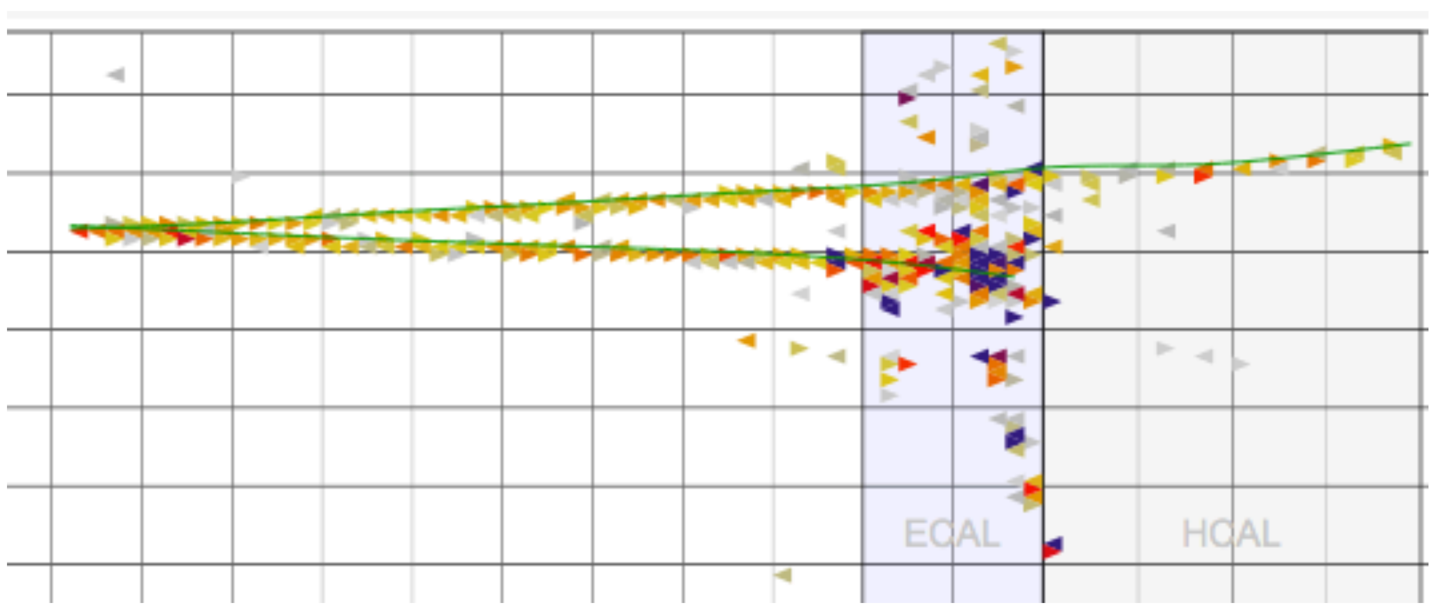
Charged Current Coherent Pion Production in MINERvA



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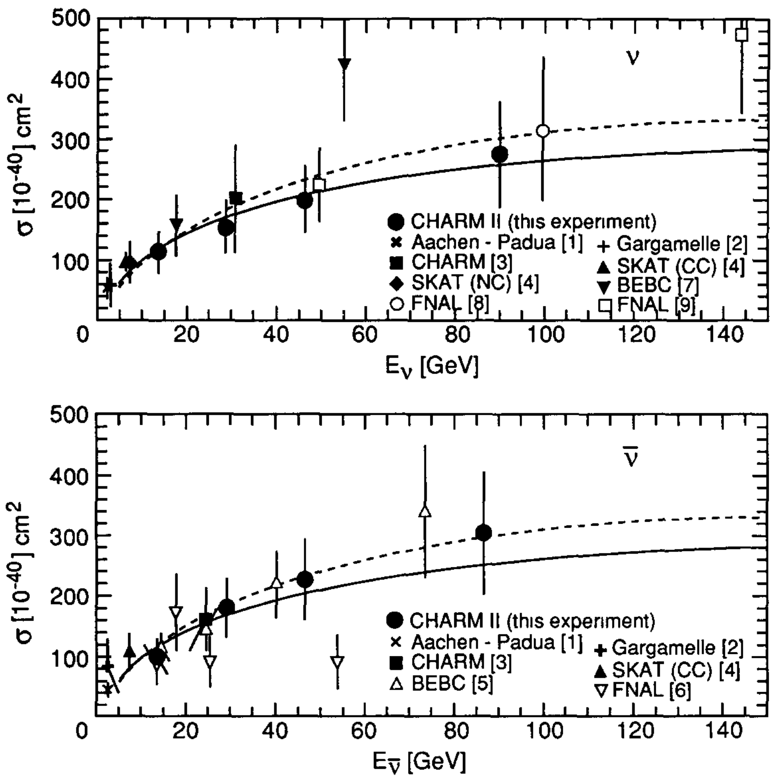
Outline

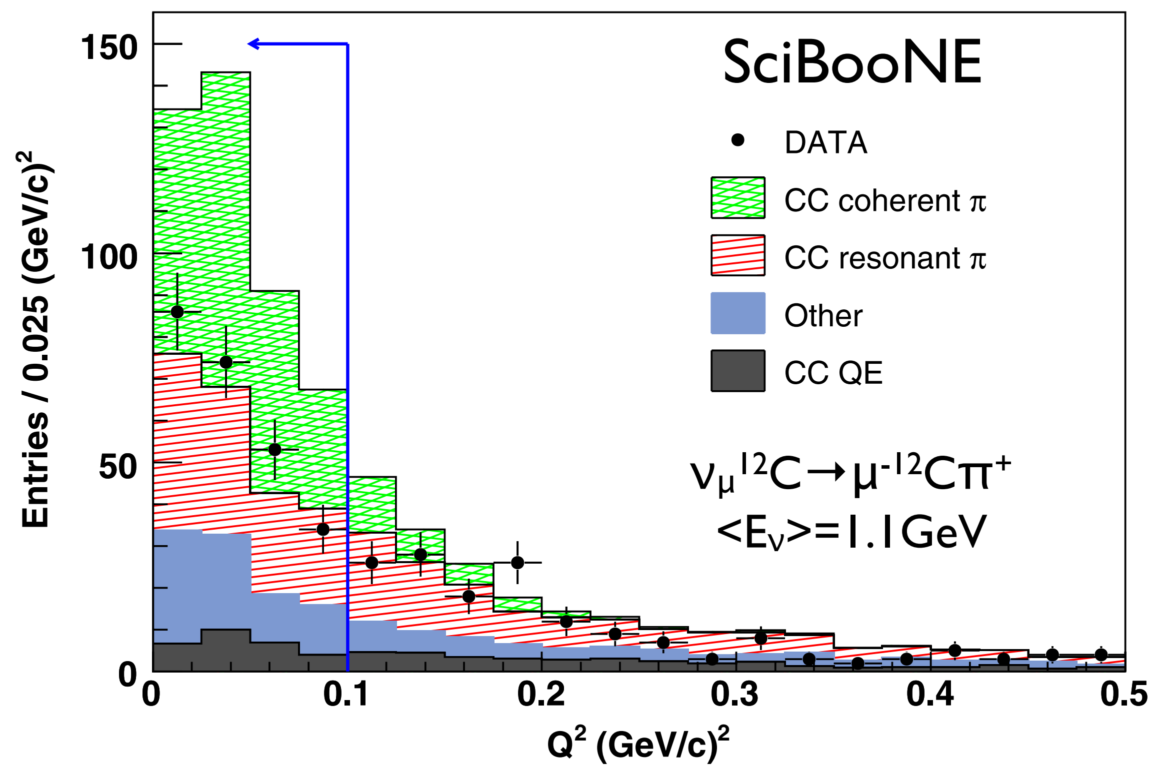
- Motivation
- MINERνA Detector and Kinematics Reconstruction
- Event Selection
- Background Tuning
- Contribution from Diffractive Scattering off Hydrogen
- Systematics
- Cross Sections

Need for New Data on CC Coherent Pion Production

Phys. Lett. B 313, 267 (1993)



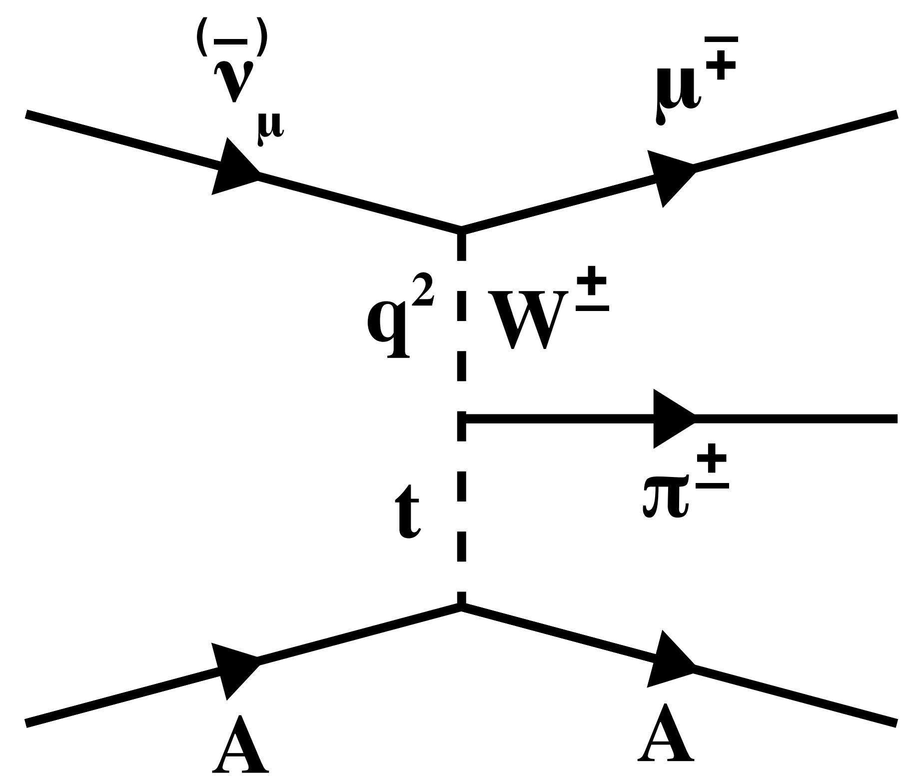
Phys. Rev. D 78, 112004 (2008)



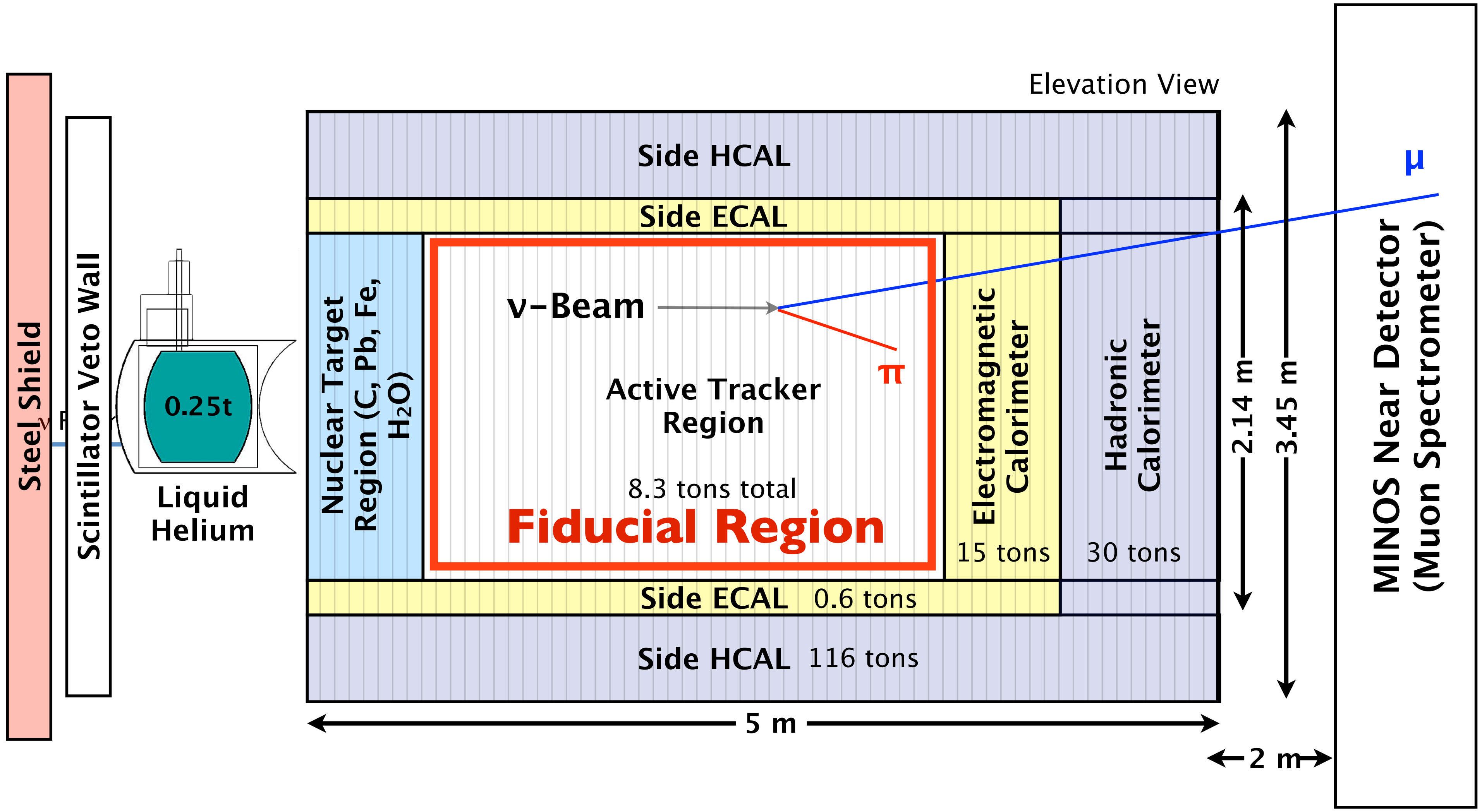
- Older data of charged current (CC) coherent pion production at higher energy (E_ν > ~10 GeV) agrees with the Rein-Sehgal model prediction
- K2K and SciBooNE data at E_ν < 2 GeV is consistent with no CC coherent pion production and places an upper limit on the production rate that is significantly lower than the Rein-Sehgal model prediction
- Limitations of the Rein-Sehgal model have been discussed in-depth at NuInt
- Constraining CC coherent pion production at 1-5 GeV is needed by oscillation experiments

Enter MINERνA

- We are measuring neutrino and antineutrino CC coherent pion production on Carbon for 1.5 GeV < E_ν < 20 GeV
- This analysis uses the GENIE v2.6.2 event generator, which uses the Rein-Sehgal model for CC coherent pion production with lepton mass corrections
- Our signal definition:
    - a positively identified muon and pion
    - a quiet event vertex (i.e. no nuclear break-up)
    - low $|t| = |(q-p_\pi)^2|$
        - model independent, unambiguous signature of coherent scattering
        - MINERνA is the first contemporary experiment measuring |t| event-by-event

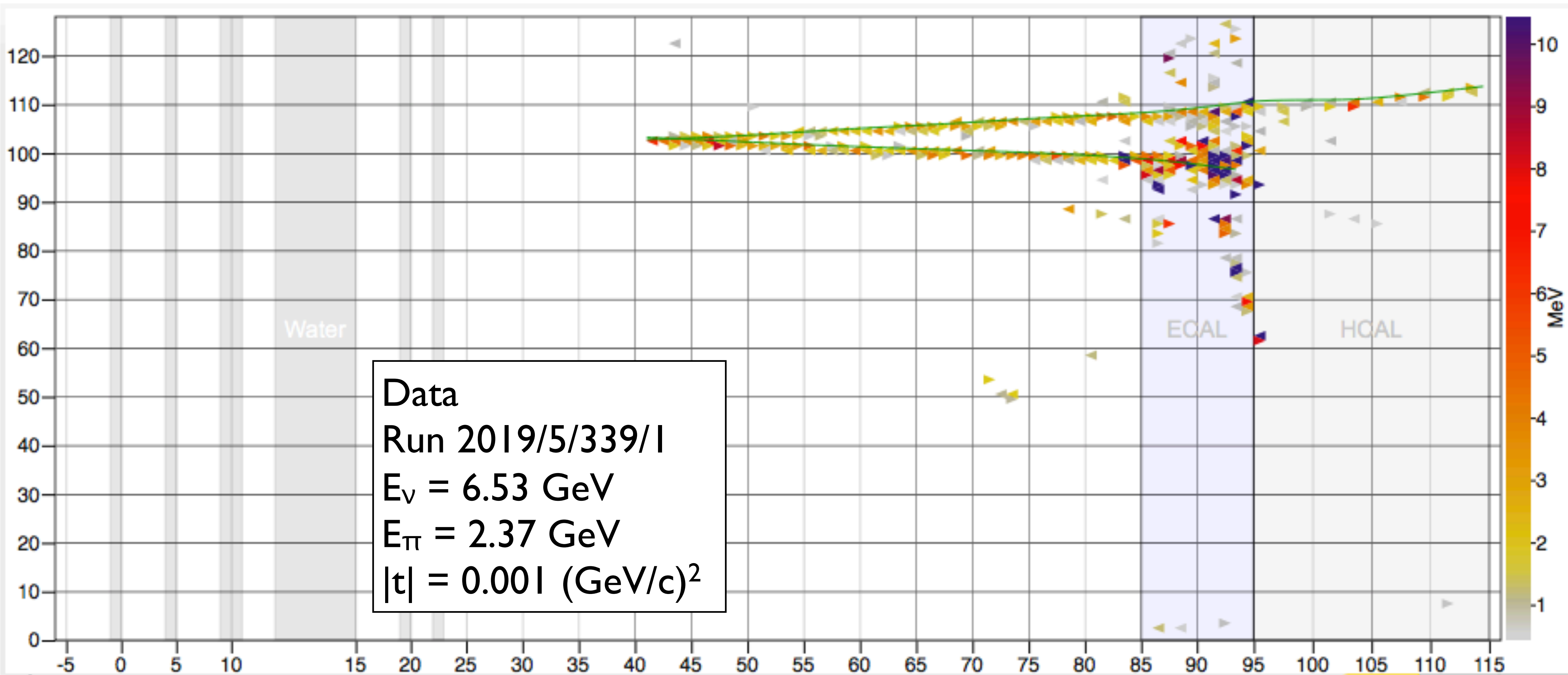


The MINERνA Detector

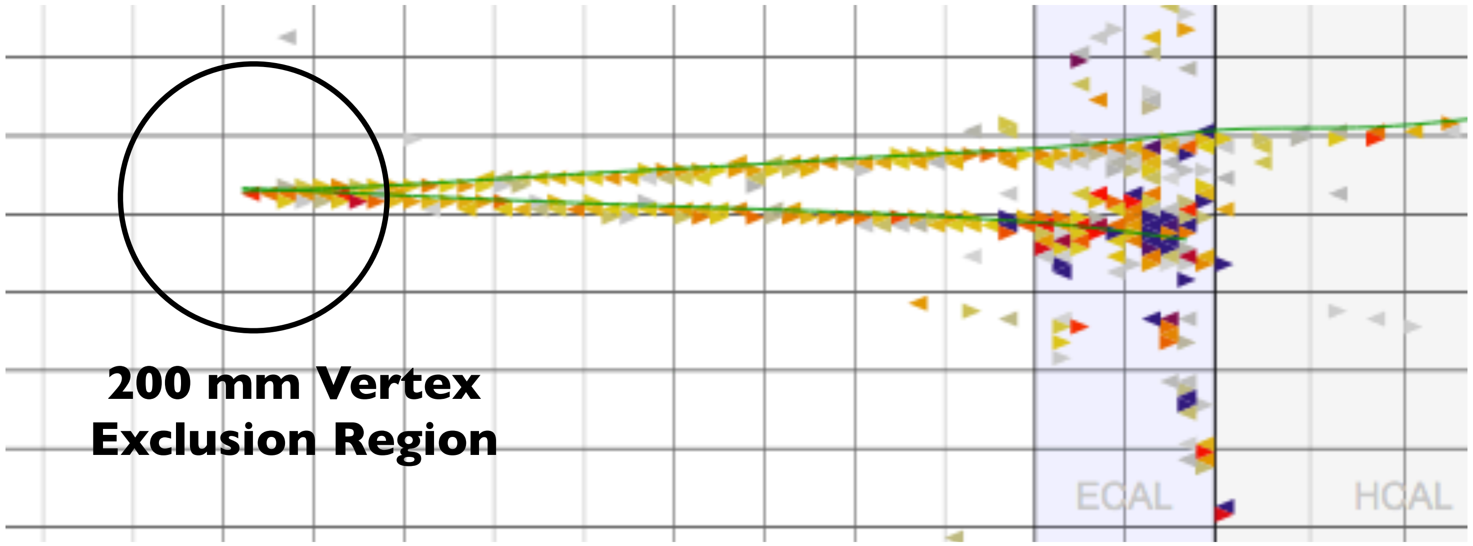


- We analyze events in our fully active central scintillator (C-H) tracker region - fine-grained for measuring μ and π direction
- Reconstructing the μ in both MINERνA and MINOS gives a measurement of p_μ and muon charge
- The downstream and side calorimeters provide containment of the π for measuring E_π
- MINERνA has full access to the μ and π kinematics for measuring $|t| = |(q-p_\pi)^2|$

ν_μ CC Coherent Pion Production Candidate in MINERνA



Kinematics Reconstruction



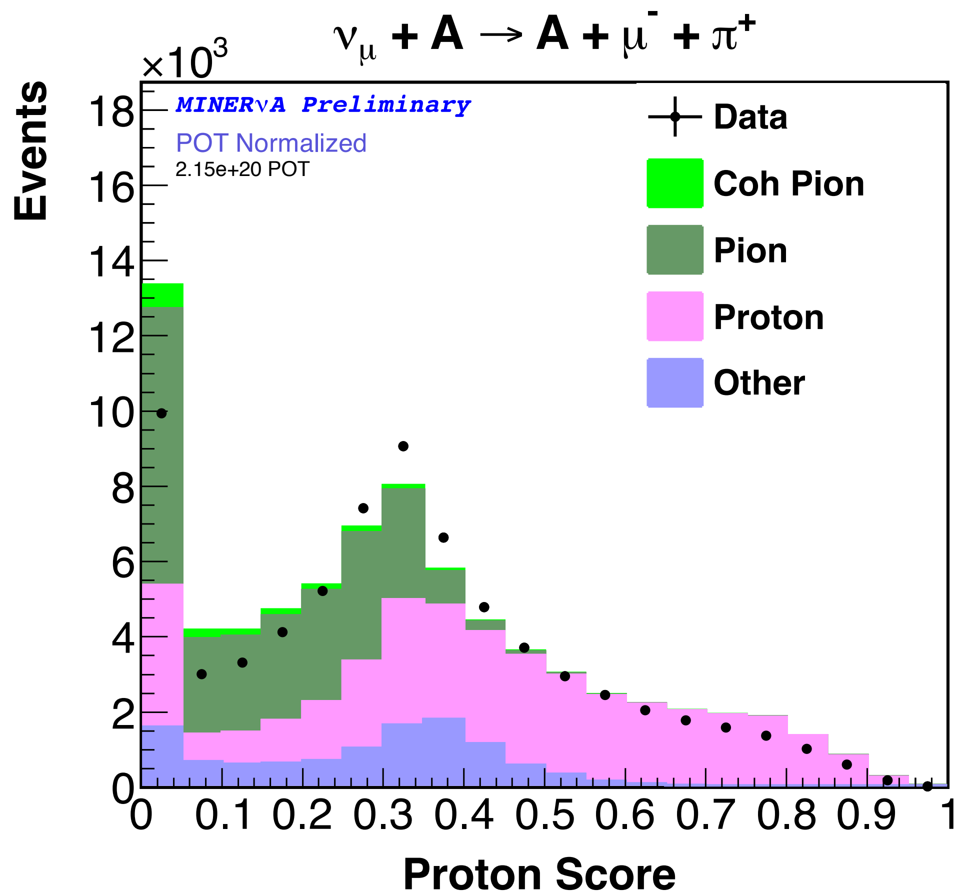
- We accurately measure p_μ for muons reconstructed in both MINERνA & MINOS
- Since most pions interact in our detector, E_π reconstructed as:
  - total non-muon calorimetric energy > 200 mm from event vertex
  - +60 MeV estimate of single pion calorimetric energy within 200 mm from event vertex
- Excluding the vertex region minimizes sensitivity to mis-modeling vertex activity in background events
- $E_\nu = E_\mu + E_\pi$ (assumes zero energy transfer to nucleus)
- Assume neutrino direction is parallel to beam axis
- $|t| = |(q - p_\pi)^2| = |(p_\nu - p_\mu - p_\pi)^2|$

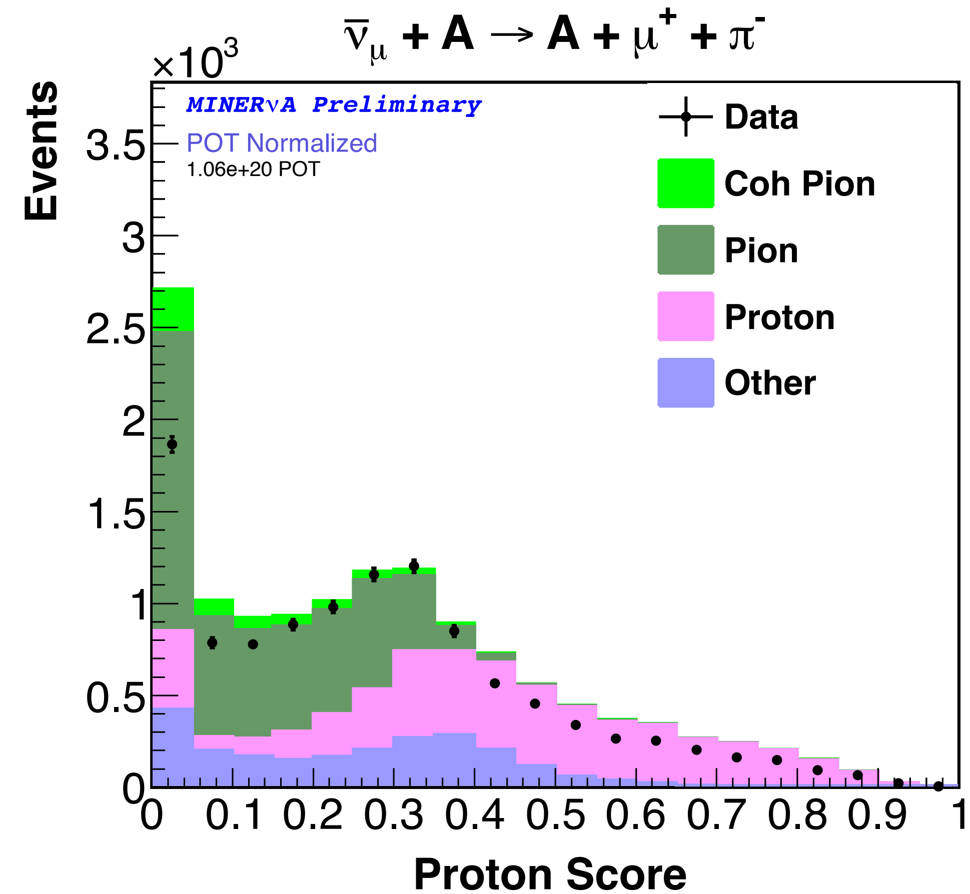
Event Selection: CC 2-Particle Sample

- Muon originates in the tracker region
- Muon is reconstructed in both MINERνA & MINOS
- Muon charge is negative for neutrinos, positive for antineutrinos
- Exactly one reconstructed hadron at the event vertex

