Recent MINERvA Double Differential CCQE Cross Section Results Using Lepton Kinematics

8/1/2017

Outline

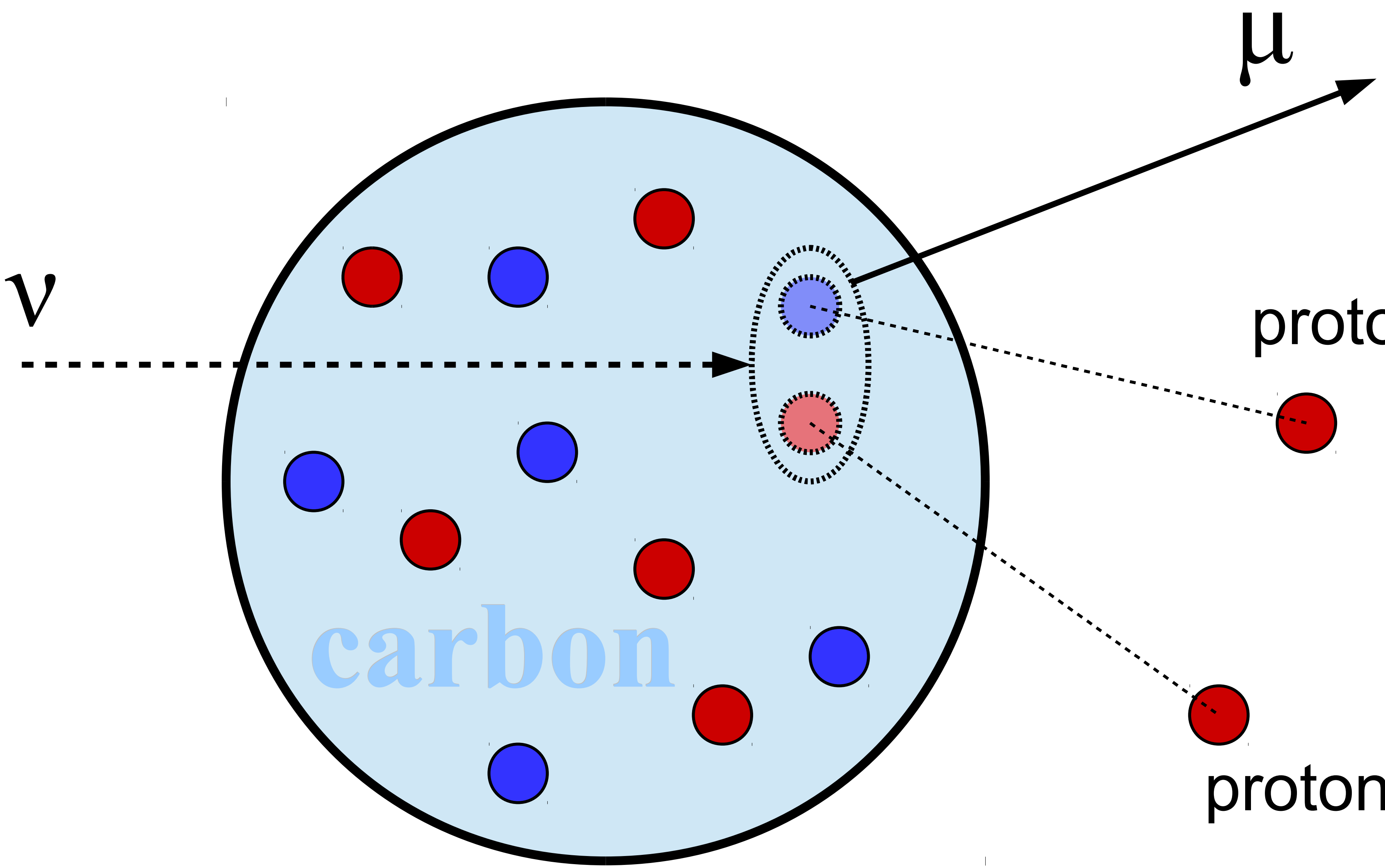
- MINERvA's Simulation
- Low recoil analysis
  - Empirical 2p2h Fit
- CCQE-like Analysis with MINERvA's Simulation
  - Neutrino
  - Anti-neutrino

MINERvA Simulation

- Using neutrino event generator Genie 2.8.4 with MINERvA modifications [1] [2]
  - Pion production reduced
- Random Phase Approximation (RPA) model [3]
- Valencia 2p2h [4][5]
  - No prediction with pions. Only protons and/or neutrons

[1] C. Andreopoulos et al., Nucl. Instrum. Meth. A 614, 87 (2010), Program version 2.8.4, with private modifications, used here.
[2] A. Higuera et al. (MINERvA Collaboration), Phys. Rev. Lett. 113, 261802 (2014), arXiv:1409.3835 [hep-ex] .
C. Wilkinson et al., Phys. Rev. D 90, 112017 (2014), arXiv:1411.4482 [hep-ex] .
C. Wilkinson et al., In preparation 90 (2015), 10.1103/PhysRevD.90.112017, arXiv:15xx.xxxxx [hep-ex] .
[3] J. Nieves, J. E. Amaro, and M. Valverde, Phys. Rev. C 70, 055503 (2004), arXiv:nucl-th/0408005 [nucl-th].
[4] J. Nieves, I. Ruiz Simo, and M. Vicente Vacas, Phys. Rev. C 83, 045501 (2011), arXiv:1102.2777 [hepph] .
[5] R. Gran, J. Nieves, F. Sanchez, and M. Vicente Vacas, Phys. Rev. D 88, 113007 (2013), arXiv:1307.8105 [hep-ph] .

What is 2p2h?



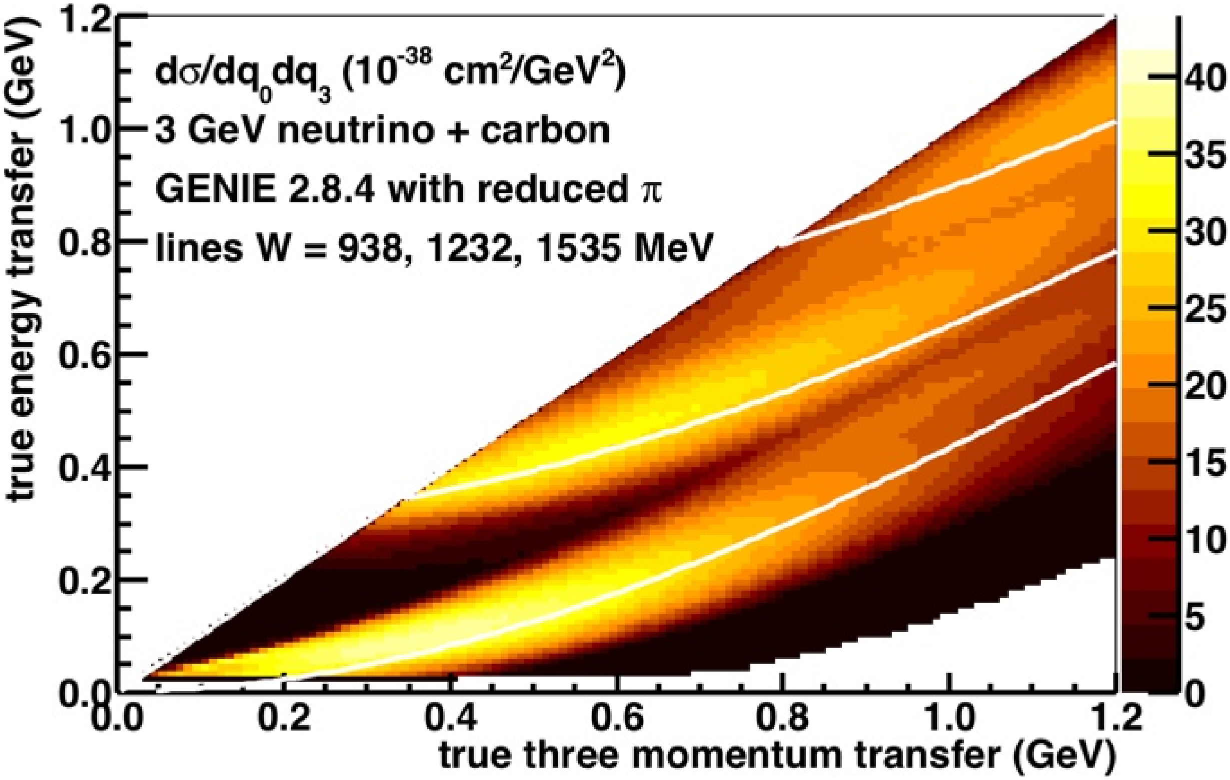
Low Recoil Analysis

$q_0 q_3$ Phase Space

- energy transfer (q_0) vs three momentum transfer (q_3)
  - Useful way to think about neutrino interactions

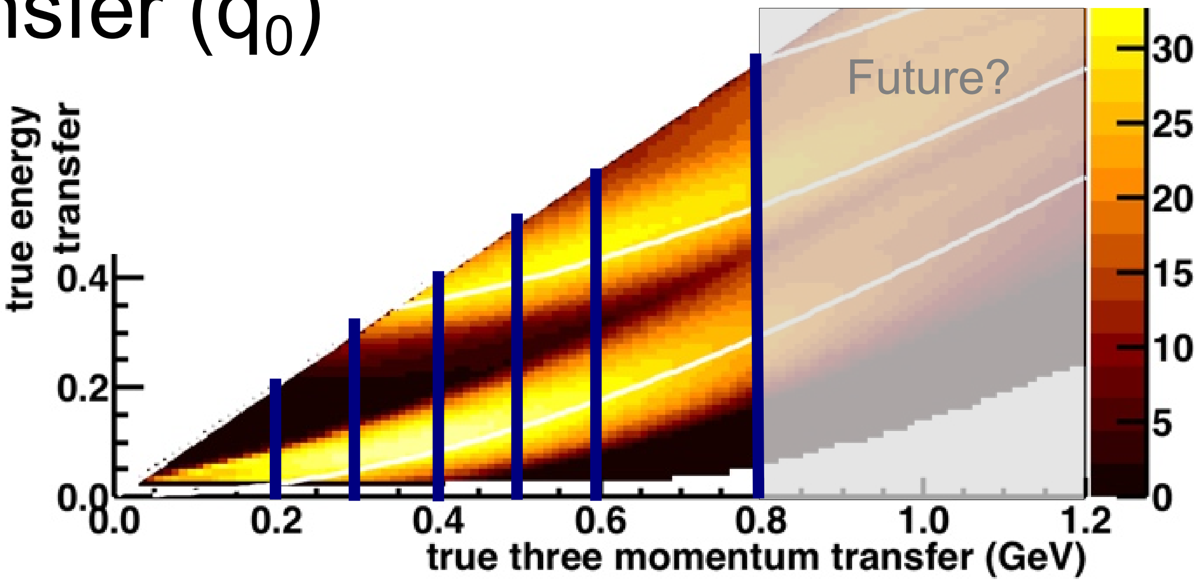
$$q_0 = E_\nu - E_\mu$$

$$q_3 = p_\nu - p_\mu$$



Low Recoil Analysis

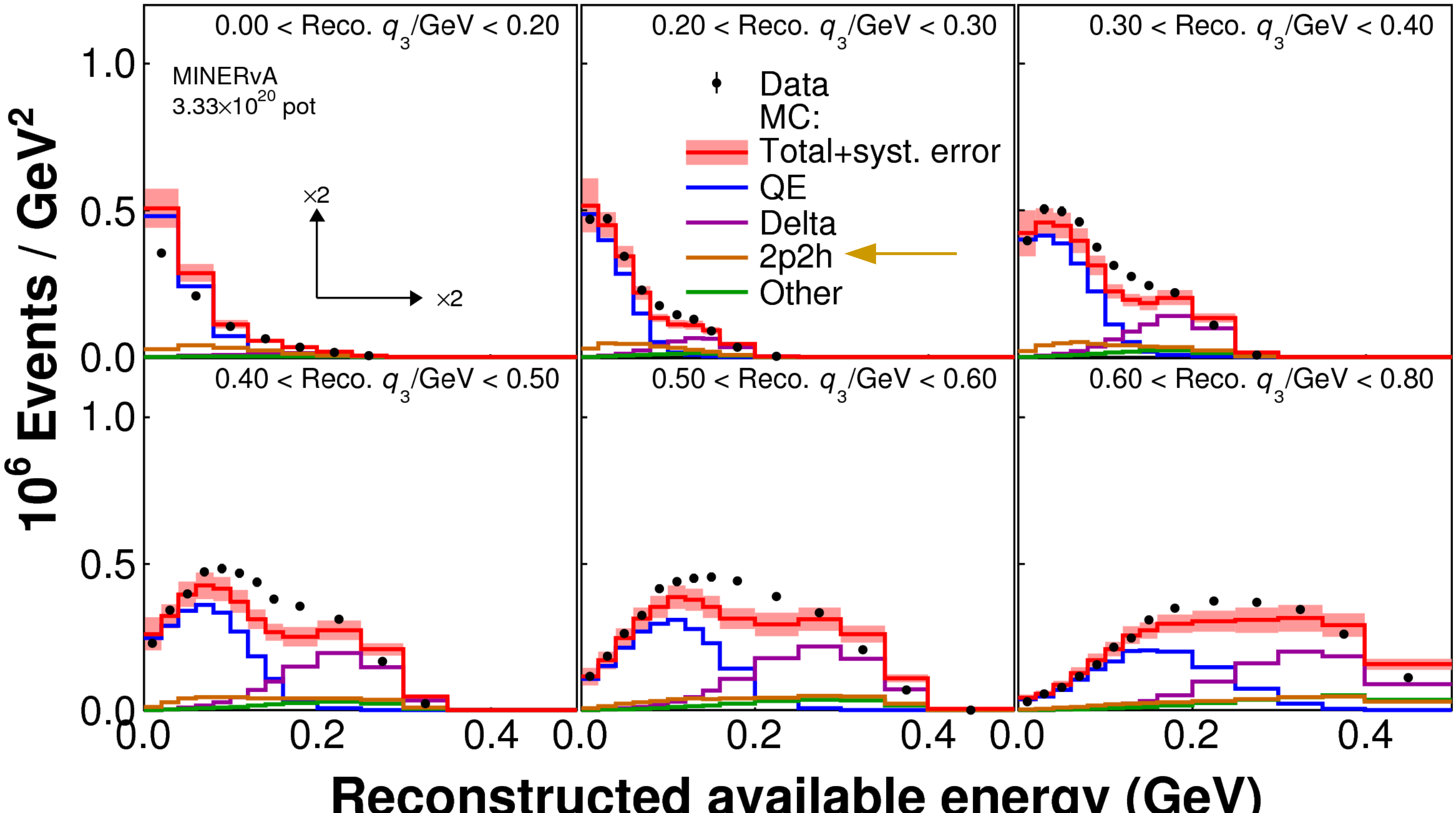
- Reconstructed momentrum transfer (reco q_3) vs reconstructed available energy
- Reconstructed available energy = calorimetric sum of all energy not associated with the muon
- Reconstructed available energy ~ energy transfer (q_0)



