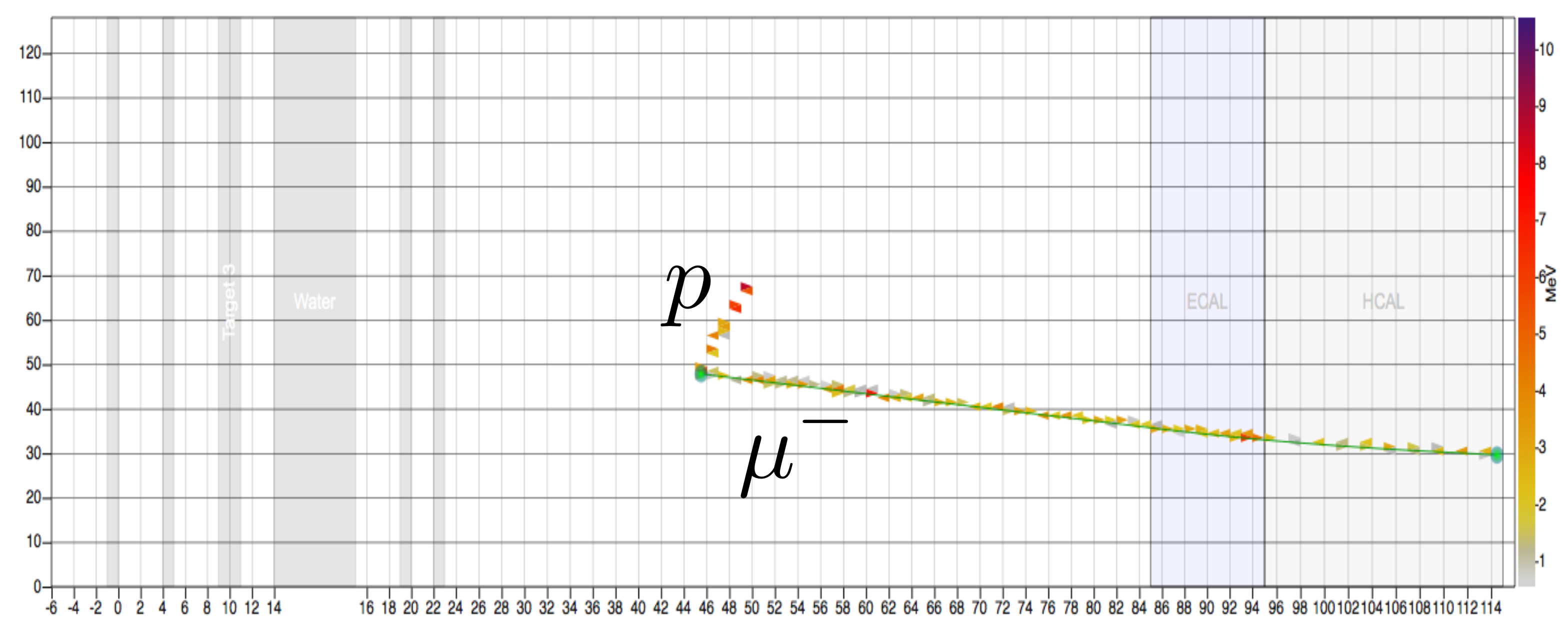
- P_{Z_μ} P_{T_μ} are less model dependent than Q^2



- Updated reconstruction and event selections
- Measuring CCQE-like topology

Selected Events in Neutrino Beam

- Event selection:
  - Muon track in MINERvA extending into MINOS
  - If second track found, it is require to be consistent with a proton
  - Michel veto
  - Require the Q^2-dependent recoil energy cut
  - QE-like: any number of nucleons, but no pions



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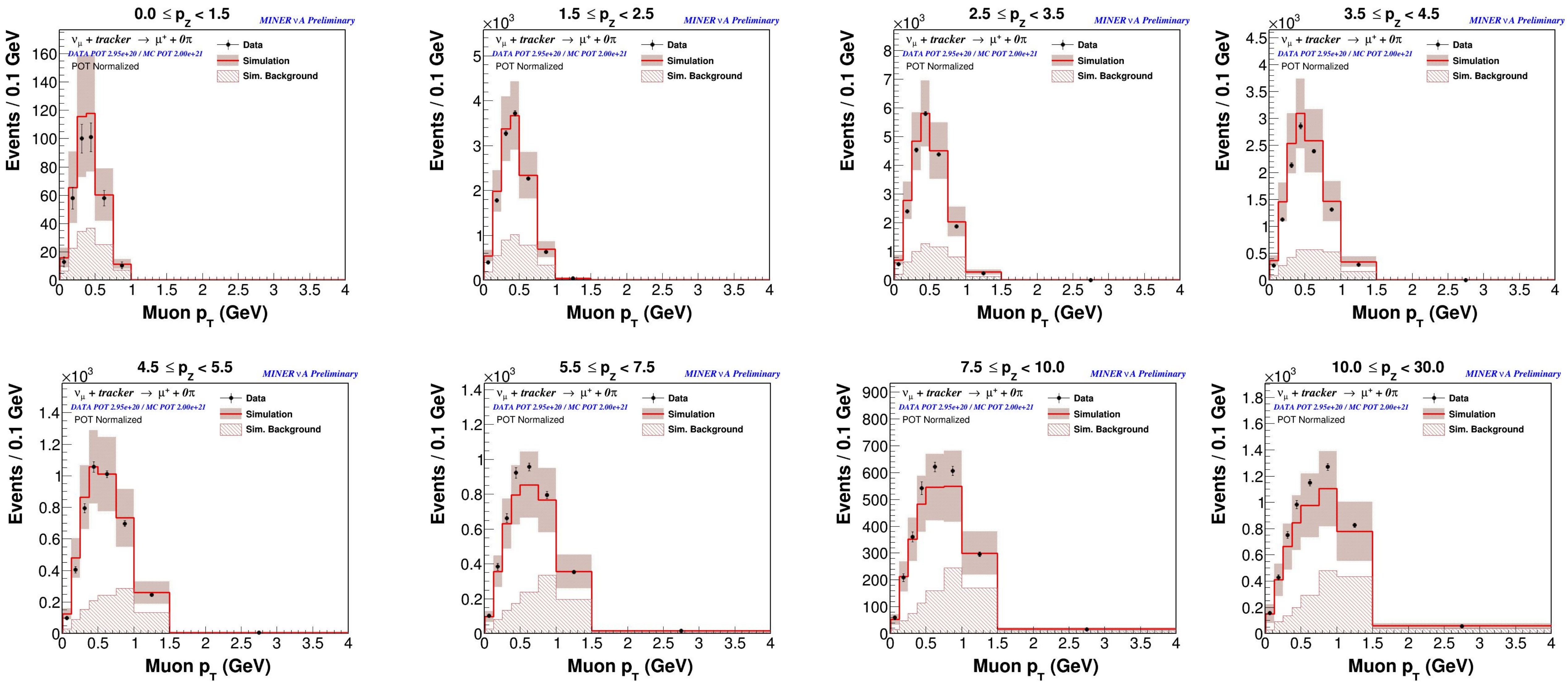
Selected Events in Neutrino

- 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, including the CCQE uncertainty