Event Selection: Proton Veto

Cuts:
CC 2-Particle Sample

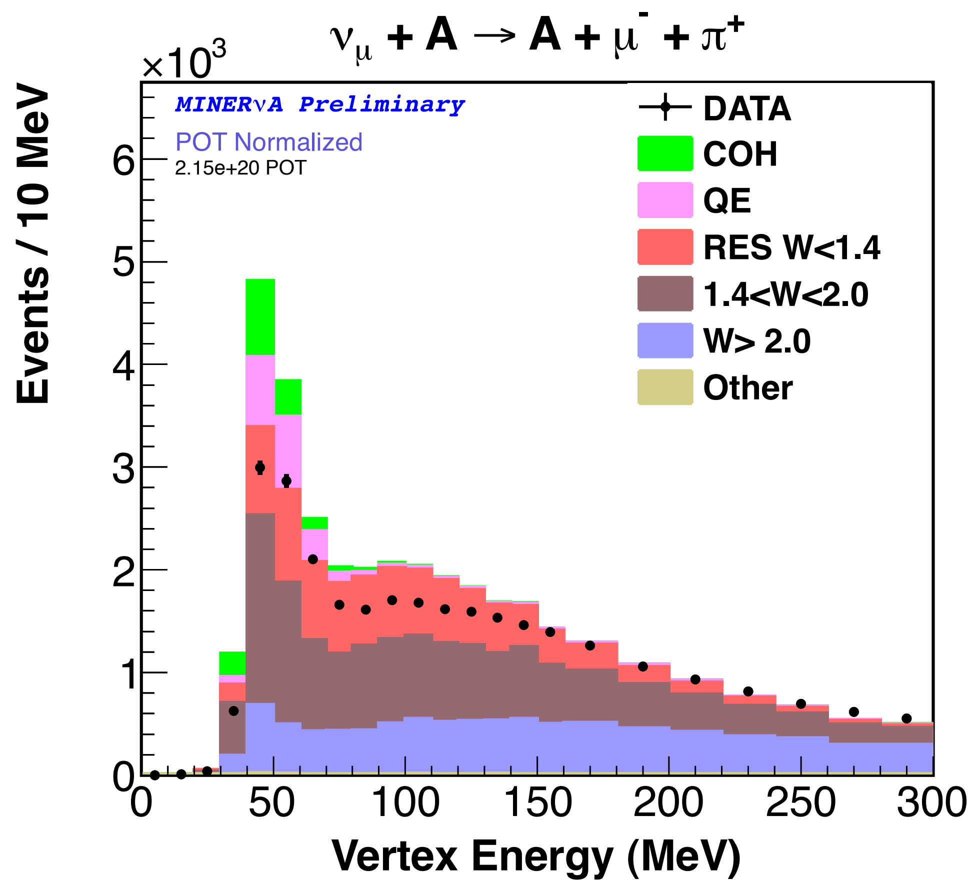


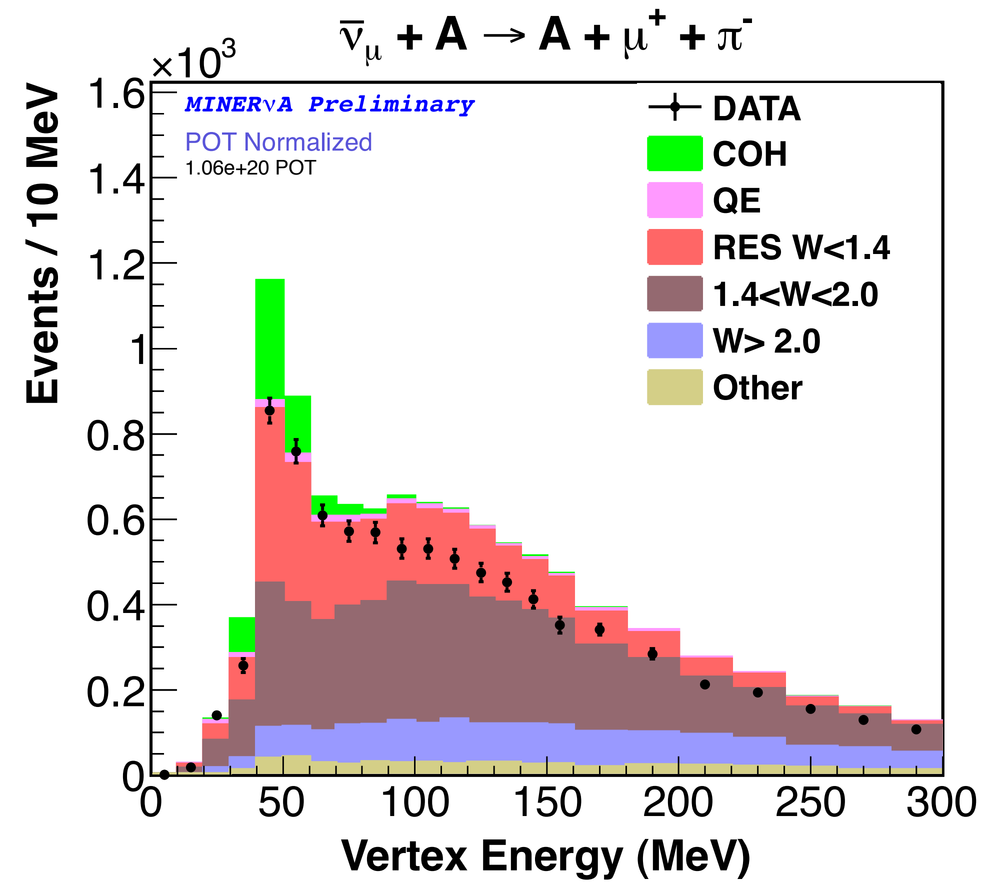


- Events with a reconstructed proton, particularly CCQE, are important backgrounds for the neutrino analysis
- Above is the proton likelihood of the reconstructed hadron from fitting the energy deposition along its reconstructed path
- To reject events with a reconstructed proton, the neutrino analysis requires the proton score be < 0.35
- The antineutrino analysis does not cut on this variable since events with a reconstructed proton are rejected by cuts on vertex energy and |t|

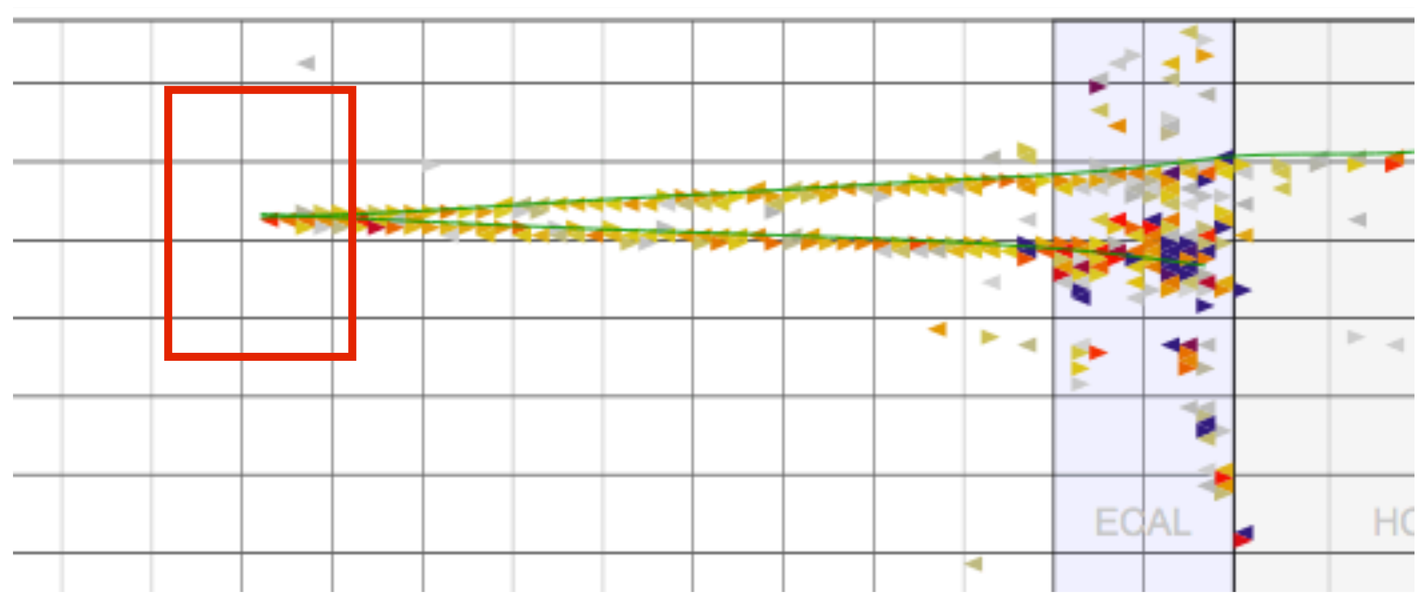
Event Selection: Vertex Energy

Cuts:
CC 2-Particle Sample
Proton Veto (ν_μ)



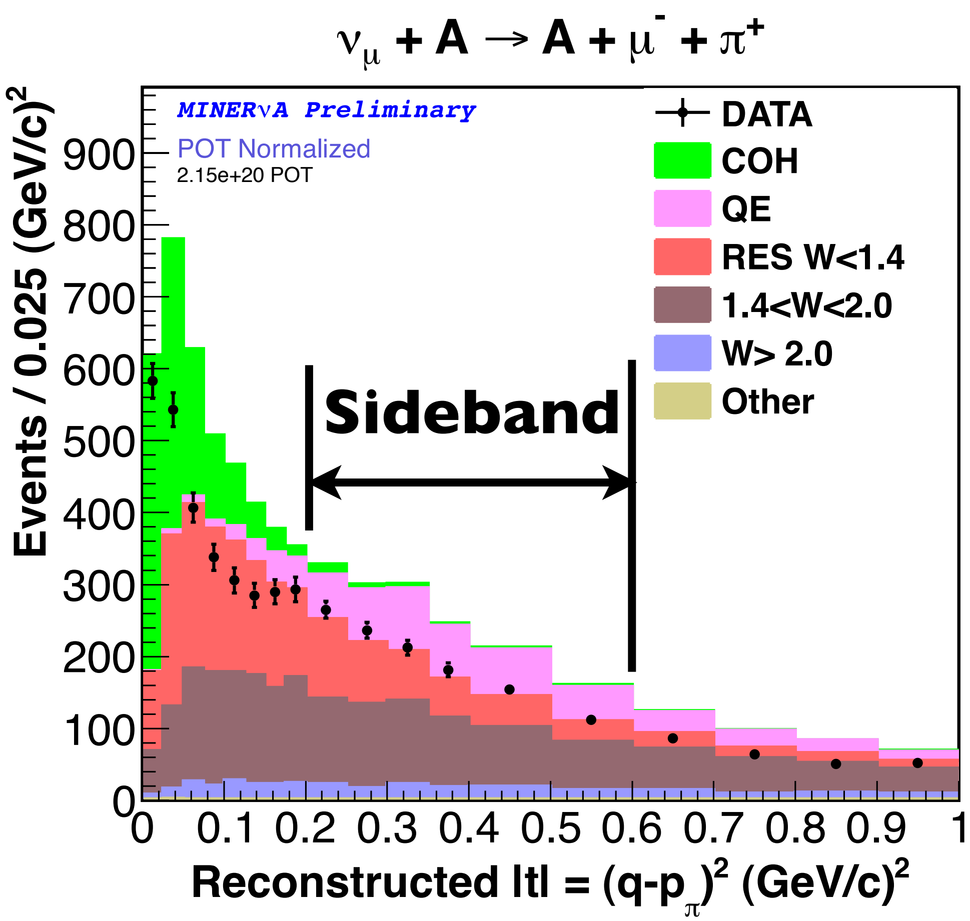


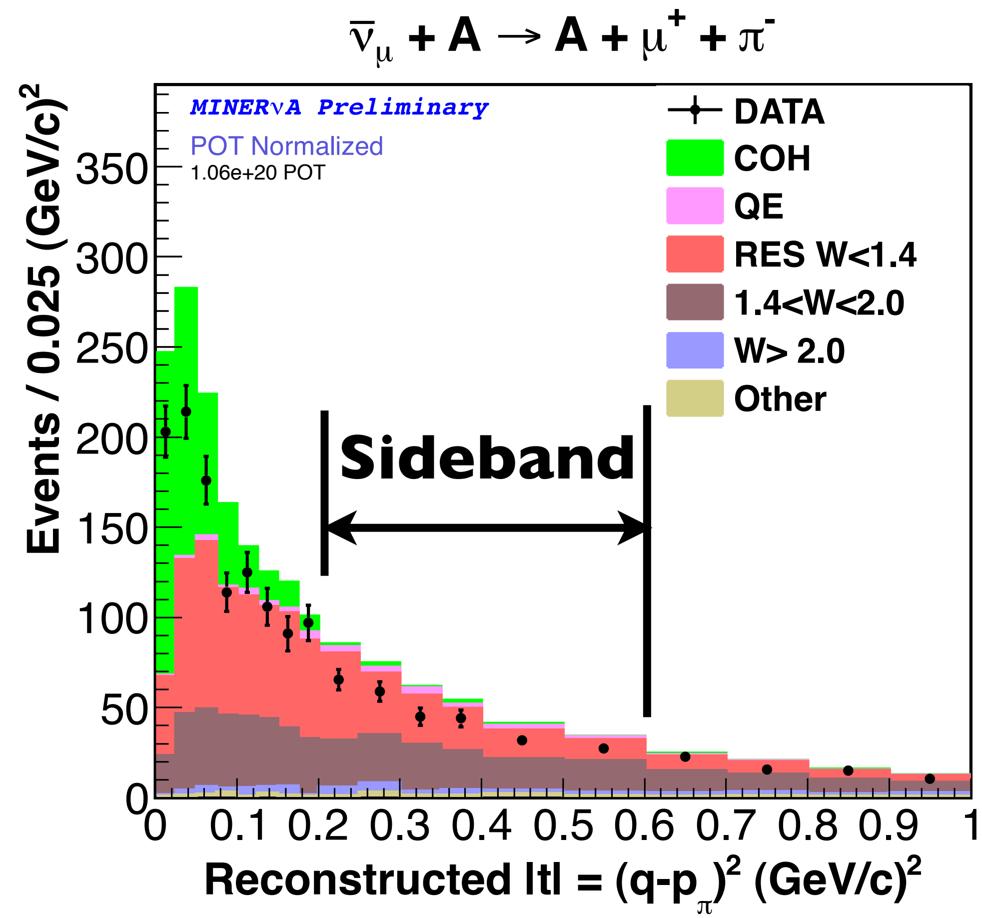
- No nuclear break-up occurs in coherent scattering
- We require the total energy within a region around the event vertex be consistent with a minimum ionizing muon and a pion
- Selected events:
  30 MeV < Vertex Energy < 70 MeV



Event Selection: |t|

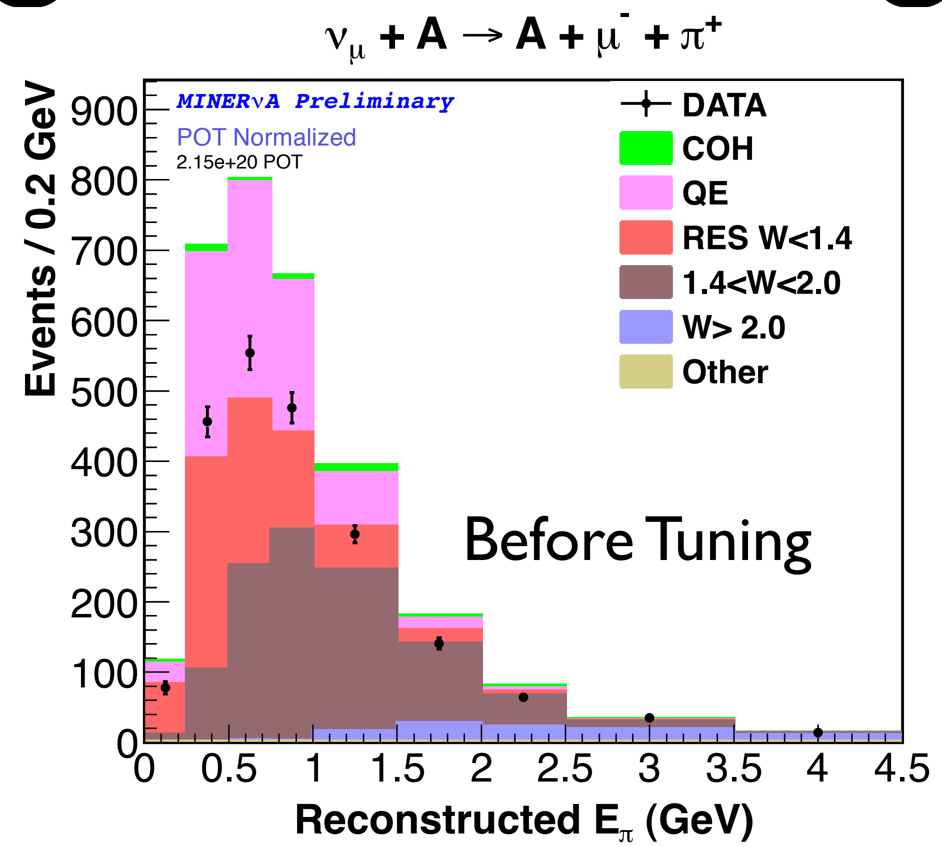
Cuts:
CC 2-Particle Sample
Proton Veto (ν_μ)
Vertex energy

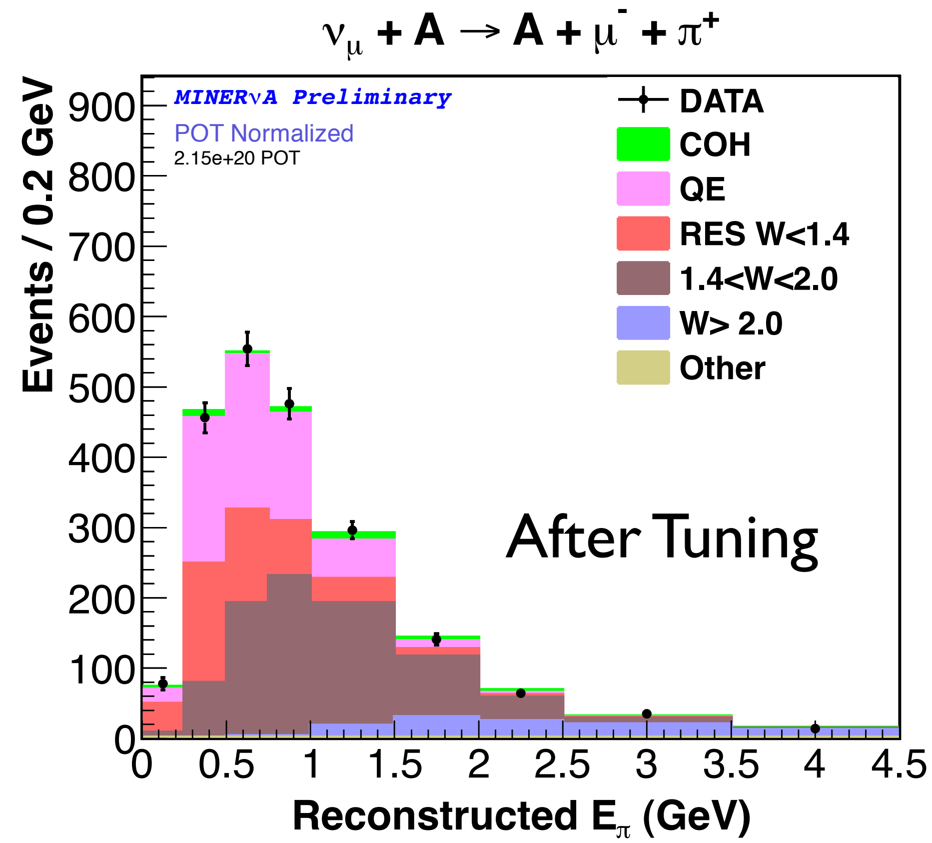




- $|t| = |(q-p_\pi)^2|$
- Selected events: $|t| < 0.125$ (GeV/c)^2
- Sideband for tuning backgrounds: 0.2 (GeV/c)^2 < $|t|$ < 0.6 (GeV/c)^2

Background Tuning: Neutrino





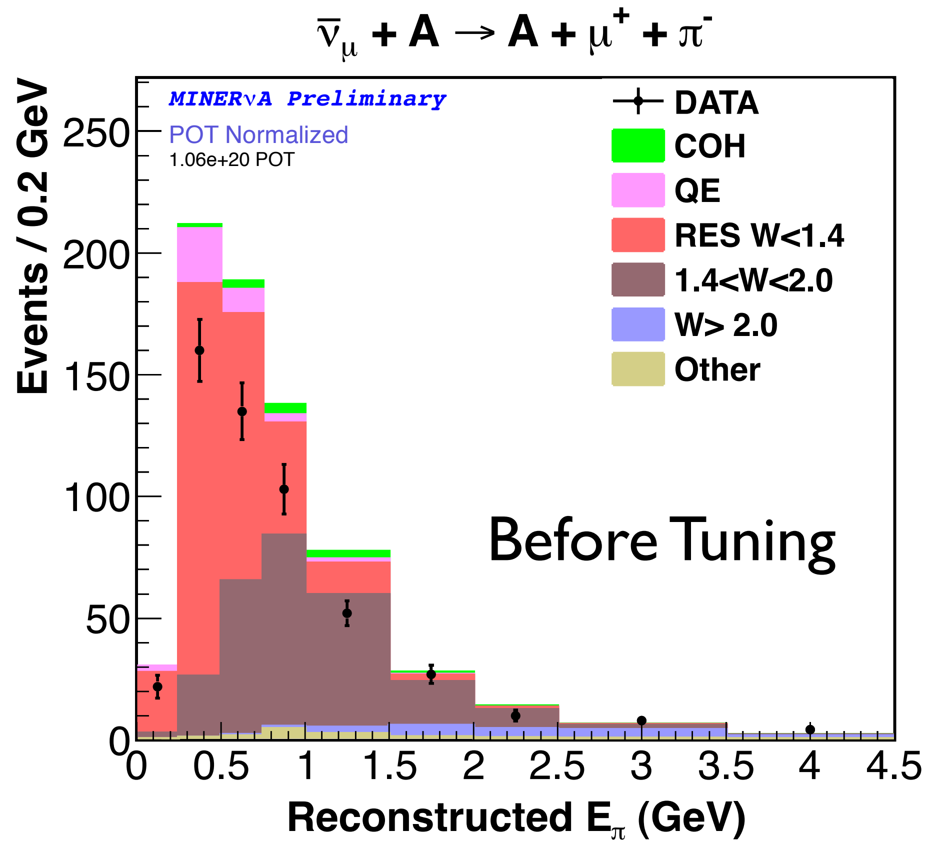
Cuts:
CC 2-Particle Sample
Proton Veto
Vertex energy
0.2 < |t| < 0.6

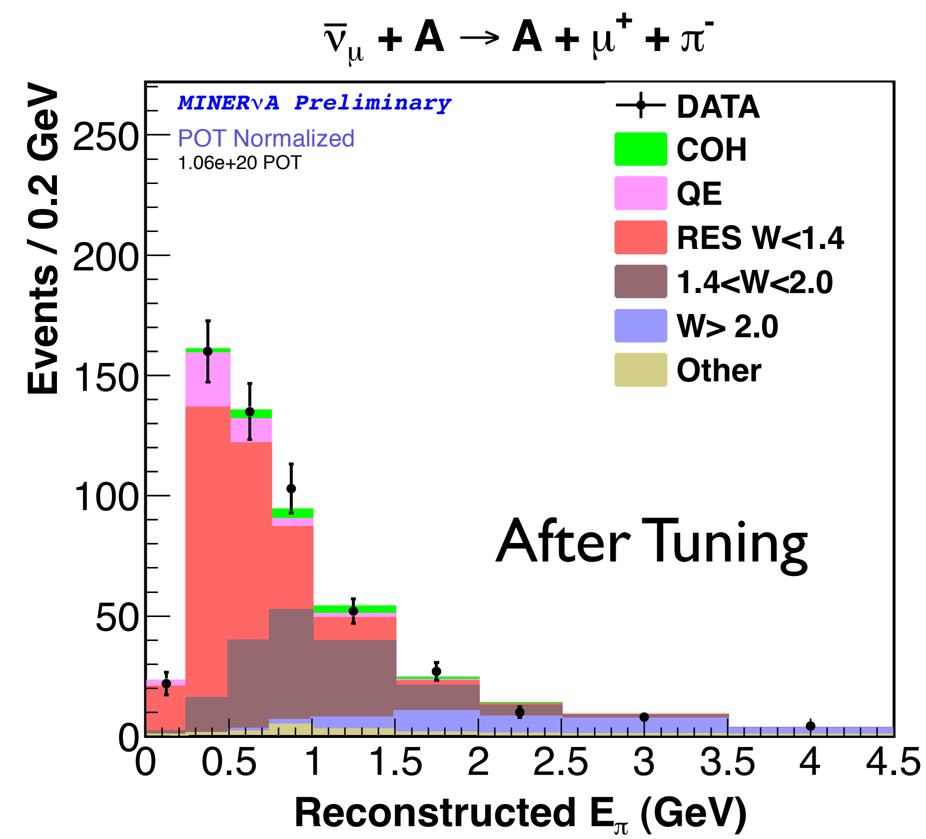
- Background tuning performed after vertex energy cut to minimize sensitivity to mis-modeling vertex activity
- Fit normalizations of MC backgrounds to data in sideband reconstructed E_π

Background (W in GeV)	Central Value Scale Factor
QE	0.7±0.3
RES W<1.4	0.6±0.3
1.4<W<2.0	0.7±0.1
W>2.0	1.1±0.1

Background Tuning: Antineutrino

Cuts:
CC 2-Particle Sample
Vertex energy
$0.2 < |t| < 0.6$

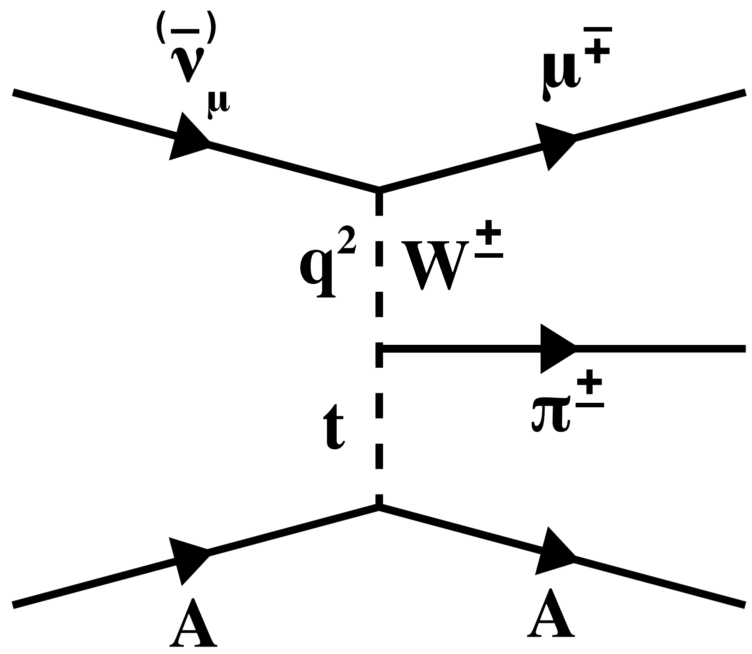




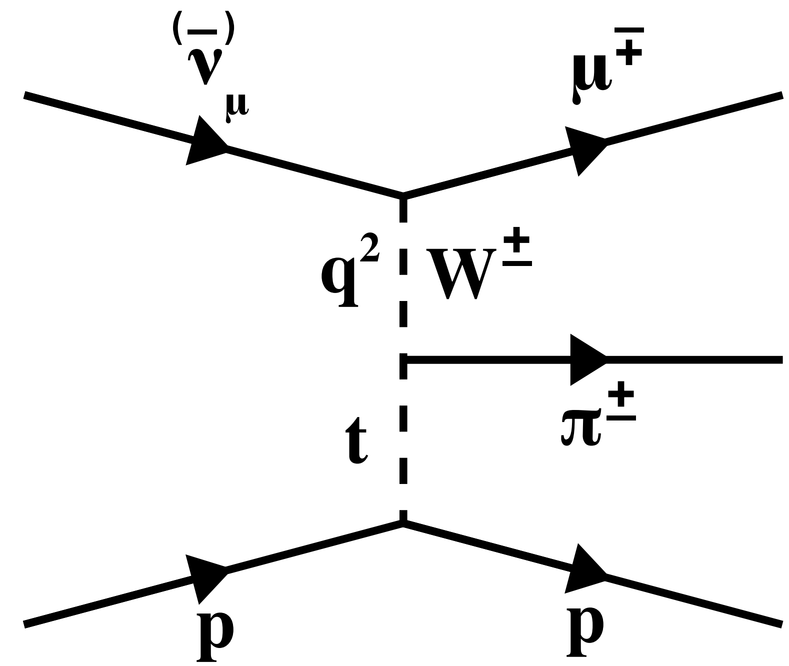
- Background tuning performed after vertex energy cut to minimize sensitivity to mis-modeling vertex activity
- Fit normalizations of MC backgrounds to data in sideband reconstructed E_π
- The normalization for CCQE is fixed in the antineutrino analysis since CCQE is a small contribution to the background

Background (W in GeV)	Central Value Scale Factor
QE	1.0 (fixed)
RES W<1.4	0.7±0.1
1.4<W<2.0	0.6±0.1
W>2.0	1.9±0.3

