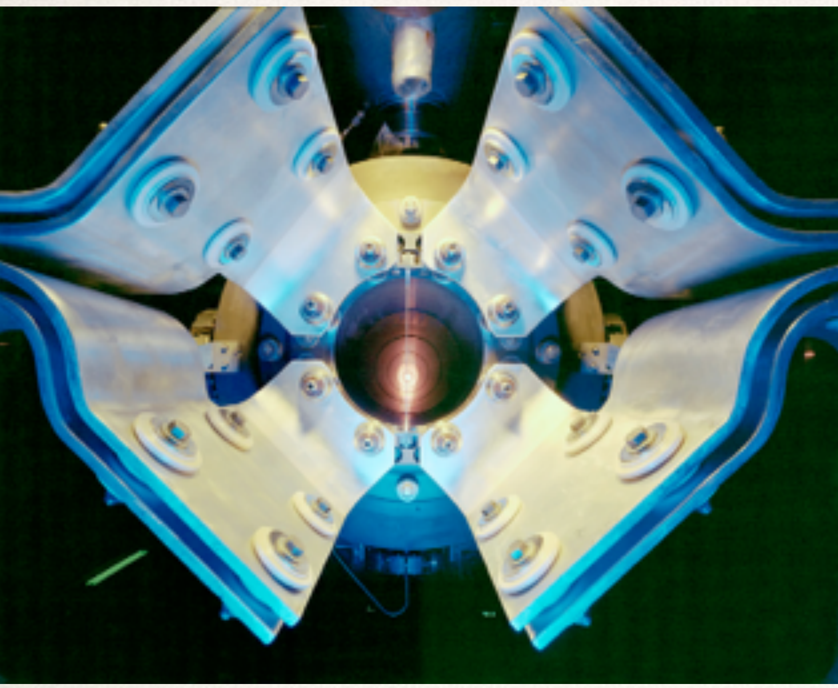
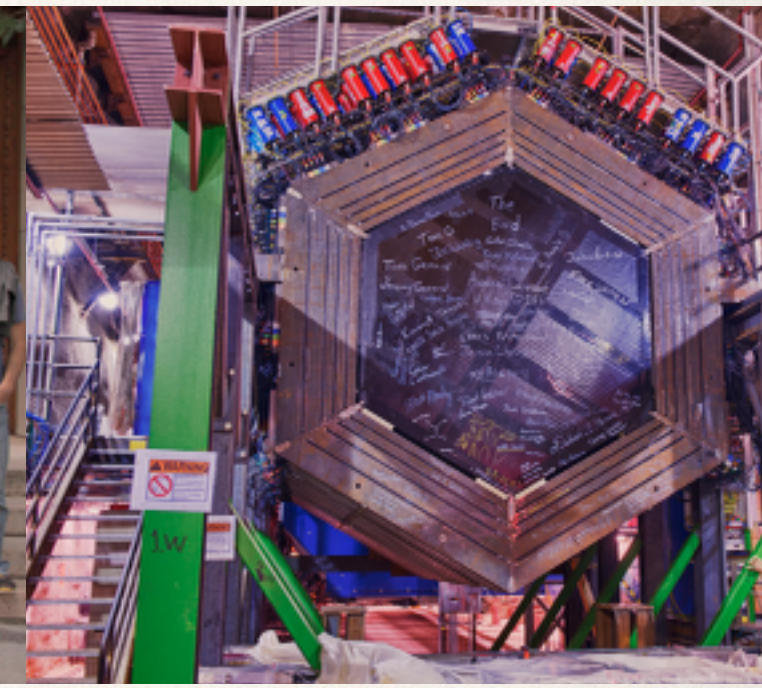
Fermilab

NORTHWESTERN UNIVERSITY



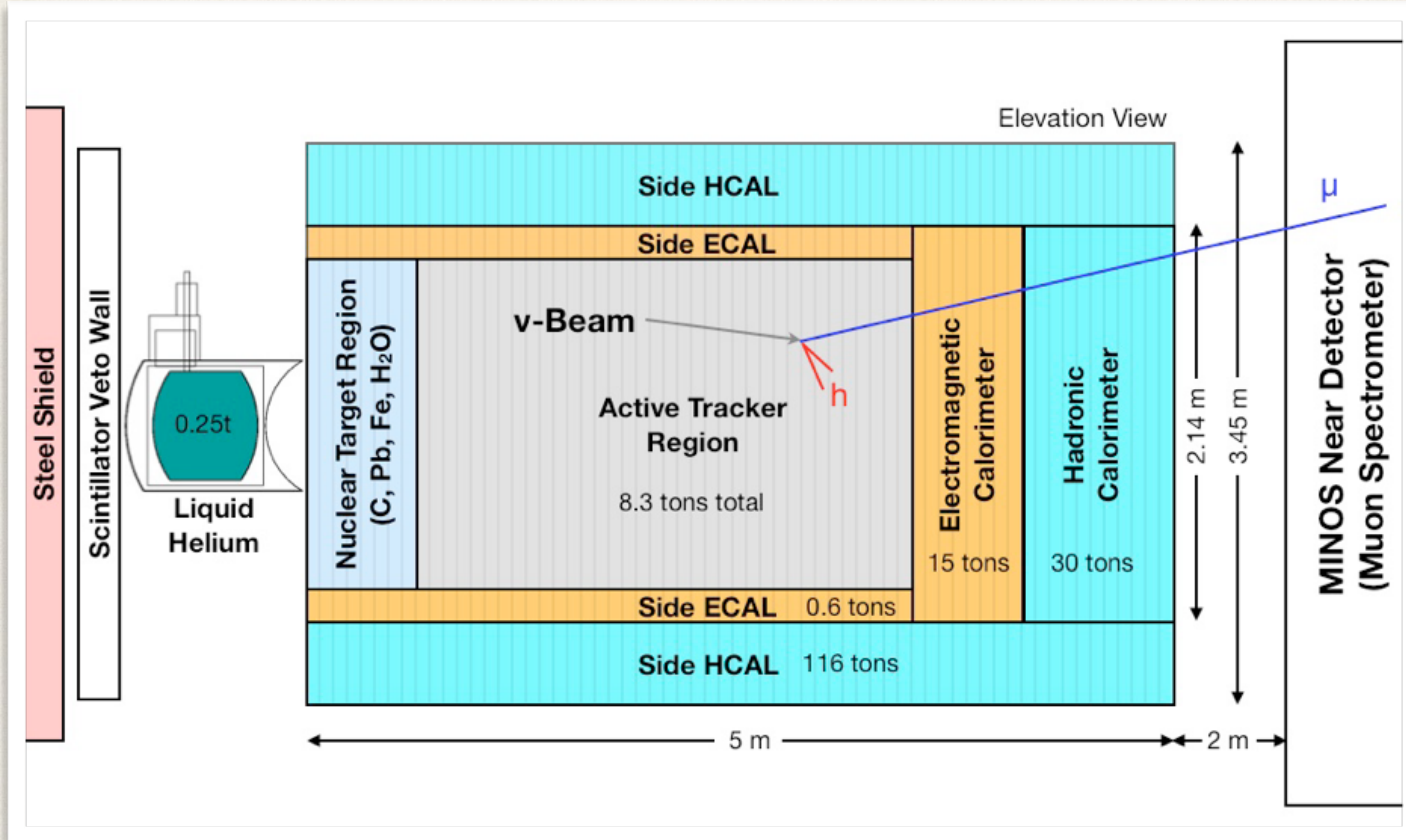


# Quasi-Elastic Neutrino Scattering at MINERνA

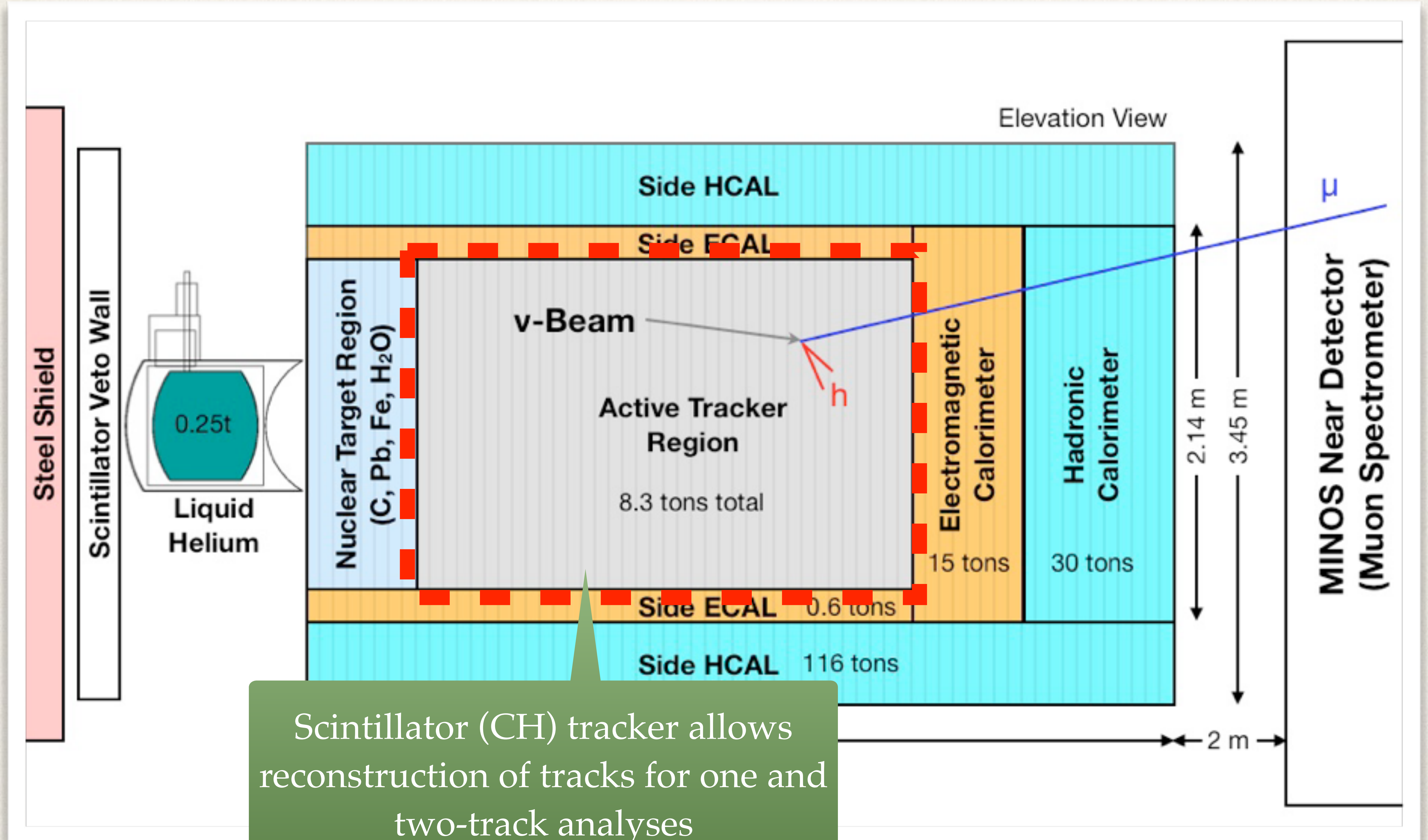
Cheryl Patrick, Northwestern University

*New Perspectives 2014, Fermilab*

# MINERνA detector

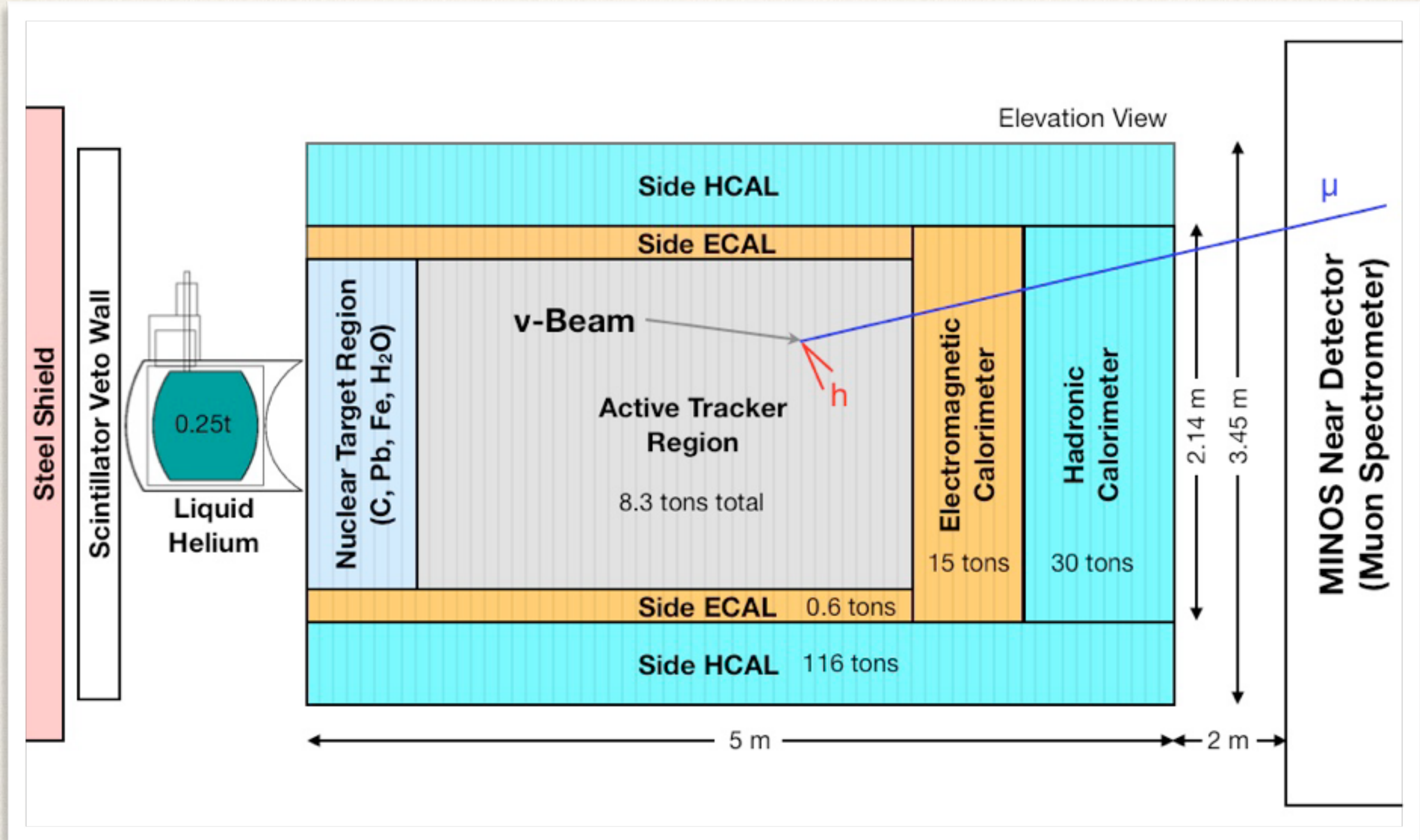


# MINERνA detector

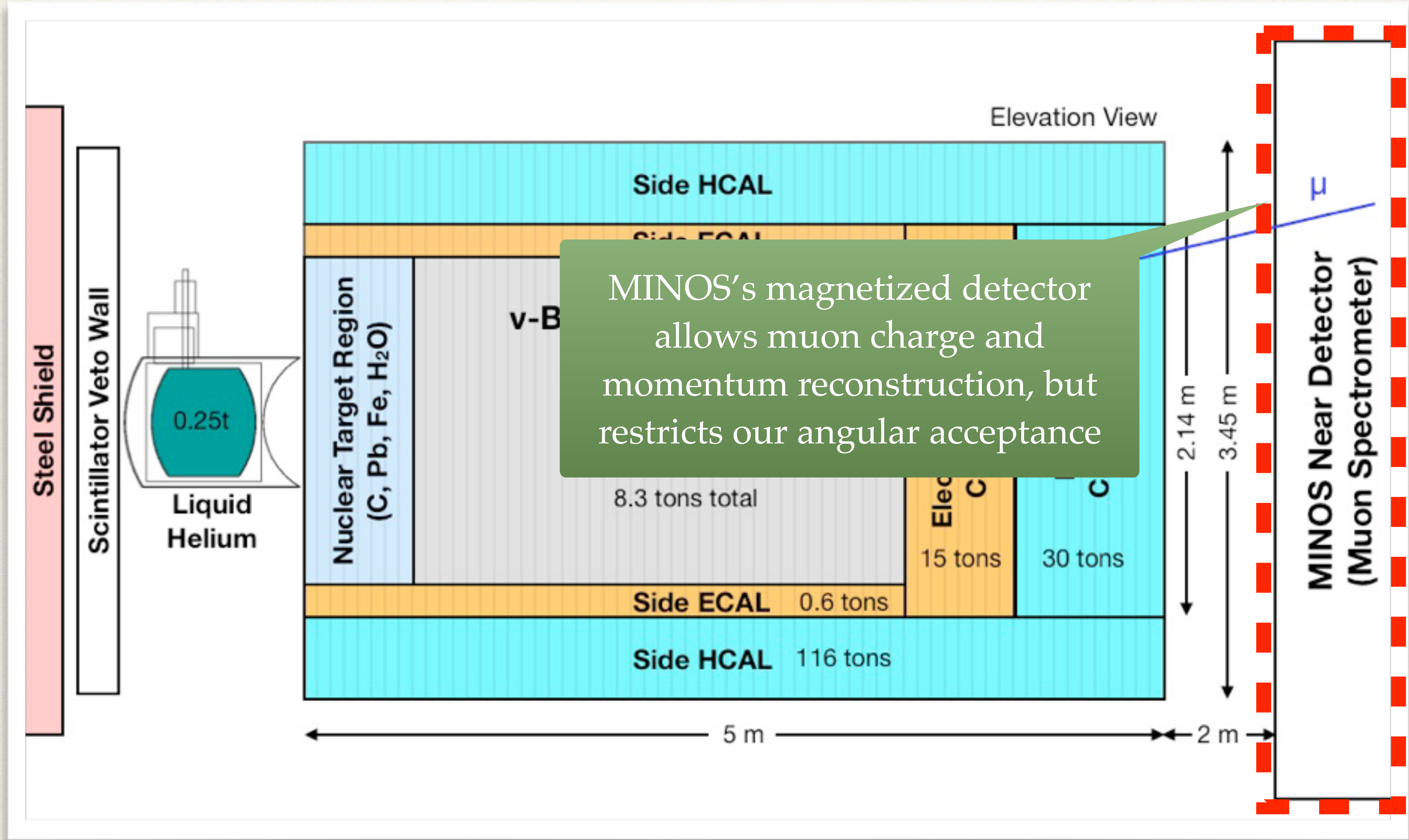



Scintillator (CH) tracker allows reconstruction of tracks for one and two-track analyses

# MINERvA detector

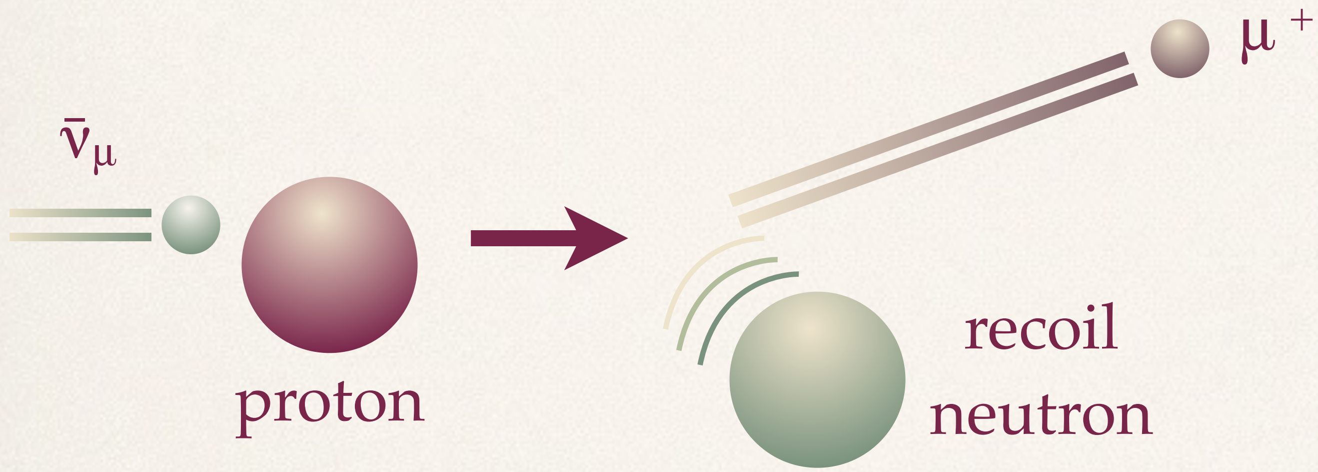


# MINERvA detector



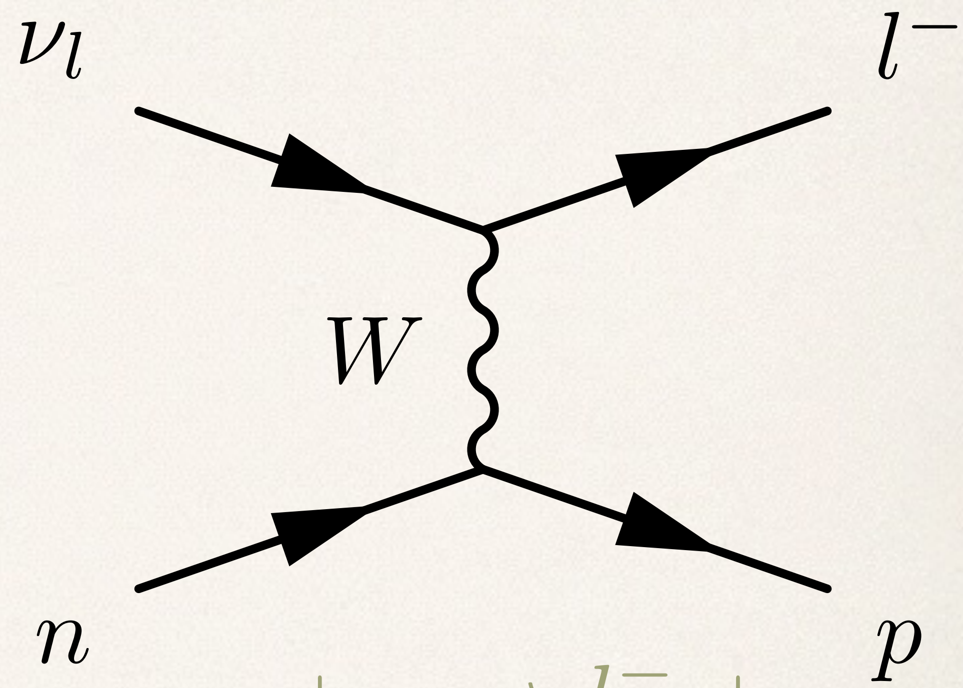
# Quasi-elastic scattering

- Key signal channel for **oscillations**
- There is a **single charged lepton** in the final state, plus the **recoil nucleon** (no pions etc)
- The lepton's charge and flavor identify the incident neutrino/antineutrino
- We can **reconstruct the neutrino energy and 4-momentum transfer** $Q^2$ from just the **lepton kinematics**

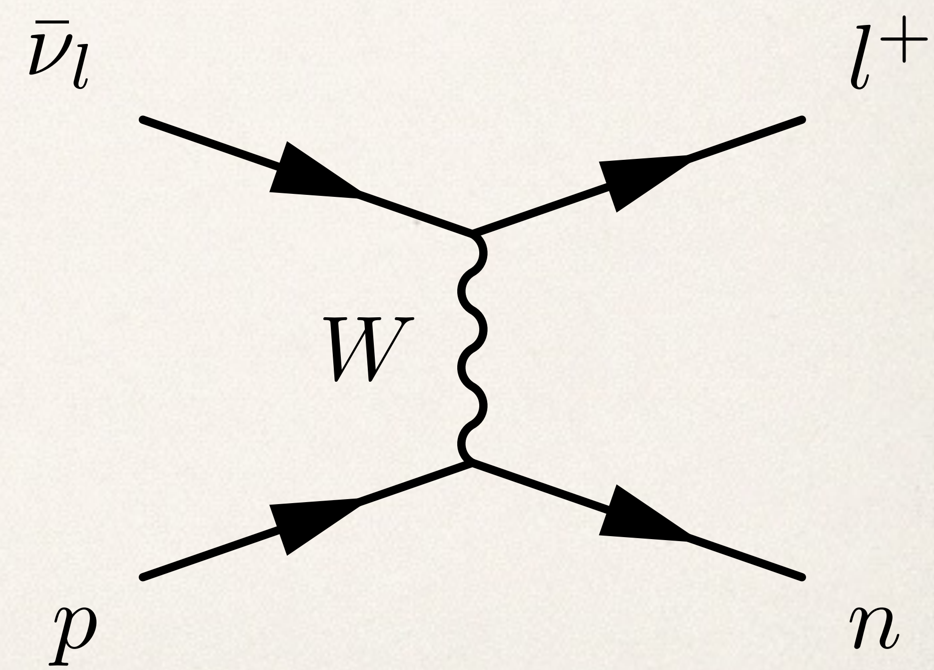



$$Q^2_{QE} = 2E_\nu^{QE}(E_\mu - p_\mu \cos\theta_\mu) - m_\mu^2$$

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



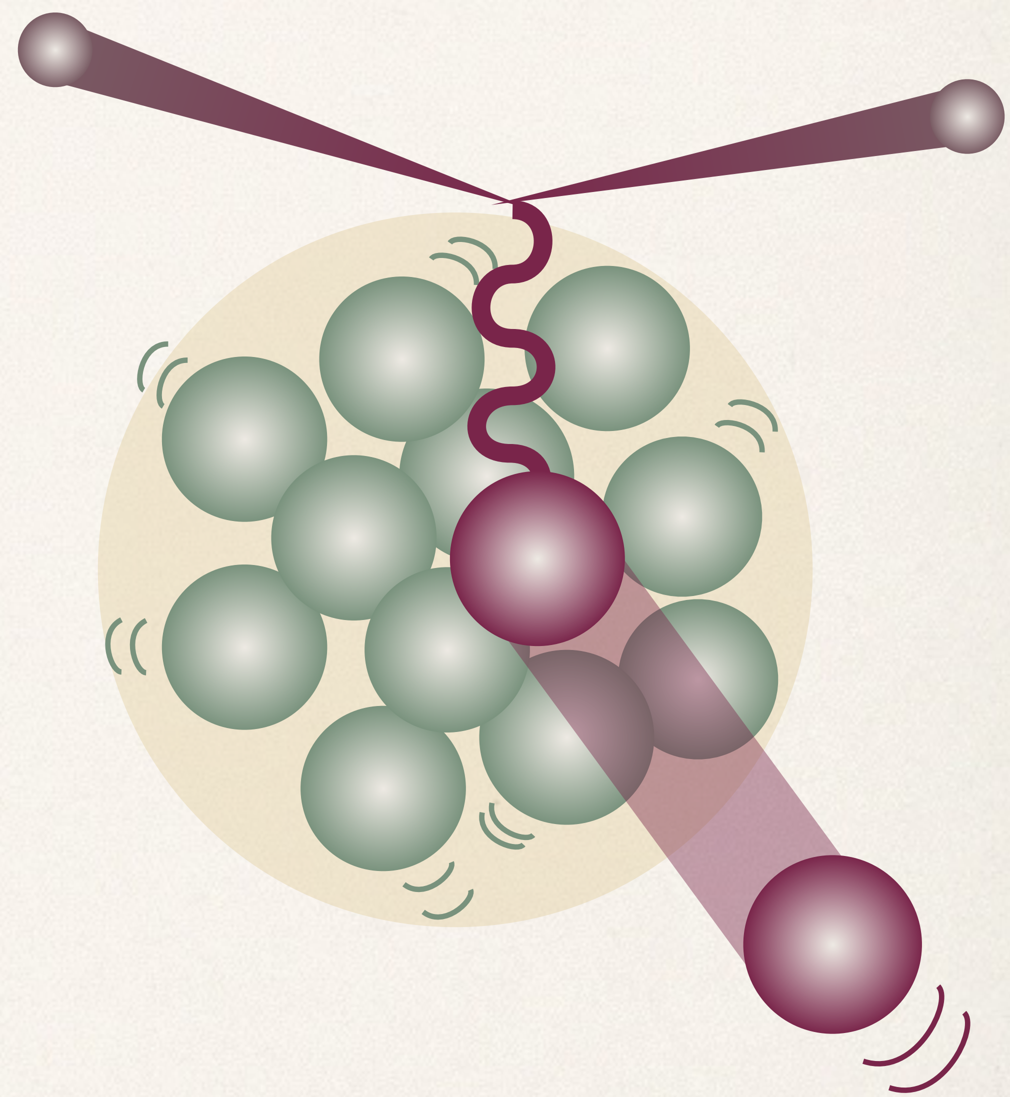

$$\nu_l + n \rightarrow l^- + p$$




$$\bar{\nu}_l + p \rightarrow l^+ + n$$

# Relativistic Fermi Gas model

- The relativistic Fermi gas (RFG) is a frequently-used nuclear model
- Nucleons behave as if they are independent particles, moving in the mean field of the nucleus
- Initial-state momenta have a Fermi distribution
- Cross-sections can be modeled by a multiplier to the Llewellyn Smith cross-section for a free nucleon
- Its free parameters (nucleon form-factors) can be determined from electron scattering, except for the axial mass, $M_A$, which must be measured in neutrino scattering