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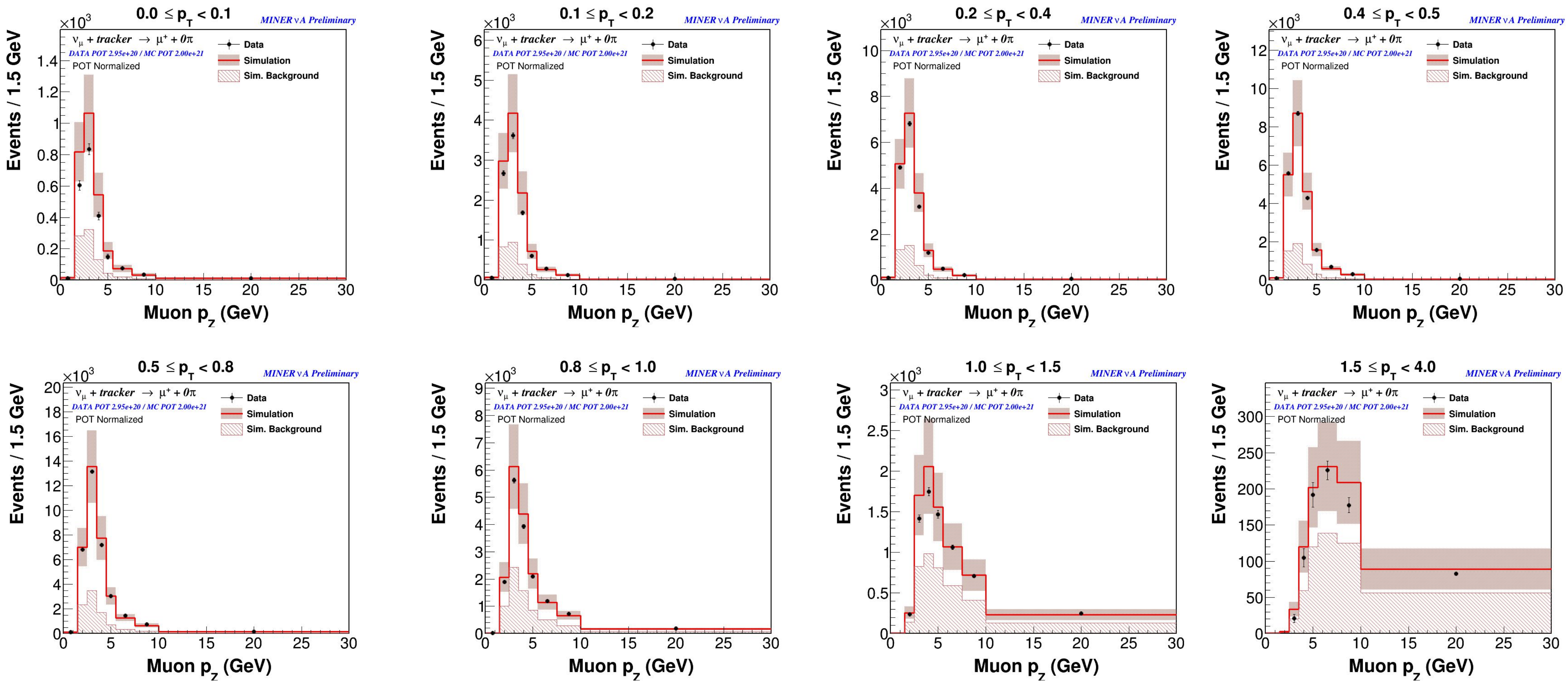
Selected Events in Neutrino

- Data and simulation event distributions vs. longitudinal muon momentum, in bins of transverse muon momentum



- Uncertainties on reconstruction and interaction model are shown on the simulation, including the CCQE uncertainty

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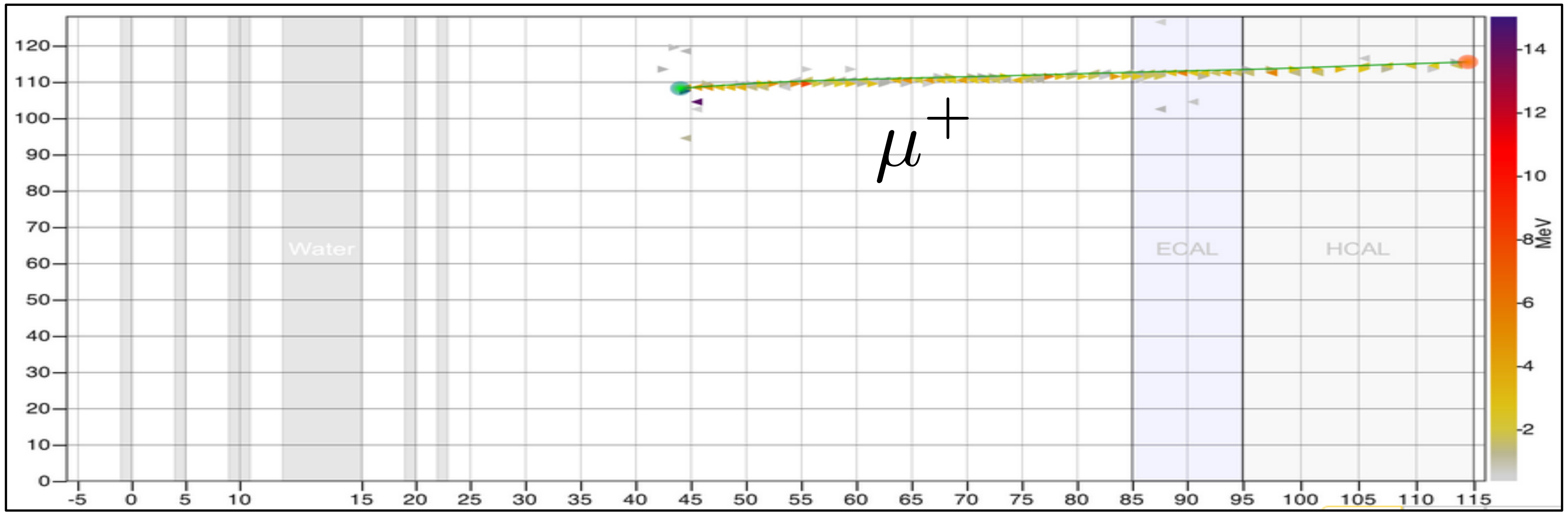
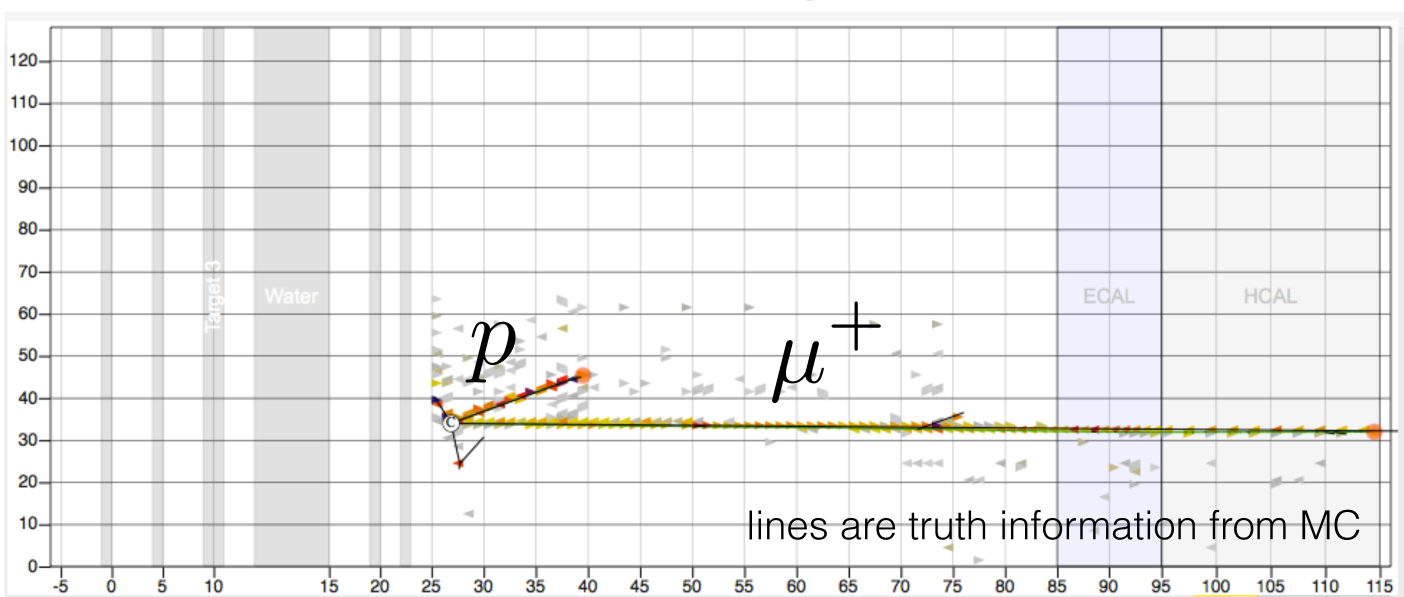
Selected Events in AntiNeutrino Beam