Diffractive Pion Production on Hydrogen



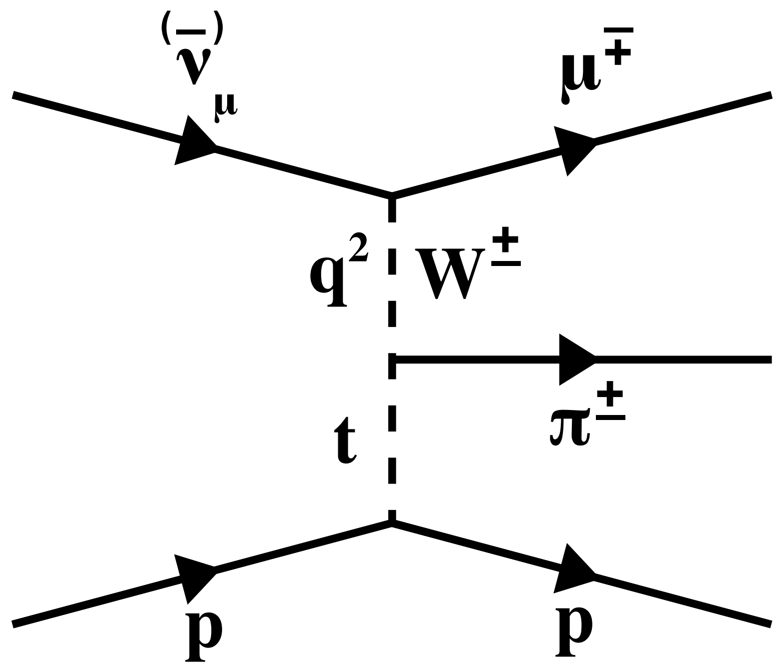
Coherent Pion Production on Carbon

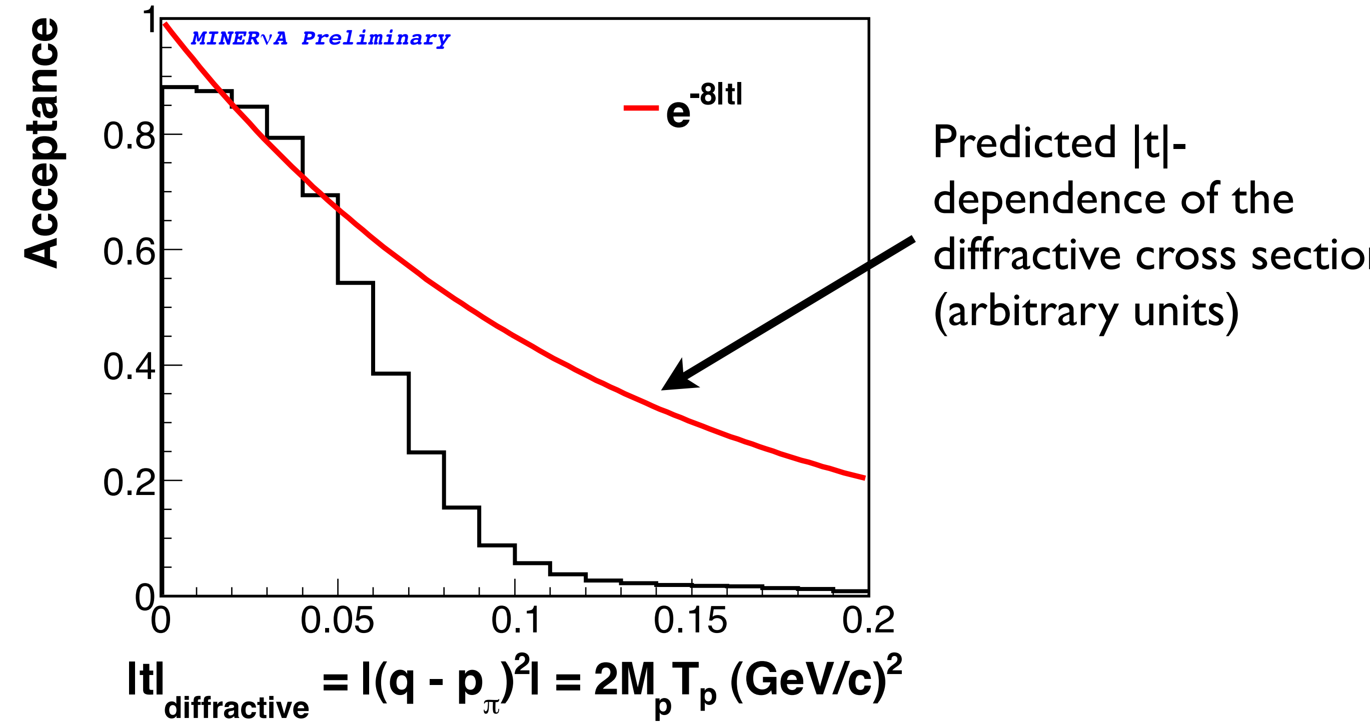


Diffractive Pion Production on Hydrogen

- By number, our fiducial volume targets are ~49% Carbon and ~49% Hydrogen
- We therefore expect a non-negligible contribution from diffractive pion production on Hydrogen which is not modeled in GENIE
- Due to the mass of the nucleus, ~0 energy is transferred to the nucleus in coherent scattering on Carbon while energy is transferred to the nucleus in diffractive scattering on Hydrogen
- We can detect the recoil proton in diffractive events when $|t|_{diffractive} = |(q-p_{\pi})^2| = 2M_pT_p$ is sufficiently large

Diffractive Pion Production off Hydrogen





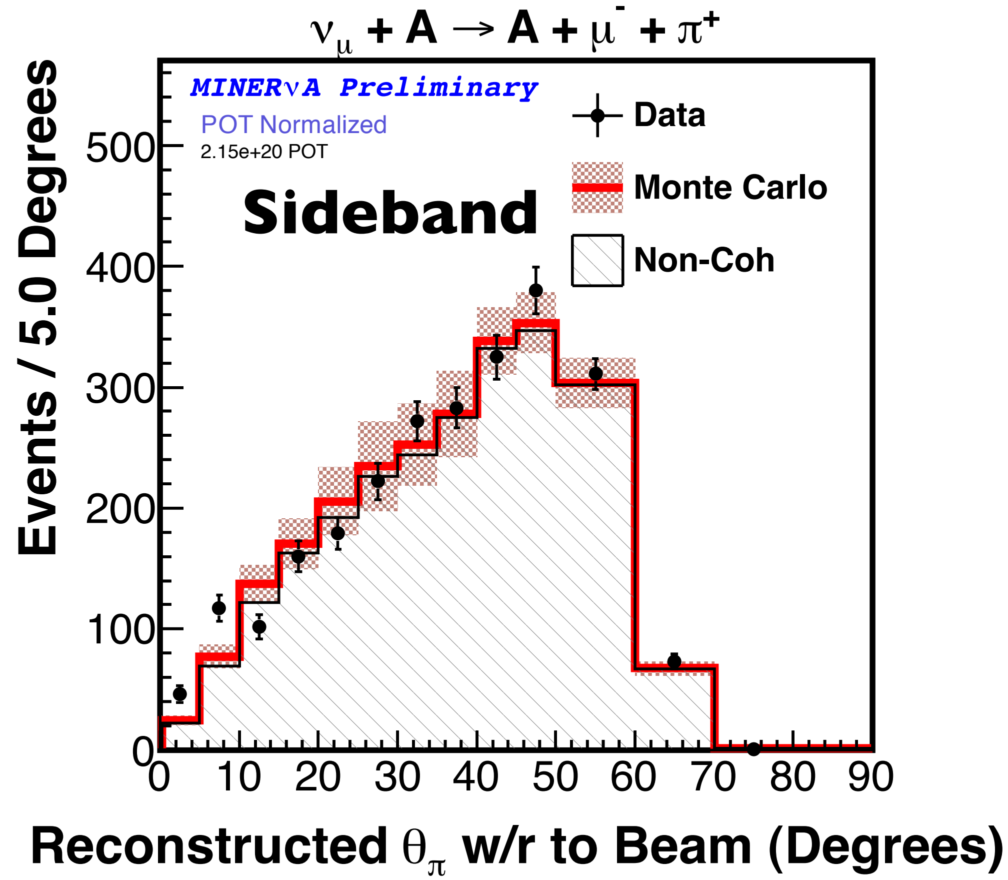
- To estimate our diffractive acceptance, we overlaid a proton onto true signal events and determined the acceptance of our vertex energy cut as a function of $|t|_{diffractive} = |(q-p_\pi)^2| = 2M_pT_p$
- We estimate our integrated relative coherent-to-diffractive acceptance to be ~40%
- Per the color dipole model (arXiv:1107.2845), the ratio of the production cross sections for coherent scattering on Carbon and diffractive scattering on Hydrogen is ~2:1 for $Q^2 = 0.13$ $(GeV/c)^2$ and $\nu = 0.9$ GeV
- From this ratio and our estimated diffractive acceptance, ~17% of our signal is diffractive
- Our |t| reconstruction, which assumes zero energy transfer to the nucleus, should give reasonable reconstructed $|t|_{diffractive}$ for small T_p
- The diffractive contribution to our sideband (0.2<|t|<0.6) should be small

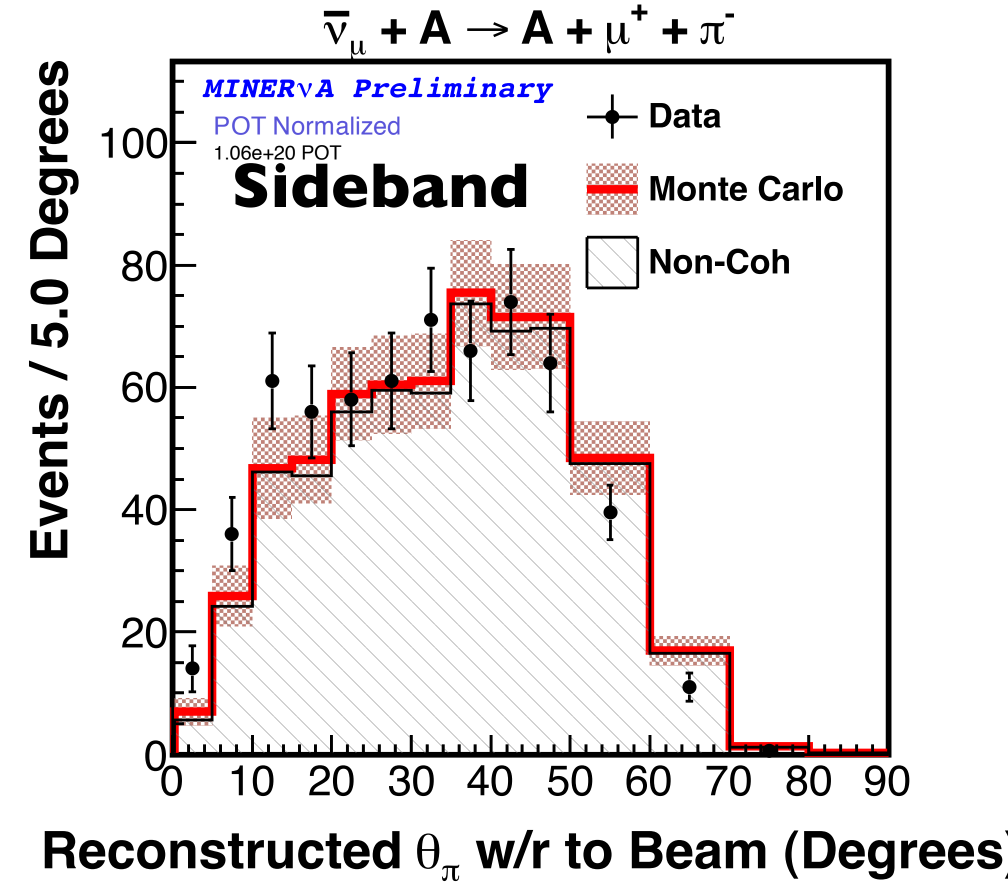
Systematics Summary

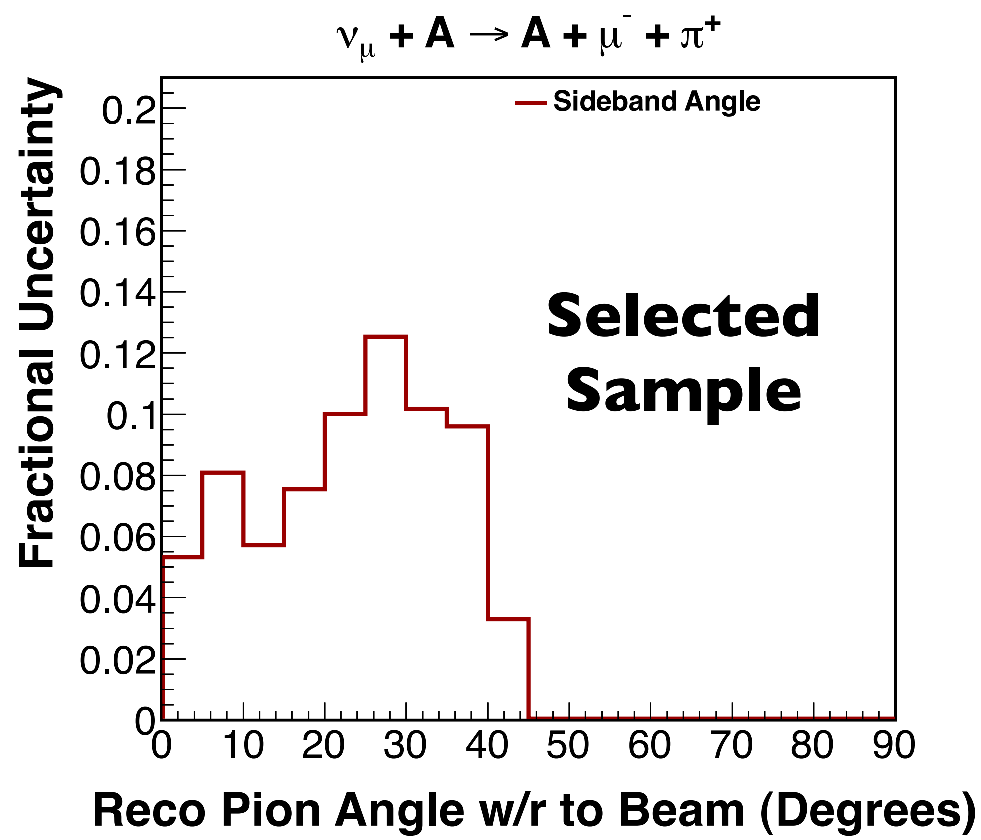
- Flux - see talk from Debbie Harris
- Interaction Model (GENIE)
  - largest contributions to error from resonance M_A and pion FSI
  - additional error for disagreement between our data and the GENIE prediction in our sideband
- MINERνA+MINOS Muon Reconstruction Efficiency
- Energy Response - constrained by MINERνA Test Beam
- Detector Model - primarily Geant4 systematics
- Vertex Energy

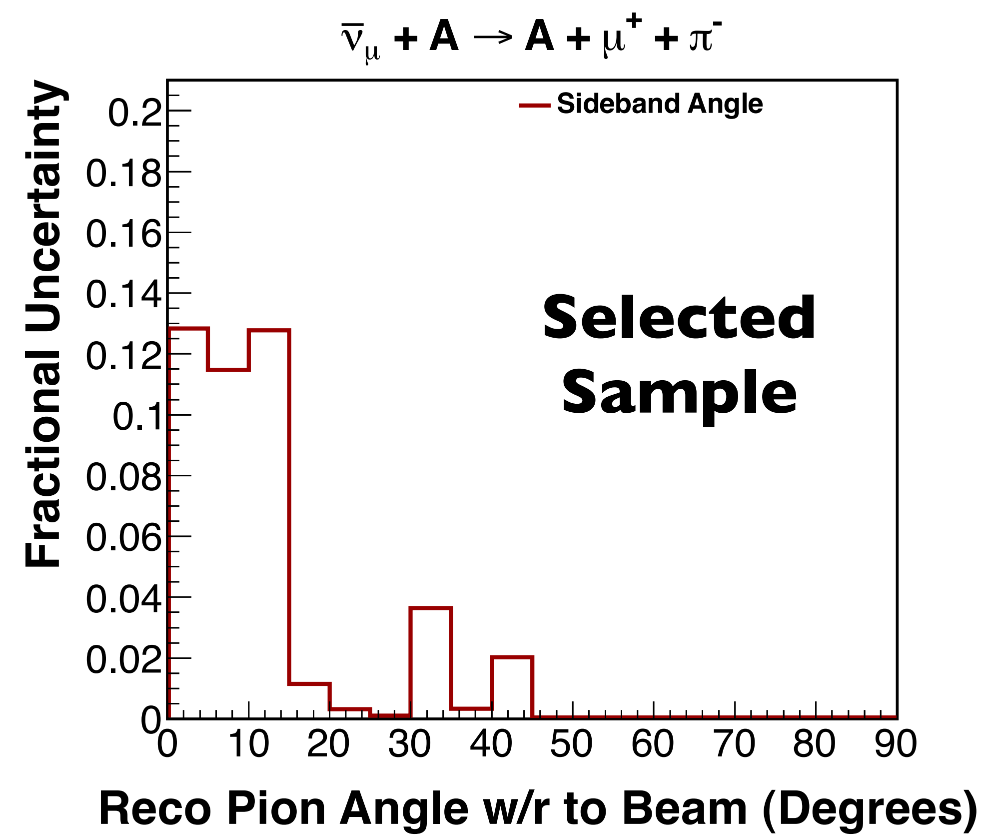
Systematics: Sideband Model

We apply an additional systematic to our selected backgrounds to cover disagreement in our tuned sideband θ_π distribution

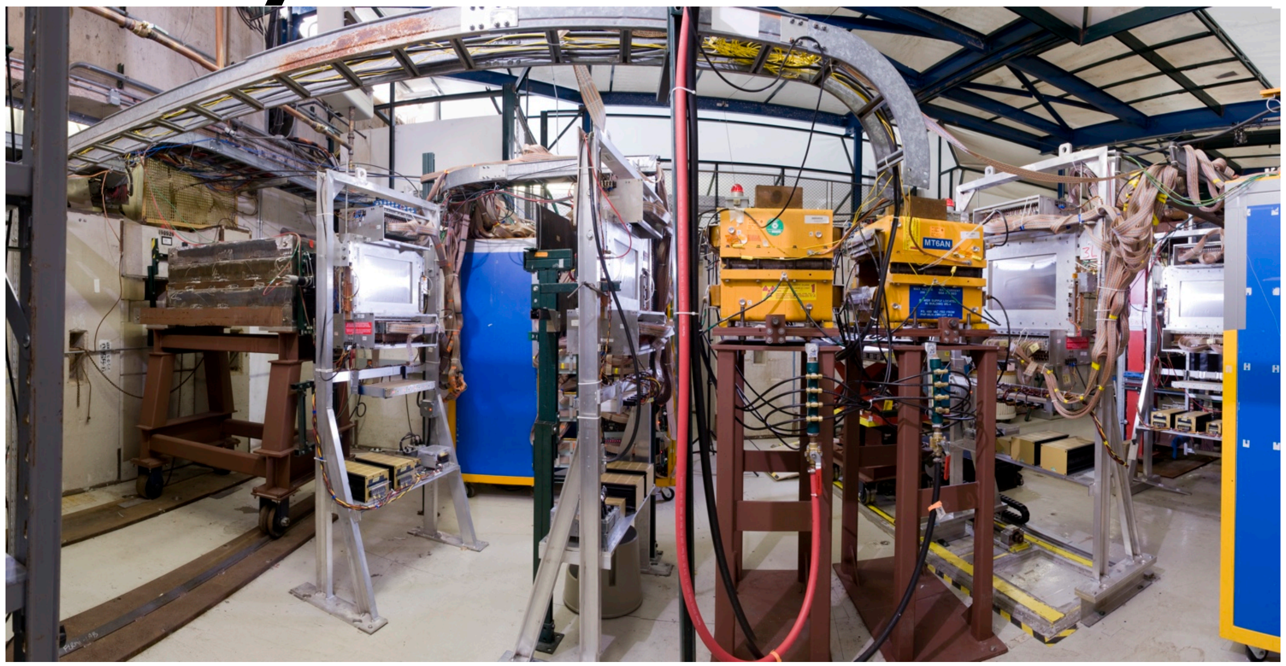


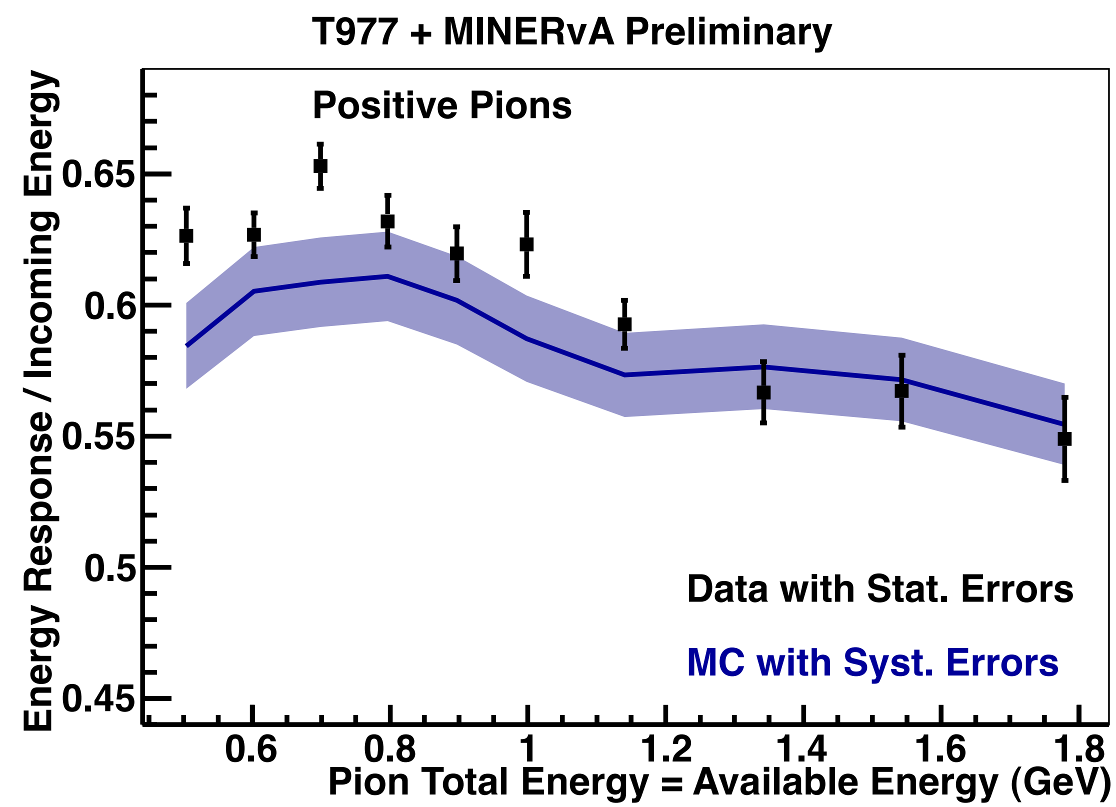


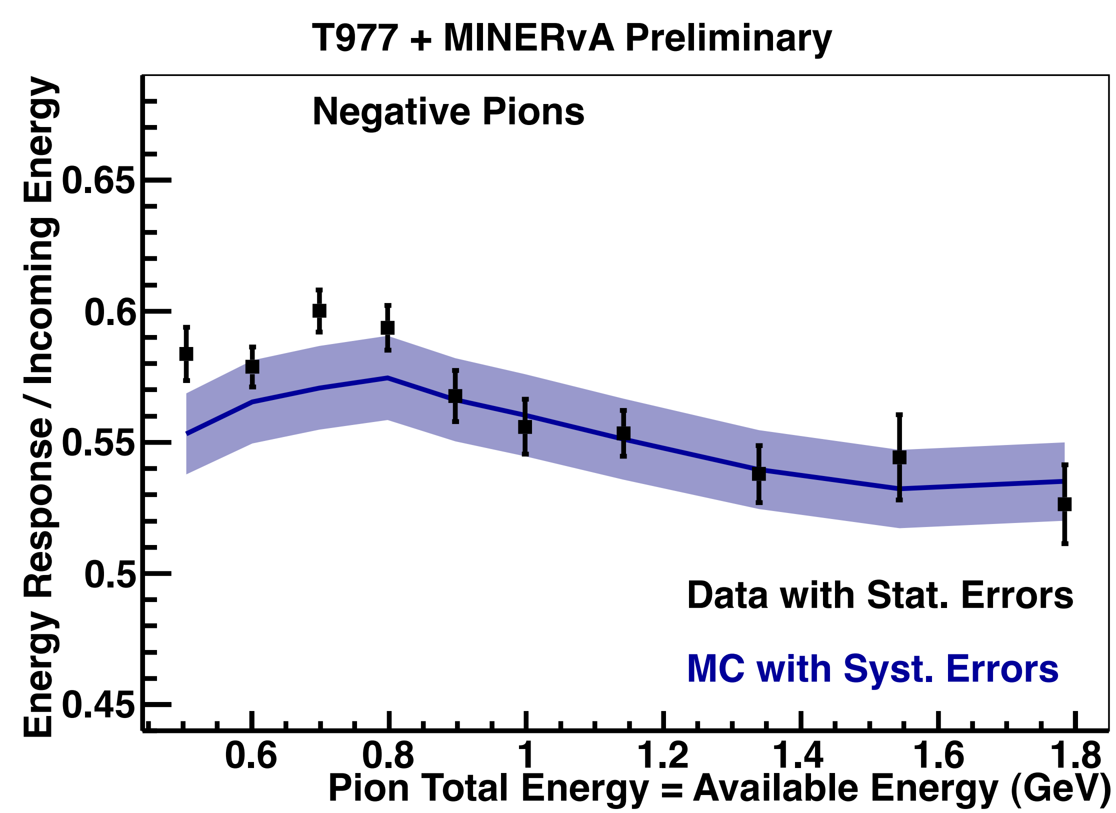




Systematics: Energy Response



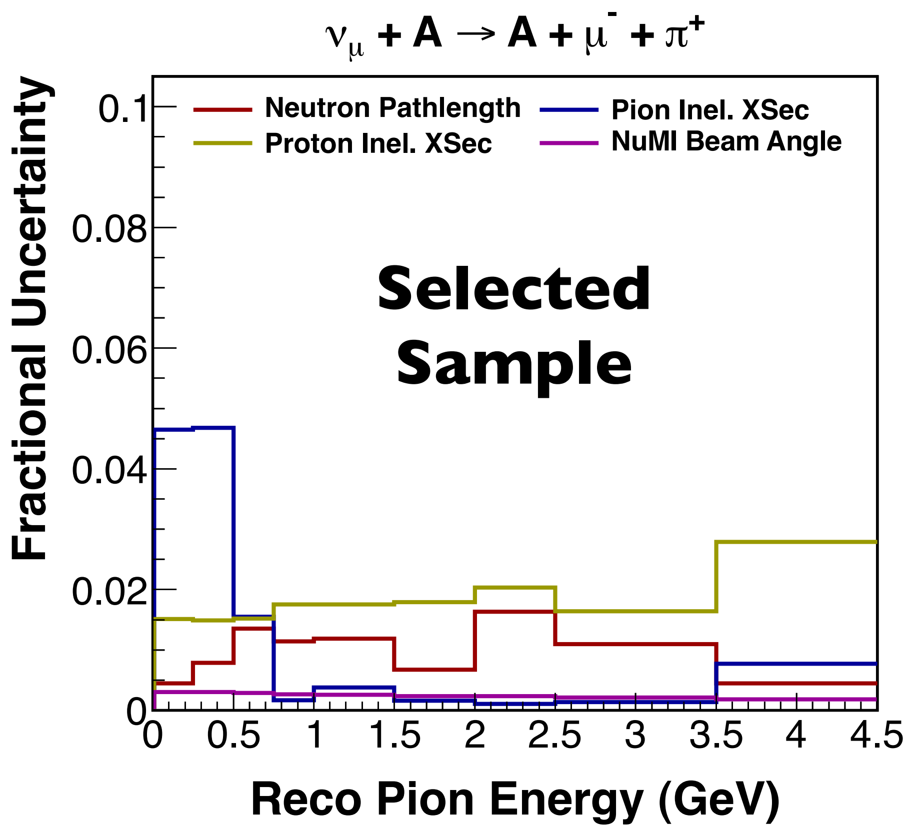


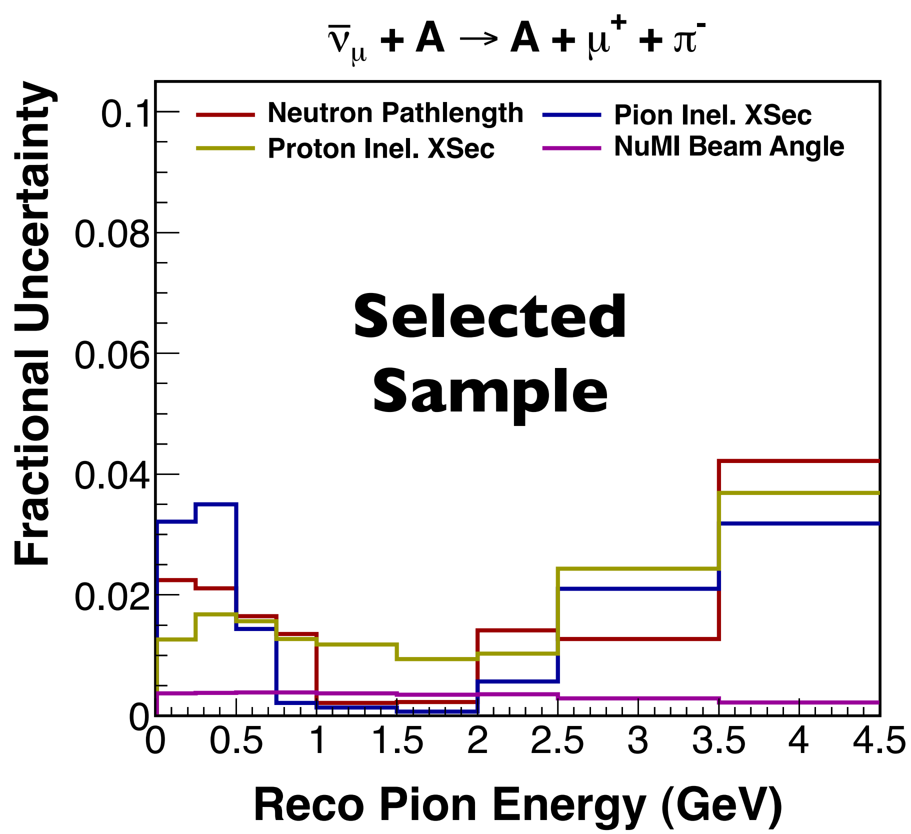


- MINERνA Test Beam:
  - a tertiary pion beam with a smaller version of the MINERνA detector in the Fermilab Test Beam Facility
  - provides a calibration of pion and proton response in the MINERνA detector
  - provides an error band (~5%) on the pion and proton response for systematics on MINERνA's
    - detector mass model
    - scintillator optical model
    - photomultiplier tube (PMT) model