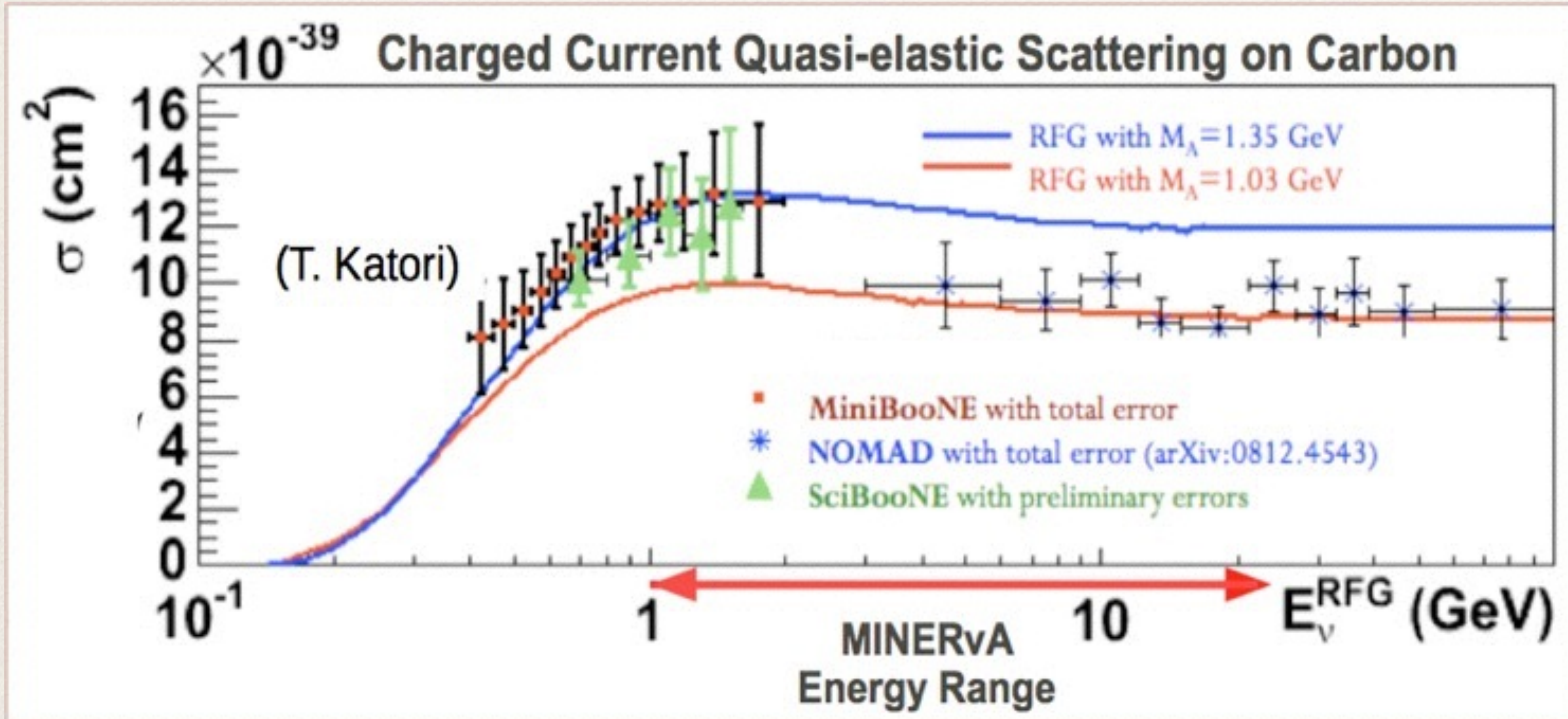


$$F_A(Q^2) = -\frac{g_A}{\left(1 + \frac{Q^2}{M_A^2}\right)^2}$$

Axial form factor

Axial mass

# Other experiments' results

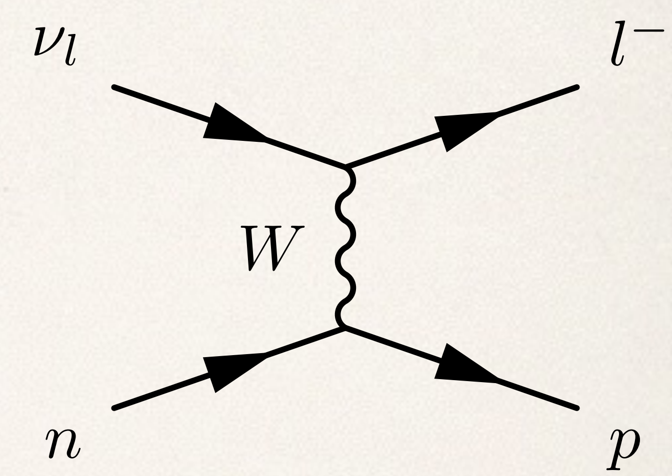


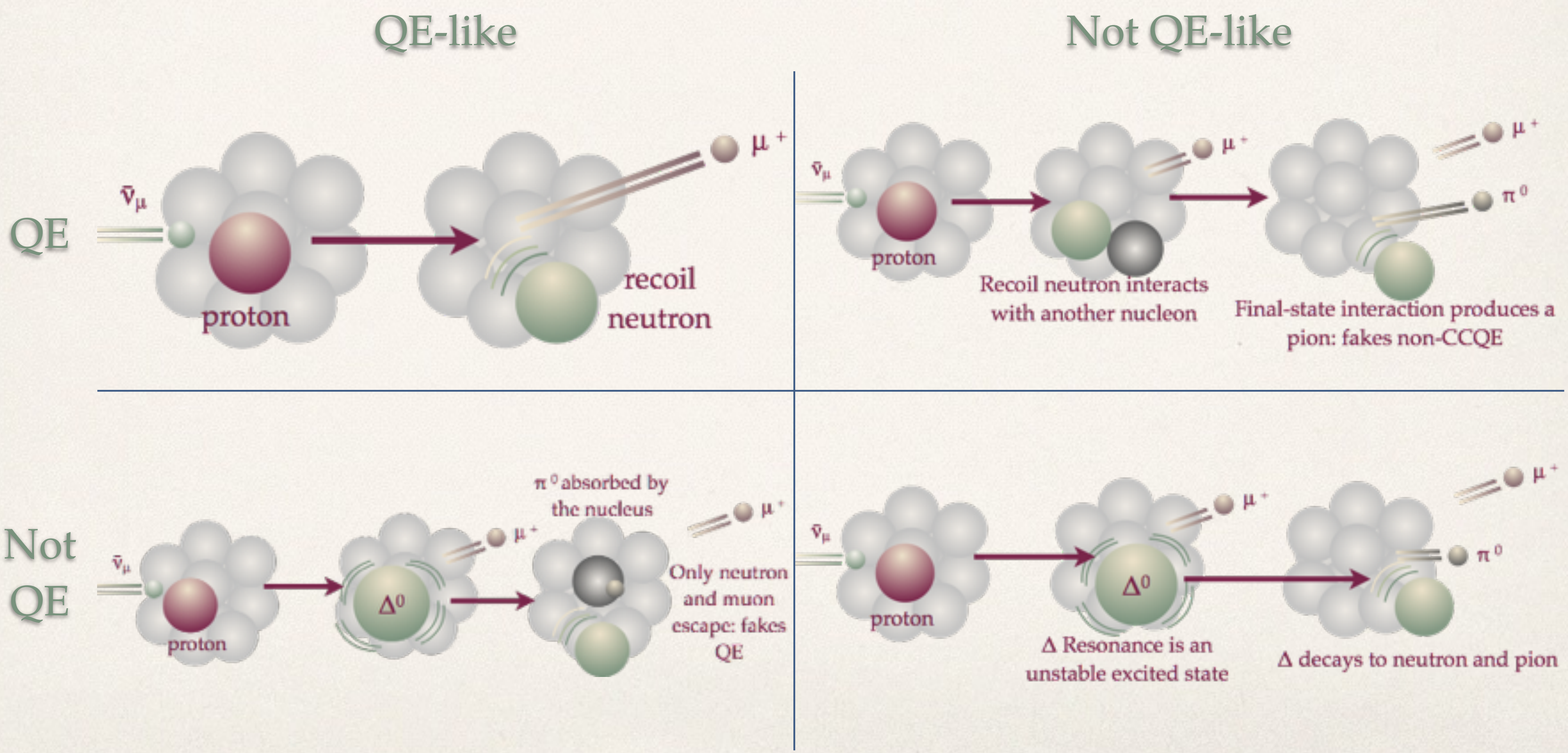

*A.A. Aguilar-Arevalo et al. [MiniBooNE Collaboration], Phys. Rev. D 81, 092005 (2010)*

- This shows best fits of MiniBooNE, SciBooNE and NOMAD cross-sections to the RFG model for carbon
- Lower-energy experiments predict $M_A$=1.35 GeV, NOMAD predicts $M_A$=1.03 GeV when fitting to the same model
- This is a hint that we could be seeing **additional nuclear effects** beyond the RFG model
- We can use MINERvA's intermediate energy data to explore **different nuclear models**

# Nuclear effects - FSI

- **Final-state interactions** (FSI) refer to re-interactions within the nucleus
- They can cause non-quasi-elastic events to **fake** a quasi-elastic event and vice versa
- Our simulations include FSI models, but these are complex



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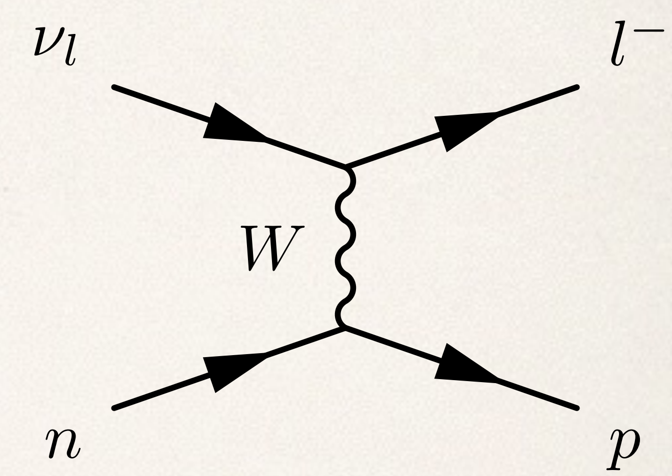


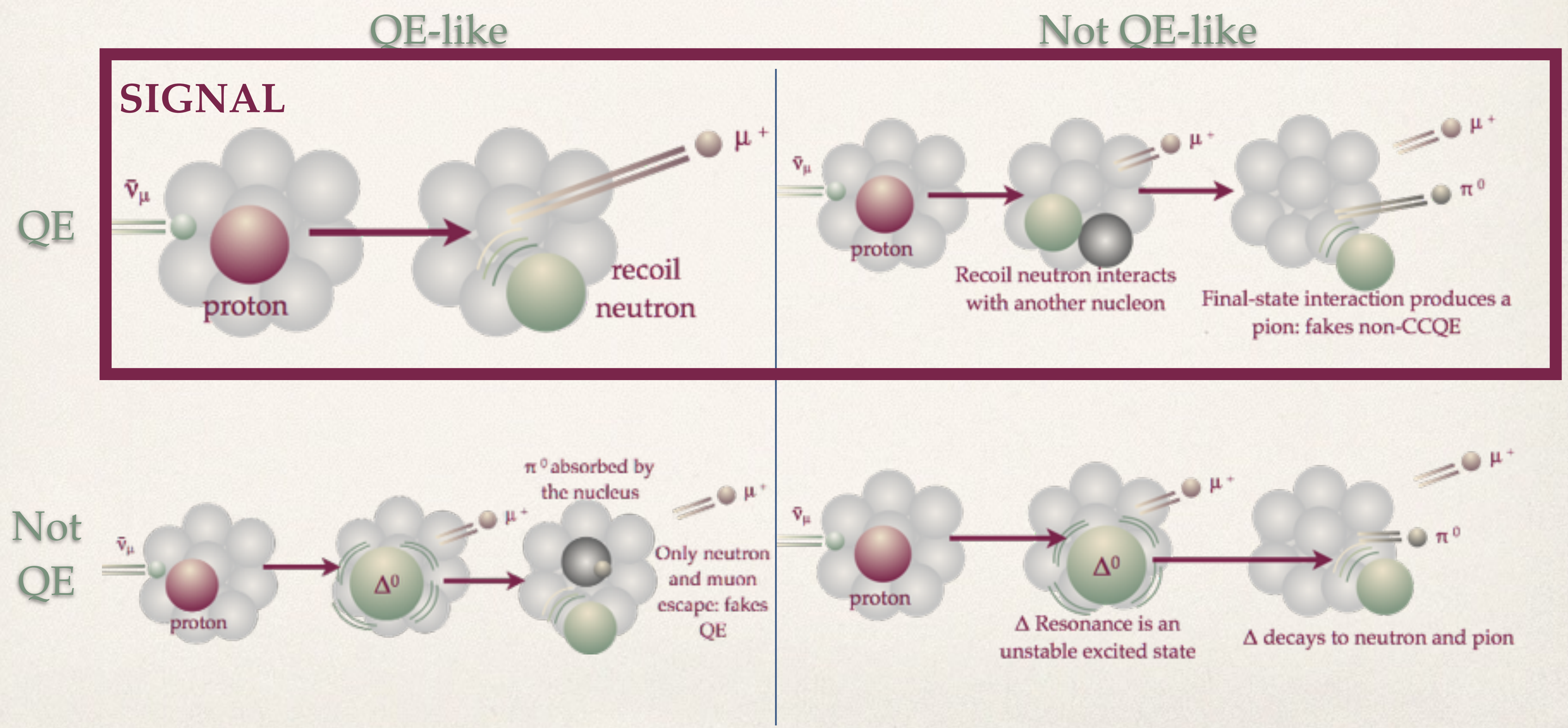

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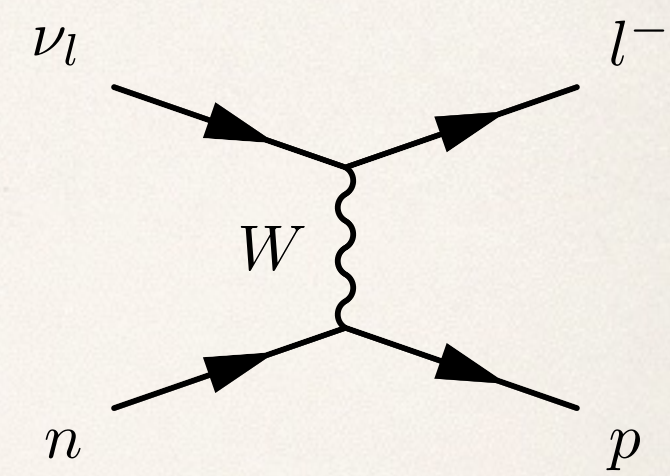
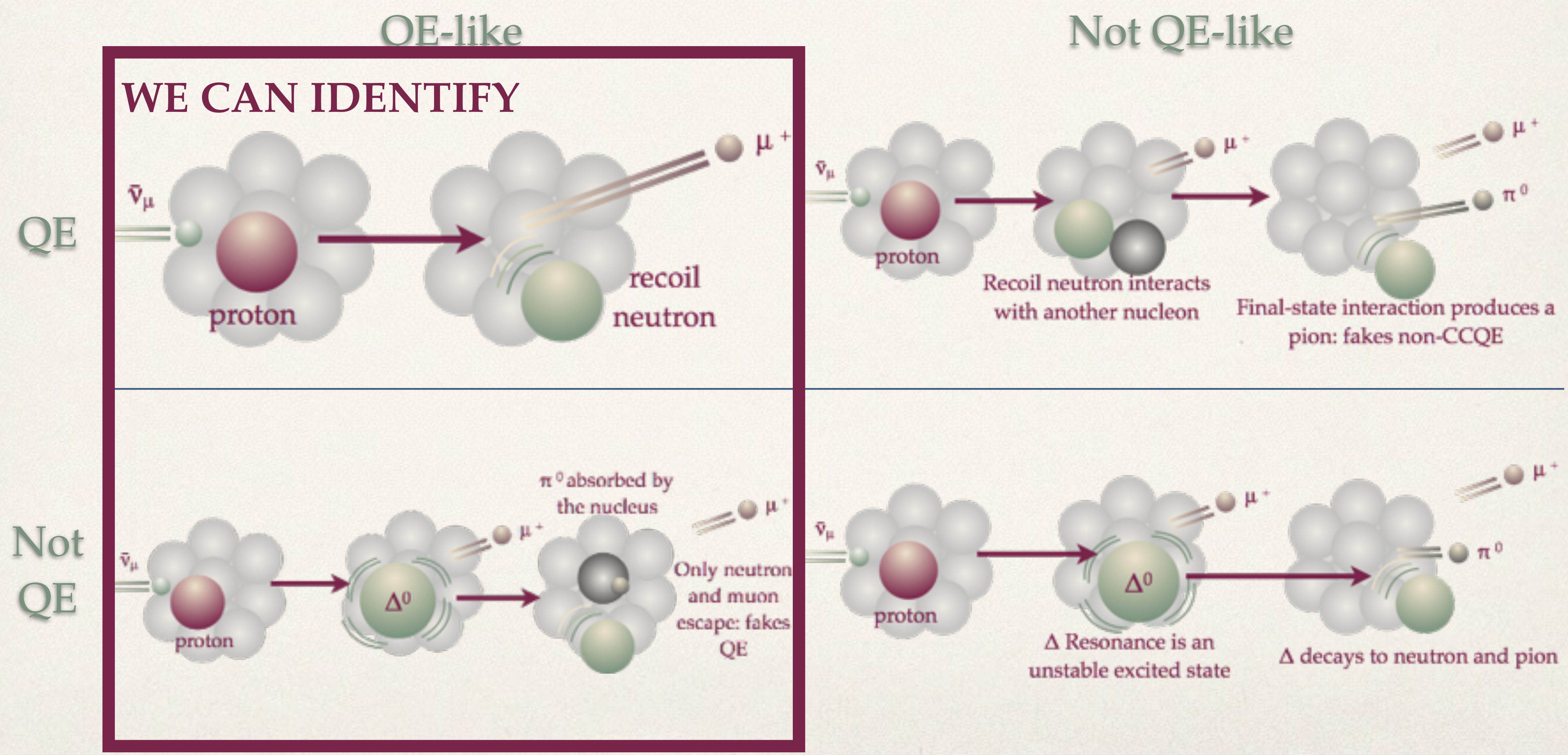
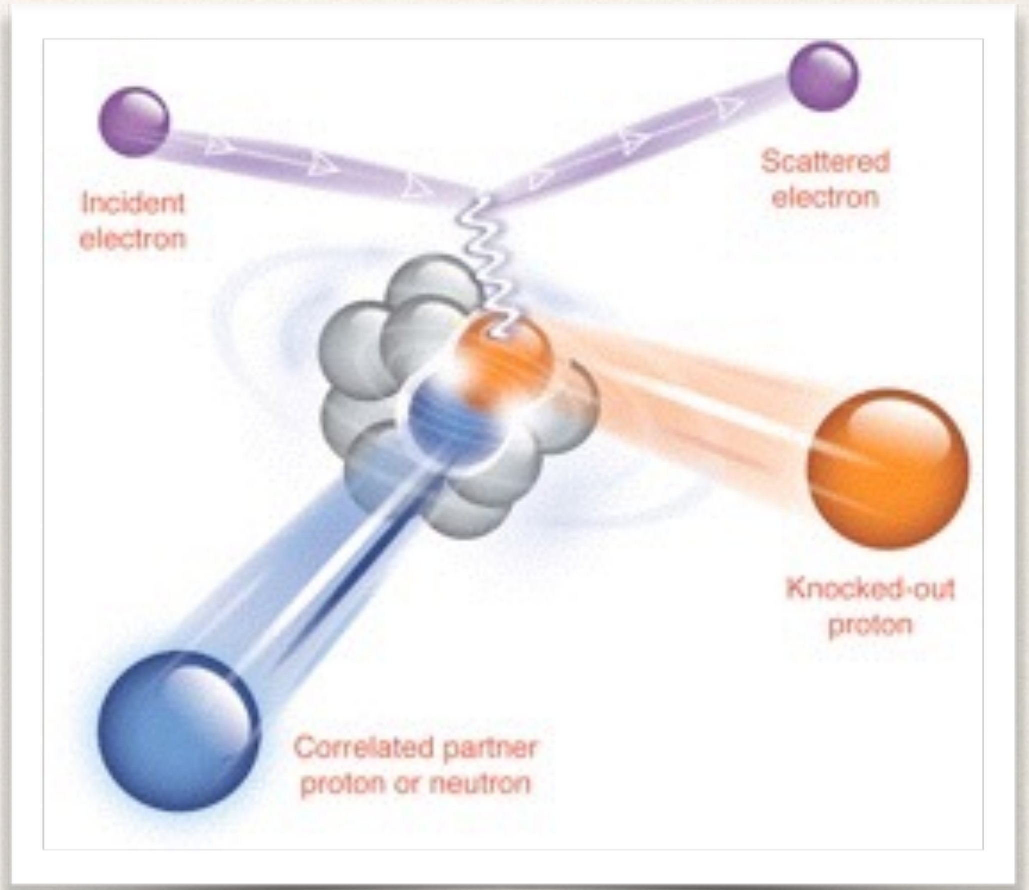


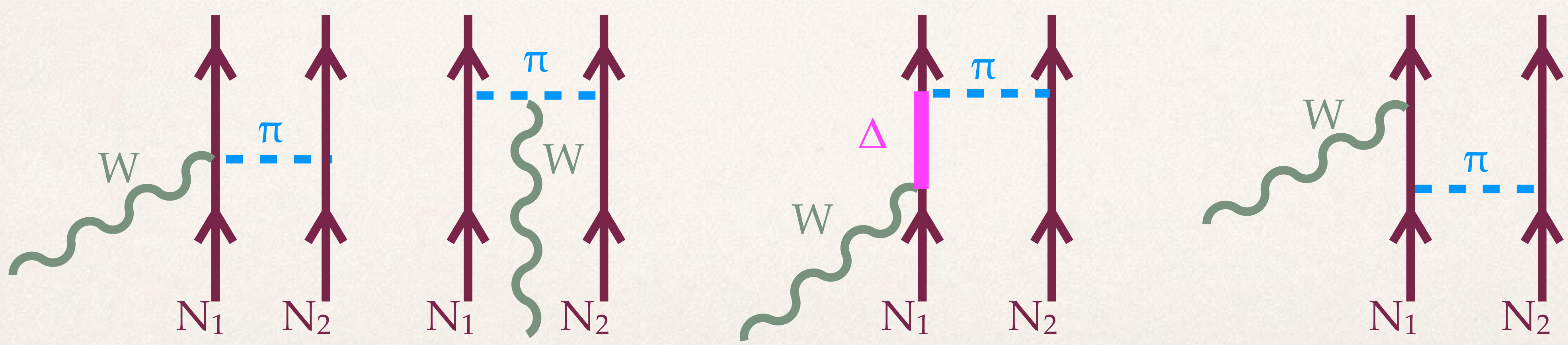



# Nuclear effects - correlations

- Electron-scattering data has shown hints of **correlations** between initial-state nucleons
- Scattering from a correlated pair of nucleons could lead to:
  - Initial momenta above the Fermi cut-off
  - "Partner" nucleons being ejected
  - Wrongly-reconstructed neutrino energies
- Correlations are a subset of nucleon-nucleon interactions known as **meson exchange currents**
- One model for these is by Nieves et al *J. Nieves, I. Ruiz Simo and M. J. Vicente Vacas, Phys. Rev. C 83 (2011)*



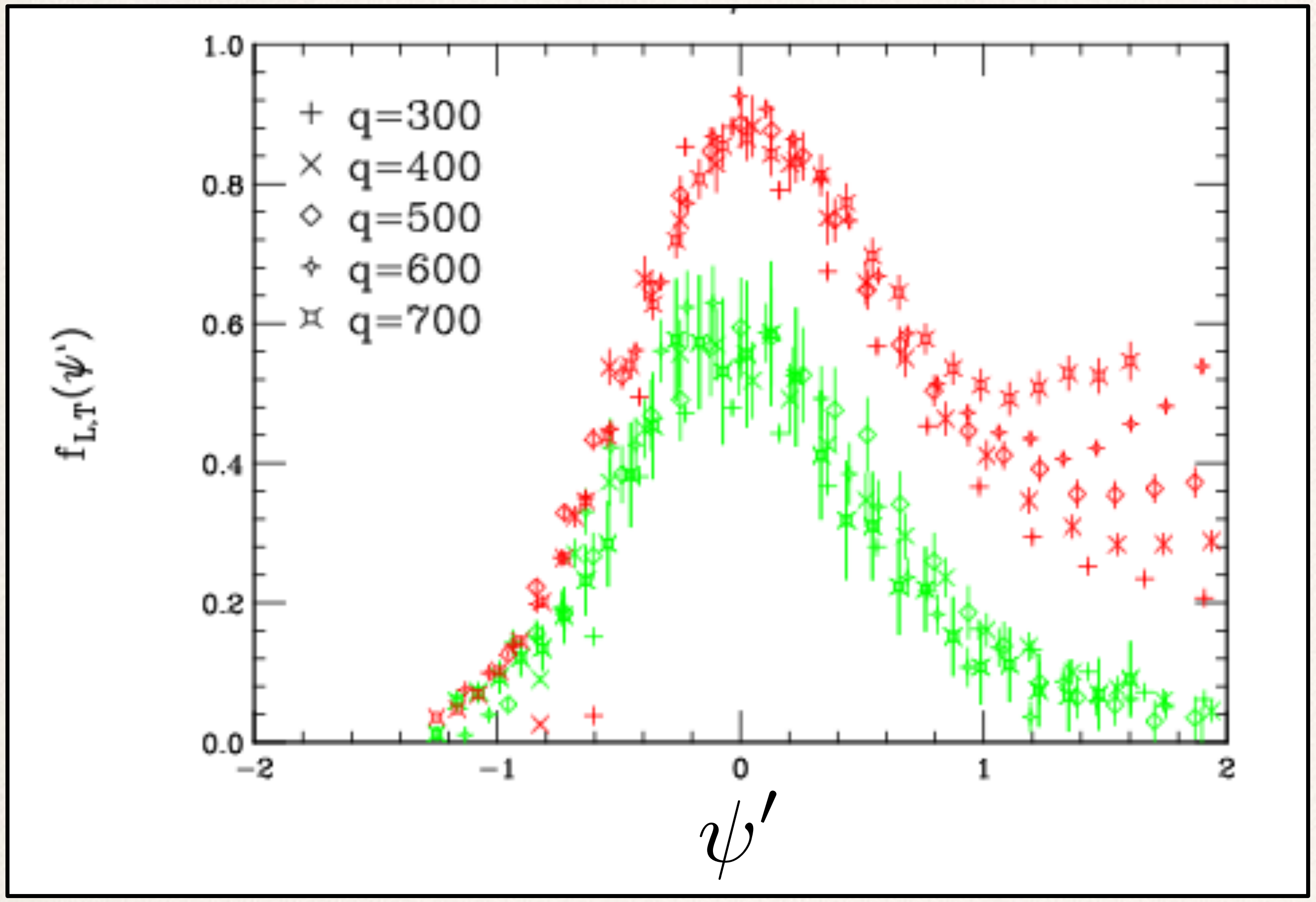

*R. Subedi et al, Science 320 1476 (2008)*




*Contact/pion-in-flight* *Δ-meson exchange current* *Correlation*

*Examples of some MEC interactions, based on a more detailed list from J Morfín*

# Nuclear effects - correlations




Transverse cross-section vs a scaling variable

Longitudinal cross-section vs a scaling variable

*J. Carlson et al, PRC 65, 024002 (2002)*

- The **transverse enhancement** effect is seen in electron-scattering cross-sections at J-Lab
- Cross-sections with transverse and longitudinally polarized vector bosons differ
  - The RFG model predicts no difference
- The exact physical process is unclear, but is believed to be caused by correlations
- The effect can be **parameterized** by modifying the magnetic form factor in our models