2 GeV < E_ν < 6 GeV

Rodrigues, Demgen, Miltenberger et al. [MINERvA] PRL 116 071802 (2015)

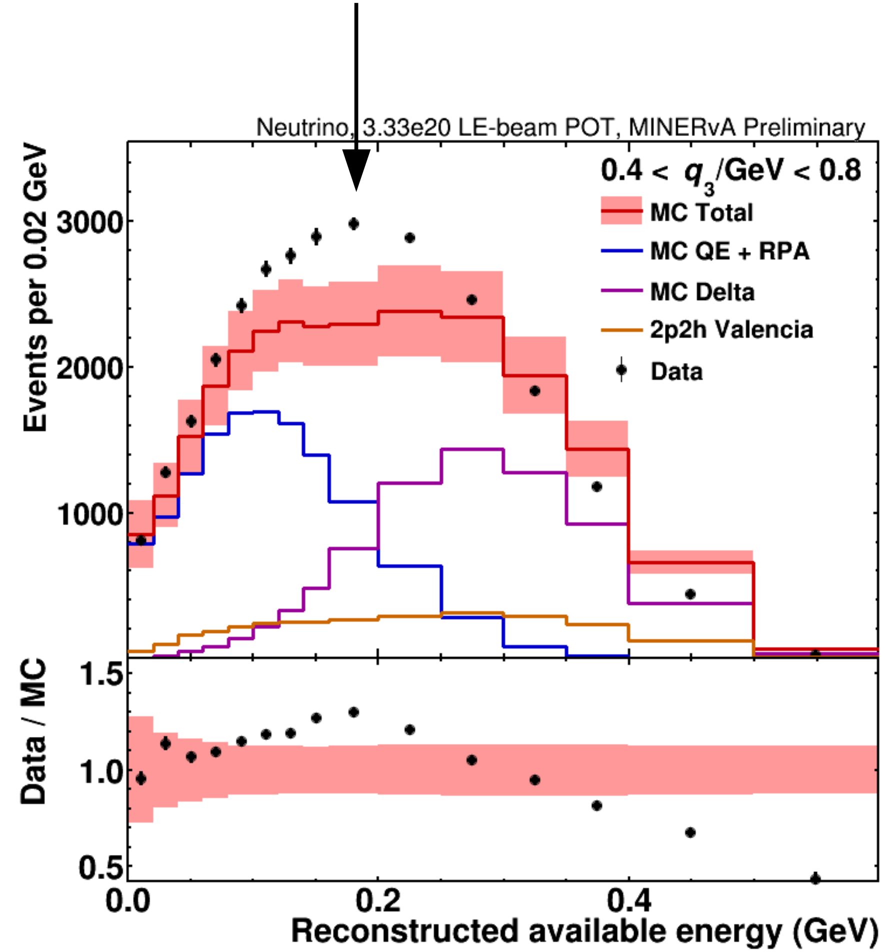
Low Recoil Analysis



Rodrigues, Demgen, Miltenberger et al. [MINERvA] PRL 116 071802 (2015)

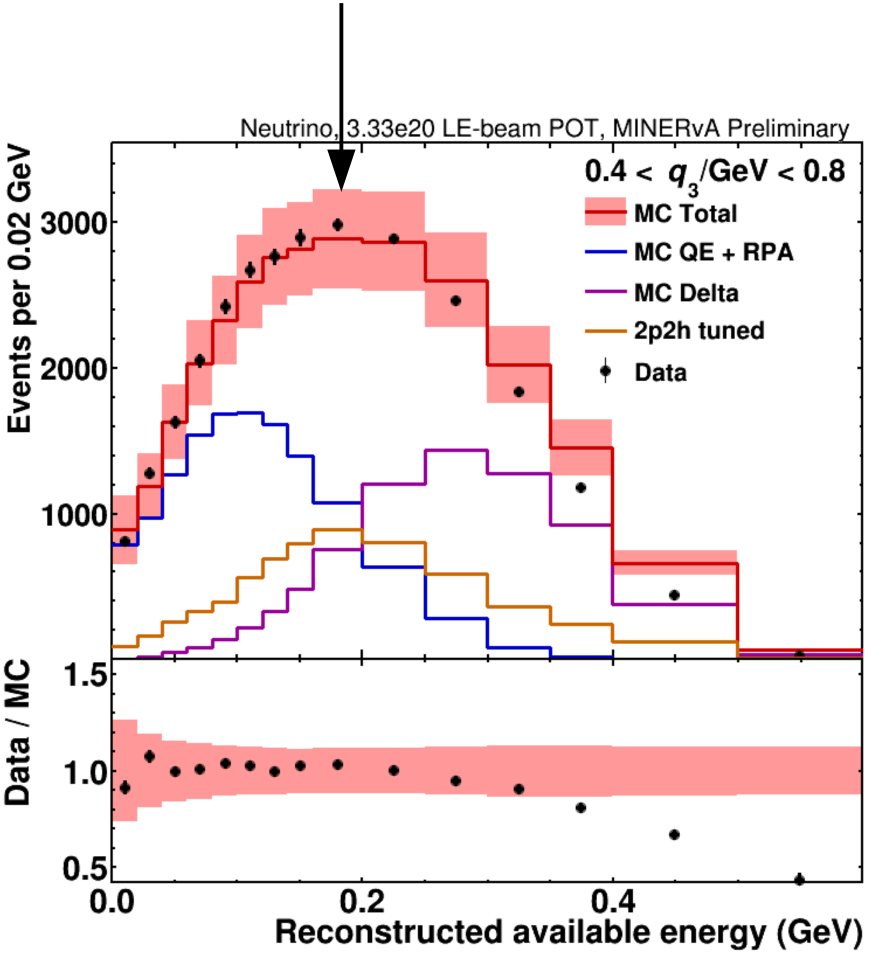
Empirical Fit

- 2p2h events are weighted up with a 2D guassian weight
  - 2D in $q_0 q_3$ space

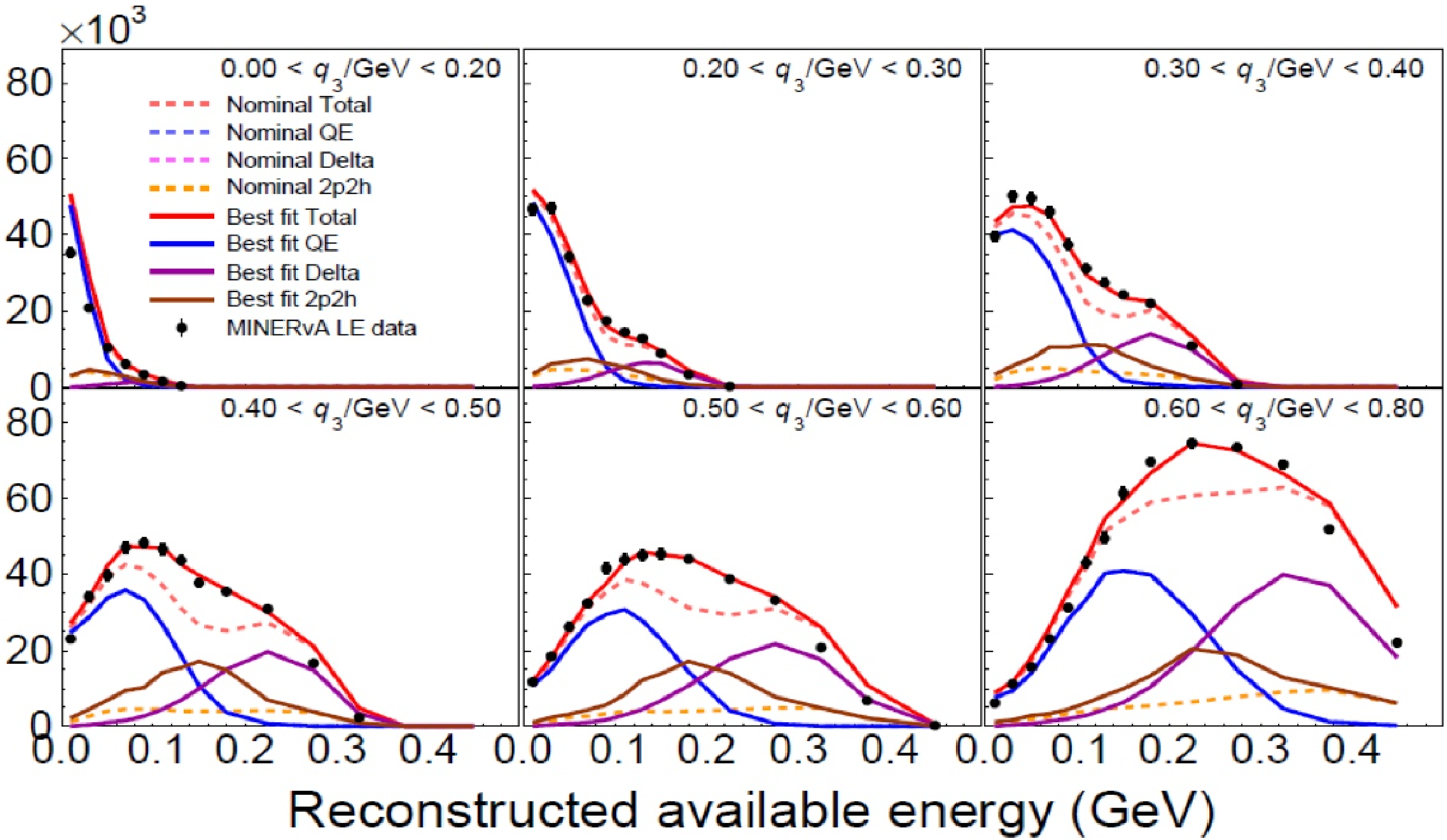


Empirical Fit

- 2p2h events are weighted up with a 2D guassian weight
  - 2D in $q_0 q_3$ space
- Adds ~50% more events, ~2x in central region
- This fills in the central region



