Fermilab



# Neutrino Interactions

Minerba Betancourt

International Neutrino Summer School 2018

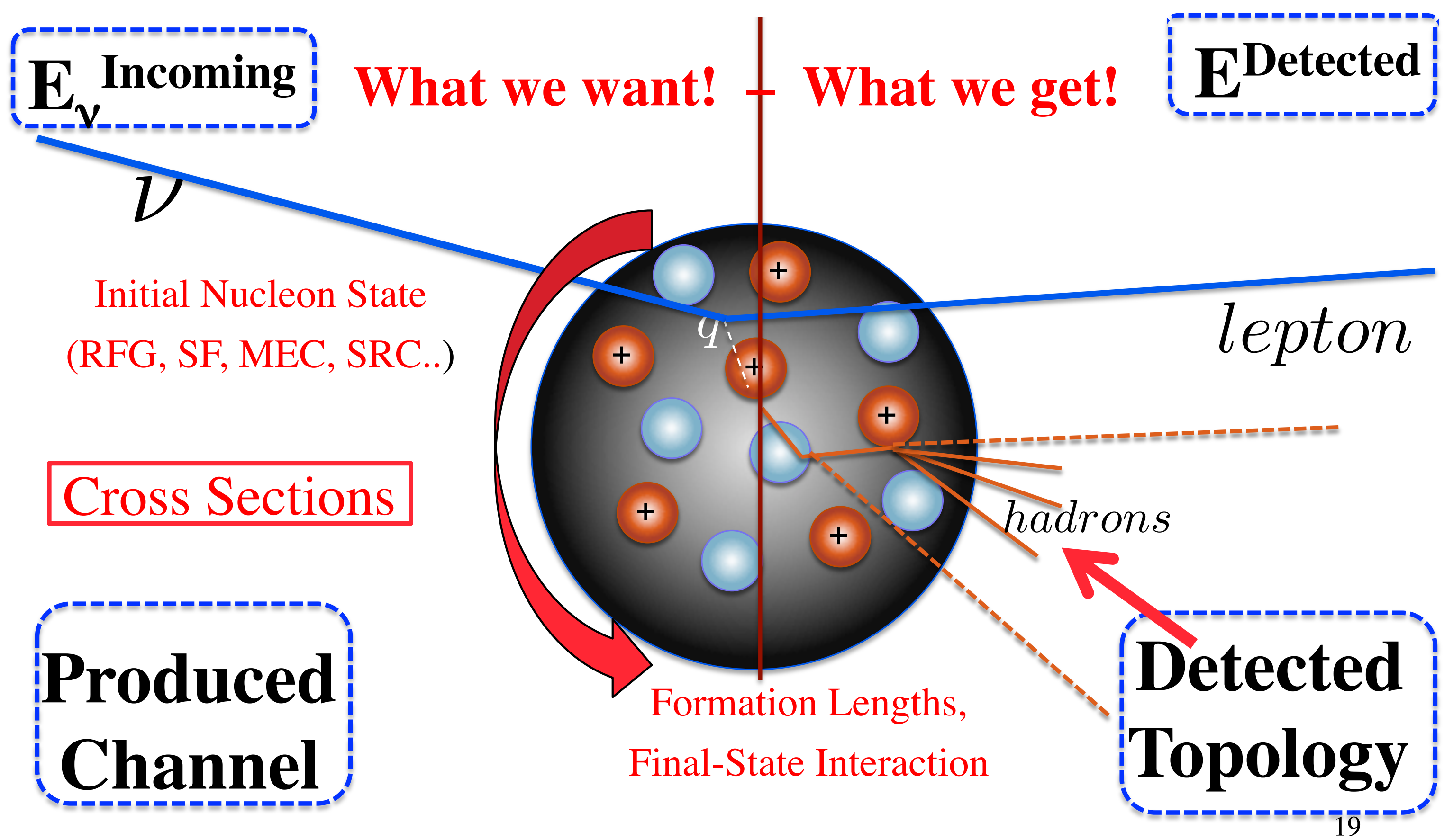
May 29 2018

# South Pole Recap

- Cons
  - Temperature
  - Isolation
  - Weather
- Pros
  - **Only one, but very big one**
  - Technically nothing can go south over there which makes it perfect for science and experiments!

# Recap

- Yesterday we reviewed:
  - The different neutrino interactions
  - The Importance of neutrino interactions
  - Some of the challenges for cross section measurements
  - Looked examples of nuclear effects
  - Reviewed some techniques to constraint the flux




Jorge Morfin, INFO 2015

# Outline

- Building cross section measurements
  - Event selection
  - Signal and backgrounds
  - Unfolding
  - Efficiency correction
  - Systematics
  - Extracting the cross section

# Example: Measuring Differential Cross Section

- Let’s review a measurement from the MINERvA experiment as an example
- We already talk about flux, number of target and number of neutrino interactions, let’s review the other components

Events Selected

Unfolding

Backgrounds

$$\left(\frac{d\sigma}{dx}\right)_{\alpha} = \frac{\sum_j U_{j\alpha}(N_{data,j} - N^{bkgd}_{data,j})}{A_{\alpha}(\Phi T)(\Delta x)}$$

Bin-width

Acceptance

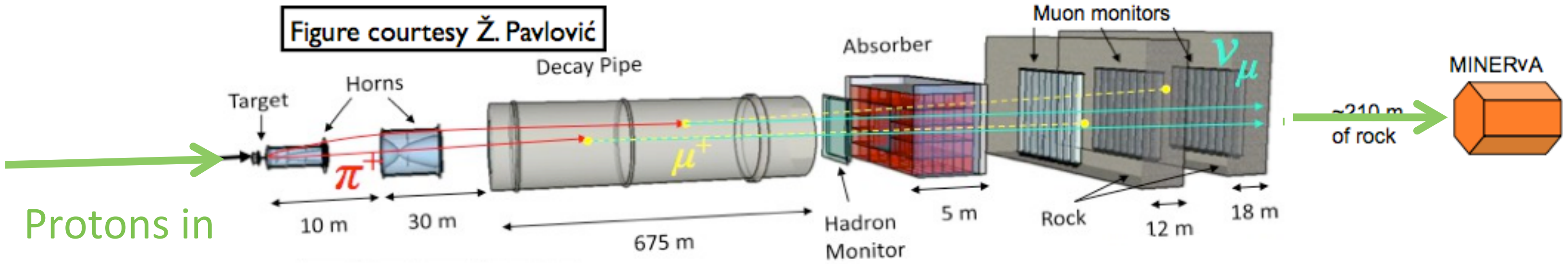
Flux

Targets

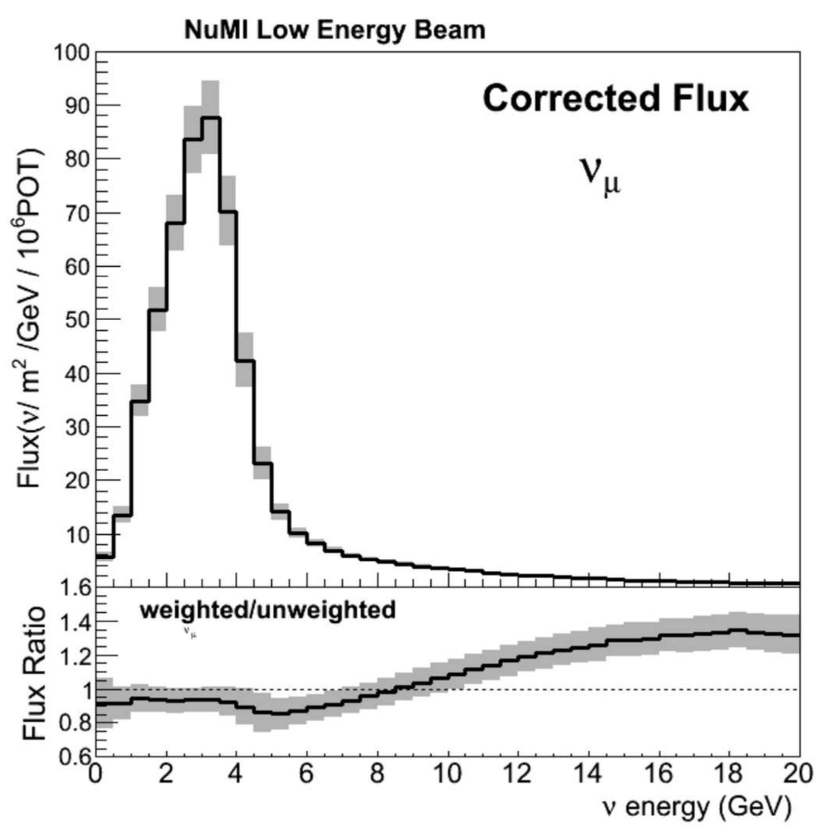

Fermilab

# Flux

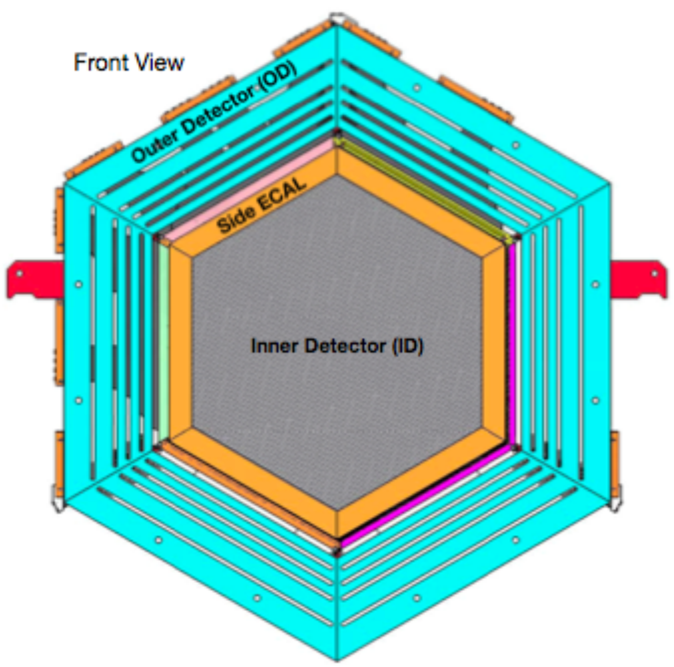
$$\left(\frac{d\sigma}{dx}\right)_{\alpha} = \frac{\sum_j U_{j\alpha}(N_{data,j} - N^{bkgd}_{data,j})}{A_{\alpha}(\Phi T)(\Delta x)}$$

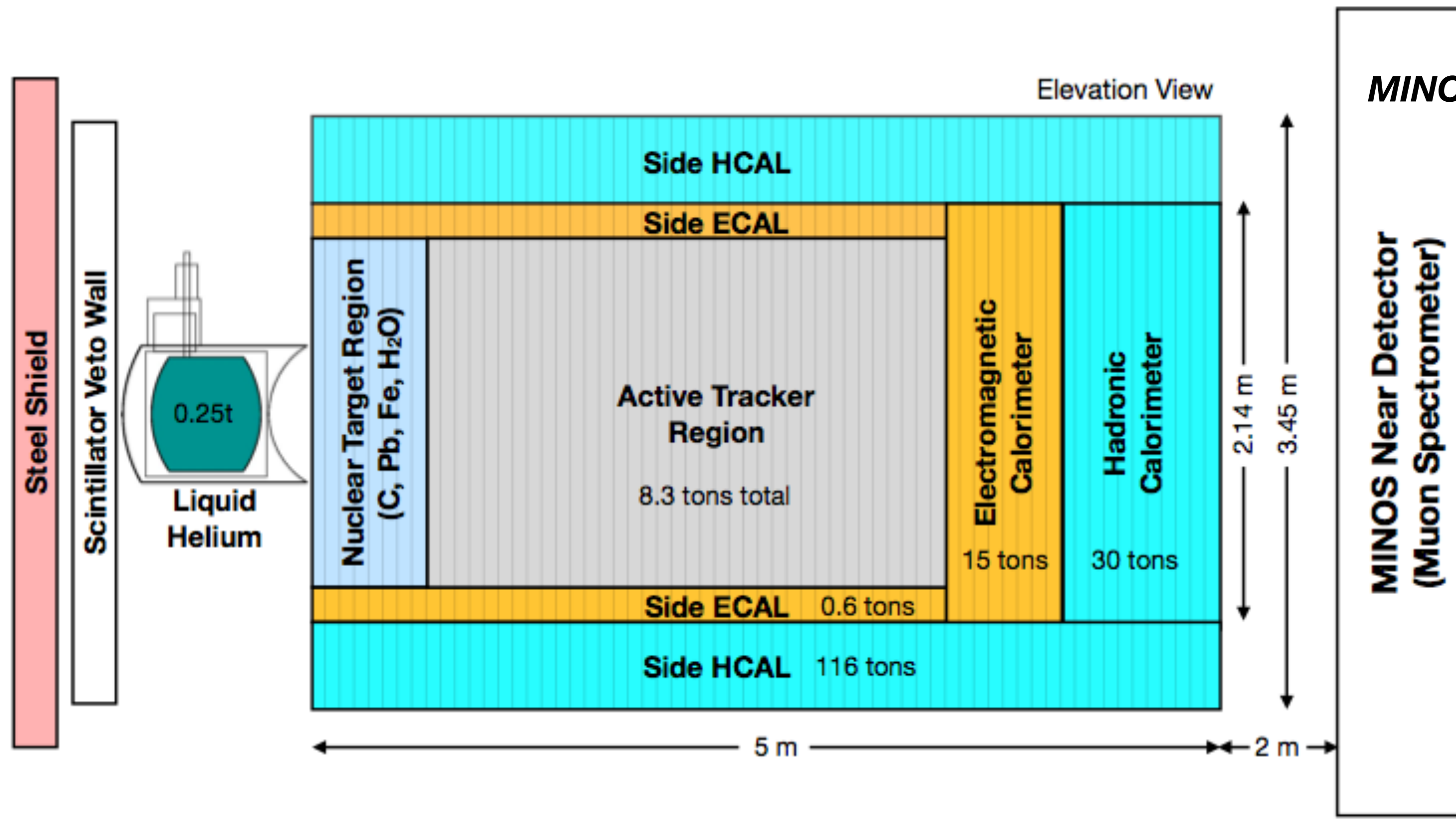



- The neutrino flux is hard to calculate and an important source of systematic uncertainty
- We have a prediction for the flux with uncertainties about ~8%

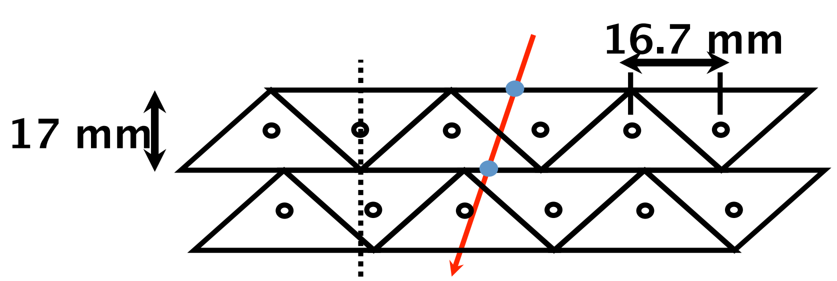


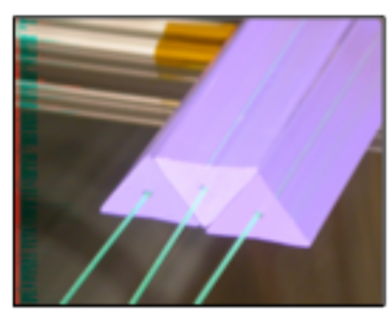
# MINERvA Experiment




Thanks to MINOS



3 different rotated plane views to resolve high multiplicity events

Design, calibration, and performance of the MINER

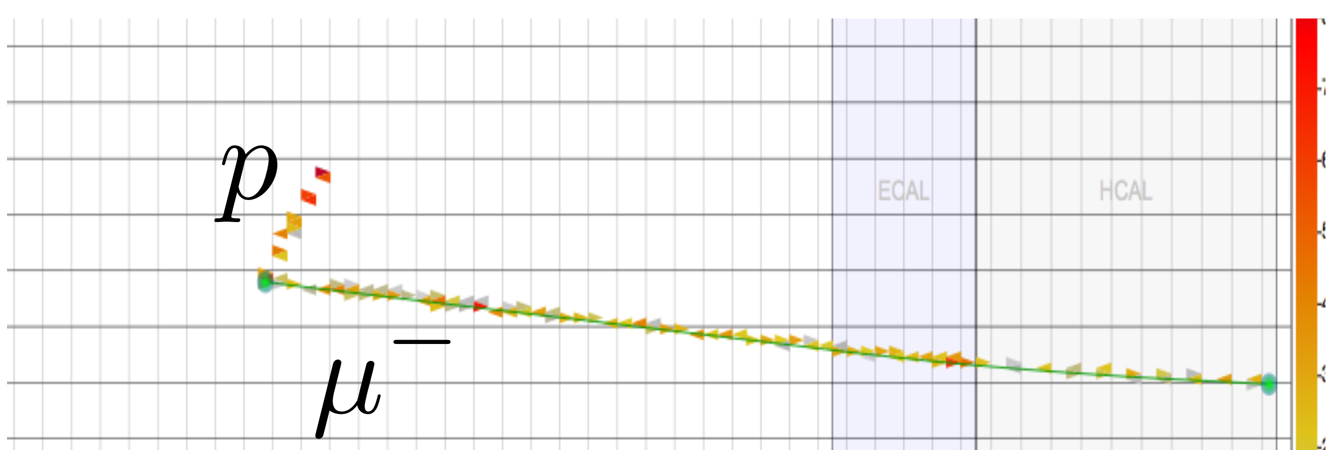
Nuclear Inst. and Methods in Physics Research, A, Volume 743, 11 April 2014, Pages 130-159

$$\left(\frac{d\sigma}{dx}\right)_\alpha = \frac{\sum_j U_{j\alpha}\left(N_{data,j} - N^{bkgd}_{data,j}\right)}{A_\alpha(\Phi T)(\Delta x)}$$

# Selected Events

- We make a selection based on the topology of the event
- But all we can measure is how energy is deposited in the detector
- We use our physics knowledge to infer what patterns of energy deposition correspond to our process, but it's not easy
  - Different processes can produce the same final state particles
  - Different initial interactions can produce the same final state particles
  - Some particles or configurations are difficult to detect (examples: neutral particles, two particles traveling right on top of one another)
- Even after our selection cuts, we have some background events that pass the cuts

- In the case of Quasi-Elastic scattering, what are we looking for in the detector?

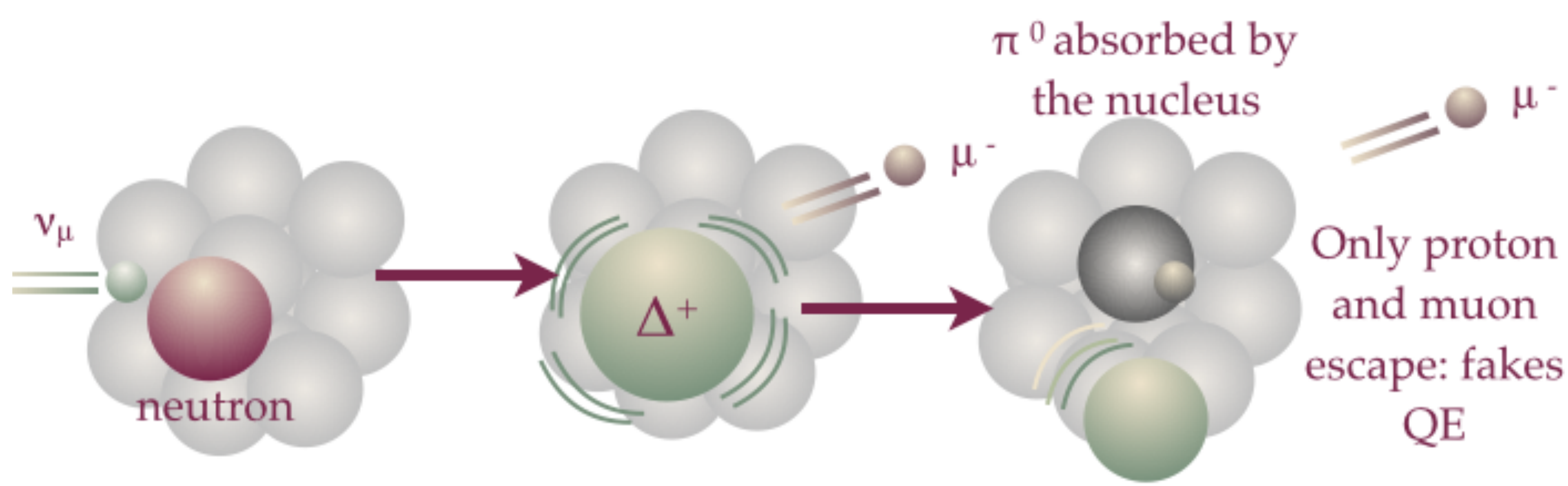


$$\left(\frac{d\sigma}{dx}\right)_\alpha = \frac{\sum_j U_{j\alpha}\left(N_{data,j} - N^{bkgd}_{data,j}\right)}{A_\alpha(\Phi T)(\Delta x)}$$

# Signal and Background

- Signal event: an event that matches what our analysis is looking for, regardless of whether we manage to identify the underlying process
- Background event: is an event that passes our analysis cuts, but which is not actually a true signal event. These events mimic our signal

Background event

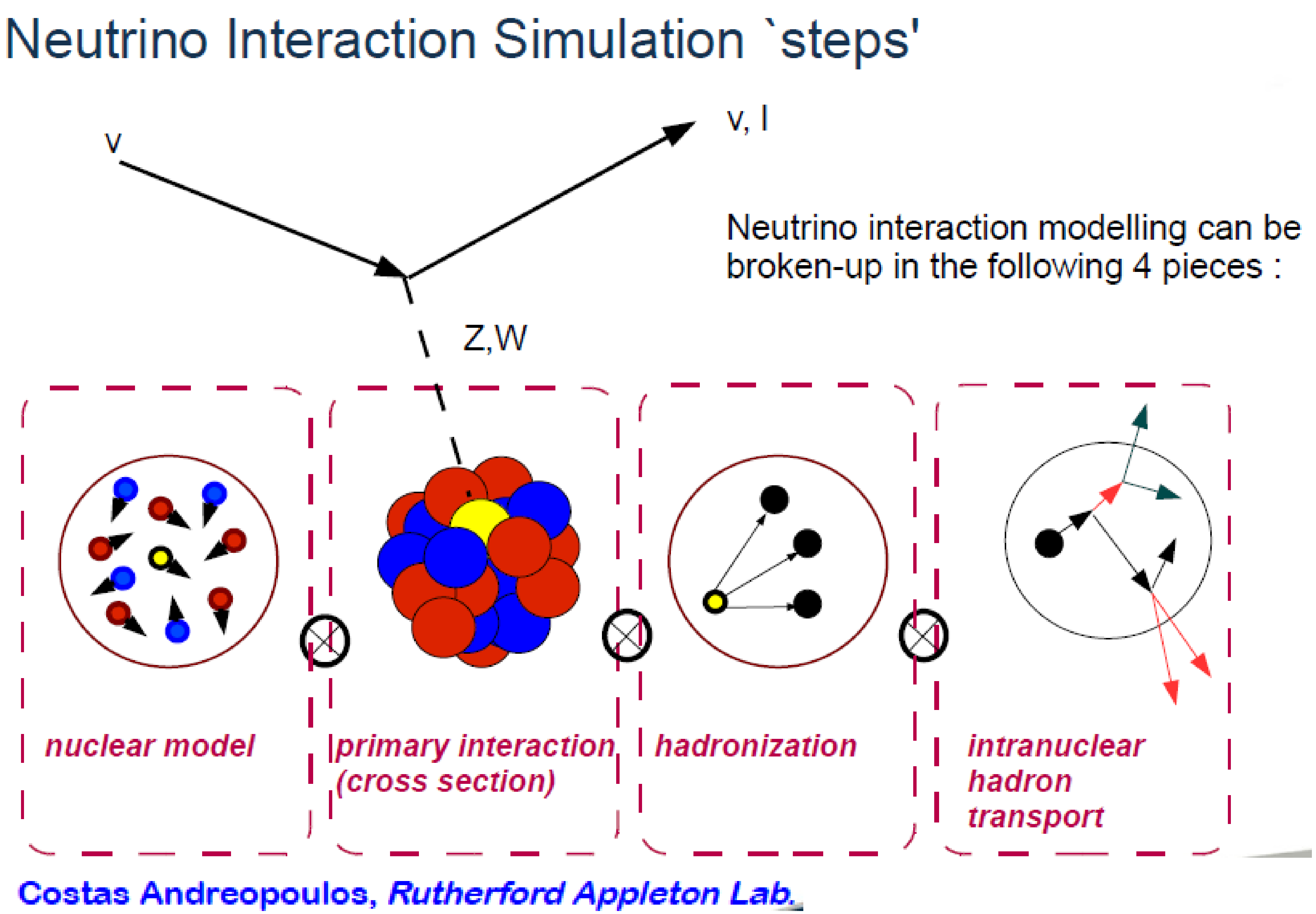



- Other processes like the resonance interactions produce pions, but these can be absorbed in the nucleus (final-state interactions), faking the signal

