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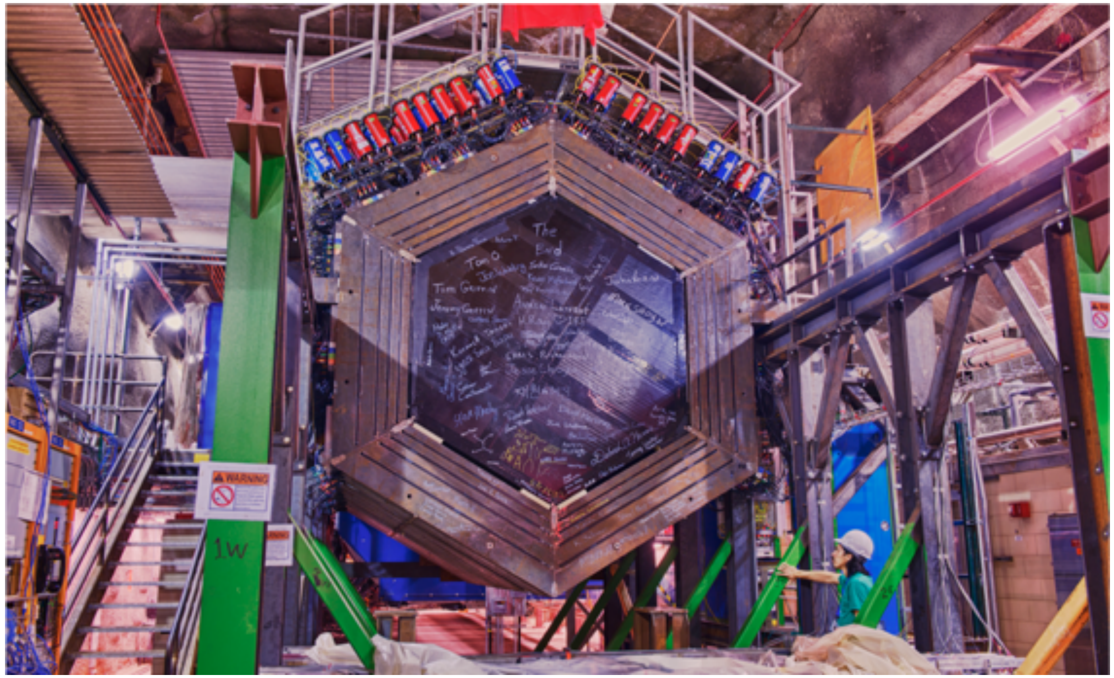
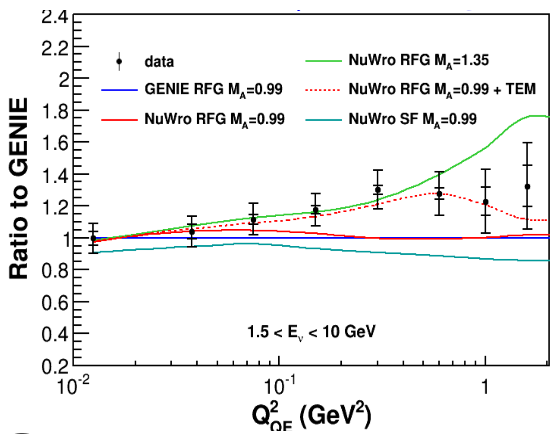


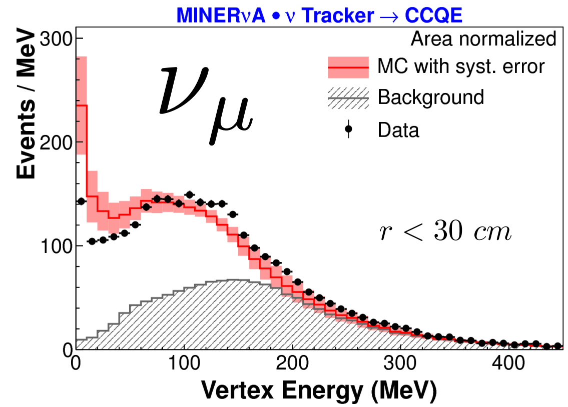
# Background Subtraction when model is horribly wrong: Lessons from MINERvA

Deborah Harris, Fermilab

# How do we know the model is horribly wrong?

- If it weren't, we wouldn't be doing the experiment
- First publications at MINERvA: $\nu_\mu$ and anti-$\nu_\mu$ CCQE



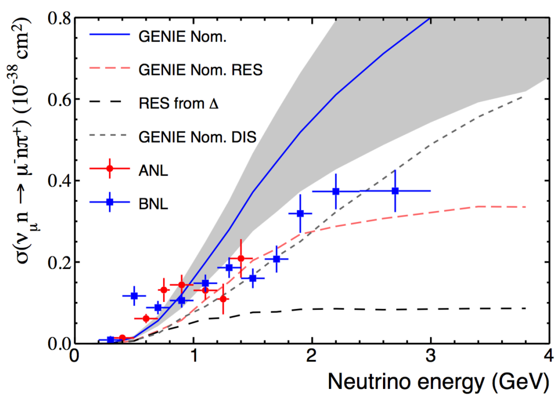



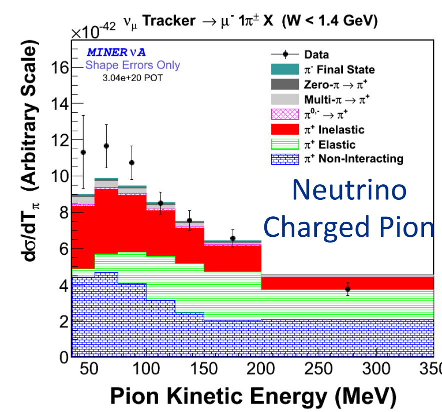

*Energy near vertex prefers with adding an extra proton to 25±9% of events, consistent with a multinucleon hypothesis*

- Other early publications: pion production

*GENIE has to be scaled by 0.46 to agree with Deuterium Data*

*Pion energies, angles, and overall cross sections do not match GENIE* Rod,Wil,McF, EPJC 76 (2016)

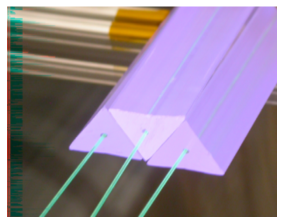


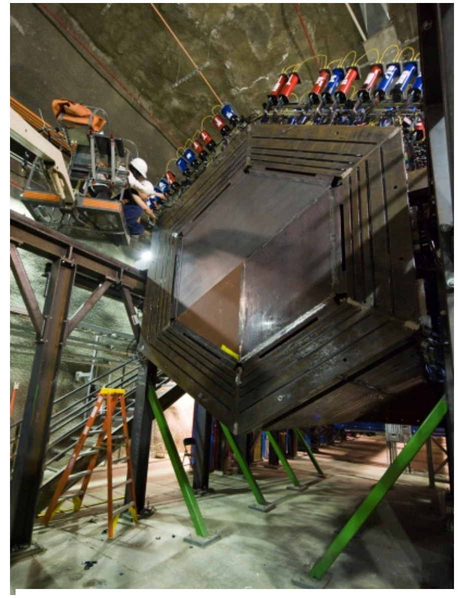



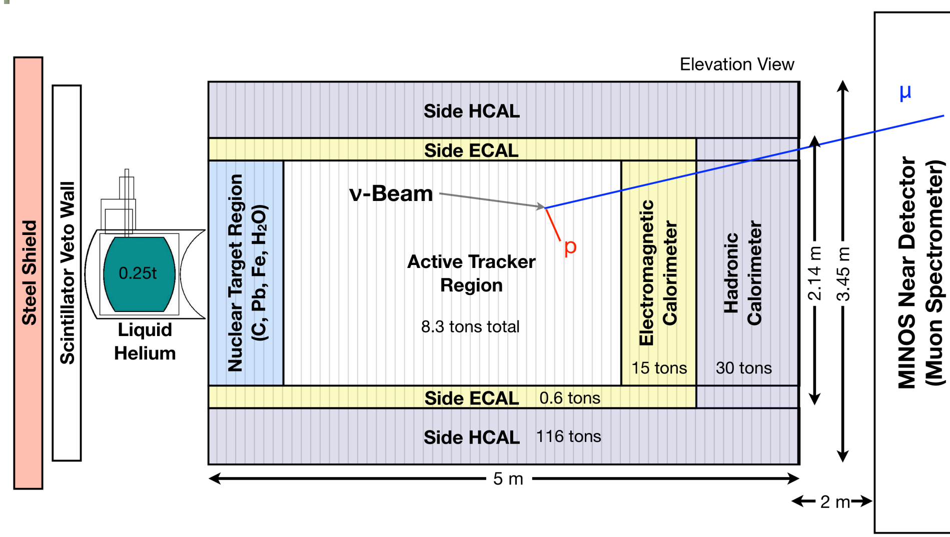

PLB749 130-136 (2015).

# MINERvA Detector

- Nuclear Targets
  - Allows side by side comparisons between different nuclei
  - Pure C, Fe, Pb, LHe, water
- Solid scintillator (CH) tracker
  - Tracking, particle ID, calorimetric energy measurements
  - Low visible energy thresholds
- Side and downstream electromagnetic and hadronic calorimetry
  - Allow for event energy containment
- MINOS Near Detector
  - Provides muon charge and momentum

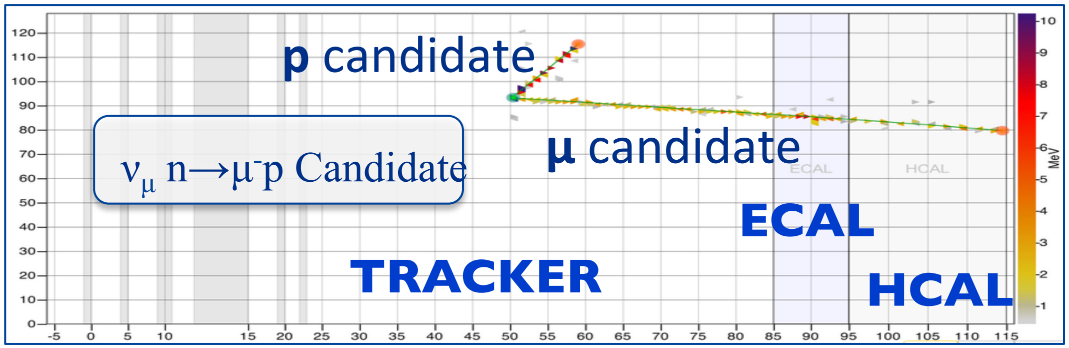




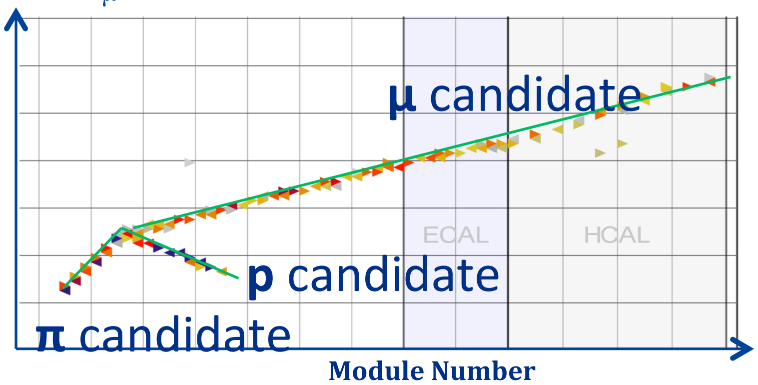


# MINERvA Events

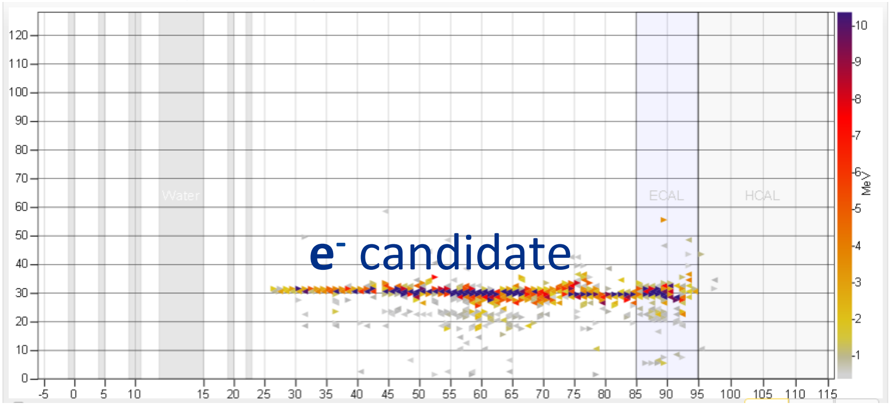
One out of three views shown, color = energy