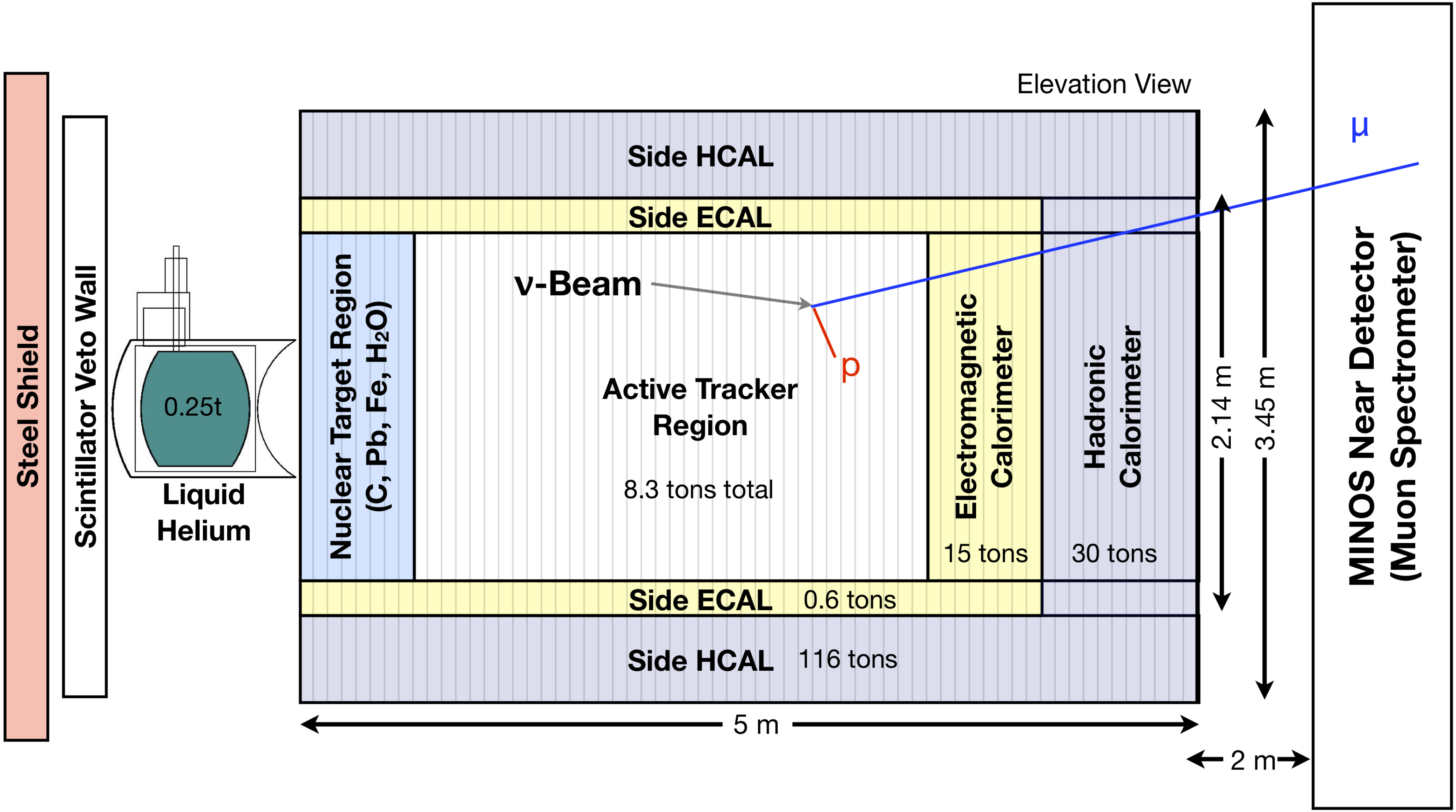
Fit Results



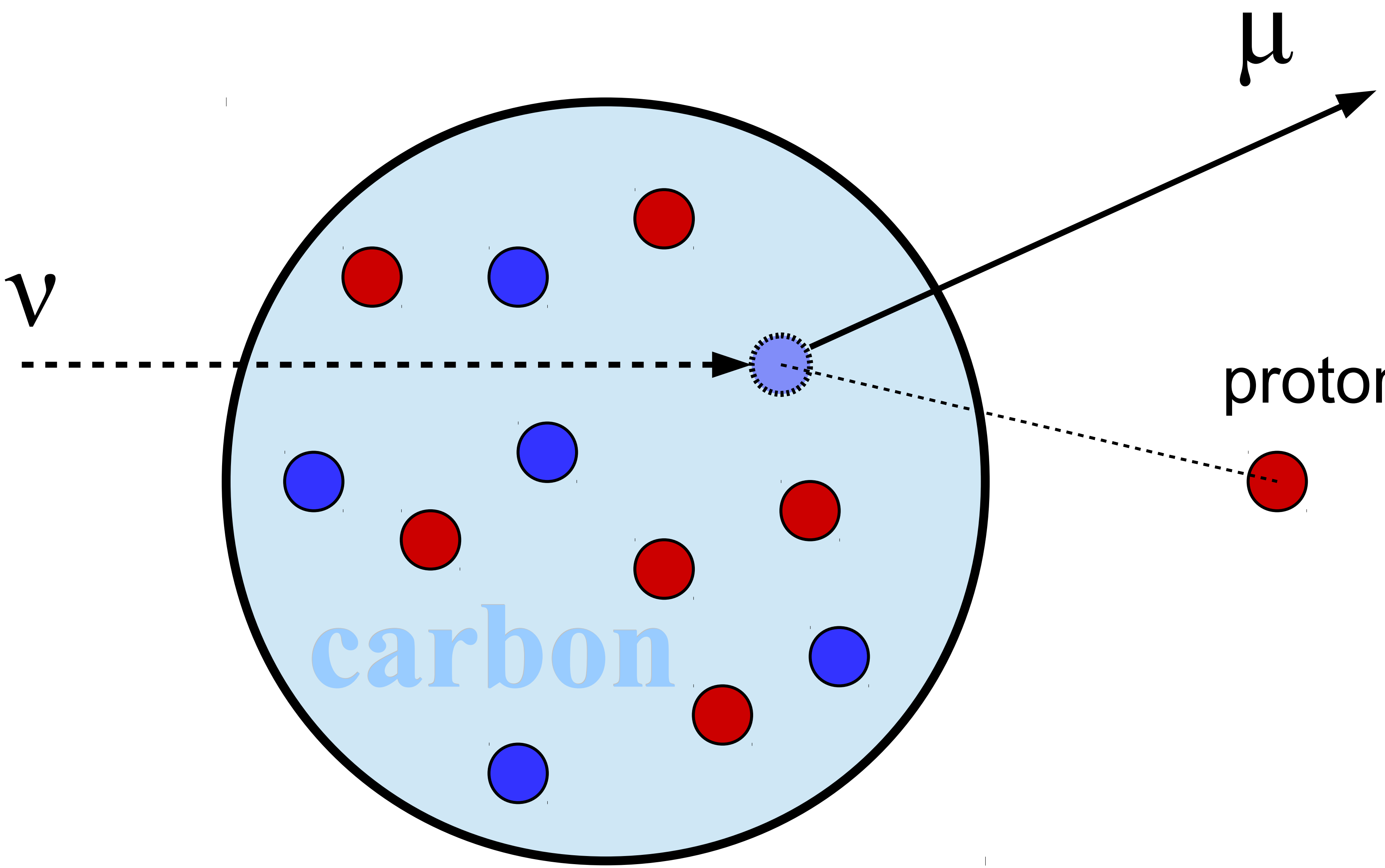
×10³
80
60
40
20
0
0.00 < q_3/GeV < 0.20
Nominal Total
Nominal QE
Nominal Delta
Nominal 2p2h
Best fit Total
Best fit QE
Best fit Delta
Best fit 2p2h
MINERvA LE data
0.20 < q_3/GeV < 0.30
0.30 < q_3/GeV < 0.40
0.40 < q_3/GeV < 0.50
0.50 < q_3/GeV < 0.60
0.60 < q_3/GeV < 0.80
0.0 0.1 0.2 0.3 0.4
Reconstructed available energy (GeV)

Using 2p2h Fit in CCQE-like 2D Lepton Momentum Cross Section Result

MINERvA Detector



Quasi-Elastic (QE)



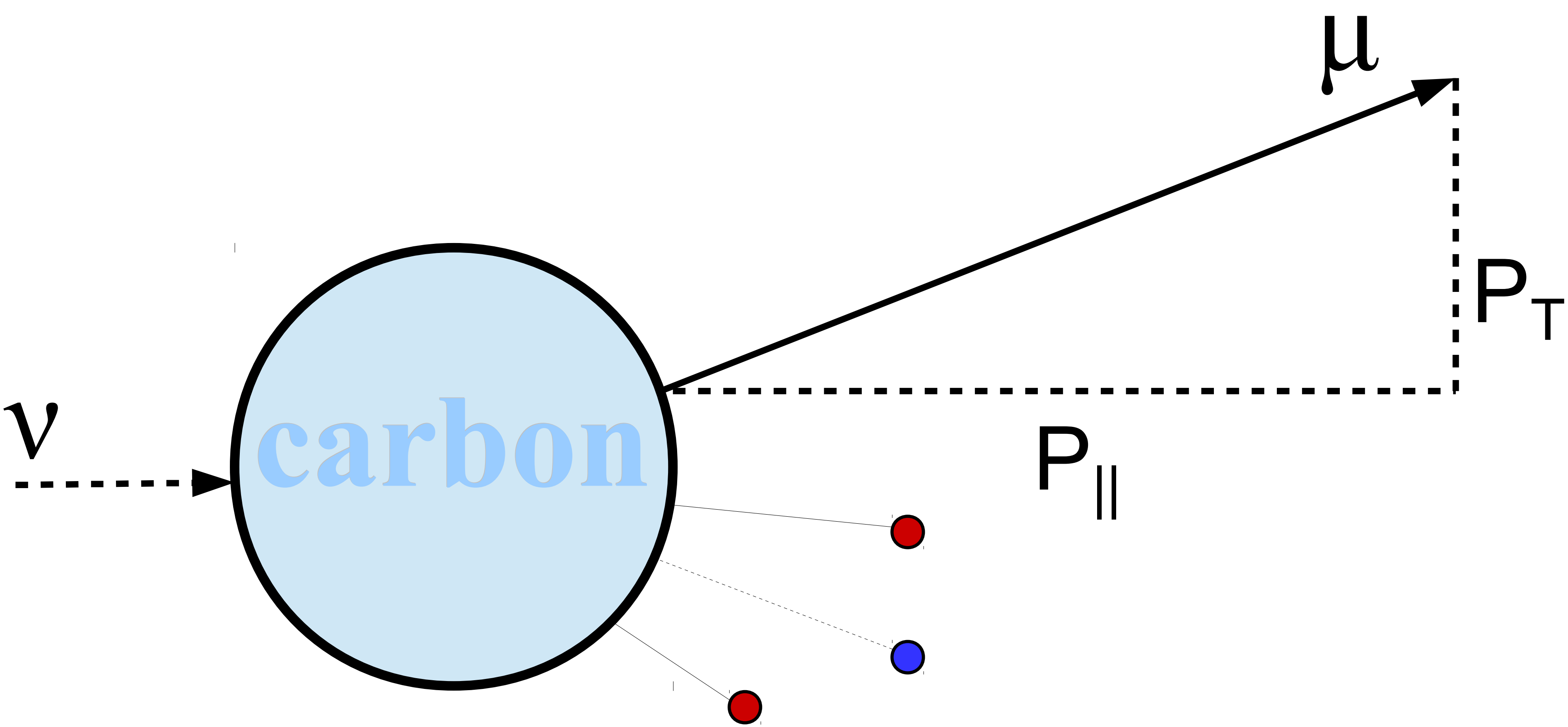
CCQE-like (CC0π)

- Final State of Muon +
  1 or more nucleons of any energy +
  any number of gammas < 10 MeV
  - No pions
- More closely matches the capabilities of proton-blind detectors
- Final State Interactions (FSI) make differentiating QE events from CCQE-like events difficult
  - CCQE-like signal has less FSI model dependent

Larger Phase Space

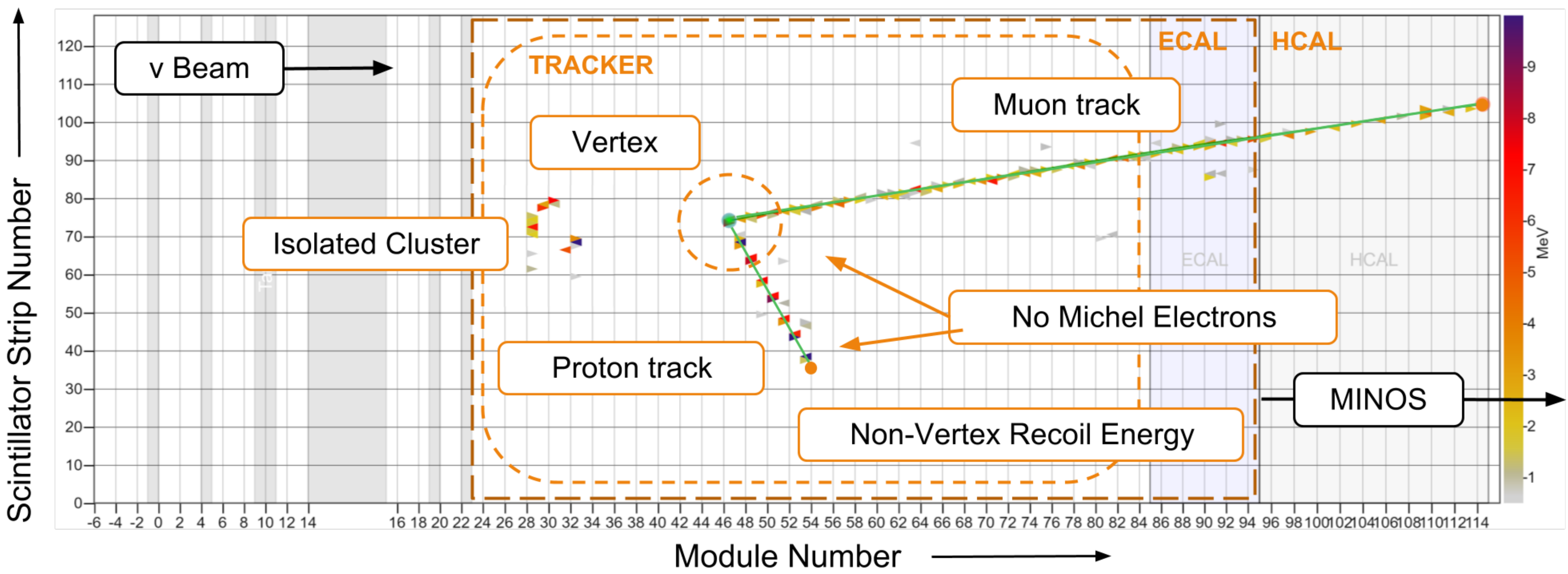
- Low recoil fit is done in a limited q_0q_3 and E_ν space
  - $q_3 < 0.8$ GeV
  - 2 GeV $< E_\nu <$6 GeV
- Both the neutrino and anti-neutrino CCQE-like results have larger acceptance in q_0q_3 and E_ν space

What are we measuring?