*A. Bodek, H. Budd, and M. Christy, Eur.Phys.J. C71, 1726 (2011)*

# Comparing cross-sections to models

We use two frameworks for modeling cross-sections:

GENIE, the Monte Carlo we use to estimate our acceptance *C. Andreopoulos, et al., NIM 288A, 614, 87 (2010)*

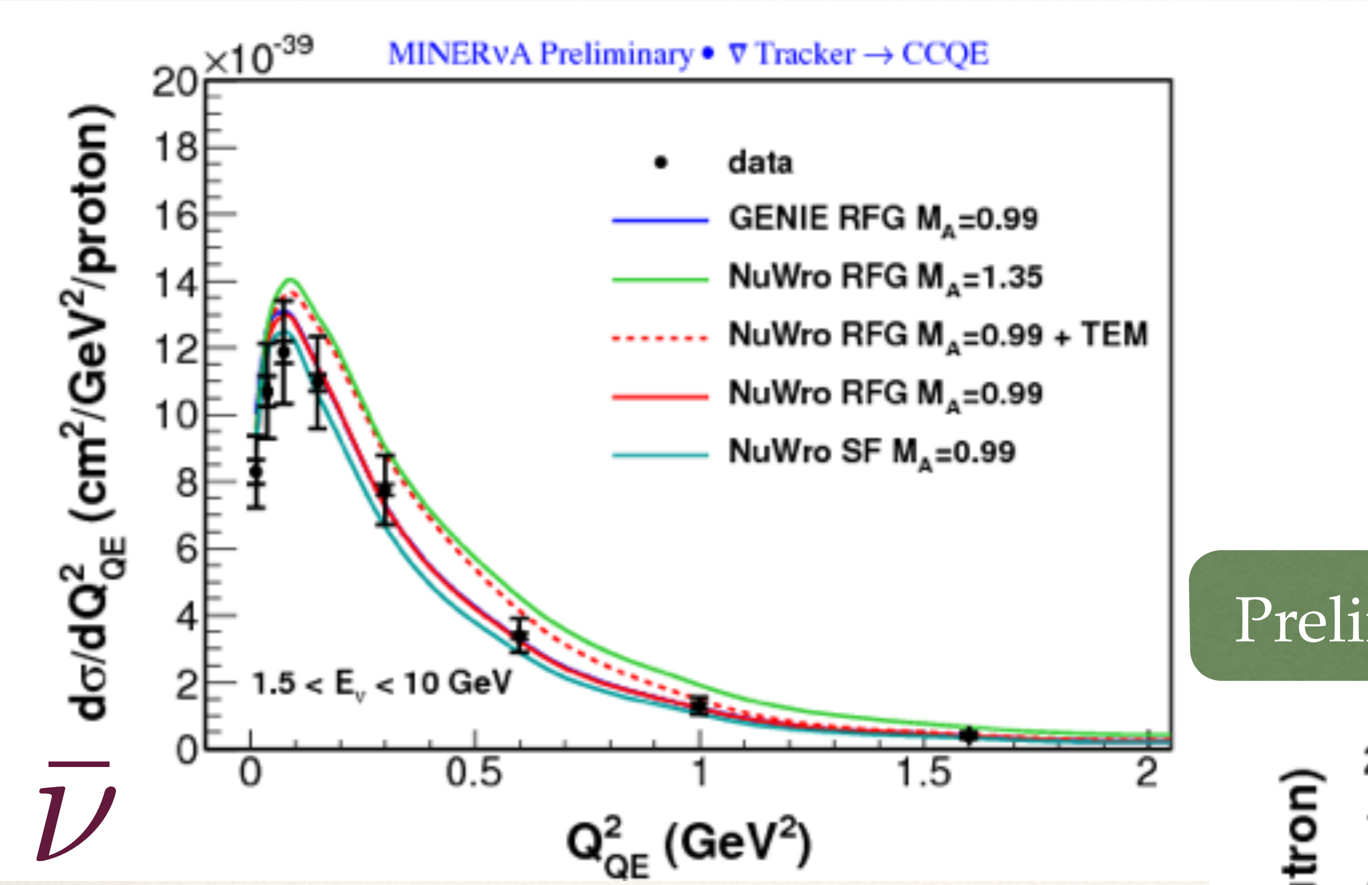
NuWro *K. M. Graczyk and J. T. Sobczyk, Eur.Phys.J. C31, 177 (2003)*

And the following nuclear models:

- Relativistic Fermi Gas (RFG) (GENIE and NuWro) *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)*
  - Constant binding energy; Fermi-distributed momenta. $p_F$=225 MeV (GENIE), 221 MeV (NuWro)
- Spectral functions (SF) (NuWro only) *O. Benhar, A. Fabrocini, S. Fantoni, and I. Sick, Nucl.Phys. A579, 493 (1994)*
  - takes correlations into account when calculating initial-state momenta and removal energies
- Local Fermi Gas (LFG) (NuWro only)
  - Fermi momentum and binding energy are a function of position in the nucleus
  - Pauli blocking is less restrictive than for RFG
- Random Phase Approximation (RPA) (NuWro only)
  - Models long-range correlations due to particle-hole excitations
  - RPA suppresses the cross-section at low $Q^2$

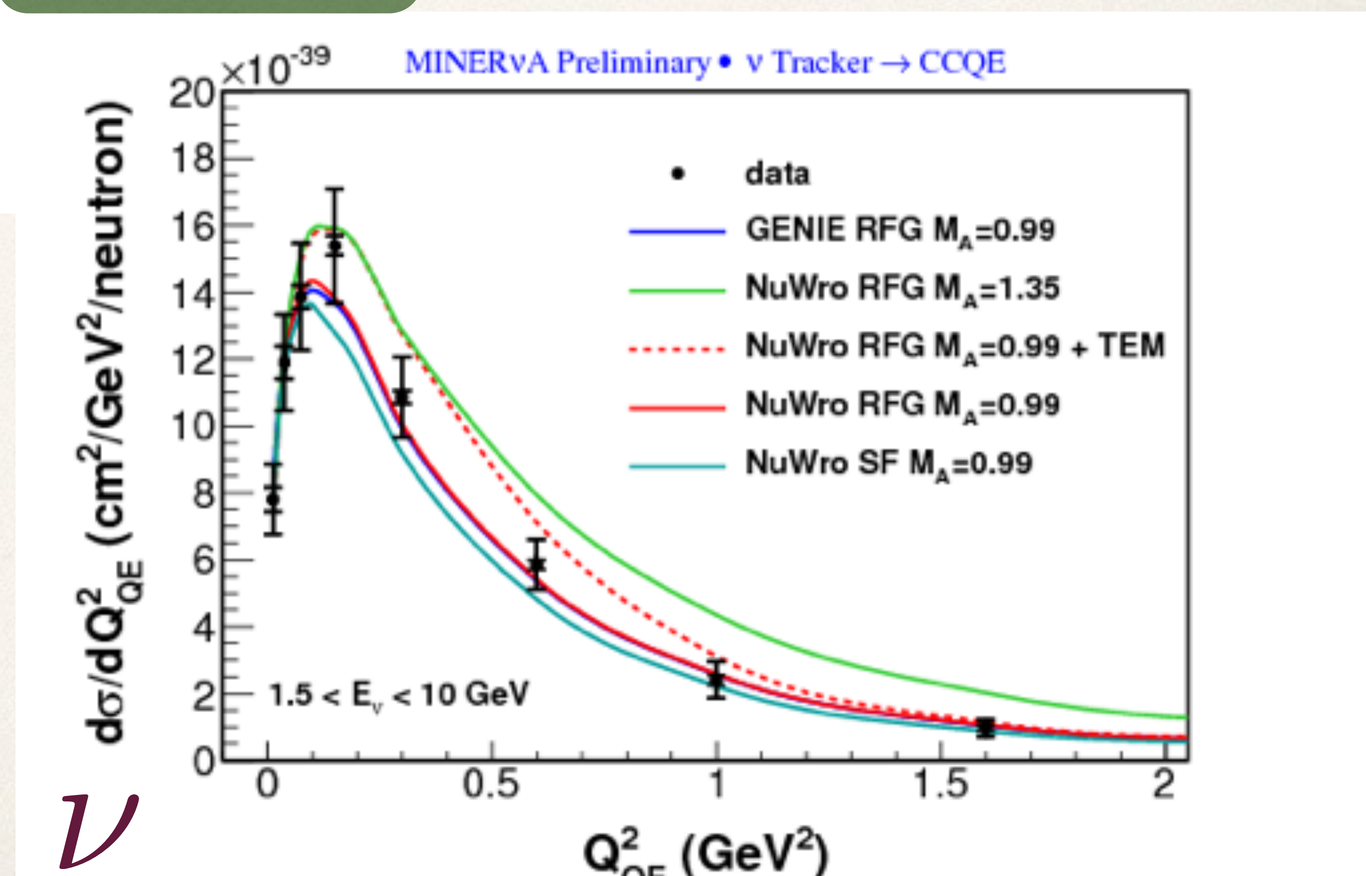
We also model nuclear effects with the **transverse enhancement** and **Nieves MEC models**

# Cross-section model comparisons




- It's hard to distinguish between the different curves, especially at high $Q^2$ where the cross-section is small
- A **ratio plot** will make it easier to see the differences

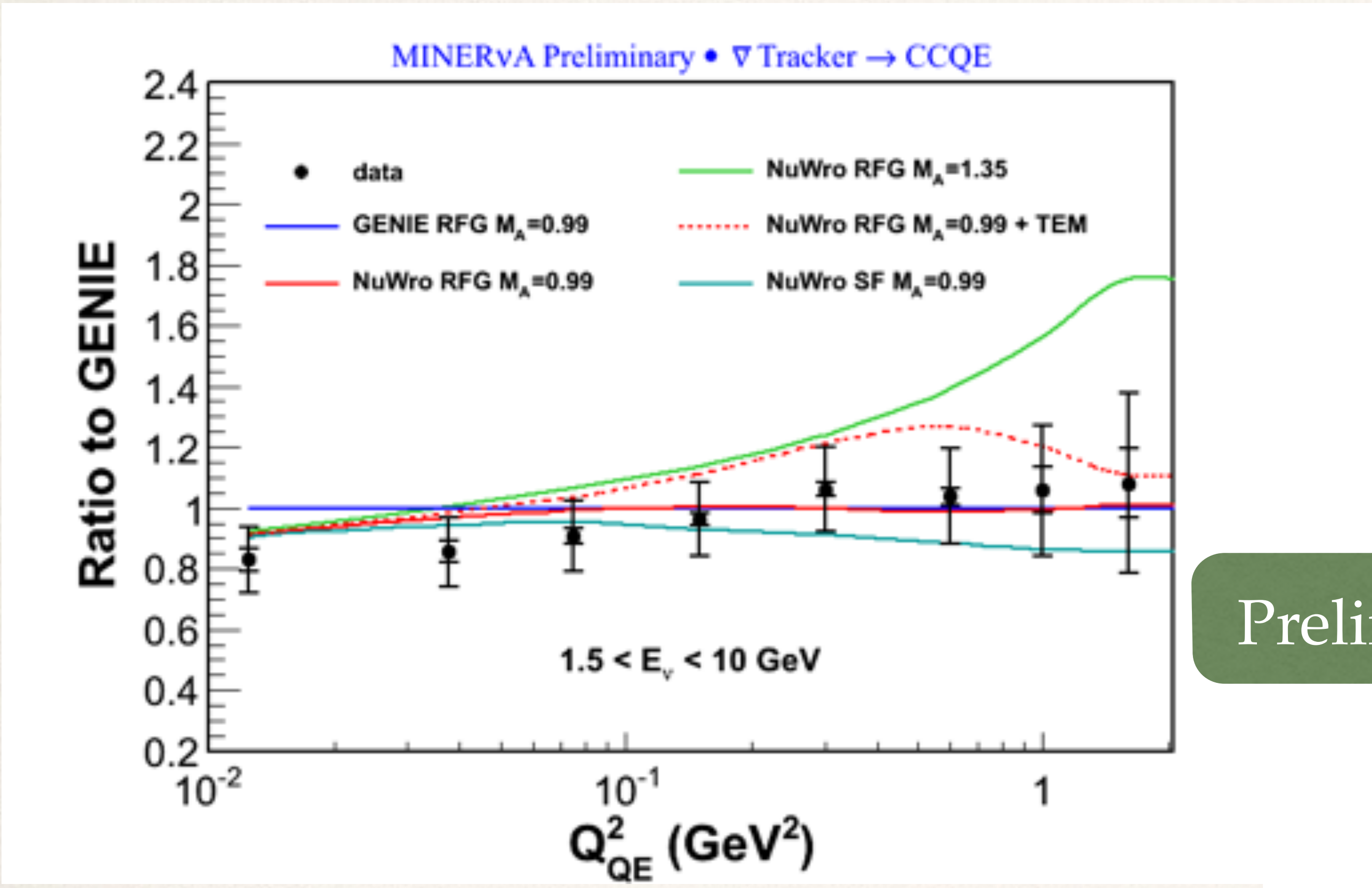
Preliminary




- GENIE RFG $M_A$=0.99
- NuWro RFG $M_A$=0.99
- NuWro RFG $M_A$=1.35
- NuWro RFG $M_A$=0.99+TEM
- NuWro SF $M_A$=0.99

In all plots, the inner marker on the error bars represents statistical uncertainty, while the outer marker represents total uncertainty

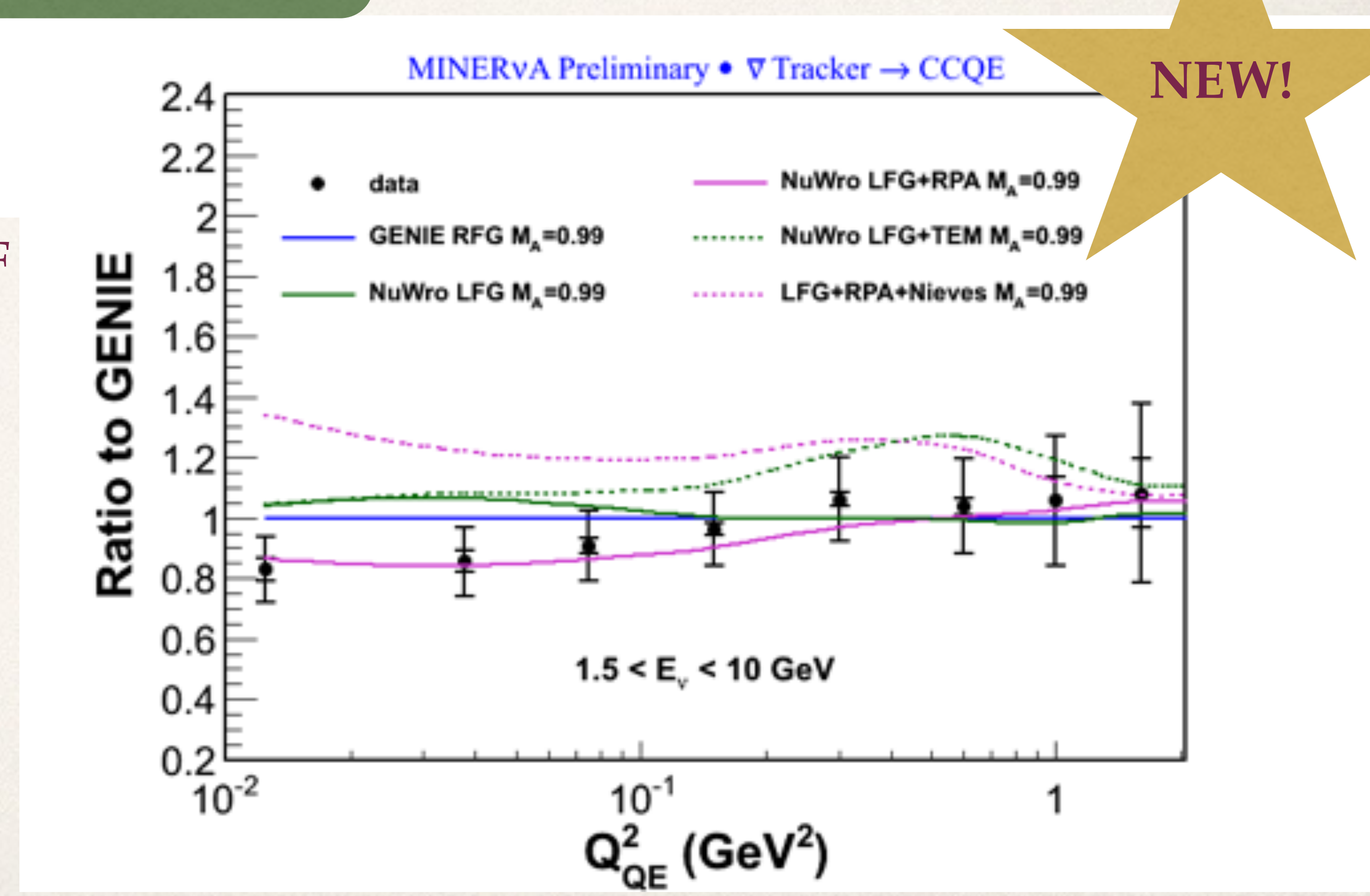
# Rate model comparisons ($\bar{\nu}$)




- Here, we have taken a **ratio** to our GENIE Monte Carlo distribution, to make it easier to differentiate between models
- Due to flux uncertainty, a **shape-only** fit may be still more valuable

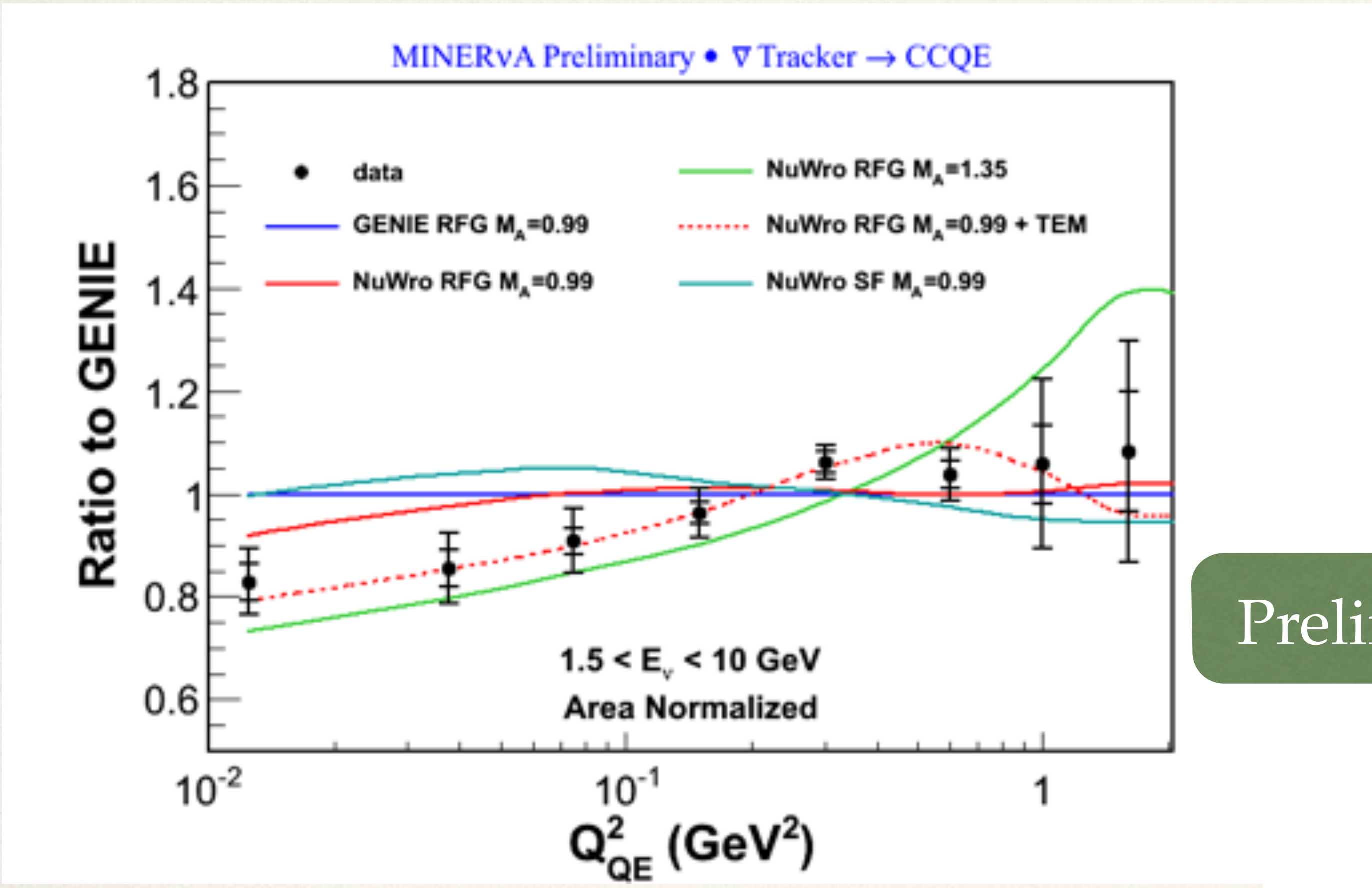
Preliminary

NEW!



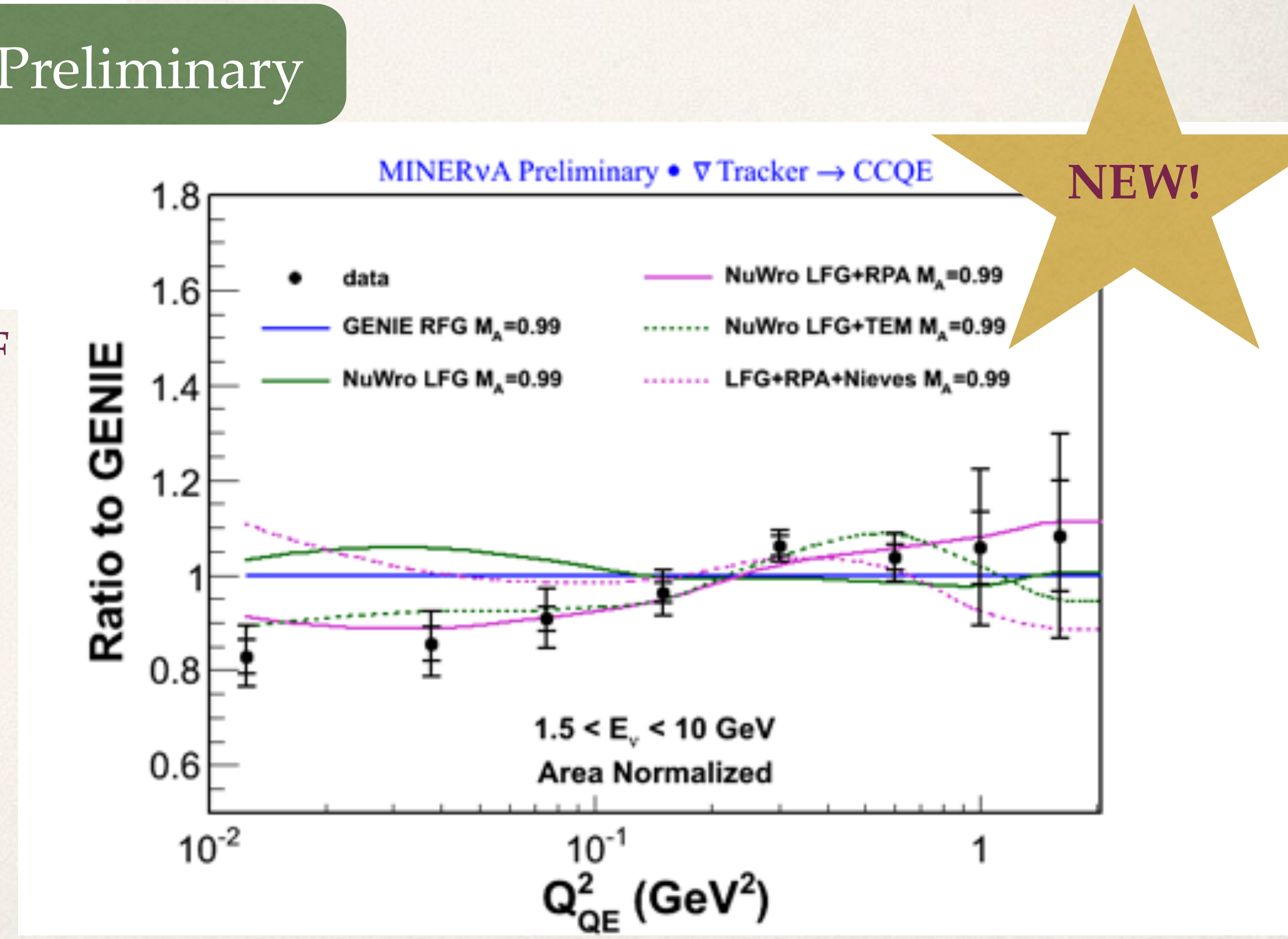

| | $\chi^2$/DOF |
|---|---|
| GENIE RFG $M_A$=0.99 | 2.20 |
| NuWro RFG $M_A$=0.99 | 1.19 |
| NuWro RFG $M_A$=1.35 | 1.98 |
| **NuWro RFG $M_A$=0.99+TEM** | **0.67** |
| NuWro SF $M_A$=0.99 | 1.89 |
| NuWro LFG $M_A$=0.99 | 3.61 |
| **NuWro LFG+RPA $M_A$=0.99** | **0.78** |
| NuWro LFG+TEM $M_A$=0.99 | 1.54 |
| NuWro LFG+RPA+Nieves $M_A$=0.99 | 7.1 |