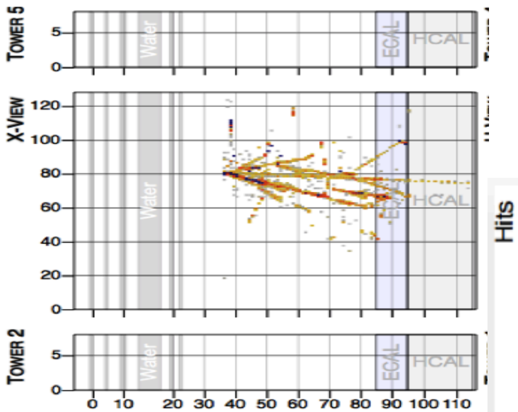



$\nu_\mu$ p→$\mu^-\Delta^{++}$, $\Delta^{++}$→p$\pi^+$ Candidate

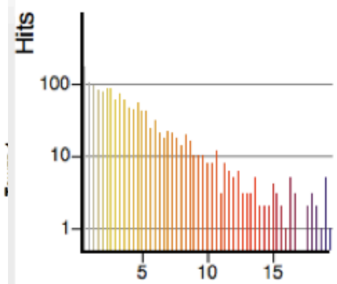



$\nu_\mu$ $e^-$→ $\nu_\mu$ $e^-$ Candidate



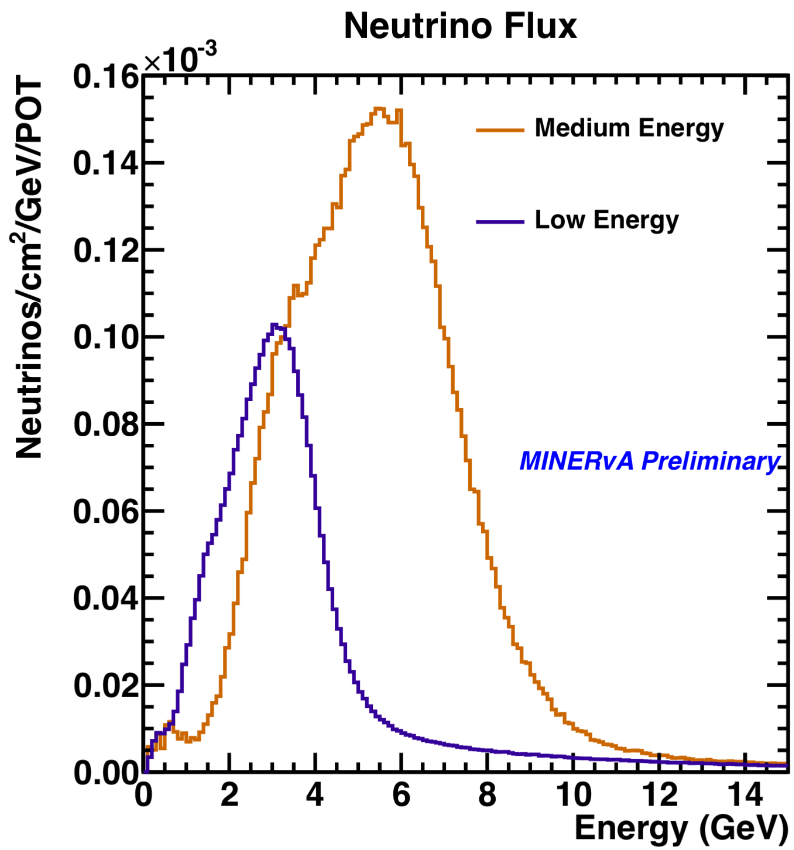




Deep Inelastic Scattering candidate



# MINERvA's Neutrino Flux

- Low energy beam:
  - Peak around 3GeV
  - "high energy tail" not negligible
  - Many processes will contribute backgrounds to any analysis (except maybe the "Charged Currrent Inclusive analysis")
- Medium Energy beam
  - Neutral currents will be larger background to $\nu_e$ or $\nu$-electron scattering measurements than Low Energy beam

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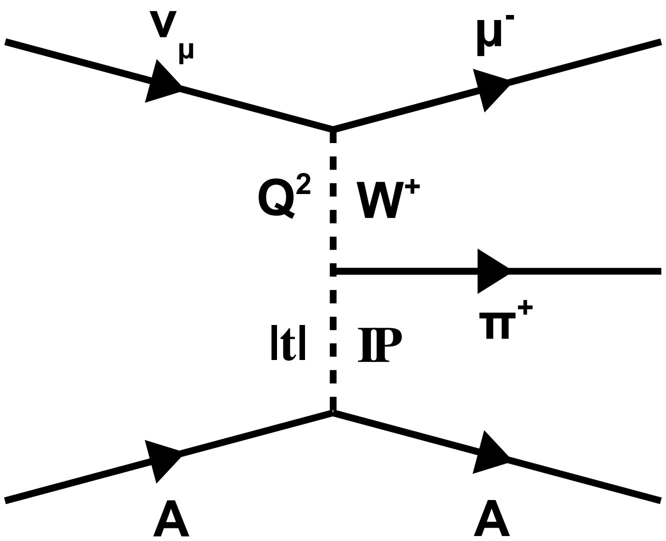
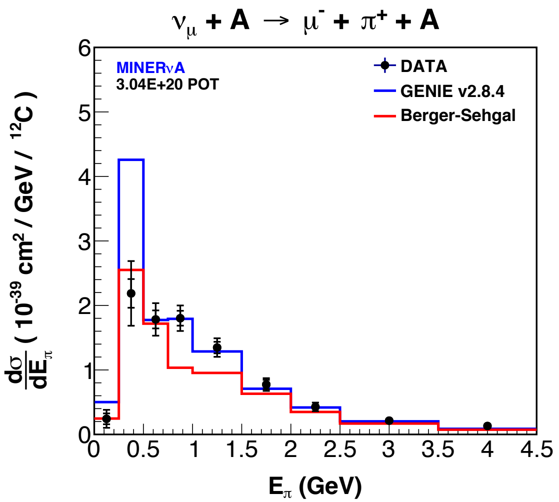
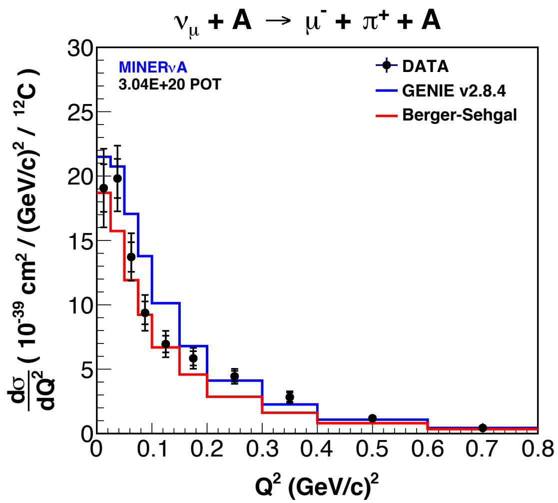
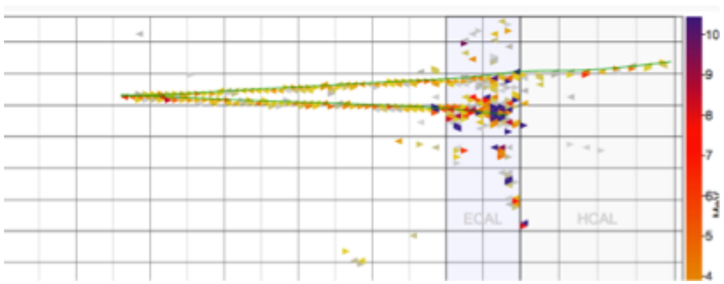
# Case Study: coherent pion production

- This low multiplicity process is a troublesome background for oscillation experiments and previous low energy data is confusing
- Model independent selection and high statistics allows test of pion kinematics
- 1628 (770) coherent neutrino (antineutrino) events



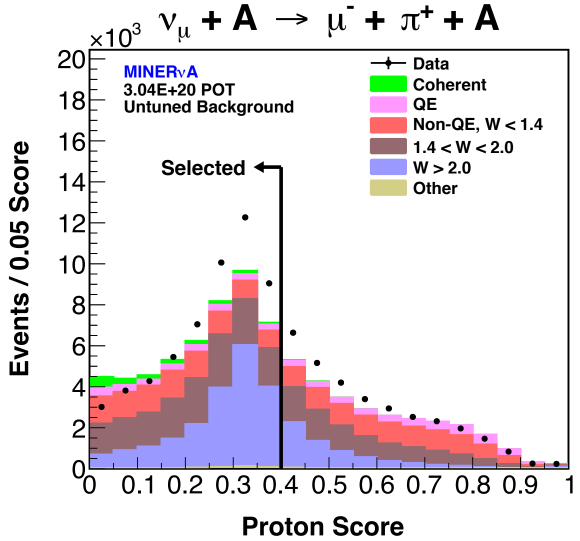



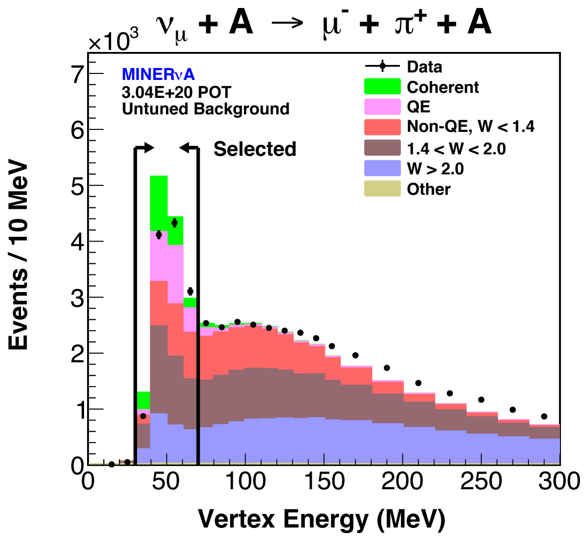




Phys. Rev.Lett. 113, 261802 (2014) and PRD in preparation.