- Event selection:
  - Muon must be matched to a MINOS track
  - There must not be tracks apart from the muon, require one or zero isolated energy shower
  - Require the Q^2-dependent recoil energy cut
  - Previous CCQE measurement used signal definition: events with a neutron and a muon



Finding a QE-like signal definition for AntiNeutrinos

- CCQE-like definition from neutrinos is not directly applicable to the antineutrinos
- Low acceptance for CC0π events that are not CCQE
- Non-CCQE CC0π events have at least three nucleons in the final state
- Events with a second neutron (events with multi nucleons?) are removed by the recoil energy cut
- For example, event with 2 neutrons, 4 protons, one of the proton with 330 MeV

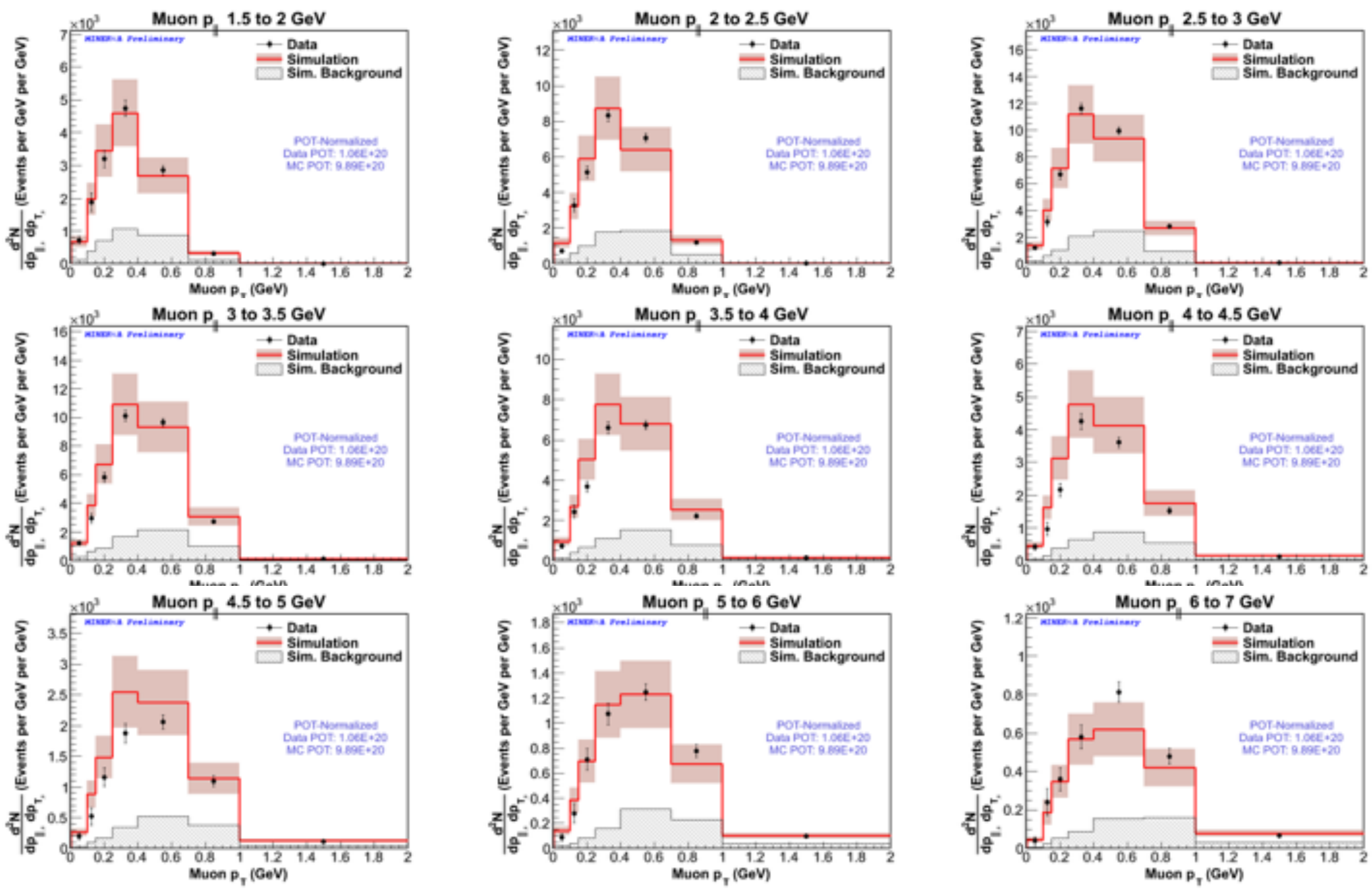


MC Simulation RES

- Finding the best selection for CCQE-like

Selected Events in AntiNeutrino (CCQE)

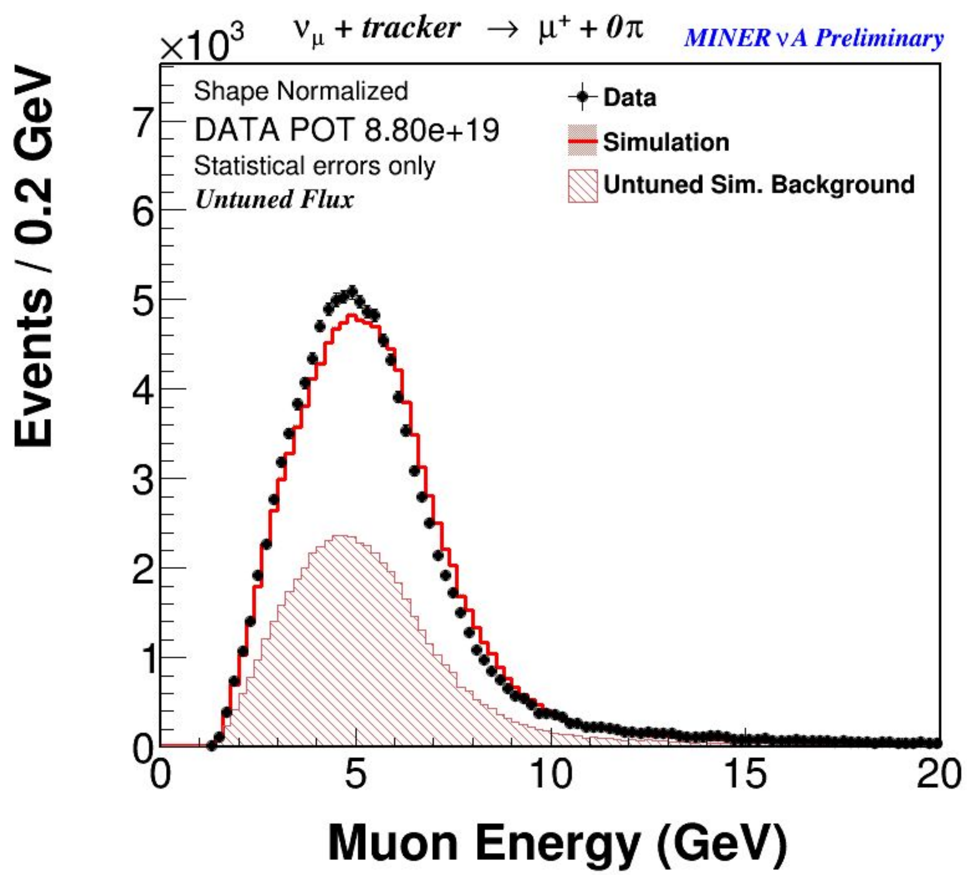
- Data and simulation event distributions vs. longitudinal muon momentum, in bins of transverse muon momentum