# Shape-only model comparisons ($\bar{\nu}$)

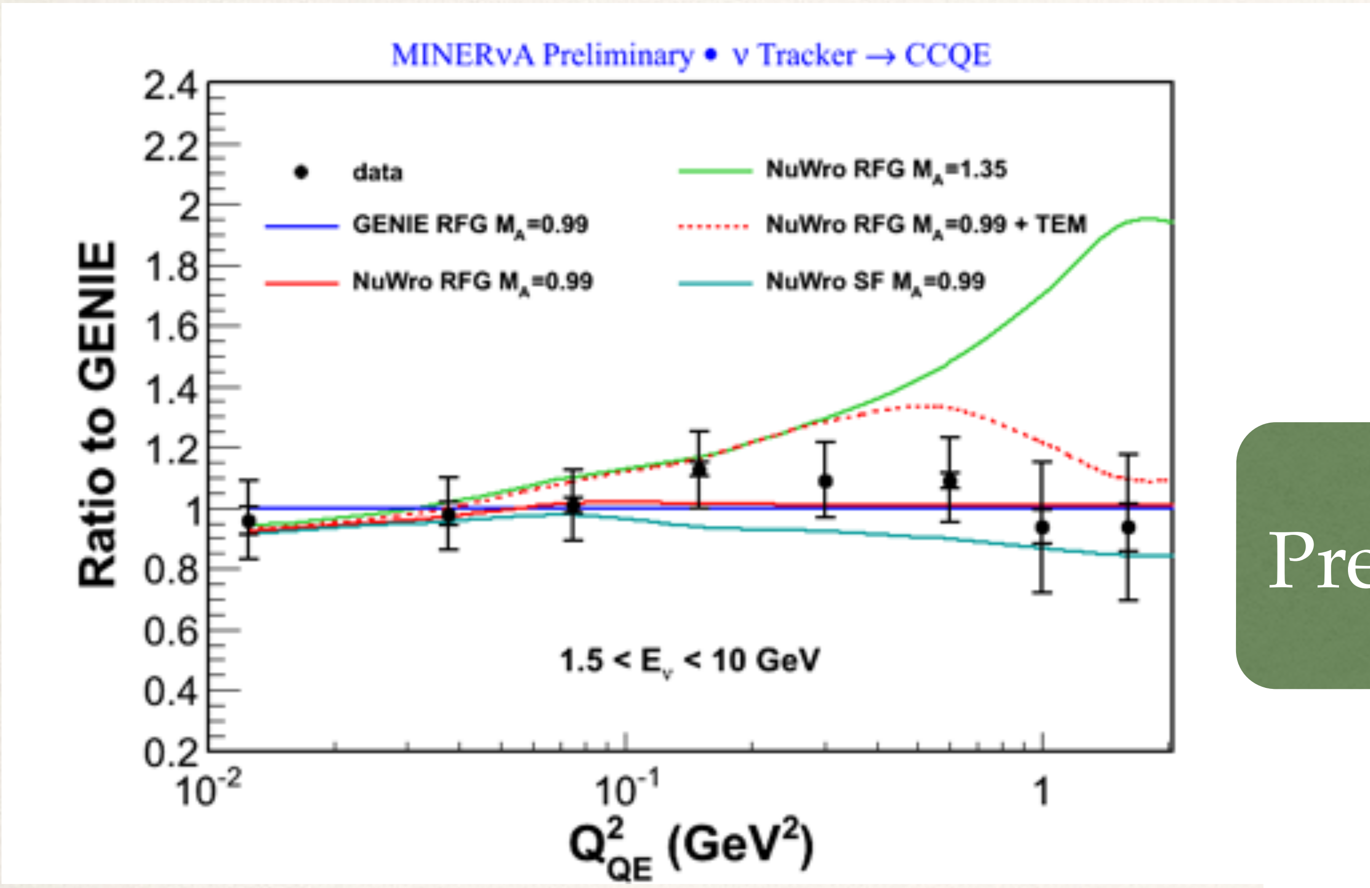



Preliminary

| | $\chi^2$/DOF |
|---|---|
| GENIE RFG $M_A$=0.99 | 2.44 |
| NuWro RFG $M_A$=0.99 | 1.37 |
| NuWro RFG $M_A$=1.35 | 1.27 |
| **NuWro RFG $M_A$=0.99+TEM** | **0.45** |
| NuWro SF $M_A$=0.99 | 2.61 |
| NuWro LFG $M_A$=0.99 | 3.97 |
| **NuWro LFG+RPA $M_A$=0.99** | **0.95** |
| **NuWro LFG+TEM $M_A$=0.99** | **1.09** |
| NuWro LFG+RPA+Nieves $M_A$=0.99 | 4.63 |



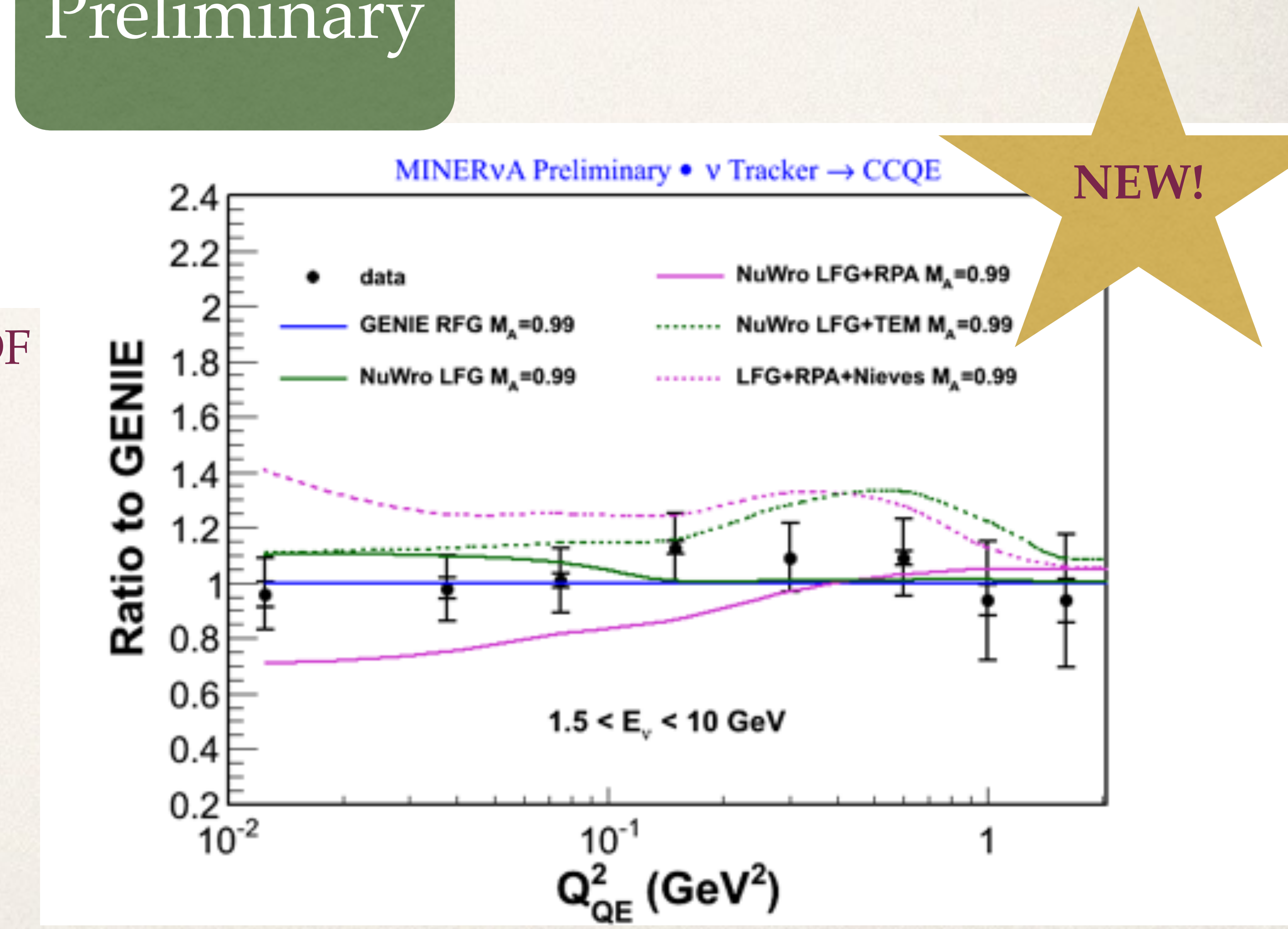
# Rate model comparisons ($\nu$)



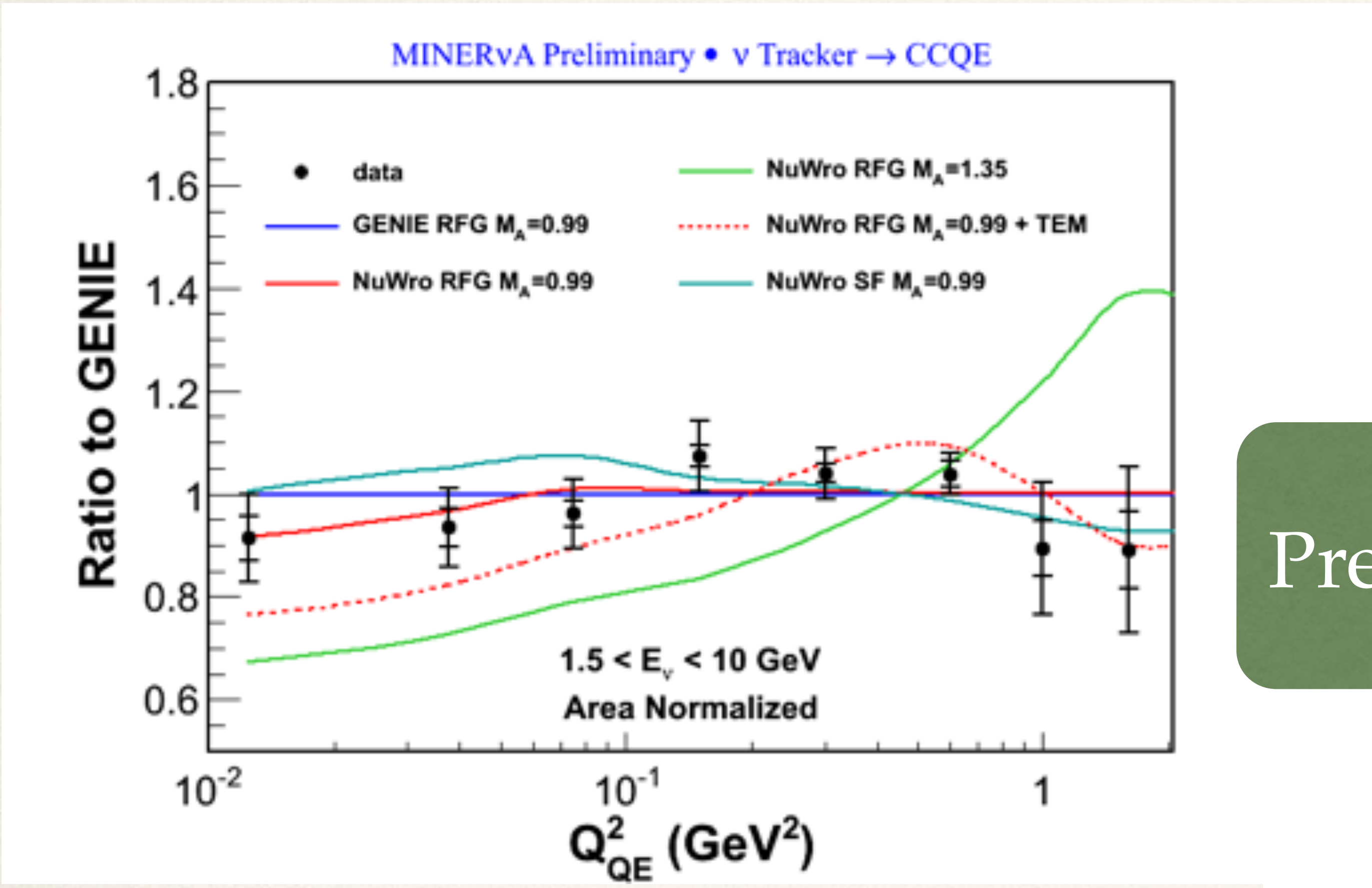

- Again, a **shape-only** comparison with models would avoid misleading results due to flux uncertainty

Preliminary

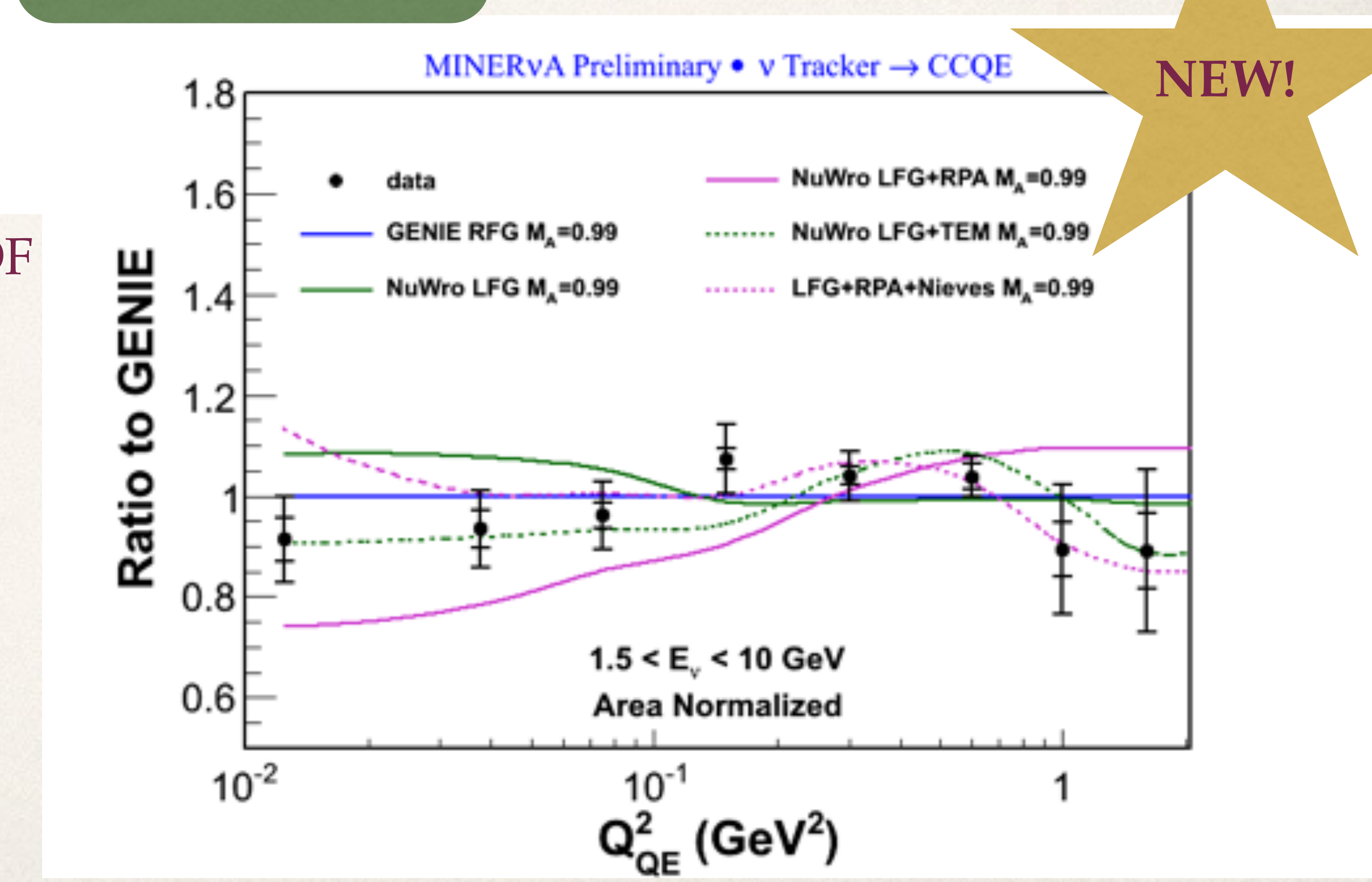
| Model | $\chi^2$/DOF |
|---|---|
| GENIE RFG $M_A$=0.99 | 1.86 |
| **NuWro RFG $M_A$=0.99** | **1.47** |
| NuWro RFG $M_A$=1.35 | 3.38 |
| NuWro RFG $M_A$=0.99+TEM | 2.92 |
| NuWro SF $M_A$=0.99 | 2.64 |
| NuWro LFG $M_A$=0.99 | 4.77 |
| **NuWro LFG+RPA $M_A$=0.99** | **1.73** |
| NuWro LFG+TEM $M_A$=0.99 | 3.53 |
| NuWro LFG+RPA+Nieves $M_A$=0.99 | 5.49 |



# Shape-only model comparisons ($\nu$)




Preliminary




NEW!

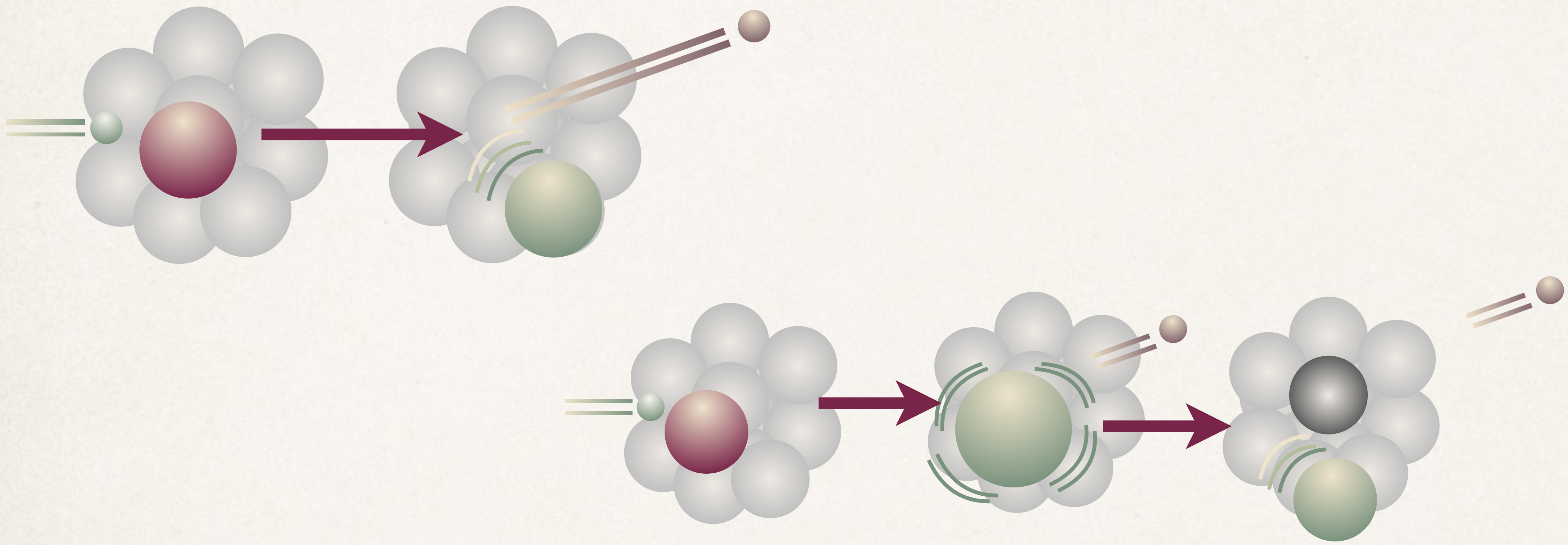
| Model | $\chi^2$/DOF |
|---|---|
| GENIE RFG $M_A$=0.99 | 2.06 |
| **NuWro RFG $M_A$=0.99** | **1.66** |
| NuWro RFG $M_A$=1.35 | 1.99 |
| NuWro RFG $M_A$=0.99+TEM | 2.26 |
| NuWro SF $M_A$=0.99 | 3.43 |
| NuWro LFG $M_A$=0.99 | 5.30 |
| **NuWro LFG+RPA $M_A$=0.99** | **1.83** |
| NuWro LFG+TEM $M_A$=0.99 | 2.75 |
| NuWro LFG+RPA+Nieves $M_A$=0.99 | 4.10 |

# $\chi^2$ for $\bar{\nu}$ and $\nu$ rates, combined

Preliminary

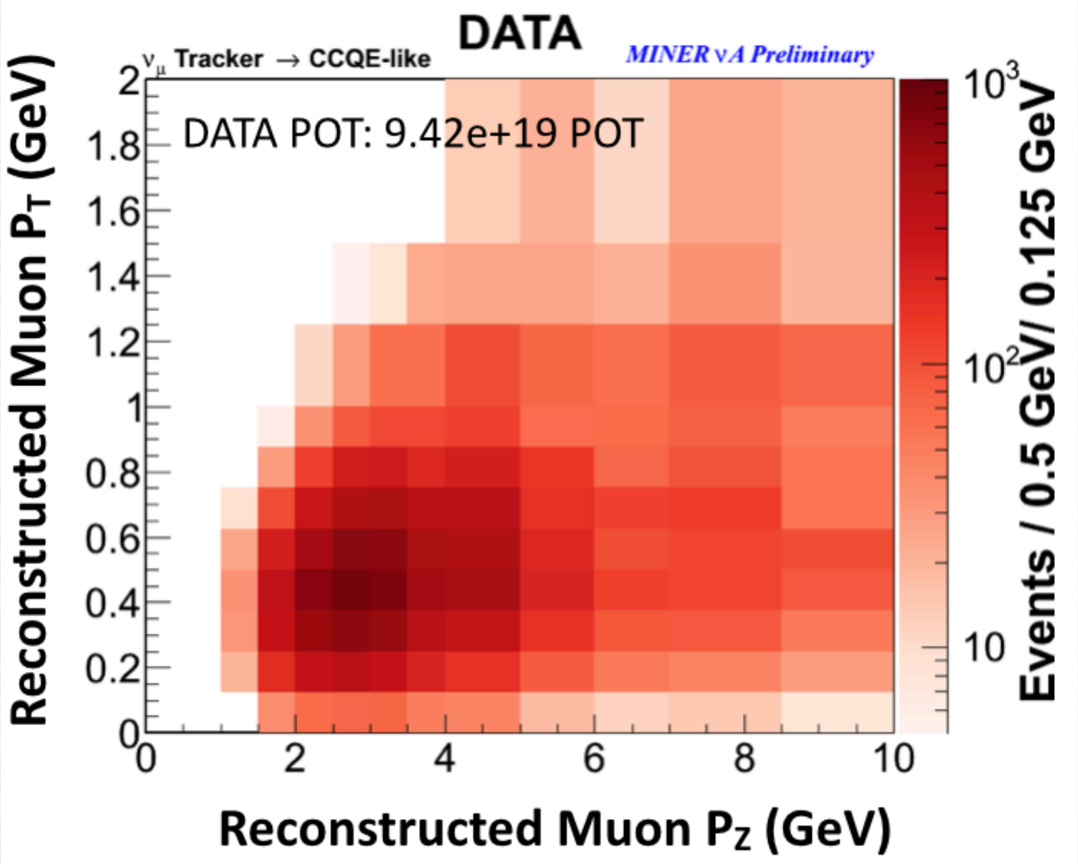
| Model | Combined rate $\chi^2$/d.o.f (16 degrees of freedom) |
|---|---|
| GENIE RFG $M_A$=0.99 | 2.04 |
| **NuWro RFG $M_A$=0.99** | **1.53** |
| NuWro RFG $M_A$=1.35 | 3.14 |
| **NuWro RFG $M_A$=0.99 + TEM** | **1.92** |
| NuWro SF $M_A$=0.99 | 2.22 |
| NuWro LFG $M_A$=0.99 | 3.88 |
| **NuWro LFG + RPA $M_A$=0.99** | **1.93** |
| NuWro LFG + TEM $M_A$=0.99 | 2.59 |
| NuWro LFG + RPA + Nieves $M_A$=0.99 | 5.79 |

# Quasi-elastic-like distributions



- With complicated nuclear effects, it's **hard to define** exactly what constitutes a quasi-elastic event in a heavy nucleus
- But a **quasi-elastic-like** event is **well defined** by the final-state particles: the muon, nucleon and no other hadrons
- Reproducing results for a **QE-like signal definition** makes it easier to compare results with other experiments' results, and with theoretical predictions
- QE-like distributions will be produced soon

# Double-differential cross-section




- Our published analysis plots cross-section vs. a reconstructed quantity - it's model-dependent
- It's hard to distinguish between the various models - we need all the information we can get!

- Plotting vs. measured quantities (a 2-D distribution of muon transverse and longitudinal momentum, for example) provides **more information** that will help us tell which models are a good fit to our data
- Double-differential cross-sections from different experiments have been suggested as the optimum data to use for **global fits** to models
- Watch this space for future updates on this project!