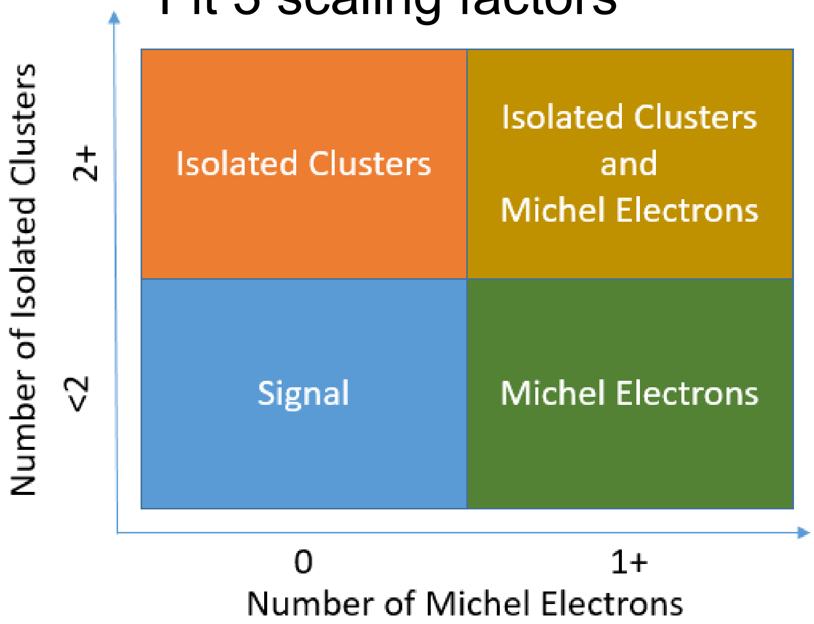


2D differential cross section
in muon P_T vs $P_{||}$ for ccqe-like events

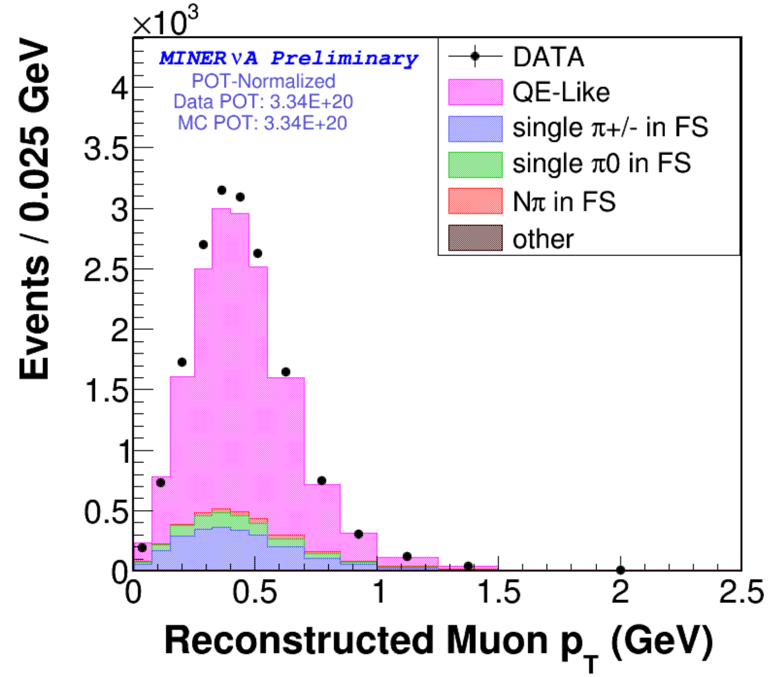
Event Selection



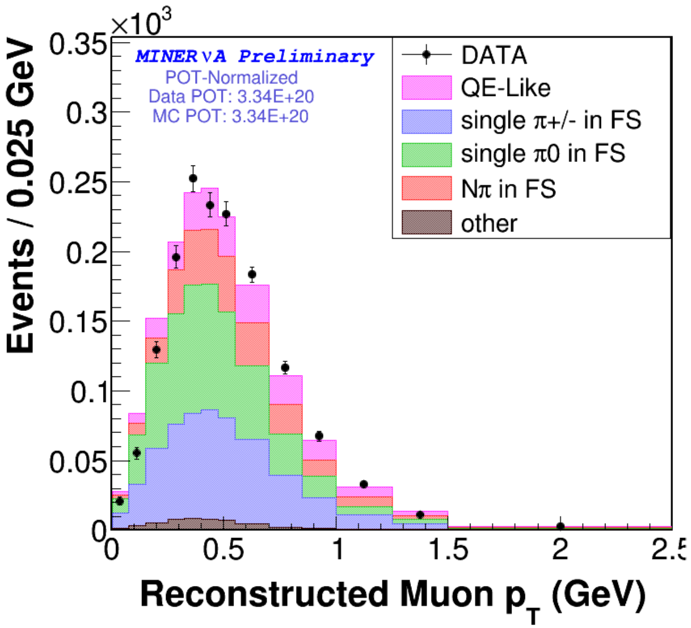
Fit 3 scaling factors



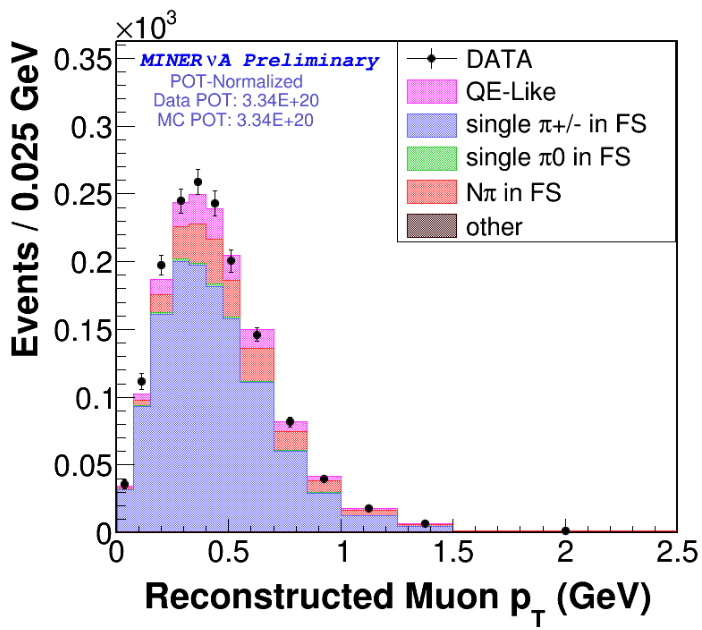
Signal



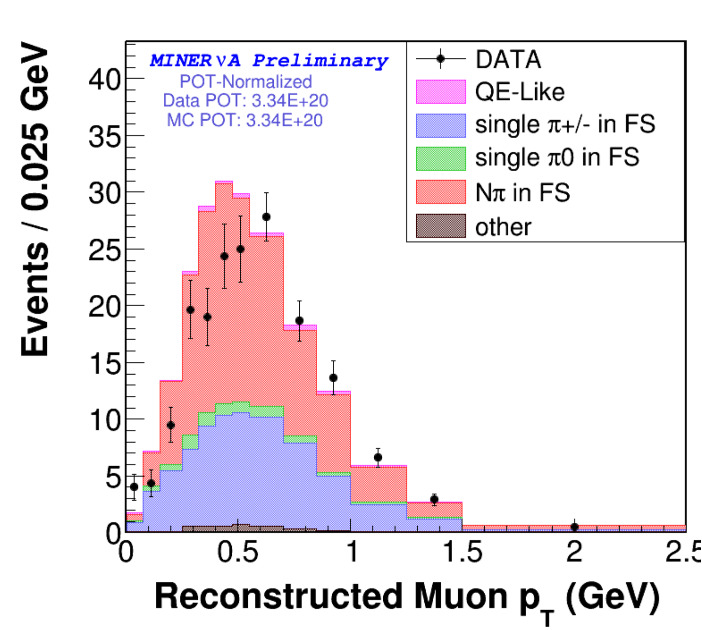
Isolated Clusters



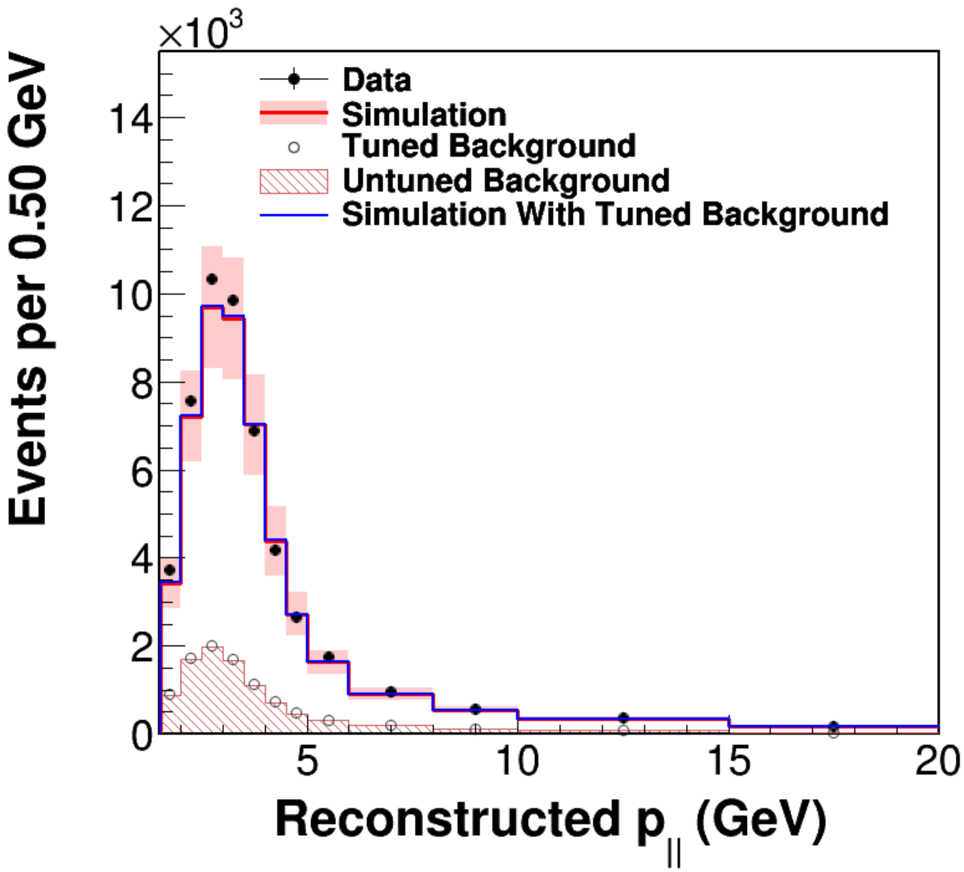
Michel Electrons

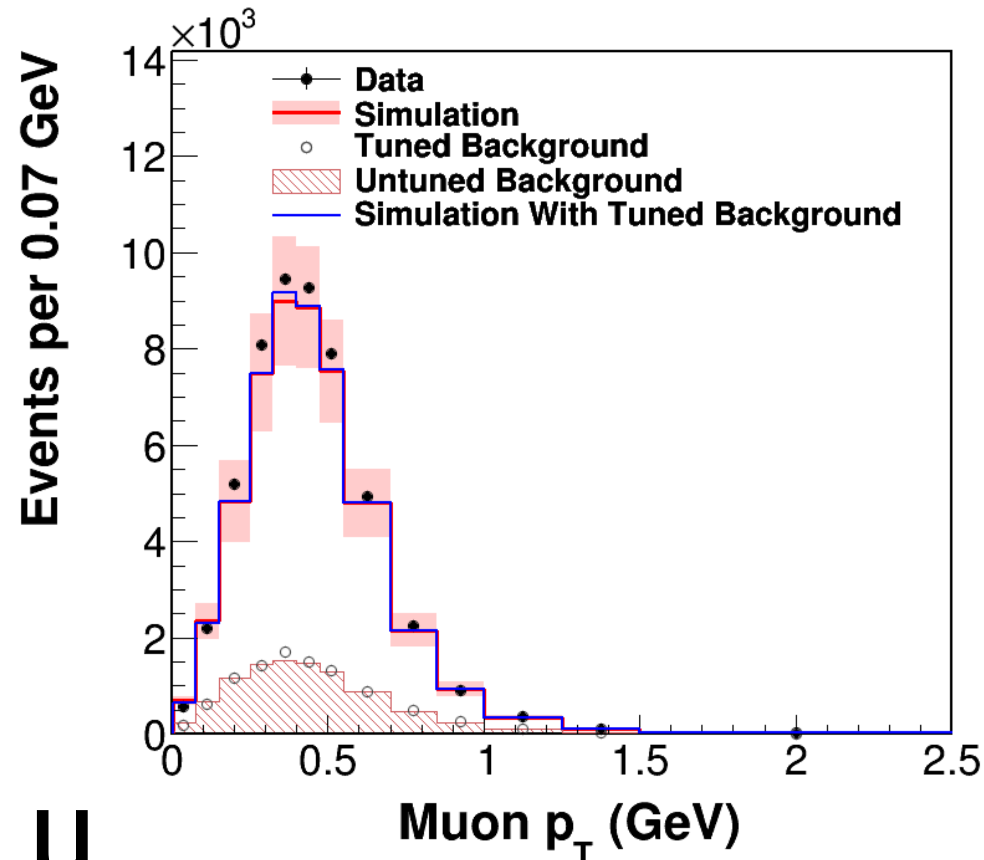


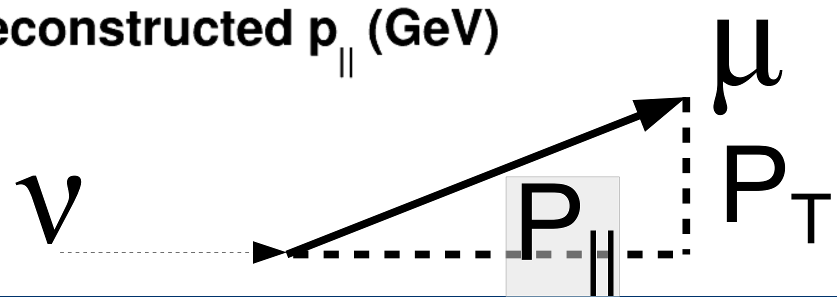
Michel + Iso. Clusters



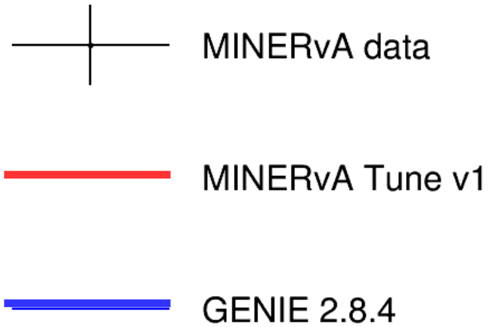