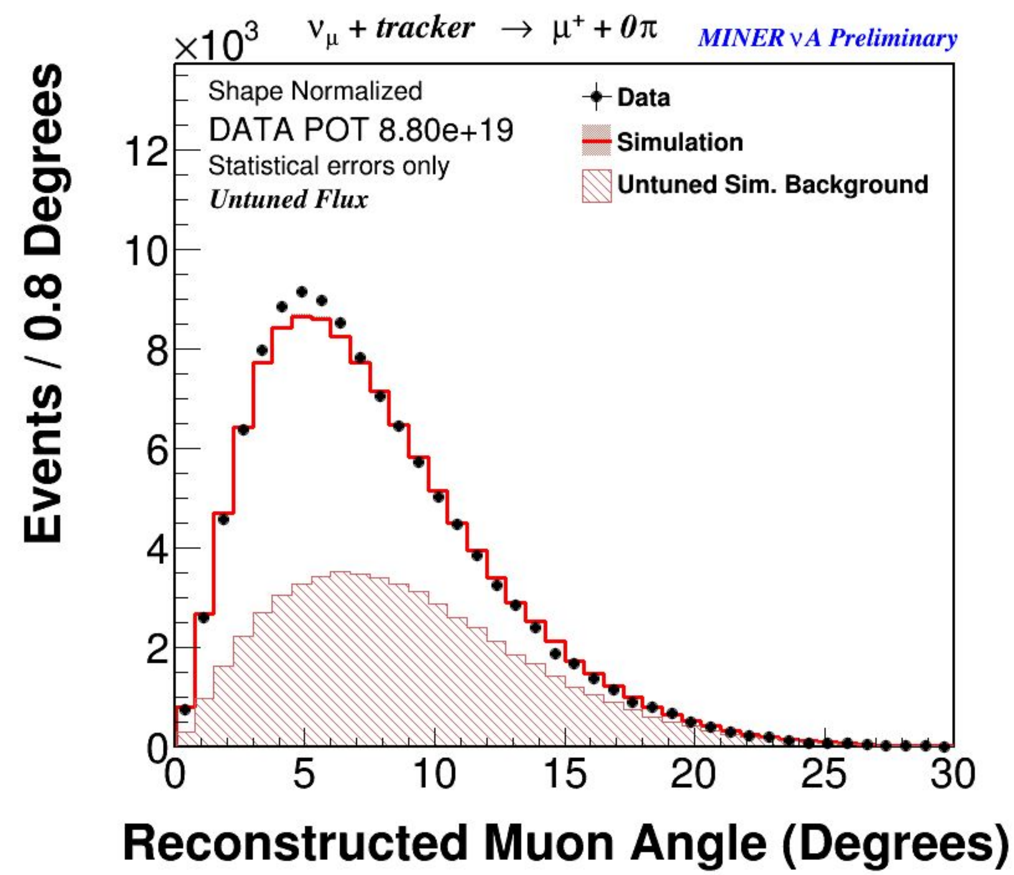


- Uncertainties on reconstruction and interaction model are shown on the simulation, including the CCQE uncertainty

CCQE Analysis in Medium Energy

- Collecting and analyzing the data from medium energy beam
- Working with the event selection
  - Muon track in MINERvA extending into MINOS, helicity cut
  - We have taken 6E20 POT

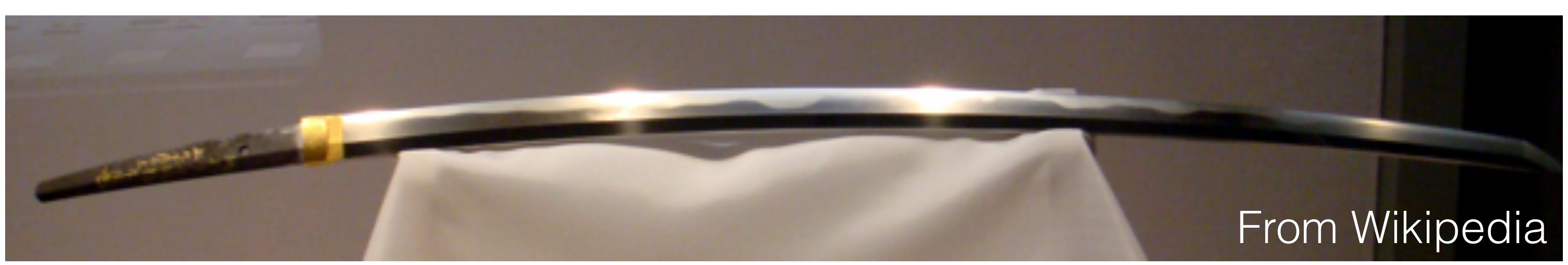




- Tuning the Michel veto and proton identification for this sample

Summary

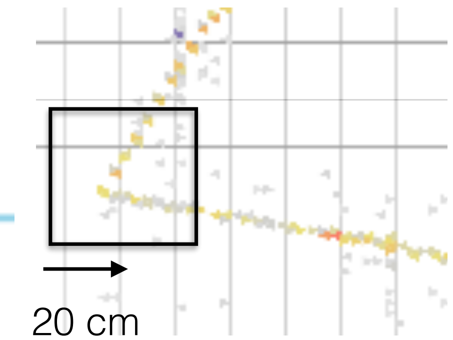
- Several ν_μ CCQE analyses in progress:
  - Double differential cross sections for neutrinos and antineutrinos
  - Study of the final state interactions using a QE-like sample
  - Cross section for neutrinos using the medium energy beam
  - Nuclear target analysis



MINERvA = cutting edge analyses!