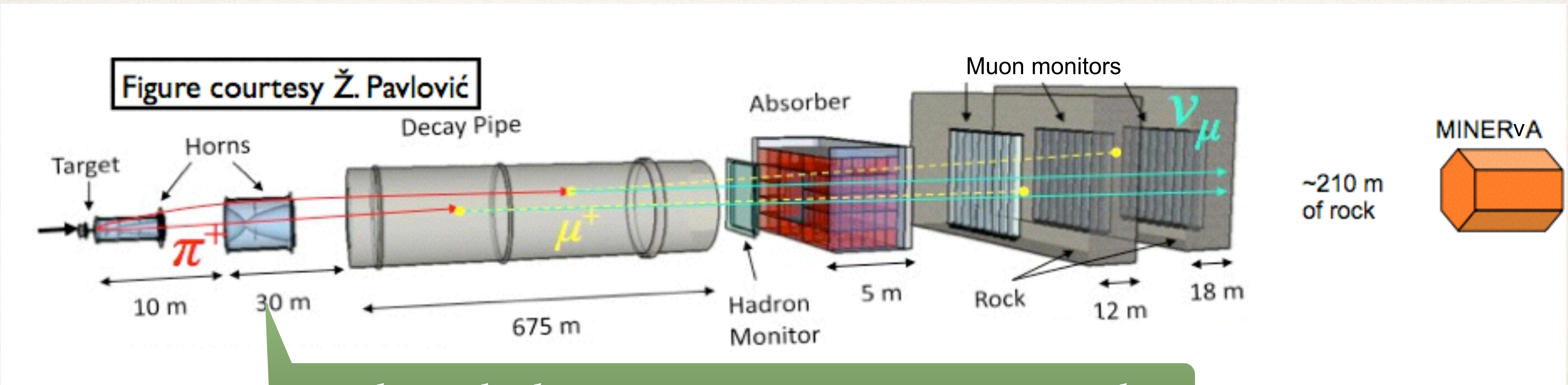
# Summary

* We've seen MINER$\nu$A's **differential cross-sections** $d\sigma/dQ^2$ for both neutrino and antineutrino quasi-elastic scattering from scintillator
* **Correlations** between bins can have a dramatic effect on $\chi^2$ values, and cannot be ignored when determining goodness of fit
* **Shape-only** comparisons help reduce flux uncertainty, but have much more significant bin-bin correlations
* The data suggest models that parameterize initial-state **nucleon-nucleon correlations** may be a good fit
* **Quasi-elastic-like** distributions will provide us with new opportunities to compare with models
* A **double-differential cross-section** will provide more information, and could be used for a global fit

*Thank you!*

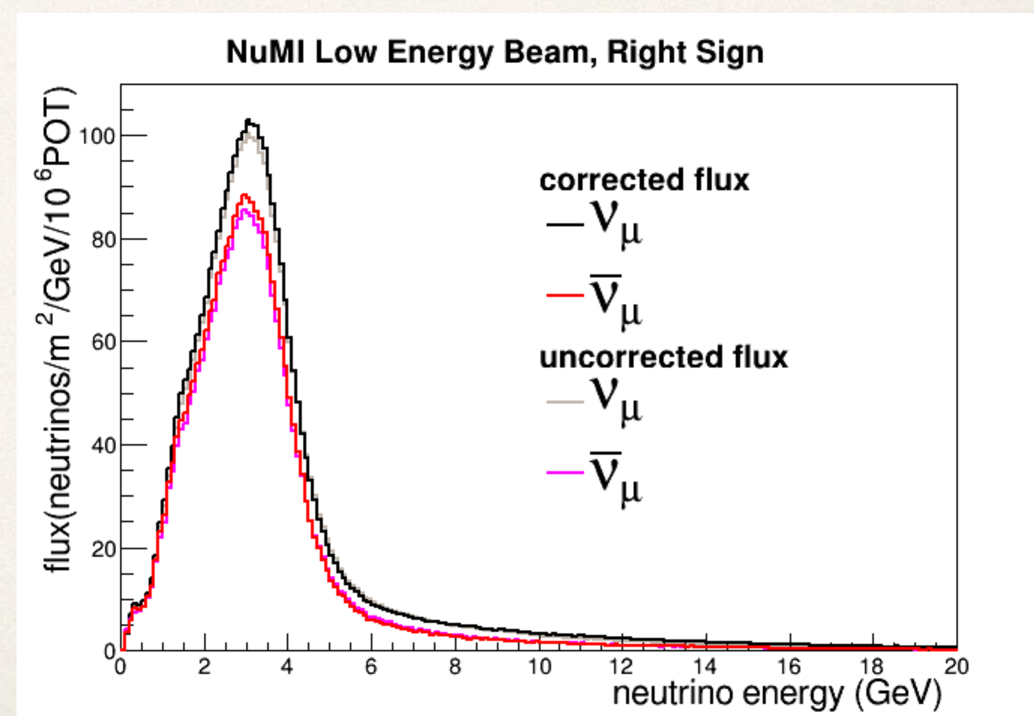
# Backup slides

# The NuMI beam




Switching the horn current selects a beam enriched in neutrinos or antineutrinos

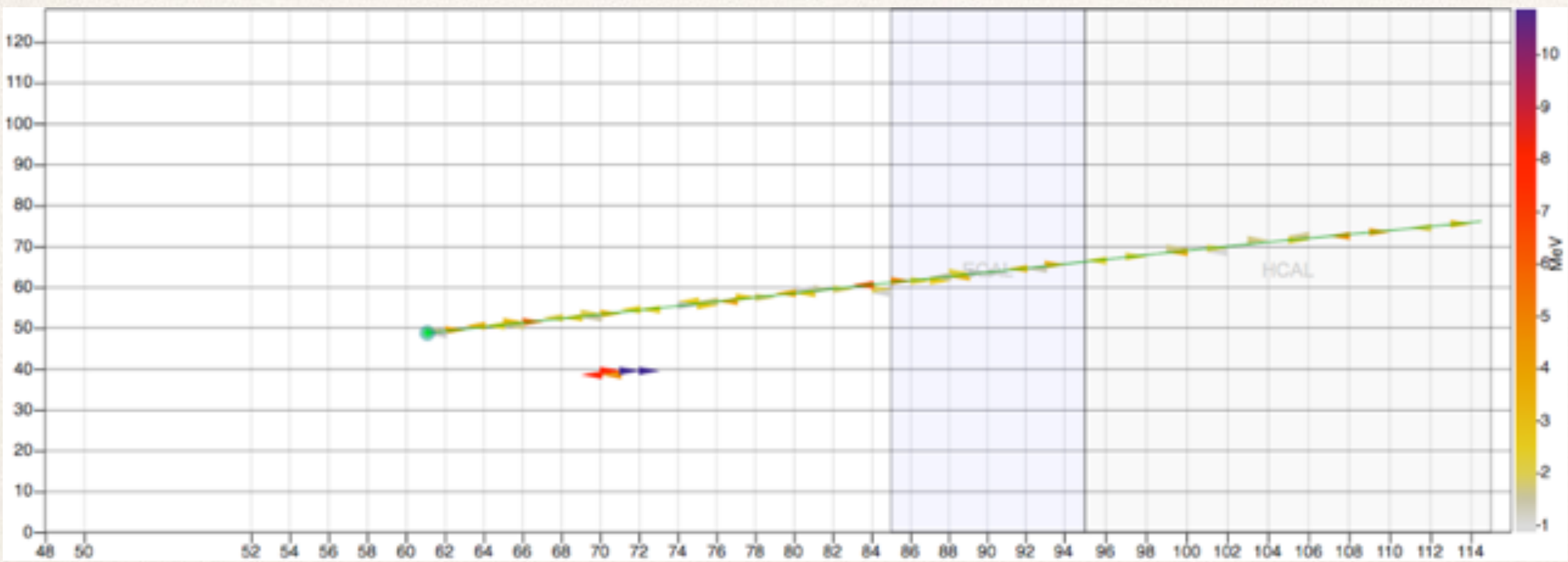
- These studies use data from the low energy run with $E_\nu$ ~3.5 GeV
- Our sample studies $E_\nu$ from 1.5 to 10 GeV, spanning MiniBooNE's and NOMAD's ranges
- See Debbie Harris's talk for more beam details



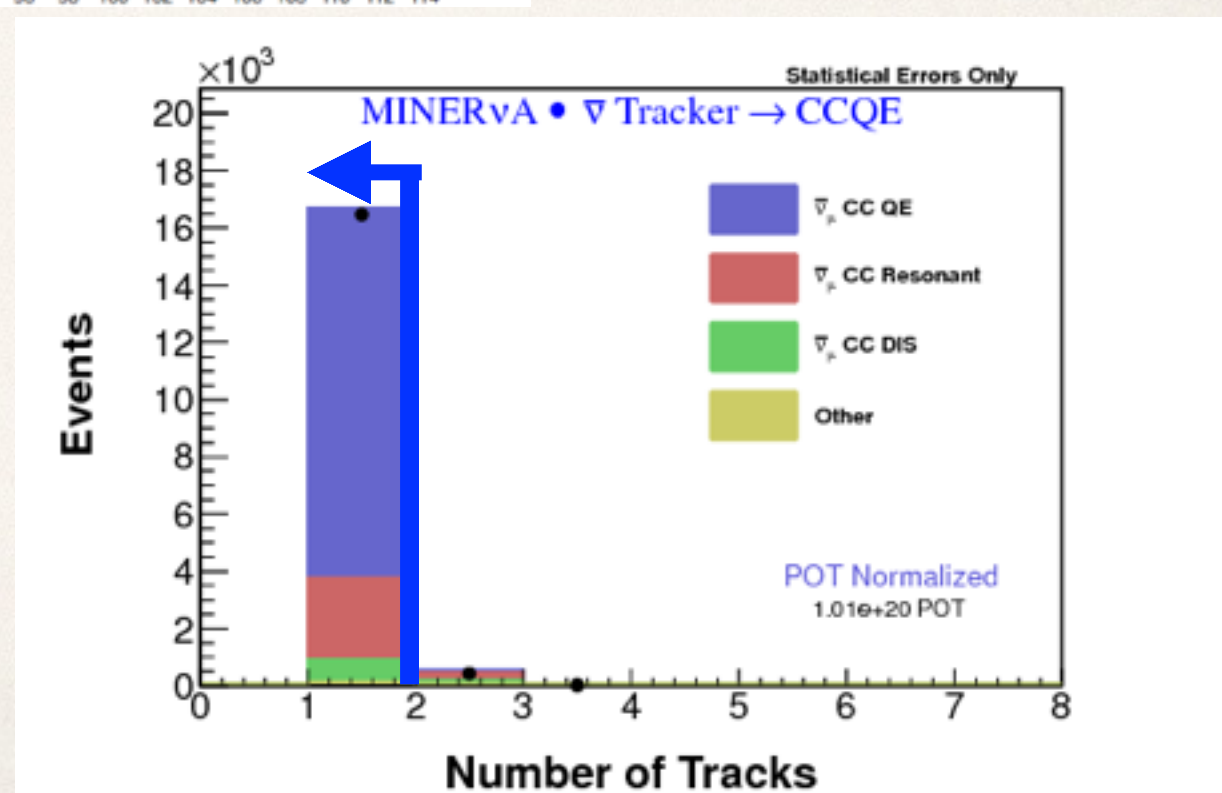

For the published analyses:
Antineutrino: 1.01 x $10^{20}$ POT
Neutrino: 9.42x $10^{19}$ POT

# Event selection: tracks: $\bar{\nu}$

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



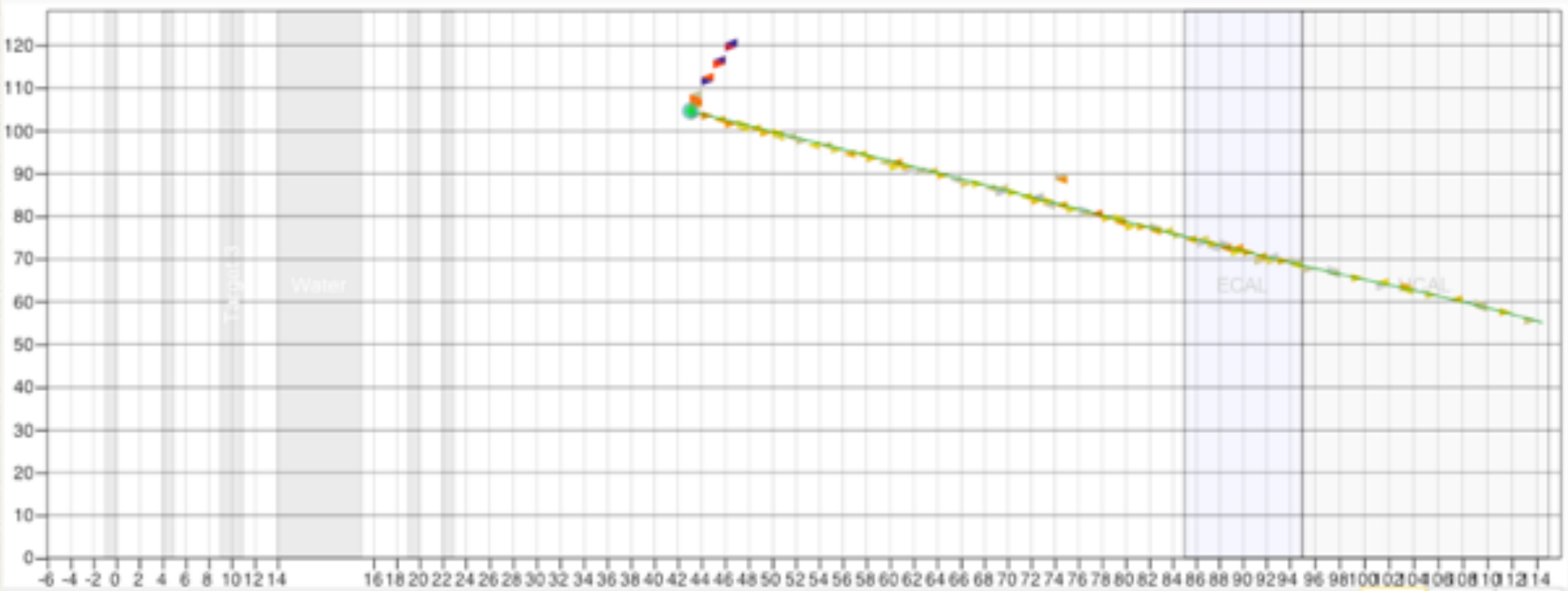

- Muon track charge matched in MINOS as a **$\mu^+$**
- **No additional tracks from the vertex**
- The ejected neutron may scatter, leaving an energy deposit, but it does not make a track from the vertex



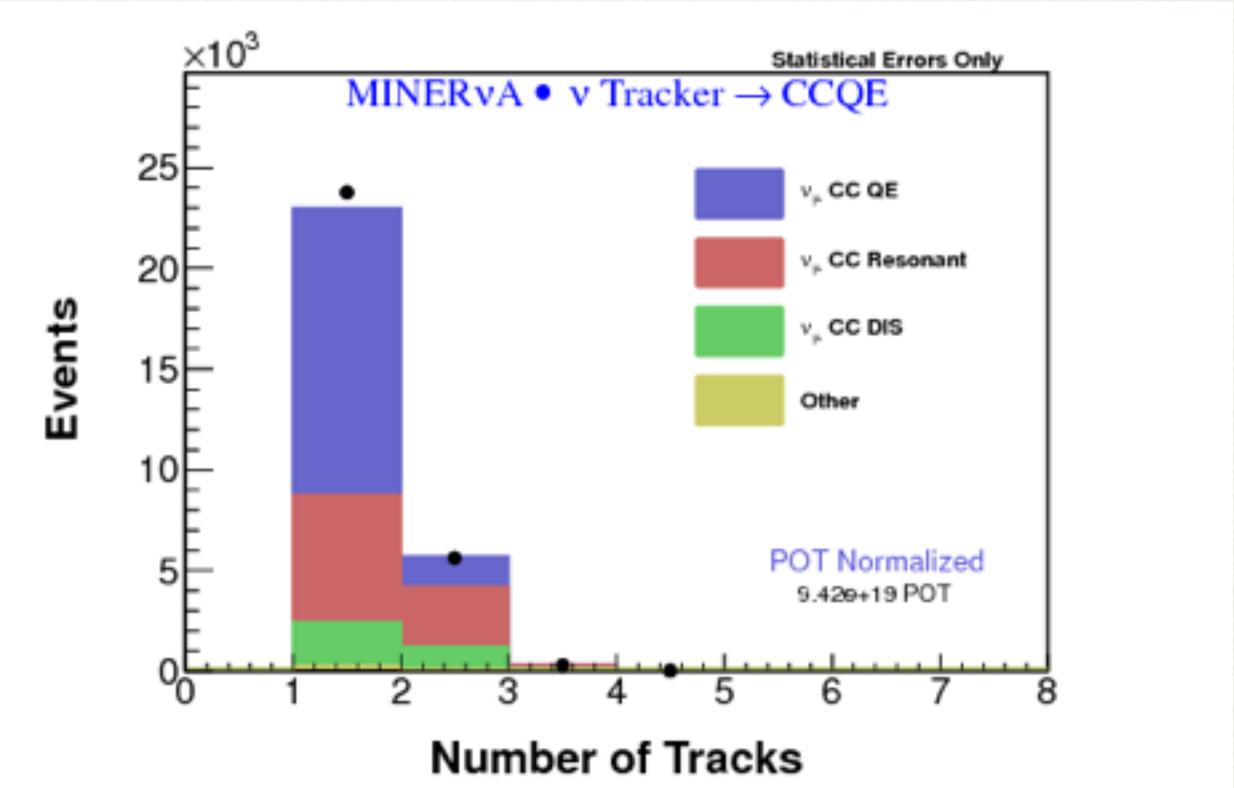
# Event selection: tracks: ν

Neutrino mode

$$\nu_\mu + n \rightarrow \mu^- + p$$

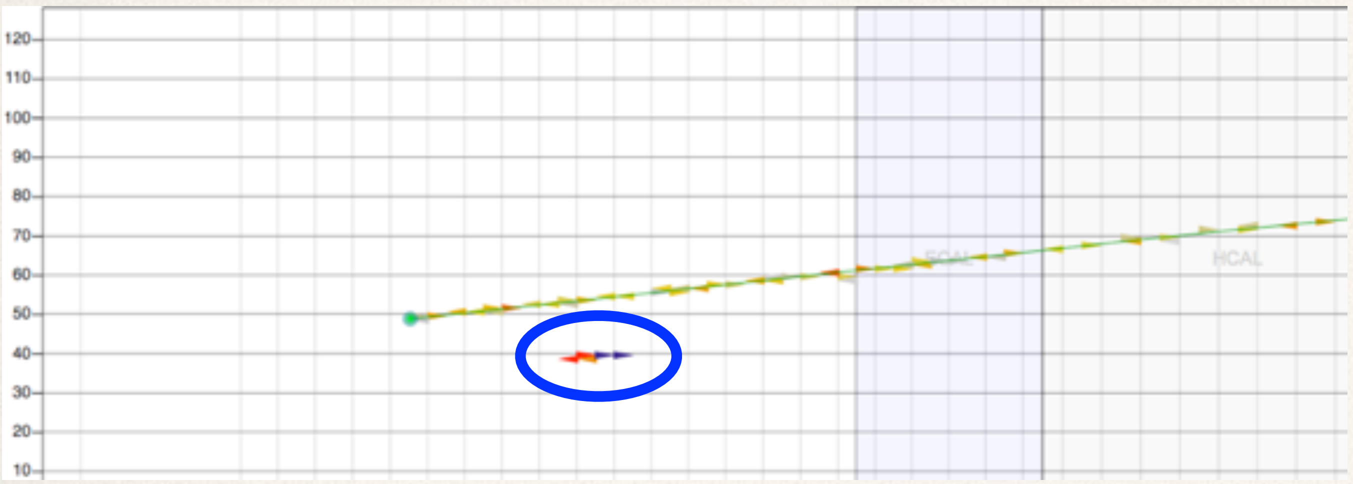


- Muon track charge matched in MINOS as a **μ**$^-$
- **No requirement** on the number of additional **tracks from the vertex**
- The ejected proton may make a track, as in the example
- An alternate study requires this proton track - see Carrie McGivern's talk

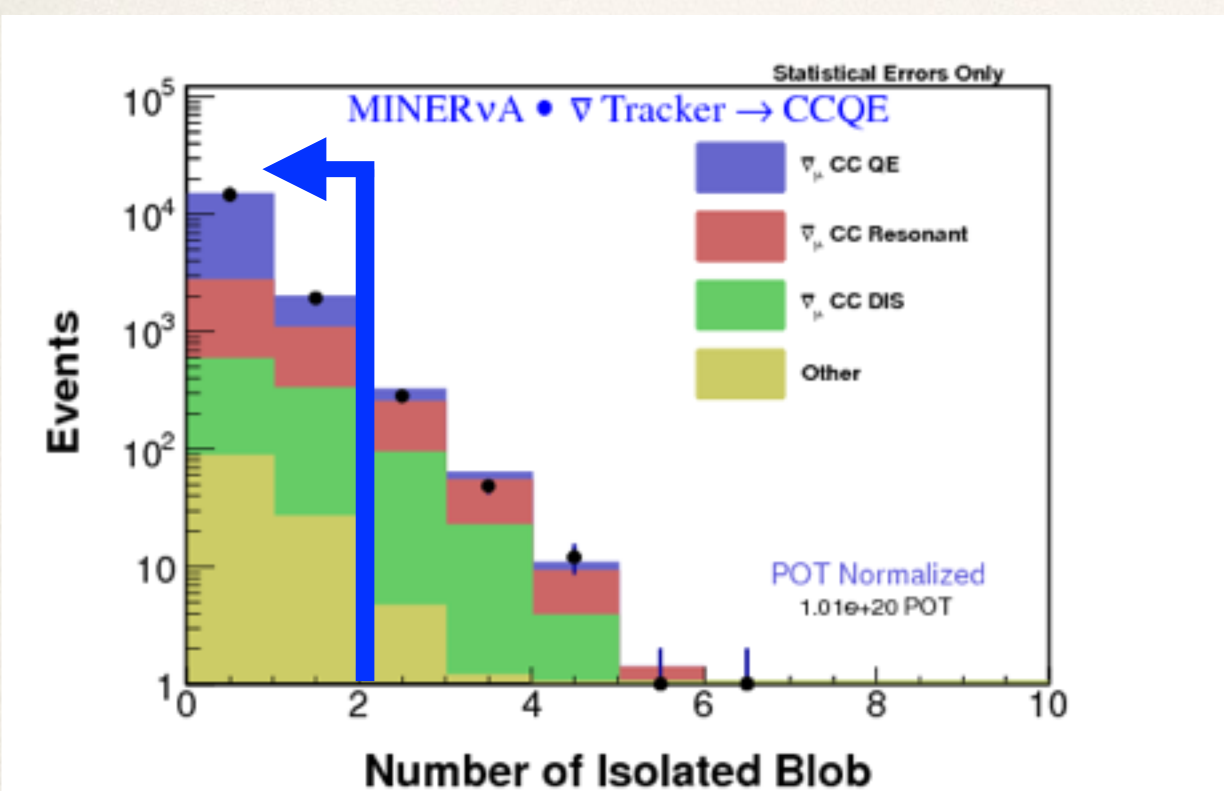


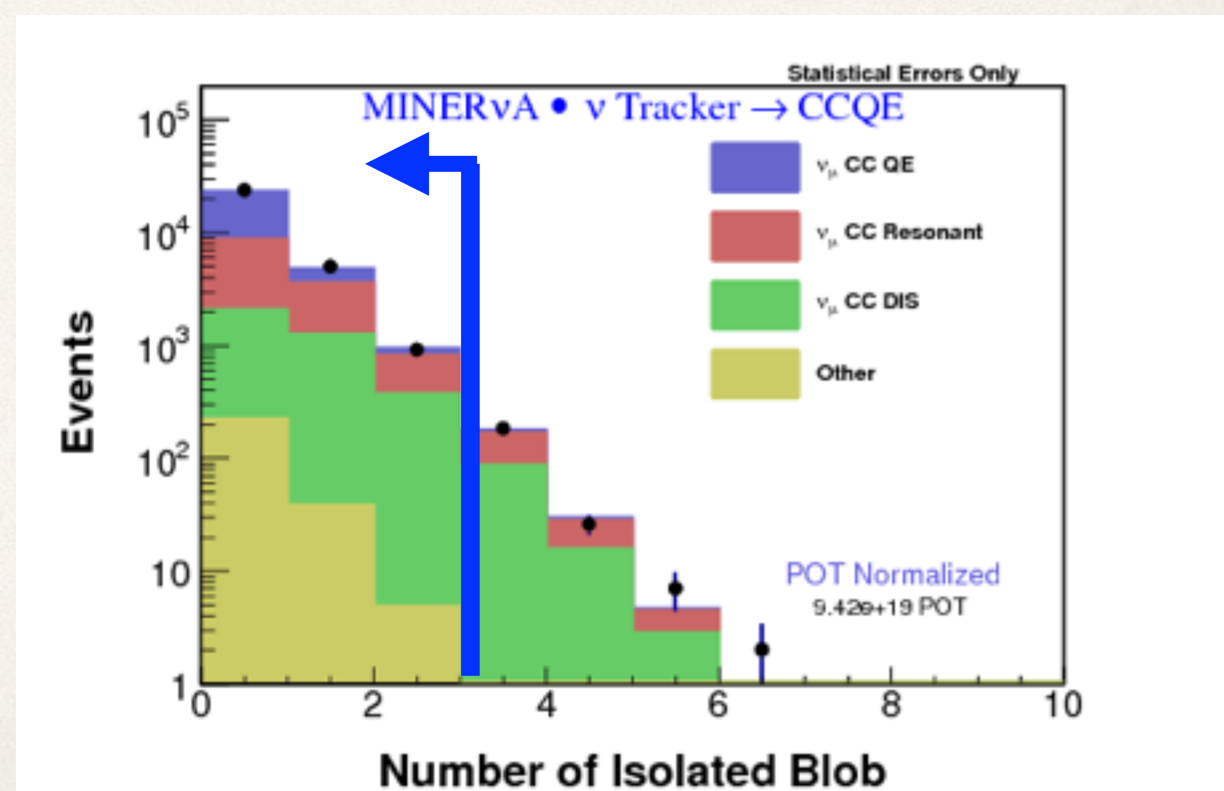
# Event selection: isolated energy

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




- Energy deposits outside of the muon track, excluding cross-talk
- Neutron scattering may deposit energy
- Frequently, only the muon track is visible; no isolated deposits
- This cut makes little difference at low $Q^2$, but greatly improves purity at high $Q^2$

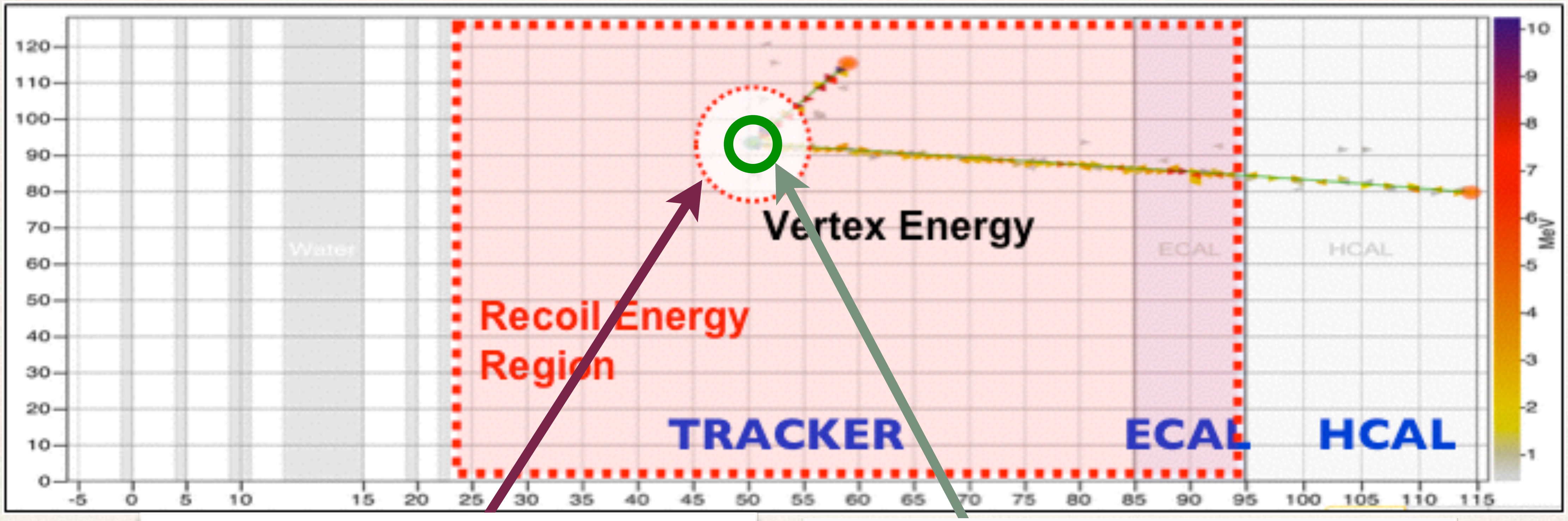



✤ Antineutrino - maximum **1** isolated

✤ Neutrino - maximum **2** isolated deposits

# Event selection: recoil energy

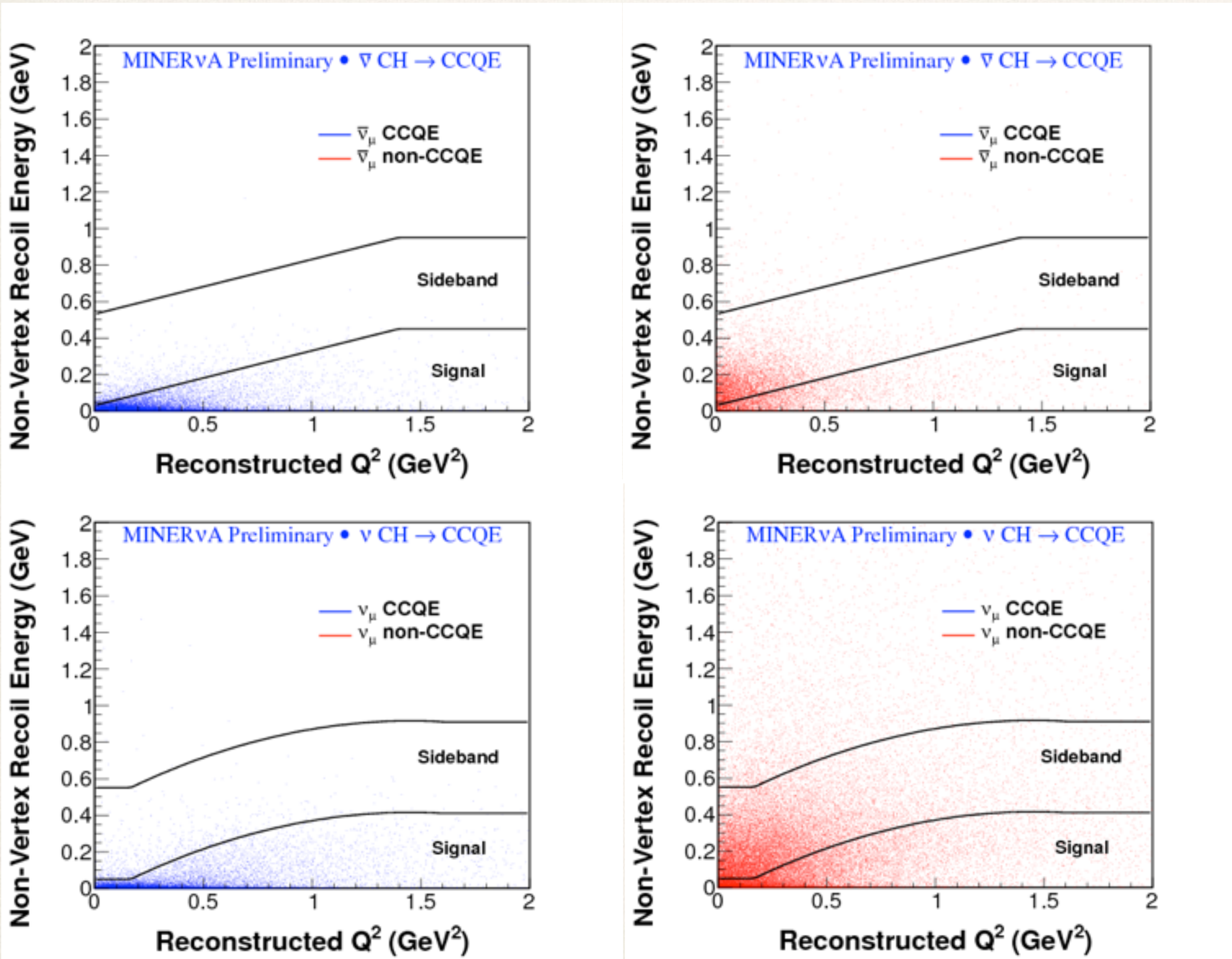



Exclude vertex region:
30 g/cm$^2$ for neutrino mode
Contains < 225 MeV protons

Antineutrino mode
exclude 10 g/cm$^2$
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