# Simulations

- We use Monte Carlo simulations (GENIE) for the analysis

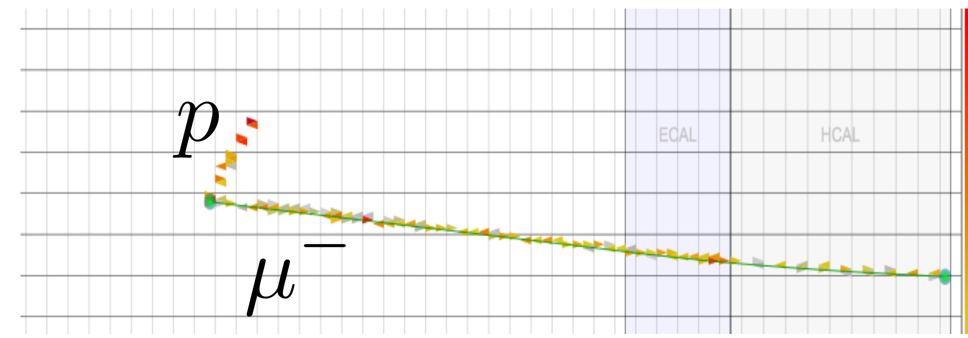
**GENIE**



$$\left(\frac{d\sigma}{dx}\right)_{\alpha} = \frac{\sum_j U_{j\alpha}\left(N_{data,j} - N^{bkgd}_{data,j}\right)}{A_{\alpha}(\Phi T)(\Delta x)}$$

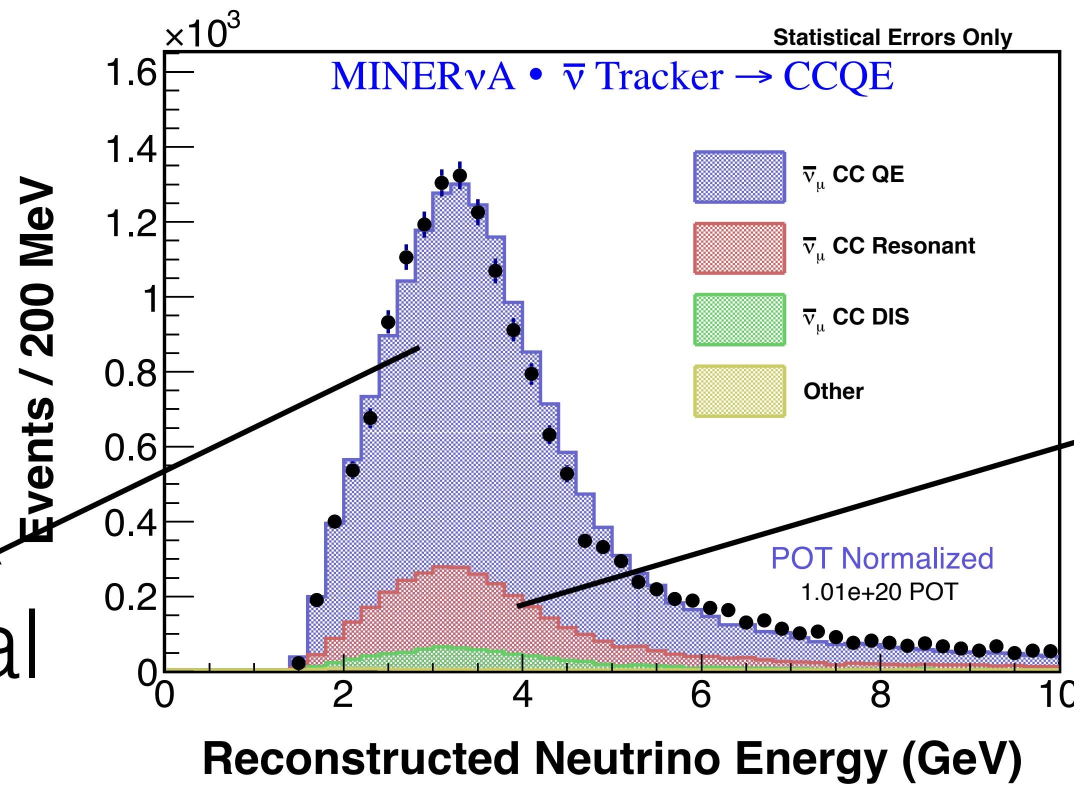
# Signal and Background

- We identify the particles
- Measure properties of those particles
  - Momentum, angle and energy




**Neutrino Energy**

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



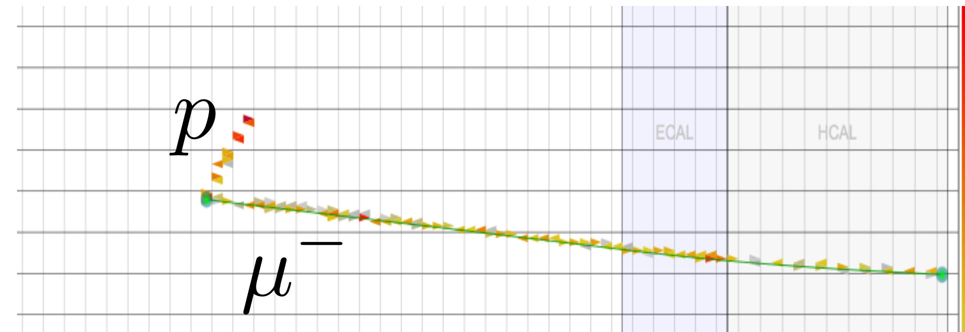

Signal

Background

We use Monte Carlo simulations (GENIE) to determine the background levels, but this is not enough, most of the time the models do not reproduce the real data

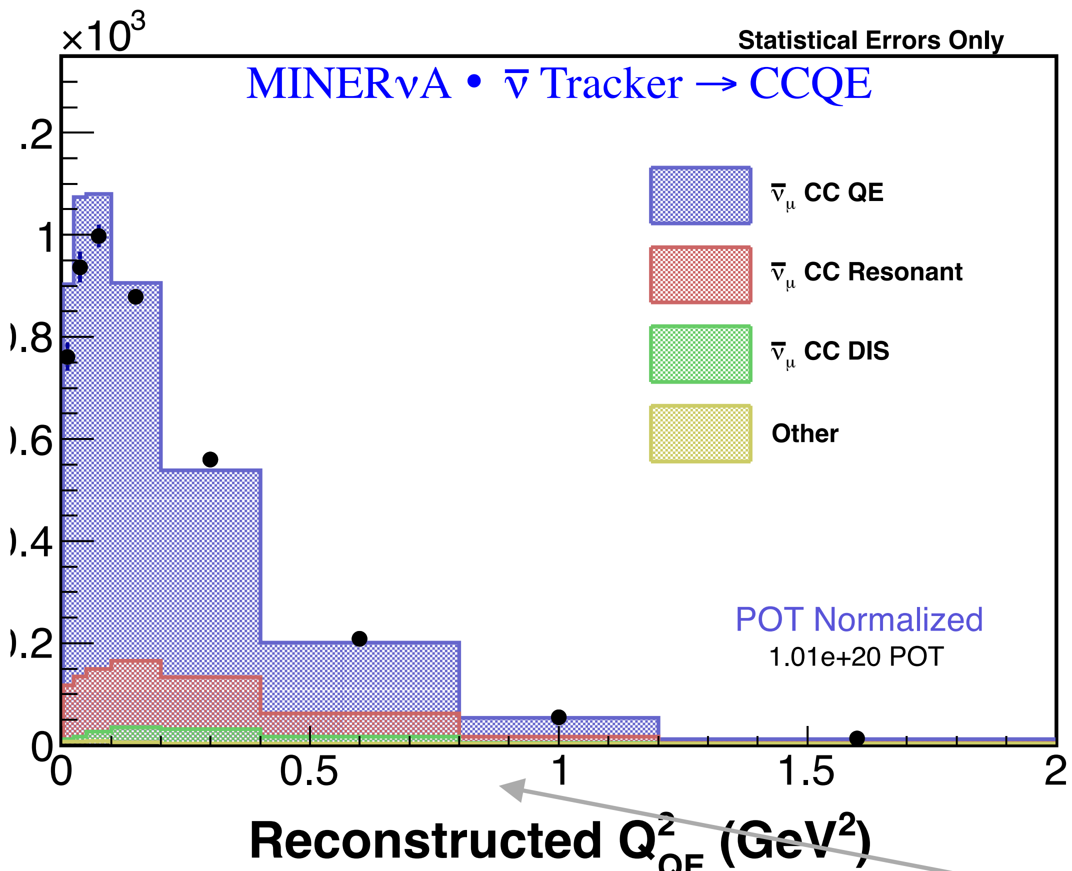
# Signal and Background

$$\left(\frac{d\sigma}{dx}\right)_\alpha = \frac{\sum_j U_{j\alpha}\left(N_{data,j} - N^{bkgd}_{data,j}\right)}{A_\alpha(\Phi T)(\Delta x)}$$




- We identifies the particles
- Measure properties of those particles
  - Momentum, angle and energy
  - Using the muon momentum and angle, we can compute the four momentum transfer $Q^2 = -m_\mu^2 + 2E_{QE}(E_\mu - p_\mu \cos\theta\mu)$ $E_{QE} = \frac{m_n^2 - (m_p - E_b)^2 - m_\mu^2 + 2(m_p - E_b)E_\mu}{2(m_p - E_b - E_\mu + p_\mu \cos\theta_\mu)}$
  - Let's concentrate on describing how to measure the differential cross section as a function of $Q^2$

Selected events

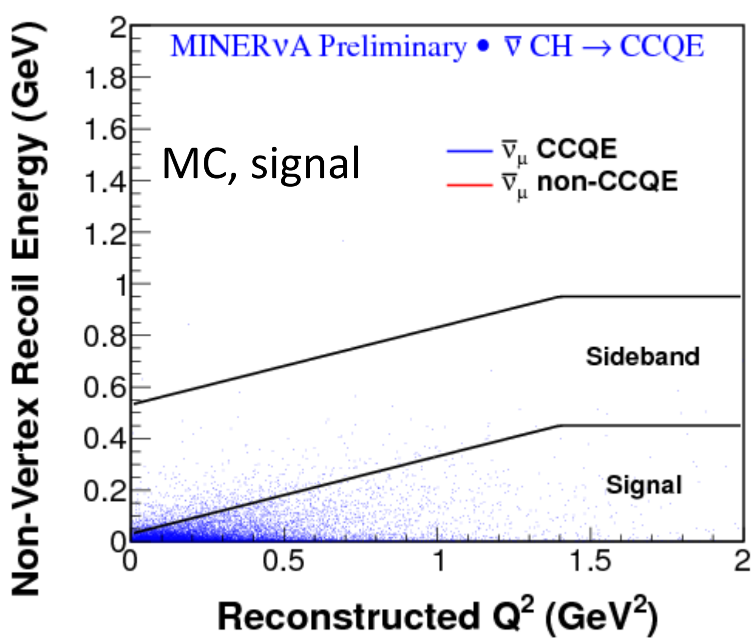


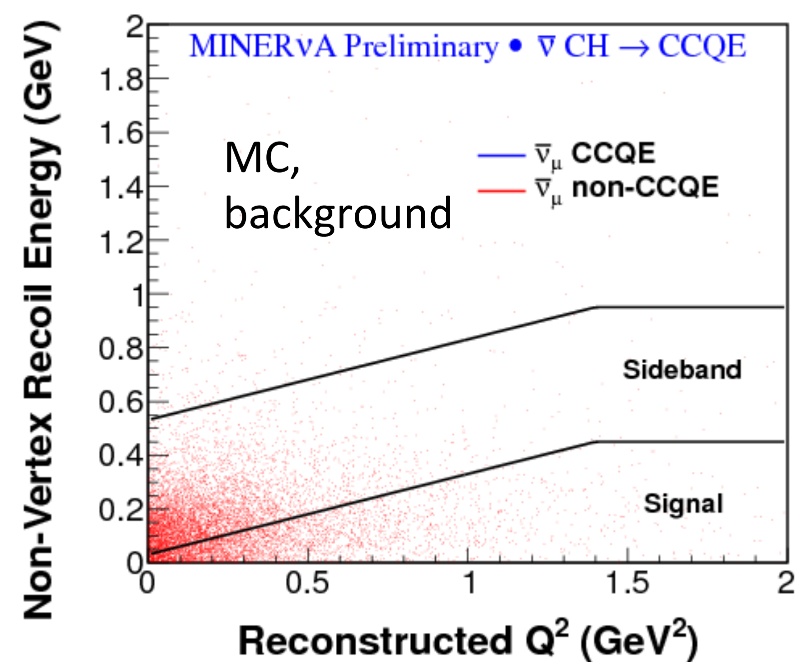

Main background from Resonant interactions

$$\left(\frac{d\sigma}{dx}\right)_{\alpha} = \frac{\sum_j U_{j\alpha}\left(N_{data,j} - N^{bkgd}_{data,j}\right)}{A_{\alpha}(\Phi T)(\Delta x)}$$

# Background Prediction

- We know the Monte Carlo models do not reproduce the real data
- Data is used to constrain the backgrounds
- Data driven background fit methods can reduce model-dependence
- An example from a MINERvA background constraint:
  - Taking the shape of the signal and background distributions in the Monte Carlo simulation
  - The relative weights of each of these distributions are varied until we get the combination that best matches the shape of the data
- Looking at the sideband region helps us to constrain the background in the signal region

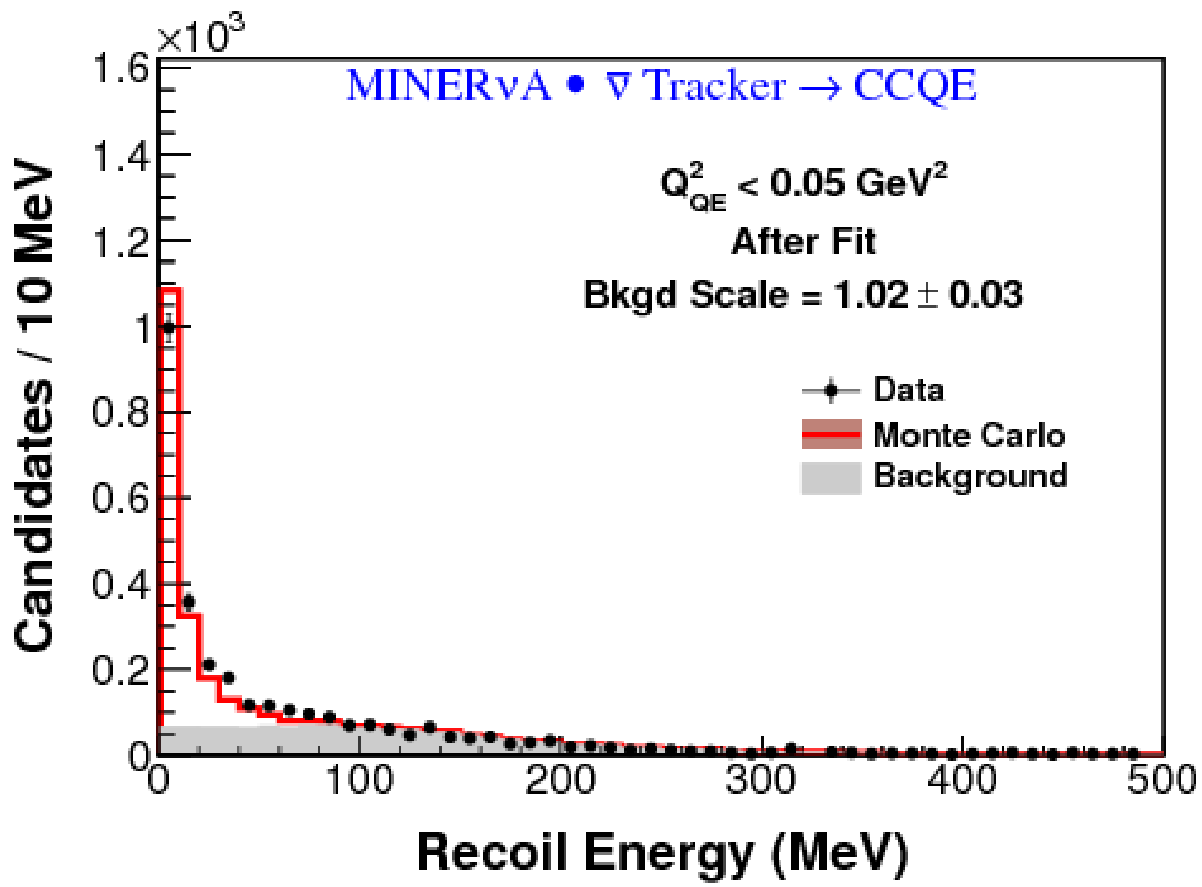


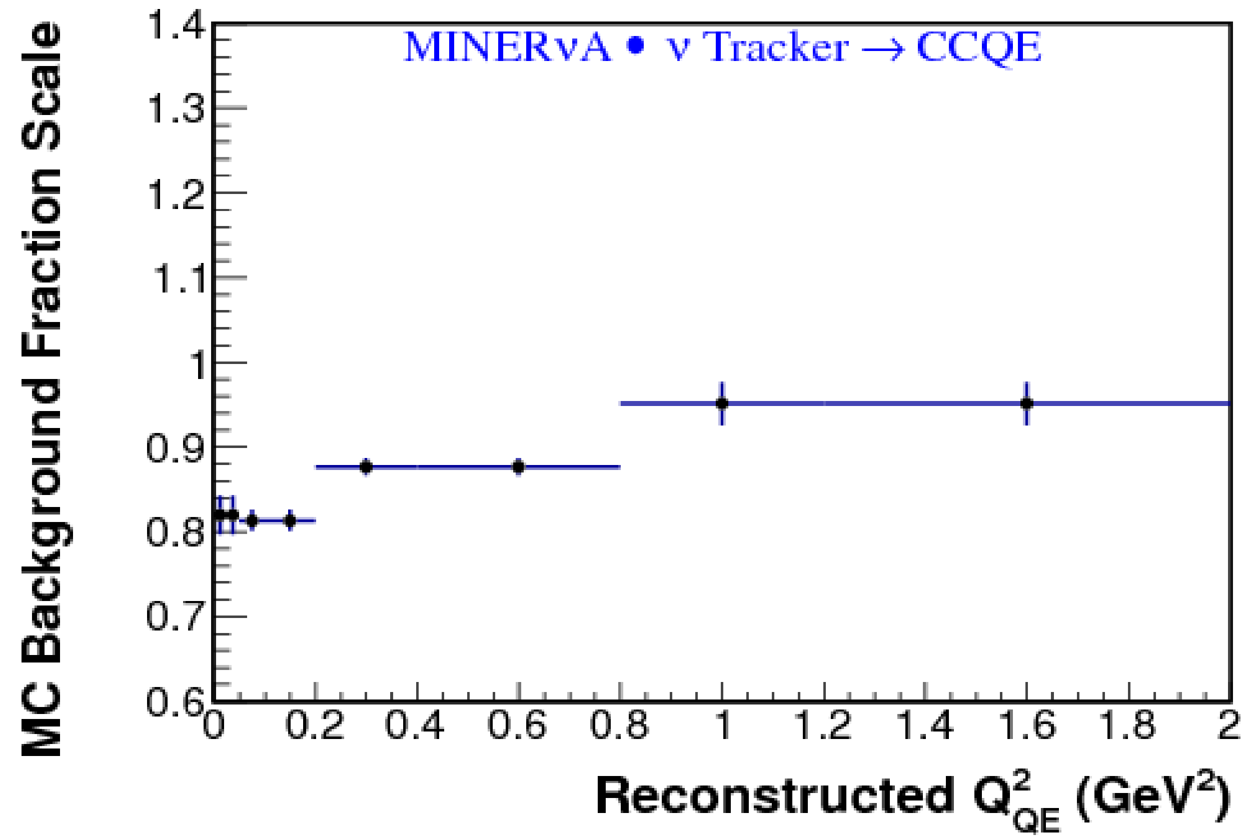



# Example of Background Constraints

$$\left(\frac{d\sigma}{dx}\right)_\alpha = \frac{\sum_j U_{j\alpha}\left(N_{data,j} - N^{bkgd}_{data,j}\right)}{A_\alpha(\Phi T)(\Delta x)}$$

- Background levels are estimated by fitting recoils distributions
- We obtain weights for each bin of $Q^2$



# Background

- Background are very important part of the analysis
- This part of the analysis is where we spend most time in many analyzes
- To compute any cross section we need to remove the background
- Our simulation has some predictions for the background, can we just subtract the background?
- Remove the background as much as possible and we must constrain the remaining background

Events Selected

Unfolding

Backgrounds

$$\left(\frac{d\sigma}{dx}\right)_\alpha = \frac{\sum_j U_{j\alpha}(N_{data,j} - N^{bkgd}_{data,j})}{A_\alpha(\Phi T)(\Delta x)}$$

Bin-width

Acceptance

Flux

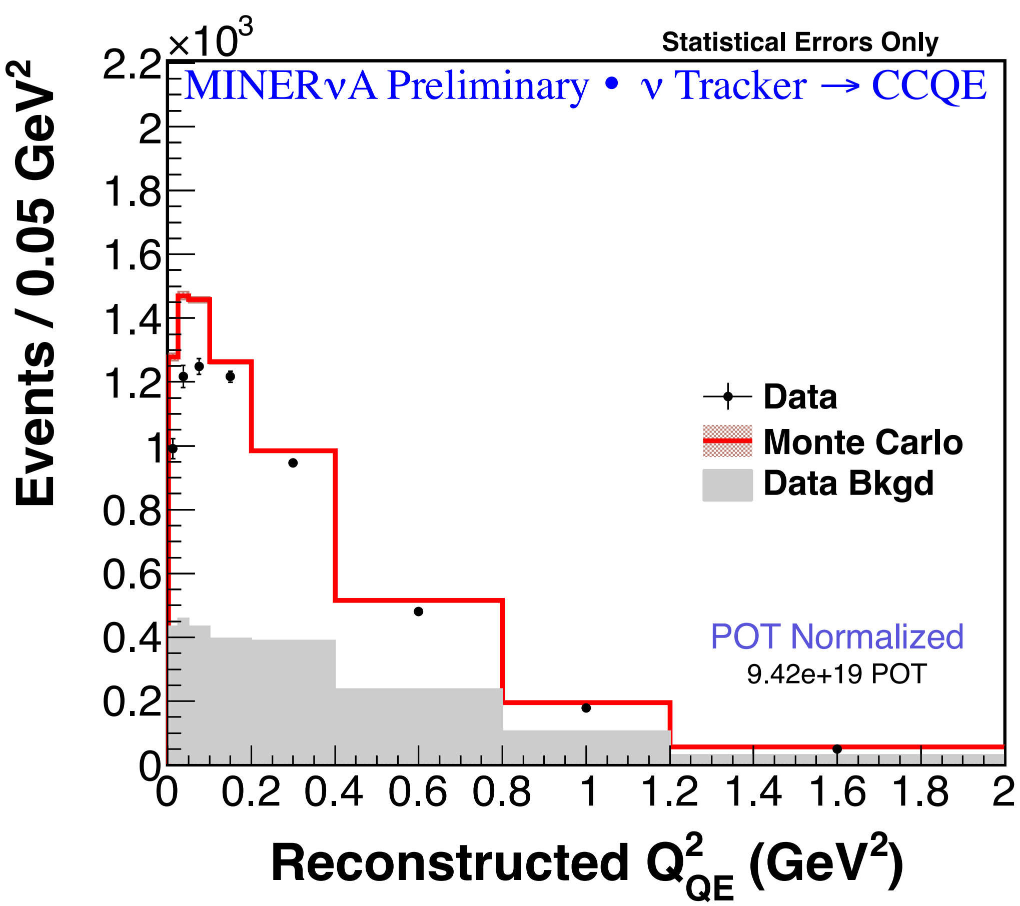
Targets

# Background Subtraction

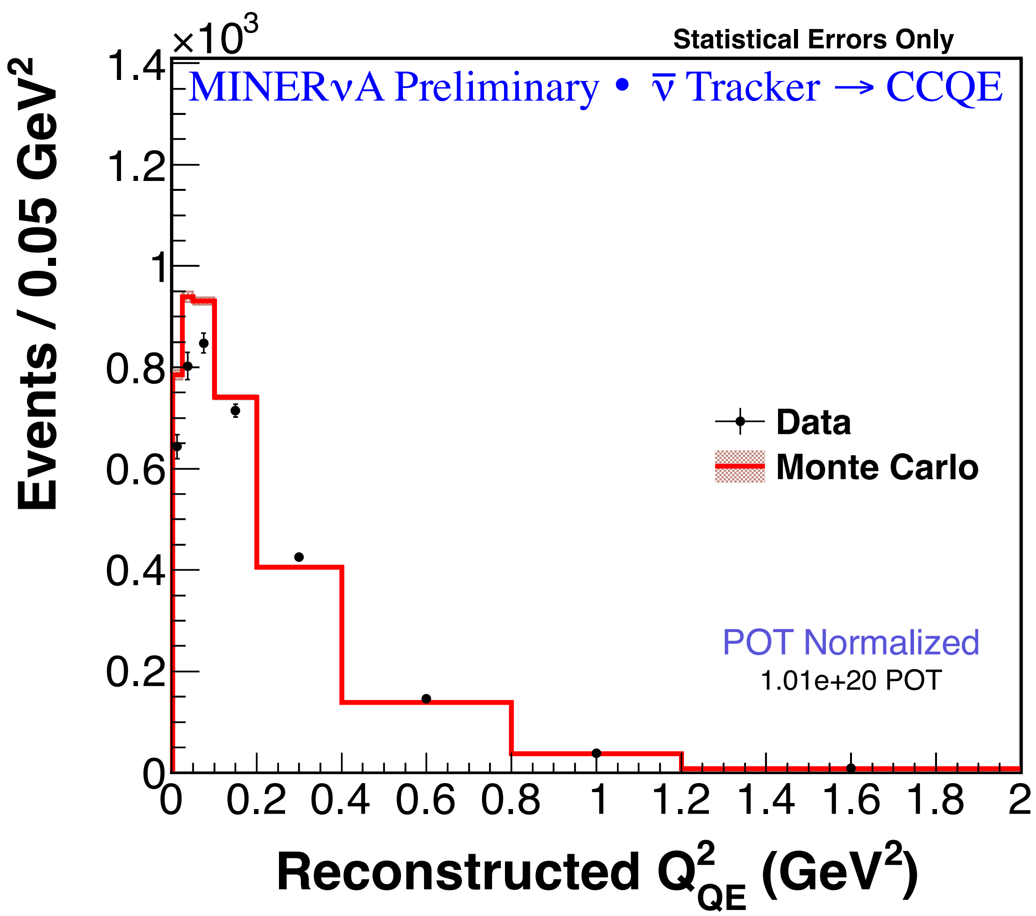
$$\left(\frac{d\sigma}{dx}\right)_\alpha = \frac{\sum_j U_{j\alpha}\left(N_{data,j} - N^{bkgd}_{data,j}\right)}{A_\alpha(\Phi T)(\Delta x)}$$