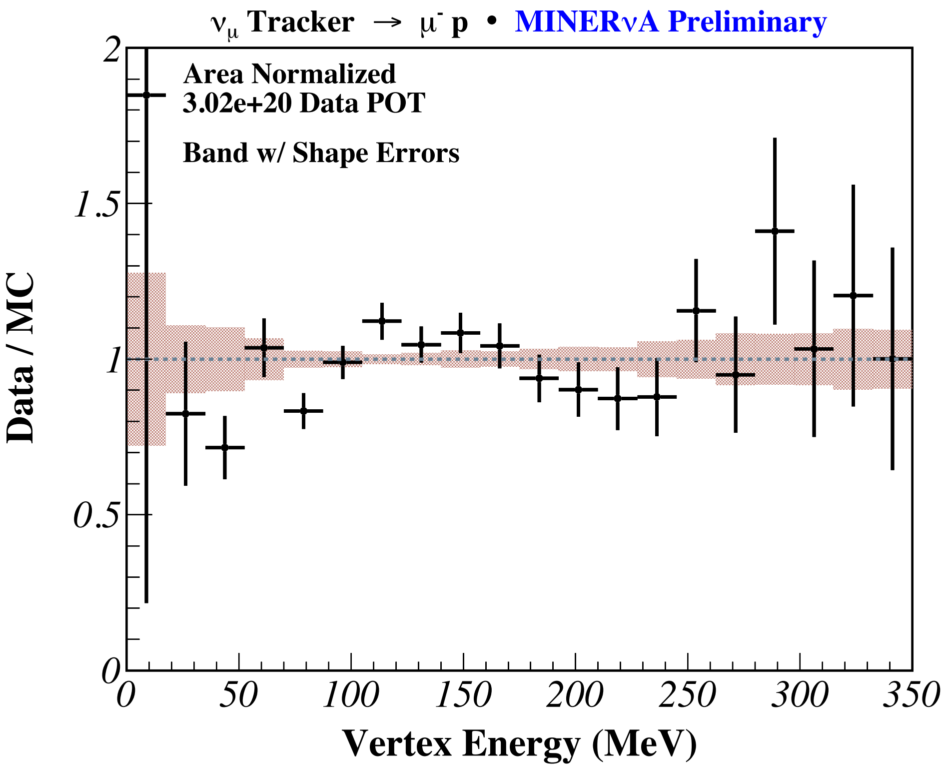
Back Slides

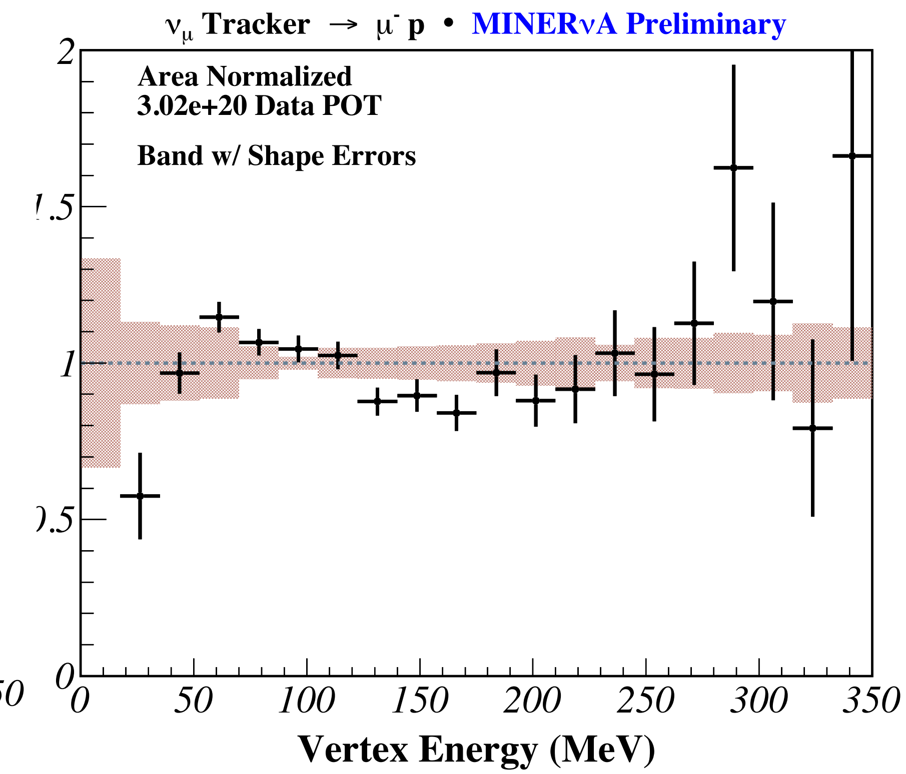
Vertex energy minus the energy from muon

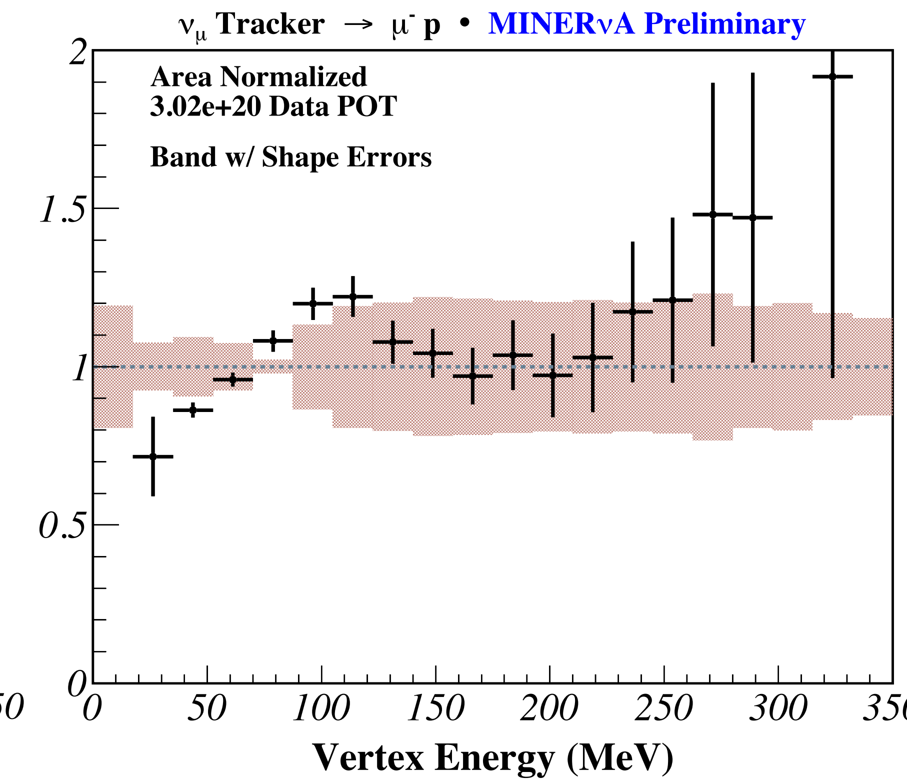


Area normalized Ratios

- Energy inside a box minus the muon energy in slices of coplanarity angle, same definition as the coherent analysis, the box contain proton information and the muon energy has been removed







$$0 < \varphi < 110$$

$$110 < \varphi < 160$$

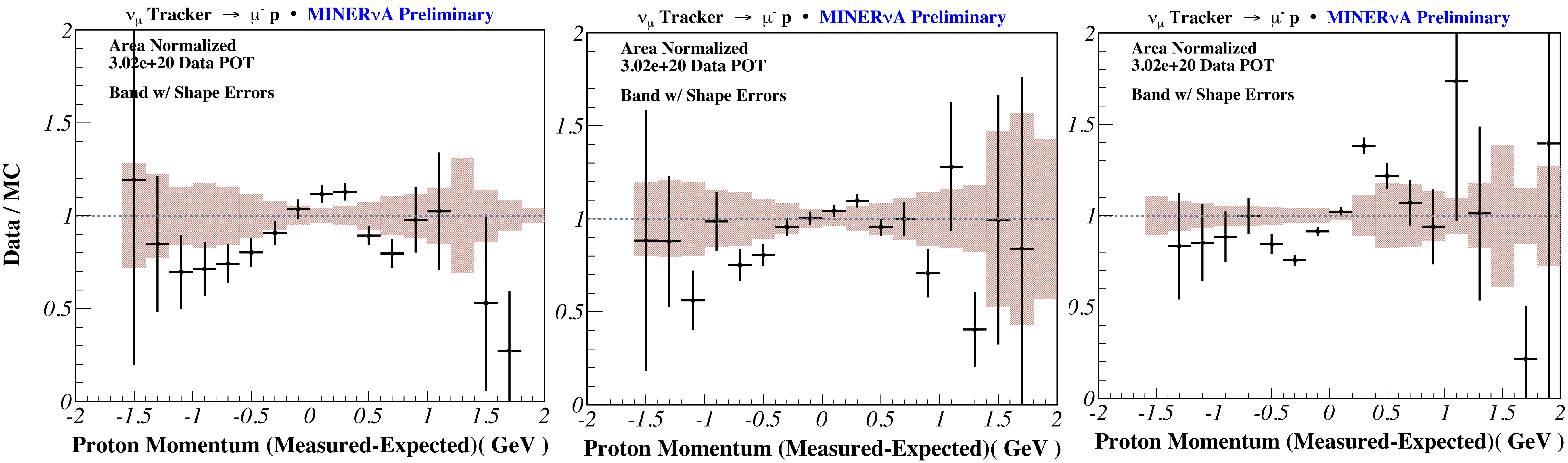
$$160 < \varphi < 180$$

Background for FSI has been tuned and simulation w/o FSI has not been tuned

Measured-Predicted Proton Momentum

Area normalized Ratios

- The predicted proton angle and momentum is calculated using the muon kinematics from the minos-match sample in different bins of coplanarity angle