# Event selection: recoil




$\bar{\nu}$

$\nu$

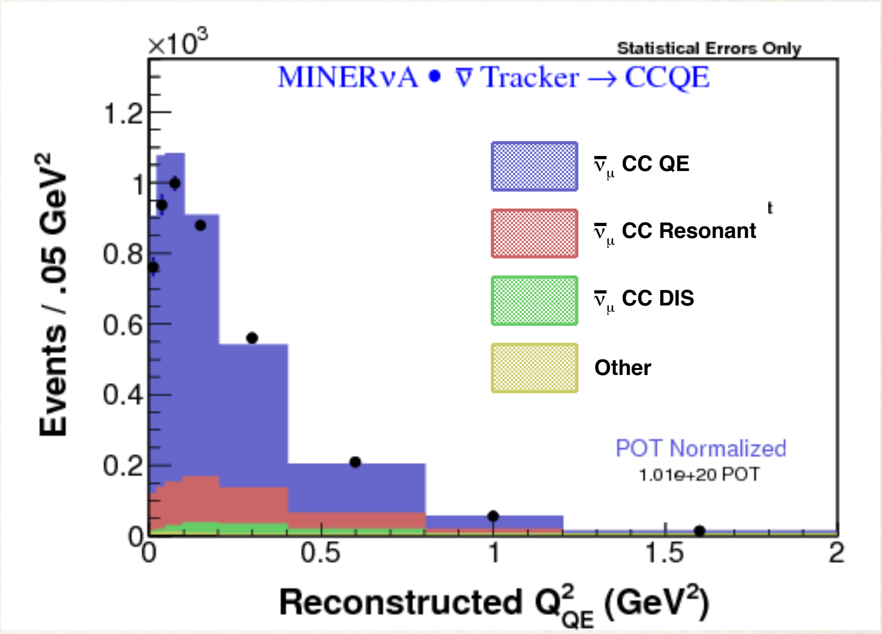
QE Not QE

# Summary of cuts

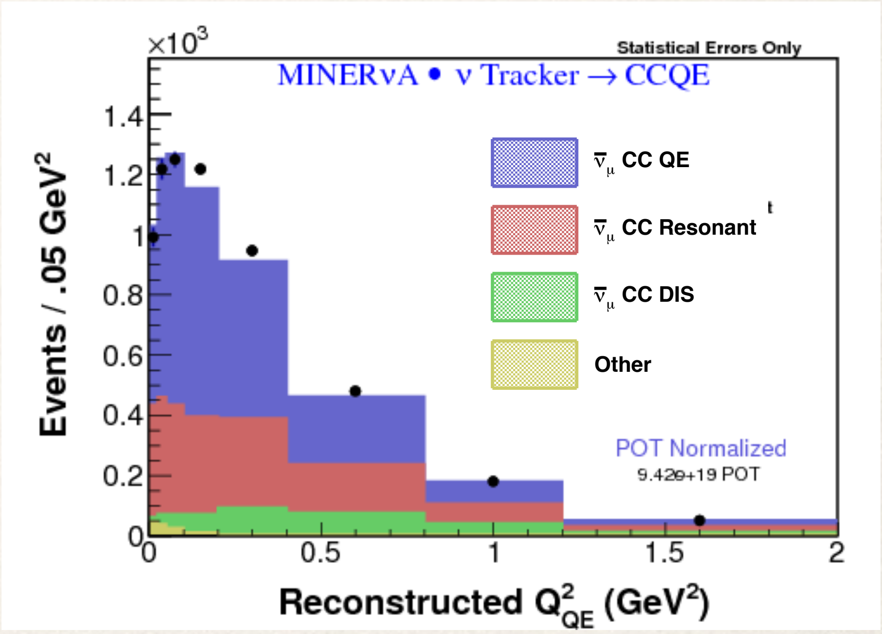
- The muon must be matched to a MINOS track
  - $\mu^-$ for neutrino mode; $\mu^+$ for antineutrino mode
- The event vertex must be within the fiducial volume
  - within the central 110 planes of the scintillator tracking region
  - no closer than 22cm to any edge of the planes
- There must be no tracks apart from the muon (antineutrino mode)
- We limit the number of isolated energy showers
  - maximum 2 (neutrino) or 1 (antineutrino)
- We make the $Q^2$-dependent recoil energy cut
- We cut on reconstructed neutrino energy: $1.5<E_\nu^{QE}<10$GeV

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

(Formula for antineutrino mode; for neutrino mode switch $m_p$ and $m_n$. $E_b$ is binding energy; this is 30 MeV for antineutrino mode, and 34 MeV for neutrino.)