- After the background is constrained with data, we subtract the predicted background contribution from each bin of the desire quantity we want to measure

## Selected sample with background



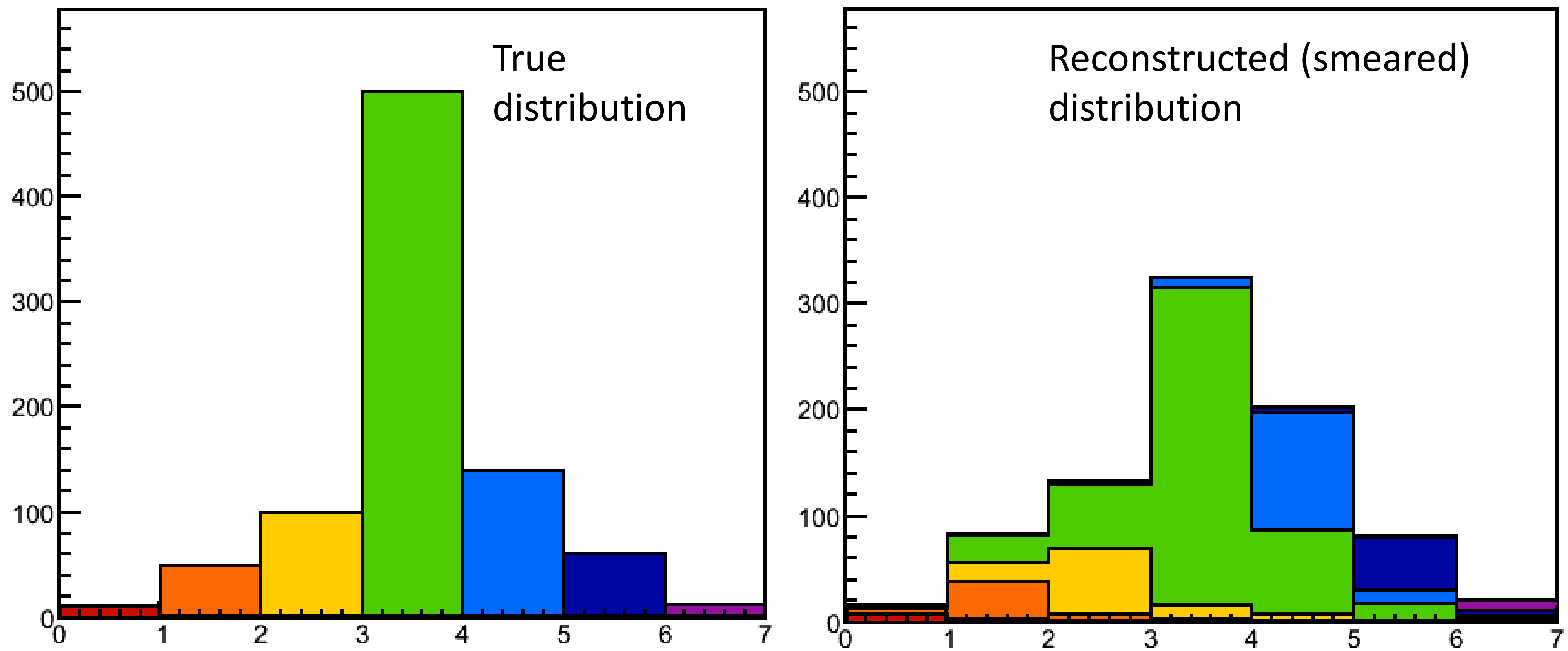

## After background subtraction



$$\left(\frac{d\sigma}{dx}\right)_\alpha = \frac{\sum_j U_{j\alpha}(N_{data,j} - N^{bkgd}_{data,j})}{A_\alpha(\Phi T)(\Delta x)}$$

# Unfolding

- We can't measure (or reconstruct) events with perfect precision, so we will always reconstruct some events into the wrong bin




- This has the effect of smearing out the features of our true distribution
- Correcting for the effects of detector smearing, which causes some events to be reconstructed into the wrong bin. The goal is, when presented with a smeared distribution, to recover out true distribution

$$\left(\frac{d\sigma}{dx}\right)_\alpha = \frac{\sum_j U_{j\alpha}(N_{data,j} - N^{bkgd}_{data,j})}{A_\alpha(\Phi T)(\Delta x)}$$

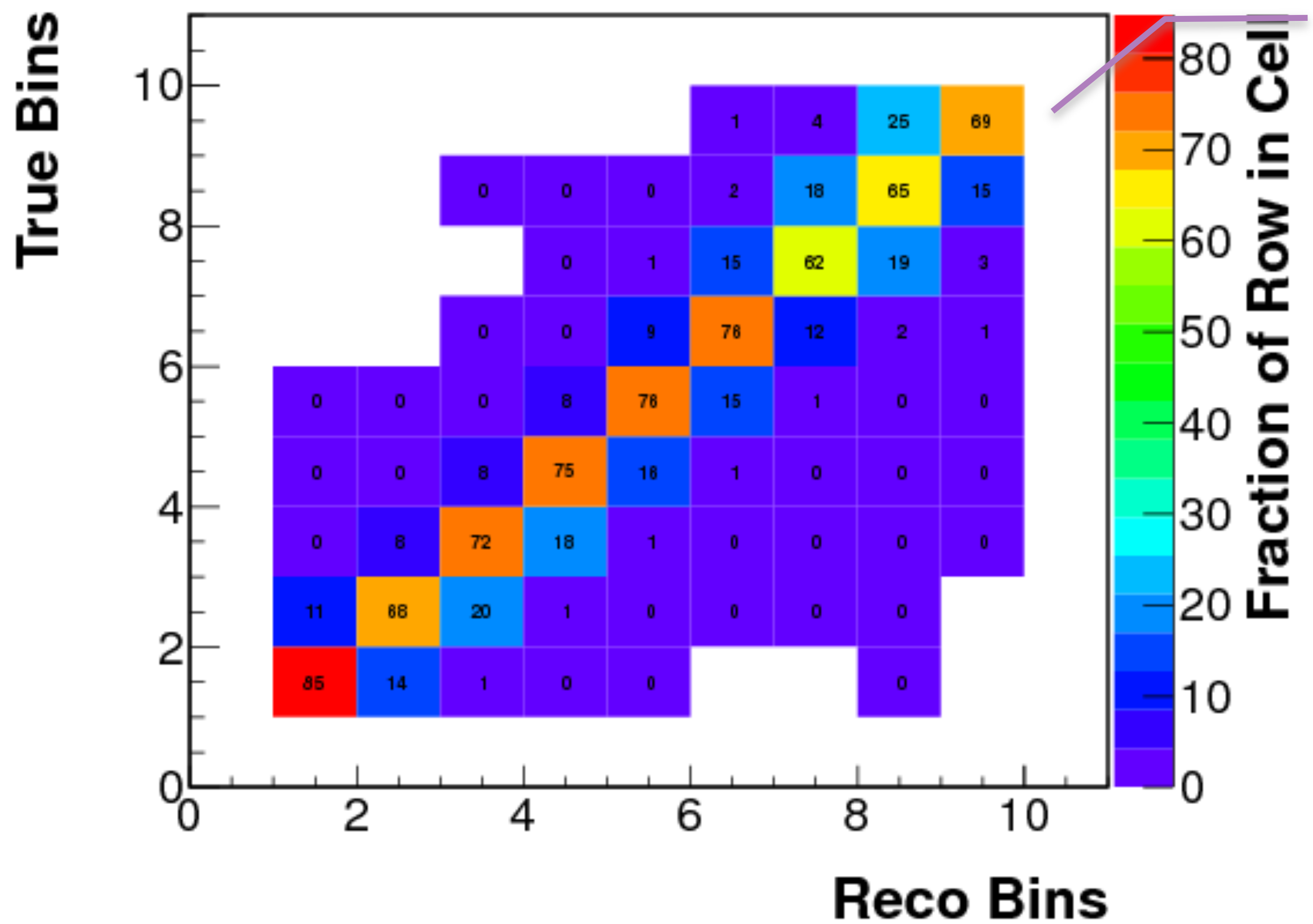
# Unfolding

- We want to know, if an event is observed in bin j, what bin did it really happen in?
- In other words, what's the probability that an event observed in bin j actually occurred in bin α?
- We can use our Monte Carlo to inform a migration matrix indicating what fraction of events generated in each bin α were observed in each reconstructed bin j
- If we've done a good job with our initial reconstruction, the matrix should be close to diagonal
- In addition, if we chose bins that are too small compared to our resolution. This is also a problem because the matrix is not as diagonal

$$\left(\frac{d\sigma}{dx}\right)_\alpha = \frac{\sum_j U_{j\alpha}(N_{data,j} - N^{bkgd}_{data,j})}{A_\alpha(\Phi T)(\Delta x)}$$

# Unfolding

- Example from Quasi-Elastic scattering




Diagonal corresponds to events reconstructed in the right bin

- To get the unsmearing matrix U, we must invert the migration matrix

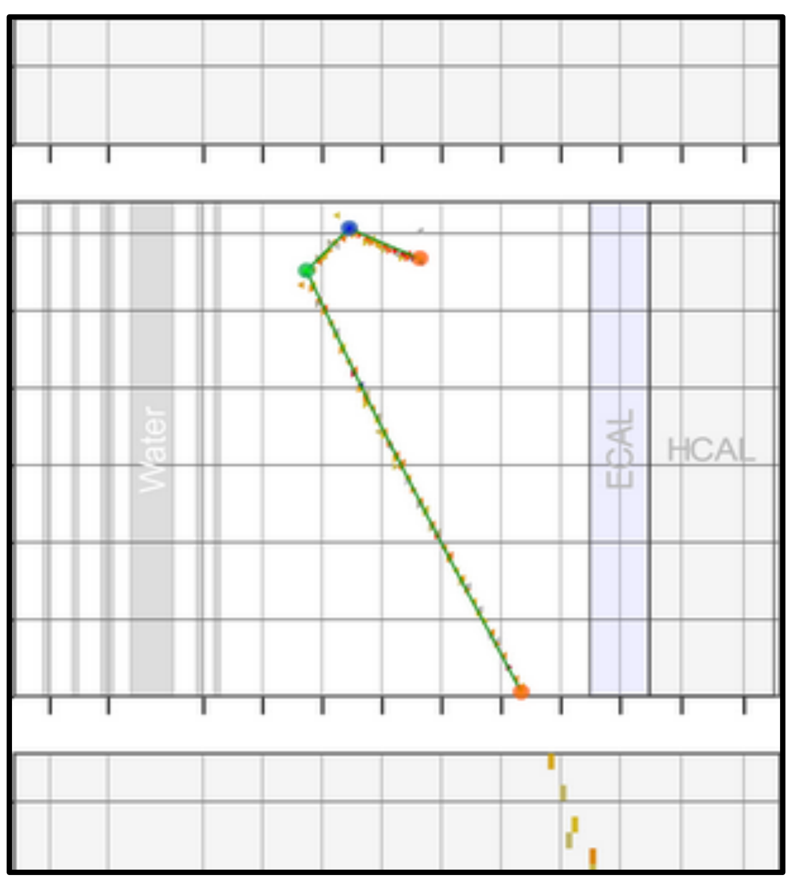
$$\left(\frac{d\sigma}{dx}\right)_\alpha = \frac{\sum_j U_{j\alpha}(N_{data,j} - N^{bkgd}_{data,j})}{A_\alpha(\Phi T)(\Delta x)}$$

# Efficiency Correction

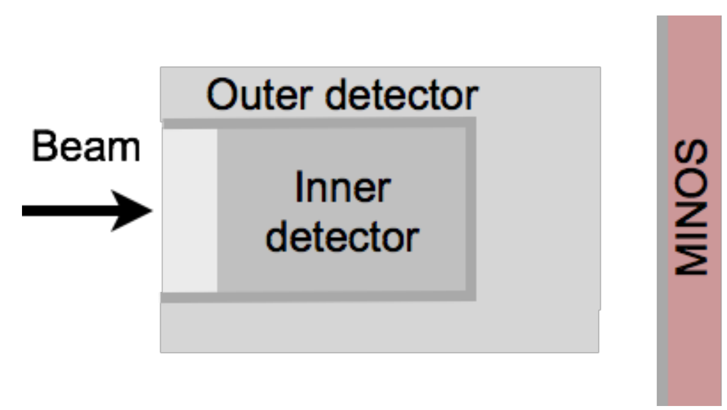
- A measure of how often we select signal events
- Inefficiency comes from reconstruction and detector geometry

$$\varepsilon = \frac{\text{number of signal events after event selection}}{\text{number of signal events in Monte Carlo}}$$

- An example from detector acceptance



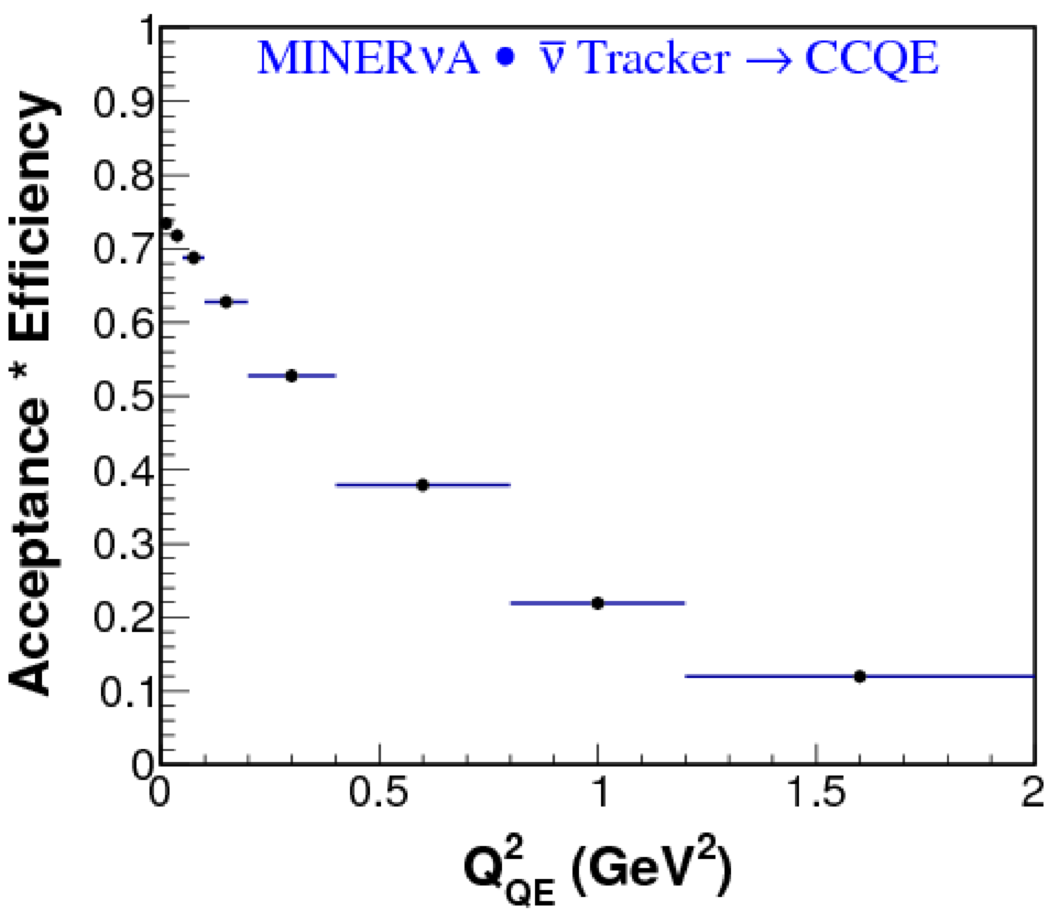

Some analyses require muon track to be matched to a track in MINOS. Events where the muon exits the side of detector will be rejected

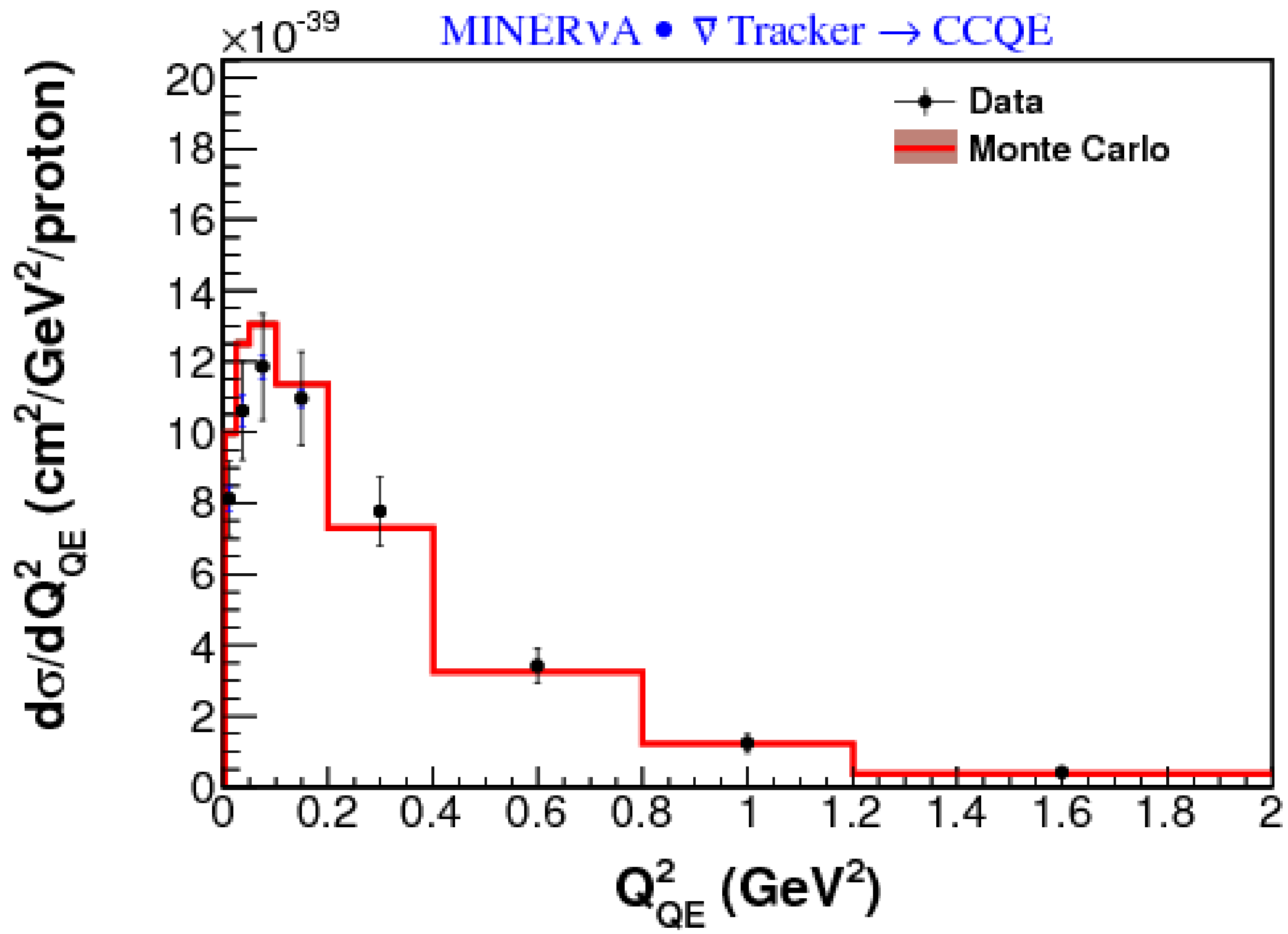


$$\left(\frac{d\sigma}{dx}\right)_\alpha = \frac{\sum_j U_{j\alpha}(N_{data,j} - N^{bkgd}_{data,j})}{A_\alpha(\Phi T)(\Delta x)}$$

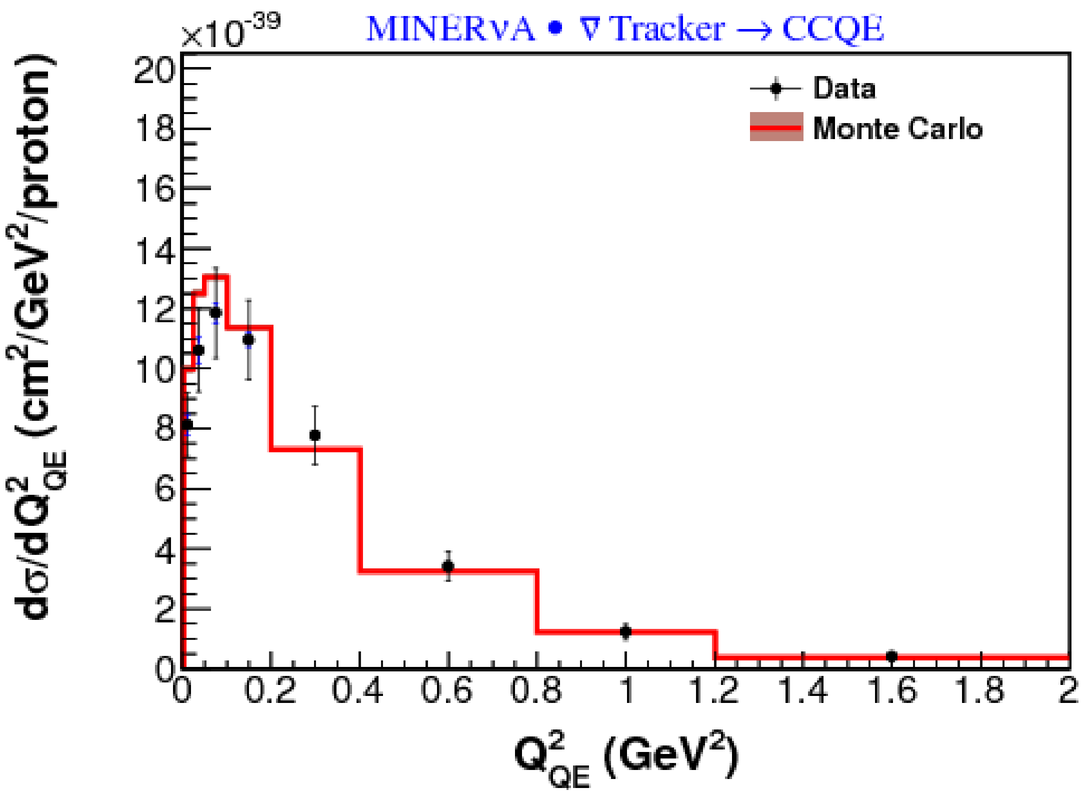
# Efficiency Correction

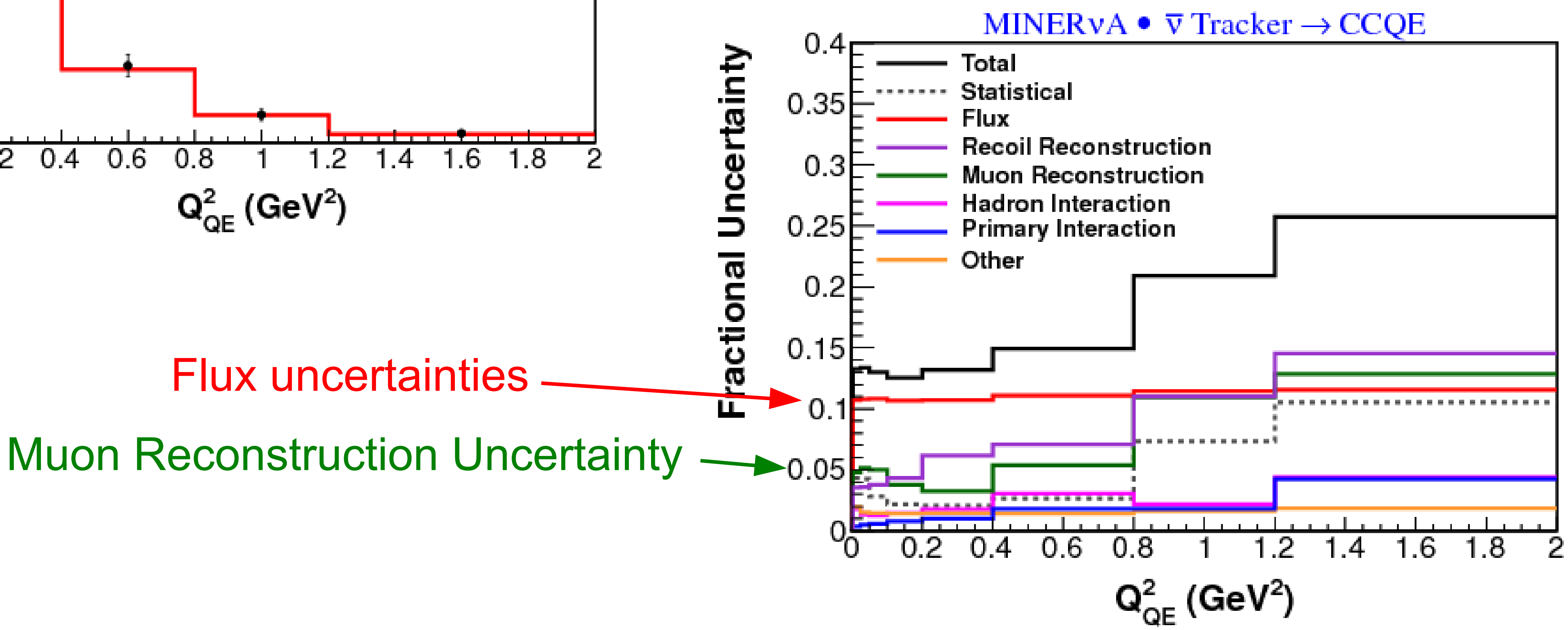
- Unfolded distributions are normalized by efficiency, flux and proton number to produce final cross section