Effects of Sideband Tuning

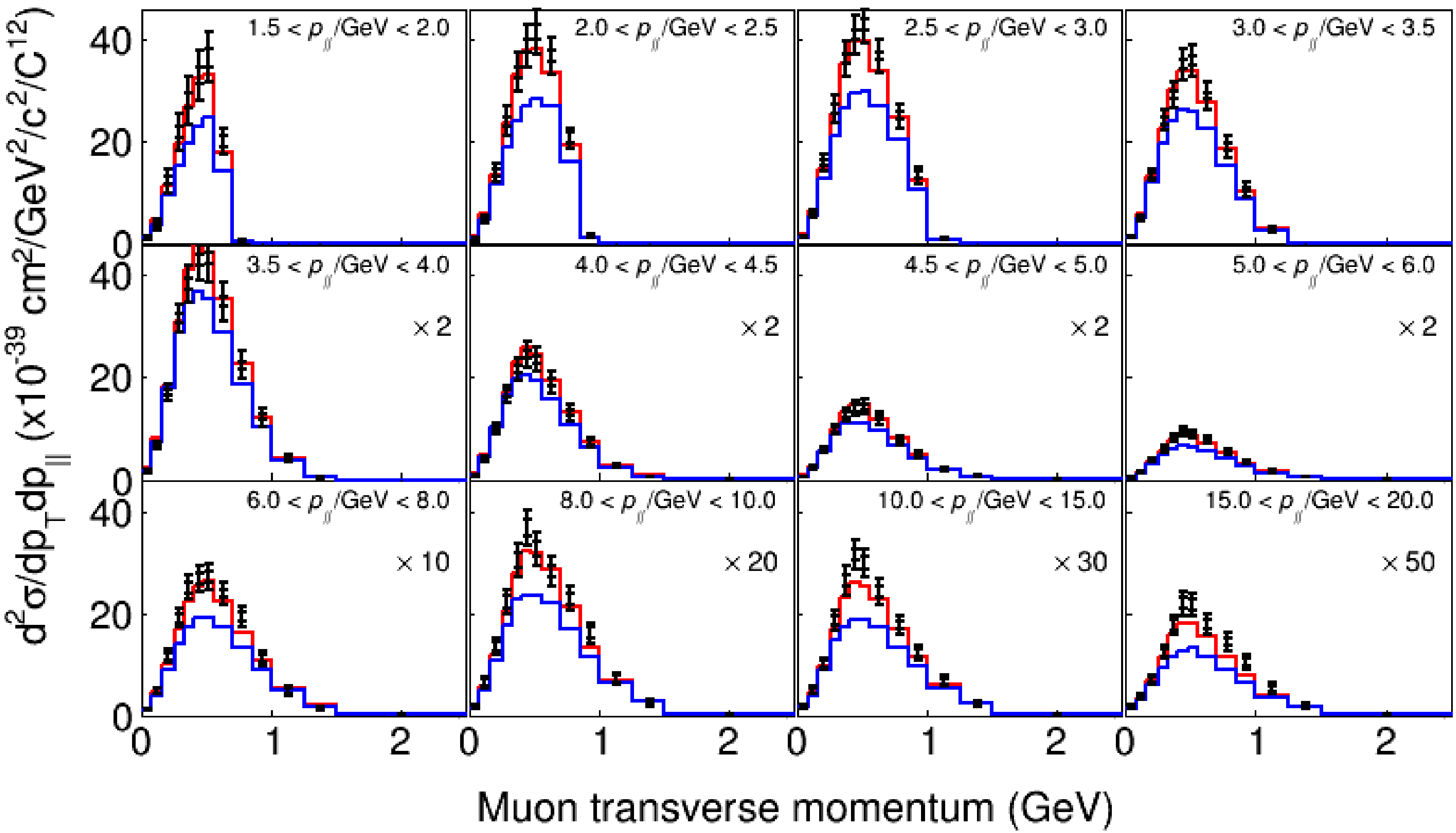




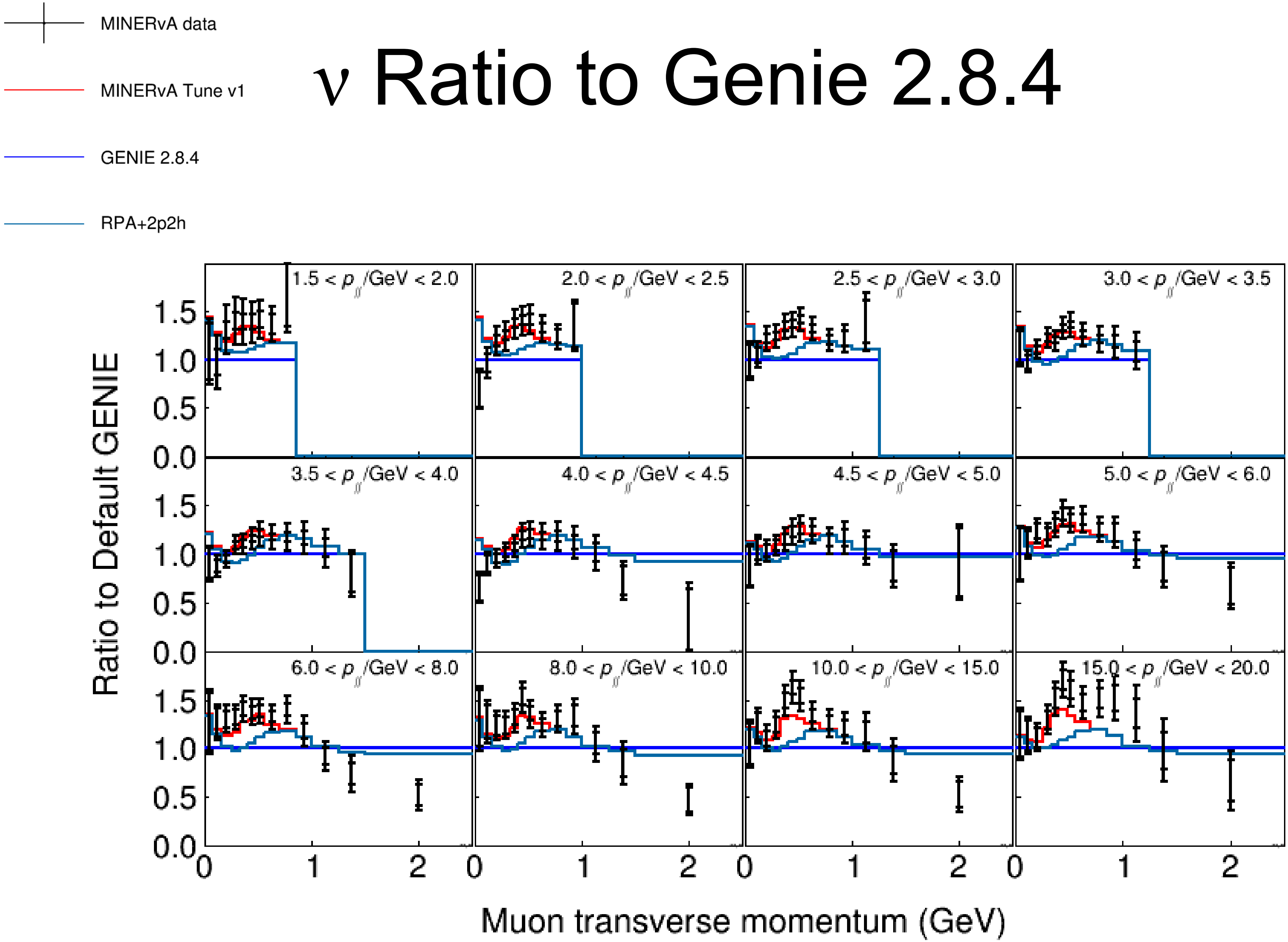


ν Results

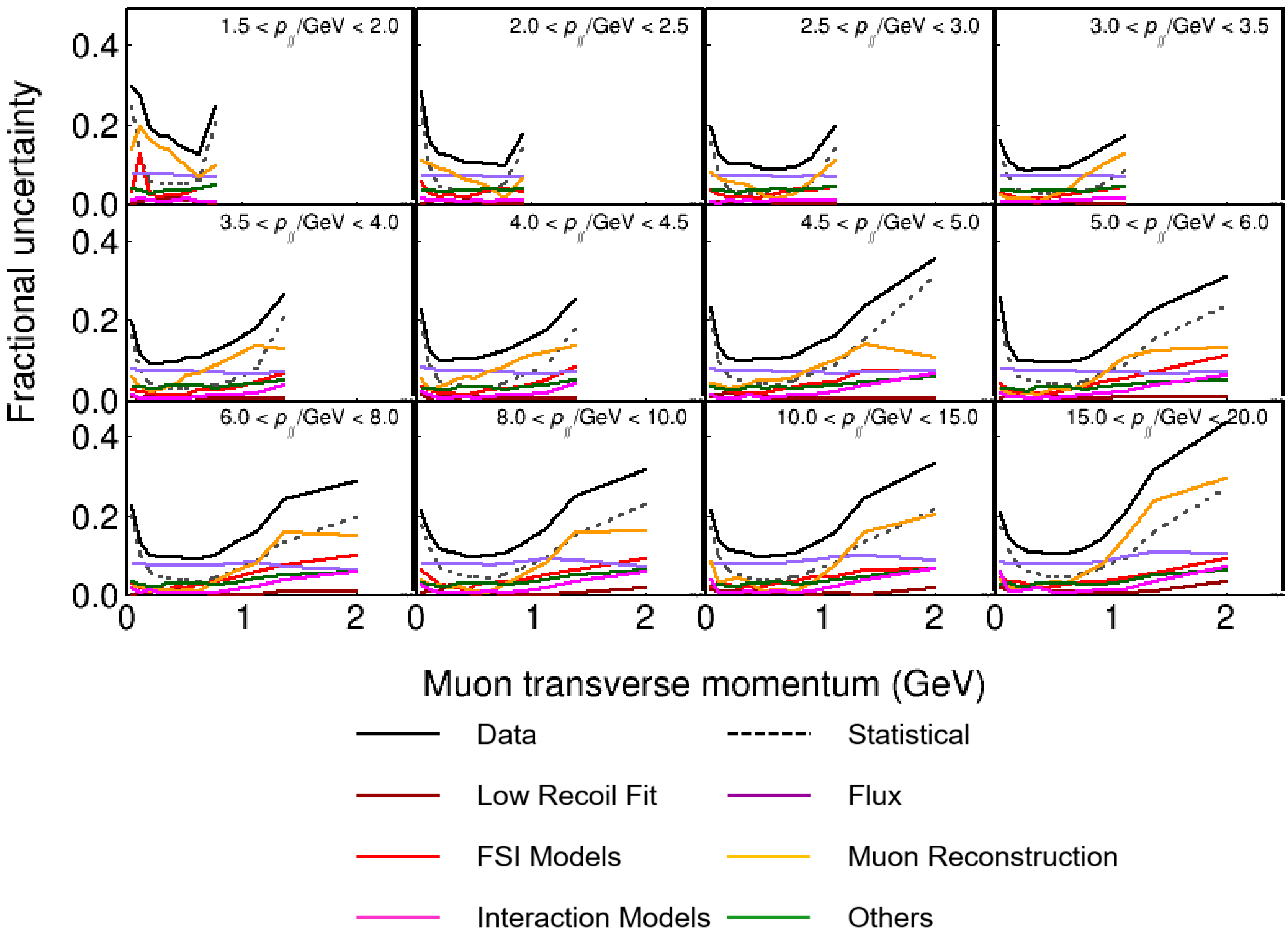

MINERvA data
MINERvA Tune v1
GENIE 2.8.4


1.5 < p_∥/GeV < 2.0
2.0 < p_∥/GeV < 2.5
2.5 < p_∥/GeV < 3.0
3.0 < p_∥/GeV < 3.5
3.5 < p_∥/GeV < 4.0
4.0 < p_∥/GeV < 4.5
4.5 < p_∥/GeV < 5.0
5.0 < p_∥/GeV < 6.0
6.0 < p_∥/GeV < 8.0
8.0 < p_∥/GeV < 10.0
10.0 < p_∥/GeV < 15.0
15.0 < p_∥/GeV < 20.0
× 2
× 2
× 2
× 2
× 10
× 20
× 30
× 50
0
20
40
0
1
2
d²σ/dp_T dp_∥ (x10⁻³⁹ cm²/GeV²/c²/C¹²)
Muon transverse momentum (GeV)