Systematics: Detector Model

- GEANT4 simulates particle propagation in MINERνA, which affects our tracking efficiency, vertex energy, and energy reconstruction
- Use re-weighting to modify
  - pion and proton total inelastic cross section ±10%
  - neutron path length
- We also apply an uncertainty on the neutrino beam angle since our reconstruction of $|t| = |(q - p_\pi)^2| = |(p_\nu - p_\mu - p_\pi)^2|$ assumes the direction of the neutrino is parallel to the beam axis



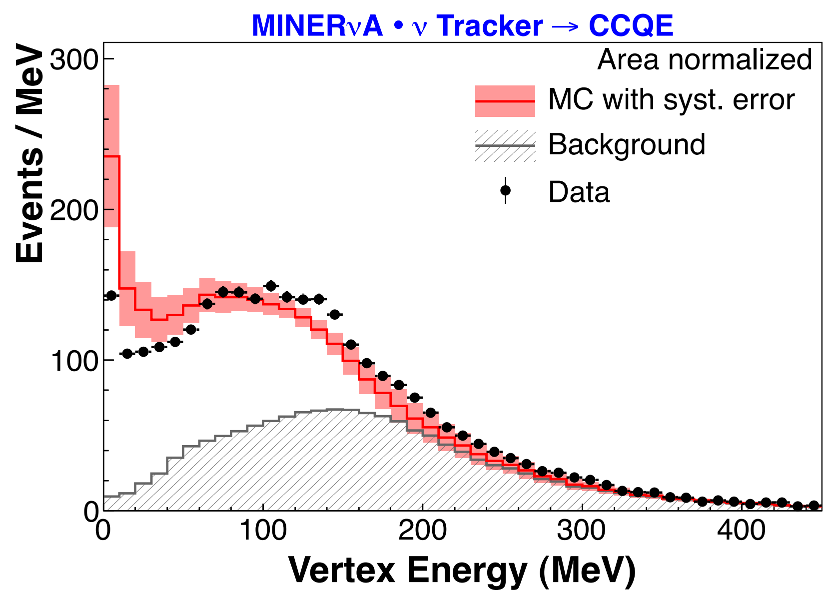


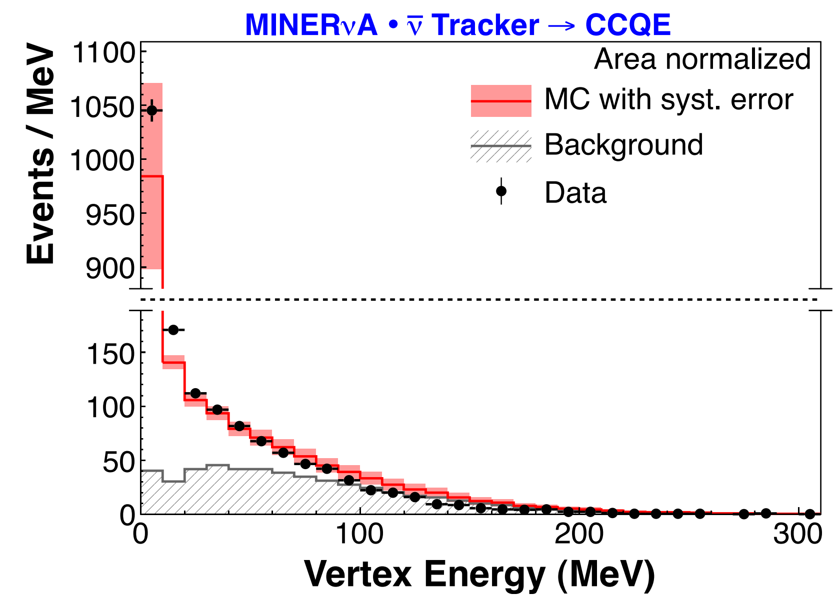
Systematics: Vertex Energy

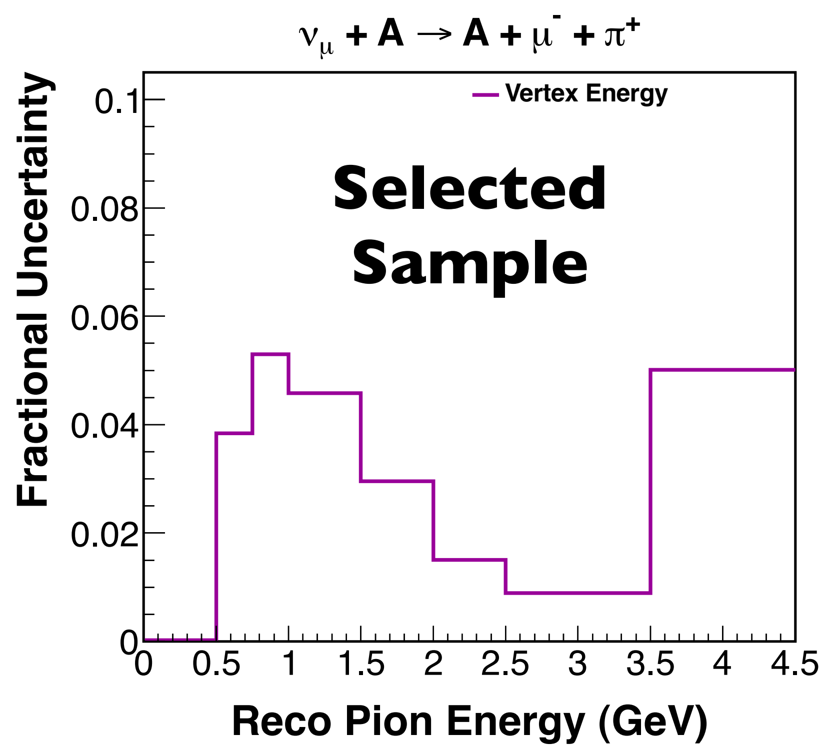
MINERνA's CCQE results found an excess in vertex energy in data compared to the GENIE prediction
Phys. Rev. Lett. 111, 022501 (2013)
Phys. Rev. Lett. 111, 022502 (2013)

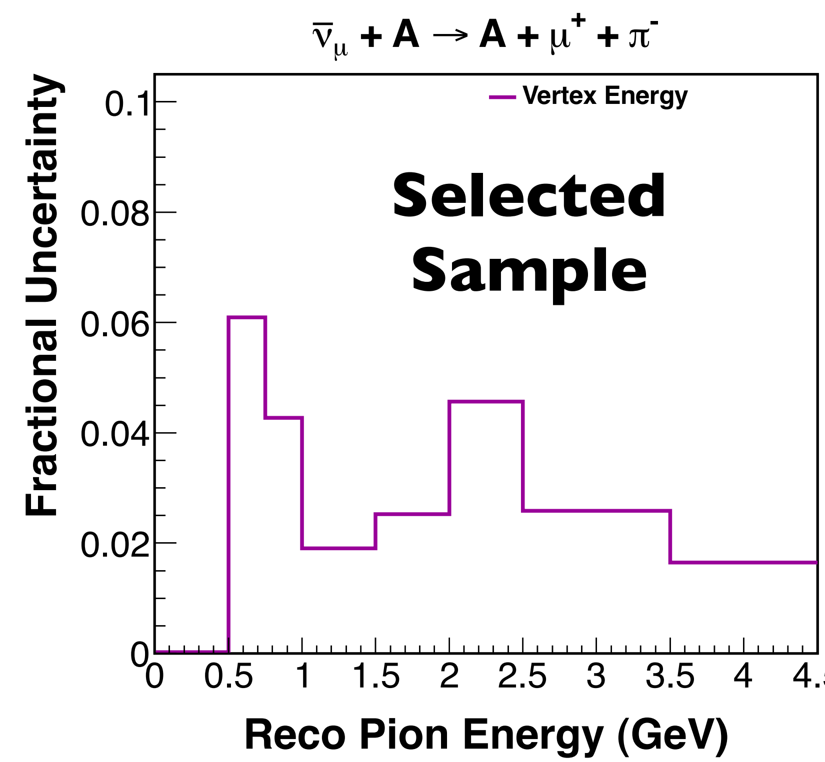
A fit to this excess prefers the addition of a final state proton with KE < 225 MeV to 25% of events with a target neutron

Motivated by these results, we estimated the effect of mis-modeling vertex activity on our analysis by overlaying a proton with KE < 225 MeV onto 25% of our background events with a target neutron







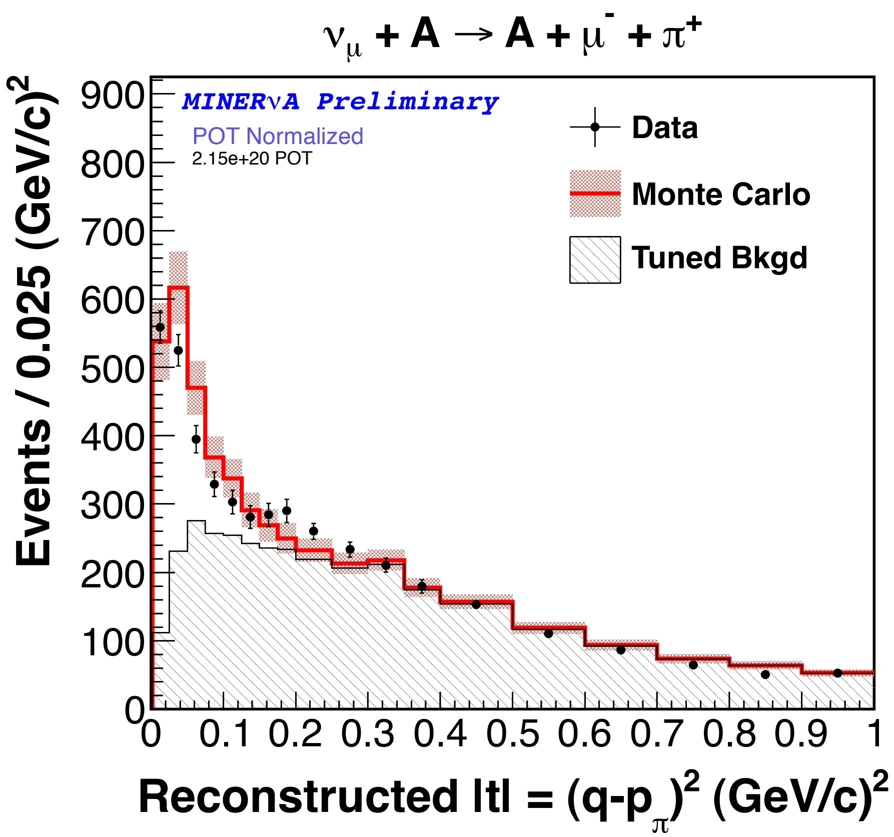


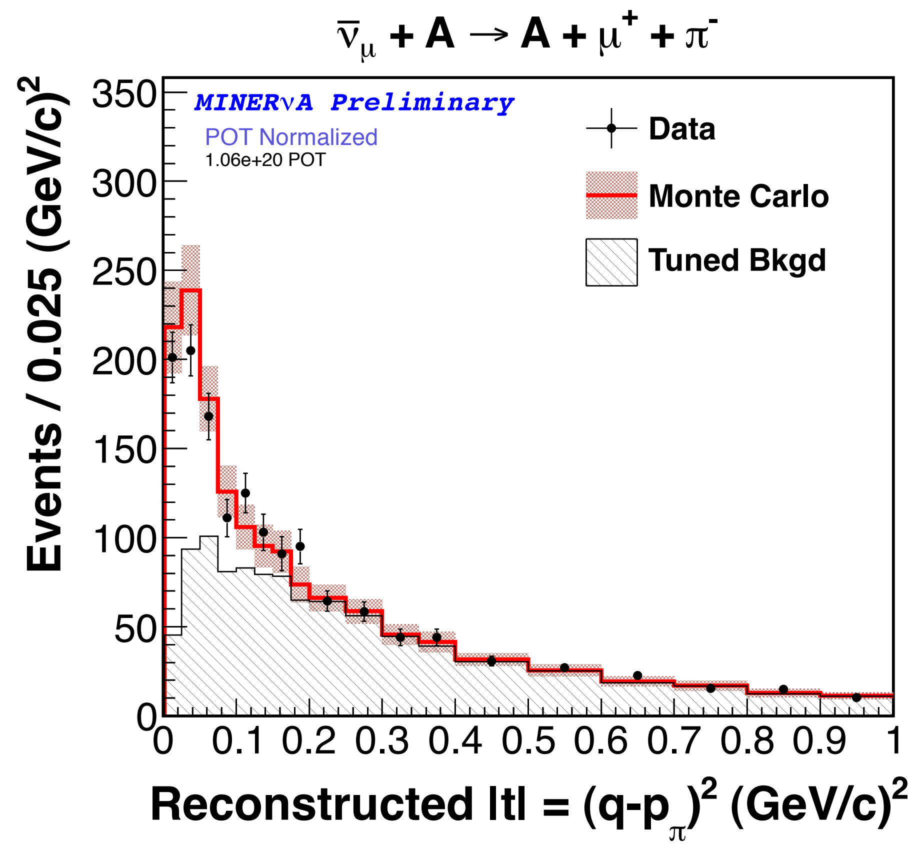
Reconstructed |t|

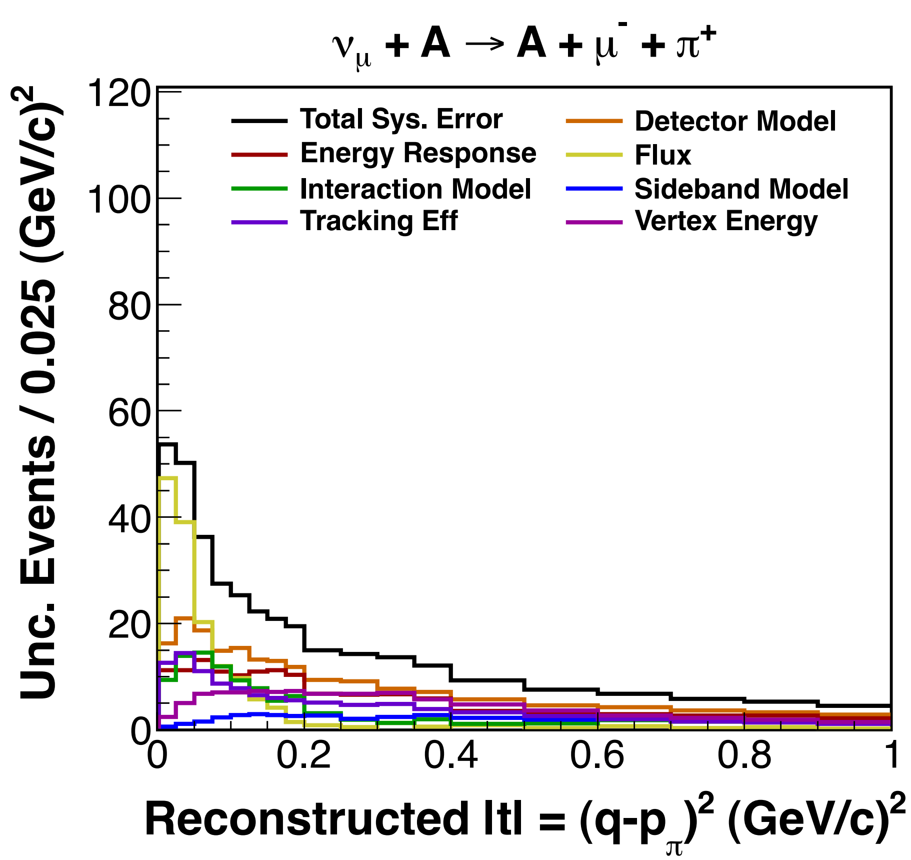
Cuts:
CC 2-Particle Sample
Proton Veto (ν_μ)
Vertex energy

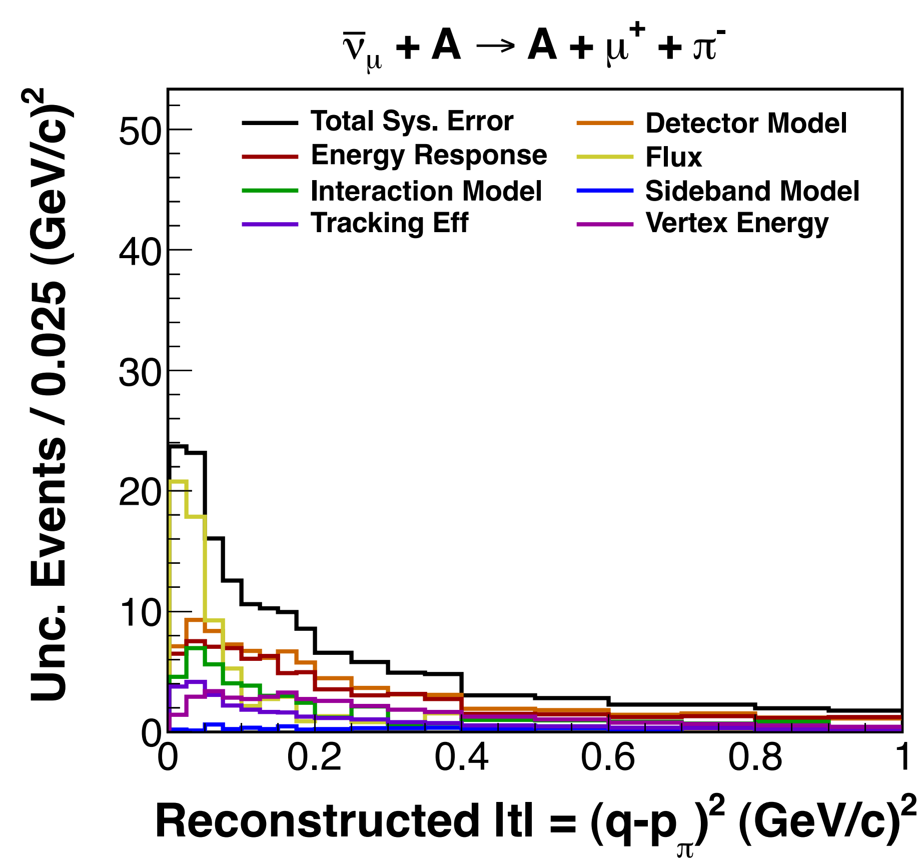
We definitely see a signal above our tuned background at low |t|

Selected Events:
$|t| < 0.125\ (\text{GeV}/c)^2$

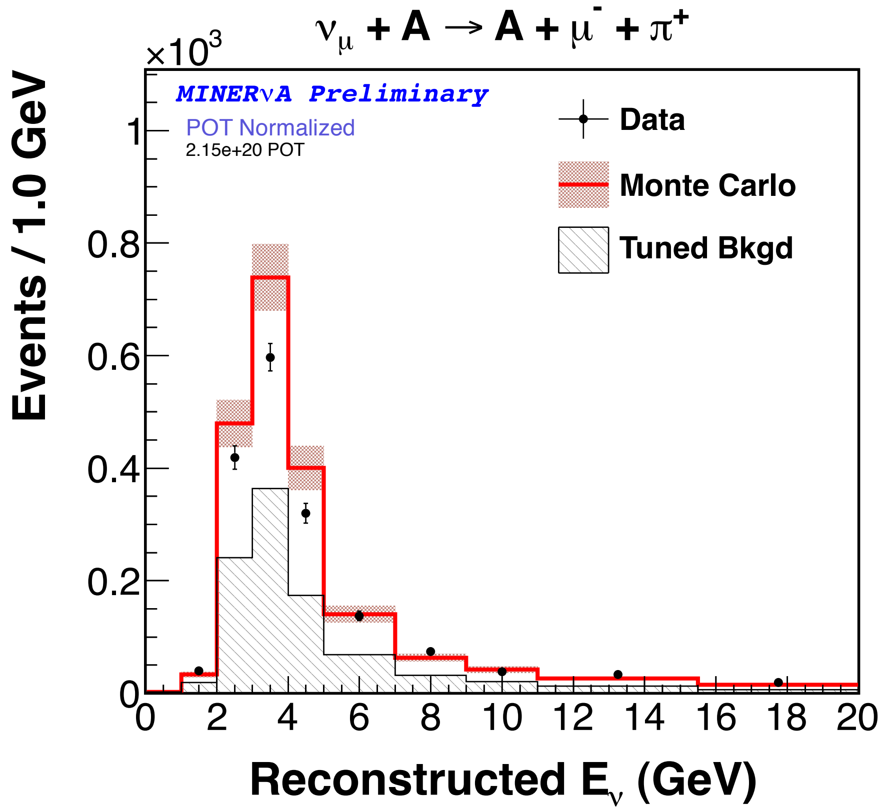


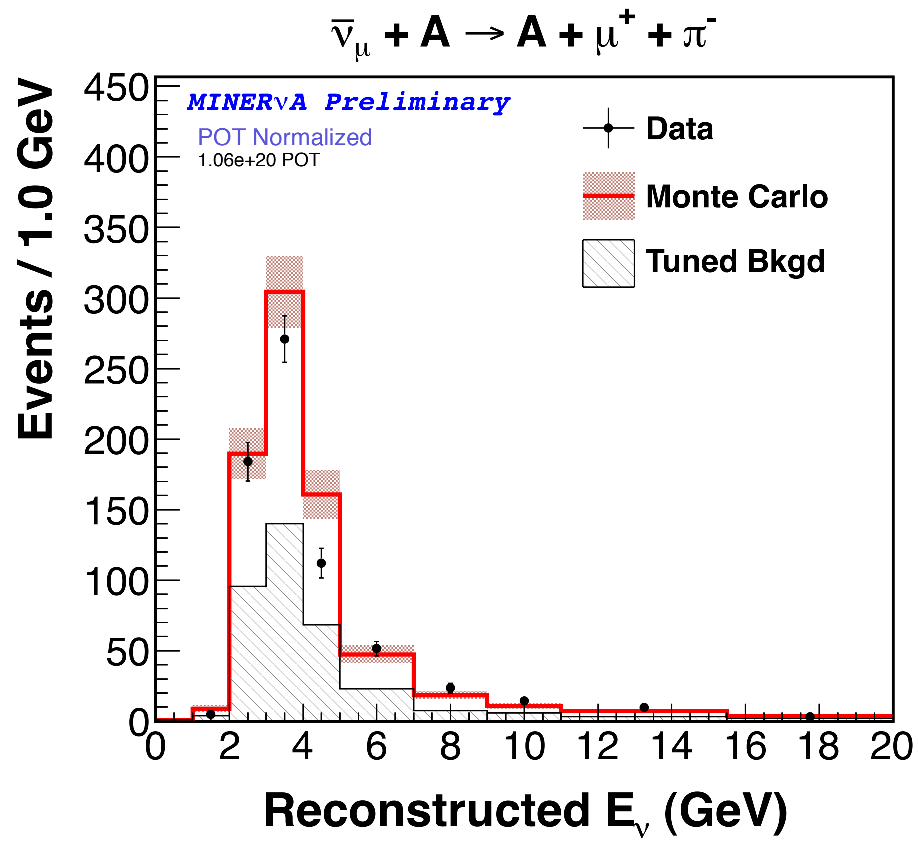


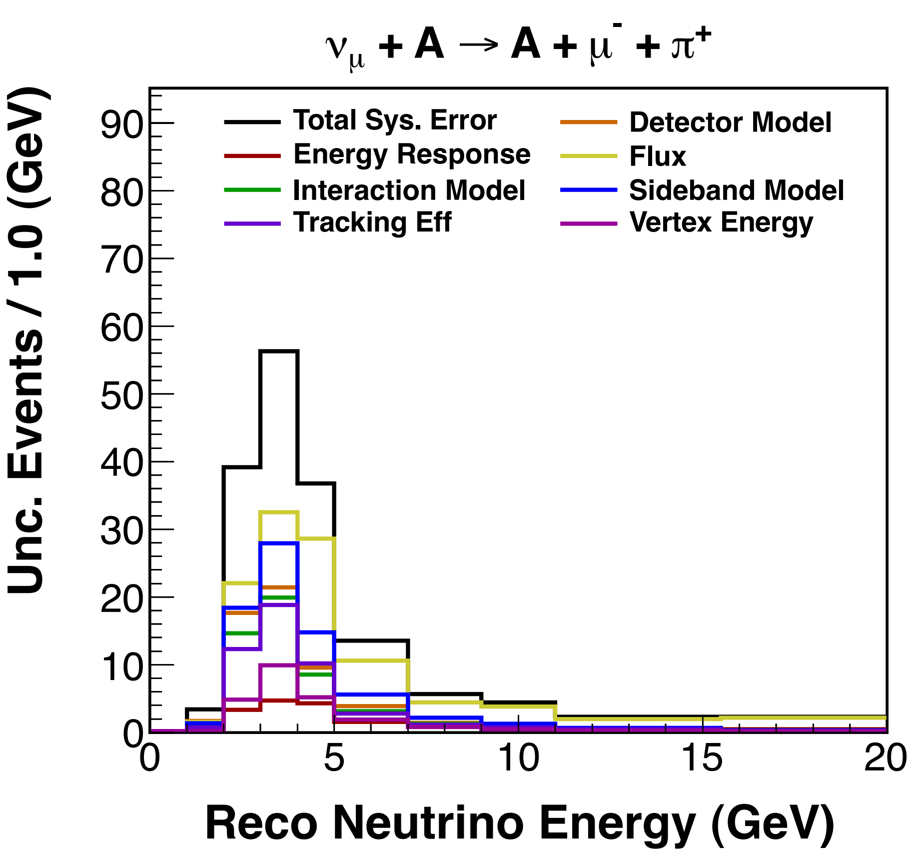


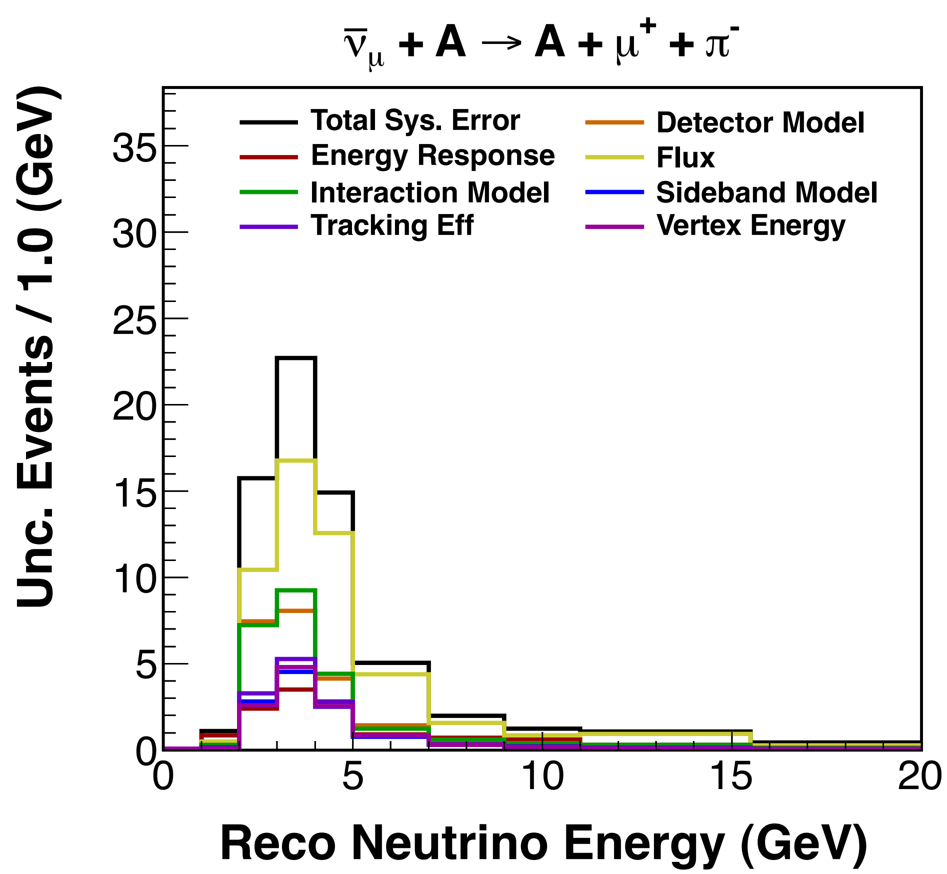


Selected Events: E_ν









Calculating the Cross Sections

$$\sigma_i(E_\nu) = \frac{1}{\Phi_i T} \frac{1}{\Delta E_{\nu,i}} \frac{\sum_j U_{ij}(N_{data,j} - N_{bg,j})}{\varepsilon_i}$$