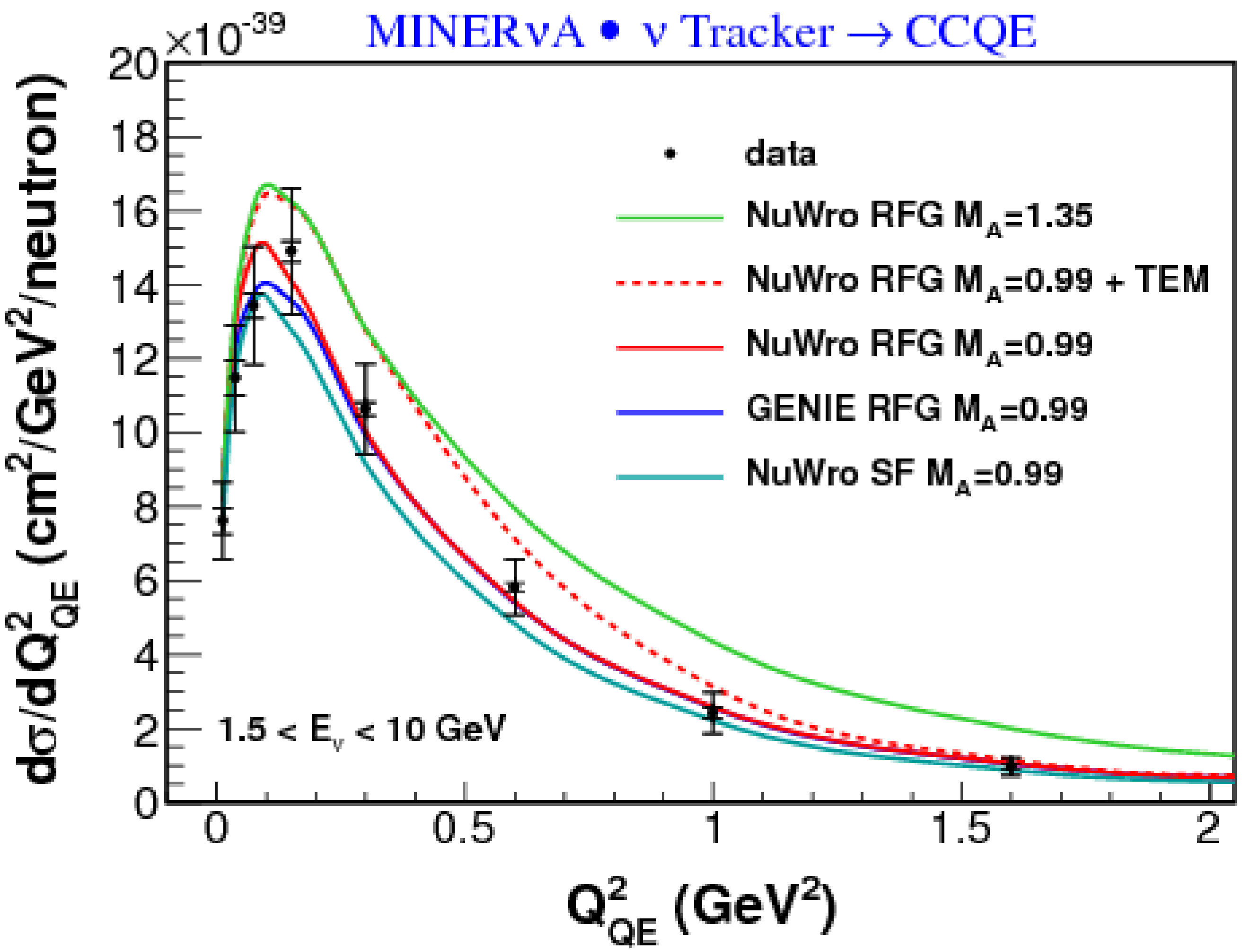
# Systematic Uncertainties

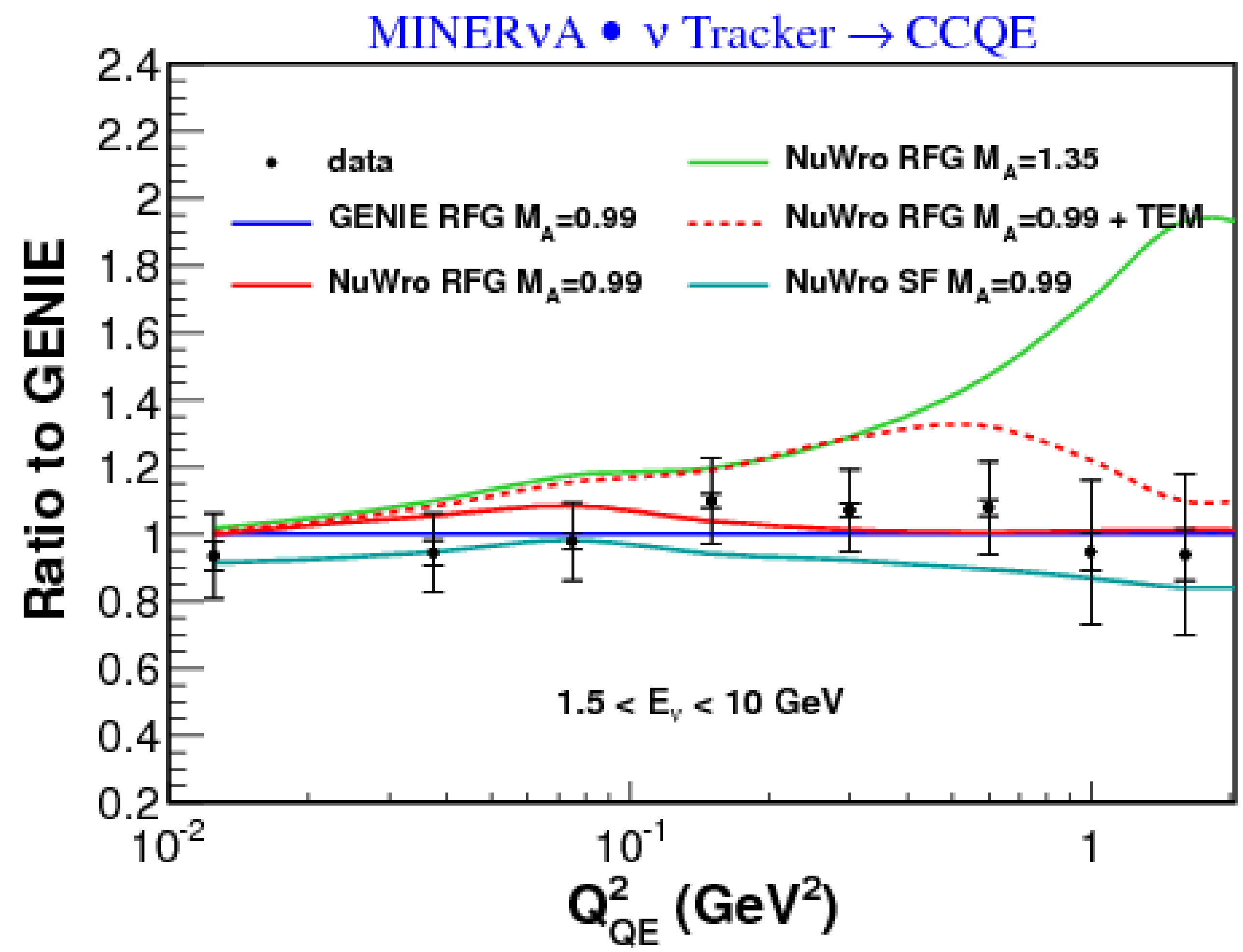


# Comparing with Models

- Data do not agree with some models

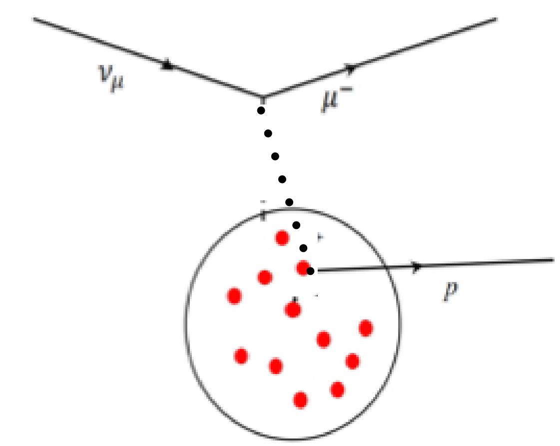


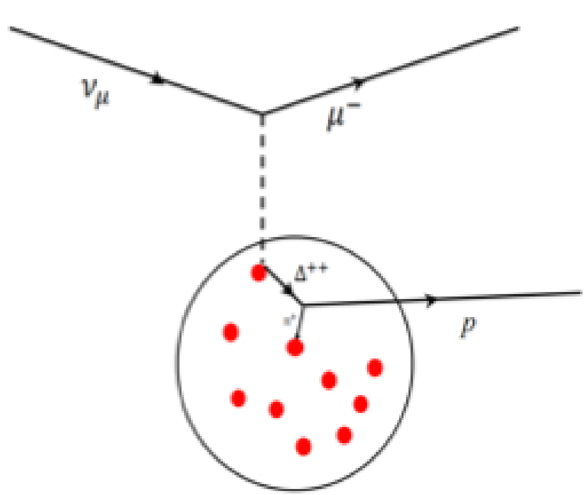

*Phys. Rev. Lett. 111, 022501 (2013)*

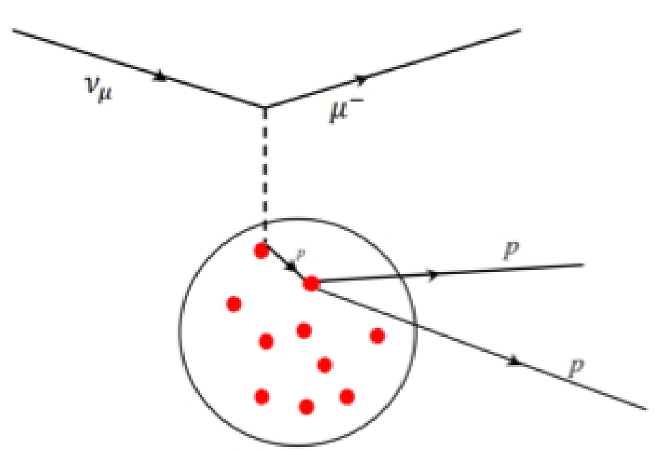
# CCQE Signal Definitions

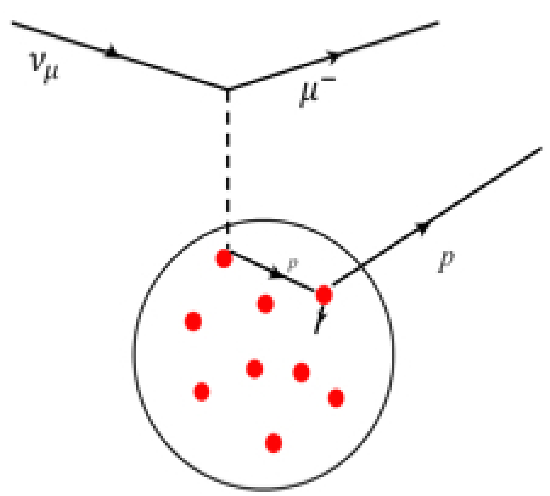
- **Old CCQE measurements:**
  - Signal is defined as an event in which the primary interaction is quasi-elastic (regardless of the final state particles)
  - Incoming (anti) neutrino energy between 1.5 and 10 GeV




- **New definition for future CCQE measurements:**
  - Signal is defined as CCQE-like, no pions in the final state
  - No cut on the neutrino energy
- **Why do we change the definitions?** CCQE-like is more clearly defined from an experimental point of view, depends less on the models

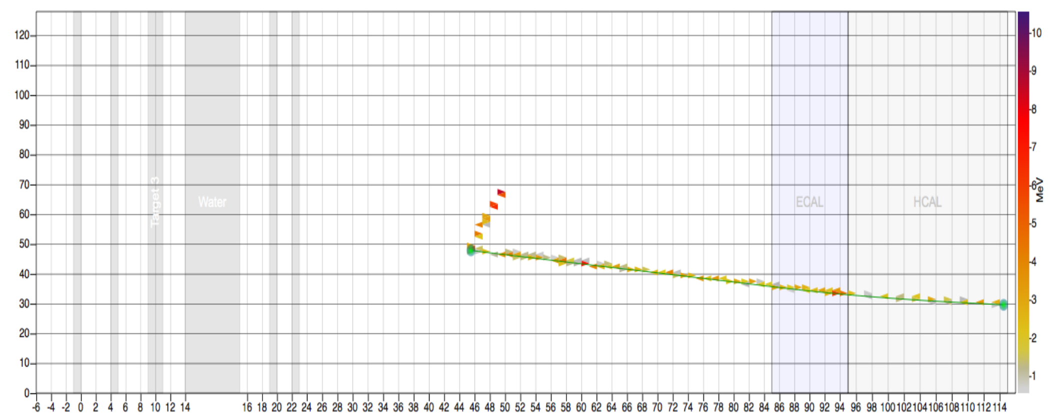


# CC0pi Neutrino Event Selection and Signal Definition

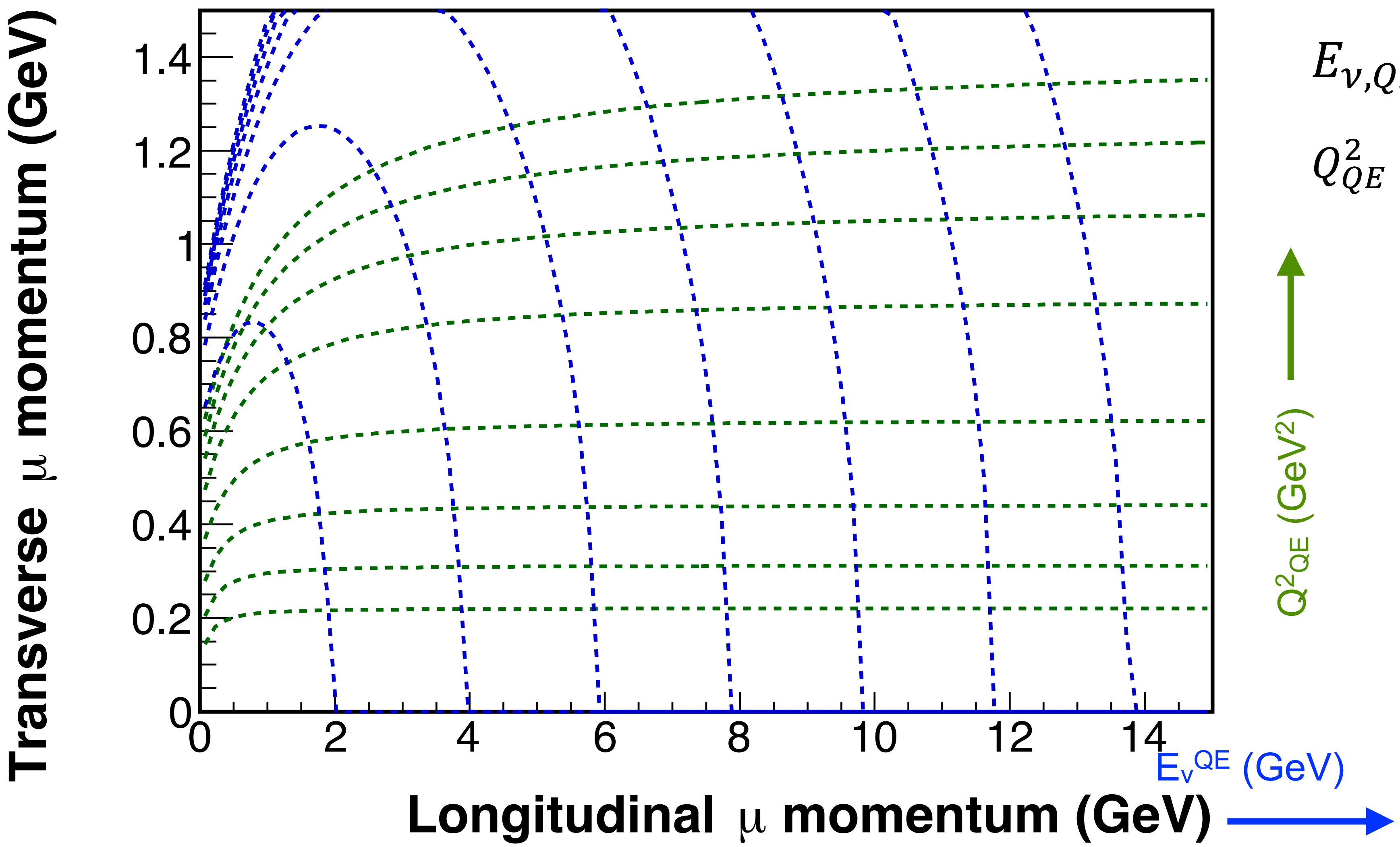
- New Selection requires a cut on non-vertex recoil energy, events above 0,5 GeV are removed
- Track pions and protons; select events based on particle identification
- Look for Michel electrons at later time to remove events with pi+




- Signal definition:
  - QE-like: defined by particles exiting the nucleus
  - Any number of nucleons of all energy
  - No pions, heavy baryons etc
  - Additional constraint: muon angle <20 degrees because of the MINERvA-MINOS acceptance

# Muon Transverse/Longitudinal Momentum vs $Q^2/E_\nu$

- Decide what to measure:
  - Observables with less model dependence as possible



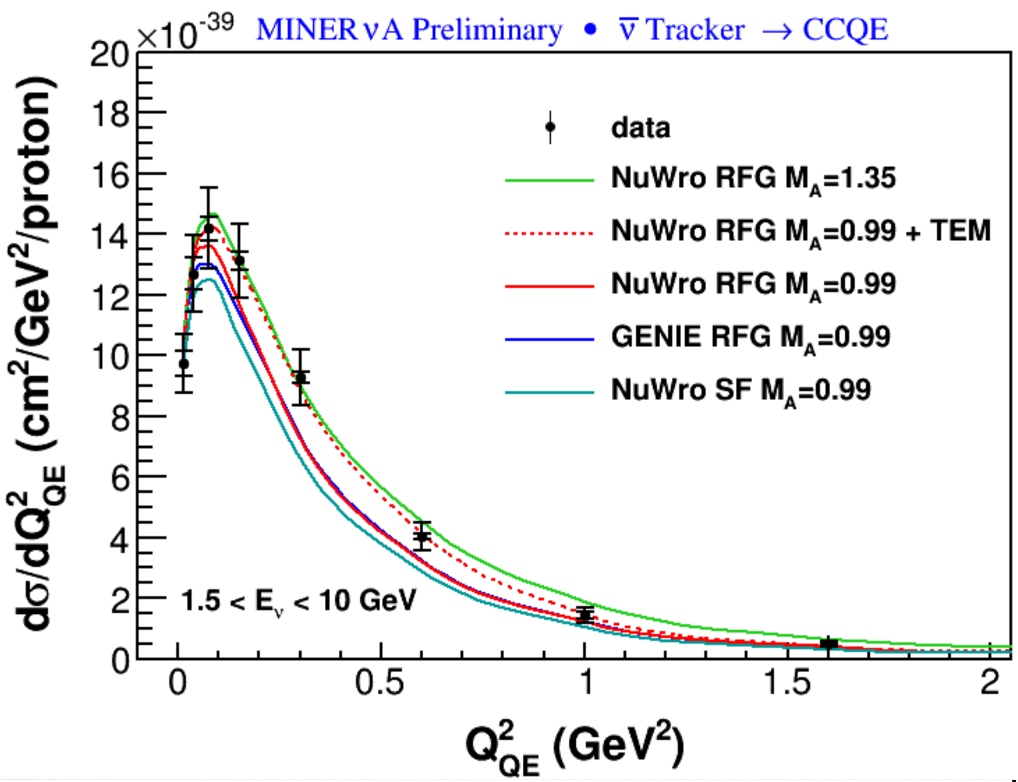

$$E_{\nu,QE} = \frac{M_n^2-(M_p-E_b)^2-M_\mu^2+2(M_p-E_b)E_\mu}{2(M_p-E_b-E_\mu+P_\mu\cos(\theta_\mu))}$$

$$Q^2_{QE} = 2E_\nu\left(E_\mu - P_\mu\cos(\theta_\mu)\right) - M_\mu^2$$

**$Q^2$~PT**

**$E_\nu$~Pz**

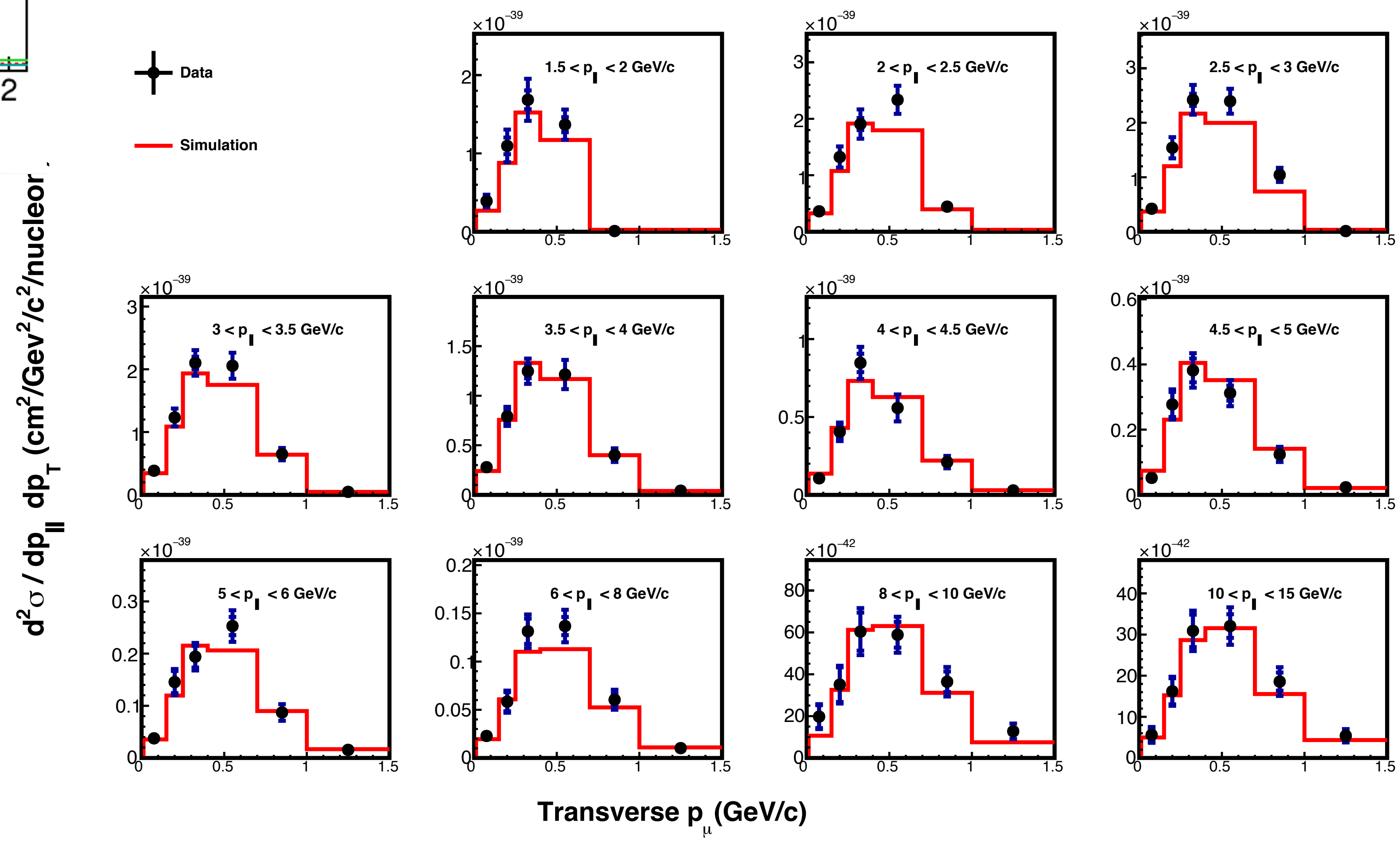
# Examples of Measurements with different Signal definition