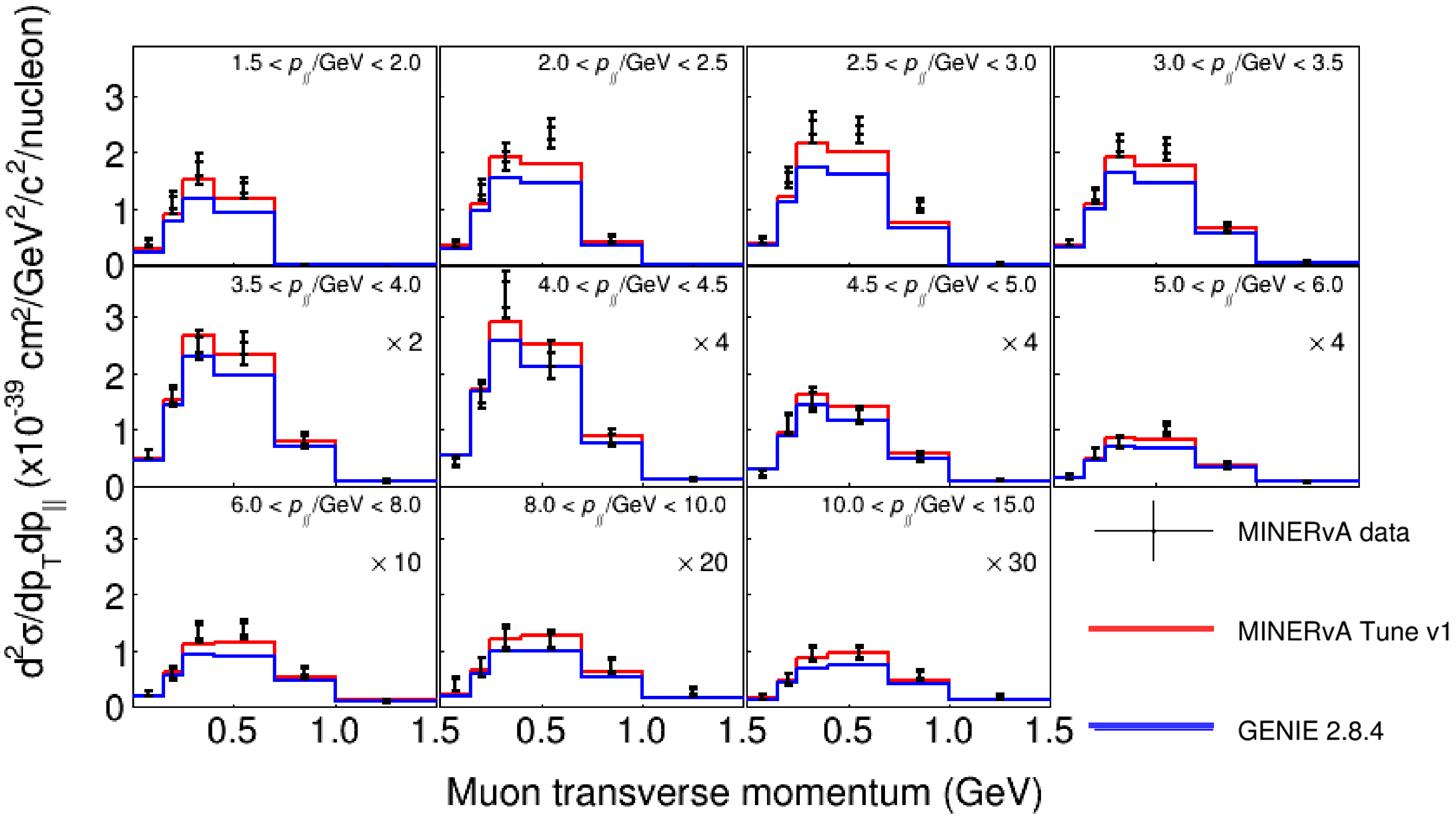
ν Ratio to Genie 2.8.4



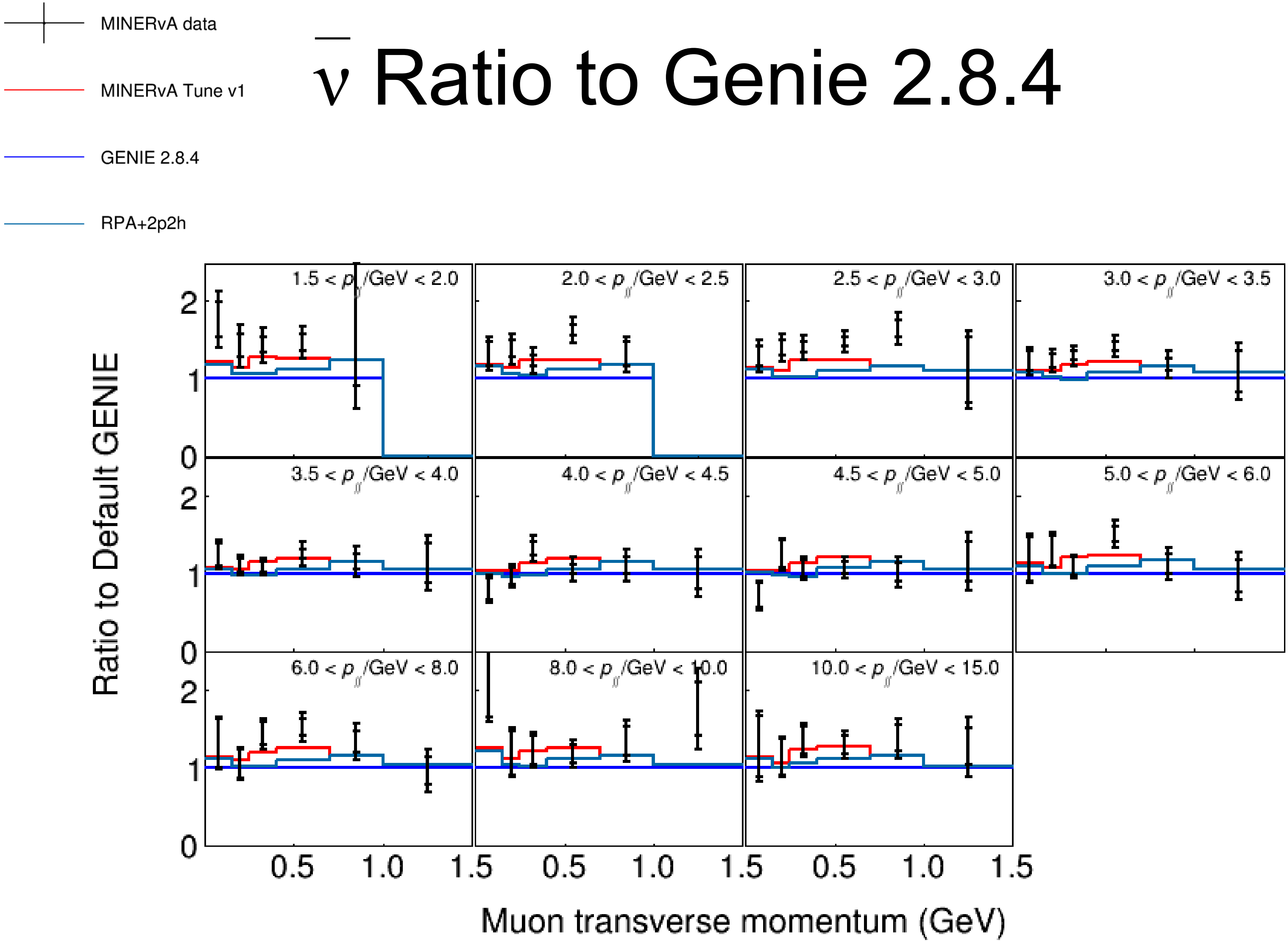
ν Systematic Uncertainty



$\bar{\nu}$ Results



$\bar{\nu}$ Ratio to Genie 2.8.4

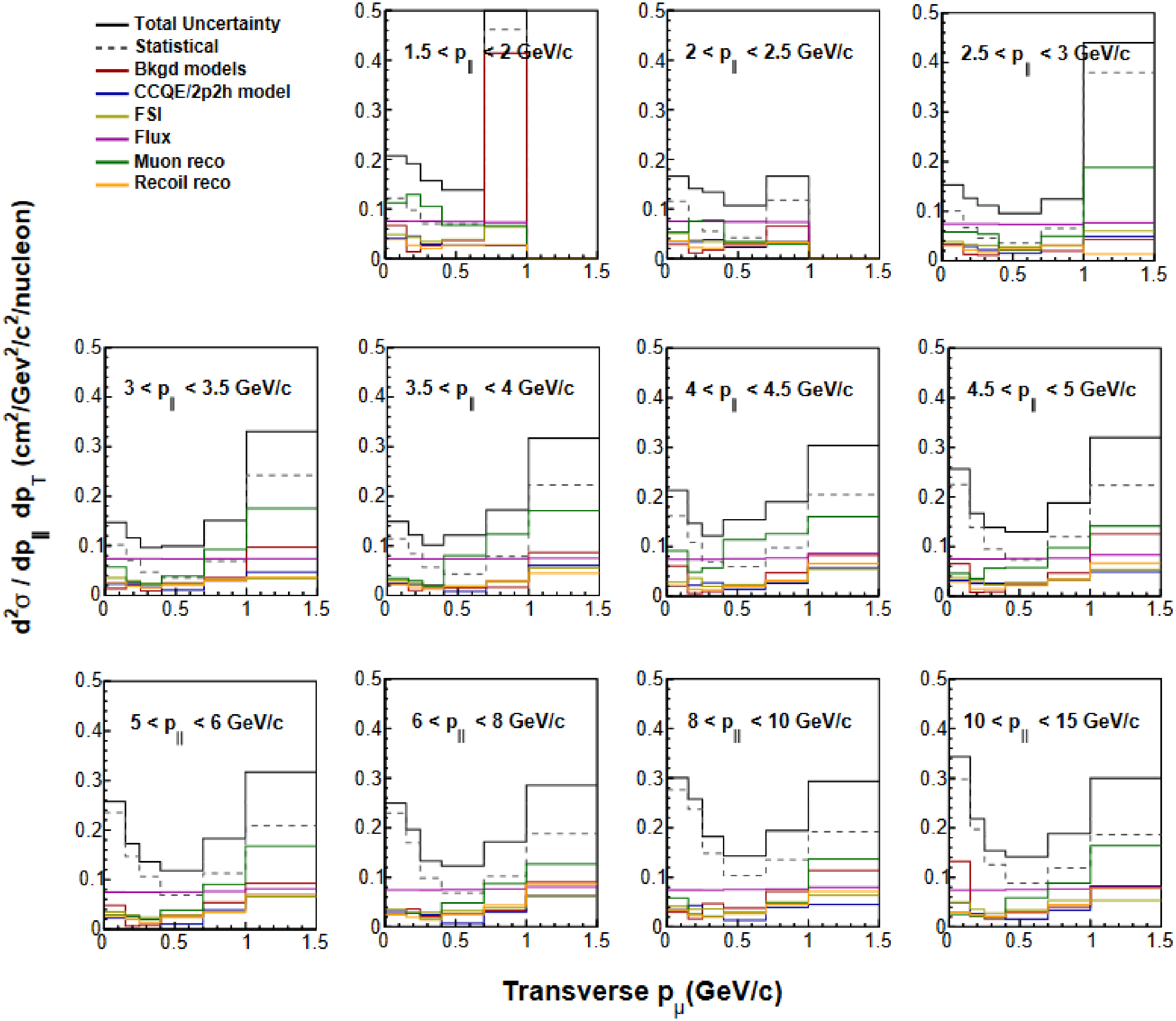


Conclusions

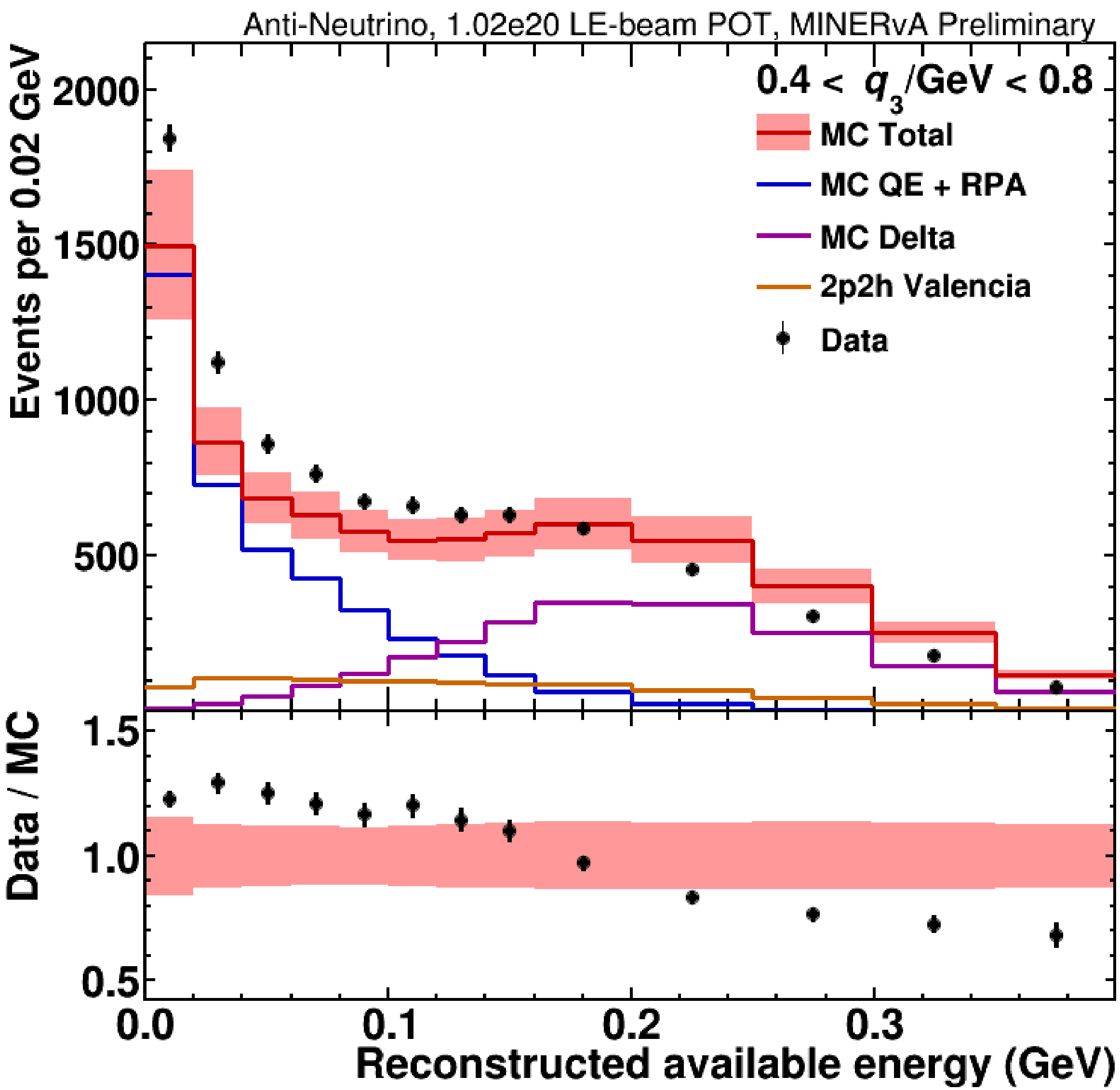
- Low recoil 2p2h fit is done in a limited q_0q_3 and E_ν space
- The MINERvA empirical model improves our aggreement in the larger phase space of the ccqe-like result
- Look forward to results from medium energy flux
  - Higher statistics + larger phase space reach