- True Bin i: σ_i
- Flux: Φ_i
- # Targets: T
- Bin Width: $\Delta E_{\nu,i}$
- Reconstructed Bins: $\sum_j$
- Unfolding: U_{ij}
- Tuned Background: $N_{bg,j}$
- Efficiency/Acceptance Correction: ε_i

$$\left(\frac{d\sigma}{dE_\pi}\right)_i = \frac{1}{\Phi T} \frac{1}{\Delta E_{\pi,i}} \frac{\sum_j U_{ij}(N_{data,j} - N_{bg,j})}{\varepsilon_i}$$

- Integrated Flux: Φ

Cross Sections

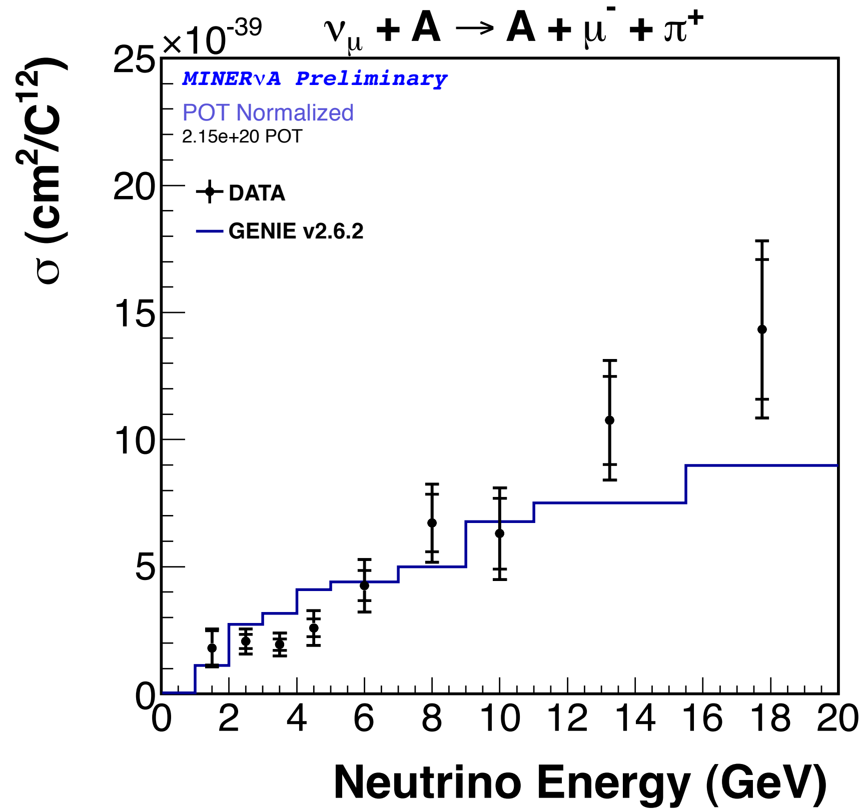
Inner error bars are systematic errors only

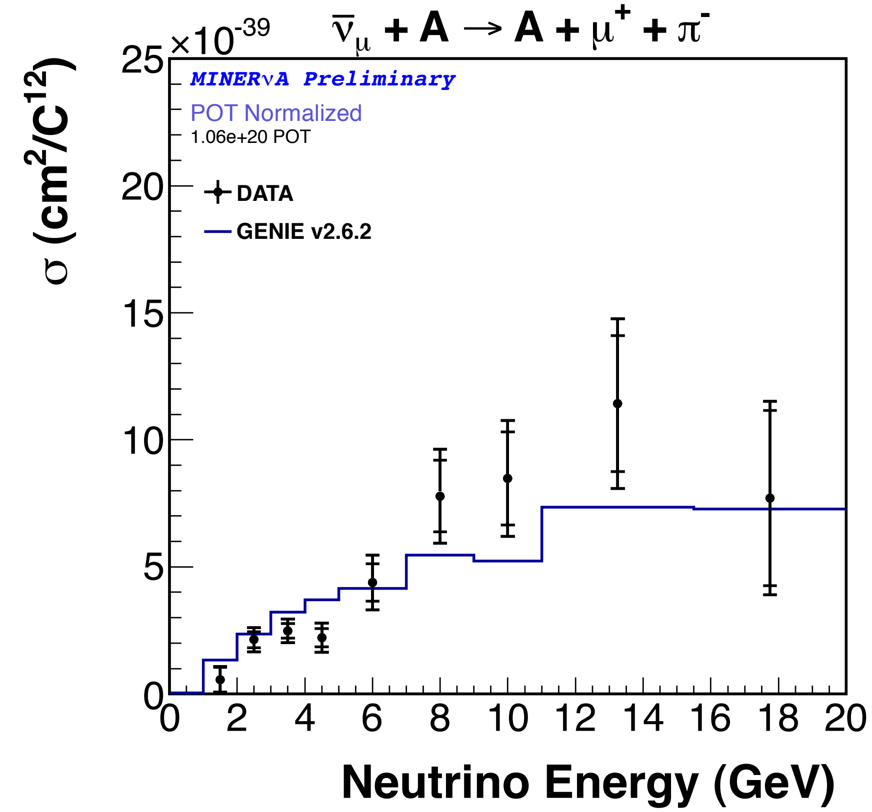
Outer error bars are systematic + statistical errors

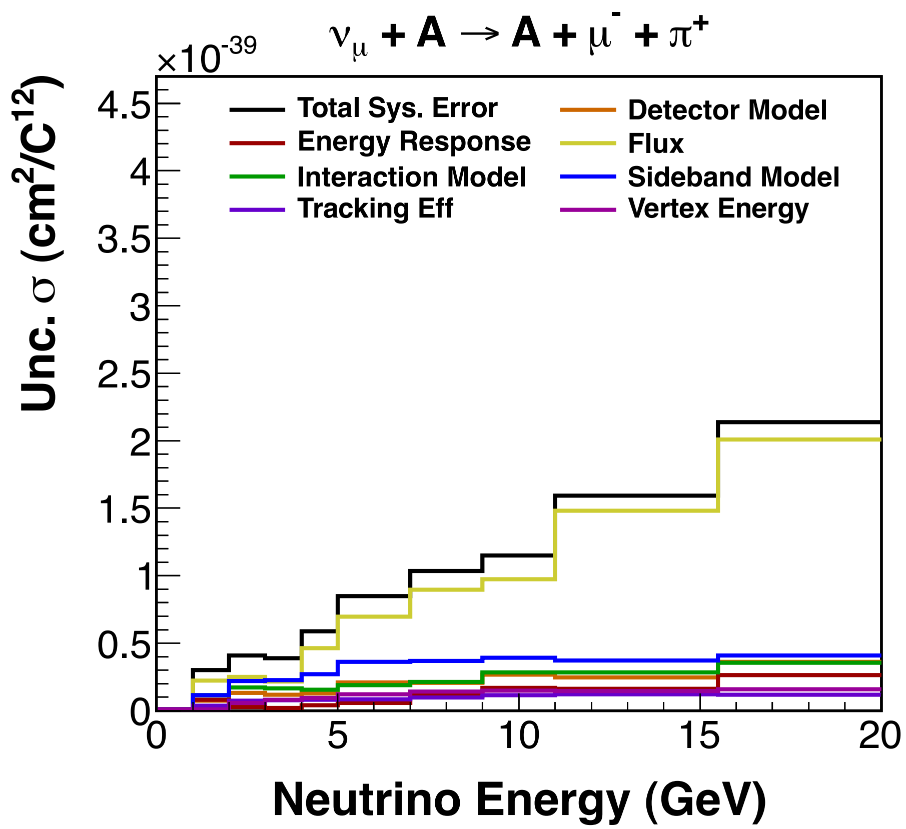
K2K and SciBooNE measurements were consistent with no CC coherent pion production for $E_\nu < 2$ GeV

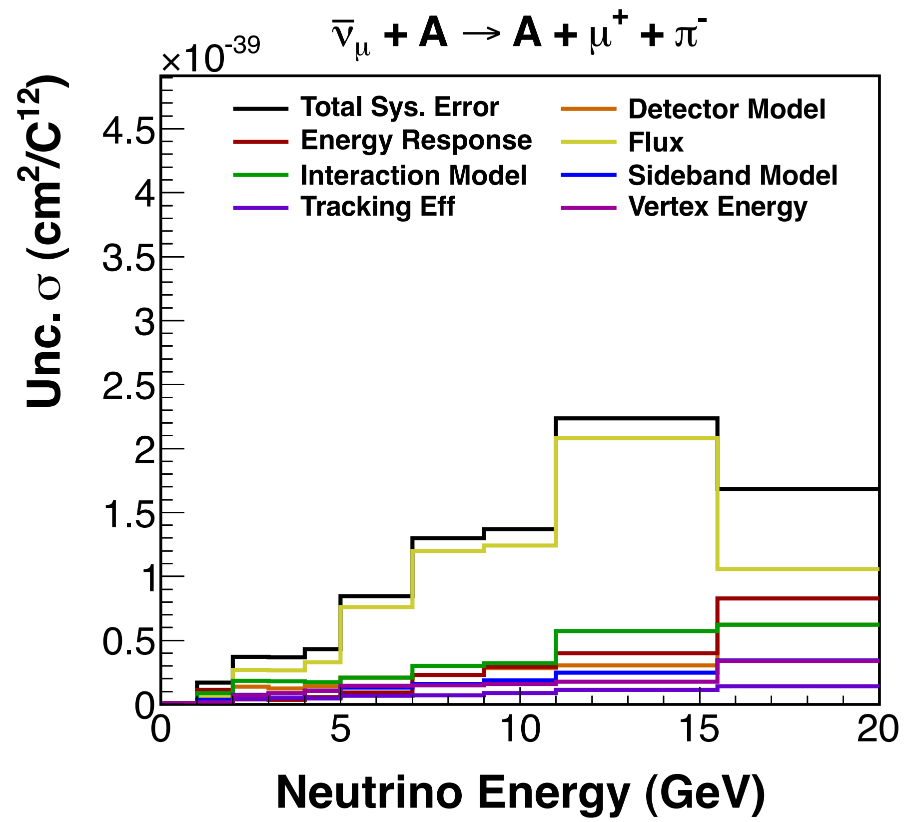
For $E_\nu < 5$ GeV, GENIE's Rein-Sehgal model predicts a higher production rate than our data

We estimate that ~17% of our signal is diffractive scattering off Hydrogen

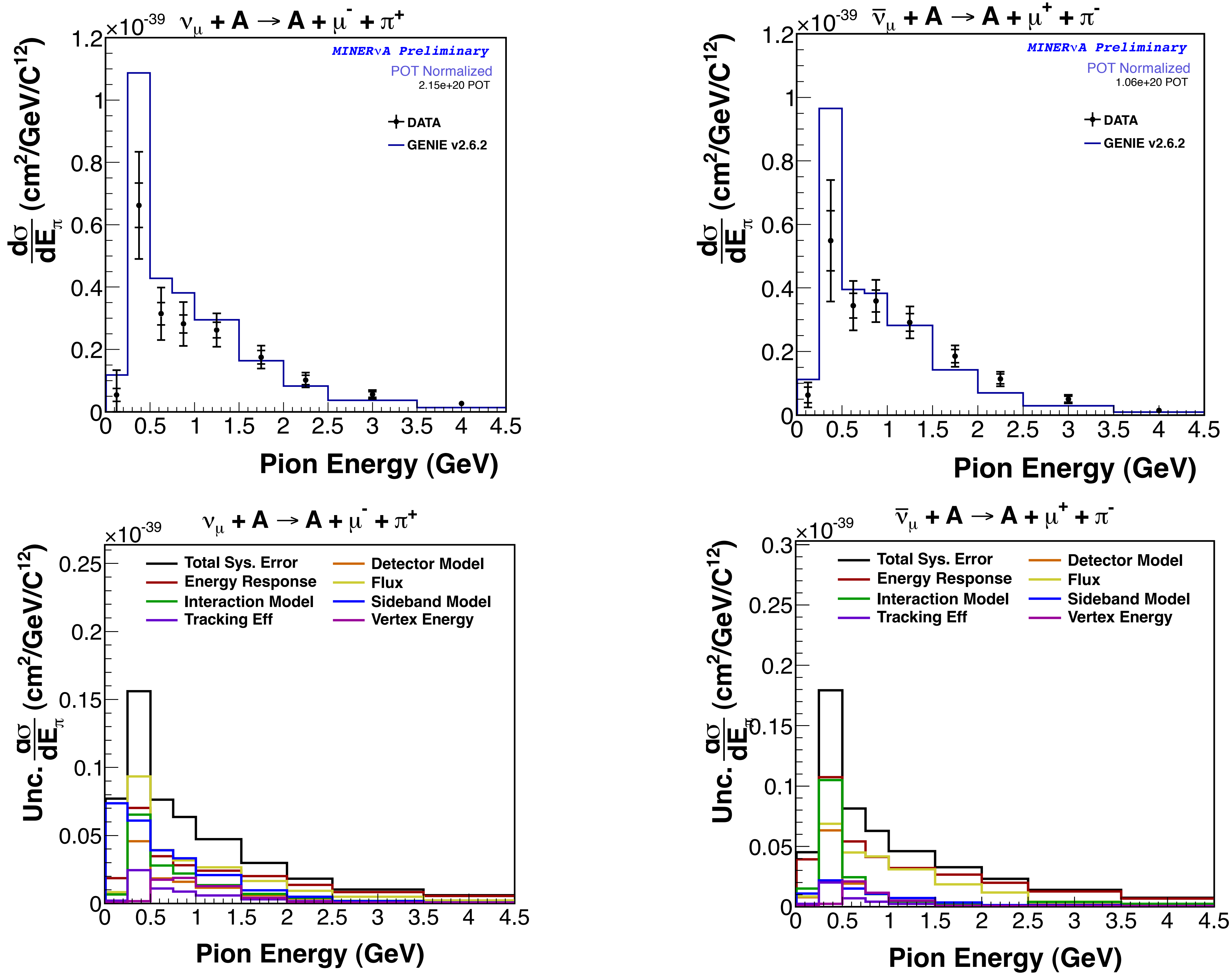




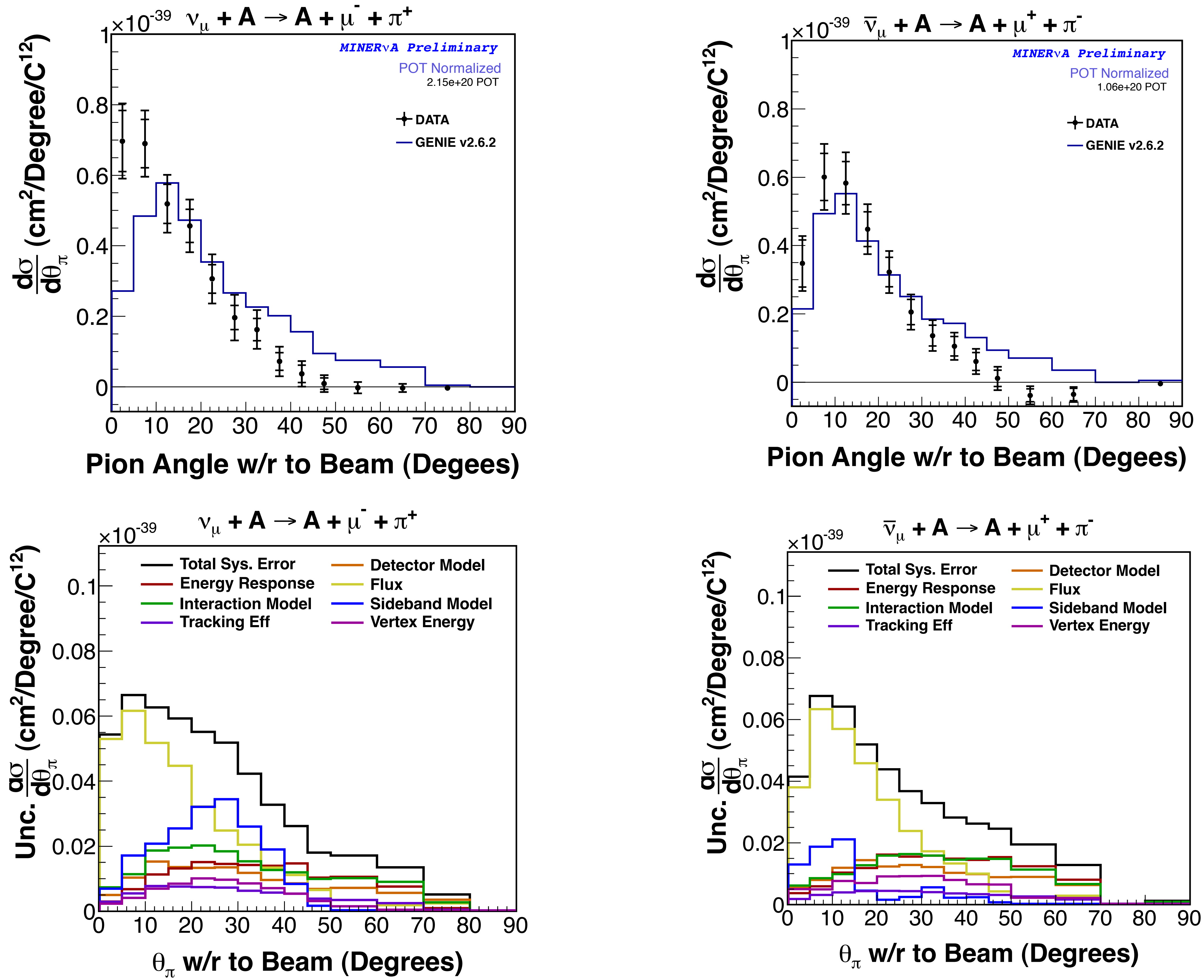




Cross Sections

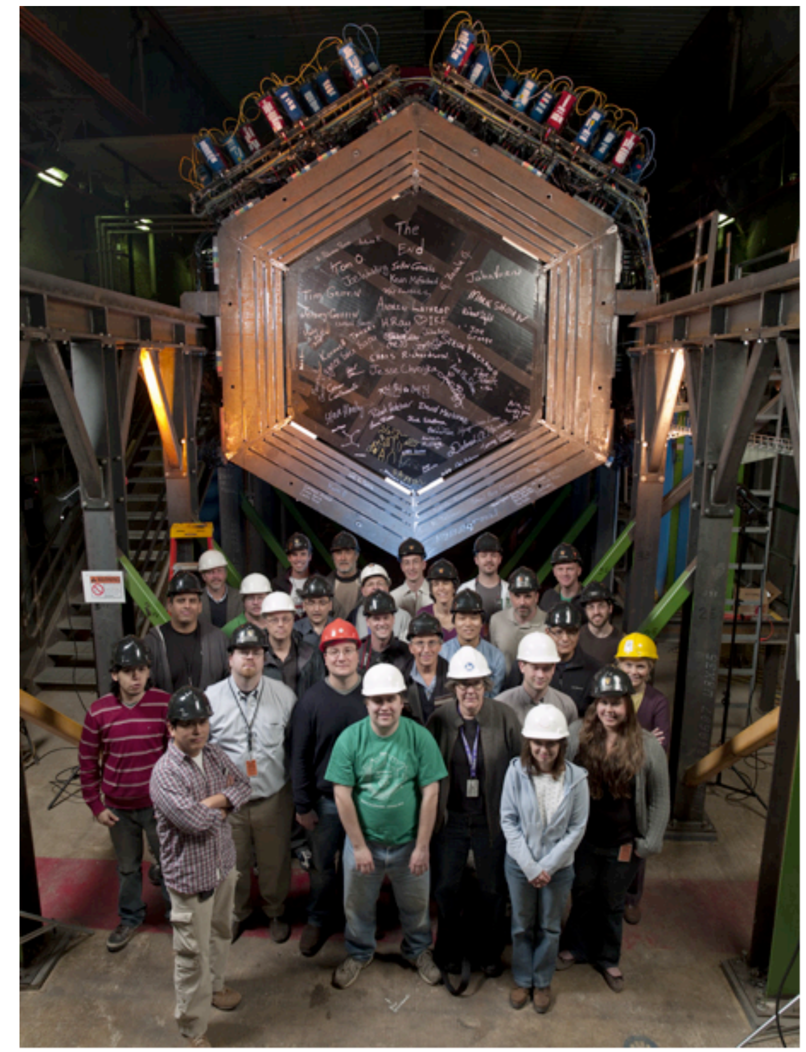


Cross Sections



Conclusions

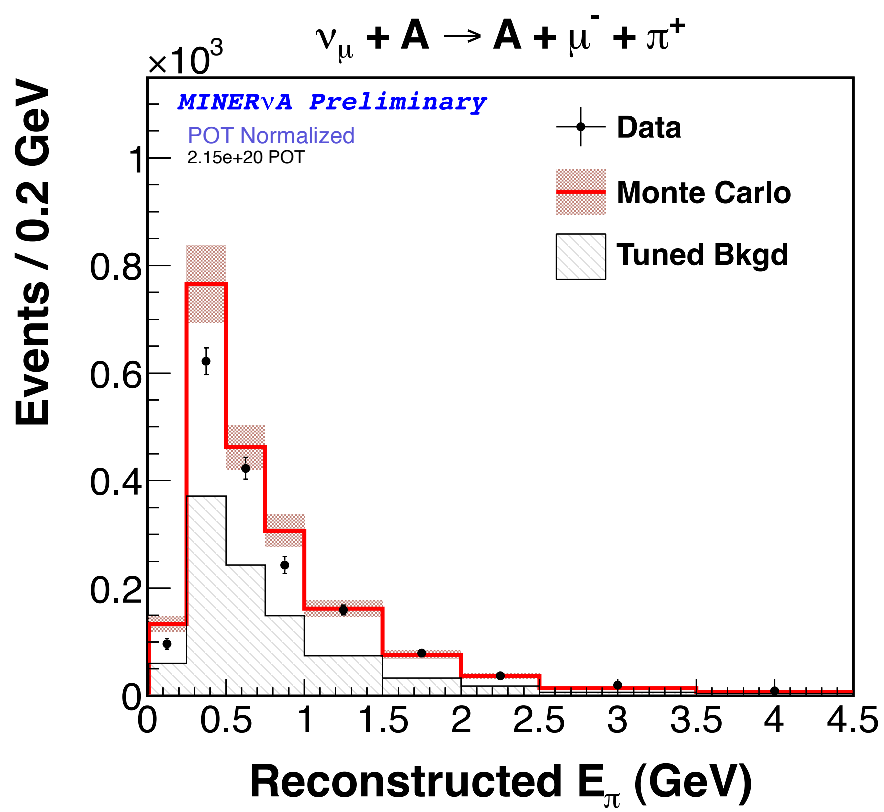
- Constraining CC coherent pion production at few GeV is needed by oscillation experiments
- MINERνA has isolated a coherent-rich sample using an event-by-event measurement of $|t| = |(q-p)^2|$
- Disagreement is observed between our data and the prediction by GENIE's implementation of the Rein-Sehgal model
- Need to compare our data with other models
- Contribution from diffractive scattering off Hydrogen needs to be considered when interpreting our data - currently estimated to be ~17% of our signal