# Experimental Signature and Backgrounds

- Signal:
  - Two final state particles (muon and charged pion)
  - Small momentum transfer to the nucleus
  - No visible recoil
- Event Selection:
  - Two tracks, one matched to MINOS
  - dE/dx of short track NOT proton-like
  - Low energy around the vertex
- Backgrounds:
  - All other pion production
  - Quasi-elastic scattering with proton-pion confusion

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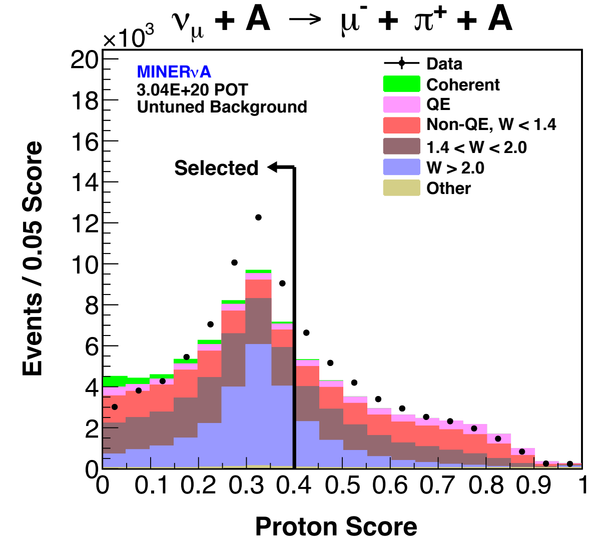
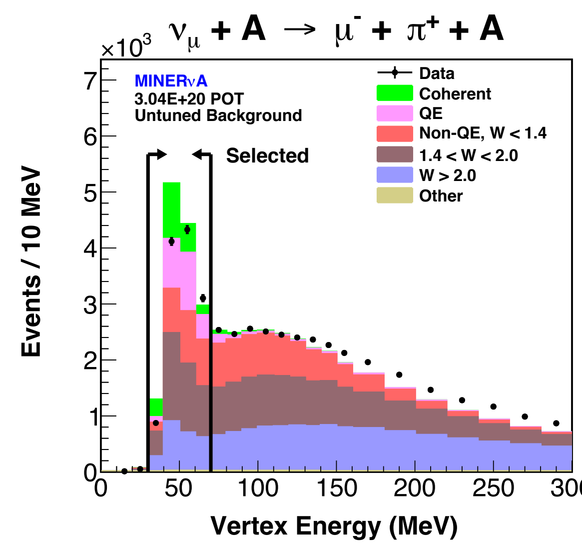
# Already see our model isn't perfect…

- Proton Score Discrepancy:
  - May be somewhat due to pion angle and momentum mismatch
  - Definitely depends on relative levels of QE and Resonance production
  - These plots ALREADY have non-resonant pion production reduced to 0.46*GENIE from D2 measurement Rod,Wil,McF, EPJC 76 (2016)
- Vertex Energy:
  - We know we don't have the vertex energy in CCQE ν events right

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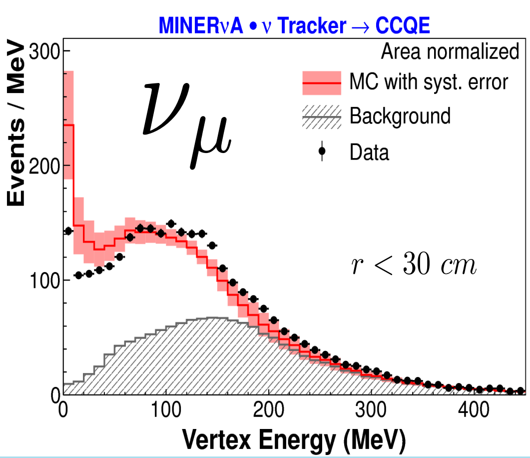
PRL 111, 002052 (2013)



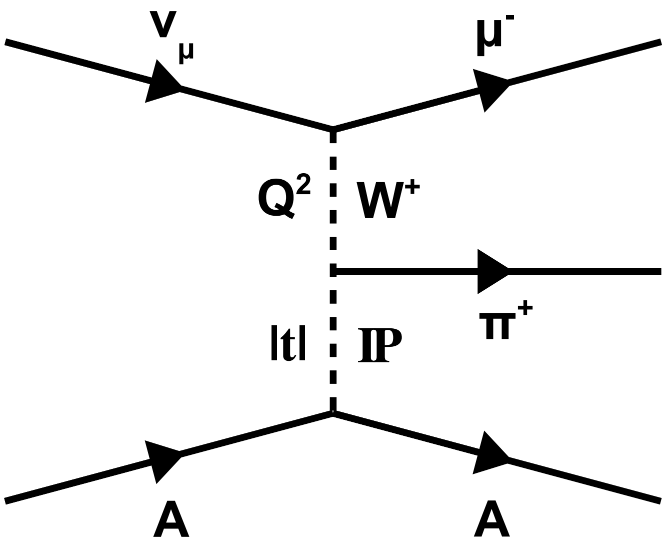

*Energy near vertex prefers with adding an extra proton to 25±9% of events, also consistent with a multinucleon hypothesis*

# Kinematics of Signal process

$$E_\nu = E_\mu + E_\pi$$

$$Q^2 = 2E_\nu(E_\mu - P_\mu cos\theta_\mu) - m_\mu^2$$

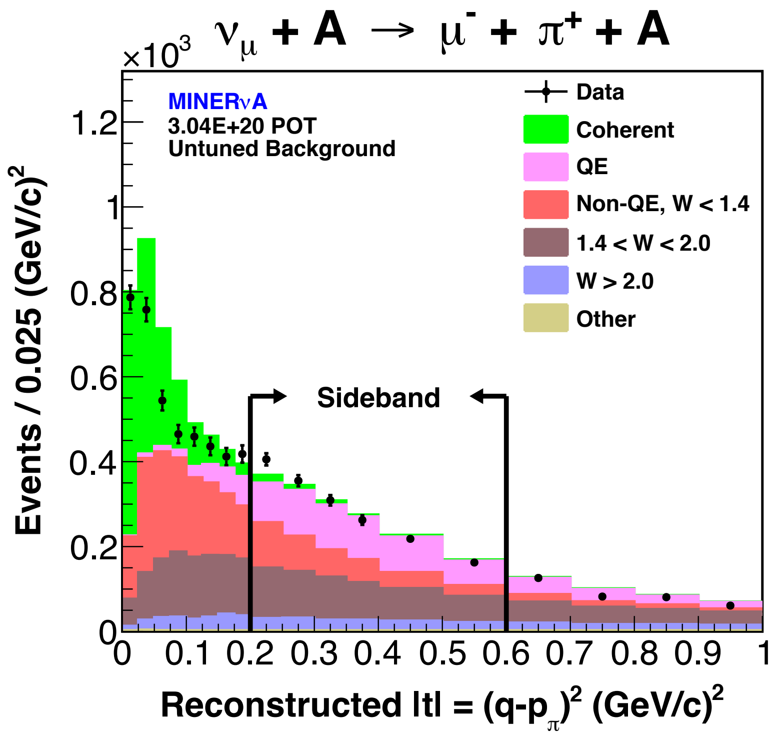
$$|t| = -Q^2 - 2(E_\pi^2 + E_\nu p_\pi cos\theta_\pi - p_\mu p_\pi cos\theta_{\mu\pi})$$

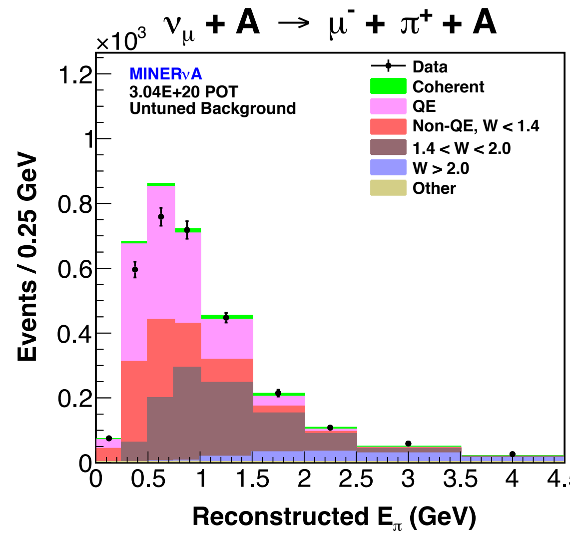


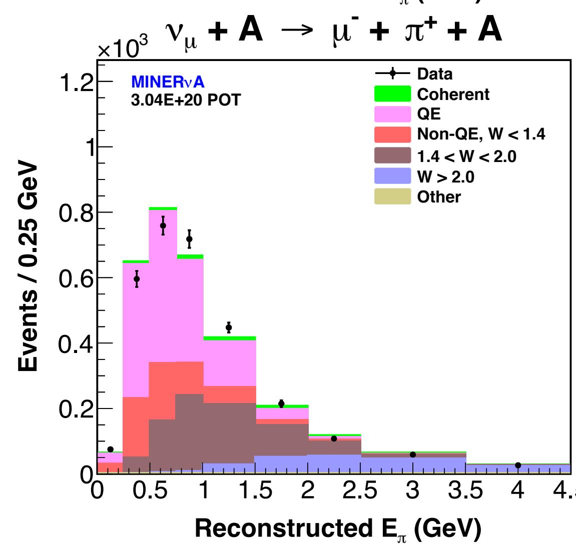

- Muon momentum $p_\mu$ is measured from reconstructed muon in MINOS
- Muon angle $\theta_\mu$ is measured from track in MINERvA
- pion energy ($E_\pi$) s reconstructed calorimetrically
- Neutrino direction is parallel to the beam axis

# Sidebands to test background model

- Use events passing vertex energy cut but with 0.2<|t|<0.6GeV$^2$
- Check "pion" kinematics and levels

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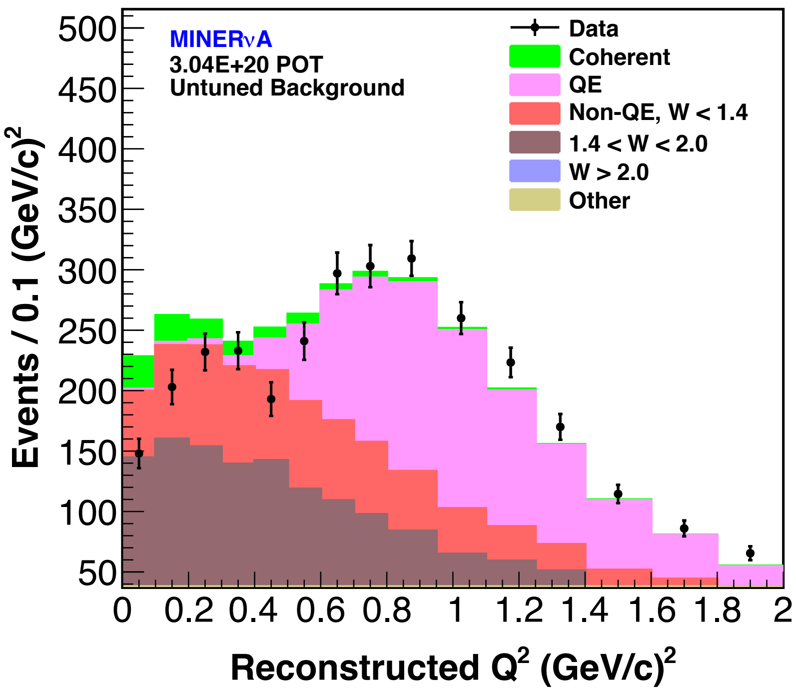
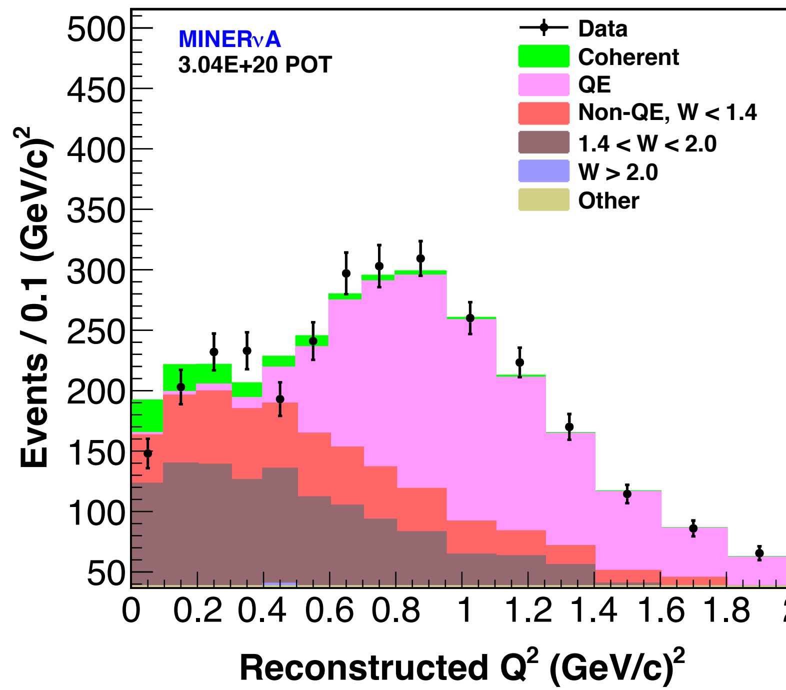
So by scaling the background levels we can get the pion energy distribution to match in the sideband