Backup

CCQE-like $\bar{\nu}$ Systematic Uncertainty

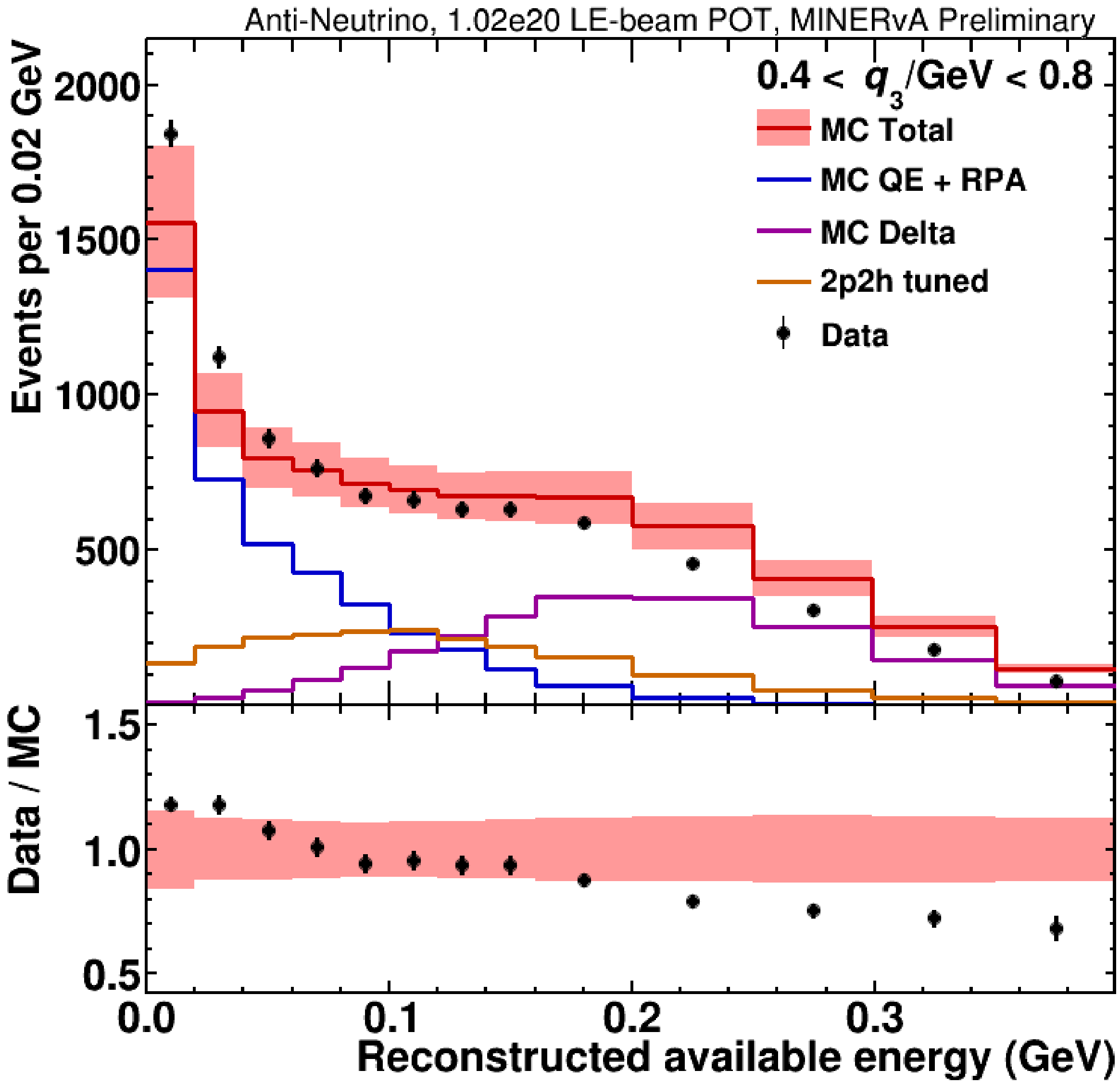


Applying fit parameters from ν result in $\bar{\nu}$ result



$\bar{\nu}$ result
using default Valencia 2p2h model

Applying fit parameters from ν result in $\bar{\nu}$ result



$\bar{\nu}$ result
using ν fit

2p2h Fit Systematics

- Additional fits varying the 2p2h and 1p1h models to modify the energy deposited in the detector.
- Fit with ONLY nucleon-nucleon initial state of the same type varied (nn or pp)
- Fit with ONLY the np initial state varied
- Fit with ONLY the 1p1h state varied

Low Nu Analysis: steps to calorimetric reconstruction

We do not start knowing the energy of the neutrino, only the direction.

Measure the energy E_μ and angle θ_μ of the outgoing muon.
Measure the detected energy attributed to hadrons $E_{visible}$.

A. turn $E_{visible}$ into $E_{available}$ using detector MC, discounts neutrons
$E_{available}$ = Proton KE, $\pi^\pm$ KE, π^0, e, γ energy (plus heavier particles)
little neutrino model dependence (some anti-nu model dependence)

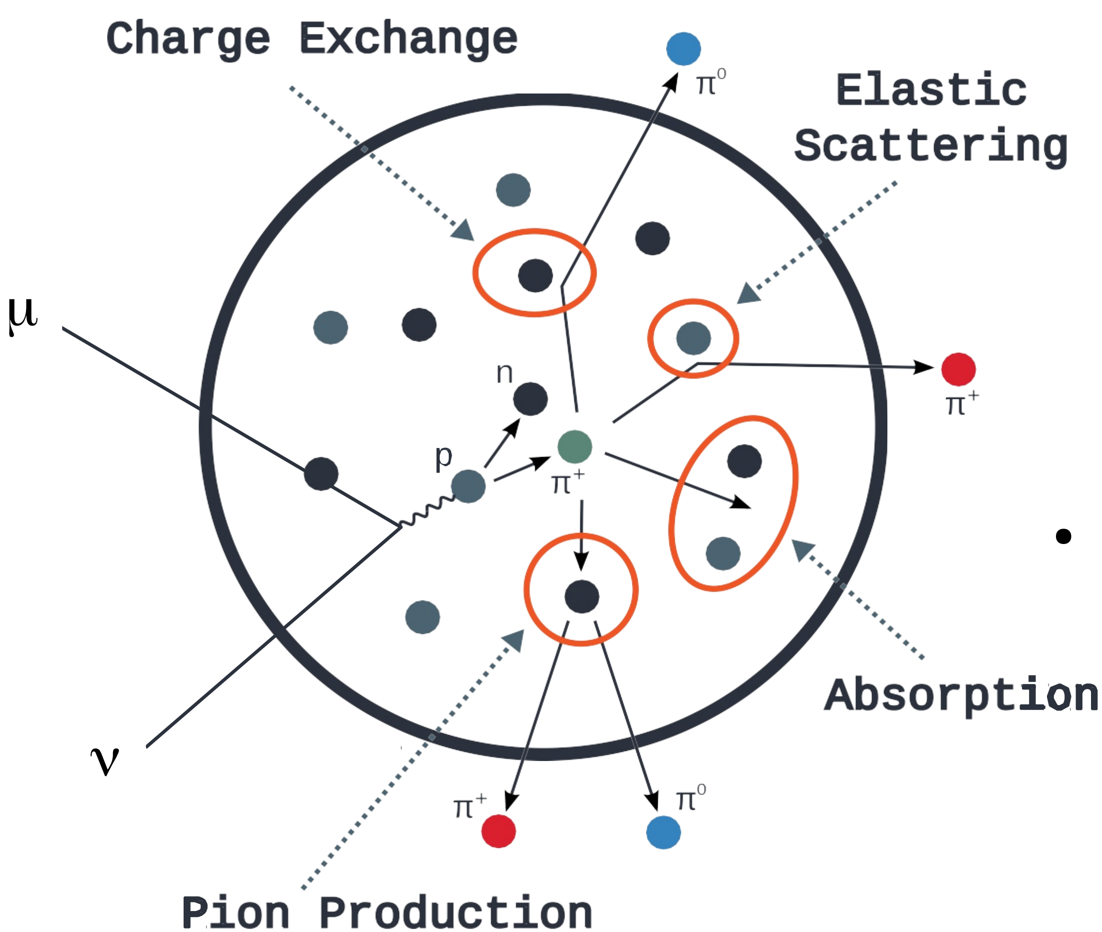
B. Use MC and correct to energy transfer q_0 (= E_{had} = ν = ω)
(unbiased, but correction has some dependence on neutrino model)

B. Estimated neutrino energy $E_\nu = E_\mu + q_0$

C. Estimated four-momentum $Q^2 = 2 E_\nu (E_\mu - p_\mu \cos\theta_\mu) - M_\mu^2$

D. Estimated momentum transfer $q_3 = \mathrm{Sqrt}(Q^2 + q_0^2)$

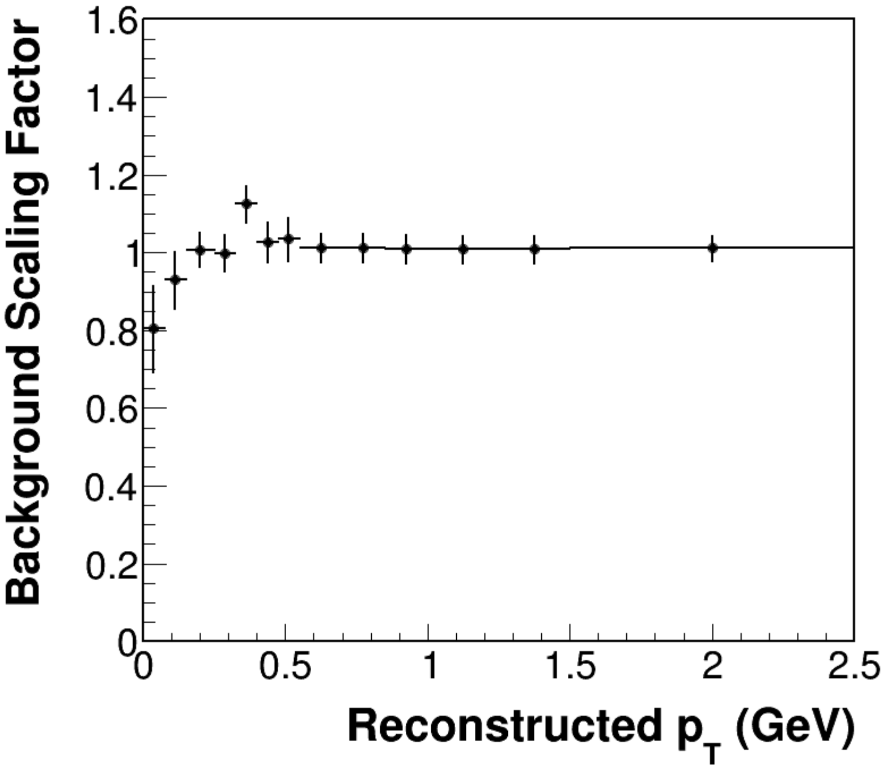
Final State Interaction



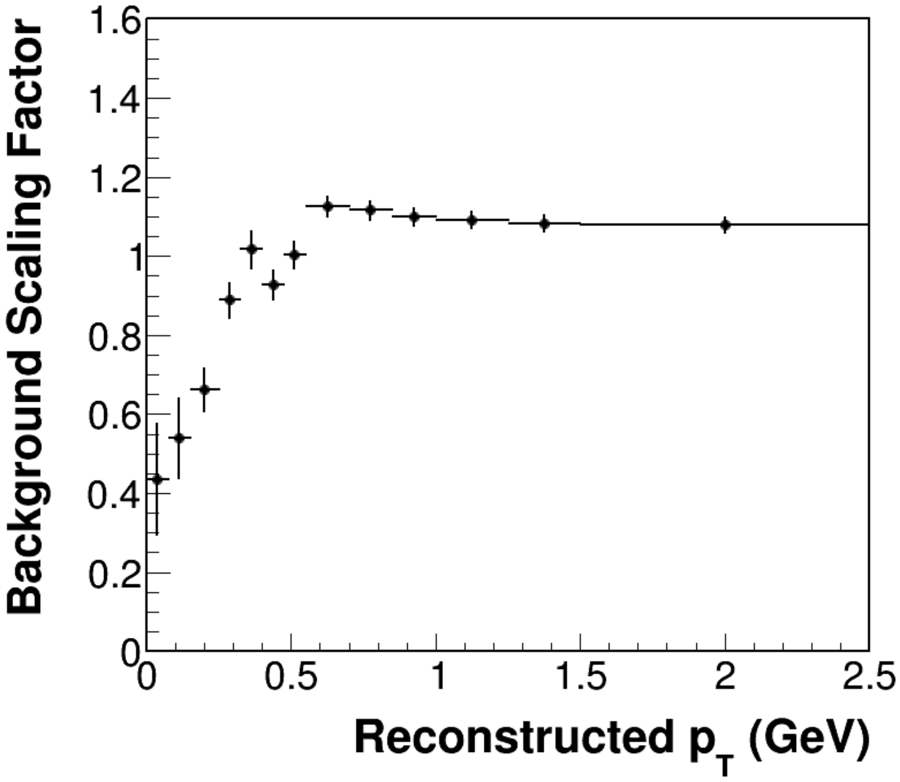
- Components of the initial hadron shower interact within the nucleus changing the apparent final state configuration and even the detected energy. Currently using mainly cascade models for FSI
- An initial pion can charge exchange or be absorbed on a pair of nucleons. The final state observed is μ + p that makes this a fine candidate for QE production
- We've probably also lost measurable energy