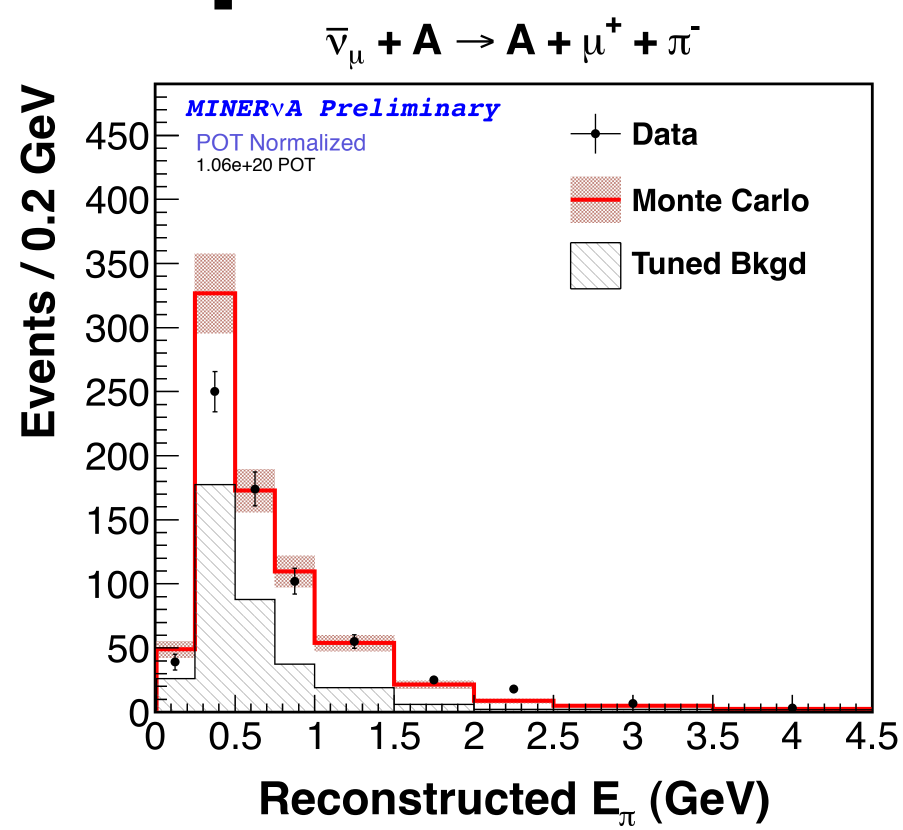


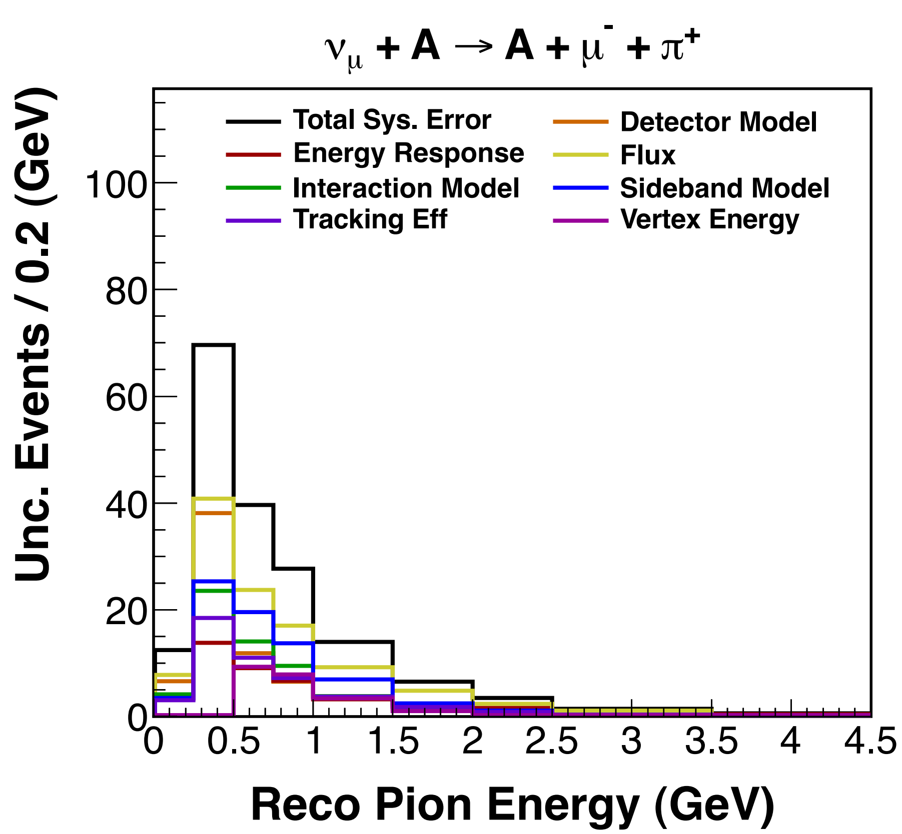
MINERνA thanks you for your attention

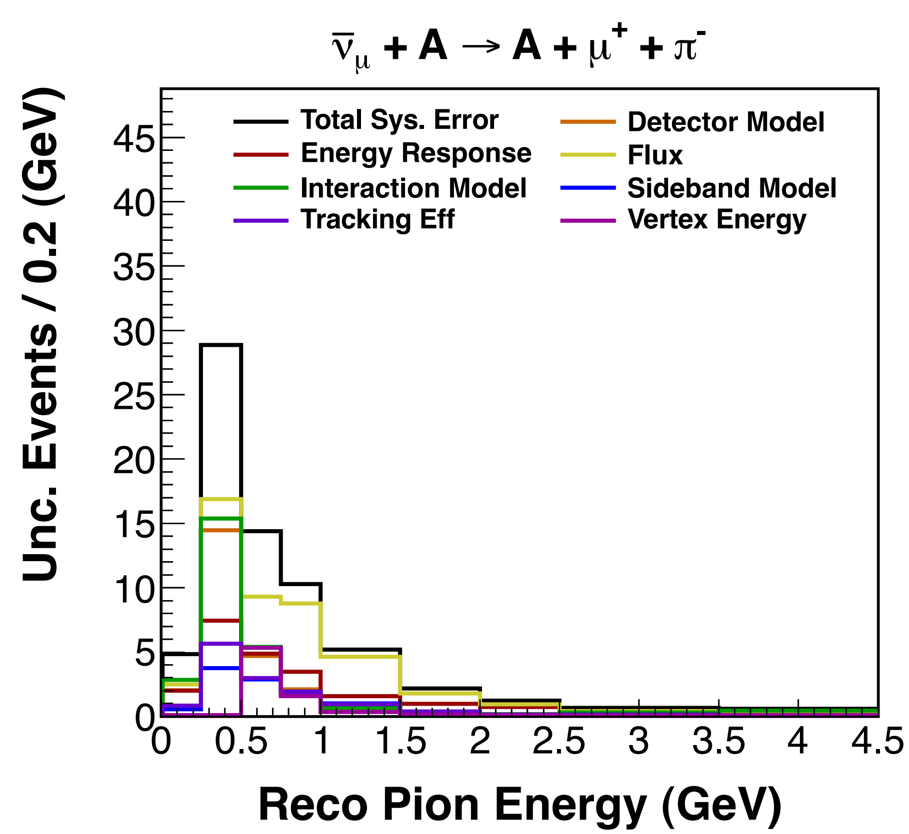
Backup

Selected Sample: E_π

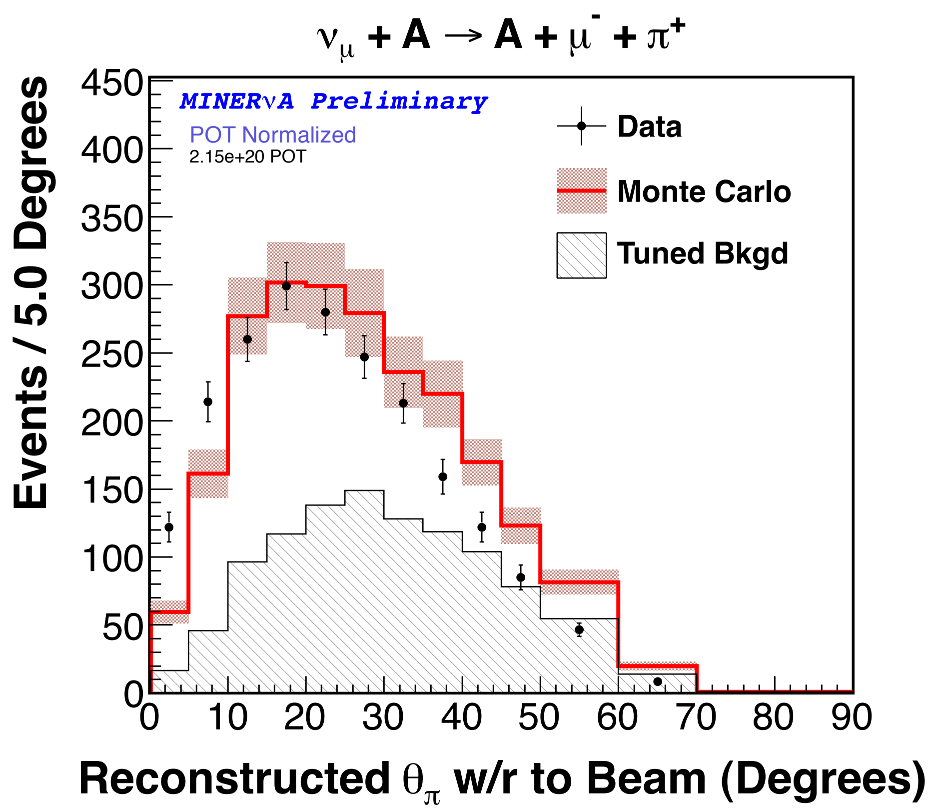


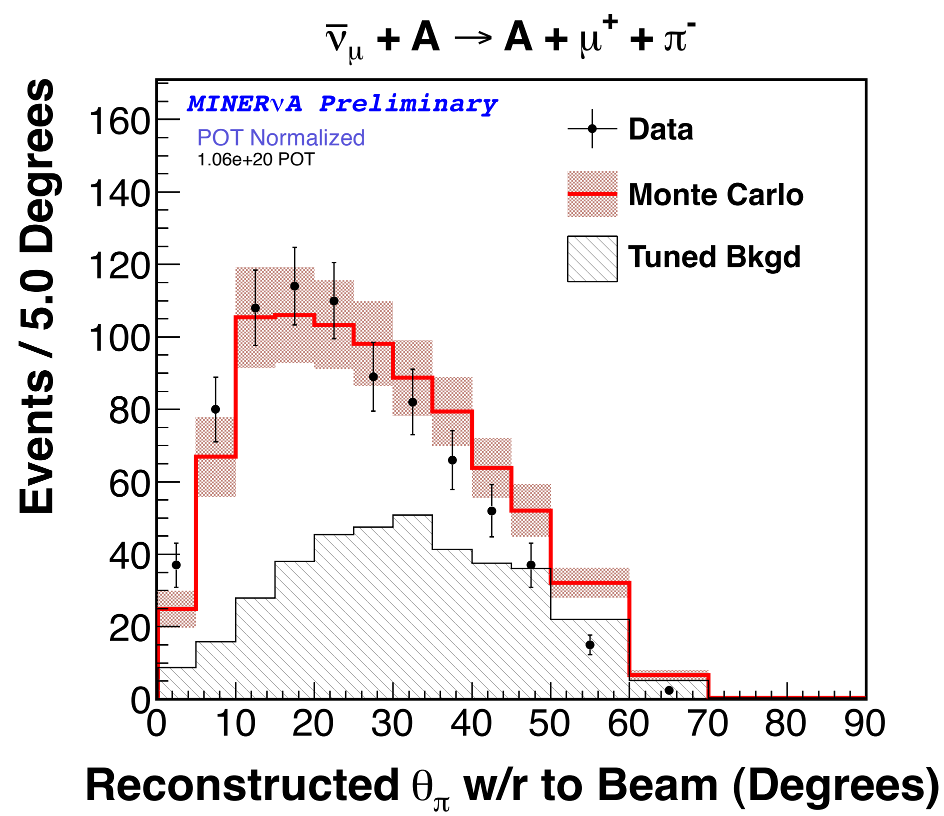


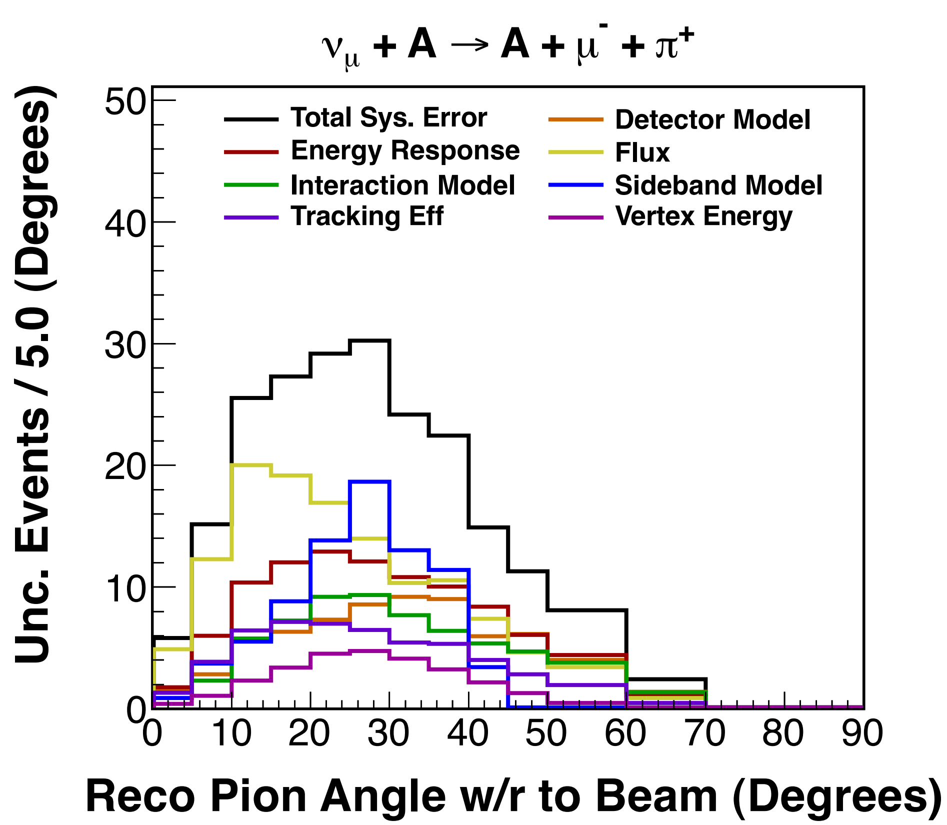


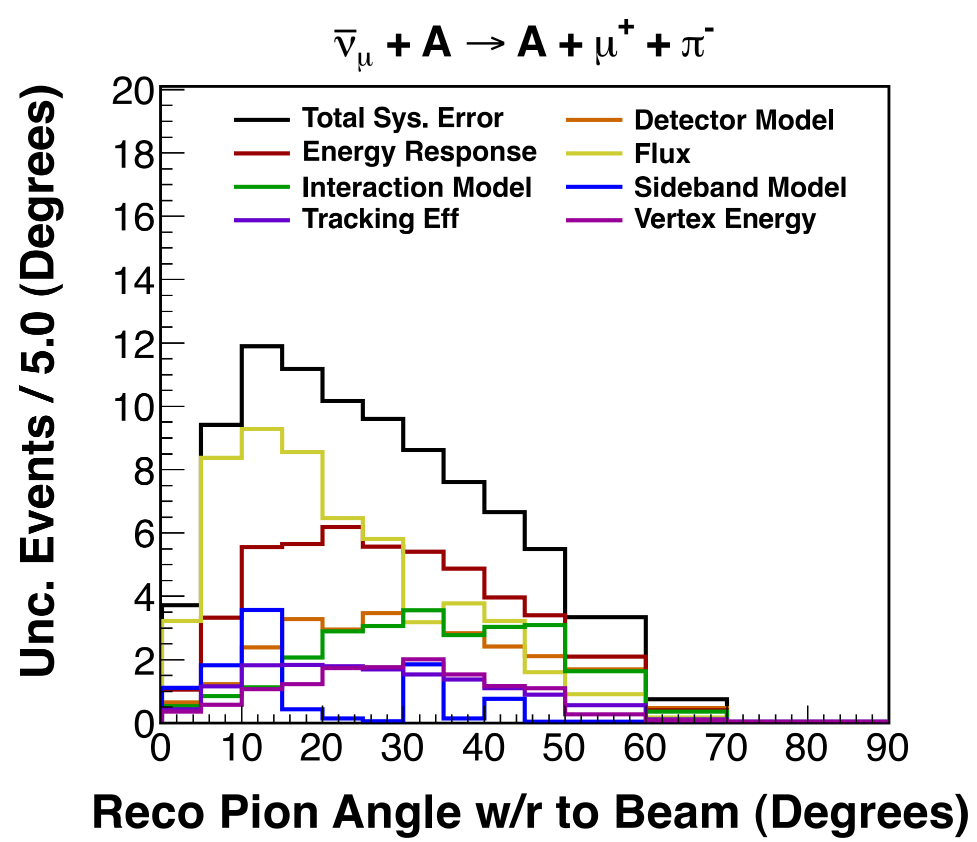


Selected Sample: θ_π

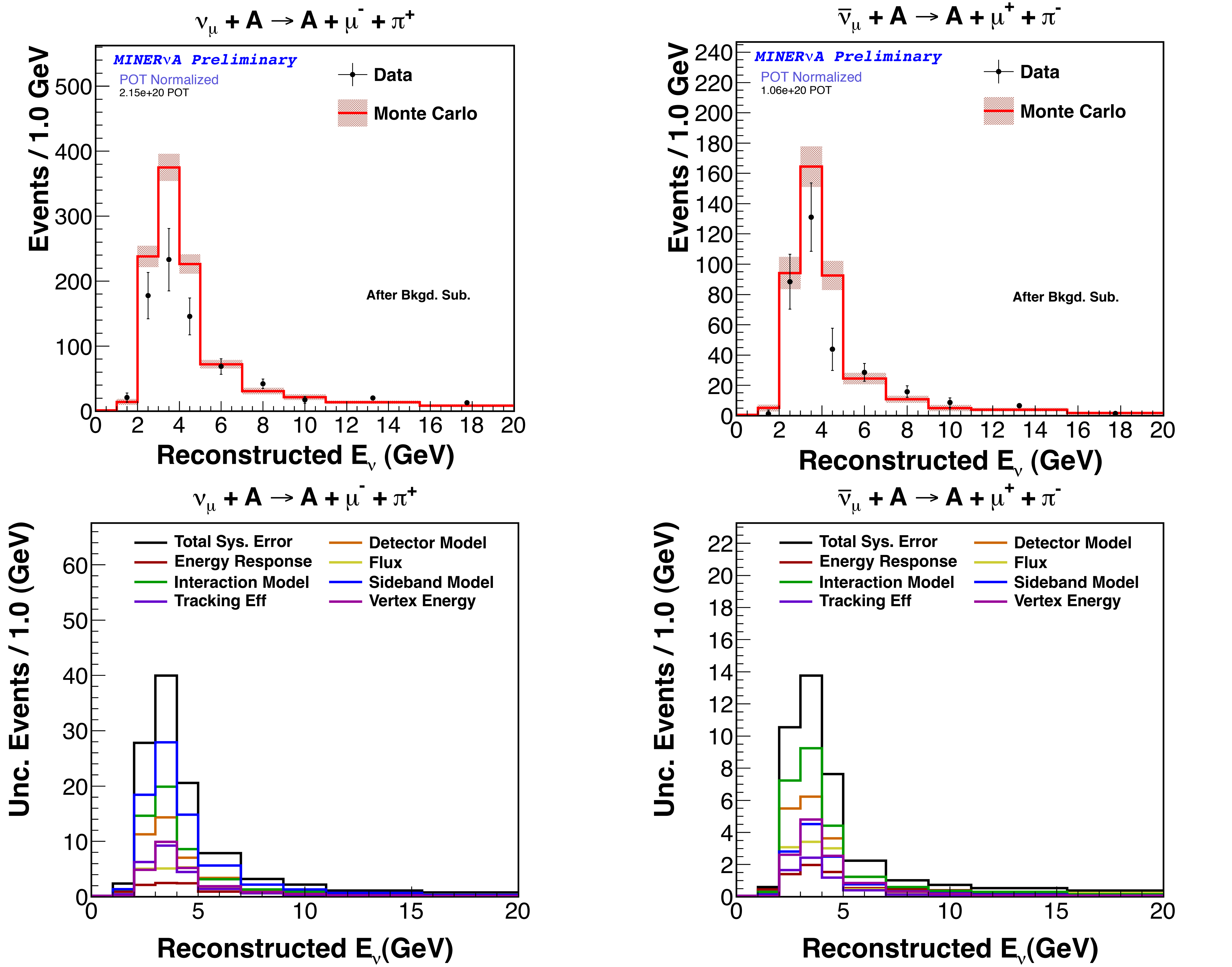




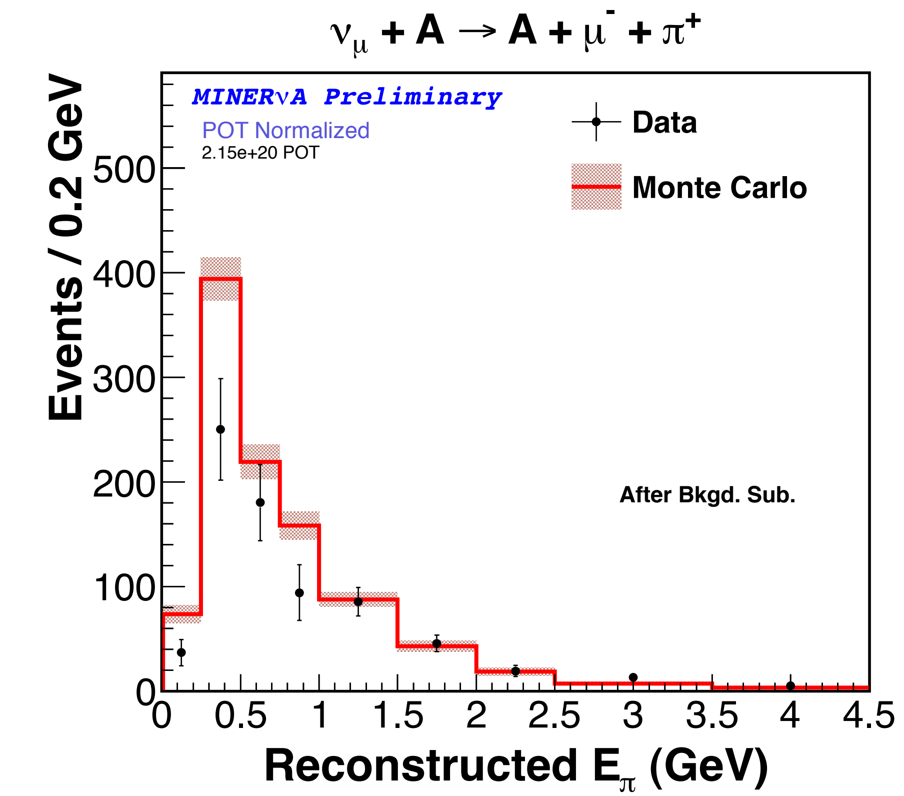


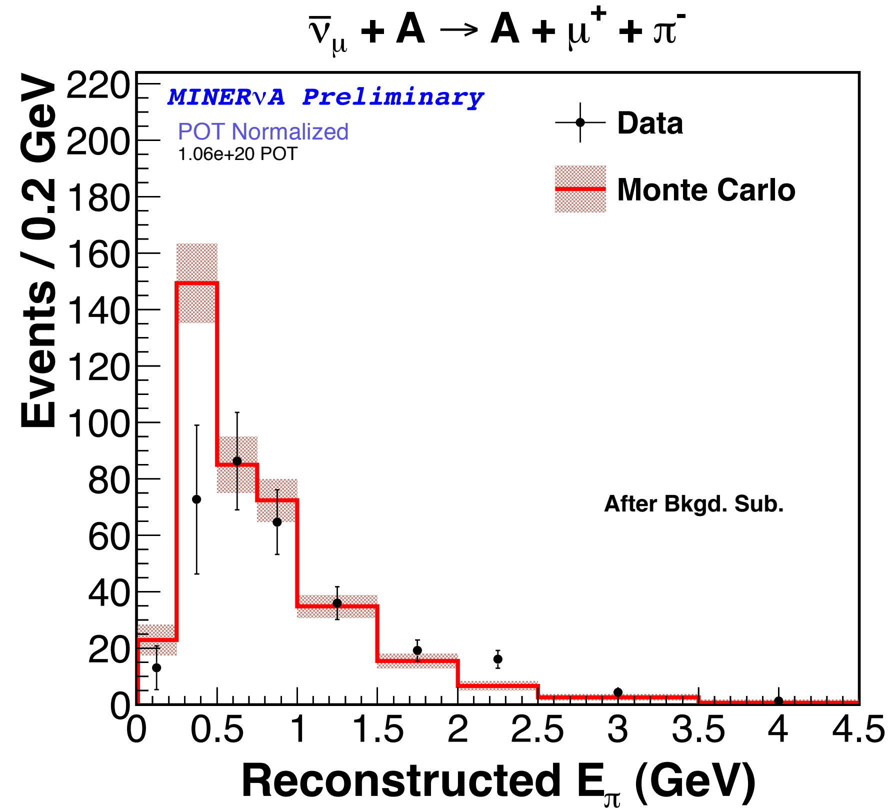


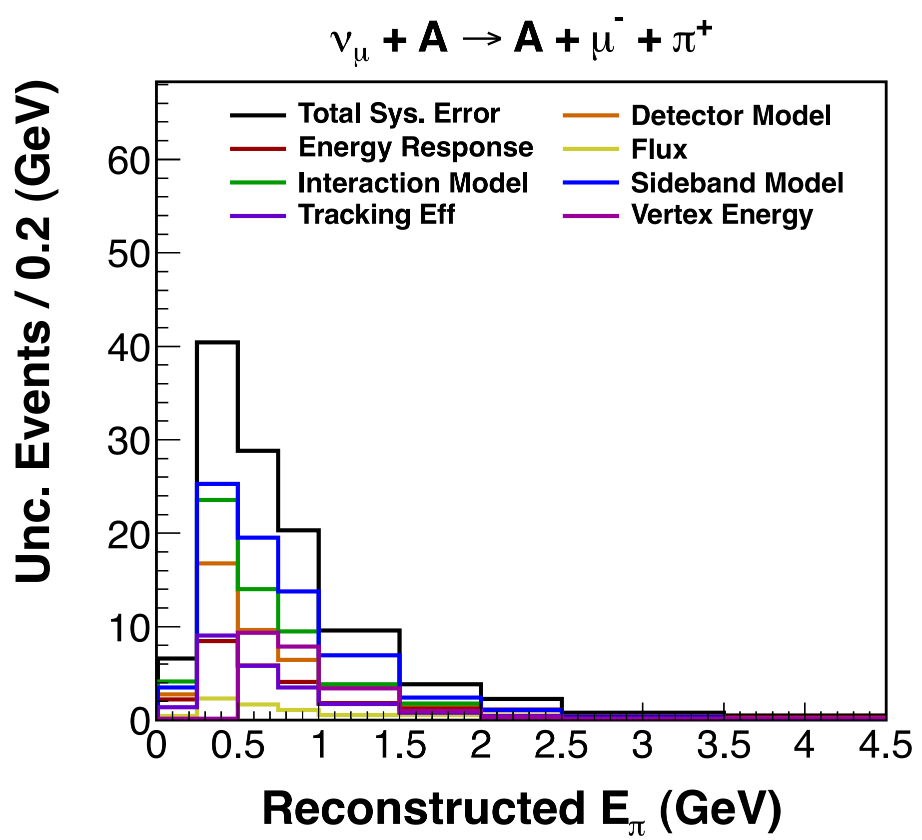
Background Subtracted: E_ν

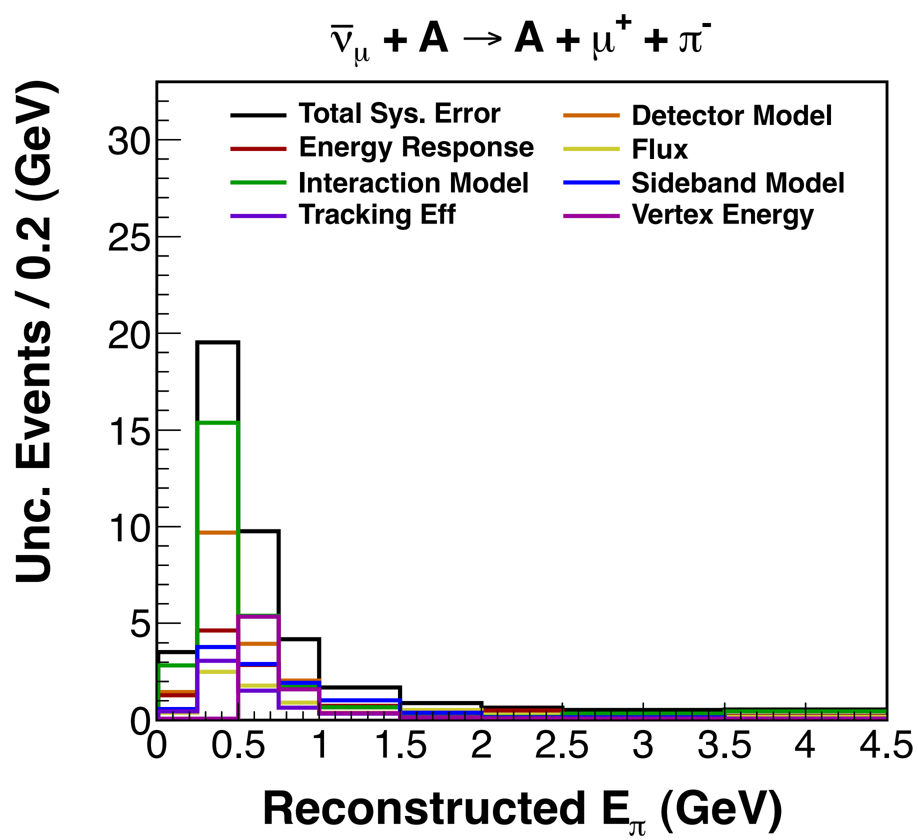