# Sideband Tuning Result by $Q^2$

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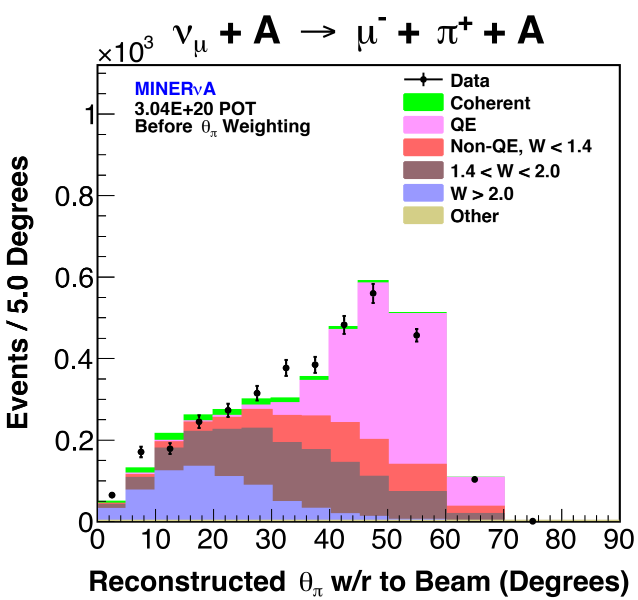
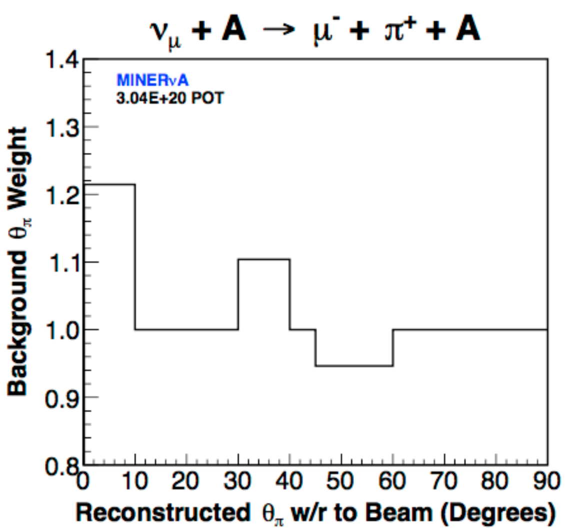
| Channel | Scale Factor |
|---|---|
| Charged Current Quasielastic | 1.13±0.04 |
| Non-Quasielastic, $W_{gen}$<1.4GeV | 0.73±0.08 |
| 1.4<$W_{gen}$<2.0 | 0.81±0.05 |
| $W_{gen}$>2.0 | 1.70±0.20 |
| Other | 1.0 (fixed) |

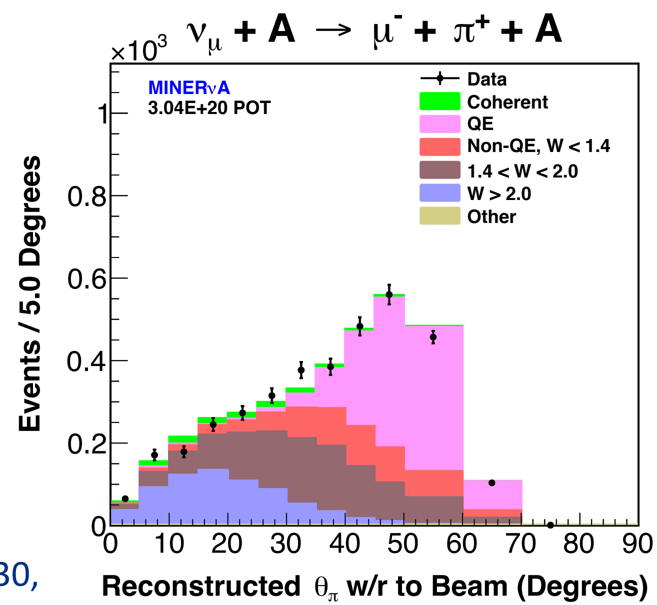
Note: this is a new suppression *after* weighting GENIE's non-resonant pion prediction by 0.46 (ref: EPJC 76, 2016 )

# Pion angle in the sidebands after tuning

- There is still a mis-match, so we added a correction assuming that nature wants the pion angles we see in the sideband IN the signal region.
- Assumed the systematic uncertainty on the background's angular distribution is the difference between the tuned and untuned pion angle

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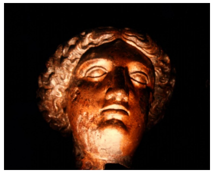
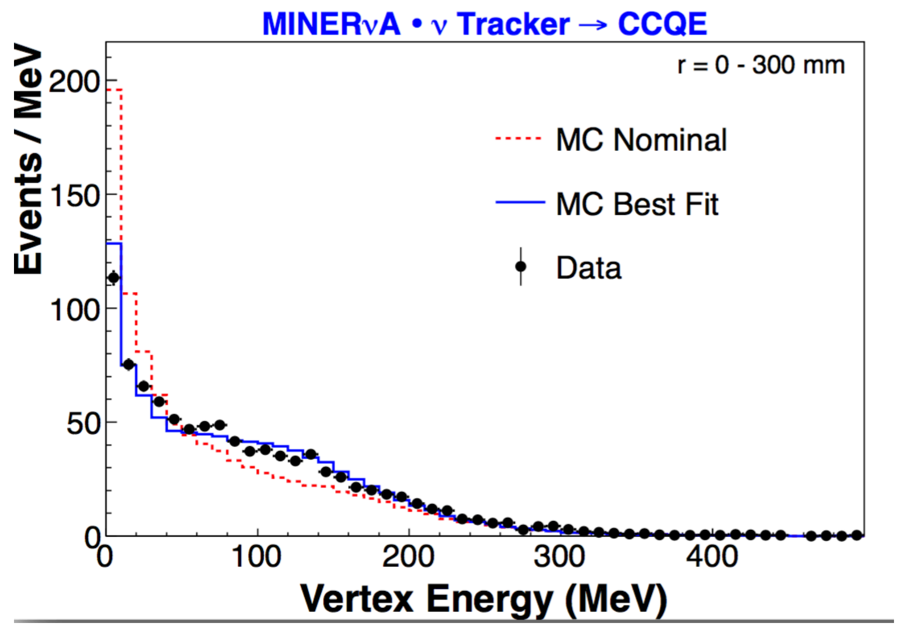
# Vertex Energy Uncertainty



- The pion backgrounds were tuned AFTER a cut on the vertex energy.
- The CCQE background that survives that cut depends on the model you assume for the CCQE process

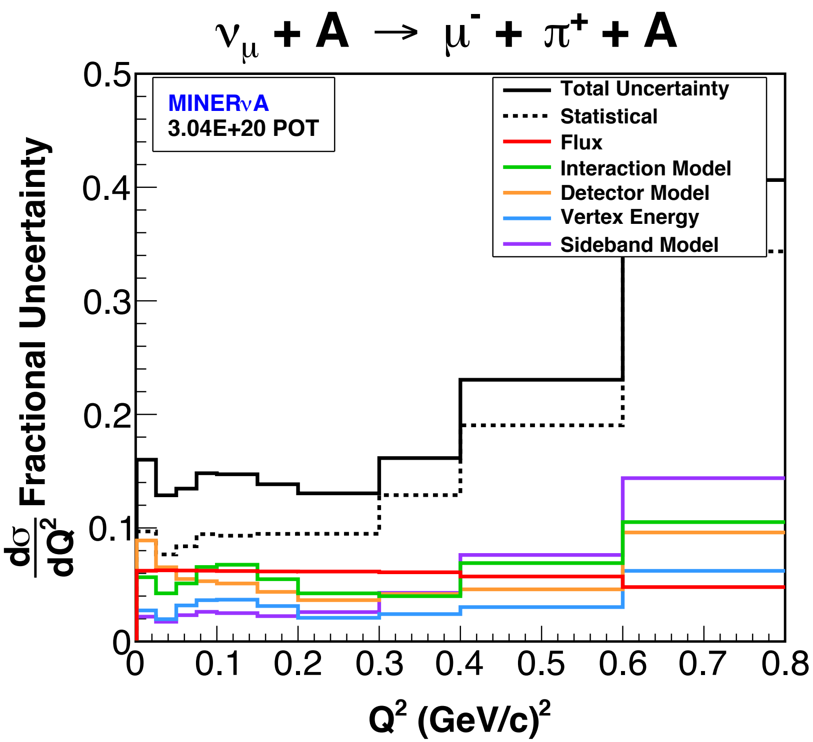


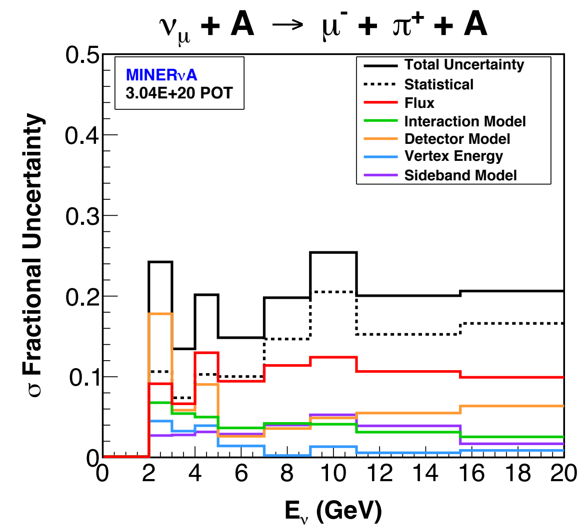

PRL 111 (2013)

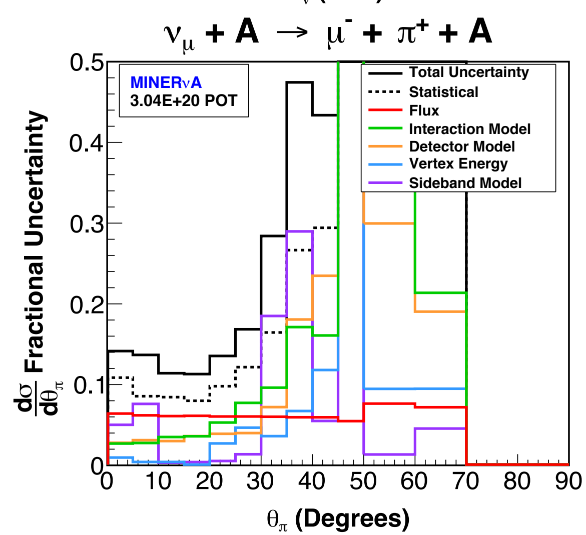
- Initial expectation was that 25% of the CCQE events had an extra proton with a momentum between 0 and 225MeV
- Re-extract the cross section after adding the additional proton to the CCQE sample, apply as a systematic uncertainty