## CCQE

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

## CCQE-like=CC0pi




Fermilab Wine and Cheese Seminar, June 17 2016
Cheryl Patrick's PhD thesis



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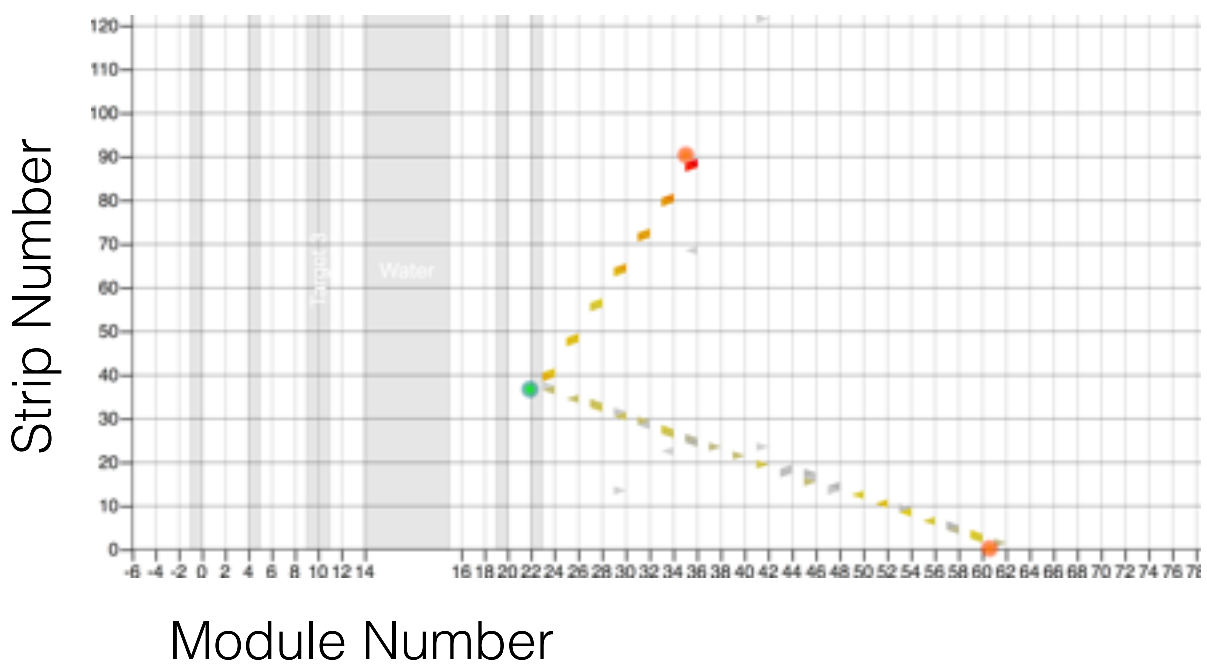
# CC0pi using the Proton Kinematics

- $Q^2$ is reconstructed using the leading proton from the event (different from the muon kinematic $Q^2$)
- Using the QE hypothesis and assuming scattering from a free nucleon at rest

$$Q^2 = (M')^2 - M_p^2 + 2M'(T_p + M_p - M')$$

- Measurement: differential cross section as a function of the proton $Q^2$



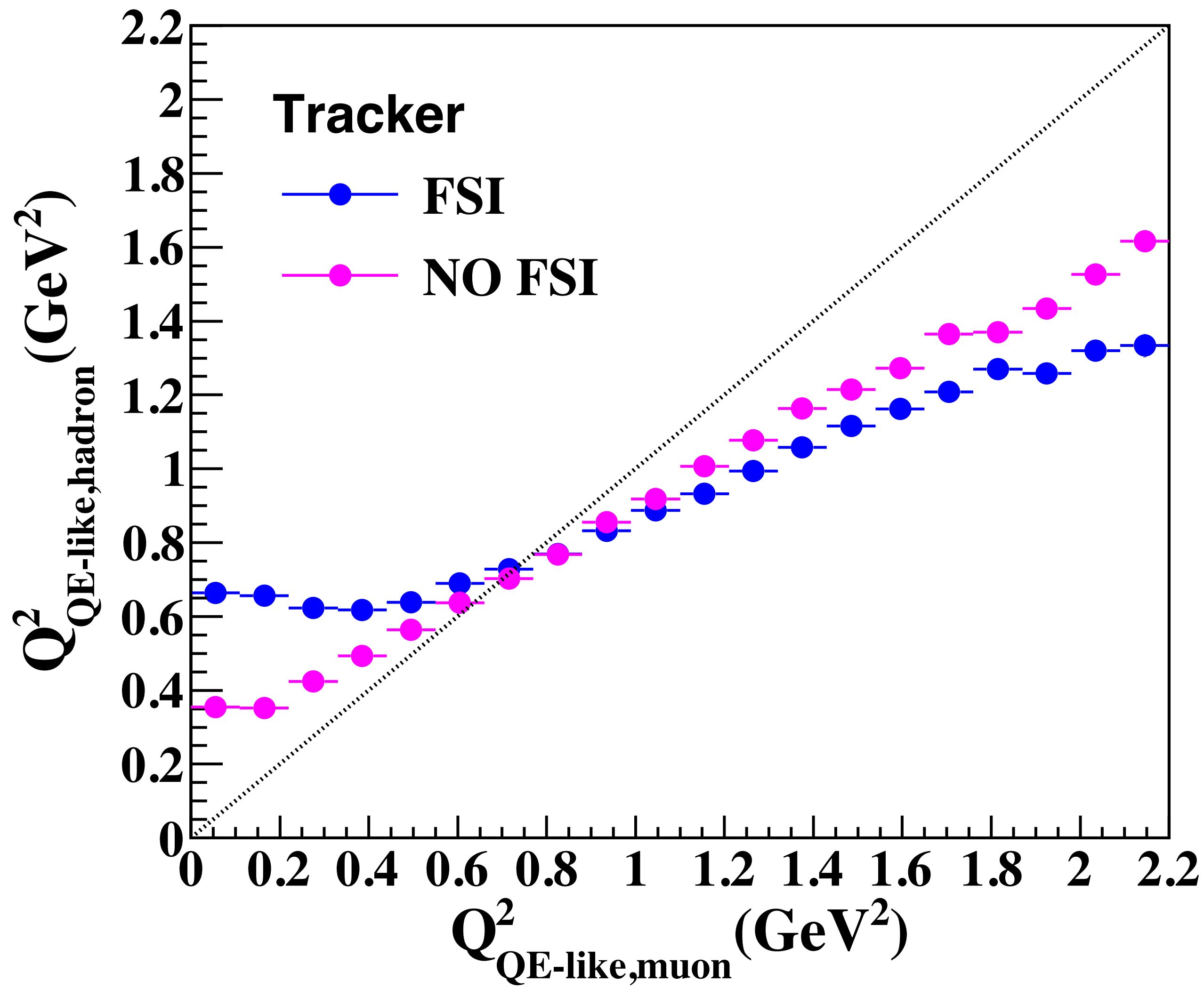

Signal (CCQE-like):
Events with one muon, no pions and at least one proton with momentum> 450 MeV/c

**CC0pi measurement on scintillator**
**Phys. Rev. D. 91, 071301, 2015**
**CC0pi new measurements on Iron, lead and Carbon**
**arXiv:1705.03791**

- Proton information allows to test FSI models

# Reconstructed Muon $Q^2$ vs Proton $Q^2$ (Plastic)

- Comparing the $Q^2$ reconstructed from muon kinematics and the $Q^2$ reconstructed from proton kinematics




GENIE simulation

$$Q^2_{hadron} = (M')^2 - M_p^2 + 2M'(T_p + M_p - M')$$

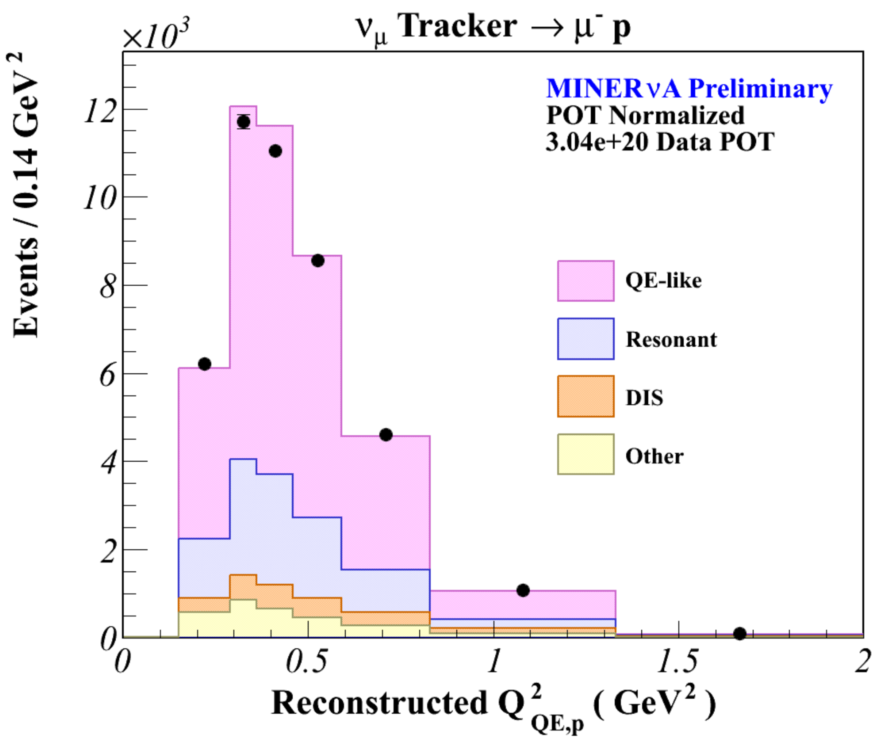
$$Q^2_{muon} = -m_\mu^2 + 2E_{QE}(E_\mu - p_\mu \cos\theta_\mu)$$

- $Q^2$ from proton kinematics is affected by final state interactions

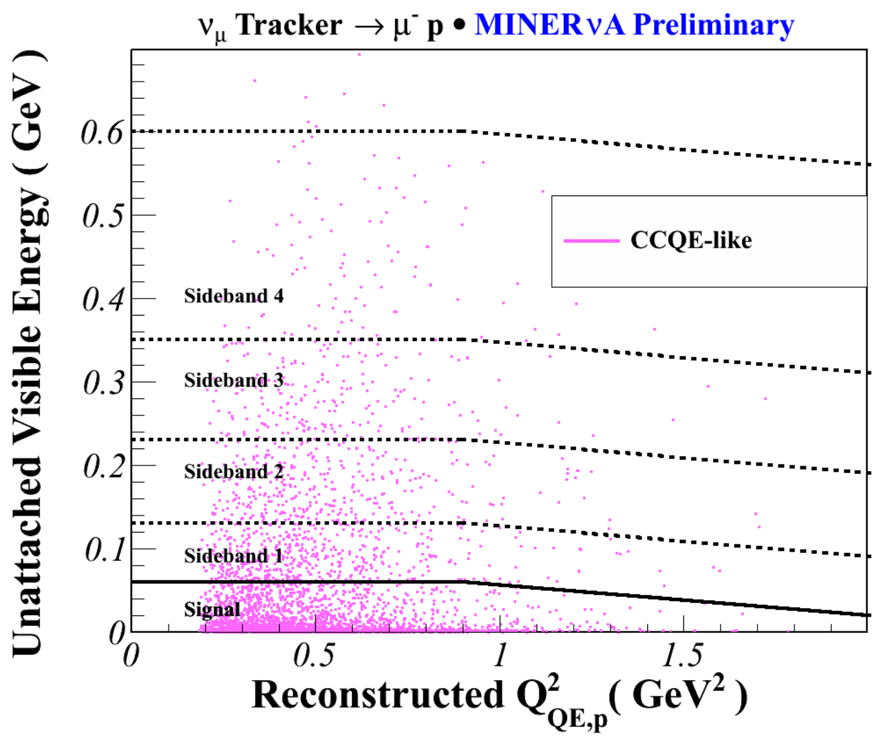
# Another Example for background constraints

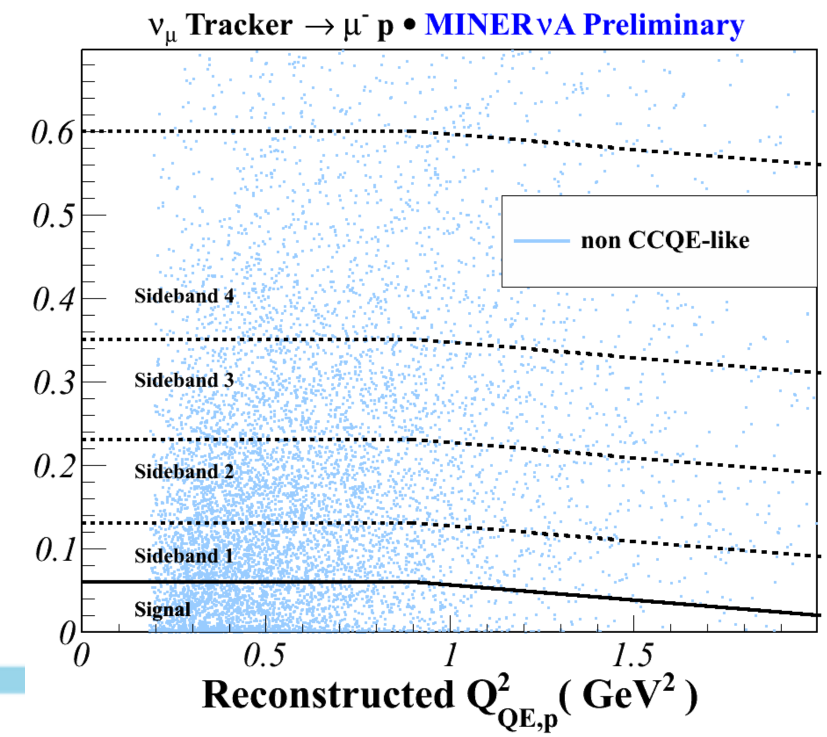
- Multi SideBand Technique to constrain the background
- $Q^2$ is reconstructed using the leading proton from the muon kinematic $Q^2$)
- Using the QE hypothesis and assuming scattering from

$$Q^2 = (M')^2 - M_p^2 + 2M'(T_p + M_p - M')$$



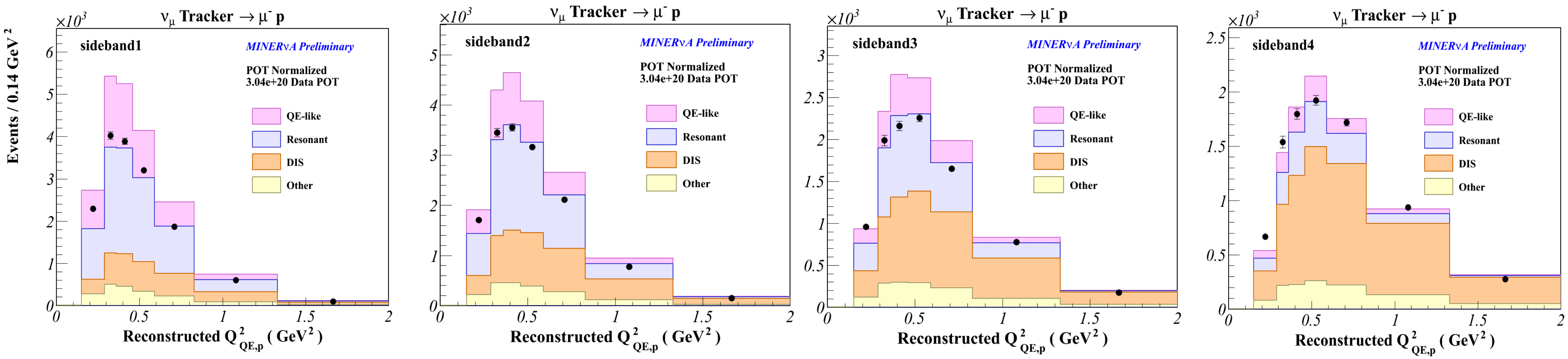

- Select four consecutive sidebands outside of the signal region



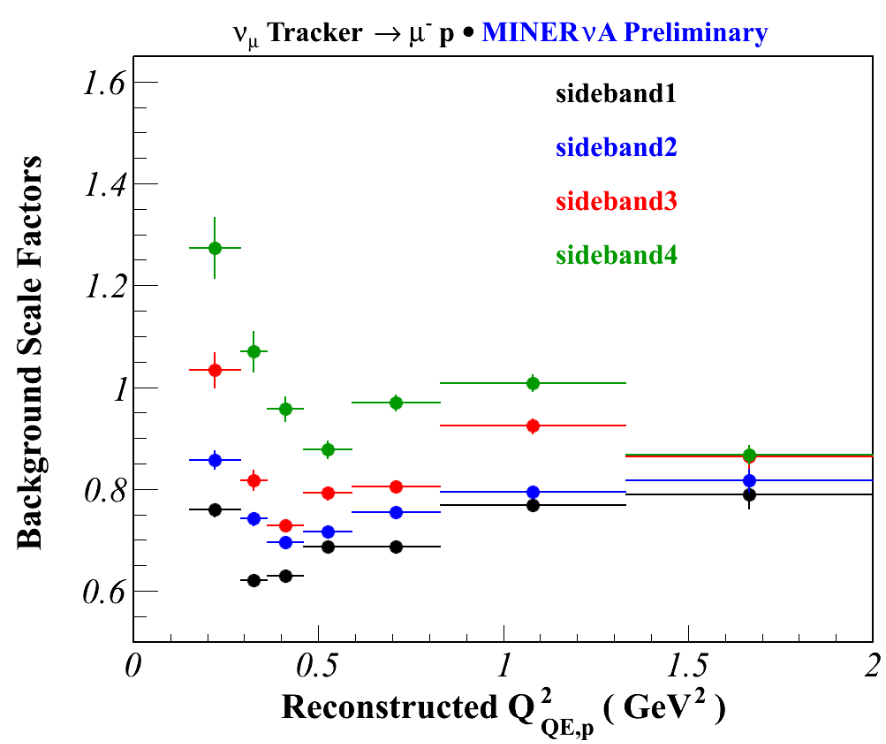



# Different SideBands

- For each sideband, extract weights that force the data and simulation to match perfectly

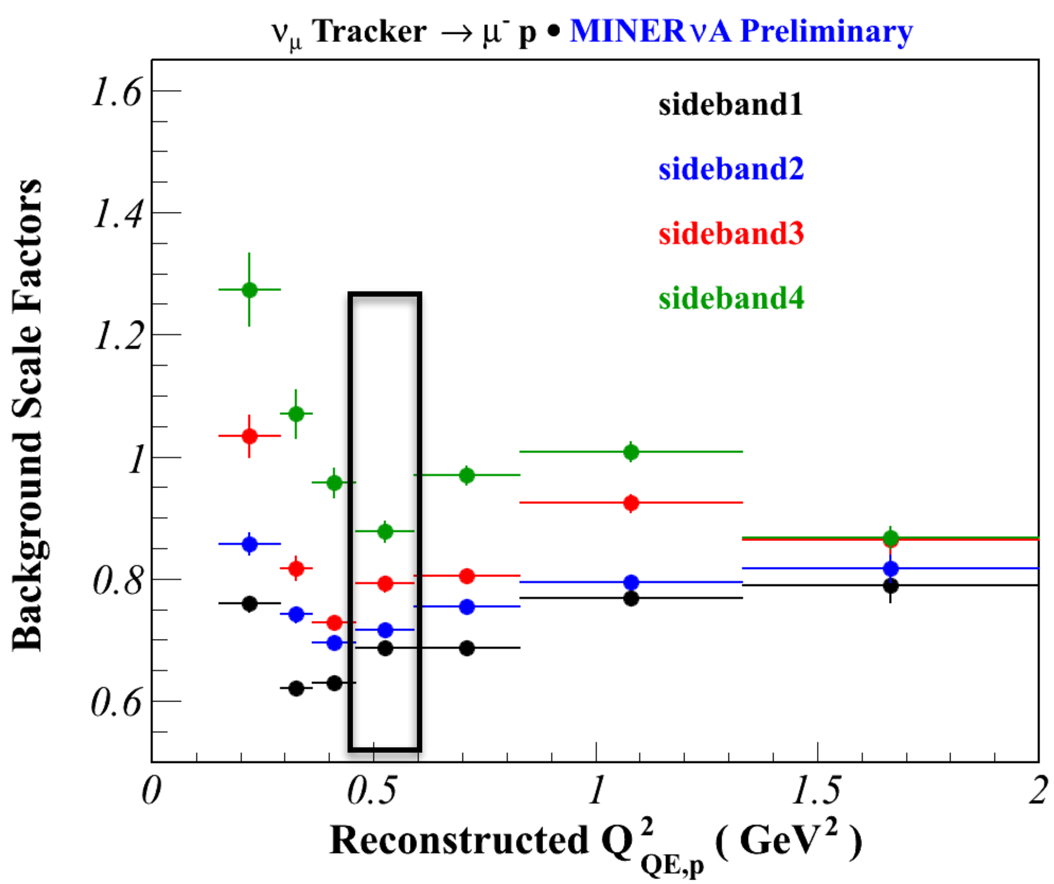


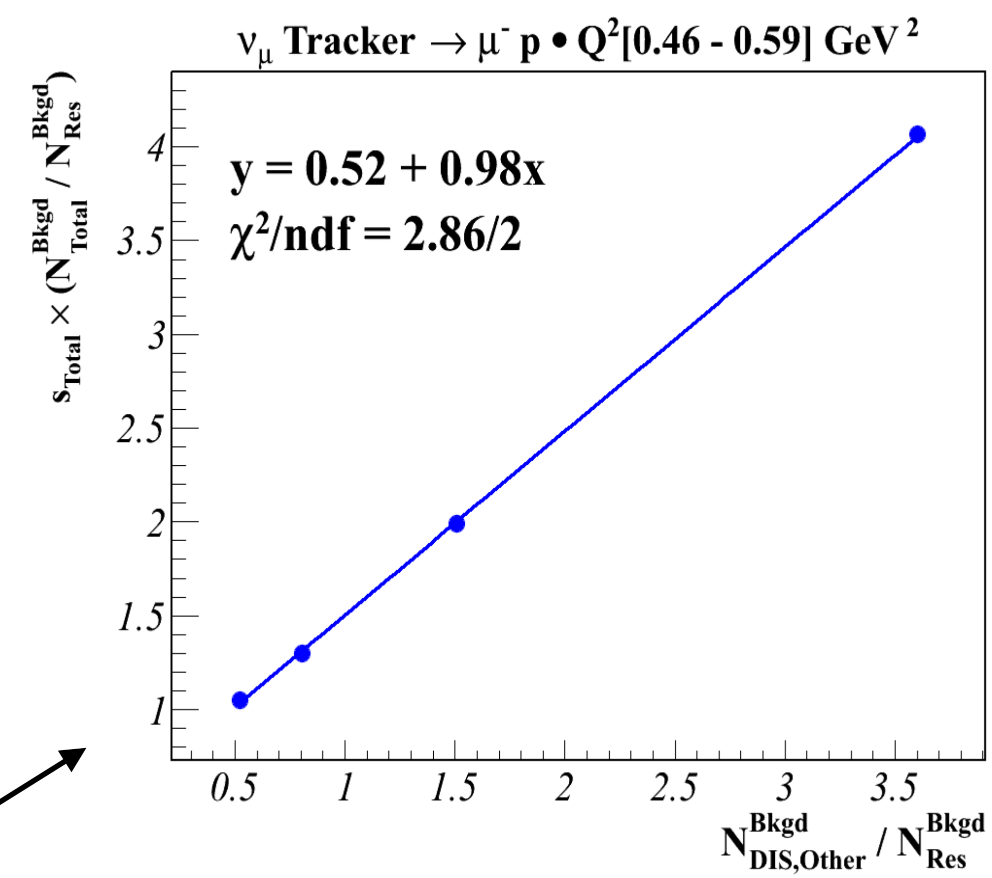

- Background factors for each sideband



# Extracting the factors

- Take all the sidebands from one bin of $Q^2$ and make a fit to straight line
- The fit extracts scale factors simultaneously for RES and DIS