Background Subtracted: E_π

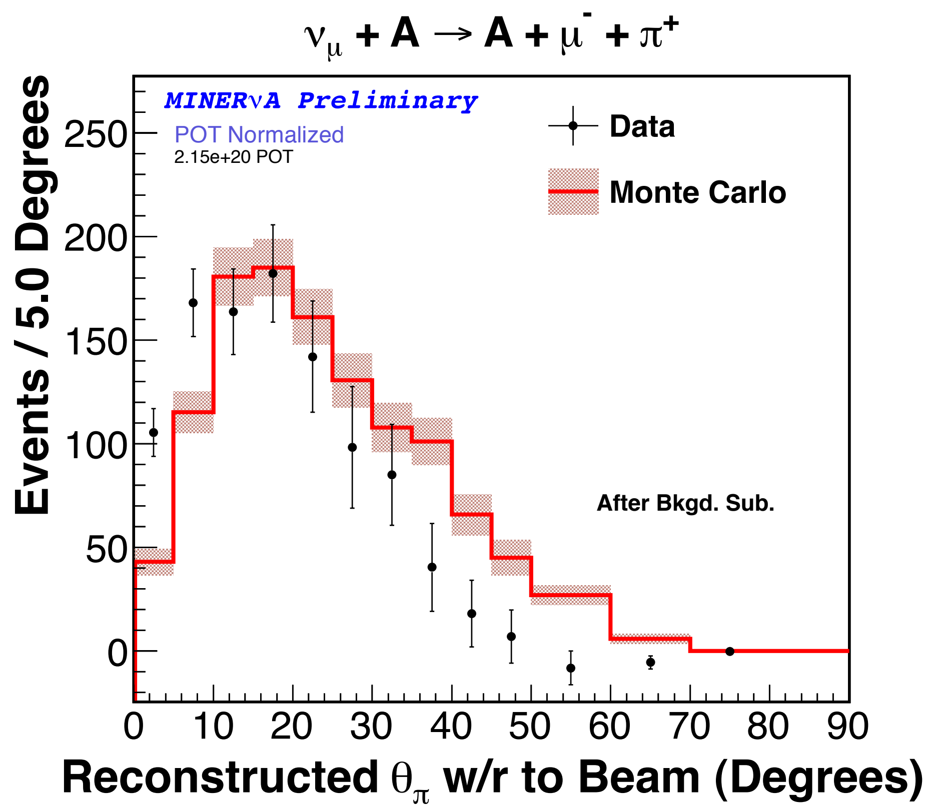


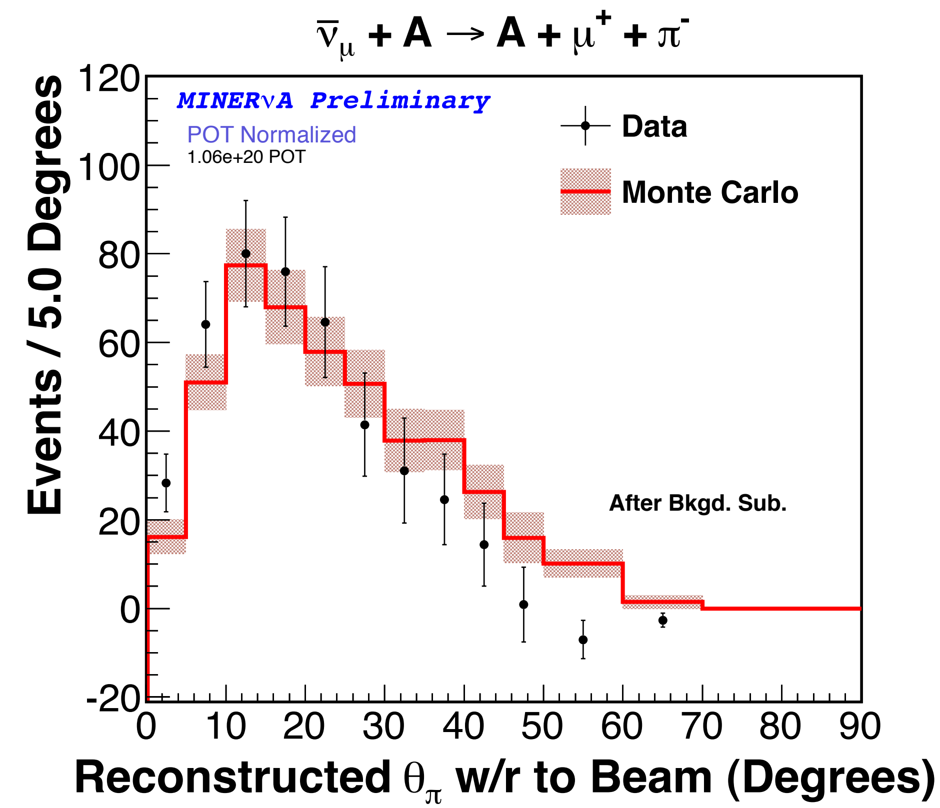


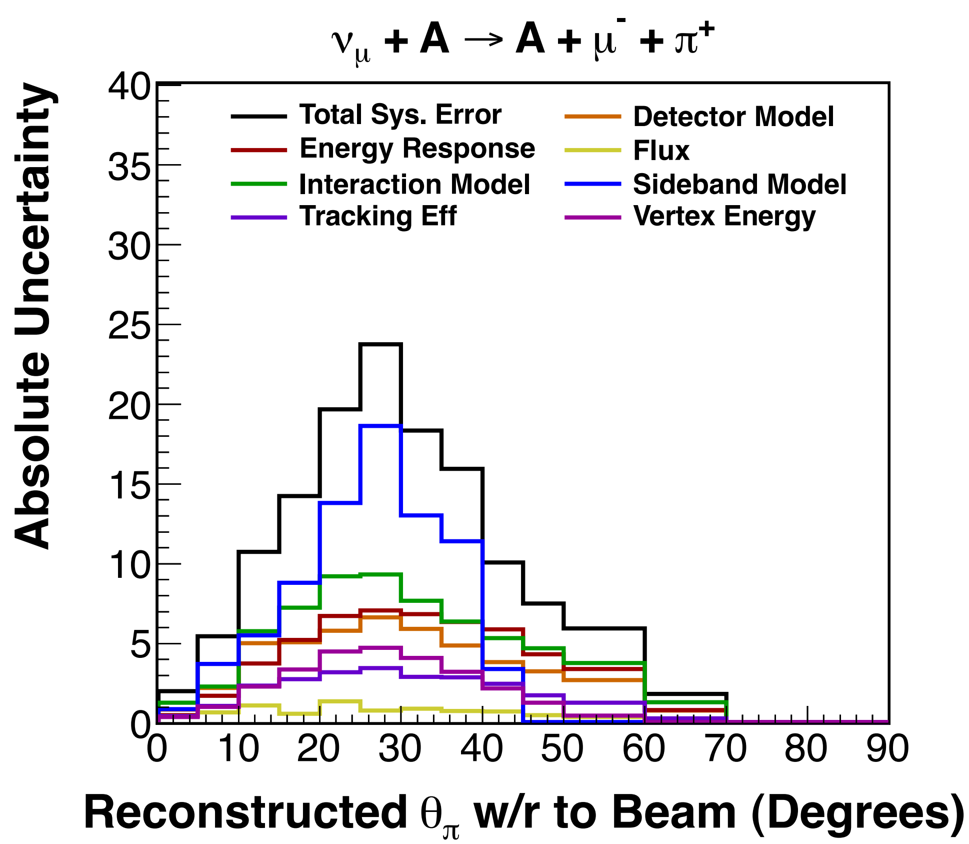


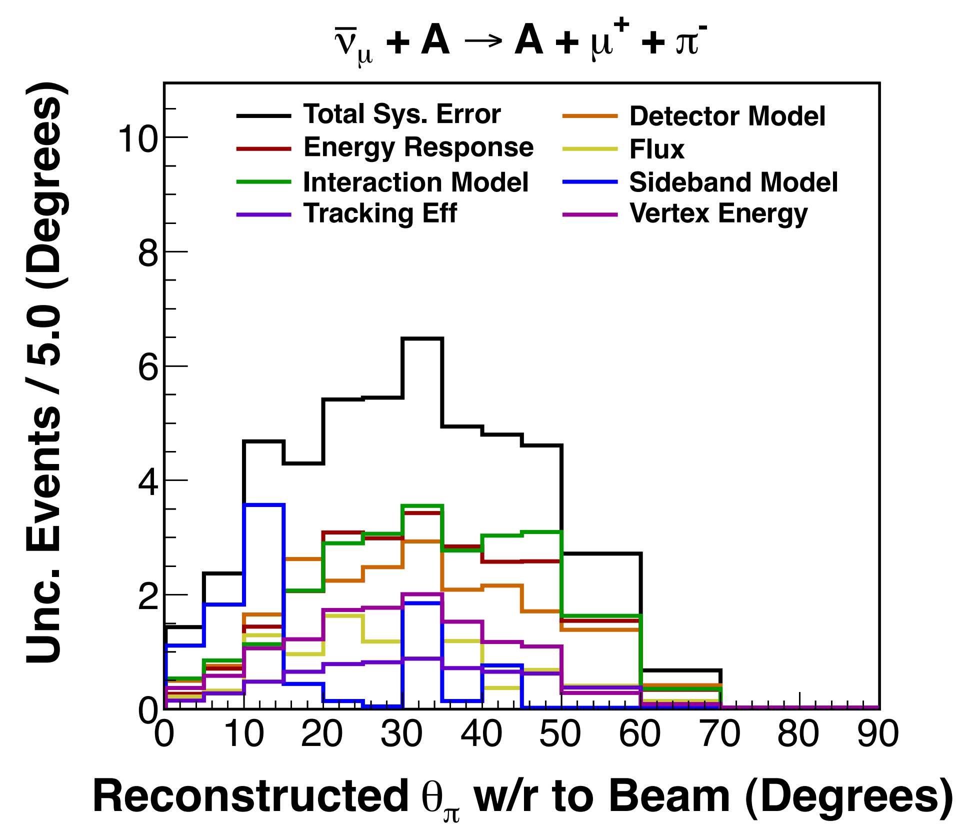


Background Subtracted: θ_π

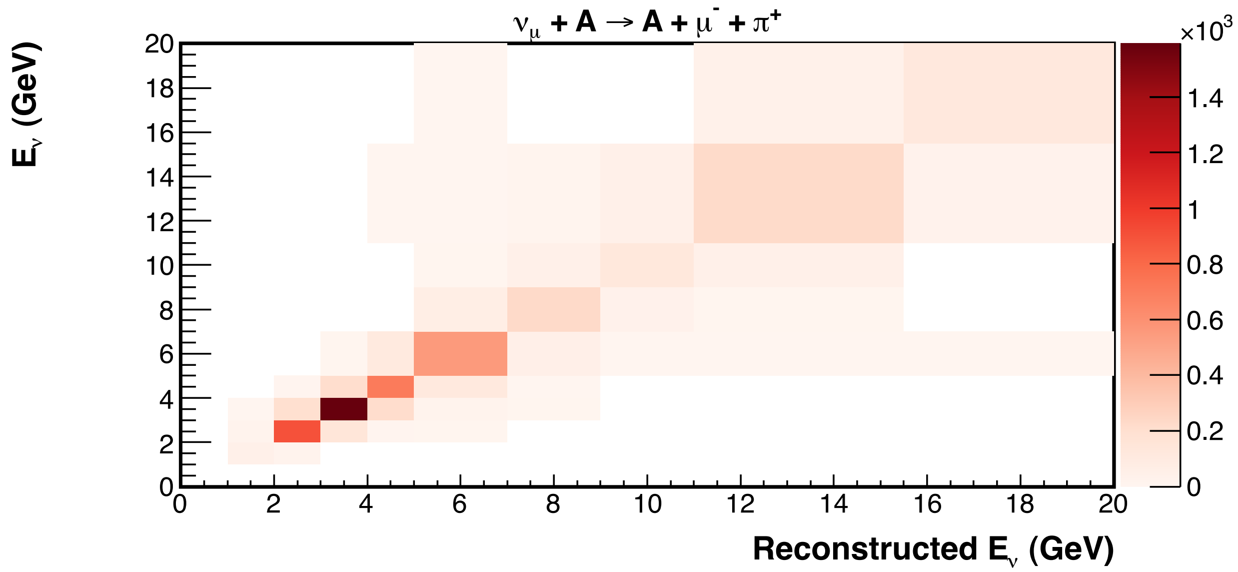


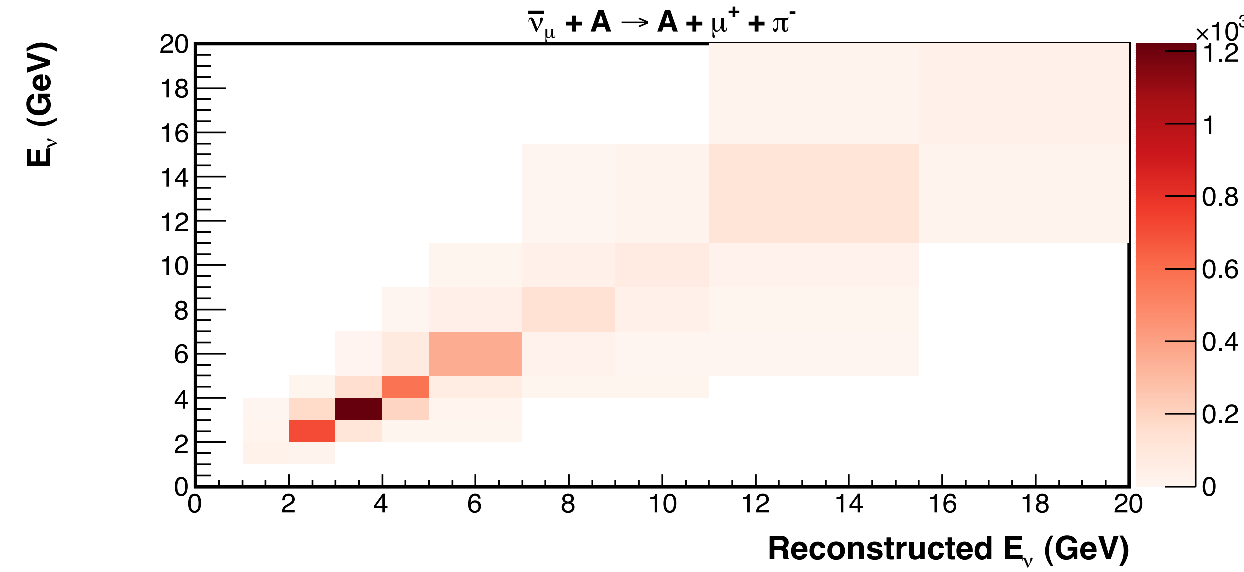


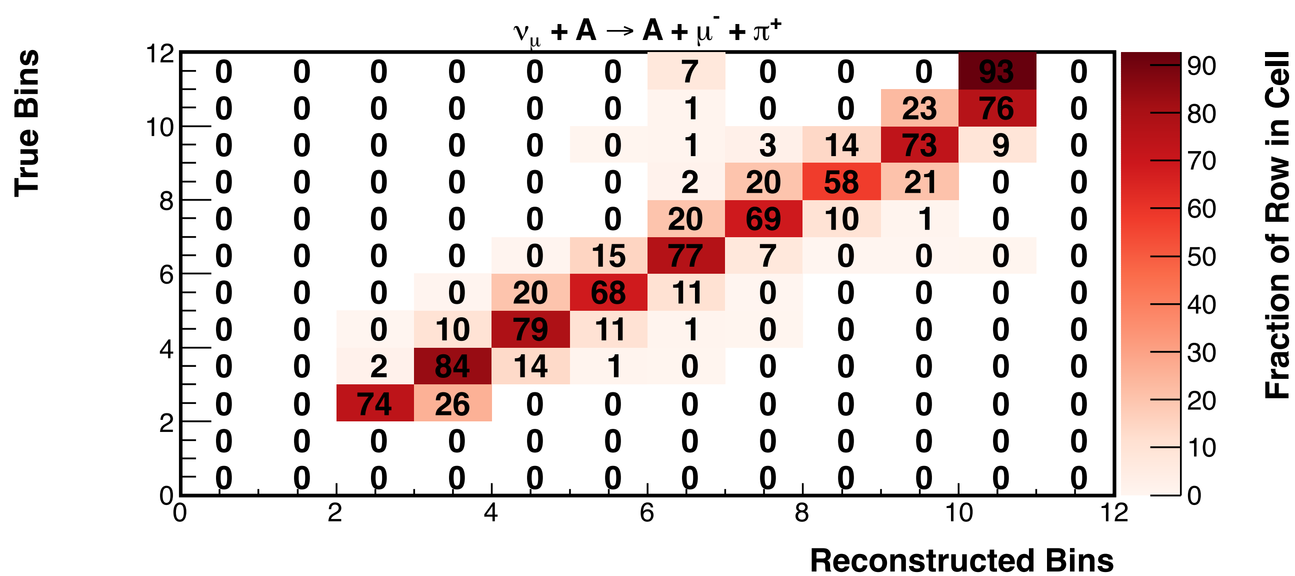


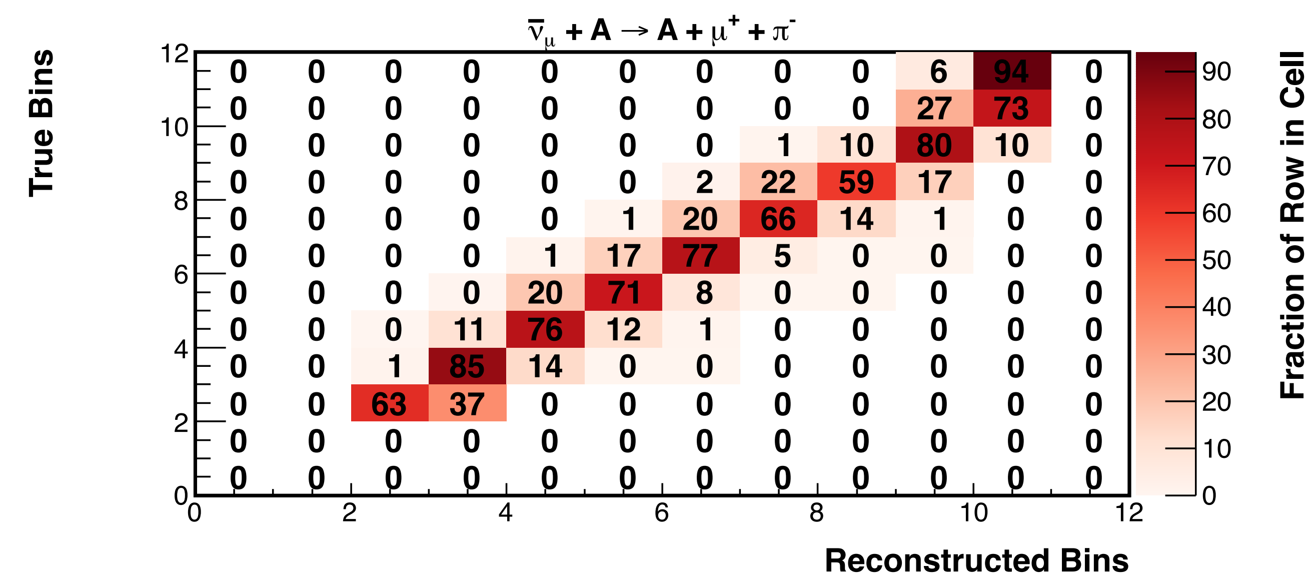


Migration Matrix: E_ν

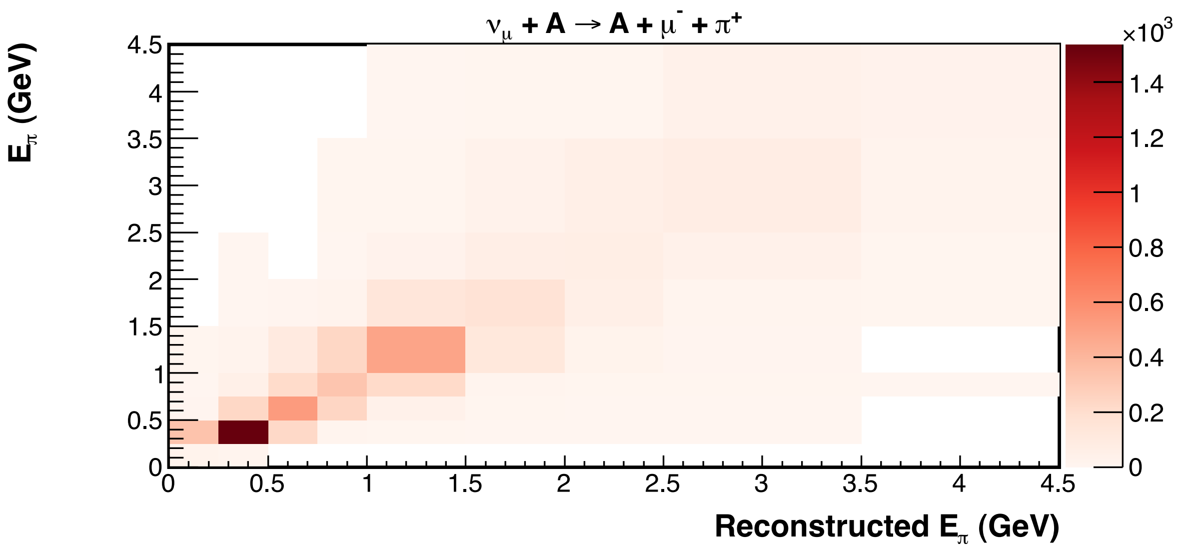


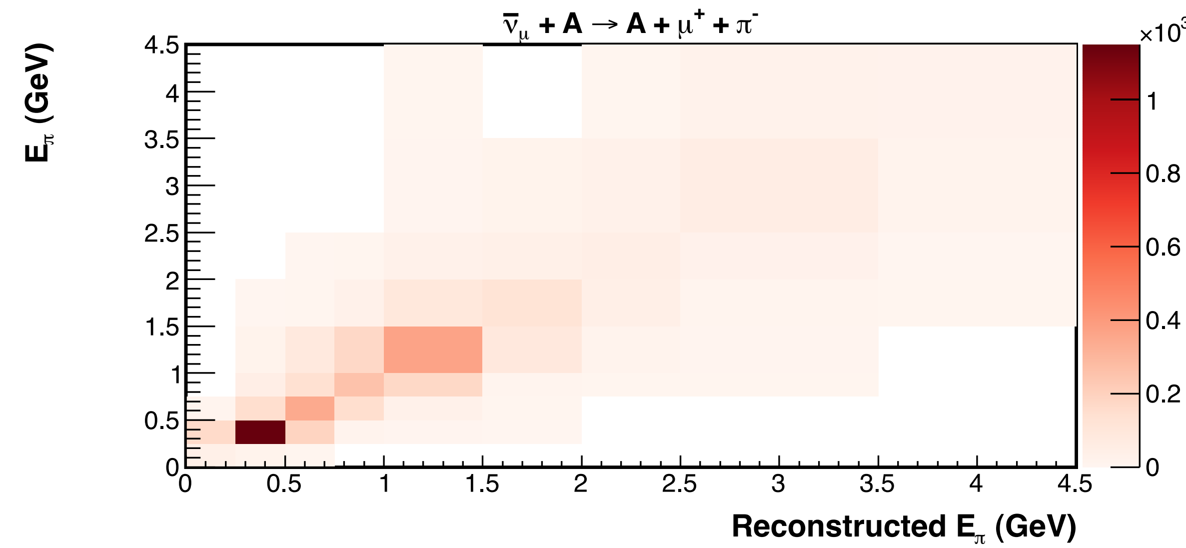


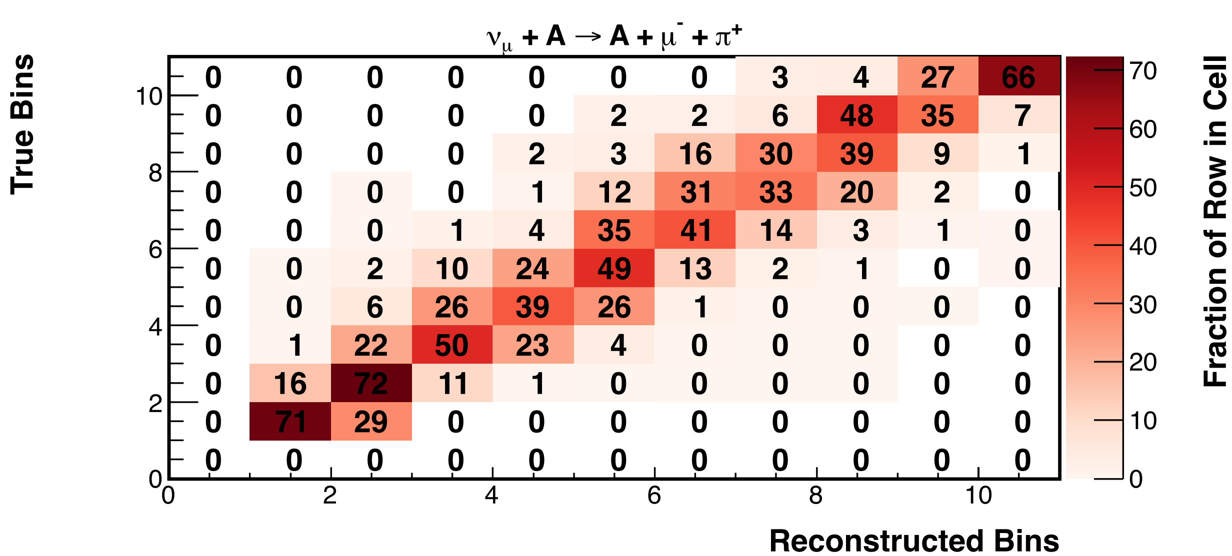


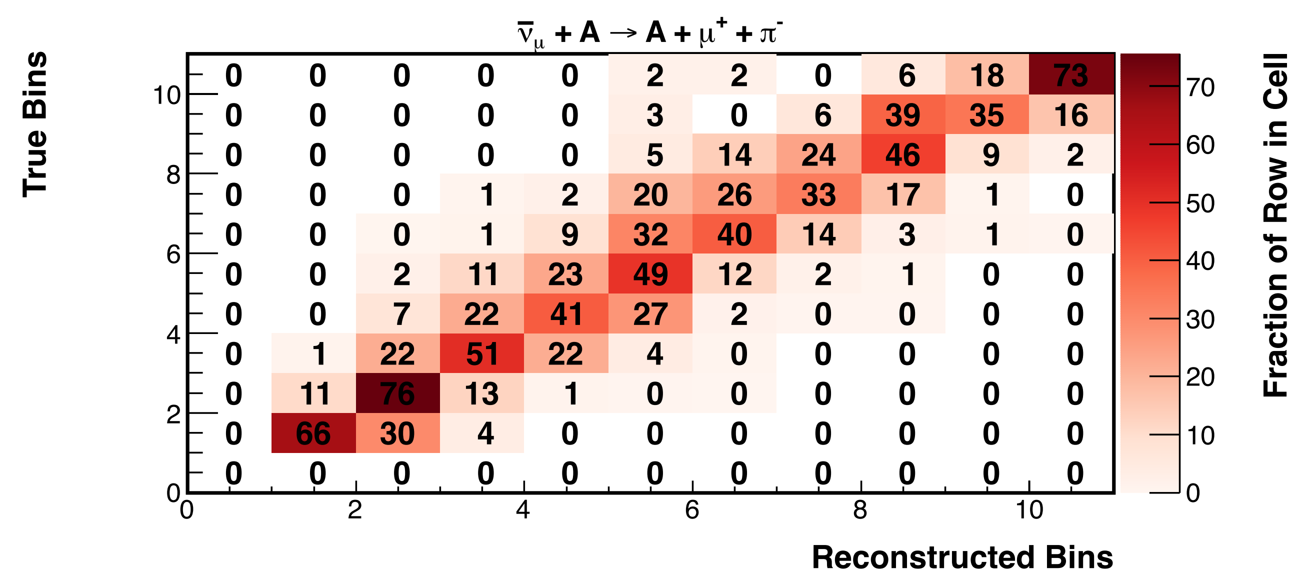


Migration Matrix: E_π