# Uncertainty on Background Modeling

- Evaluate δ(background prediction) by marginalizing over systematic uncertainties
- Additional “Sideband model” shows up differently in different observables



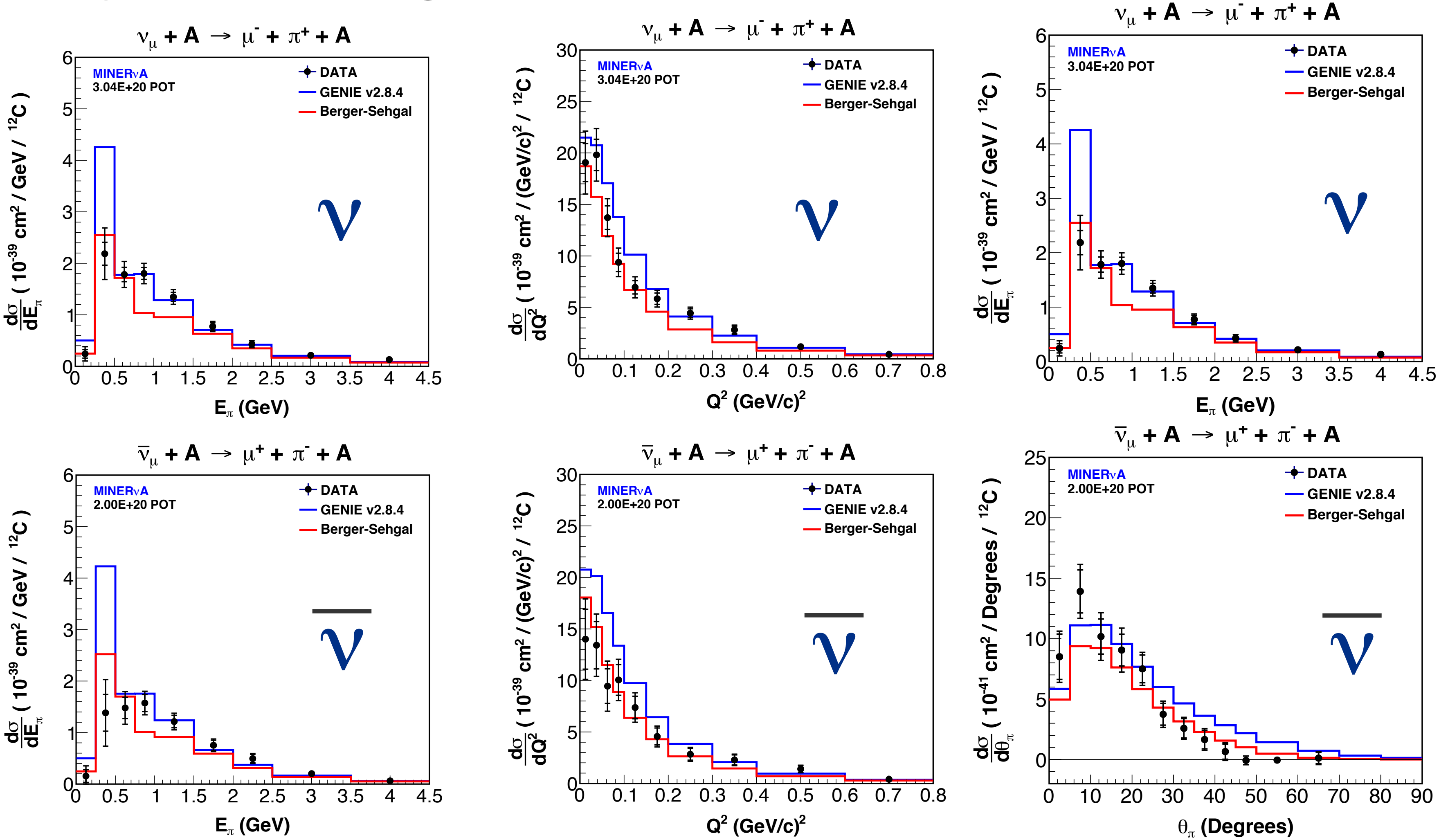

A. Mislivec, FERMILAB-THESIS-2016-30, PRD in preparation

# Lessons learned from Coherent Pions

- Adding extra vertex energy and modifying the pion background kinematics as systematics is something MINERvA does for many measurements
  - Neutrino-electron scattering
  - Electron neutrino CCQE measurement
  - CCQE in the nuclear targets (there it's the signal, not the background)
- As we start to develop better models, the background prediction process also changes
  - Add "2p2h events" instead of just adding extra protons
  - Add different sources of "2p2h" instead of just turningn on or off 2p2h (nn, np, pp, or just extra QE contribution)
  - Stop using difference between GENIE and MINERvA result as a systematic uncertainty, use uncertainty ON MINERvA result

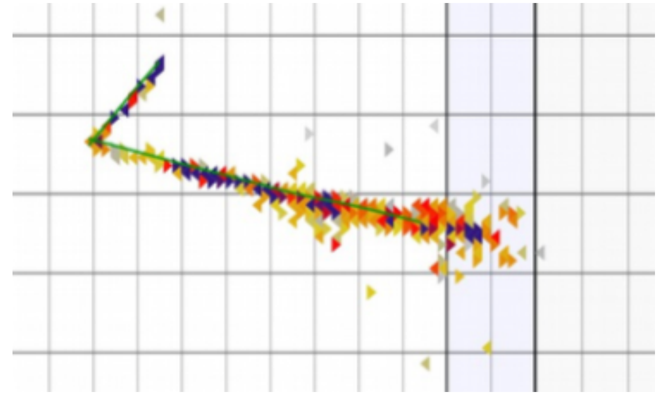
# Neutrino Coherent Pion Results

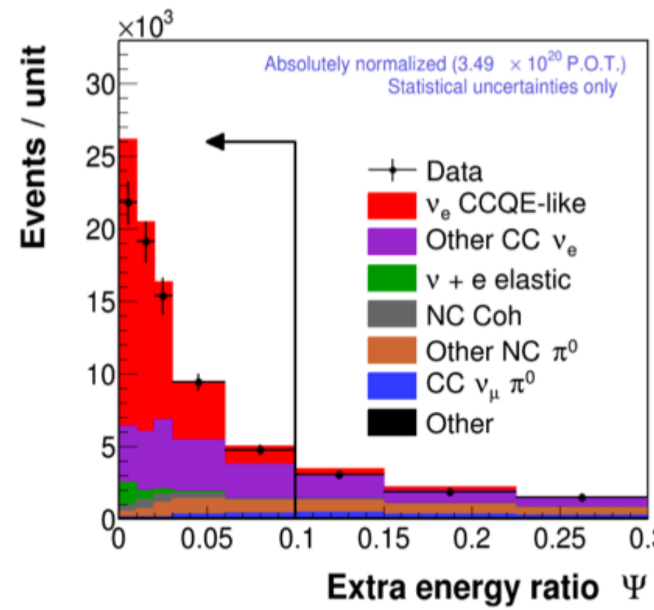
- Stay tuned, a long PRD is in preparation with these results…



# Next example: $\nu_e$ CCQE

- Event selection:
  - Identify an EM-like shower
    - Energy deposit at track end
    - “Width” of the track
    - Average dE/dx of entire track
  - Remove non-CCQE events
    - No Michel electrons
    - Anything not within a $7.5^o$ $e^-$ cone or 30cm of vertex is called “extra energy”, cut on $\Psi$= E(extra)/E(cone)
  - Remove photons by early dE/dx cut



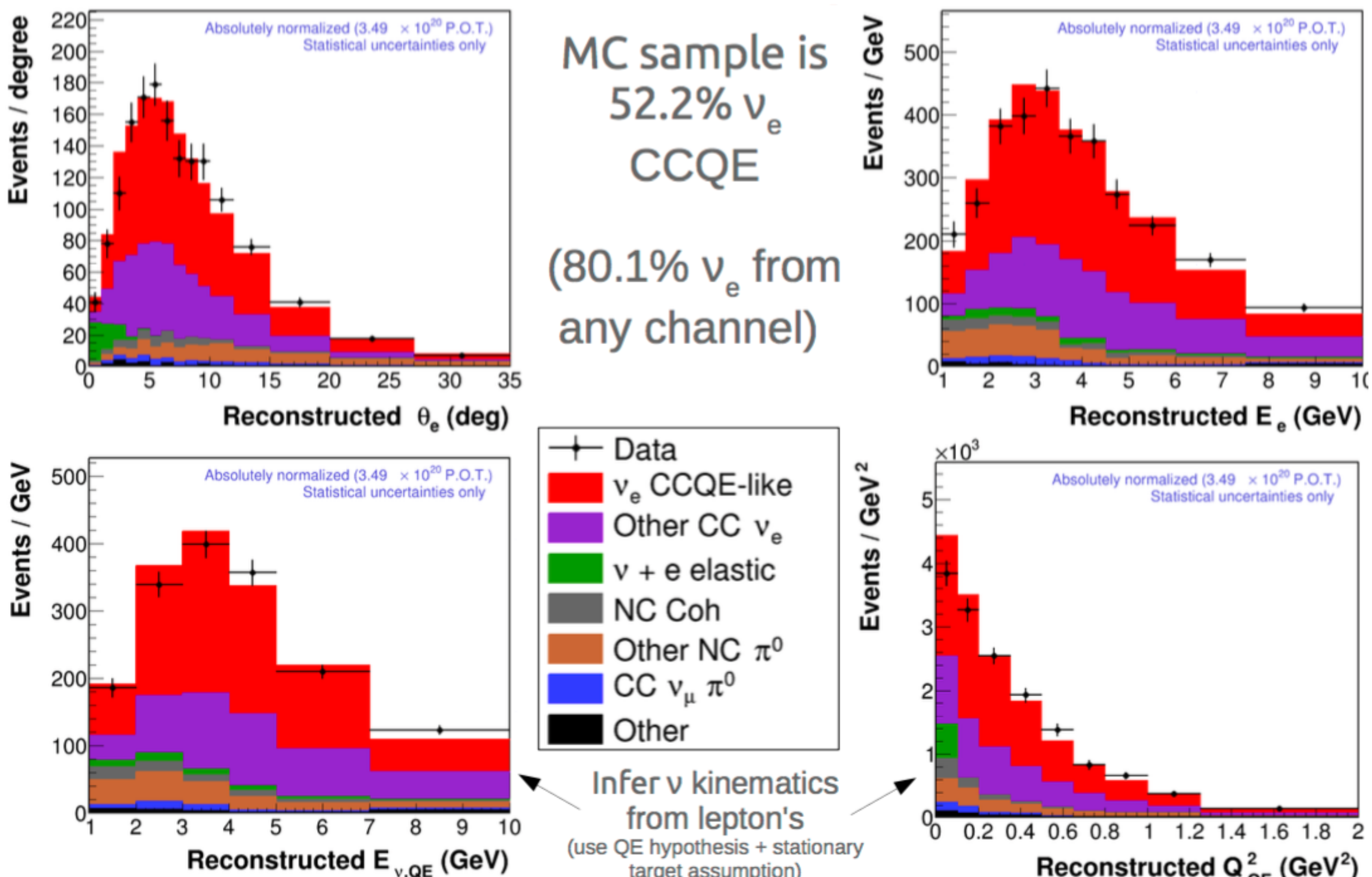



(Actual cut is a function of $E_{vis}$. This plot illustrates cut near most probable value of $E_{vis}$= 1.25 GeV.)