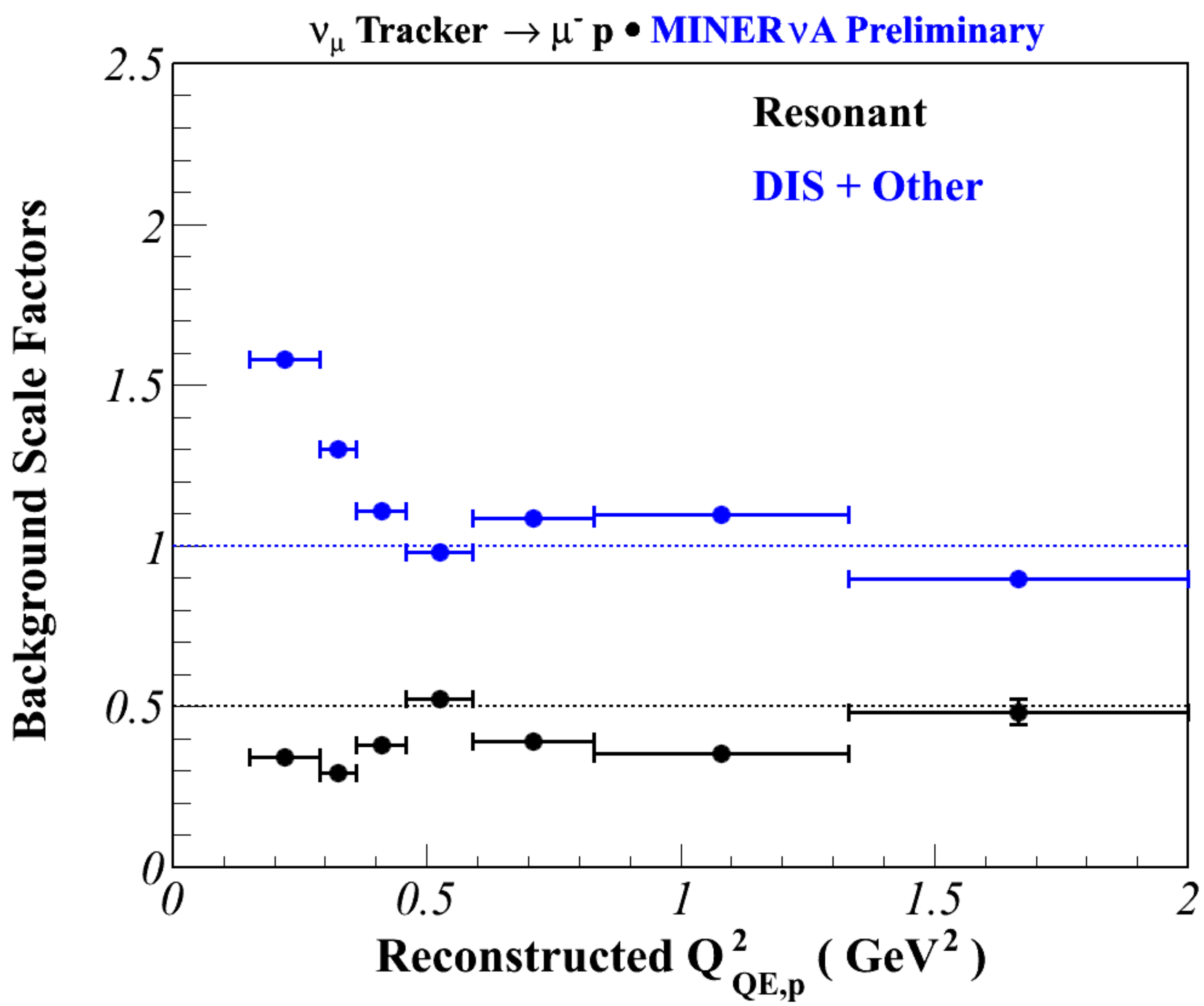




**slope = DIS scale factor**

**y-intercept = Resonant scale factor**

# Background Scale Factors

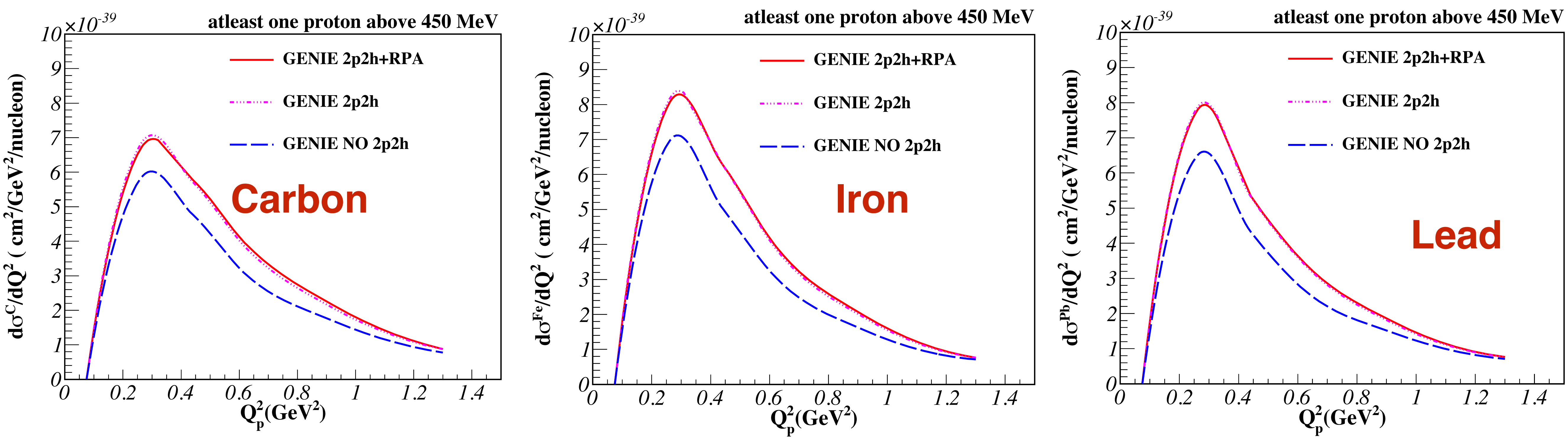
- Extracting scale factors for each bin of $Q^2$




- Example of the scale factors we apply to the simulation before the background subtraction

# Effect of 2p2h and RPA

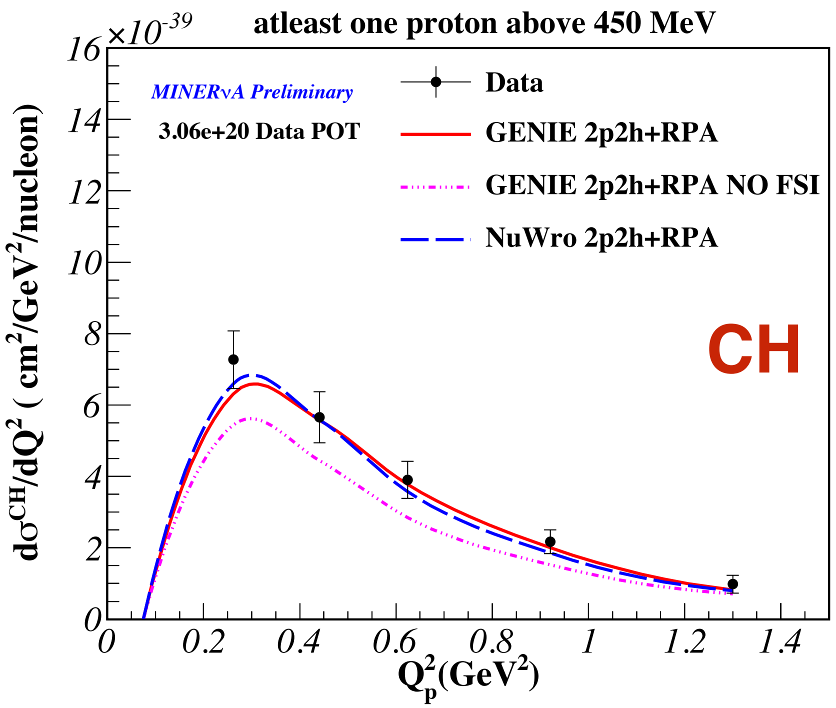
- Comparisons of differential cross sections with different simulations no 2p2h, 2p2h, and 2p2h+RPA

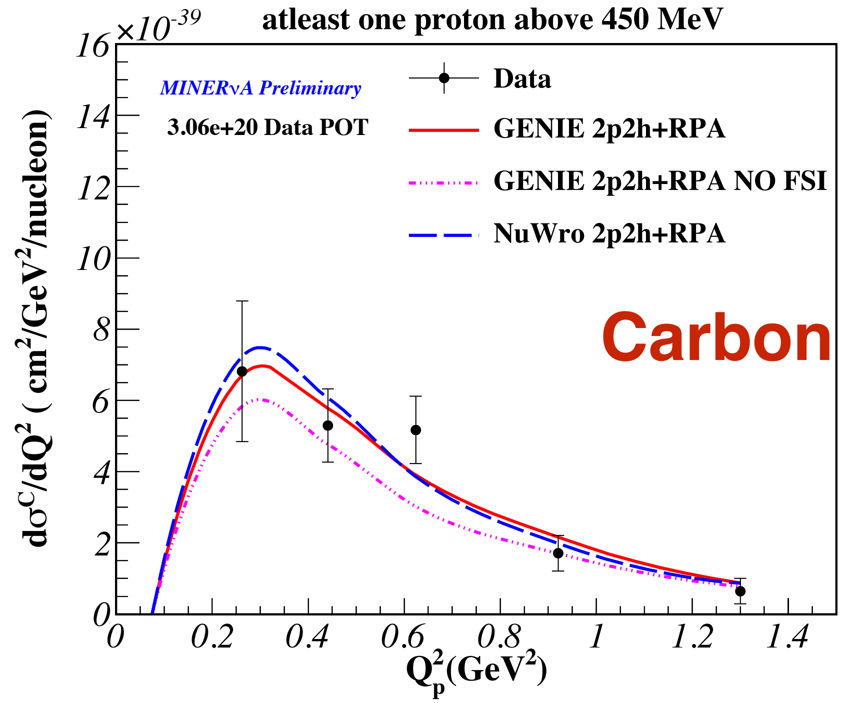



- There is an A dependence in the 2p2h model
- Most of the RPA suppression is below the proton threshold 450 MeV

# Comparing with Generators (GENIE vs NuWro)

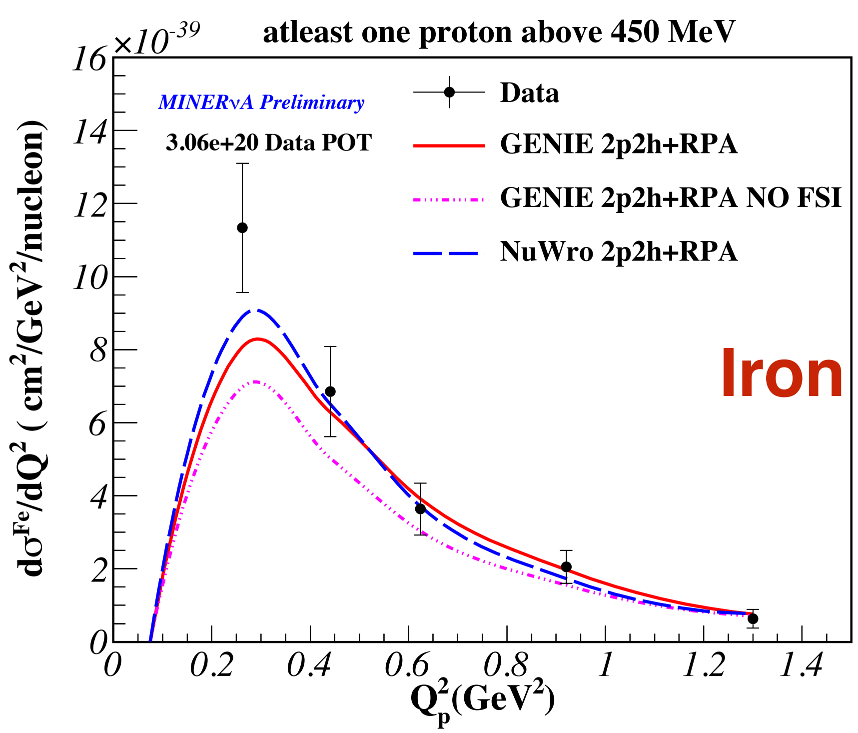
- Data prefers the simulation with final state interactions

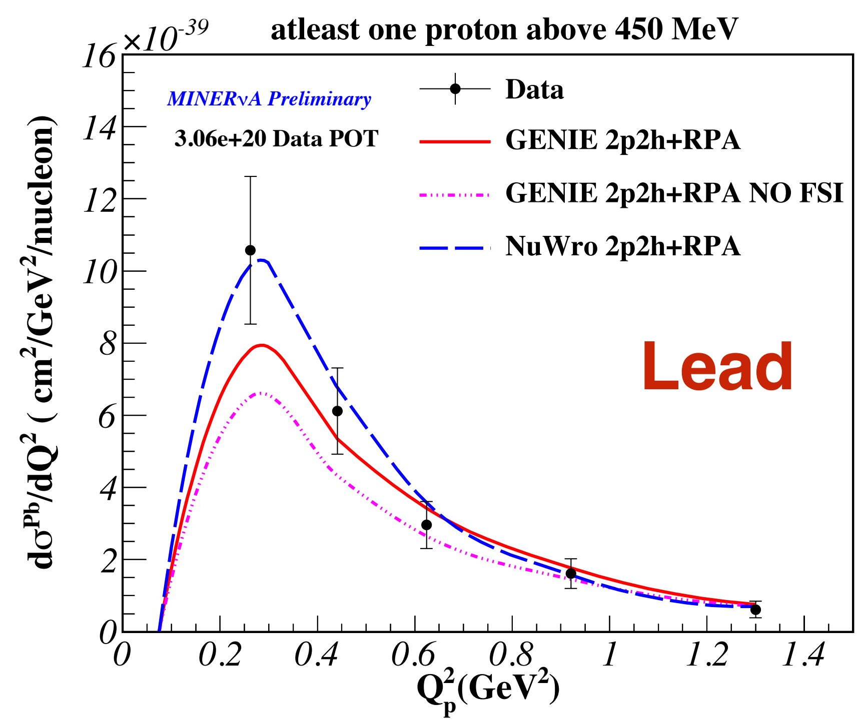



X²/d.o.f

| | carbon | iron | lead |
|---|---|---|---|
| GENIE | 5.9/5 | 19.9/5 | 17.5/5 |
| NuWro | 6/5 | 14.6/5 | 11.1/5 |



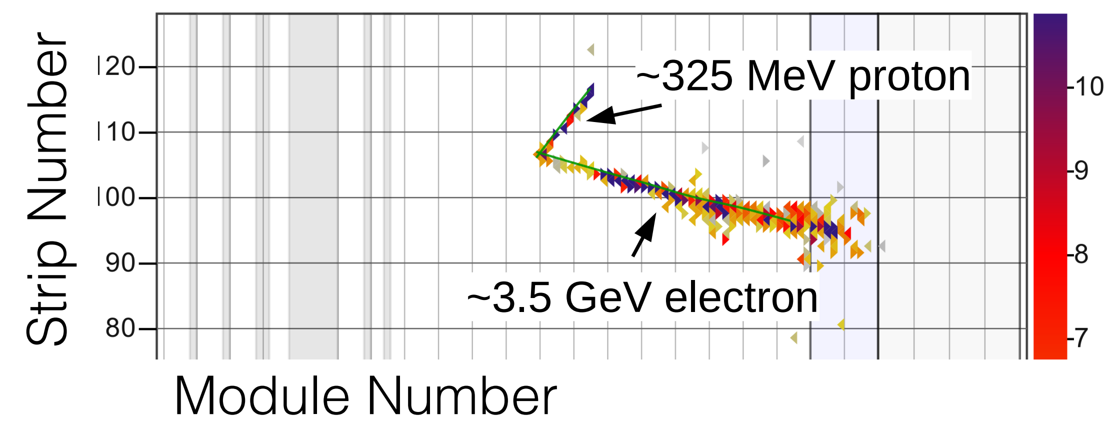

Phys.Rev.Lett. 119 (2017) no.8, 082001

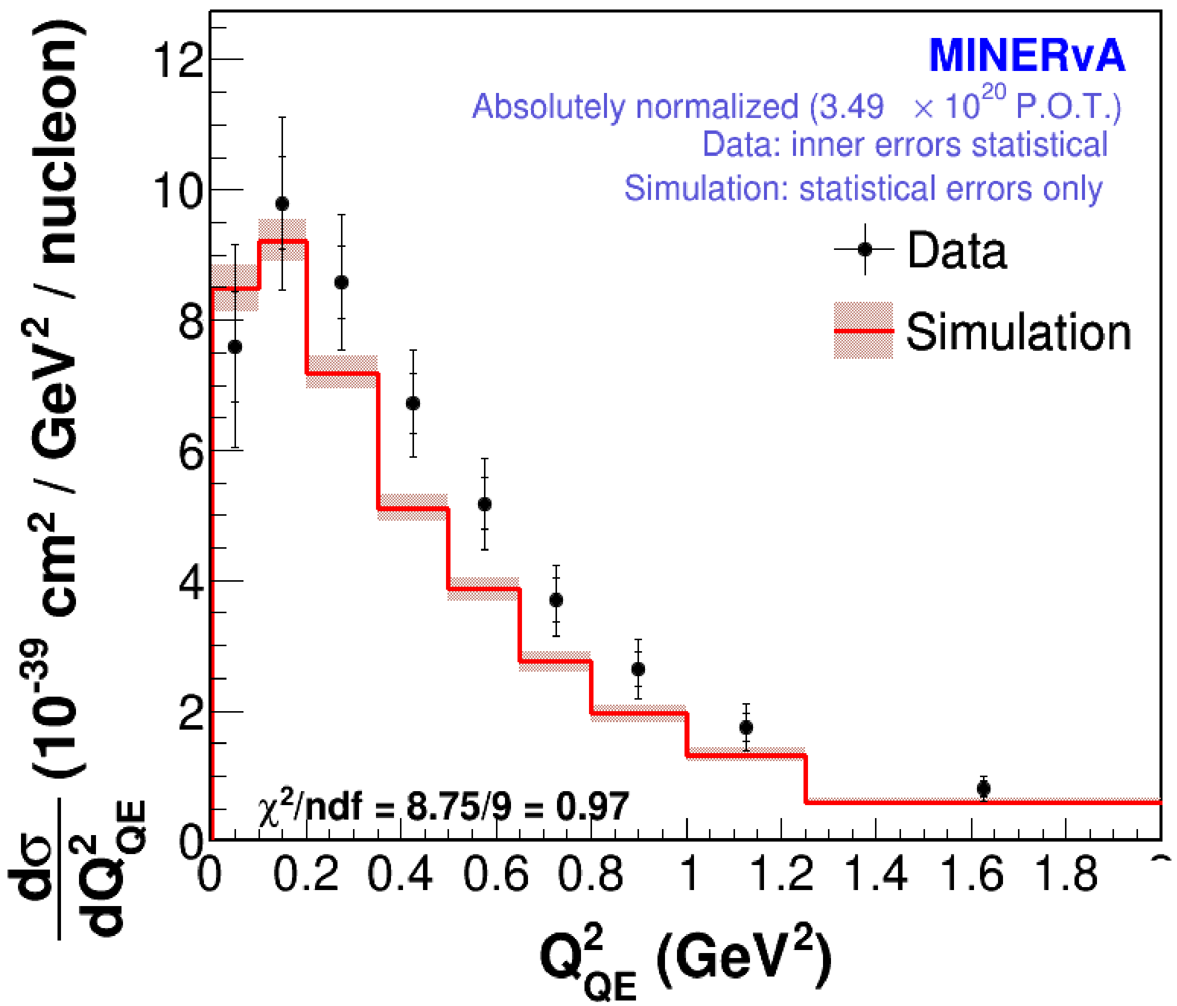
- The A dependence in NuWro seems to be more favored by the data

# ve CCQE Measurements

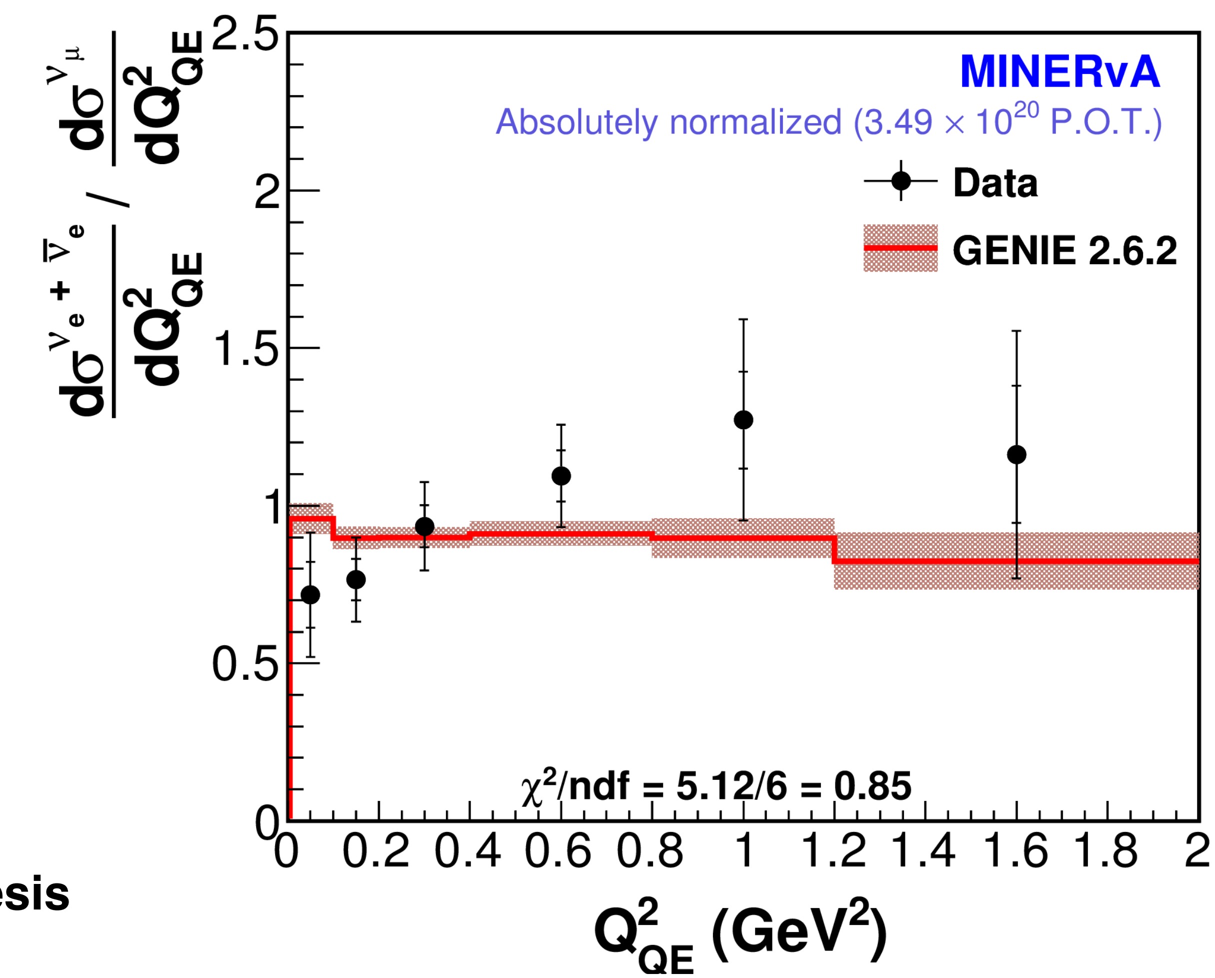
$$\pi^+ \to \nu_\mu \mu^+, \quad \mu^+ \to e^+ \nu_e \bar{\nu}_\mu$$