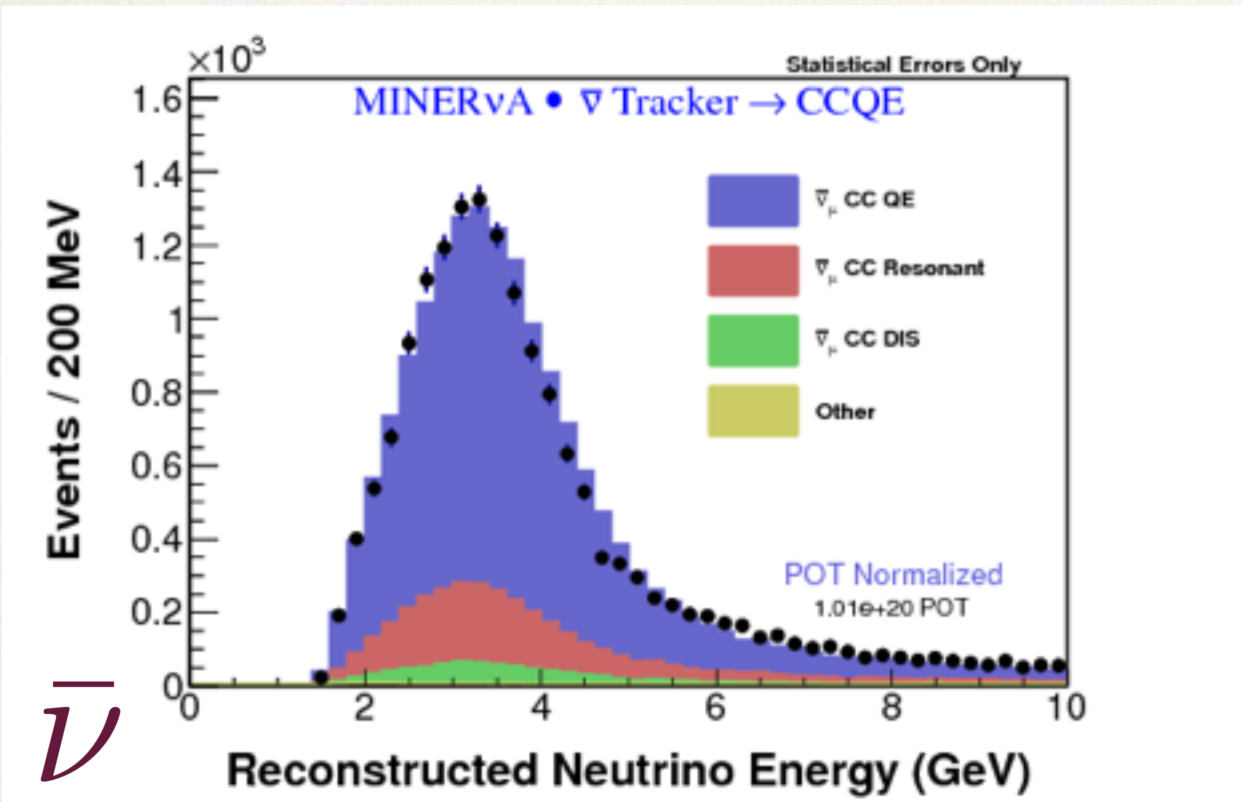


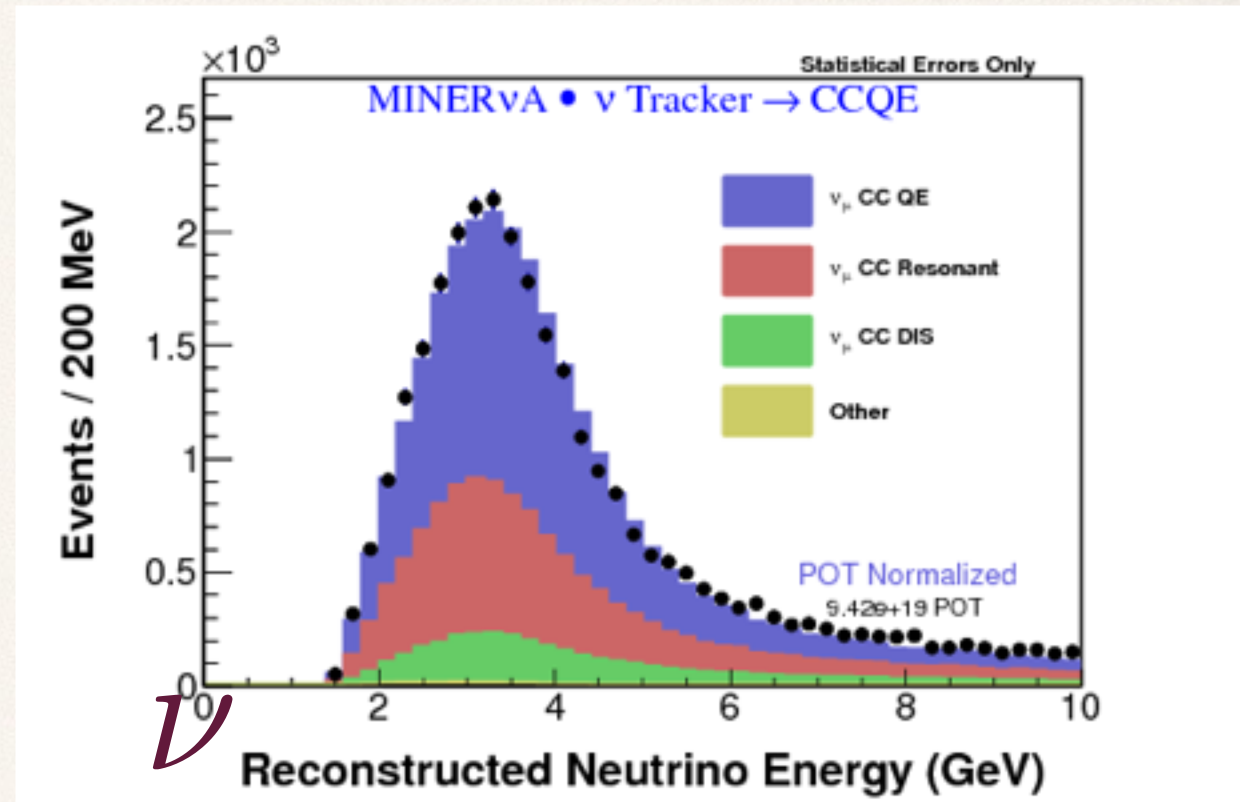

$\bar{\nu}$: 54% efficiency, 77% purity




$\nu$: 47% efficiency, 49% purity

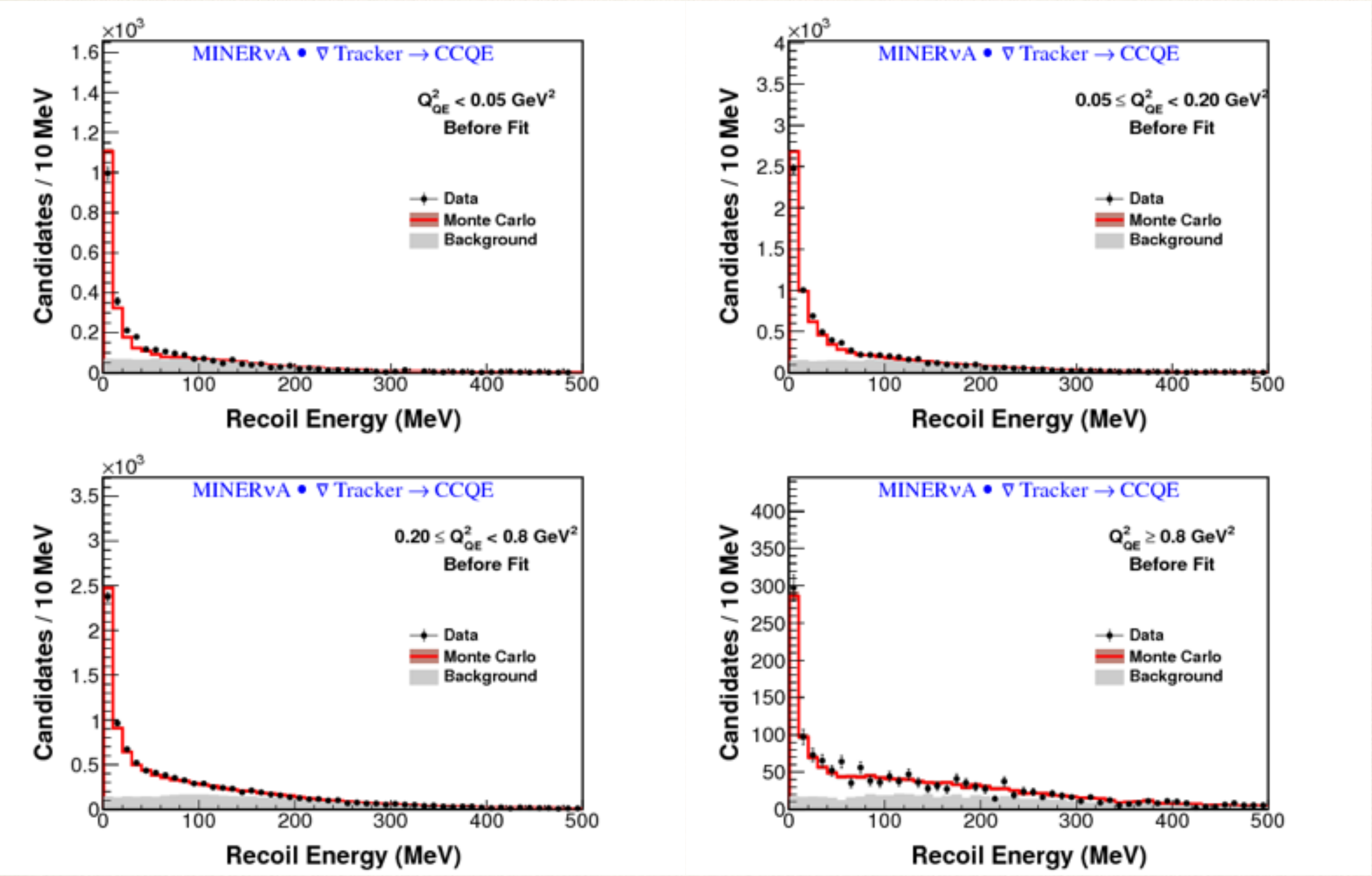
# Background subtraction




- 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

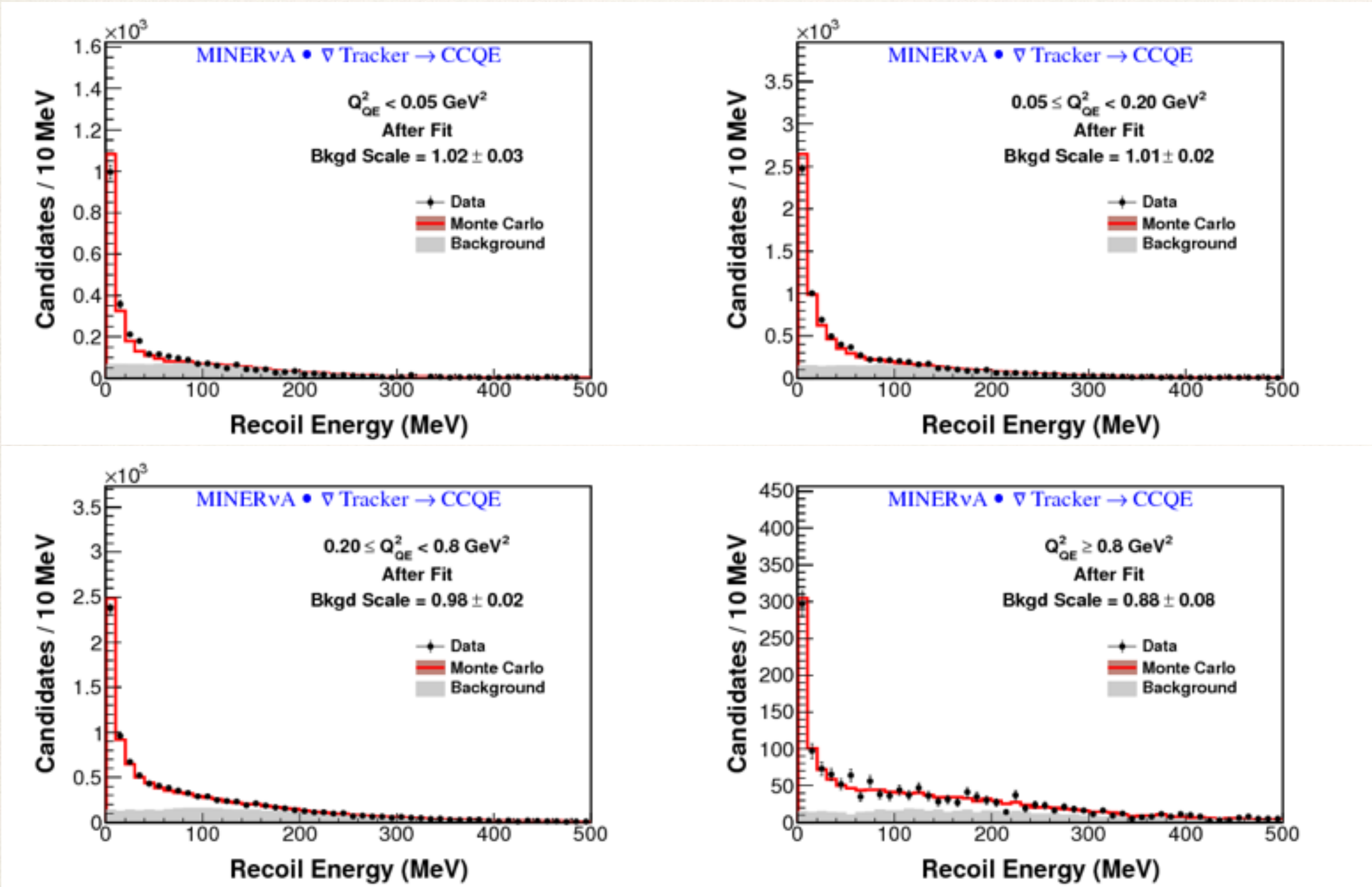
# Background subtraction: before




These plots show data for **antineutrinos, before** the background fit

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 $Q^2$ bins

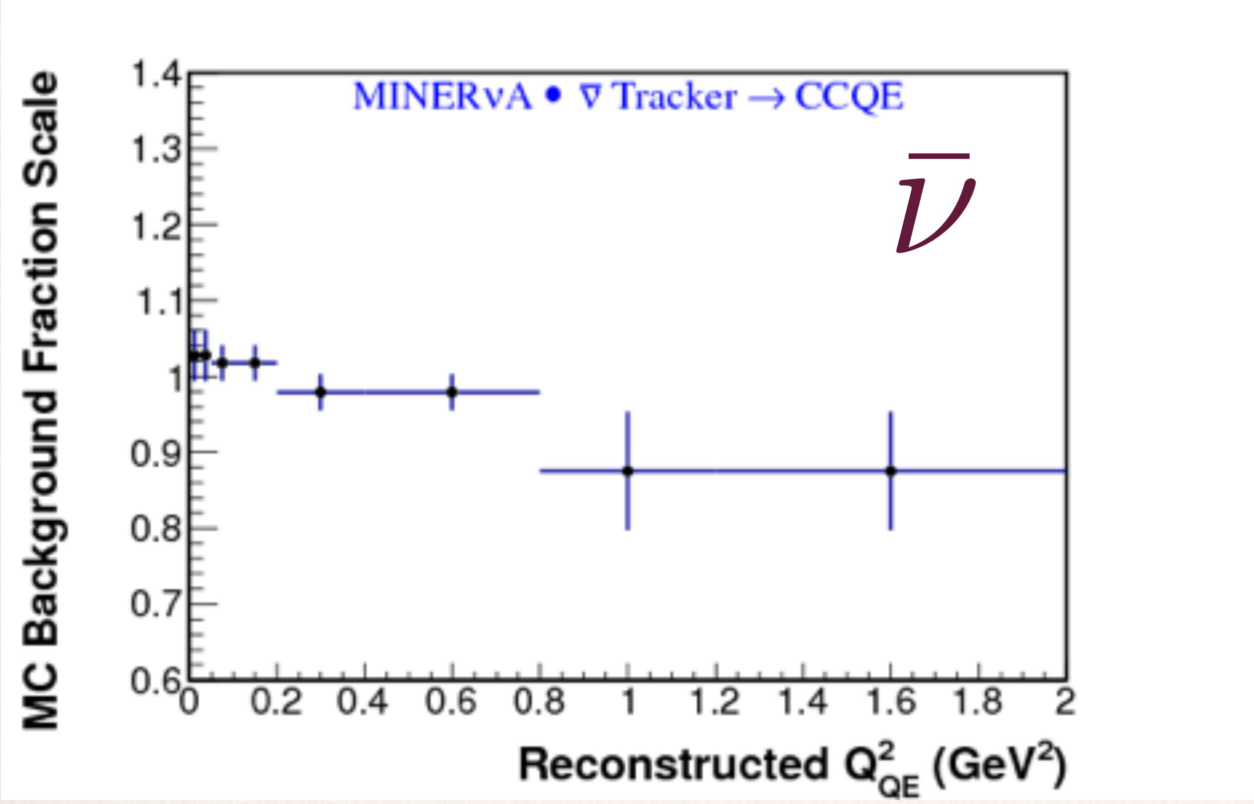
# Background subtraction: after

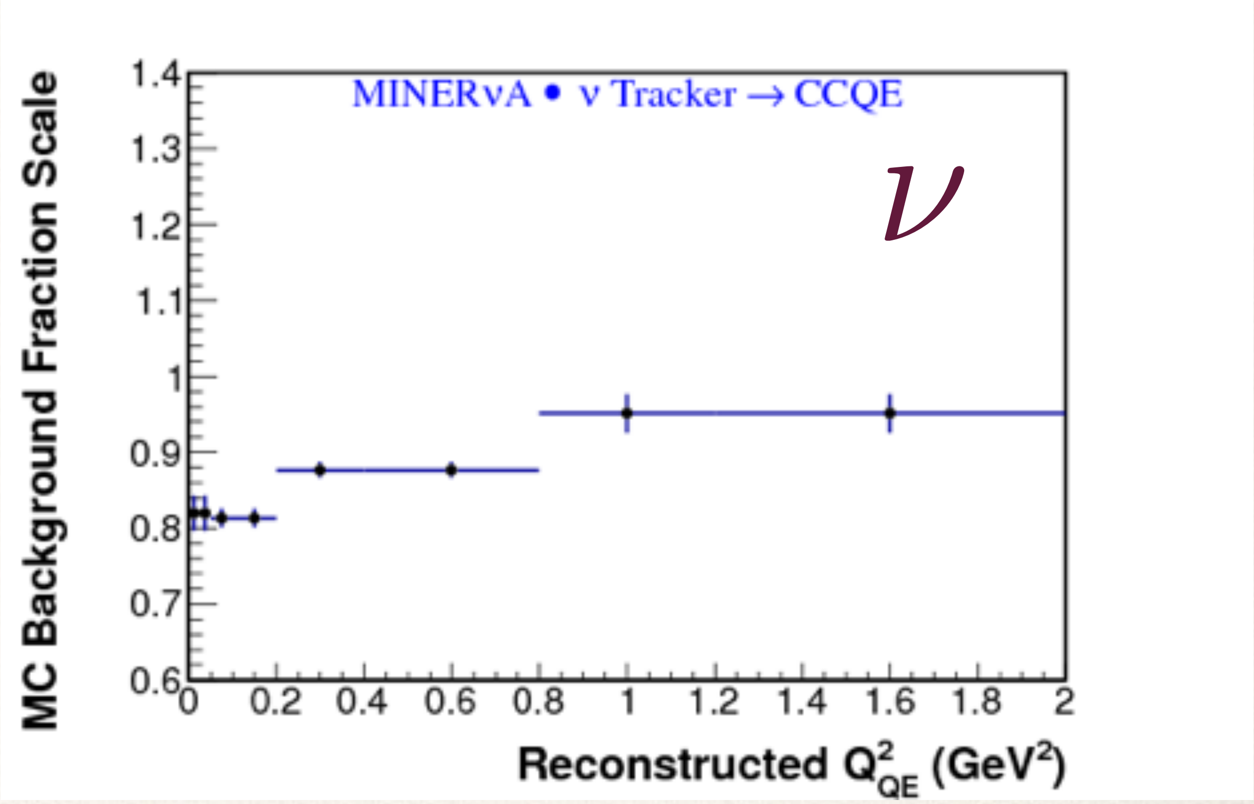



These plots show data for **antineutrinos, after** the background fit

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 $Q^2$ bins

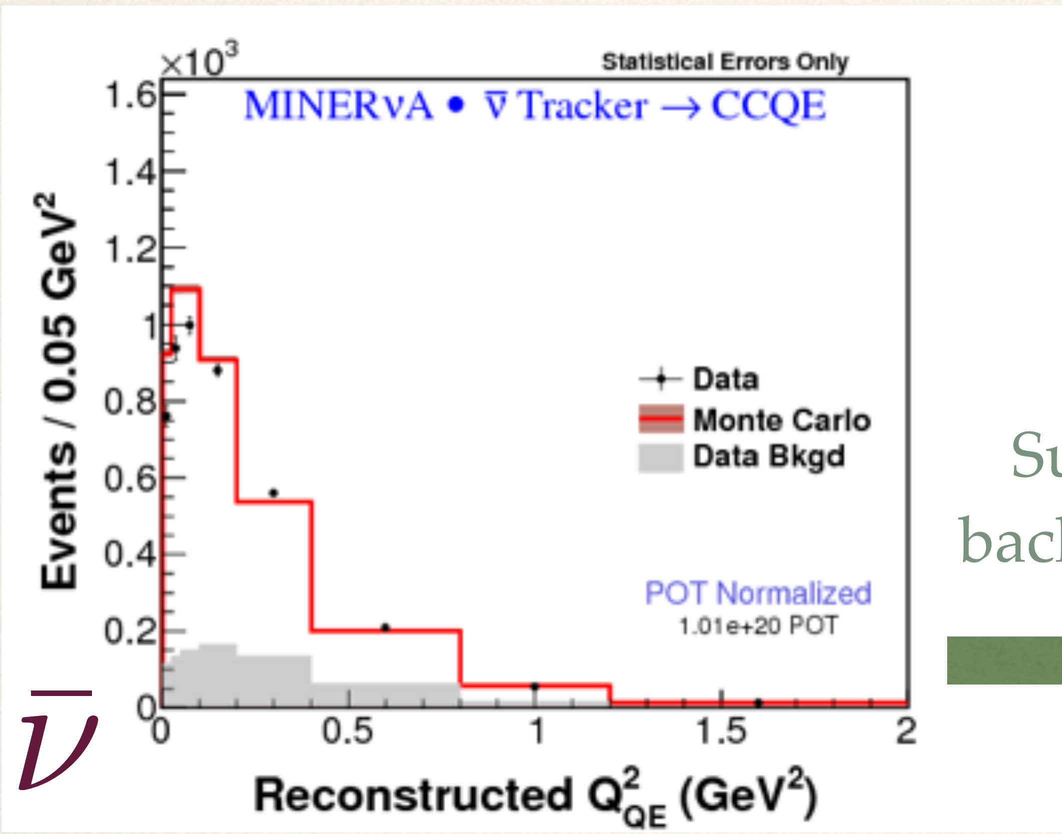
# Background scales



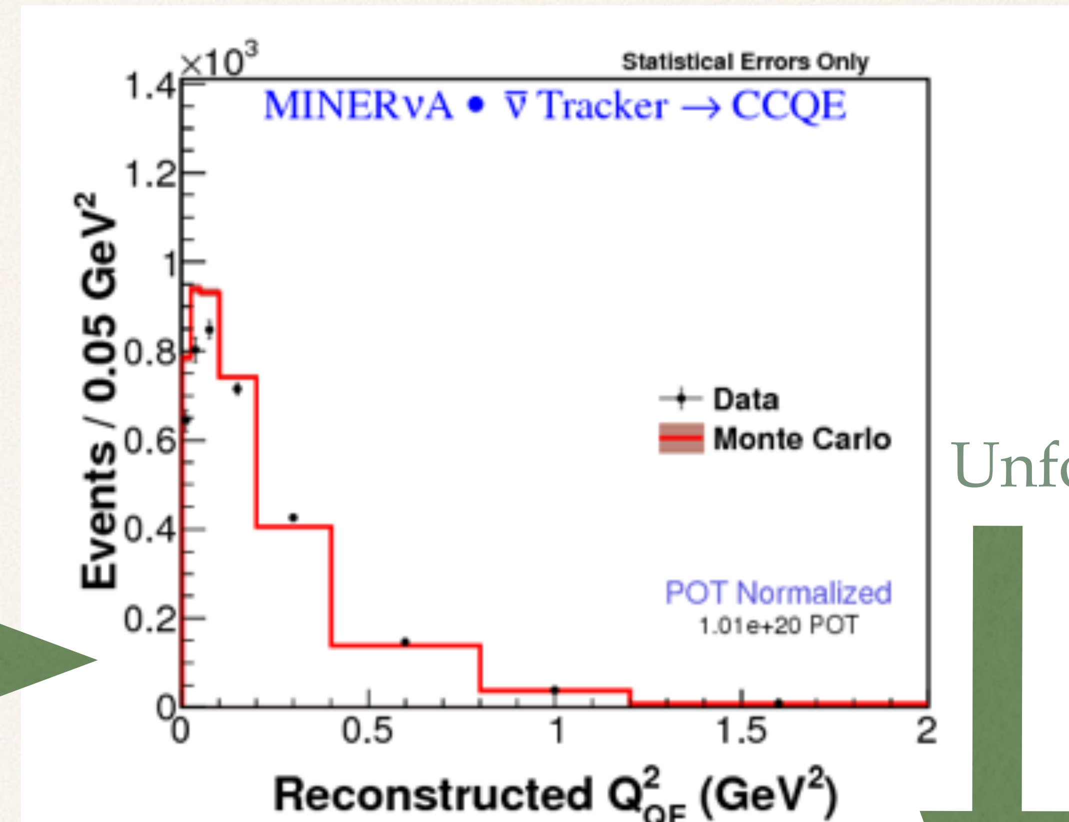




The background scales are shown for both antineutrinos and neutrinos

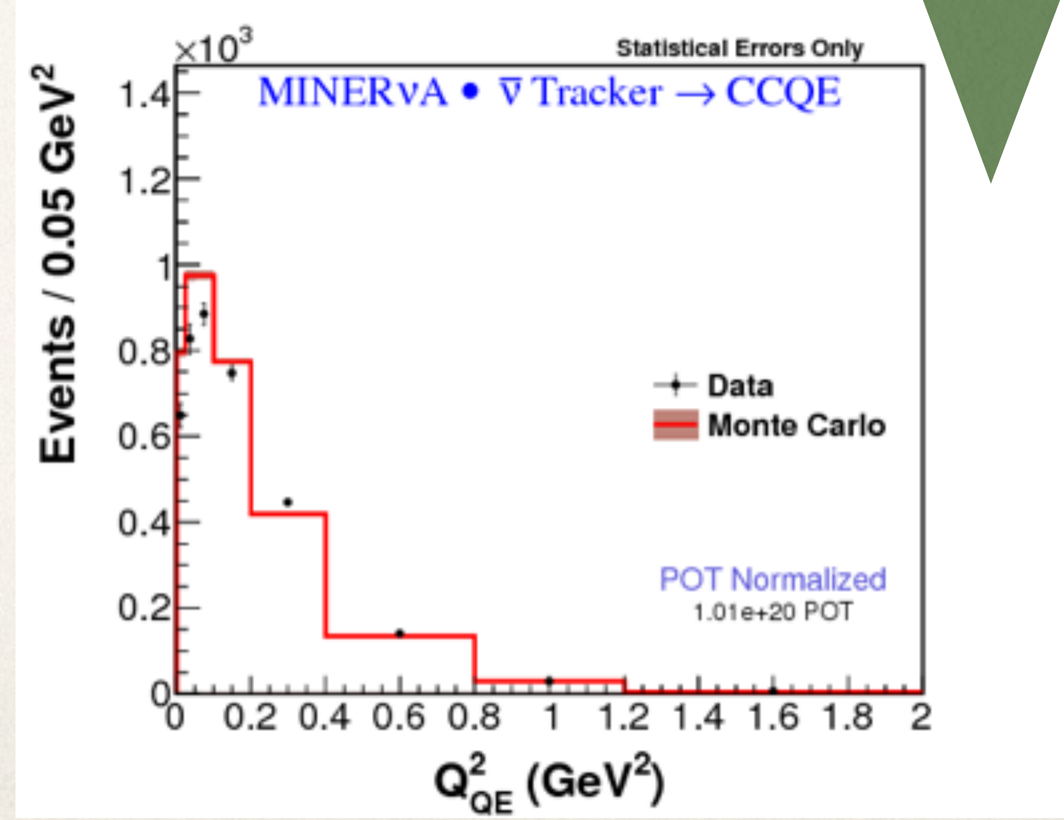
# Unfolding




Subtract background

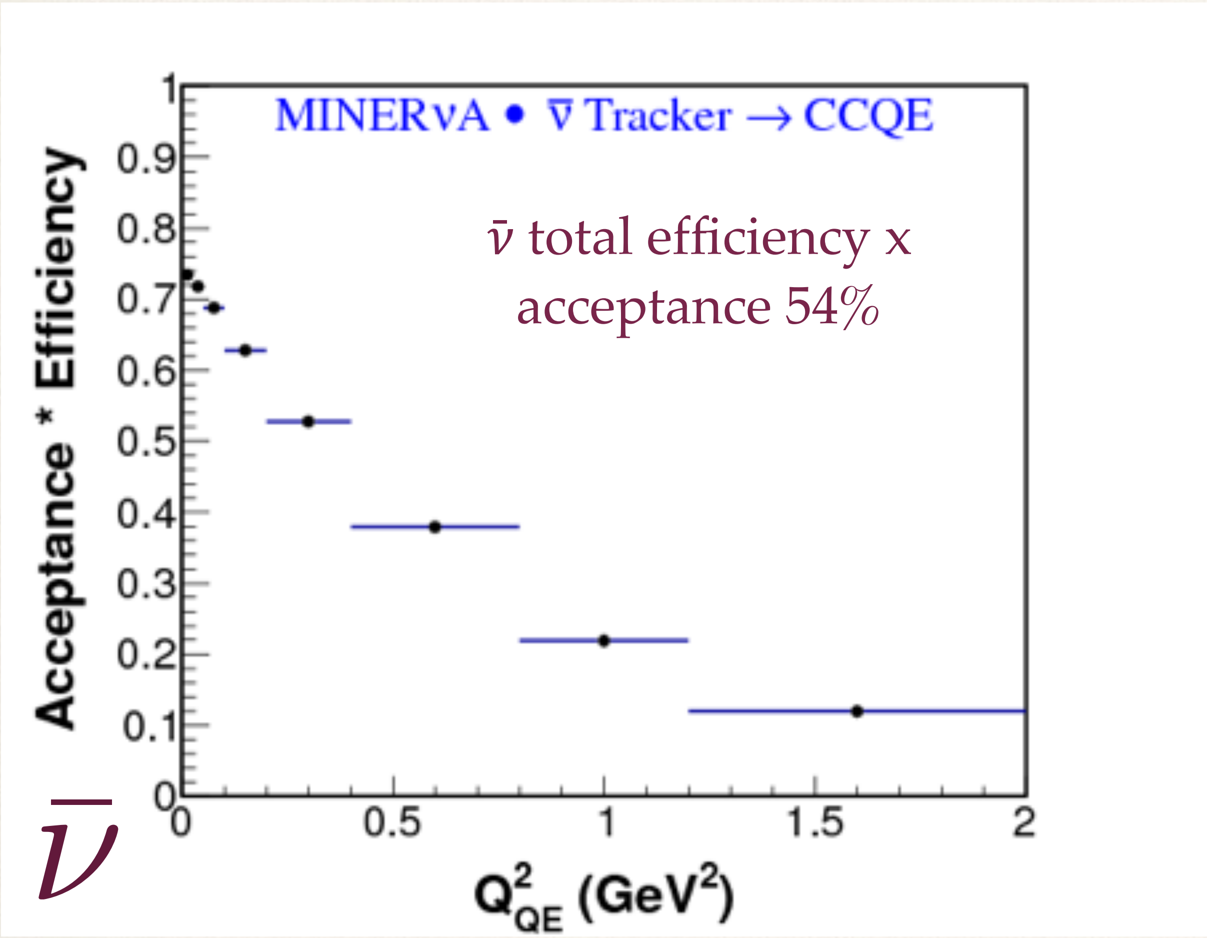


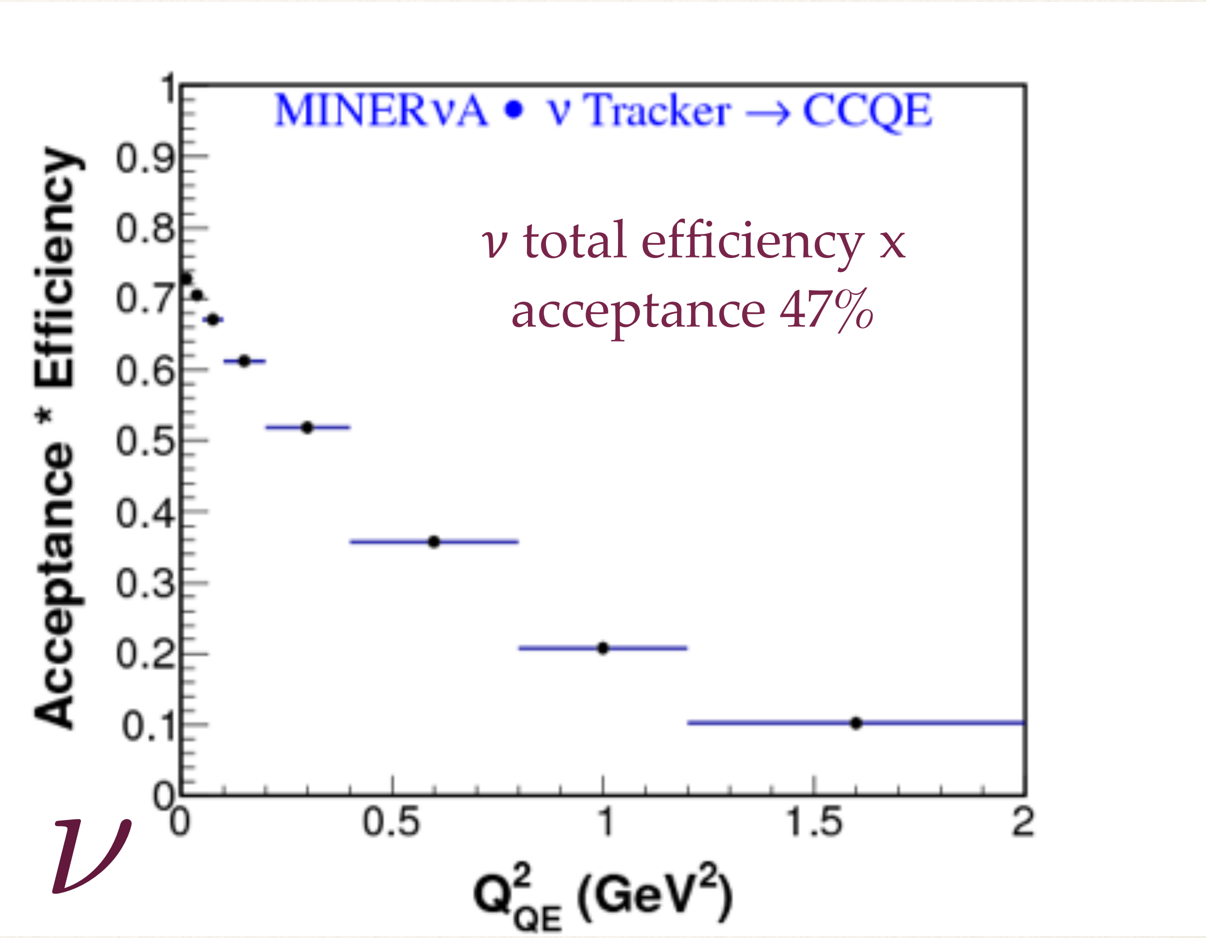

Unfold




- We use four iterations of a Bayesian unfolding method
- The unfolding maps reconstructed $Q^2_{QE}$ to generated $Q^2_{QE}$
- Note: True $Q^2_{QE}$ refers to $Q^2$ as constructed from true muon kinematics in the CCQE hypothesis, NOT to the actual 4-momentum transfer squared

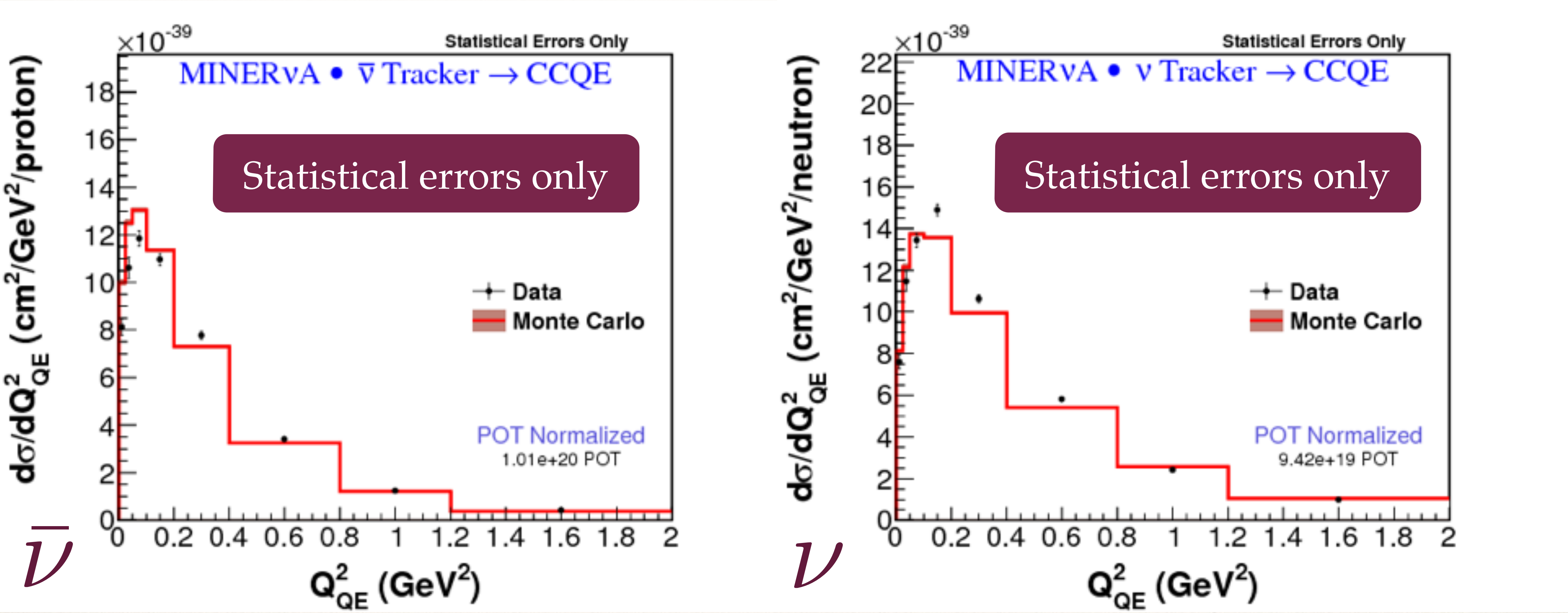
# Efficiency and acceptance




- The MINOS-match requirement limits acceptance at high muon angle
- See Carrie McGivern's talk for ways to address this

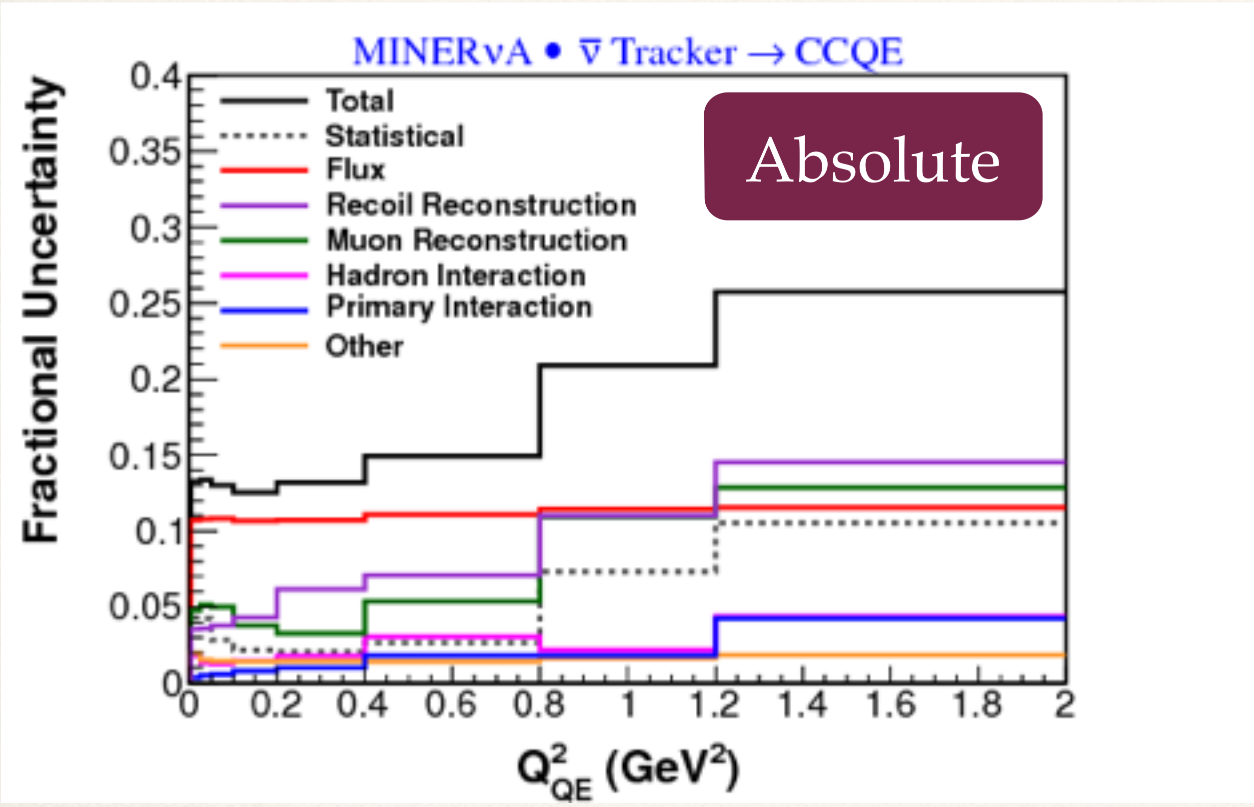
# Cross-sections




- To get a final cross-section, we normalize by number of **target nucleons**, number of **protons on target** and integrated (anti)neutrino **1.5-10 GeV flux** per proton on target

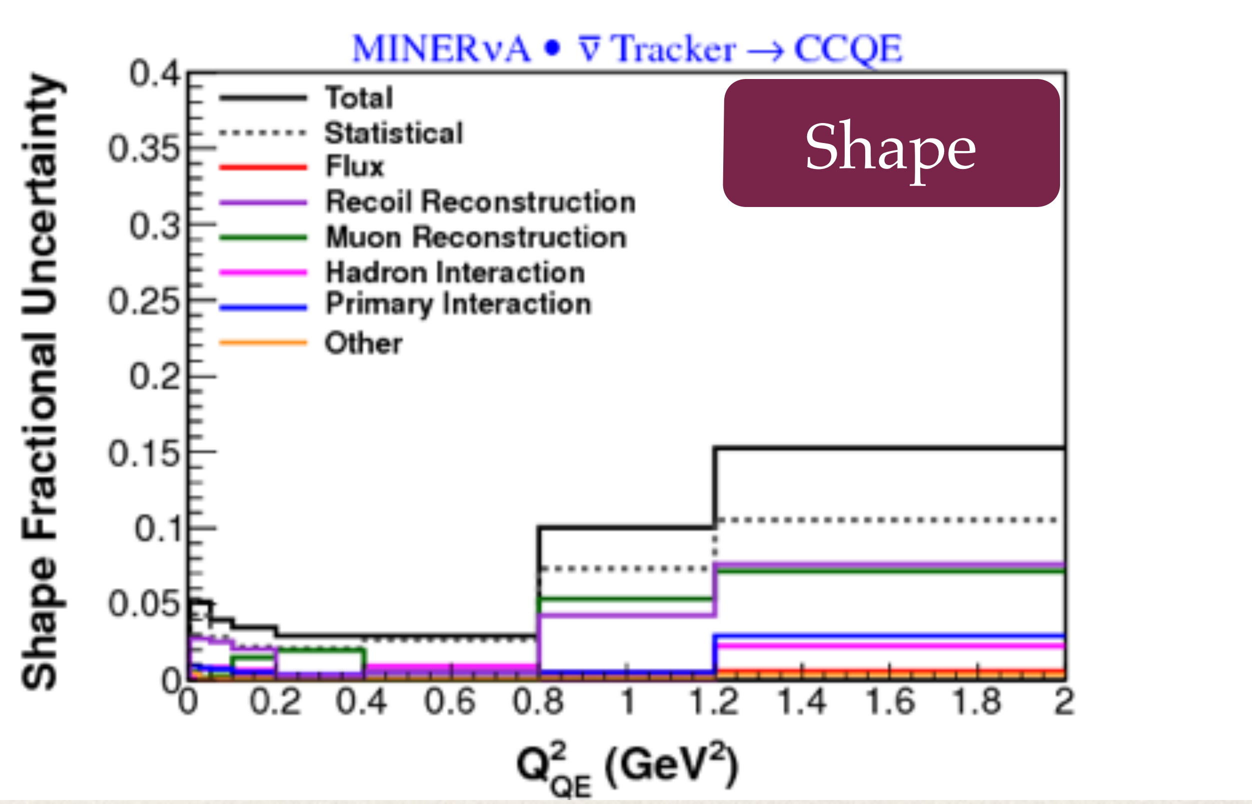
| | **Antineutrino** | **Neutrino** |
|---|---|---|
| **Protons on target** | 1.01 e20 | 9.42 e19 |
| **Integrated flux (1.5-10 GeV)** | 2.43 e-8 /cm^2/POT | 2.91 e-8 /cm^2/POT |
| **Target nucleons** | 1.91 e30 protons | 1.65 e30 neutrons |