*Graphics from: J. Wolcott JETP 9/15*

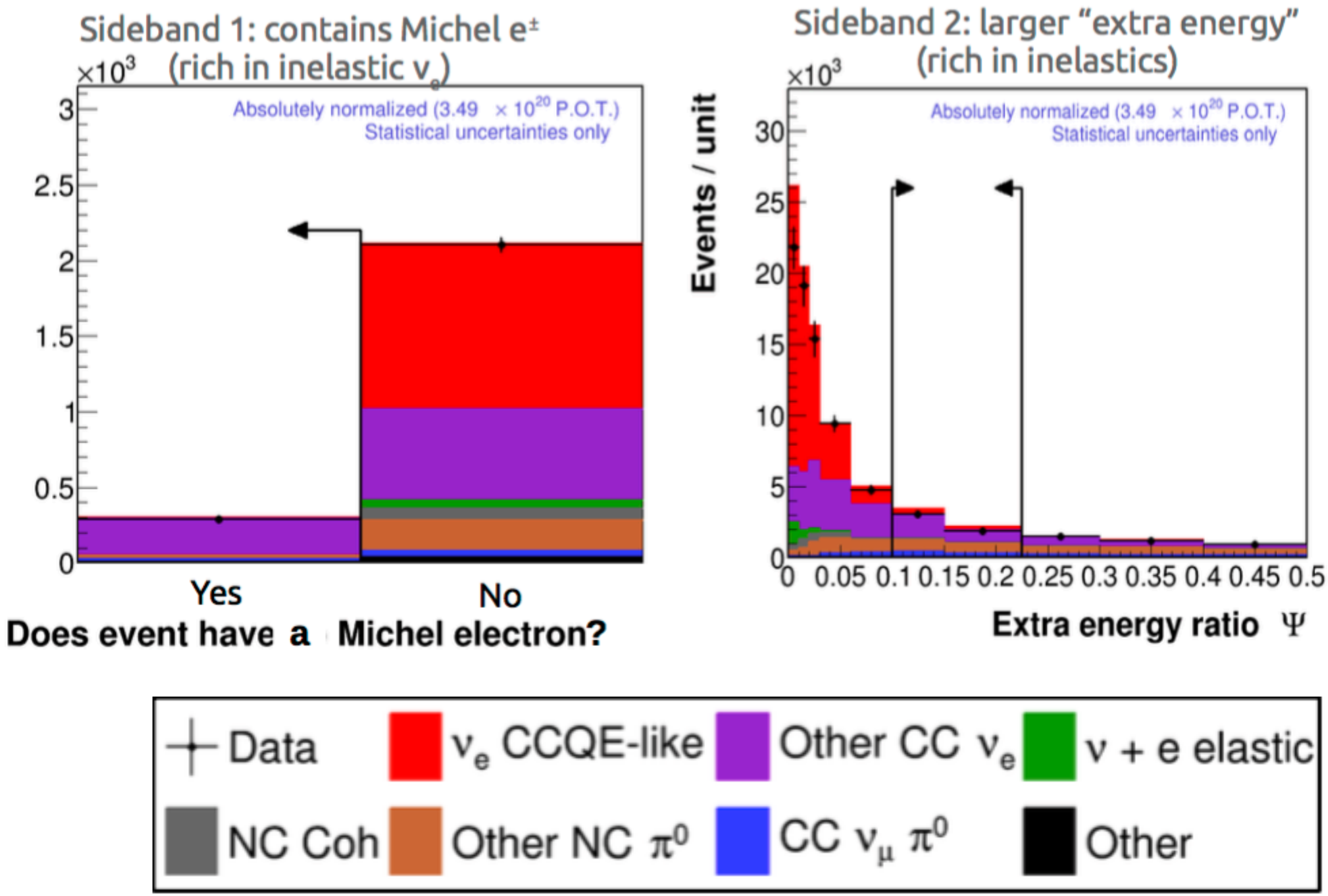
# Events after e$^-$ ID and "extra energy" cut

- Several different backgrounds persist




*Graphics from: J. Wolcott JETP 9/15*

# Find sidebands to constrain backgrounds




*Graphics from: J. Wolcott JETP 9/15*



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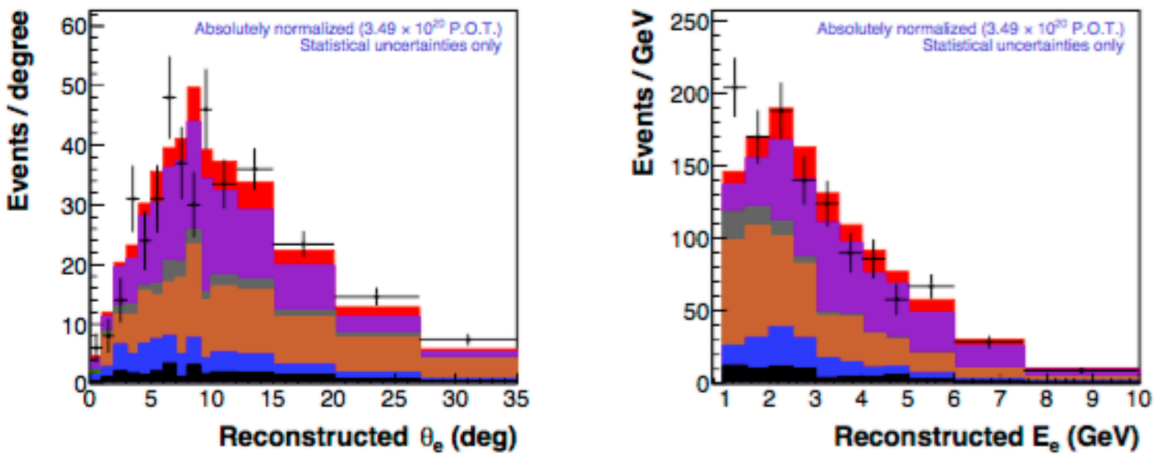
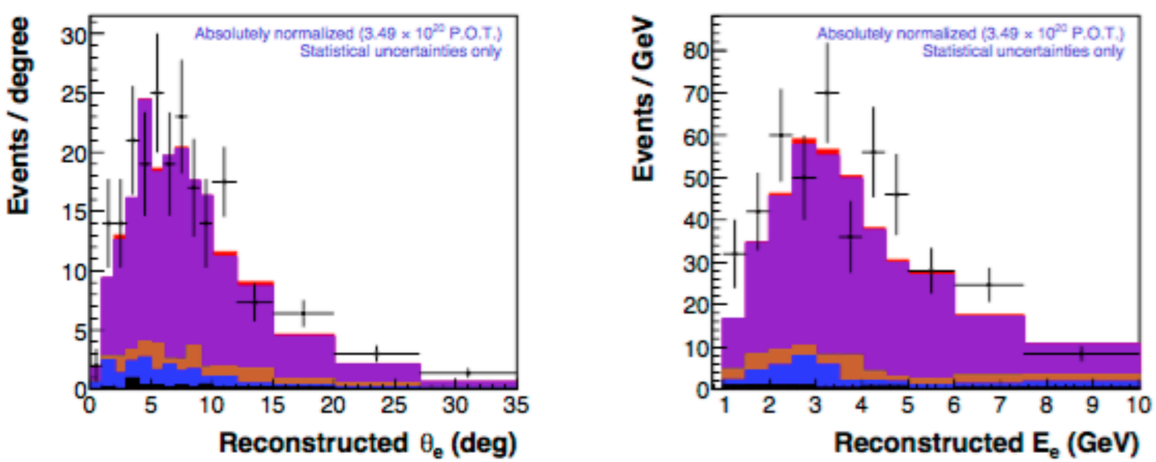
# Signal and Sideband Distributions

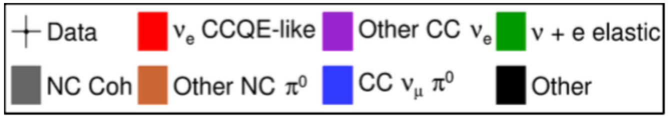



(a) Extra energy sideband




(b) Michel-match sideband

- Fit the kinematic distributions in the sidebands for overall normalizations for 3 scale factors
  - 0.90 for "other $\nu_e$", 1.11 of "Other NC $\pi^0$" and "CC $\nu_\mu$ $\pi^0$"
- But even after constraining model with the sidebands…

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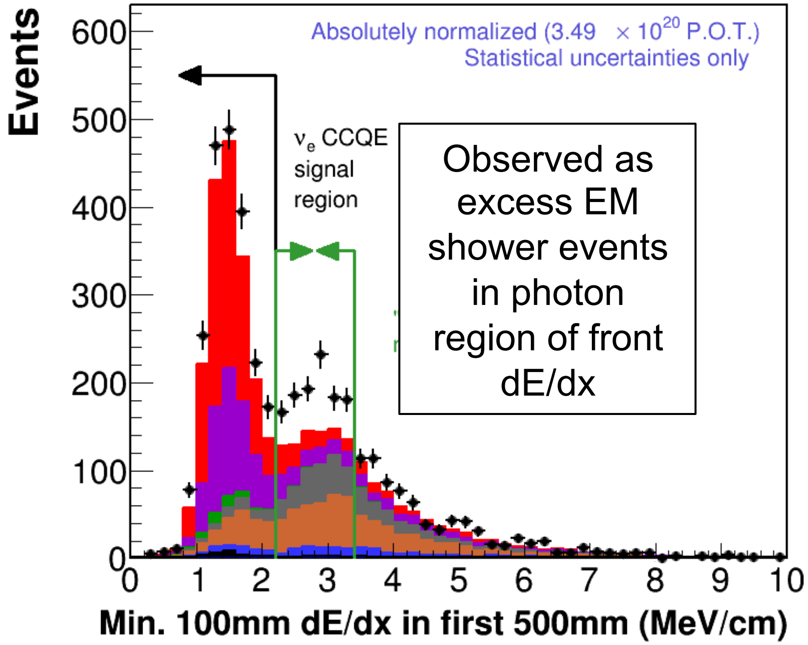
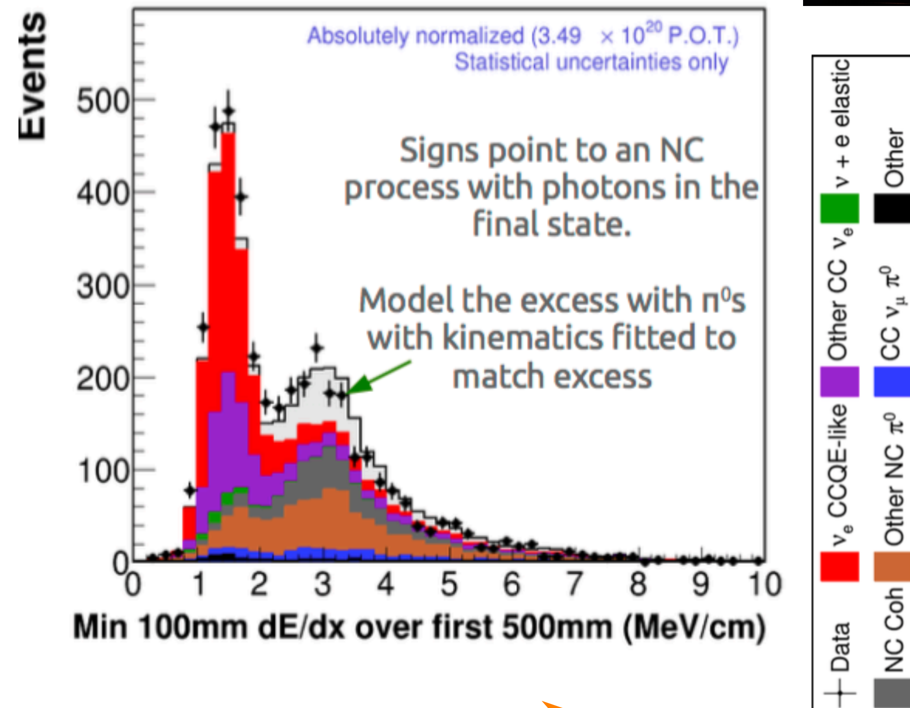
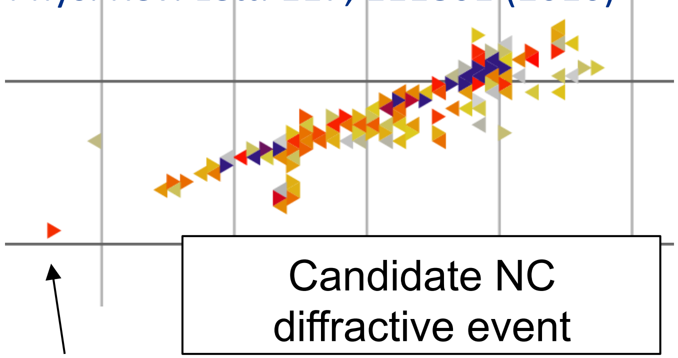
# Need to add: Diffractive $\pi^0$ Production