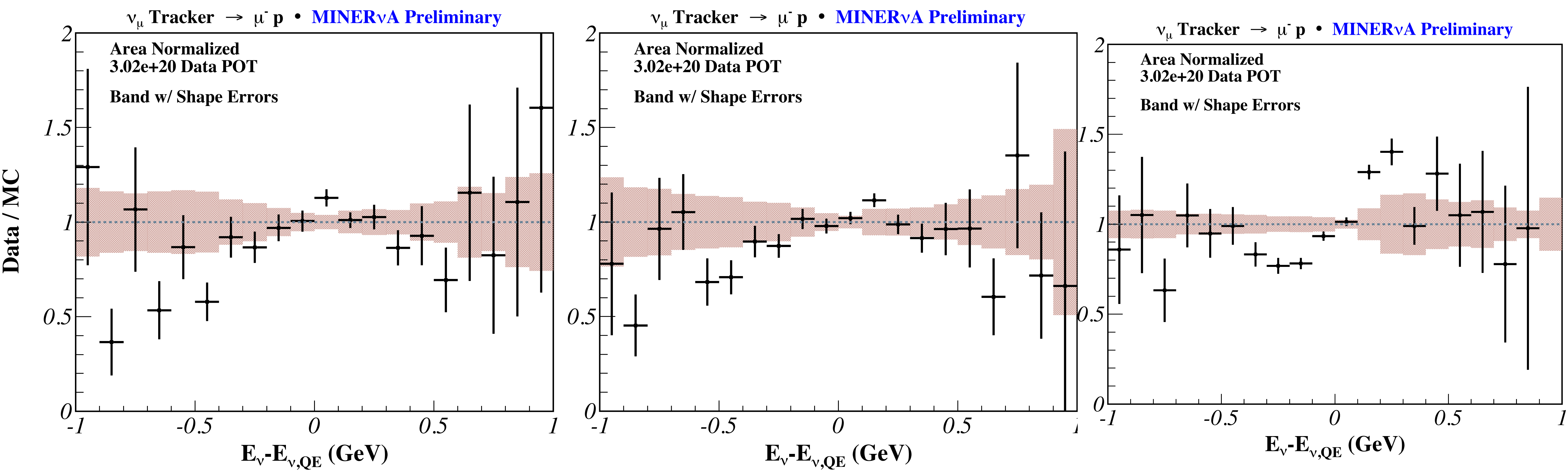
$0 < \varphi < 110$ $\quad 110 < \varphi < 160$ $\quad 160 < \varphi < 180$

Background for FSI has been tuned and simulation w/o FSI has not been tuned

Neutrino Energy(proton+muon) - Neutrino from QE Hypothesis

Area normalized Ratios

- Neutrino energy prediction differences
  - E_ν is reconstructed using the muon and proton information
  - $E_{\nu,QE}$ is reconstructed using the QE hypothesis from muon angle and momentum



$0 < \varphi < 110$ $\quad$ $110 < \varphi < 160$ $\quad$ $160 < \varphi < 180$

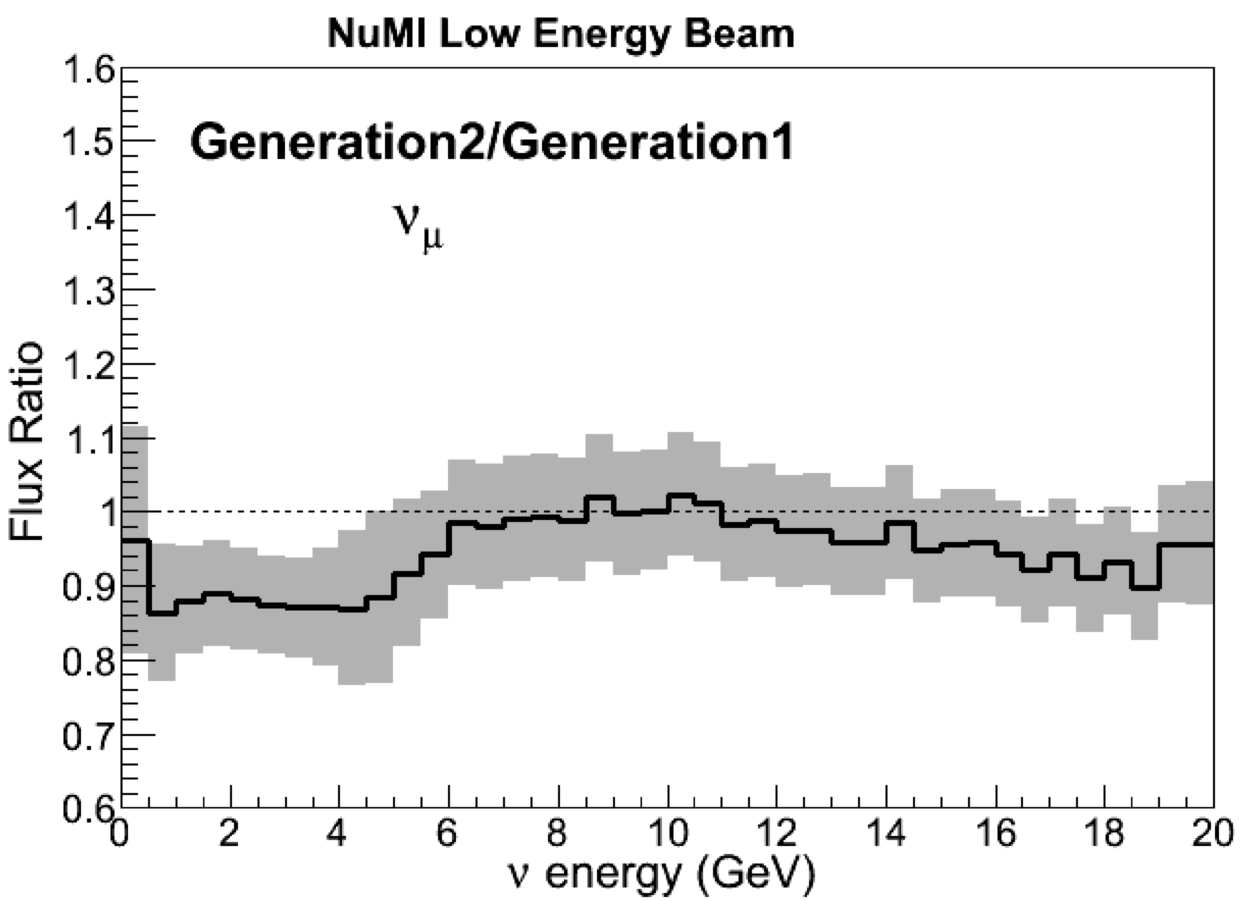
Background for FSI has been tuned and simulation w/o FSI has not been tuned