- Led the first electron neutrino CCQE analysis:
  - CCQE-like definition: any number of nucleons, but no other hadrons allowed in final state




## ve to vμ differential cross section ratio




Phys. Rev. Lett 116 (2016) 081802, Jeremy Wolcott's PhD thesis

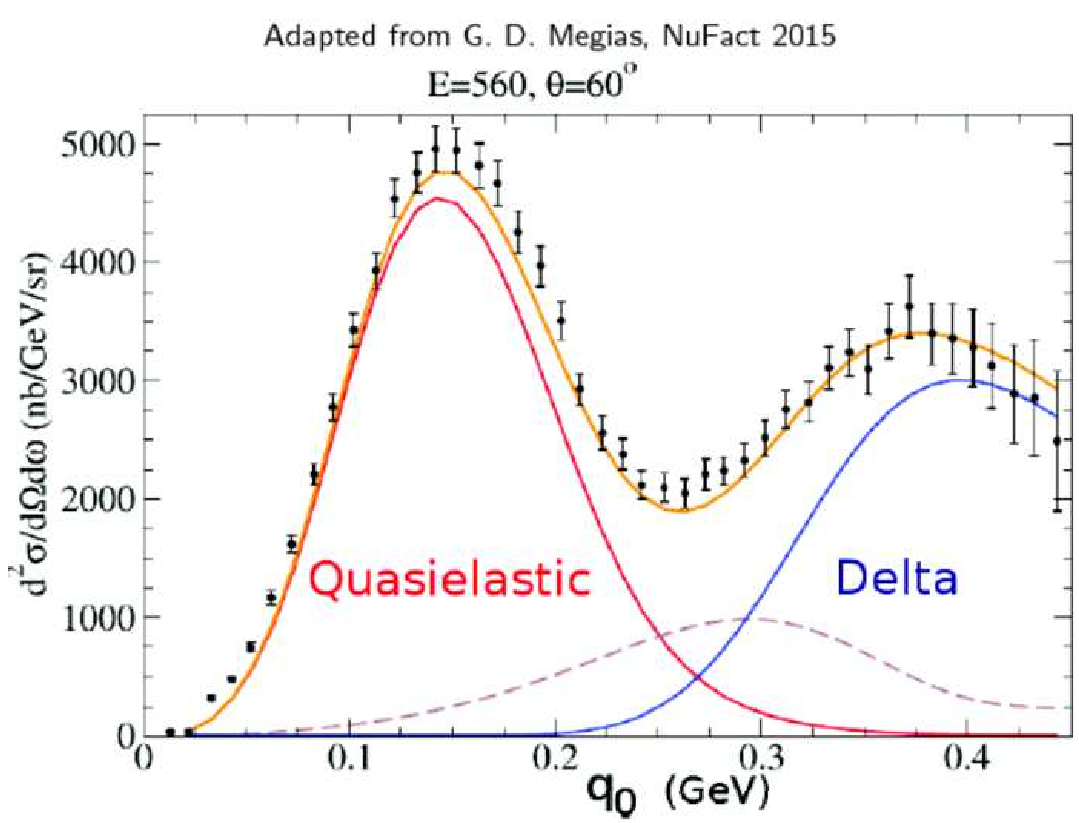
# Identification of Multinucleon Effects

- Inclusive CC double differential cross section in $q_0$ and $q_3$
  - $q_0$ is calorimetric hadronic energy and $q_3$ is the three momentum transfer where $Q^2$ is the four momentum transfer squared

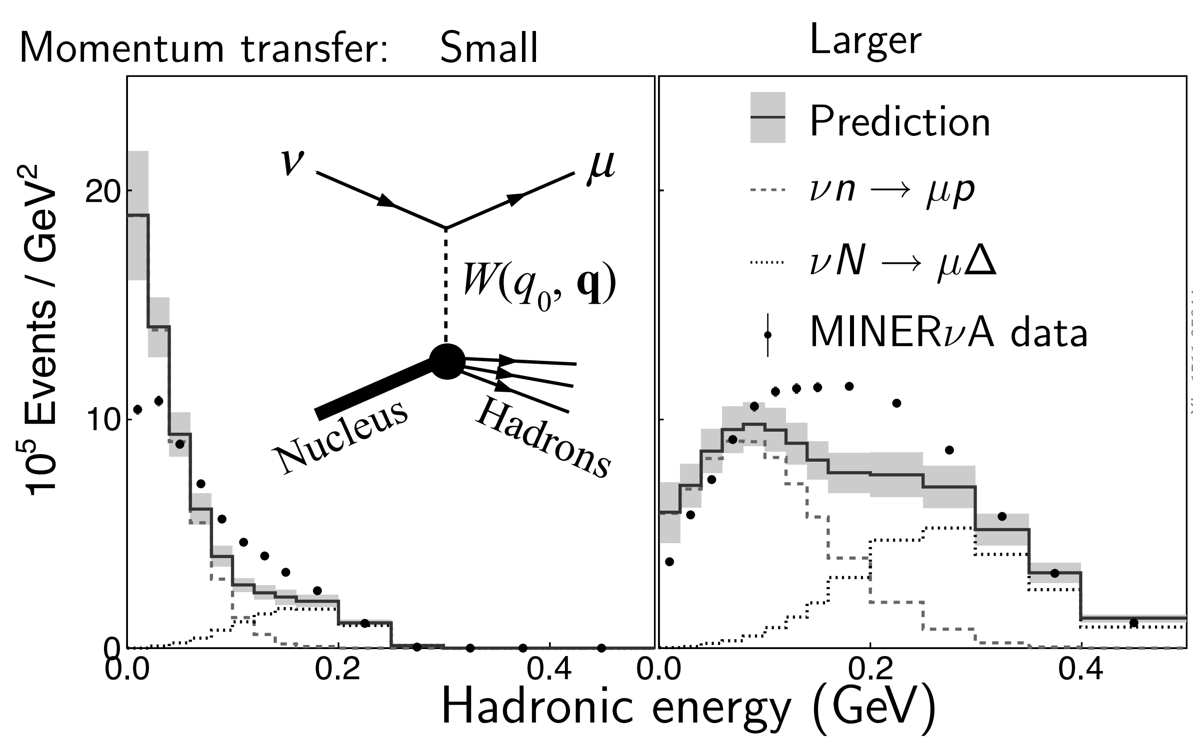
$$Q^2 = 2E_\nu(E_\mu - p_\mu \cos\theta_\mu) - M_\mu^2 \qquad E_\nu = E_\mu + q_0 \qquad q_3 \equiv |\mathbf{q}| = \sqrt{Q^2 + q_0^2}$$

From electron scattering

Similar measurement for neutrinos using the hadronic system and the lepton



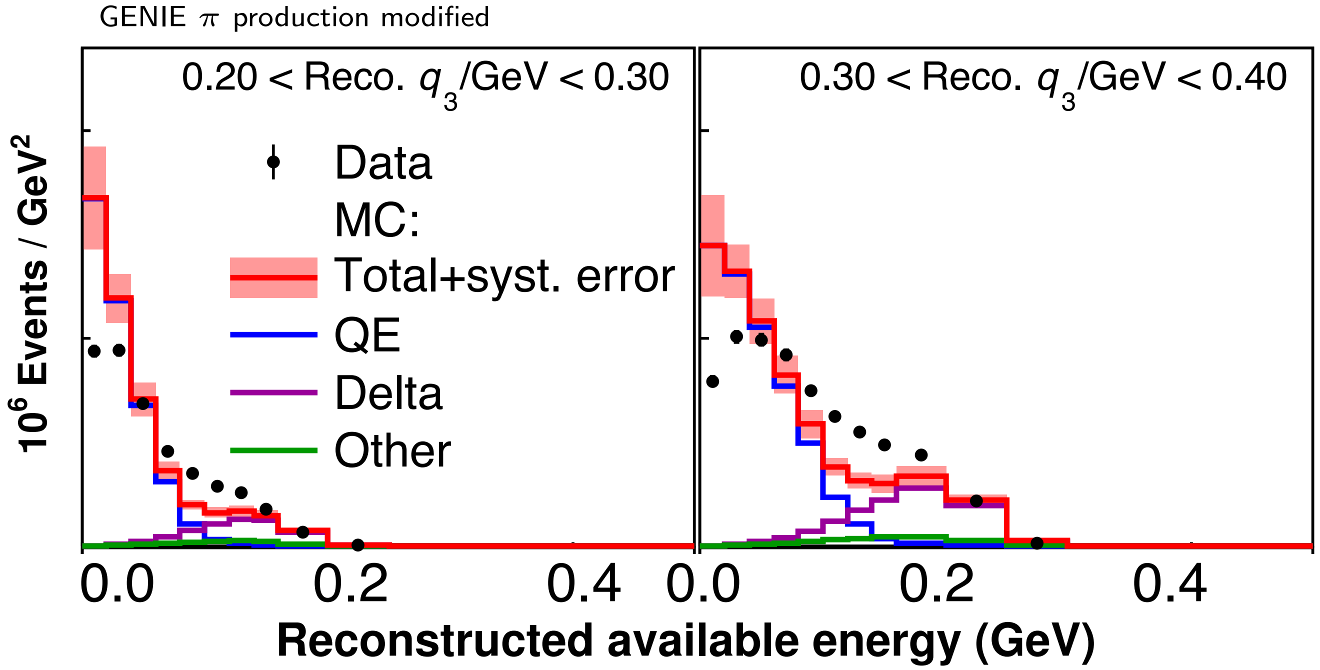

$$q_0 = E_e - E_{e'}$$



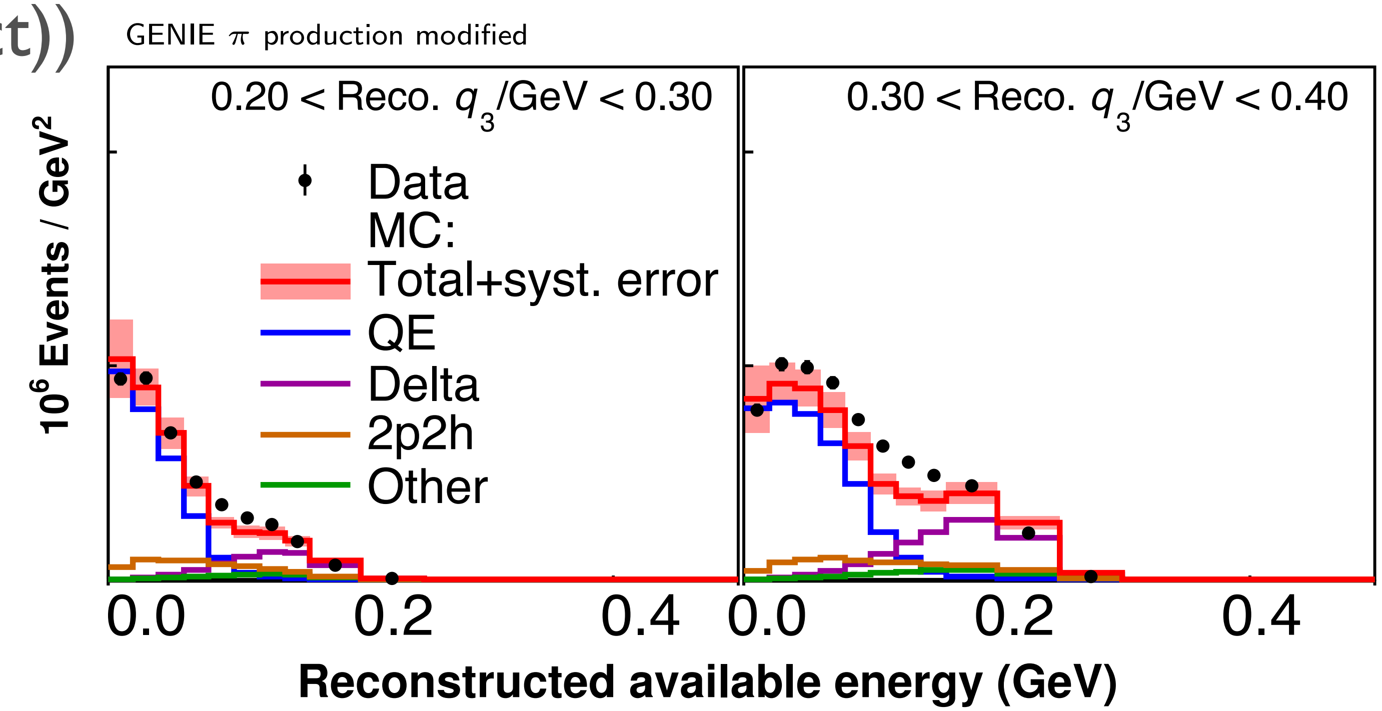

**Phys. Rev. Lett. 116 (2016) 071802**

# Nuclear Effects at low Three Momentum Transfer

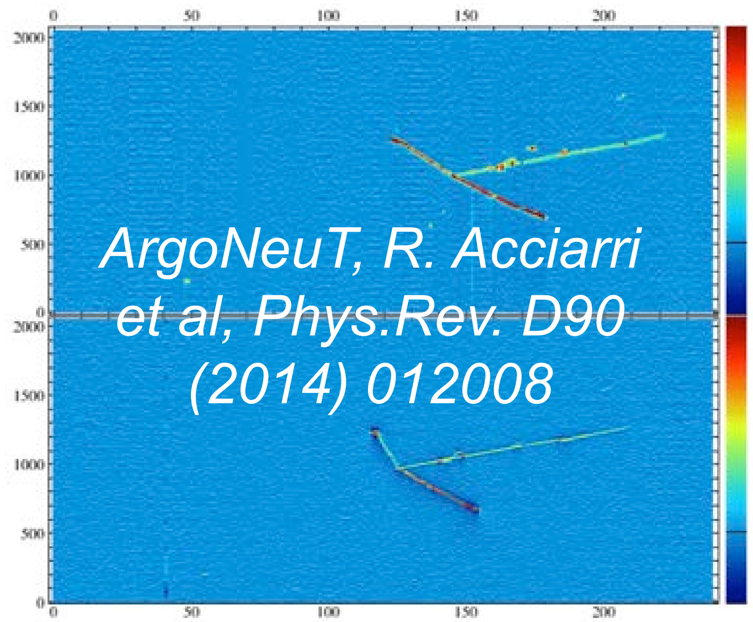
- Default nuclear model struggles to explain data

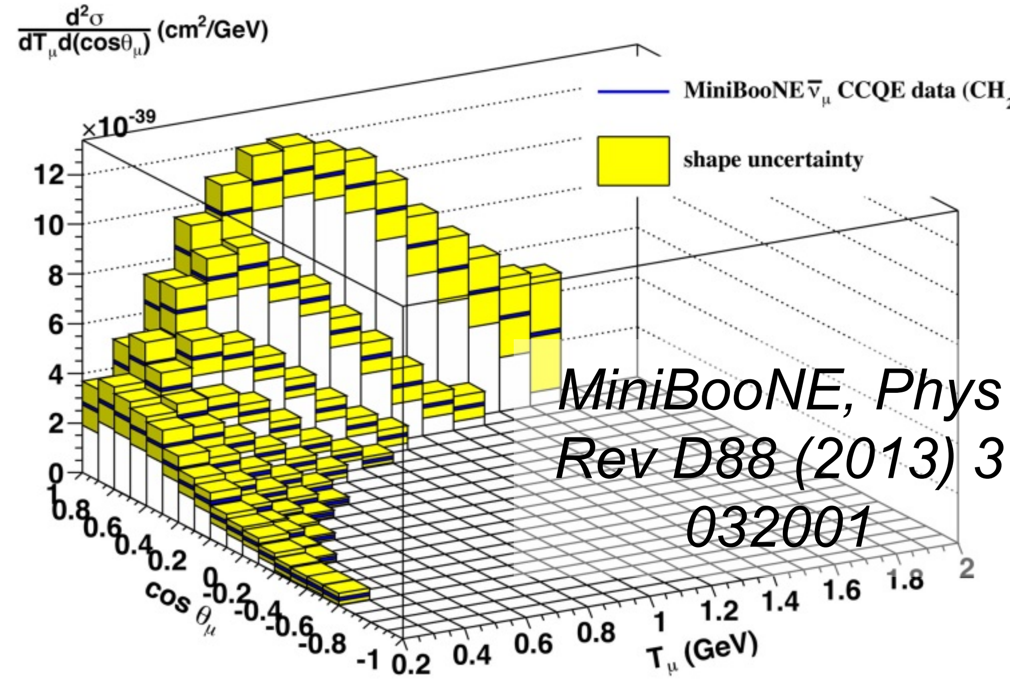



- Including more sophisticated nuclear models: (2p2h effects and RPA (a charge screening effect))

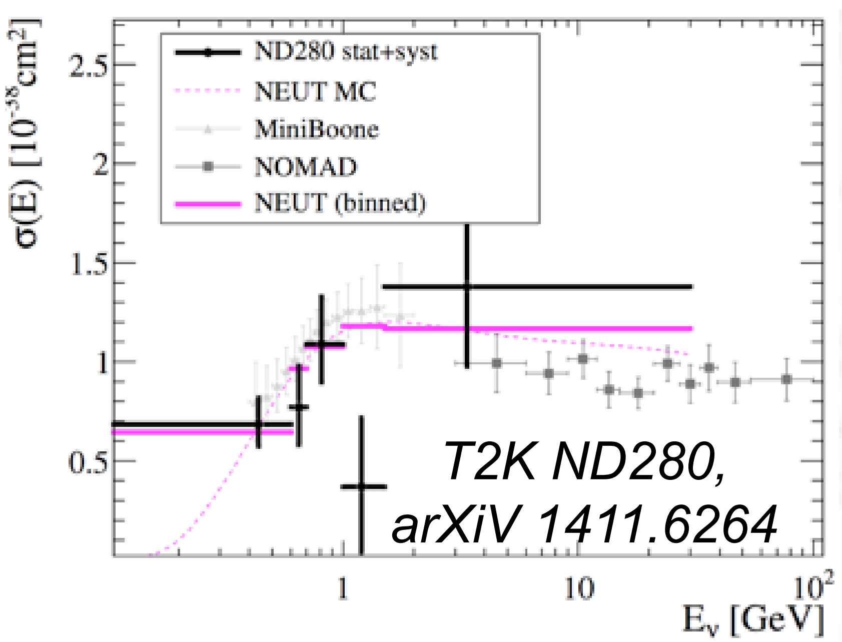


# Many Measurements

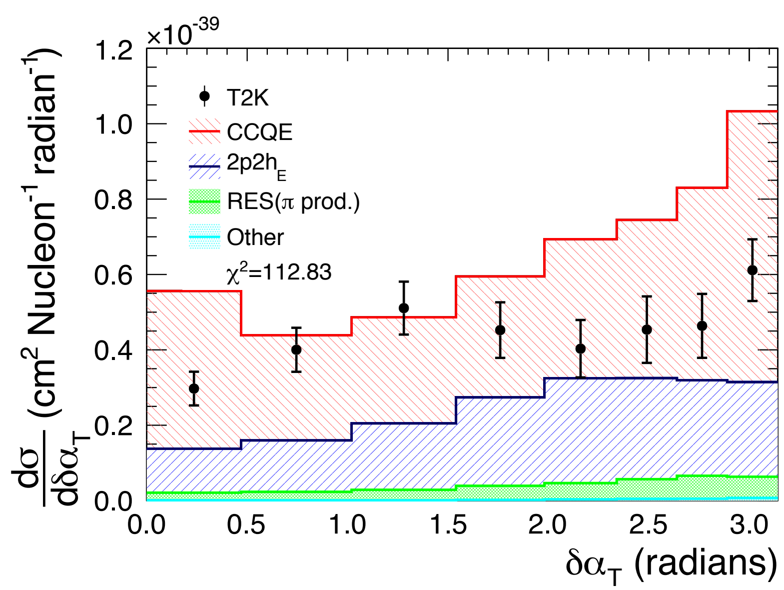

ArgoNeuT, R. Acciarri et al, Phys.Rev. D90 (2014) 012008



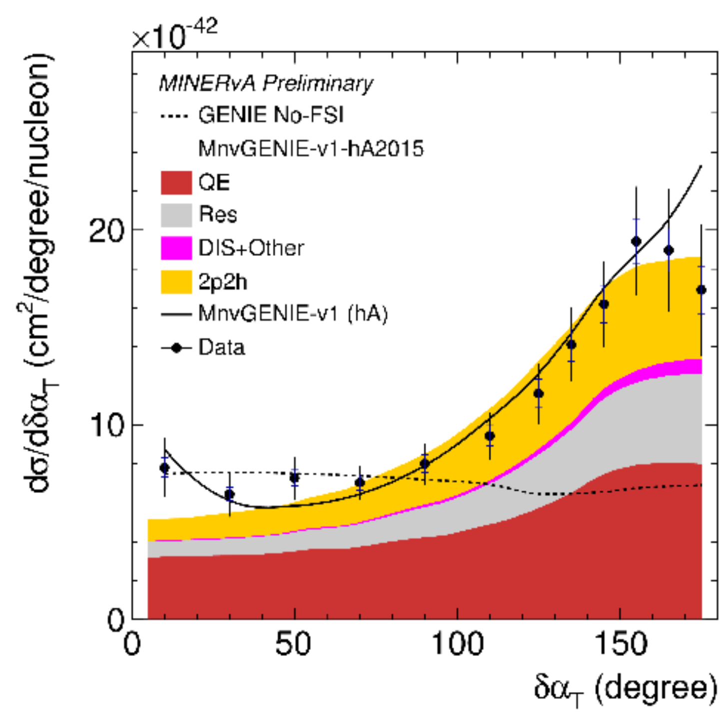
MiniBooNE, Phys Rev D88 (2013) 3 032001



T2K ND280, arXiV 1411.6264



T2K arXiv 1802.05078

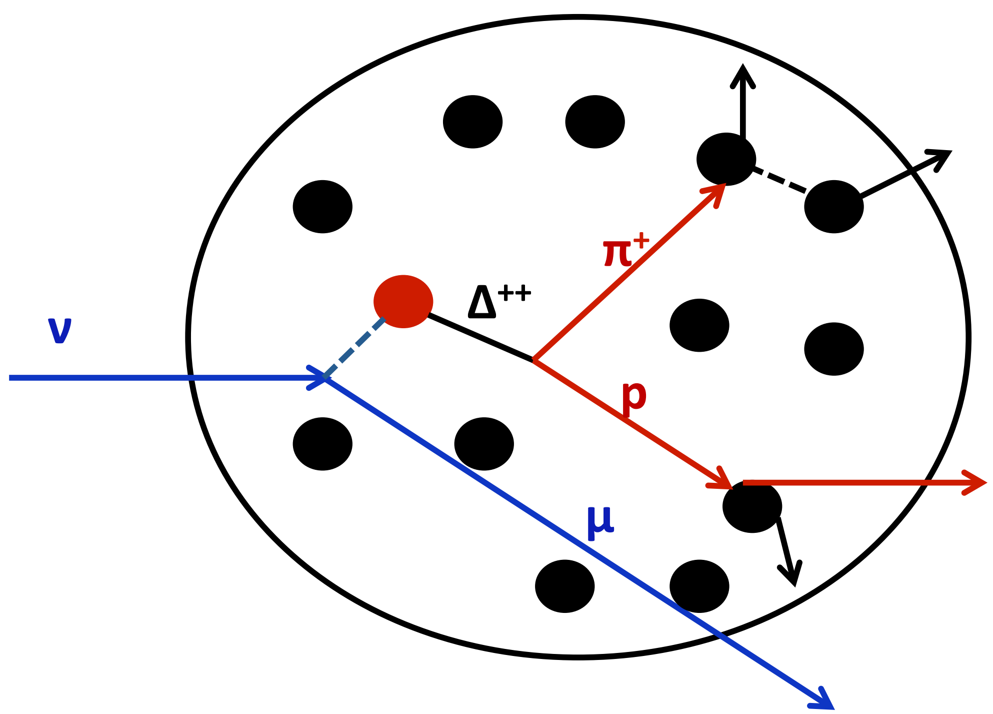


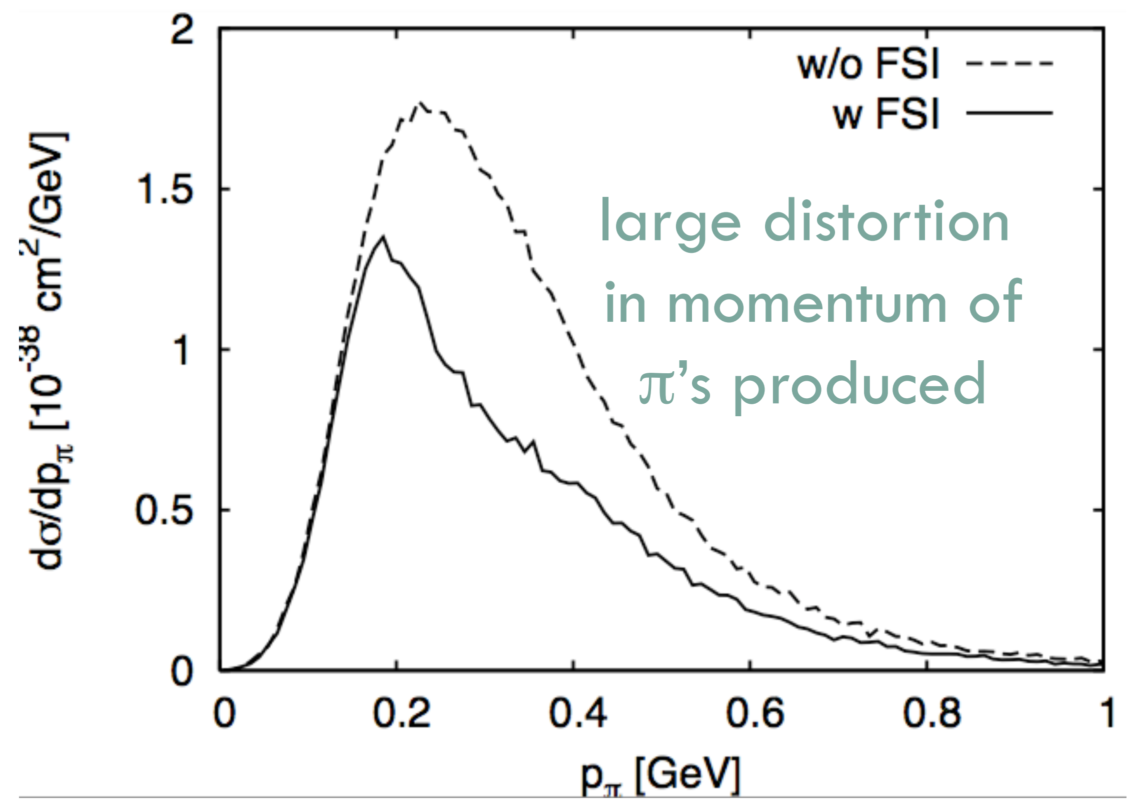
MINERvA arXiv 1805.05486

## As an example of final state interaction effects, let's review a couple of examples from pion production

# Final State Interactions

- Final state interactions: Hadrons produced in a scattering interaction re-interact with other nucleons before they escape the nucleus
- Thus the particles that exit the nucleus my be different, both in type and in energy from those generated in the initial interaction
- Final states where pion is absorbed can contribute to apparent "quasi-elastic" scattering
- These effects are big