CCQE-like Analysis: Sideband Scale Factors

Only Muon Reconstructed

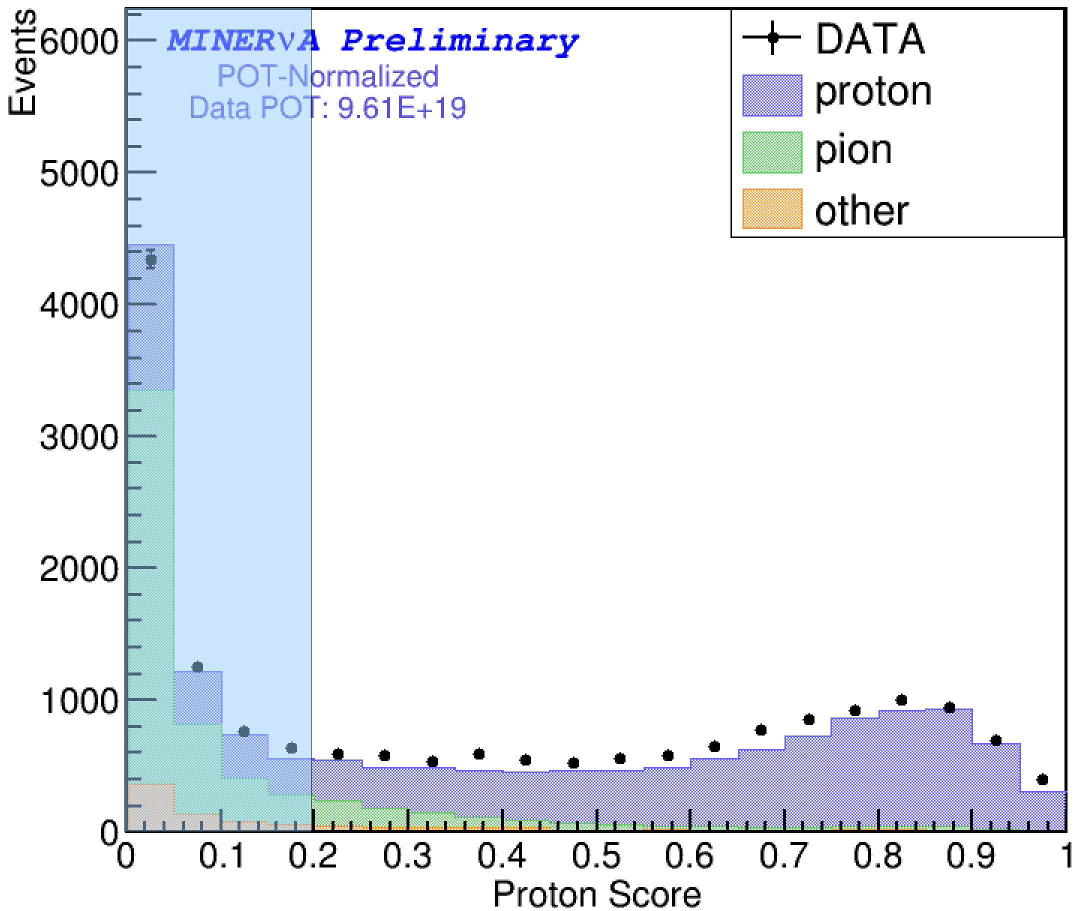


2+ tracks Reconstructed

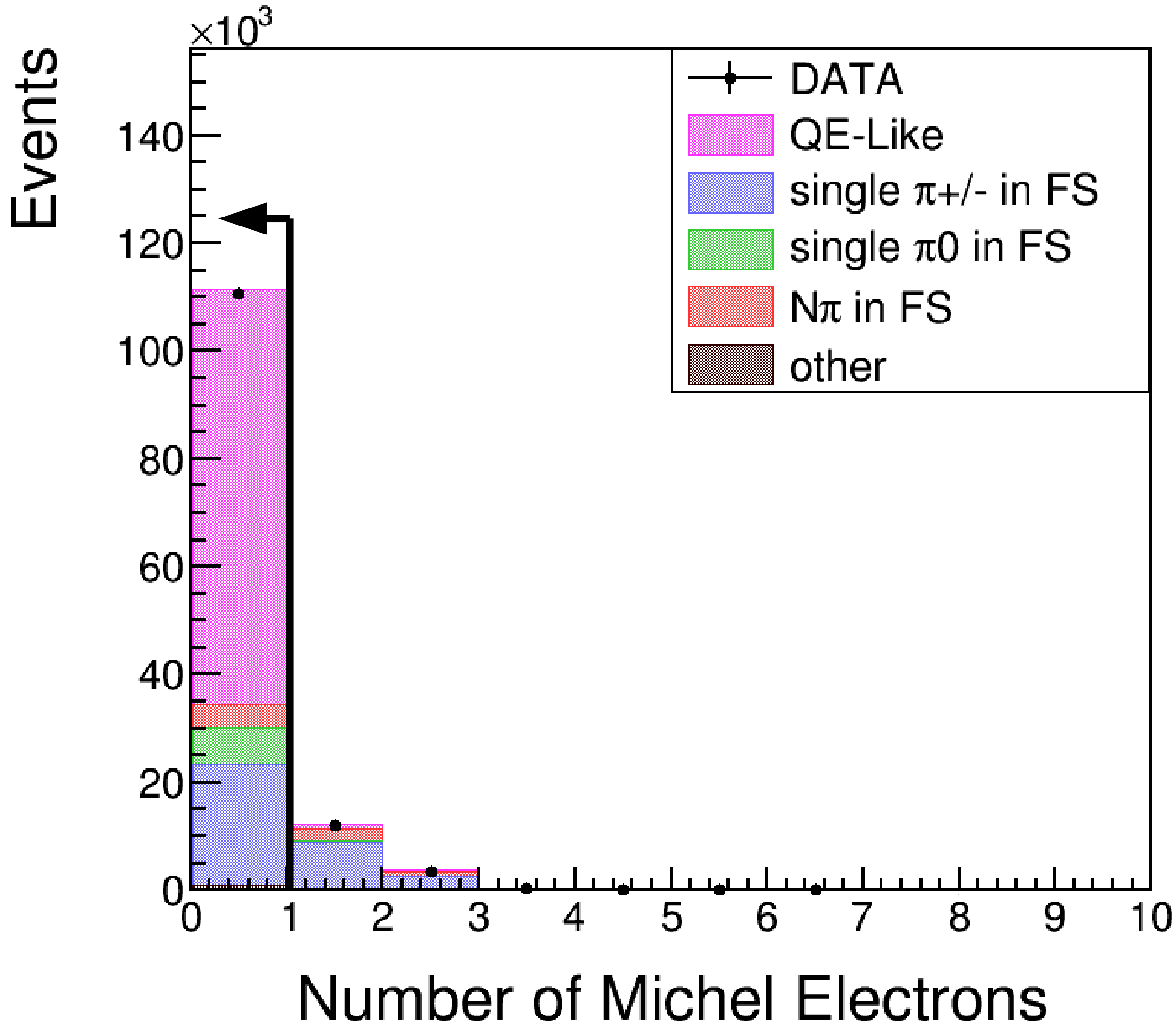


CCQE-like Analysis: Proton PID

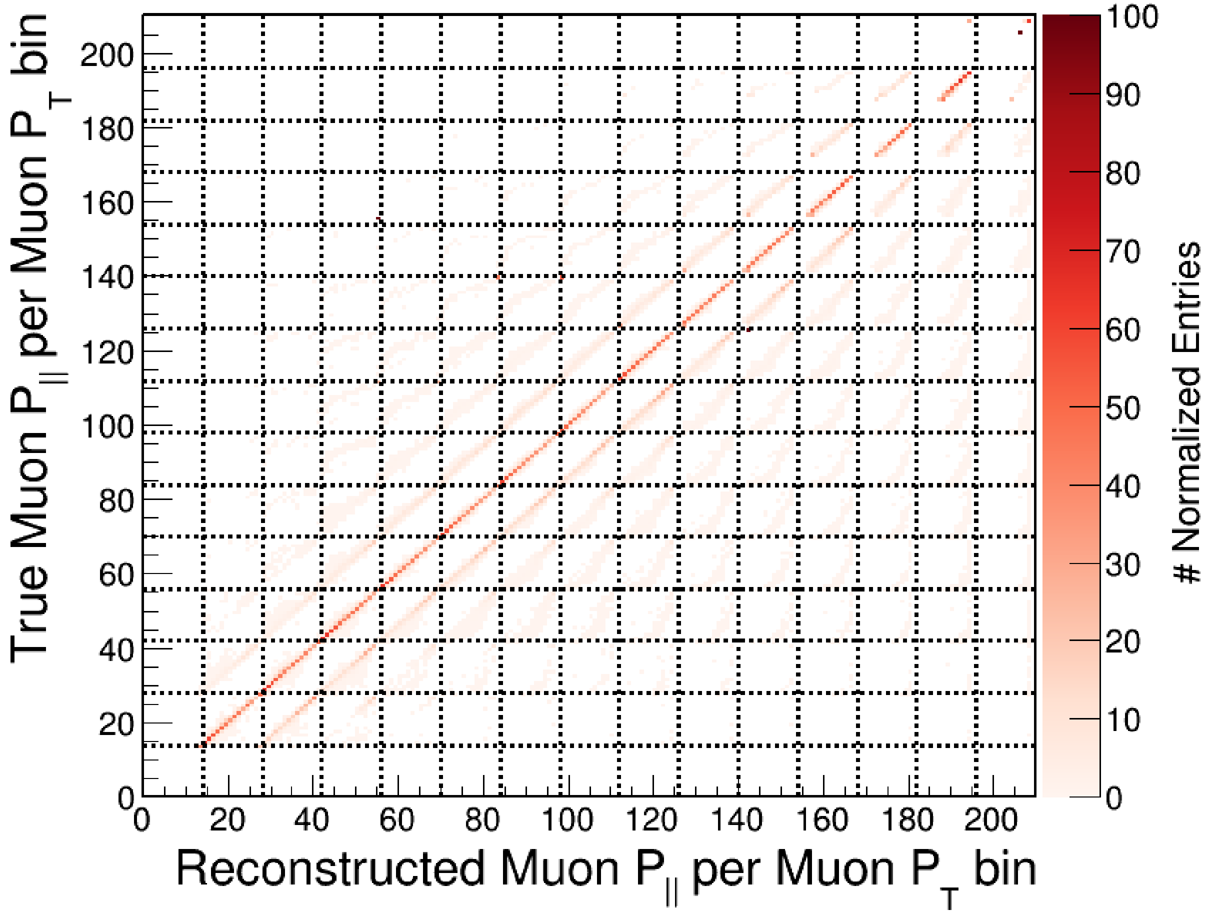
- Proton cut is Q2 dependent



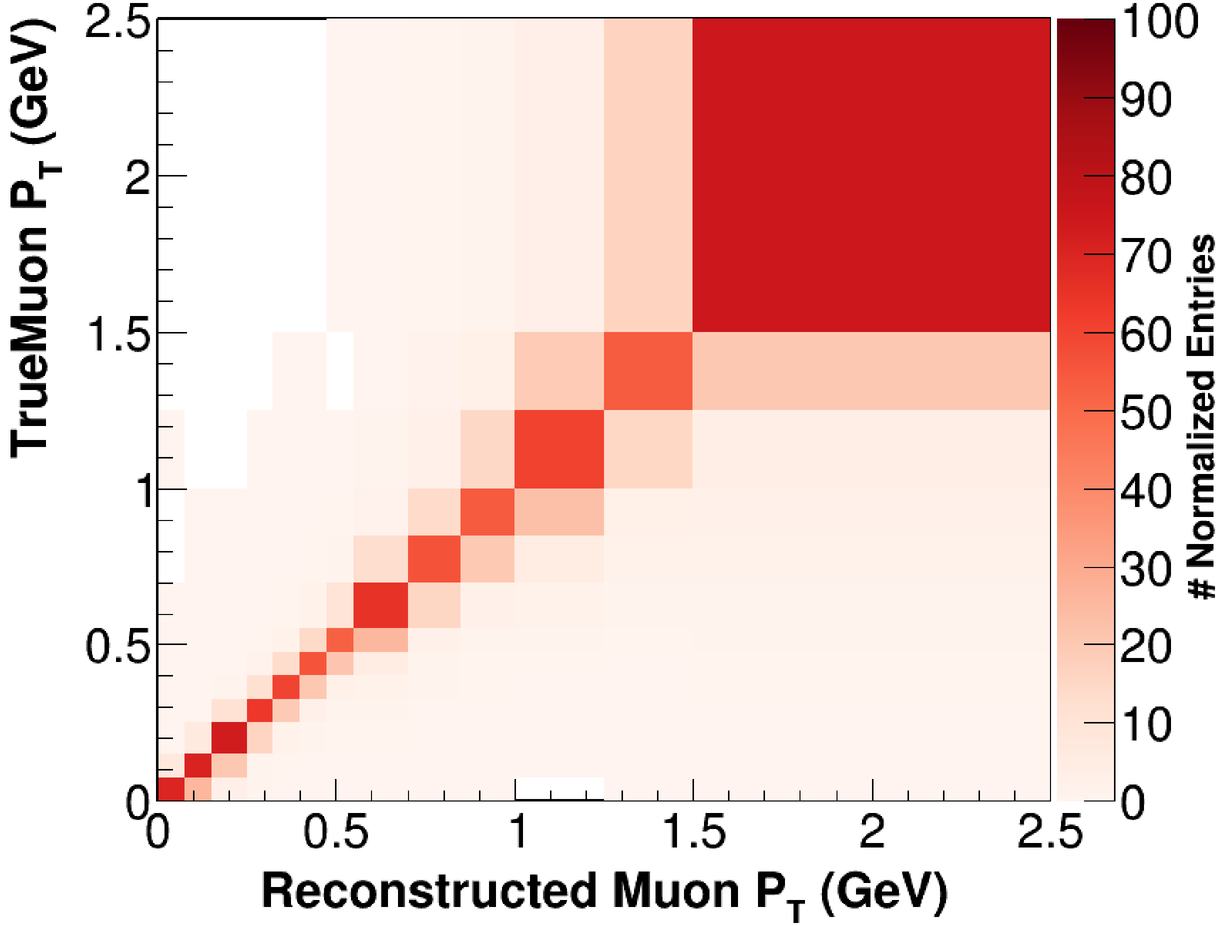
CCQE-like Analysis: Michel Electrons



CCQE-like Analysis: $P_t P_{||}$ Migration Matrix



CCQE-like Analysis: P_t Migration Matrix



CCQE-like Analysis: $P_{||}$ Migration Matrix