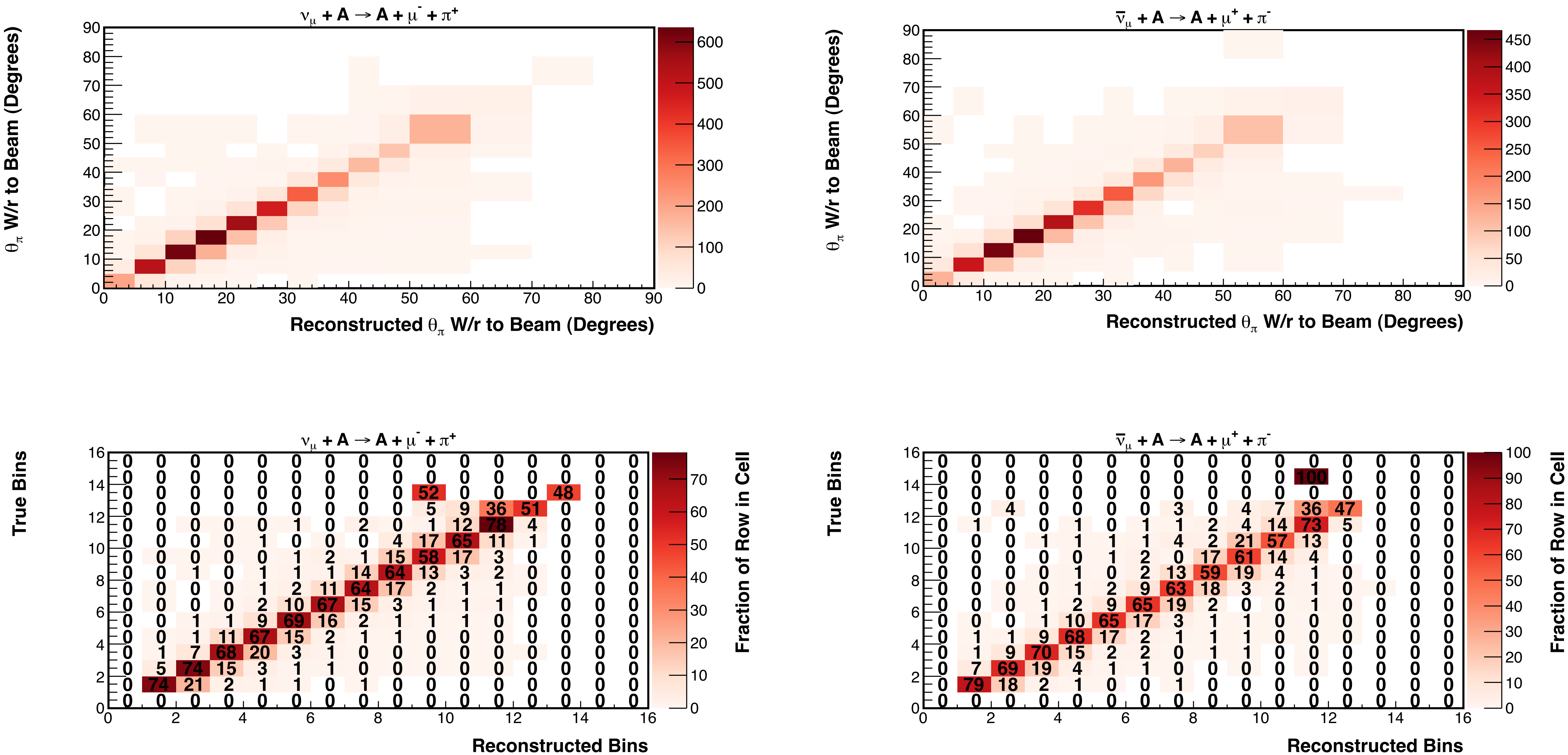




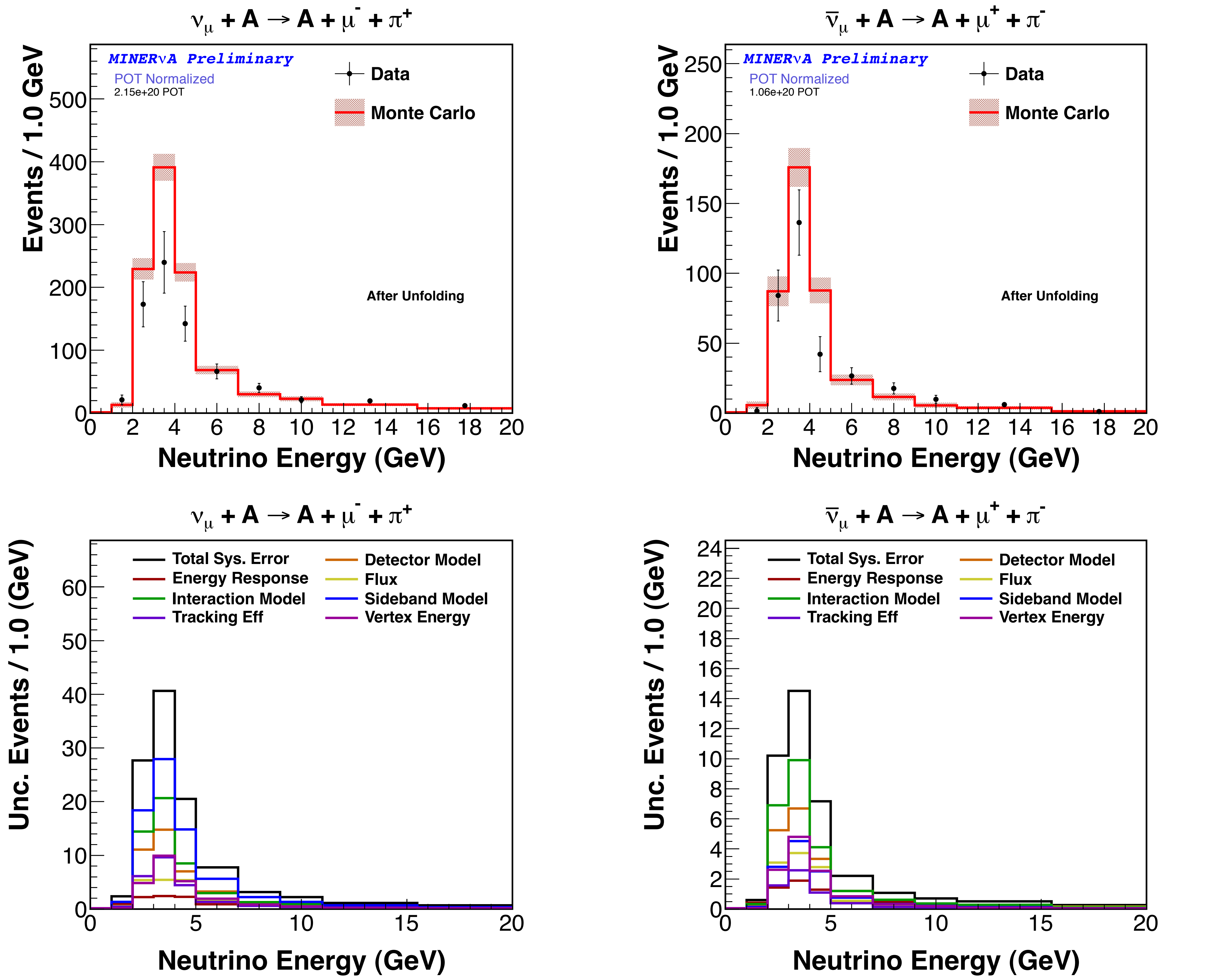




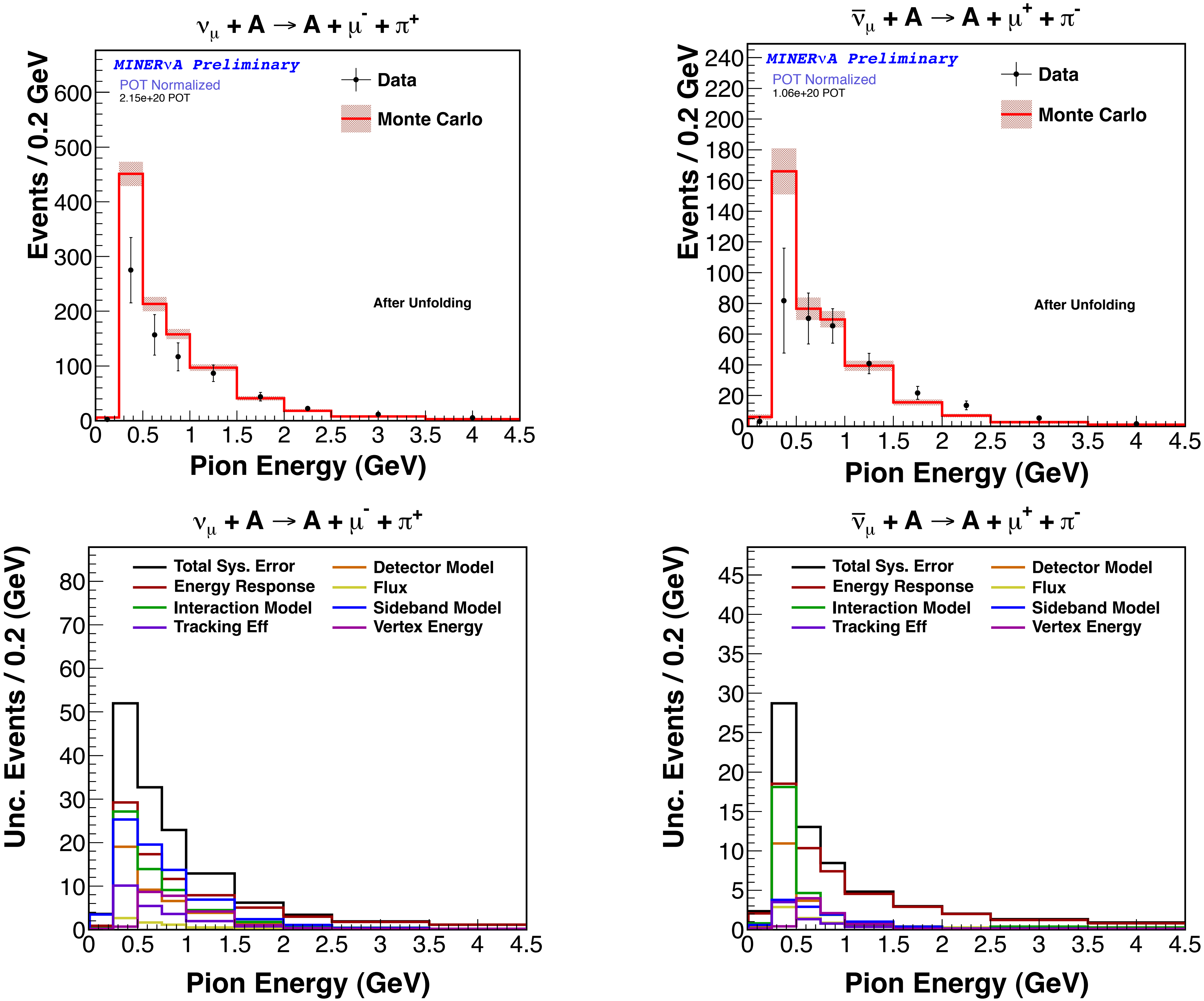
Migration Matrix: θ_π



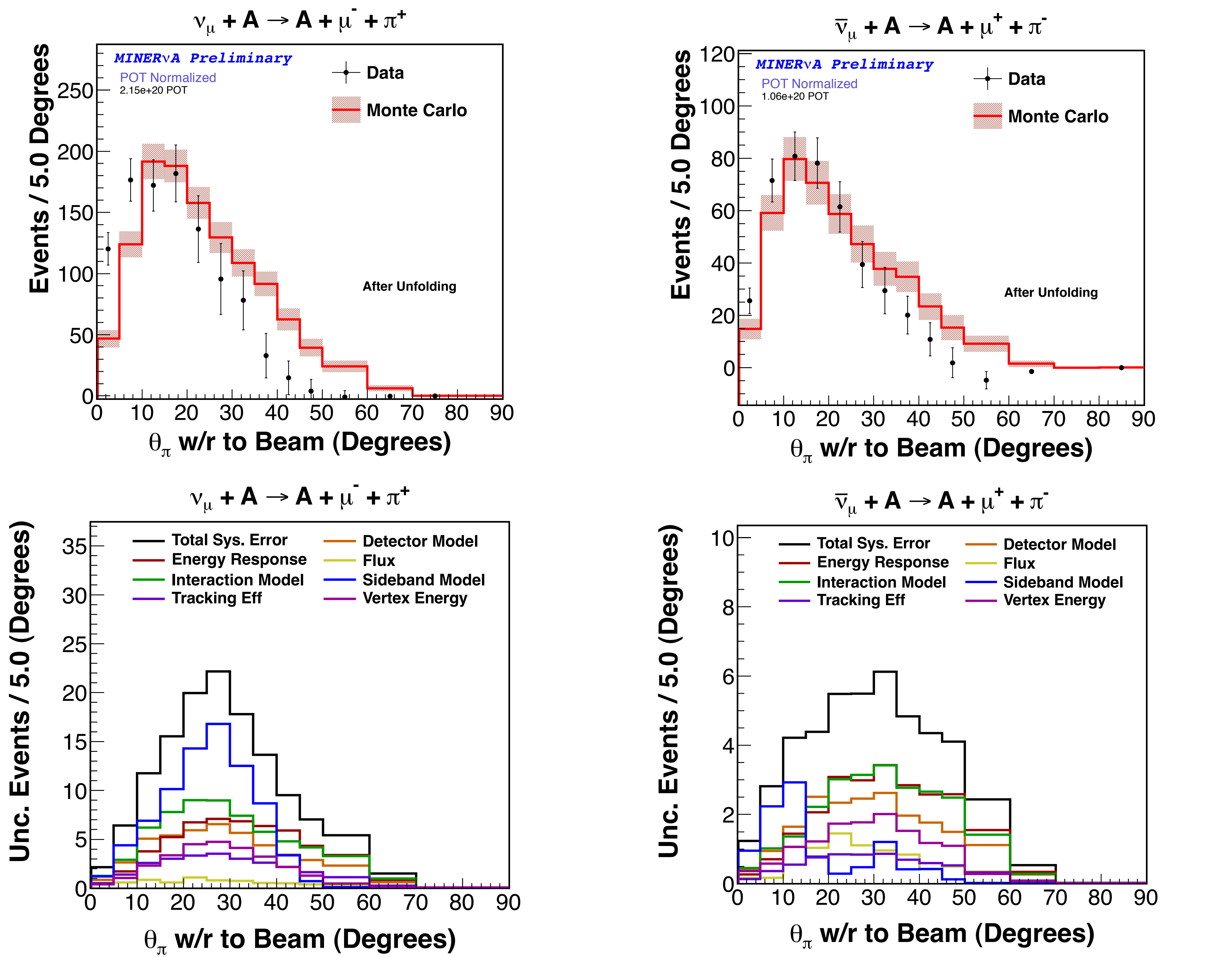
Unfolded: E_ν



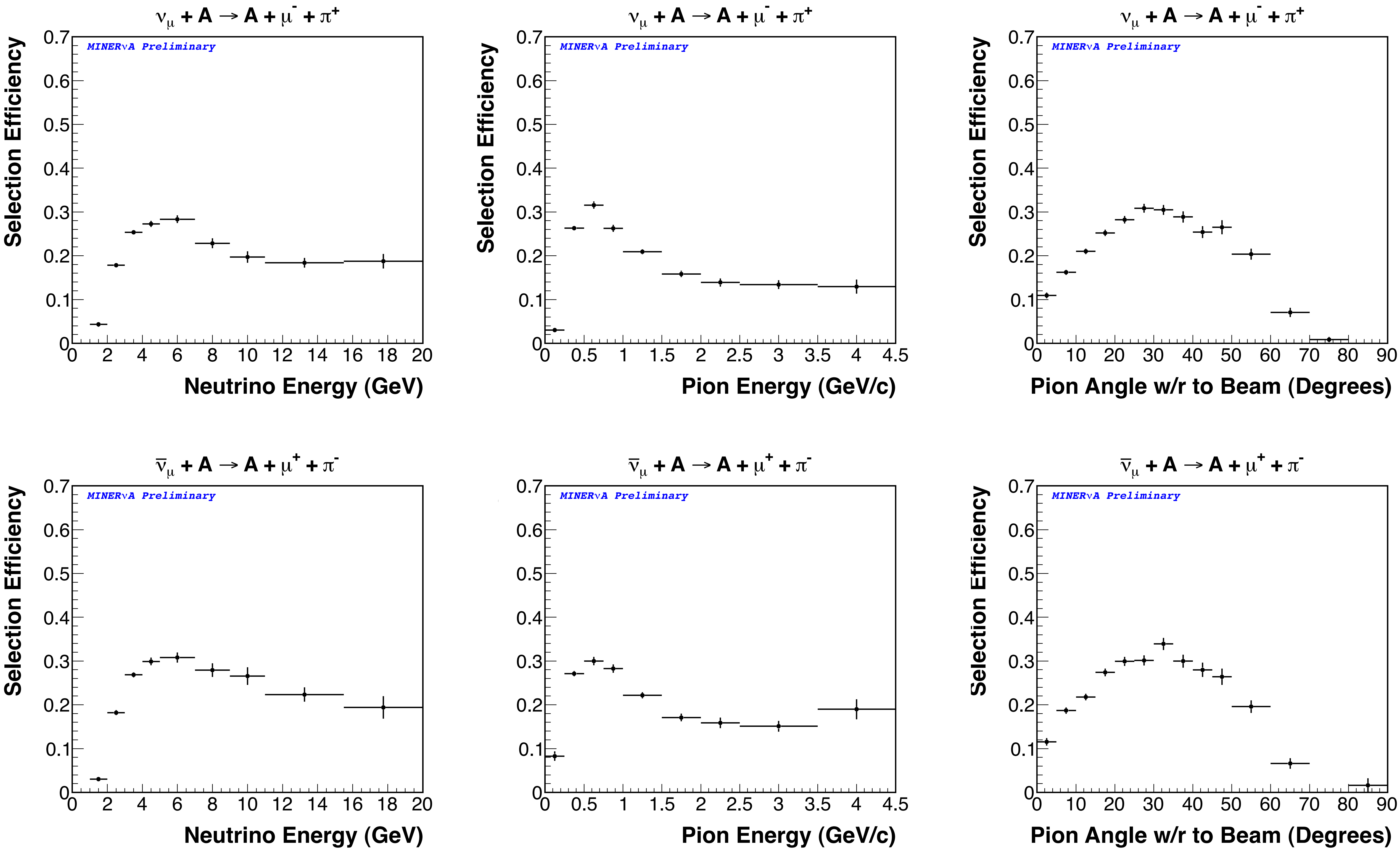
Unfolded: E_{π}



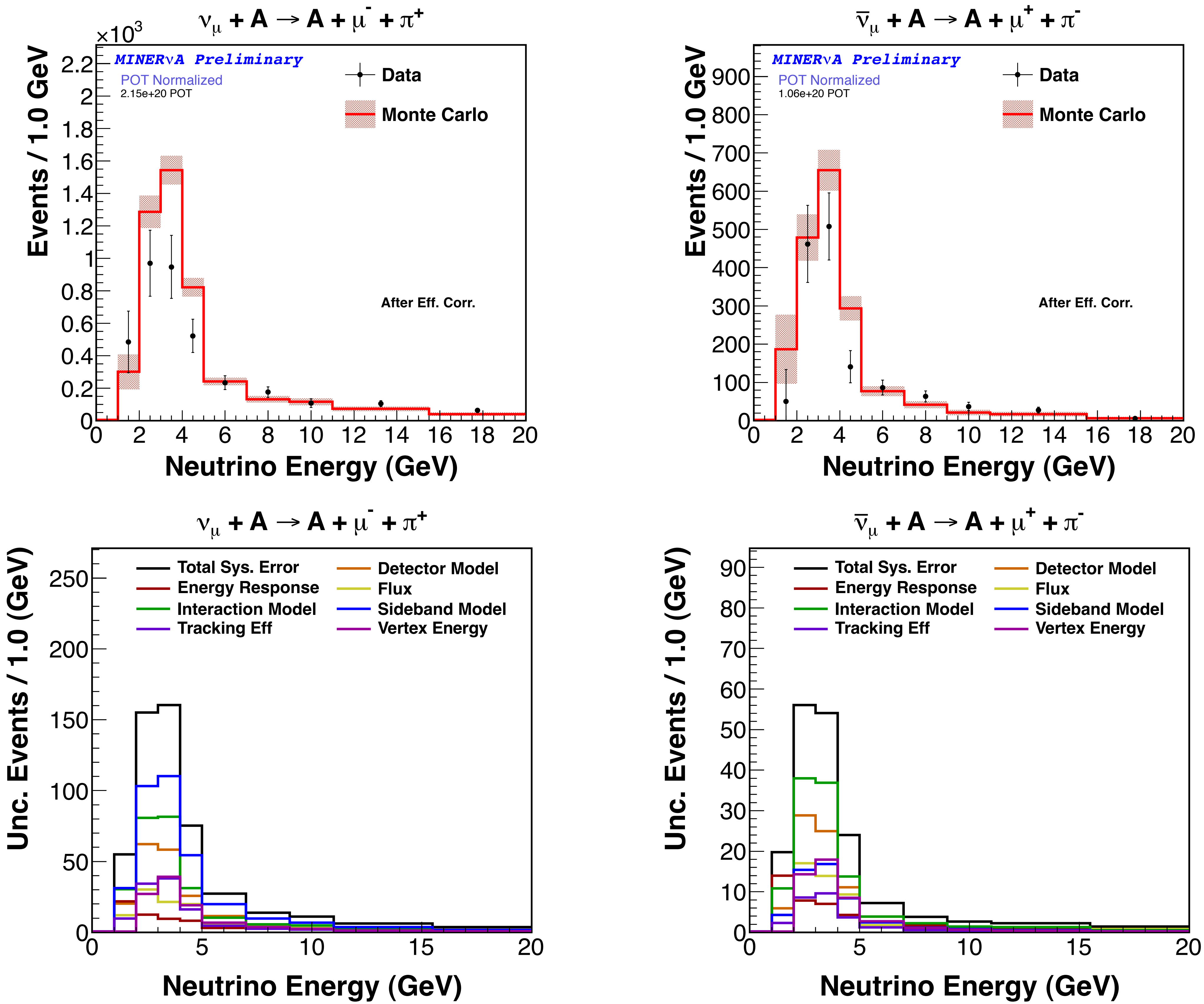
Unfolded: θ_π



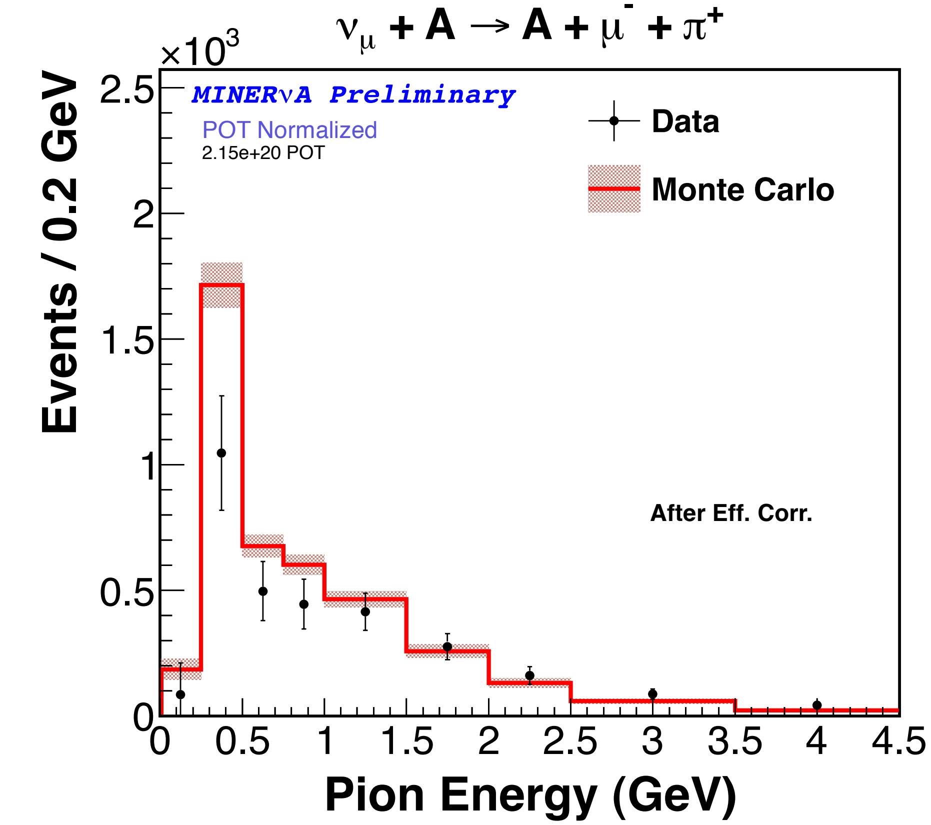
Efficiency Corrections

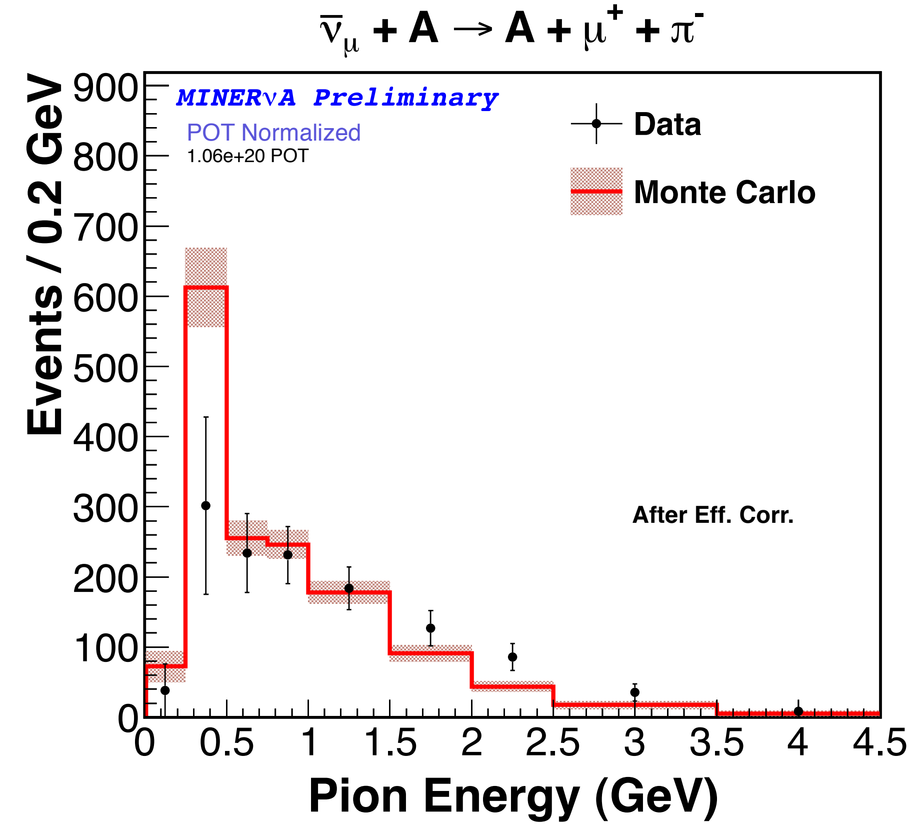


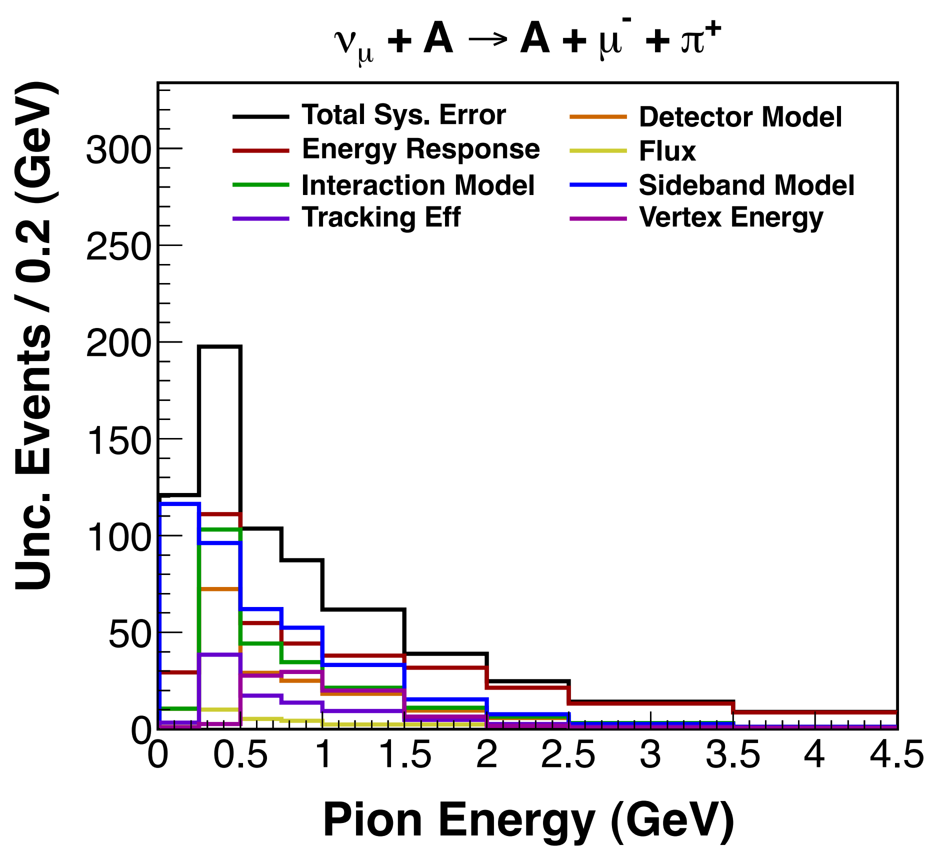
Efficiency Corrected: E_ν

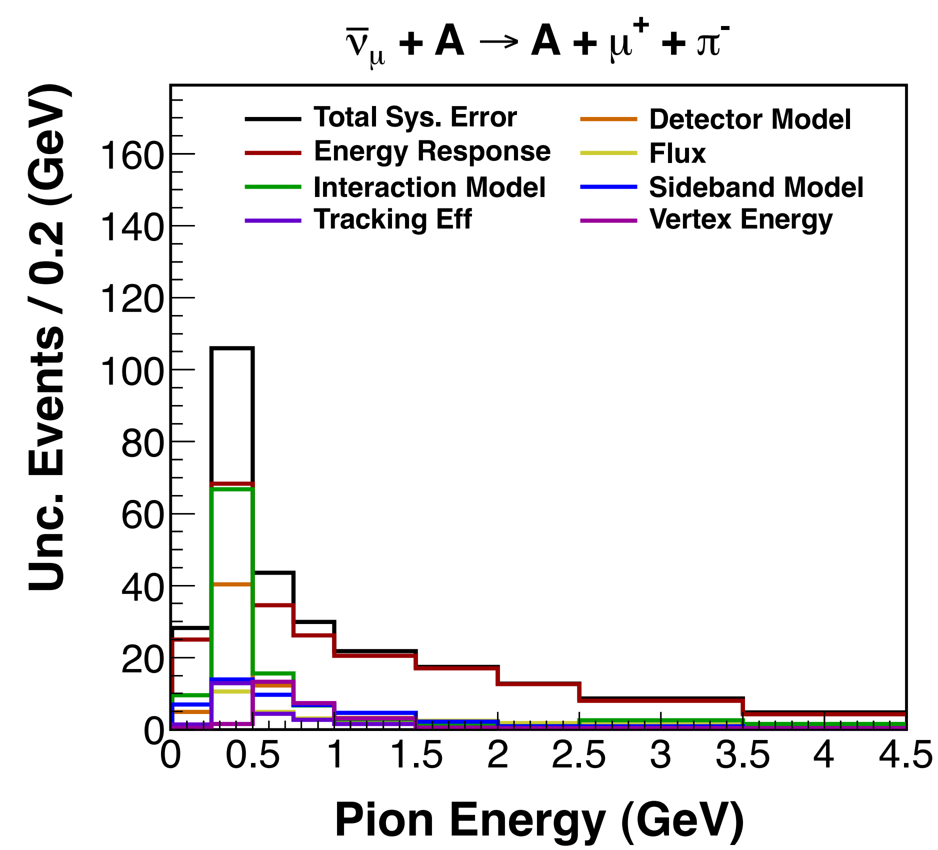


Efficiency Corrected: E_{π}









Efficiency Corrected: θ_π