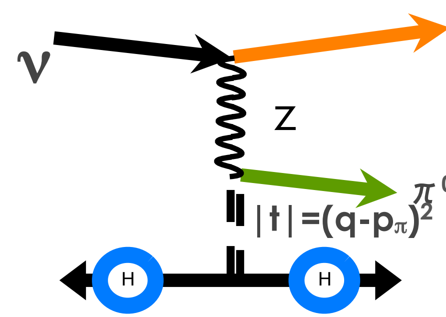



”, Phys. Rev. Lett. 117, 111801 (2016)




Probable recoil from proton

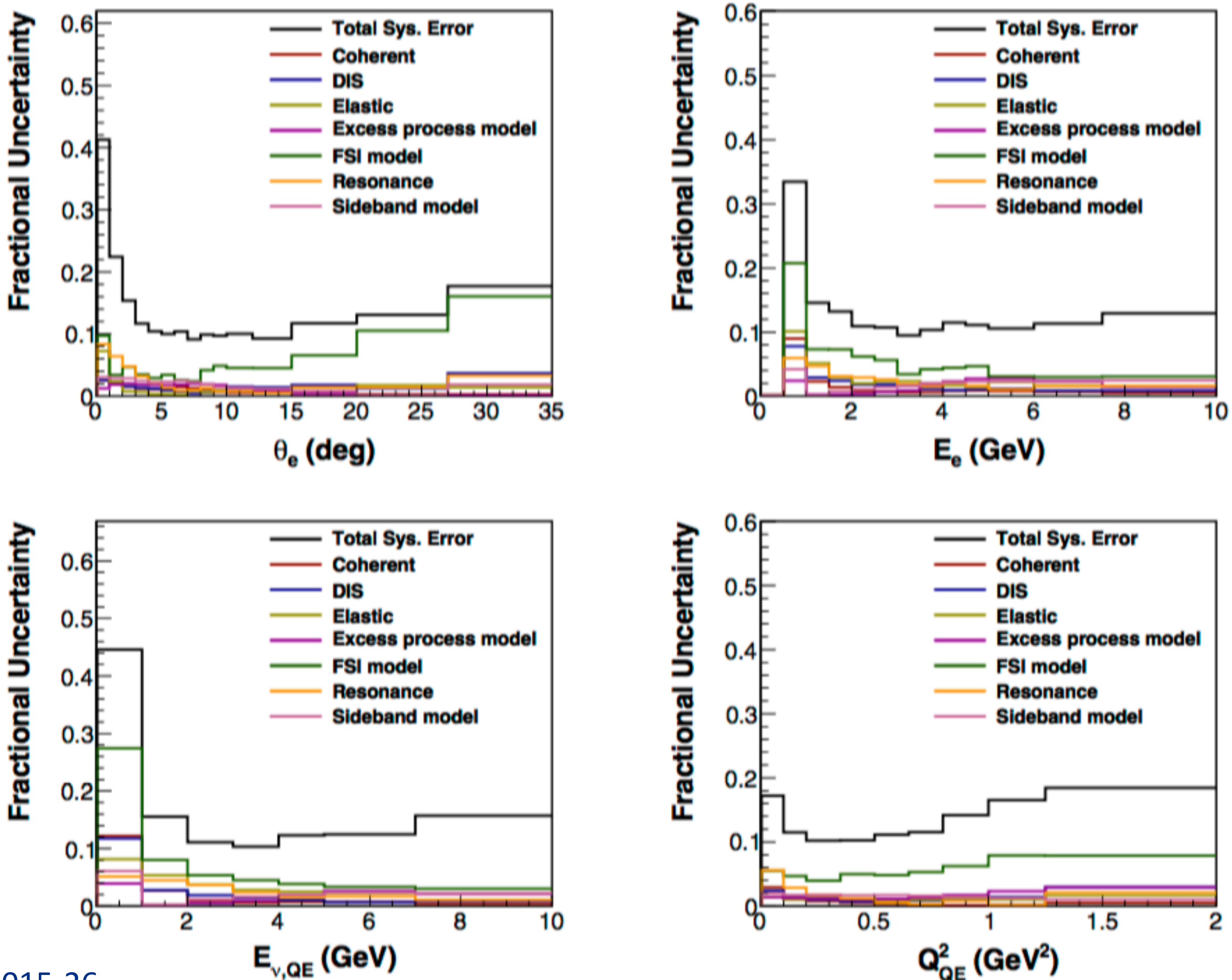



*Graphics from:*
*J. Wolcott*
*JETP 9/15*

Analogous to NC coherent production. Potential background for $\nu_e$ appearance. Not in default generator models.

# Systematic Uncertainties on Backgrounds

- For $\nu_e$ CCQE result: sideband model not a big factor
- Excess process is a small contribution
- FSI still most important interaction systematic on CCQE

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# Lessons learned from coherent and $\nu_e$ CCQE analyses:

- The more rare the process, the more different channels the backgrounds may have, some of which you didn't know existed
- The more channels you worry about, the more sidebands you need to constrain those backgrounds
- Award for most (confusing) sidebands:  neutrino-electron scattering analysis



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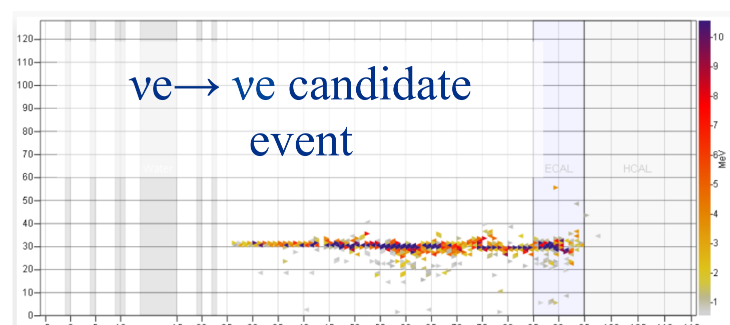
# Neutrino-electron Scattering

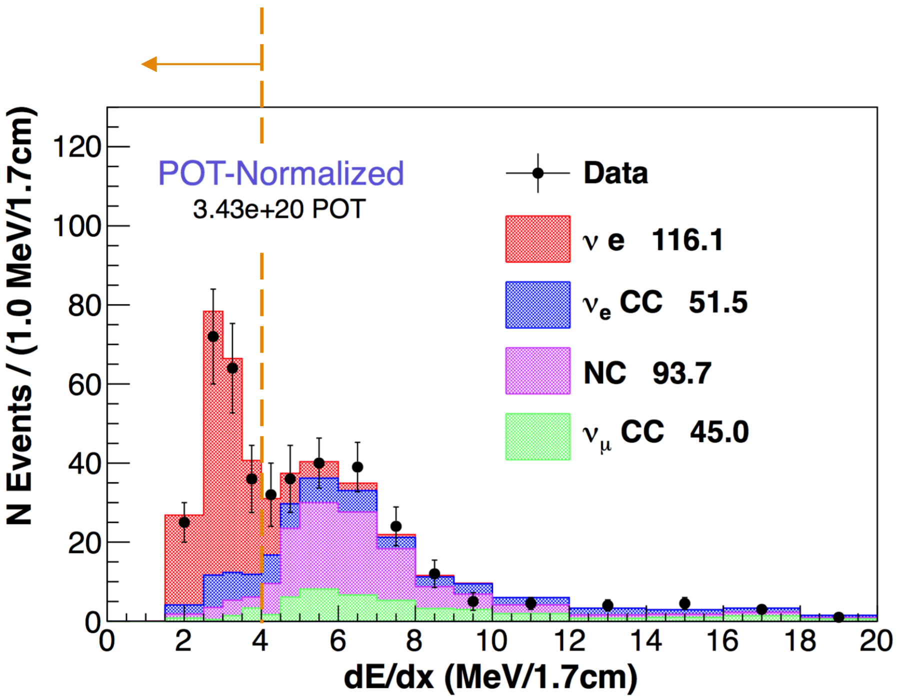
- Well-predicted cross section, useful for flux constraint
- Simple final state: single electron in direction of neutrino beam
- Can isolate electrons from dE/dx at beginning of the shower
- Observables:
  - electron energy ($E_e$) and angle with respect to beam ($\theta$)
  - From kinematics, know that $E_e\theta^2$ should be $m_e^2/2$
  - dE/dx at beginning of shower
- Cut on all energy outside of electron cone to get rid of backgrounds
- Lots of possible sidebands to pick

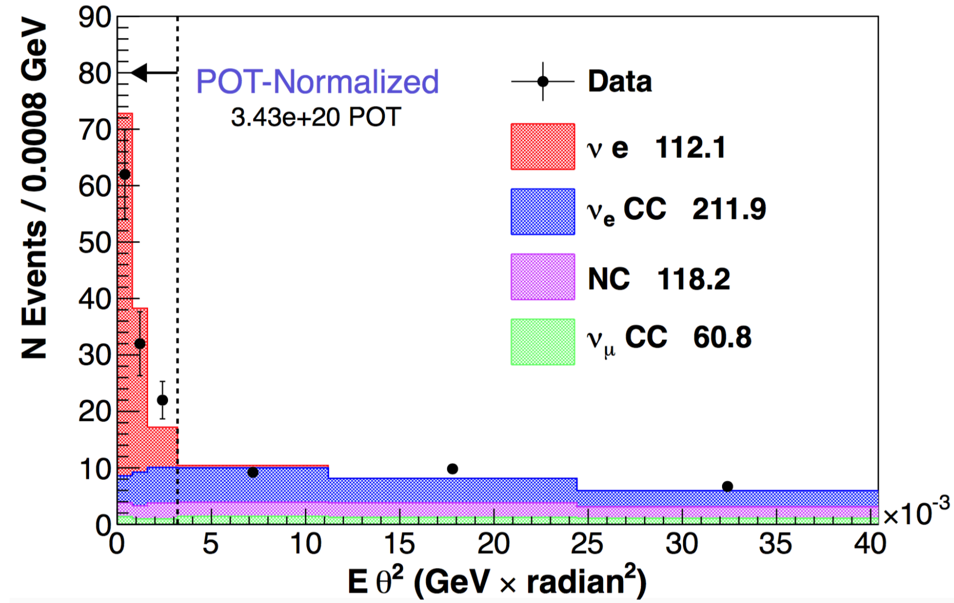



Phys. Rev. D 93, 112007 (2016)