# Systematic uncertainties ($\bar{\nu}$)

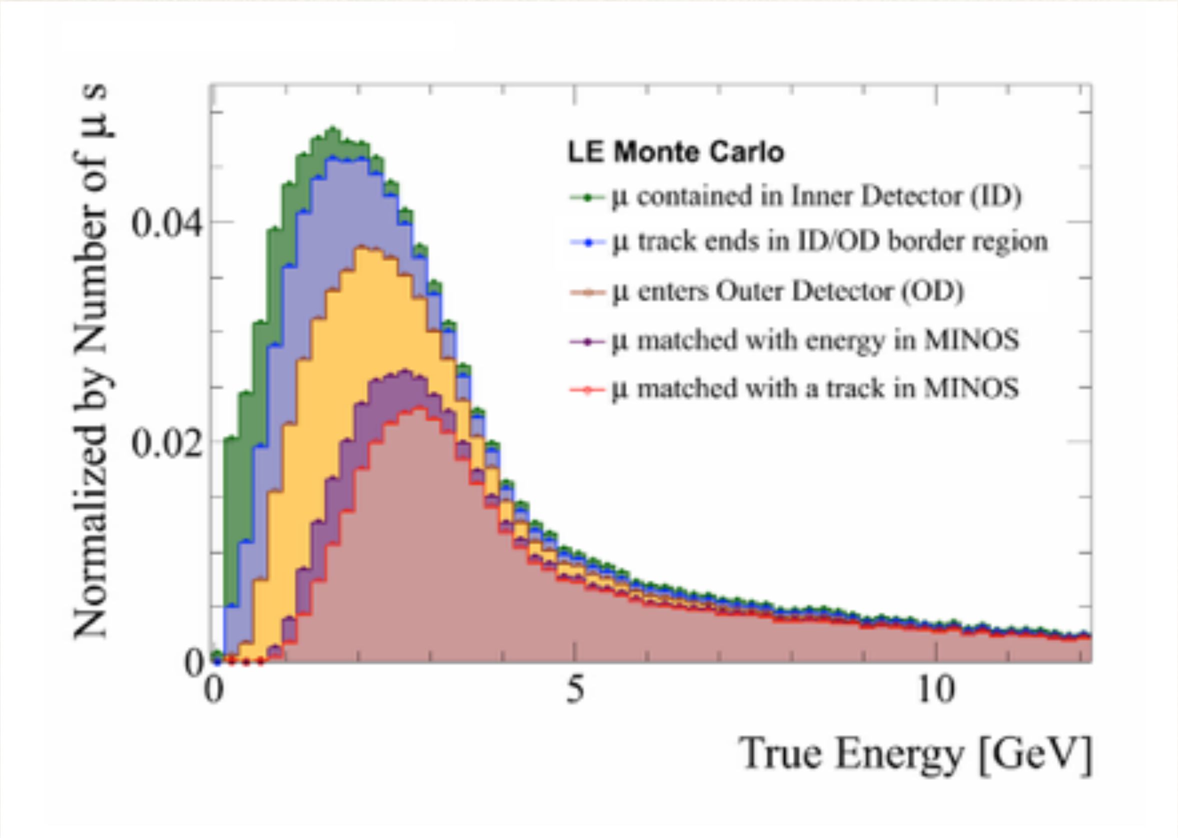


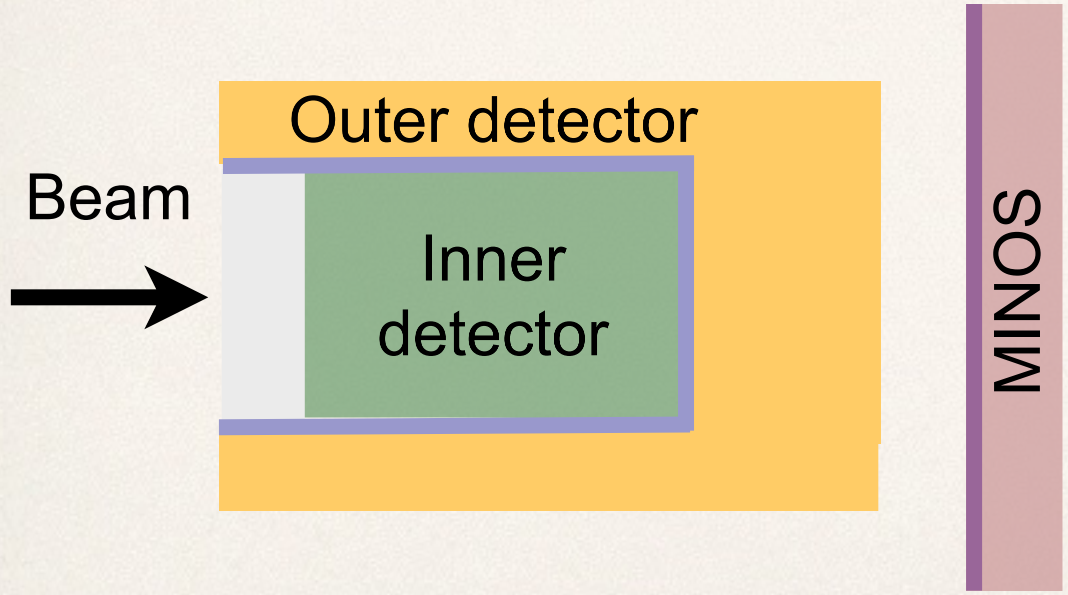

- Flux uncertainty
- Statistical uncertainty
- Hadron interaction model uncertainty
- Total uncertainty

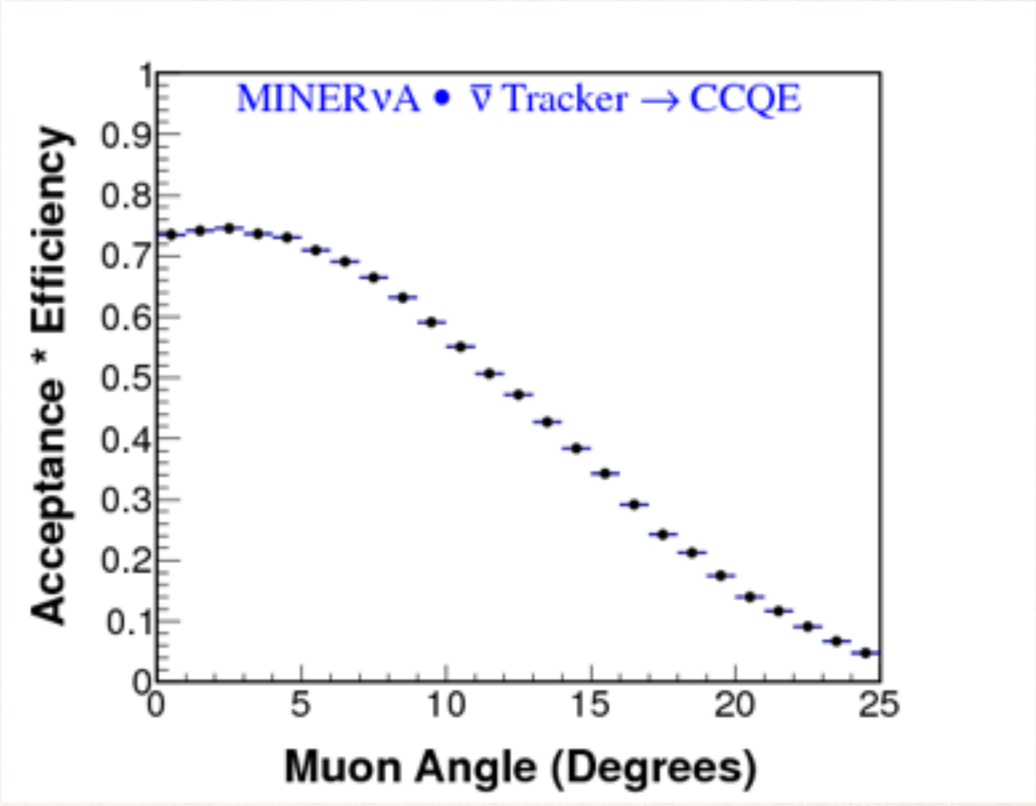
- Plot above shows absolute uncertainties
- Plot to right shows shape-only uncertainties
- **Flux** dominates the **absolute** uncertainty
- **Uncertainty in flux mostly affects normalization**, not shape
- Statistical uncertainties dominate the shape distribution, and total uncertainty is reduced

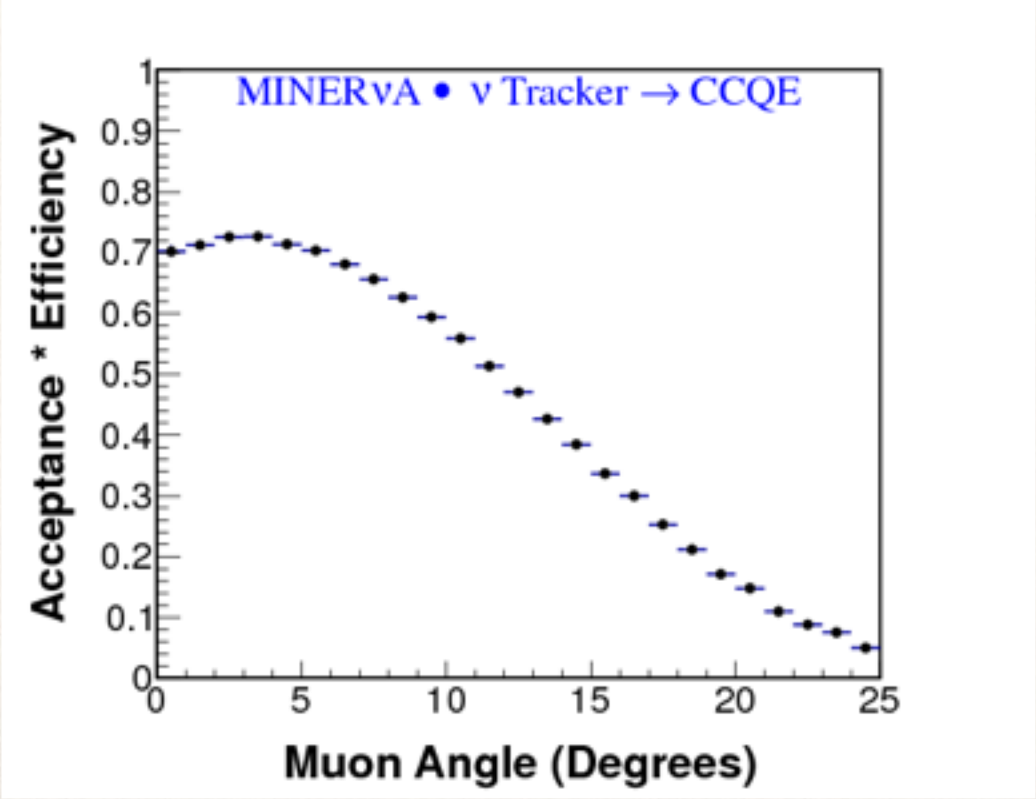


# MINOS-match requirement



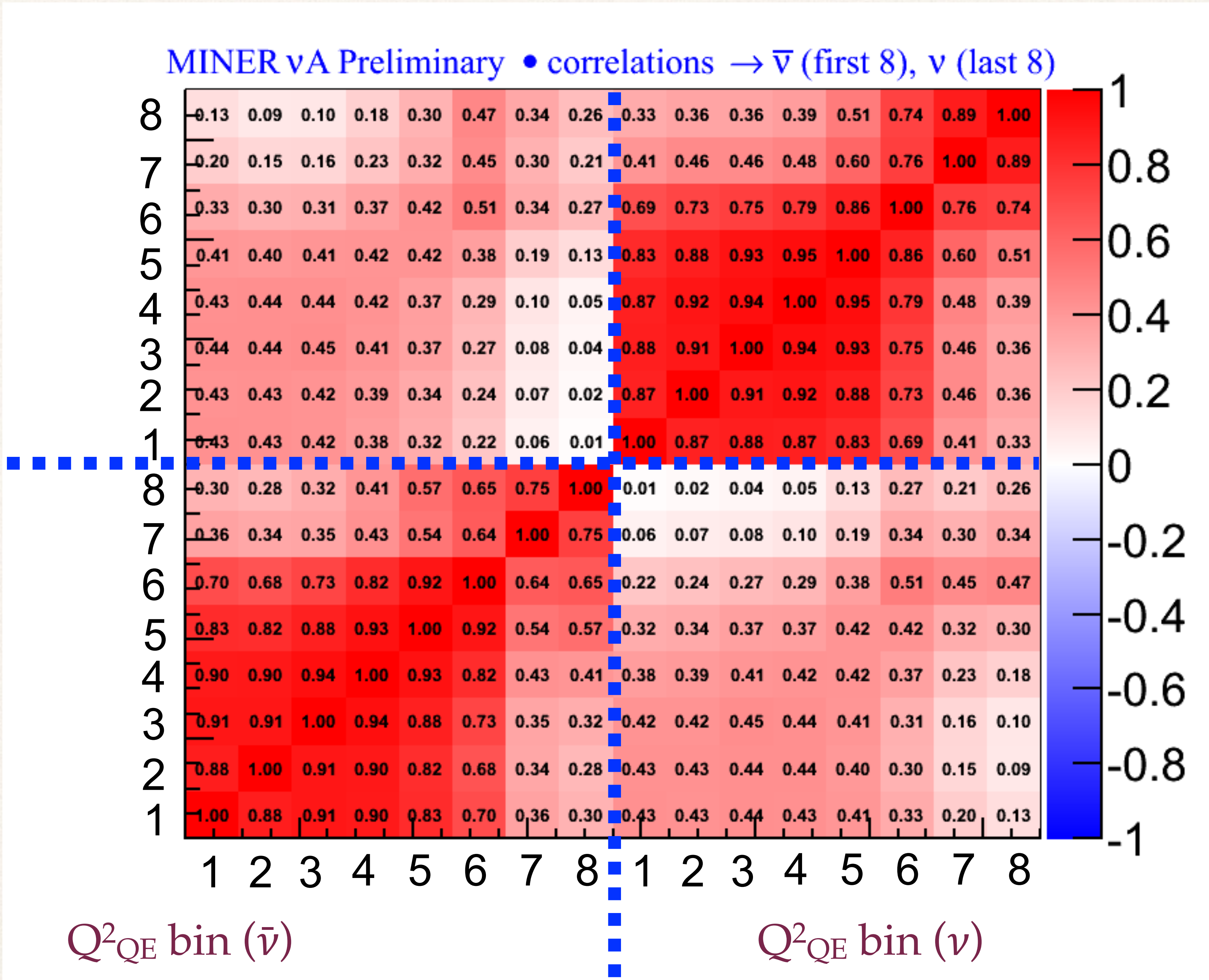




- MINOS-match requirement limits angular acceptance

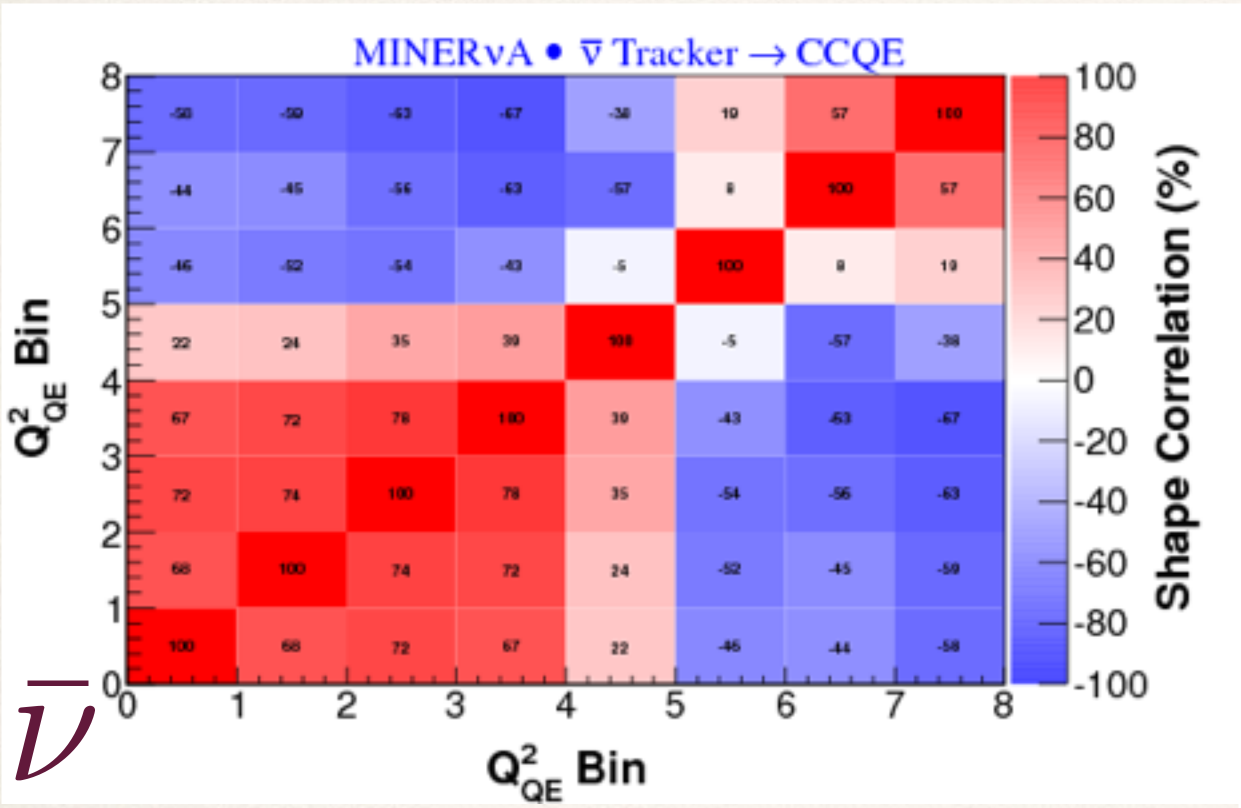
# Correlation matrix - absolute

$Q^2_{QE}$ bin ($\nu$)

$Q^2_{QE}$ bin ($\bar{\nu}$)

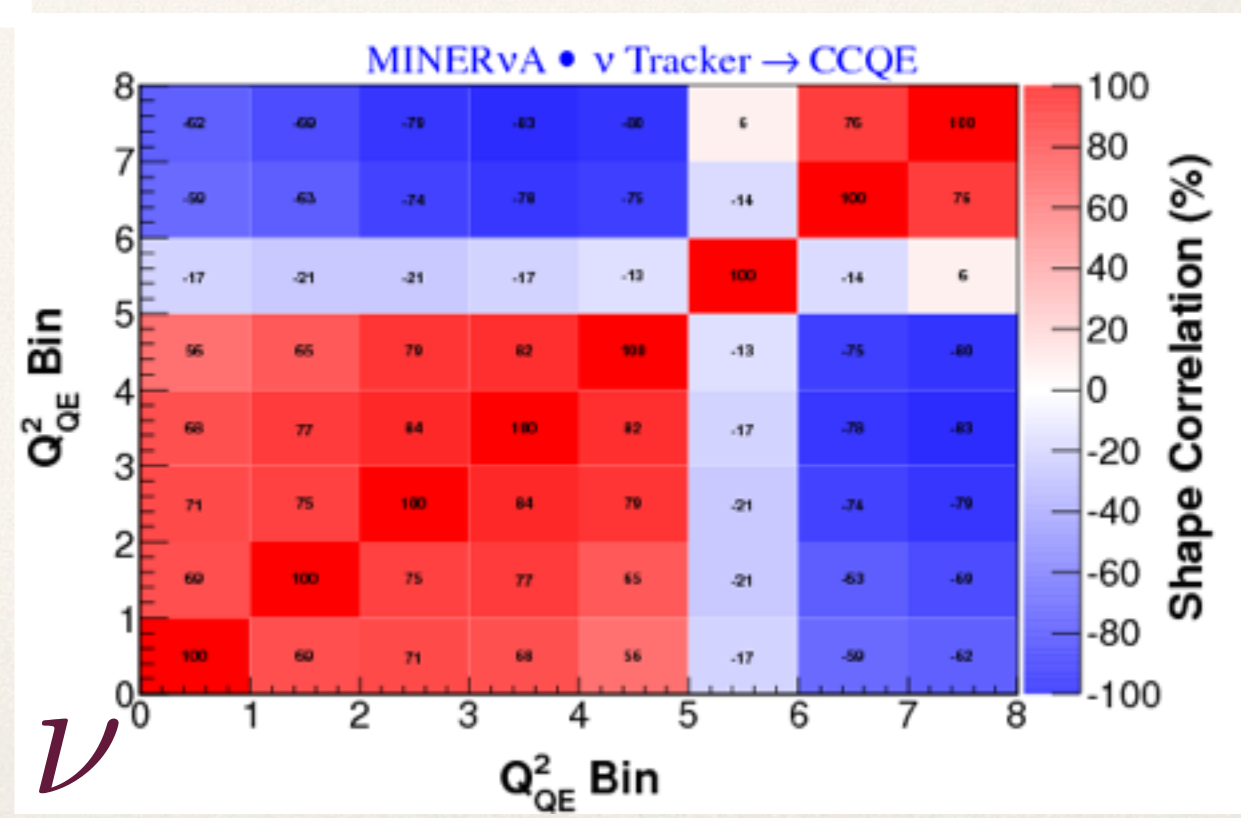


# Correlation matrices: shape-only

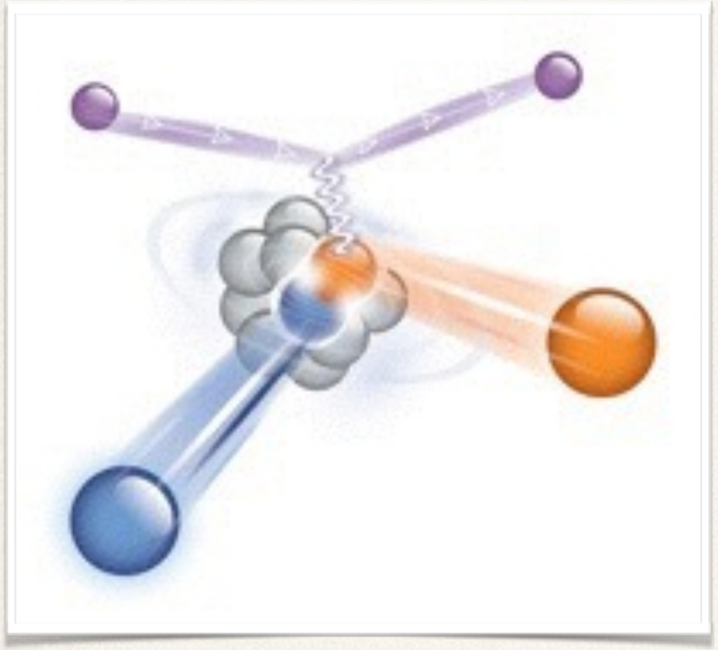



- Red indicates positive correlation
- Blue indicates negative correlation

- The strong positive and negative correlations between bins can lead to surprisingly low $\chi^2$/NDF when data is compared to models that at first glance seem poor fits
- Conversely, a model that appears to be a good fit can have a poor $\chi^2$/NDF



# Energy around the vertex



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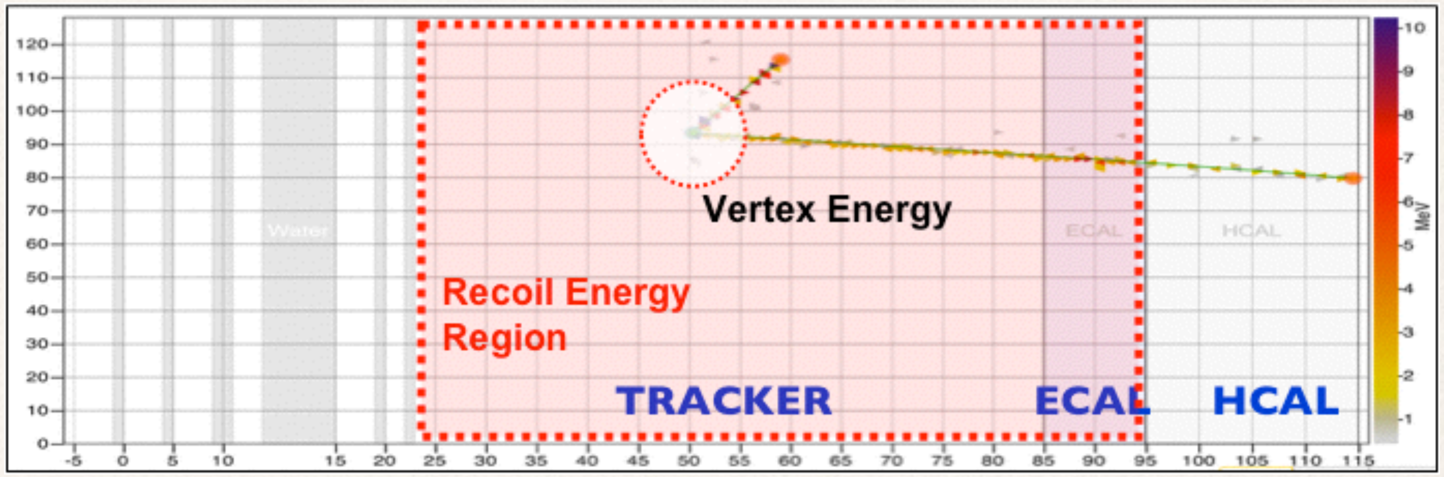
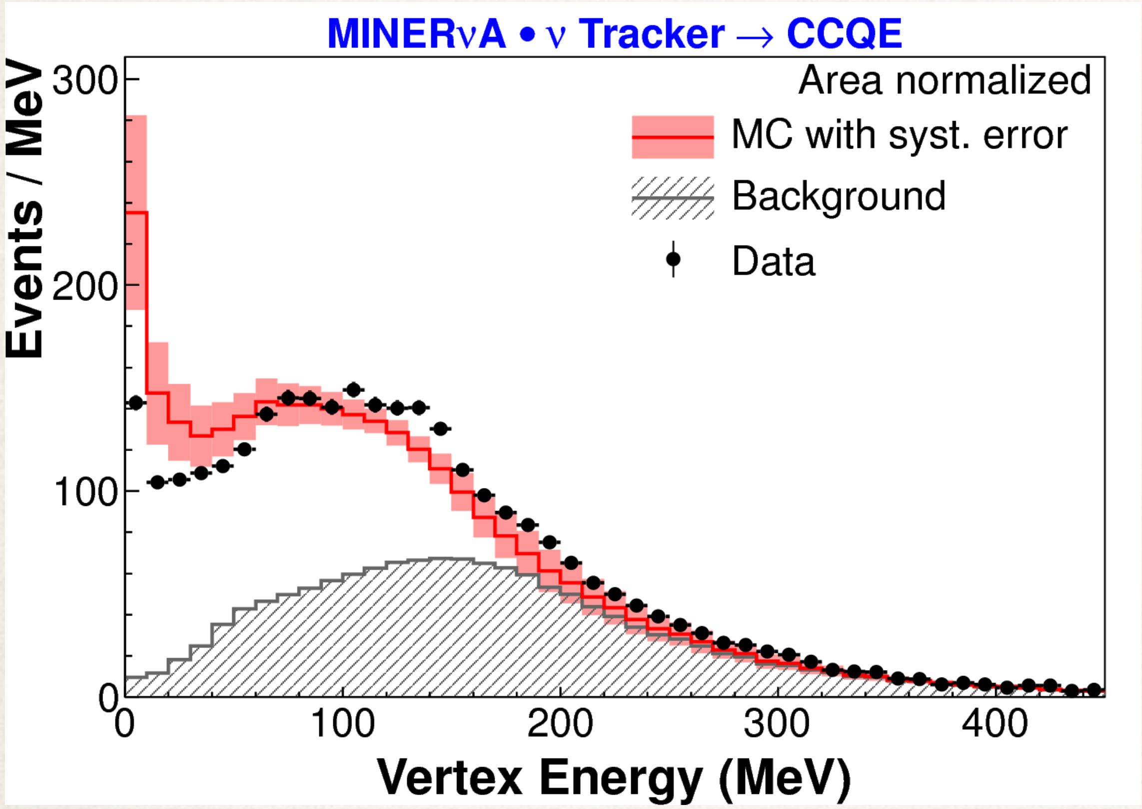
- Transverse enhancement parameterizes a model with **correlated pairs** of nucleons
- If a neutrino interacts with a paired nucleon, its partner may also be ejected




- Recall that we neglected an **area around the vertex** when we counted the total recoil energy
- We now compare the non-track energy deposited within that region to our Monte Carlo, to look for evidence of **additional nucleons**
- Our "vertex region" would contain nucleons with an energy up to 225 MeV (neutrino mode) or 120 MeV (antineutrino mode)

# Vertex energy - extra protons




- A **harder neutrino-mode energy spectrum** is seen in data than Monte Carlo
- It is not seen in antineutrino mode
- We simulated extra protons with kinetic energies up to 225 MeV to see how this would change the Monte Carlo distribution

- Modeling an **additional proton 25±9%** of the time gave the best fit to the data
- Final state protons suggests initial state **proton-neutron correlations**
- This would explain why no such effect was seen for **antineutrino mode**; we would expect **low-energy neutrons**, to which we have low sensitivity