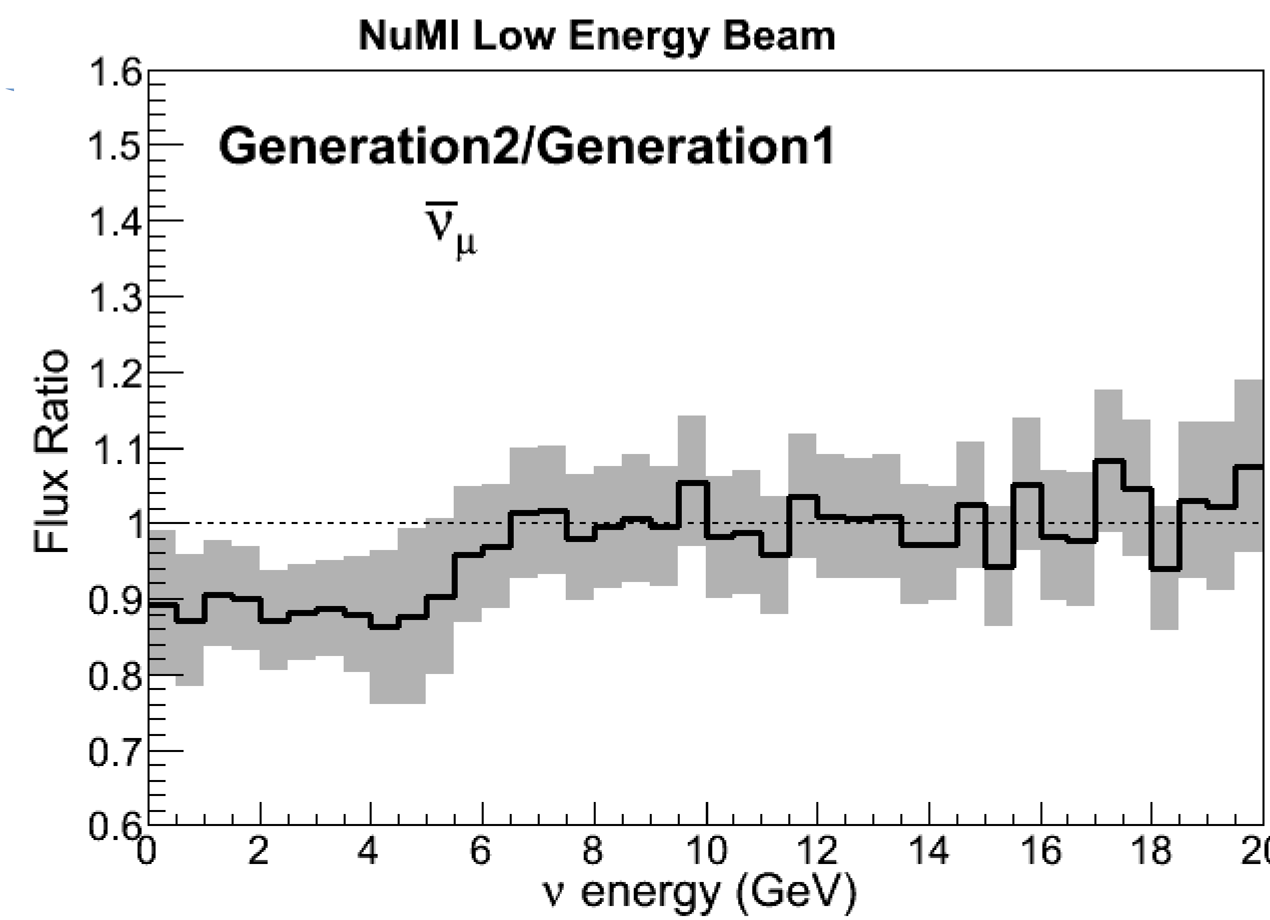
Updates to the CCQE measurements

- In the analysis background are estimated from sidebands, we expect modest changes to our background estimates. For this update, we have estimated a conservative upper limit on the size of this change and applied it as a systematic uncertainty
- Updates to the data only, change in the MC predictions should be small since the $d\sigma/dQ^2$ varies by <25% over the entire region of out acceptance flux, with the bulk of the change occurring below the flux peak
- The change would then be the product of how much the flux changes with this effect, so plasysibly <2% everywhere even if we binned in energy and probably <1% in all $d\sigma/dQ^2$ bins

Comparing the fluxes Neutrino

- We have a new flux with improvements, main changes to beamline geometry and updates to the simulation (simulation has been constrained to hadron production data)
- Comparison of the new vs old flux (updated flux version Generation 1)