# ν-e candidates after Electron ID cuts

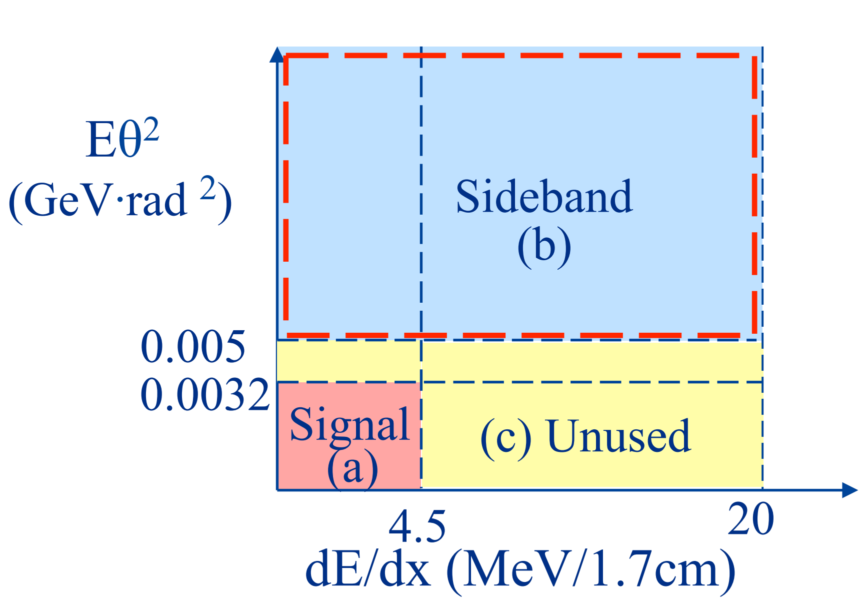
- This is after background tuning, but you see how many backgrounds contribute
- Tuning is done as function of OTHER variables

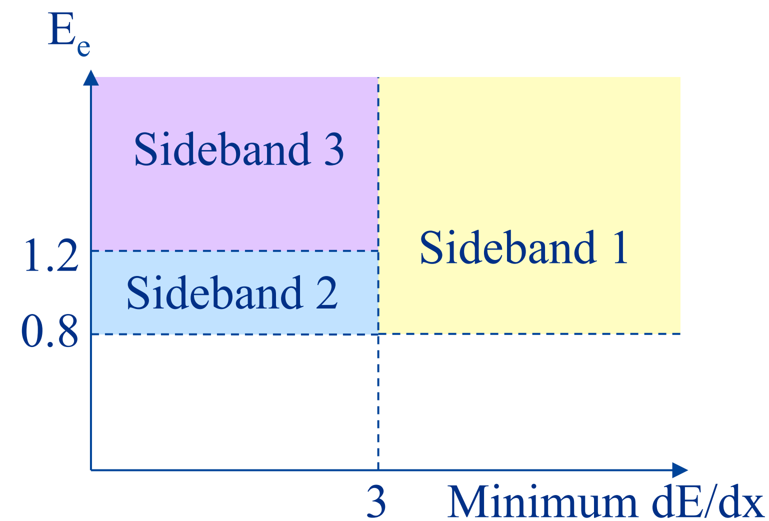


# Sideband Definitions for ν-e scattering

- Use dE/dx and $E_e\theta^2$ to define the sidebands, then fit events in those windows as function of other observables

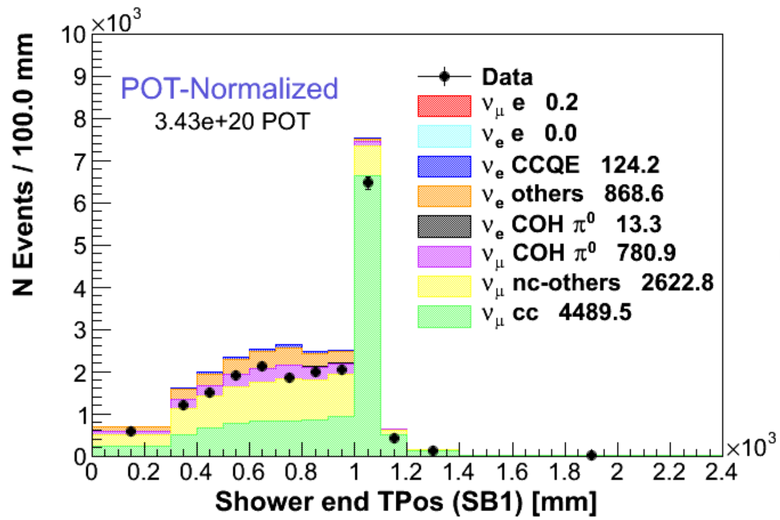


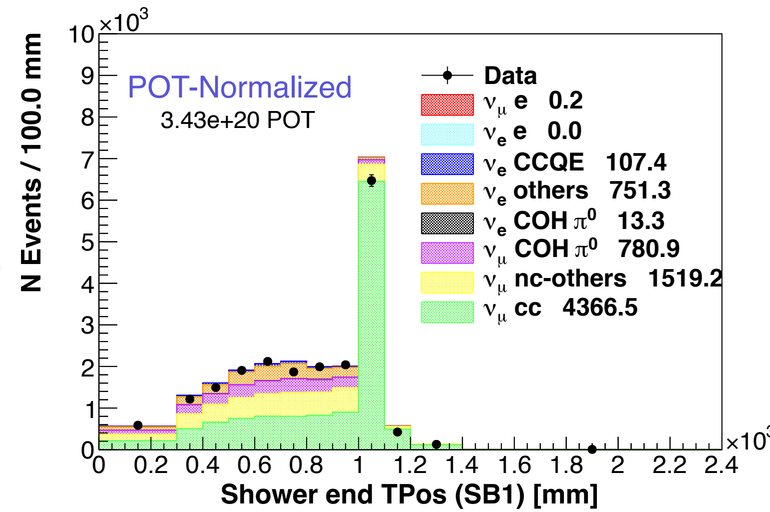




- Sideband (b) is then broken up into 3 regions to determine 3 overall normalization factors
  - Minimum dE/dx to prevent vertex energy mismodeling
- Remove cut on shower end transverse position and fiducial track length to get full statistical power of the sideband

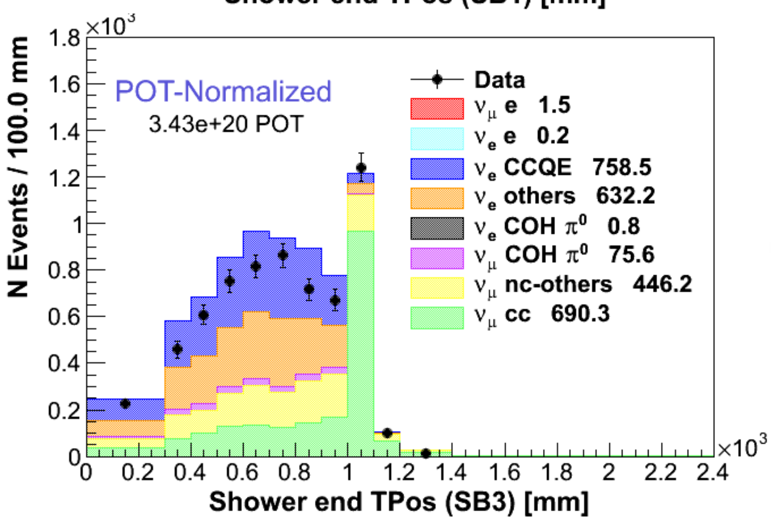
# Sideband Distributions before and after tuning

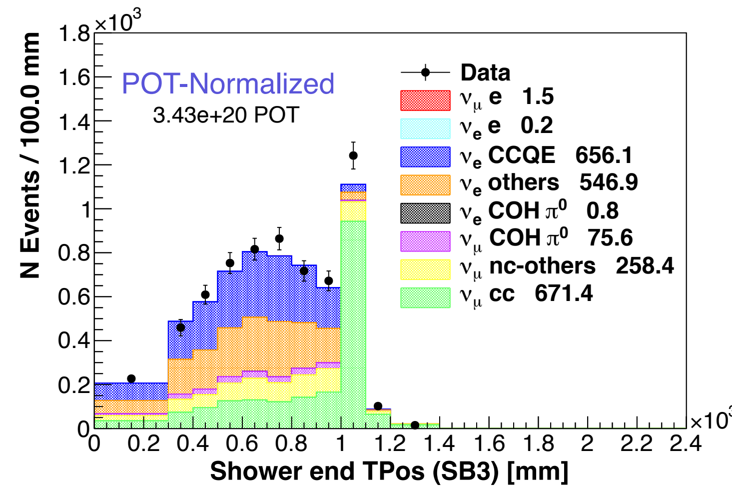
- Shower End Transverse position distributions for $E\theta^2$>0.05GeVrad$^2$




Minimum dE/dx > 3

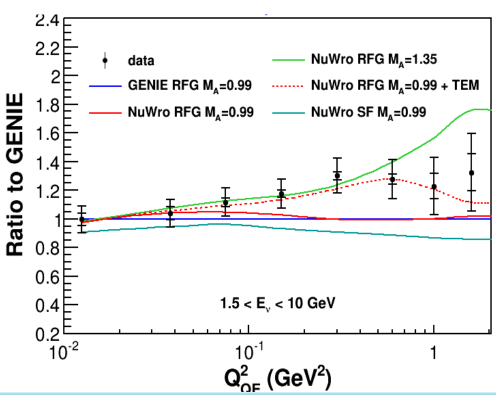


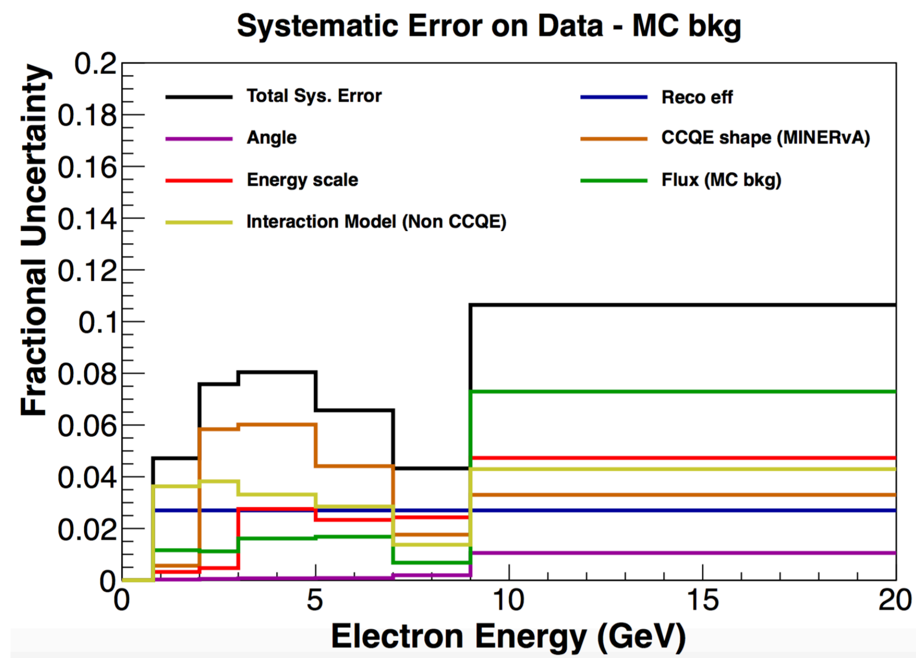




Minimum dE/dx < 3 but Electron energy>1.2GeV

# Systematic Uncertainties on ν-e scattering

- Interaction Model is important—but uncertainties were reduced from sideband tuning
- CCQE shape uncertainty is called out separately
  - Need to extrapolate from high $E\theta^2$ to low $E\theta^2$, similar to extrapolating from high $Q^2$ to low $Q^2$
  - Took as the systematic uncertainty the entire difference between GENIE and MINERvA



# Conclusions

- The better foundation you have to make models for all the different processes you have in your data, the better your background predictions will be
- Still will need sidebands and clever strategies to really test these background predictions

- MINERvA's medium energy data set has lots more statistics, so there are lots more background techniques we can explore
- Future focus on nuclear targets means more background subtraction challenges:
  - Need to subtract non-target backgrounds AND specific channel backgrounds