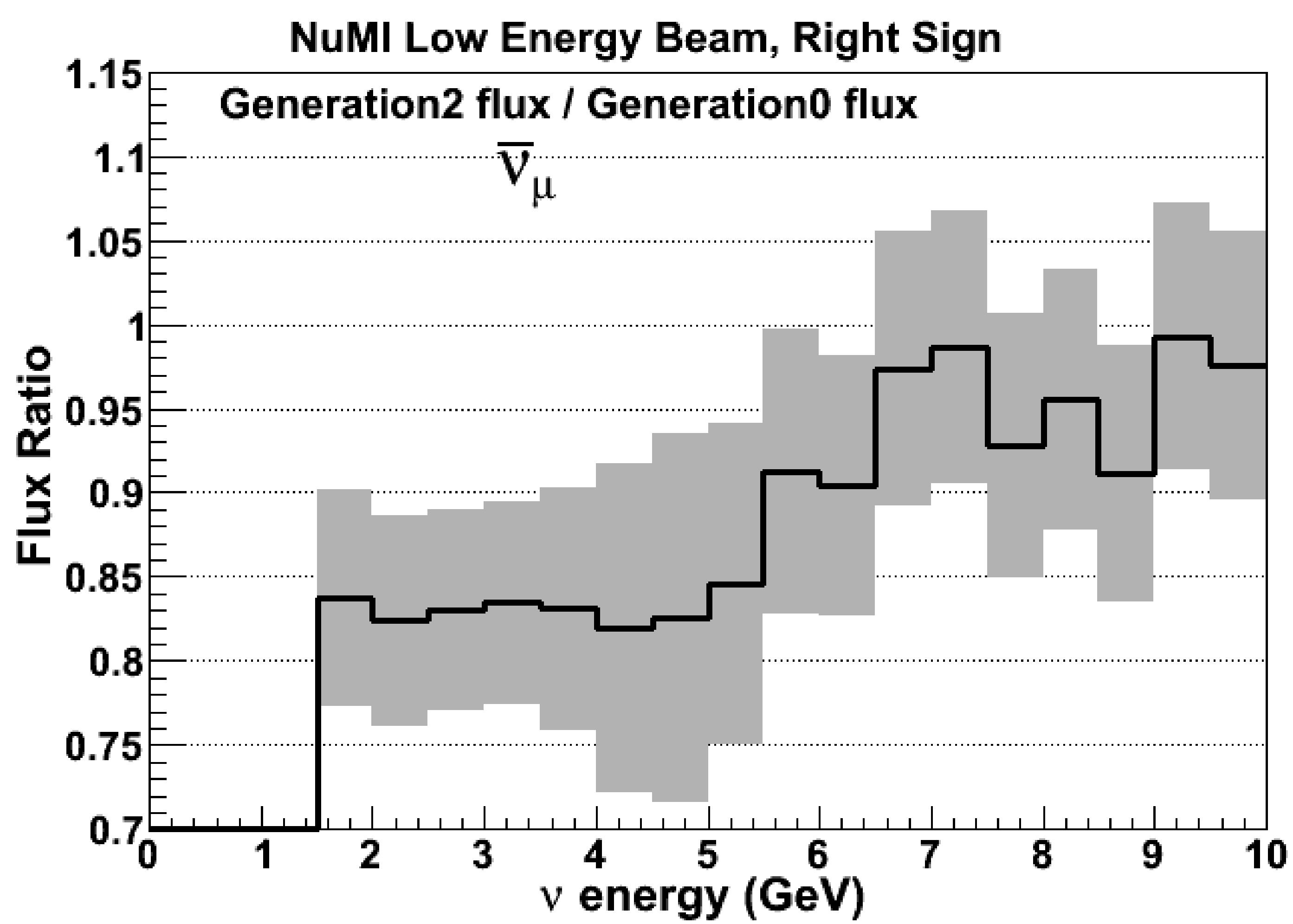




For details see Tomasz Golan's talk from yesterday

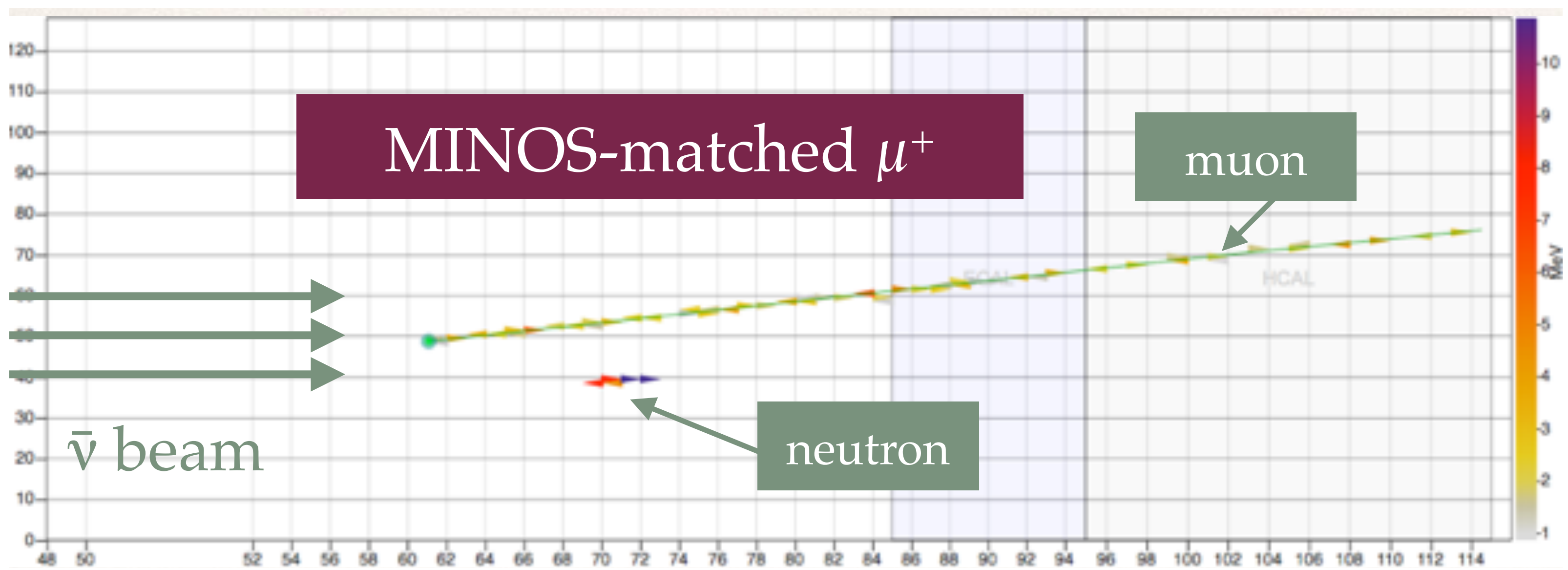
Comparing the fluxes AntiNeutrino

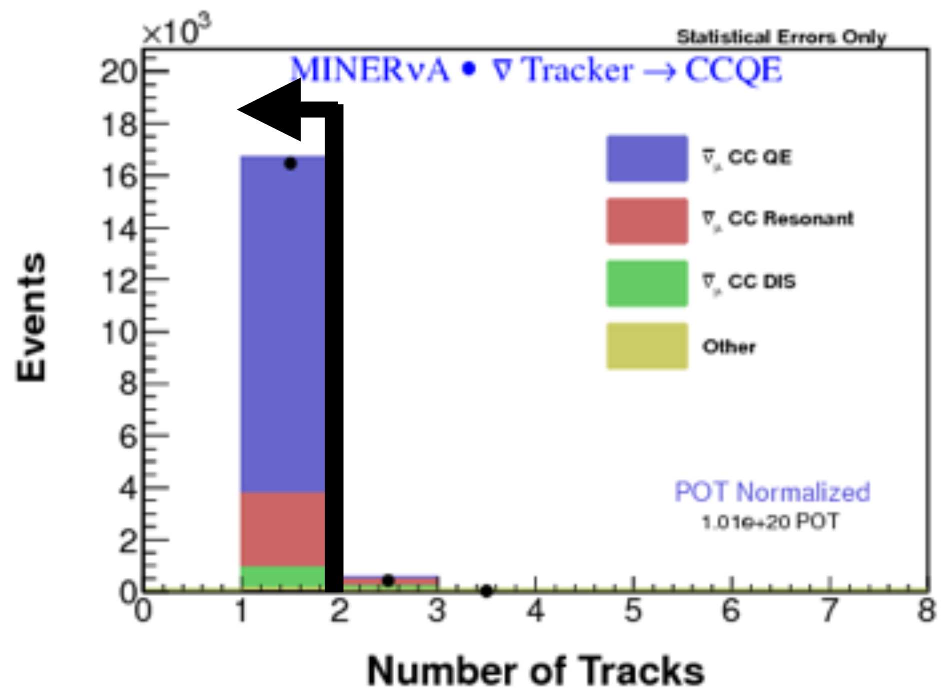
- Comparison of the new vs old flux, (old flux from 2013 publications)

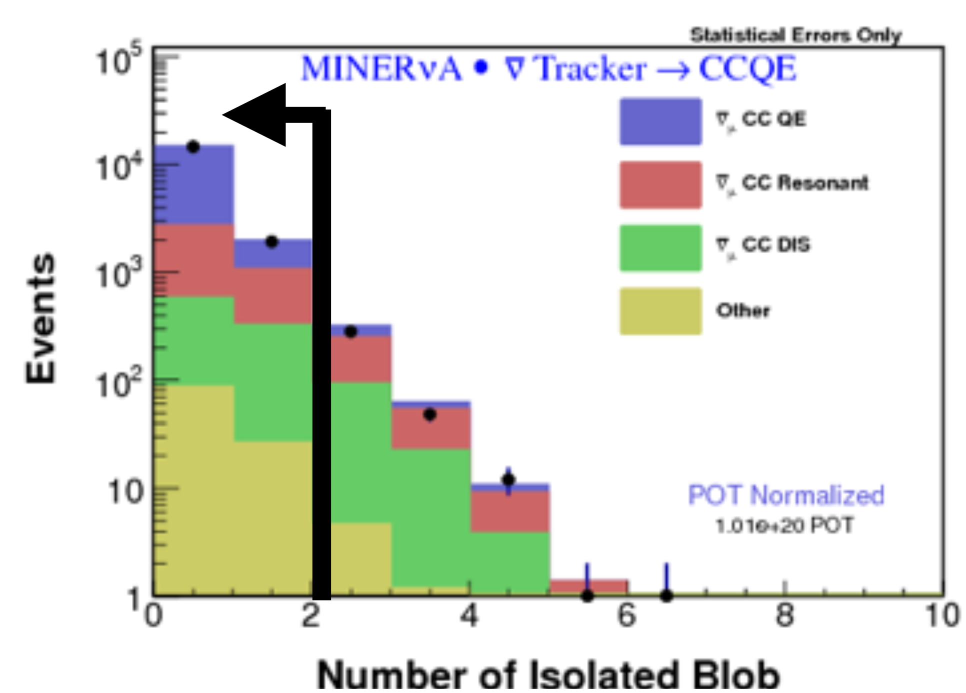


For details see Tomasz Golan's talk from yesterday

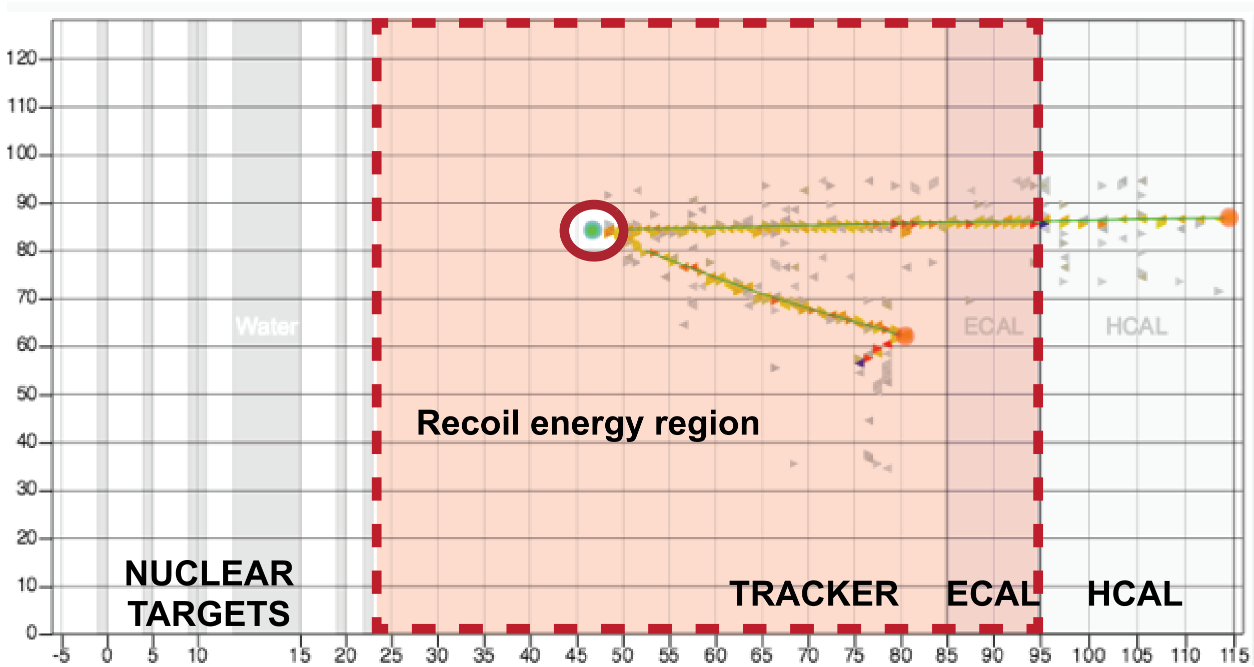
Selecting Antineutrinos CCQE







Selecting Antineutrinos CCQE



Sum the energy deposited in the recoil region, exclude the vertex region where extra low-energy nucleons could result from correlated pairs