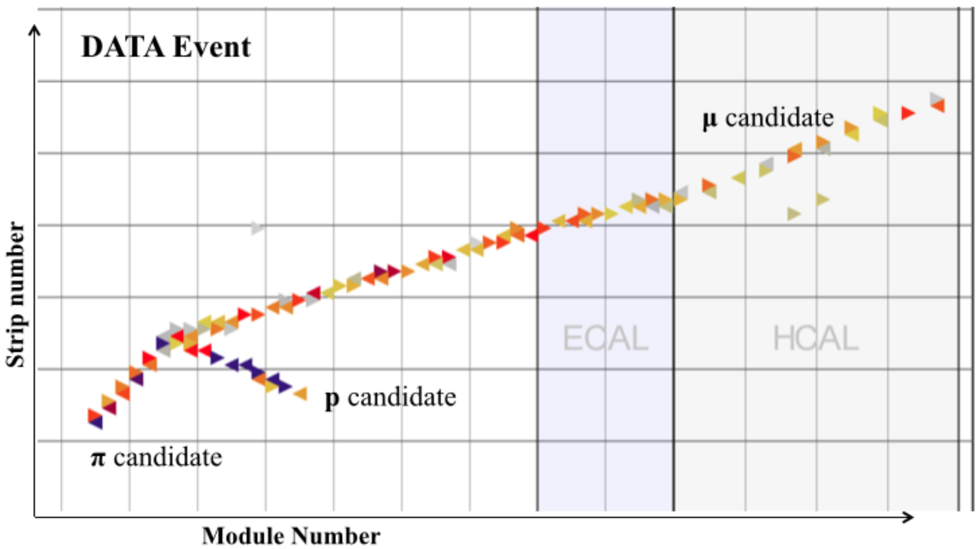


# Charged current pion production

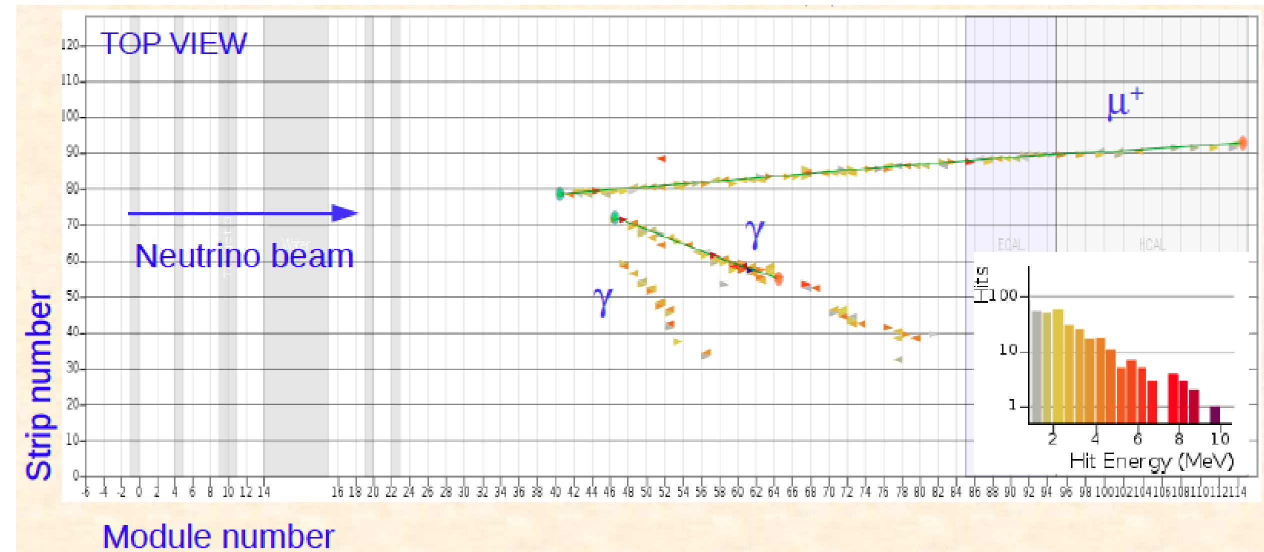
- Charged pion production

$$\nu_\mu + \mathrm{CH} \rightarrow \mu^- + n\pi^\pm + X$$




- Neutral Pion production

$$\bar{\nu}_\mu + \mathrm{CH} \rightarrow \mu^+ + \pi^0 + X'$$

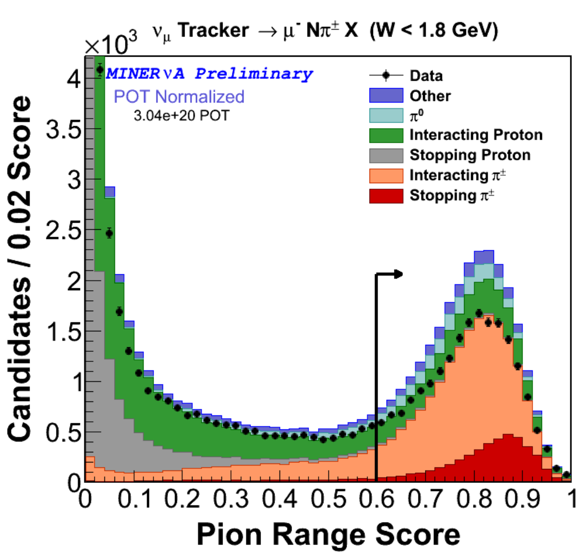



$$E_\nu = E_\mu + E_H \ (E_H \text{ determined calorimetrically})$$

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

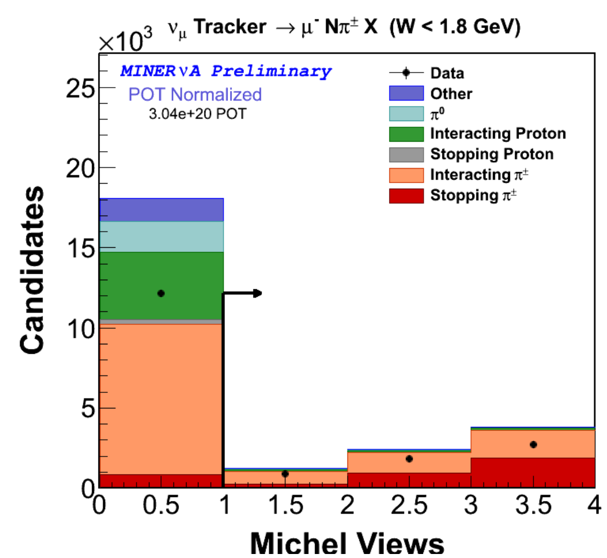
$$W_{exp}^2 = -Q^2 + m_N^2 + 2m_N E_H \ (m_N \text{ nucleon mass})$$

$$W_{gen} : W_{exp} \text{ w/o the assumption of a nucleon at rest}$$



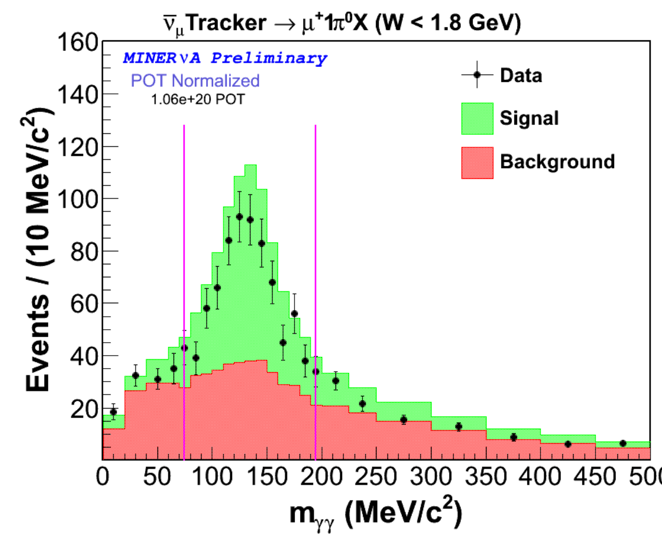

Pion identification

Use energy loss (dE/dx) profile of each hadron track to separate pions from protons




Michel electron

$$\pi^+ \rightarrow \mu^+\nu_\mu, \mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu$$

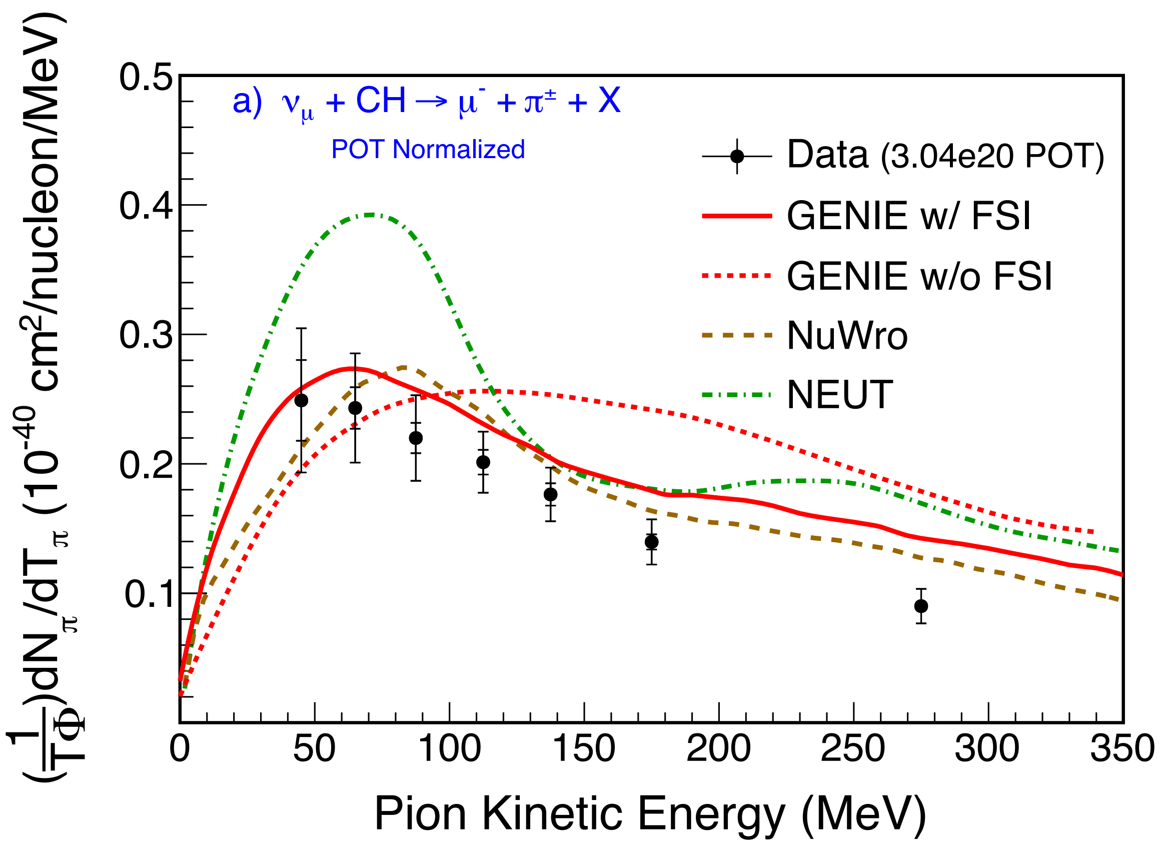


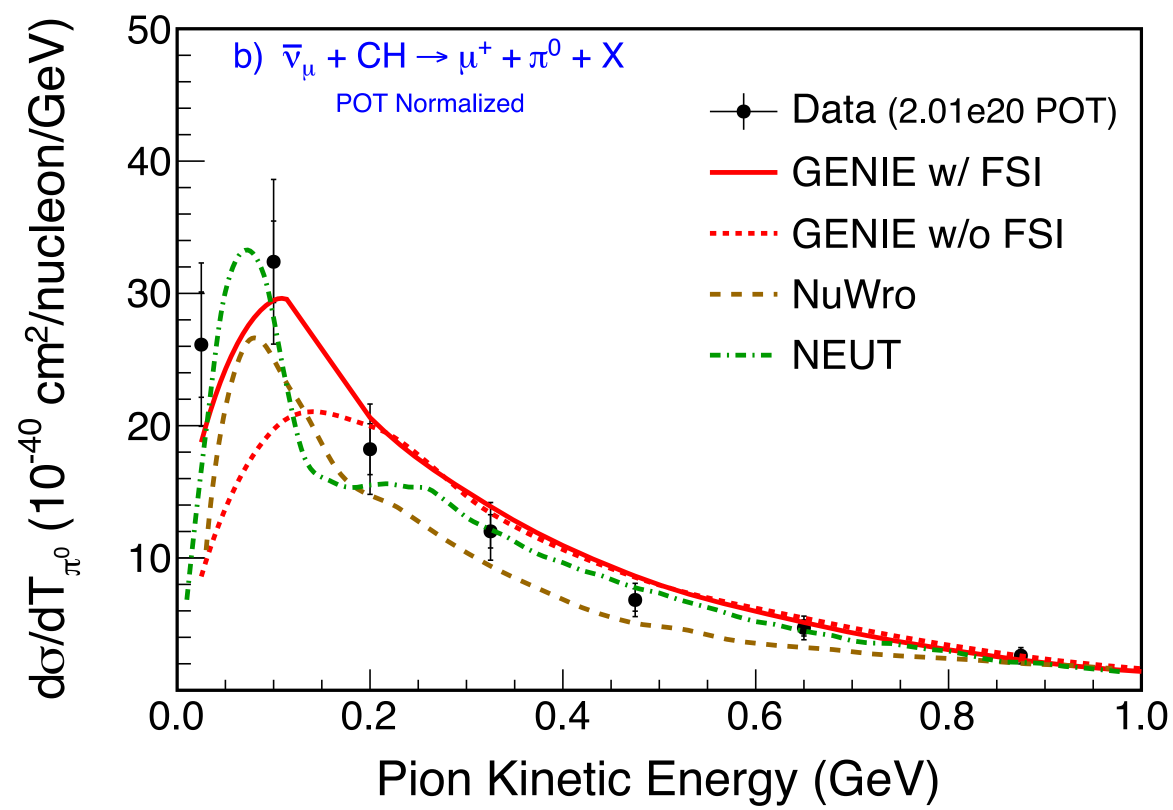

Di-photon Invariant Mass

$$M_{\gamma\gamma} = 2E_1E_2(1 - \cos\theta_{\gamma\gamma})$$

# Differential Cross Section as Function of Kinetic Energy

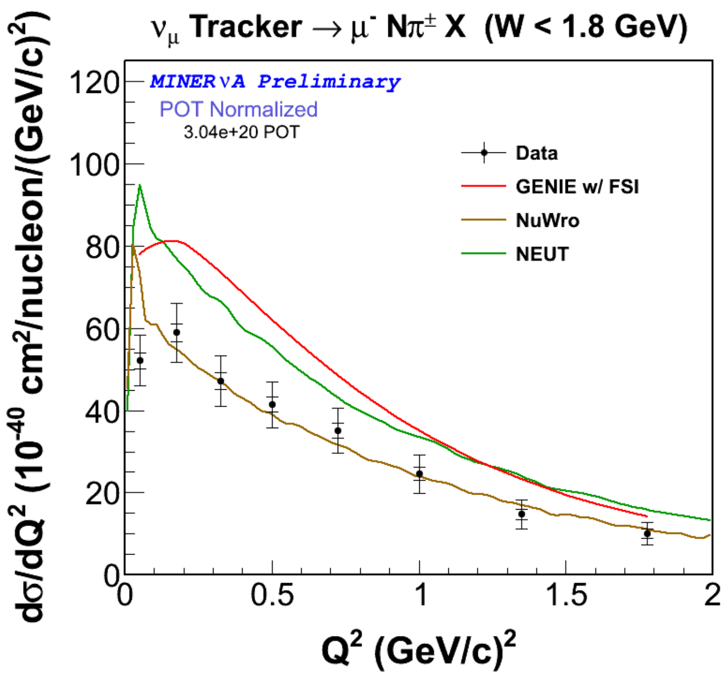
- Data compared with different simulations including simulation with FSI and without FSI

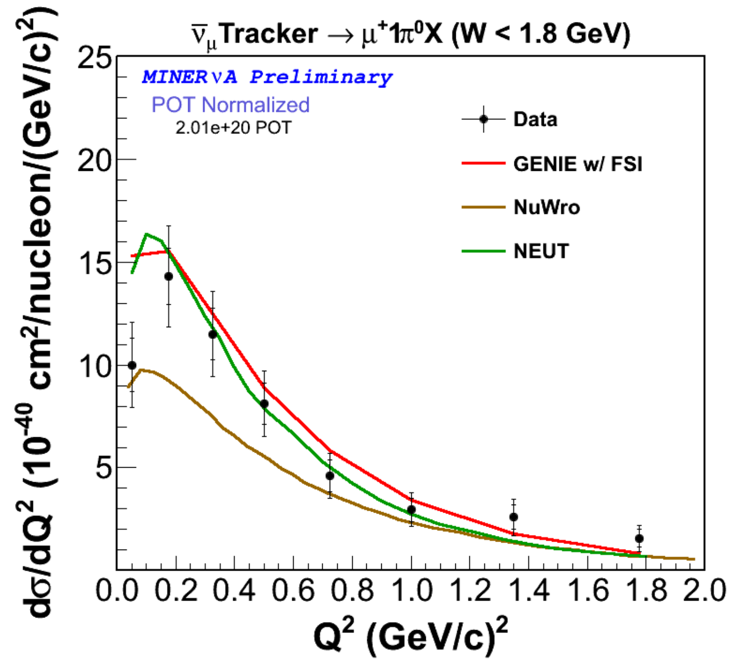


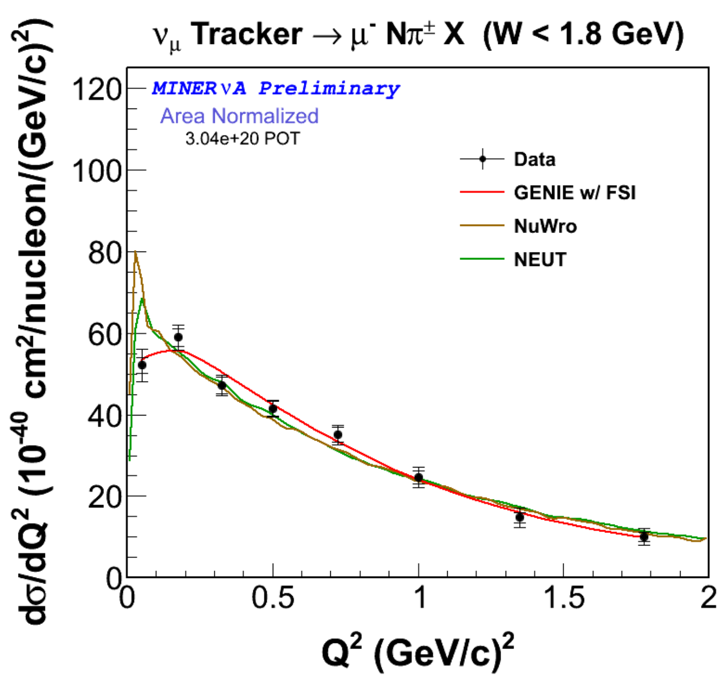

**Phys.Rev. D94 (2016) no.5, 052005**

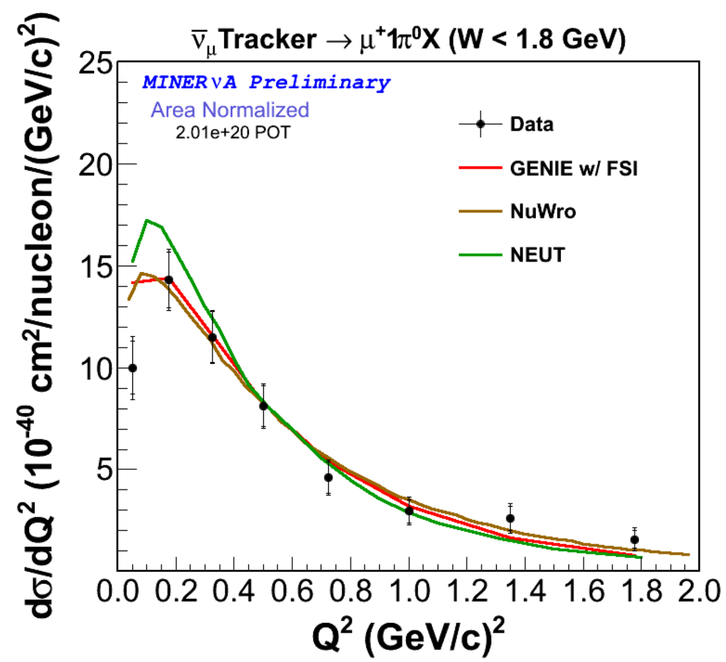
# Differential Cross Section as a Function of $Q^2$




## Shape comparisons

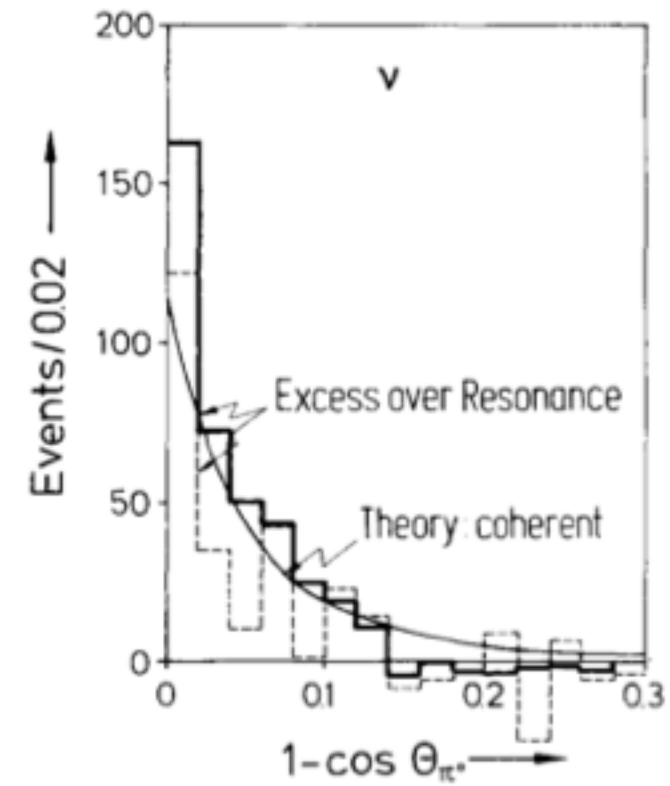



Fermilab

# Coherent Pion Production by Neutrinos

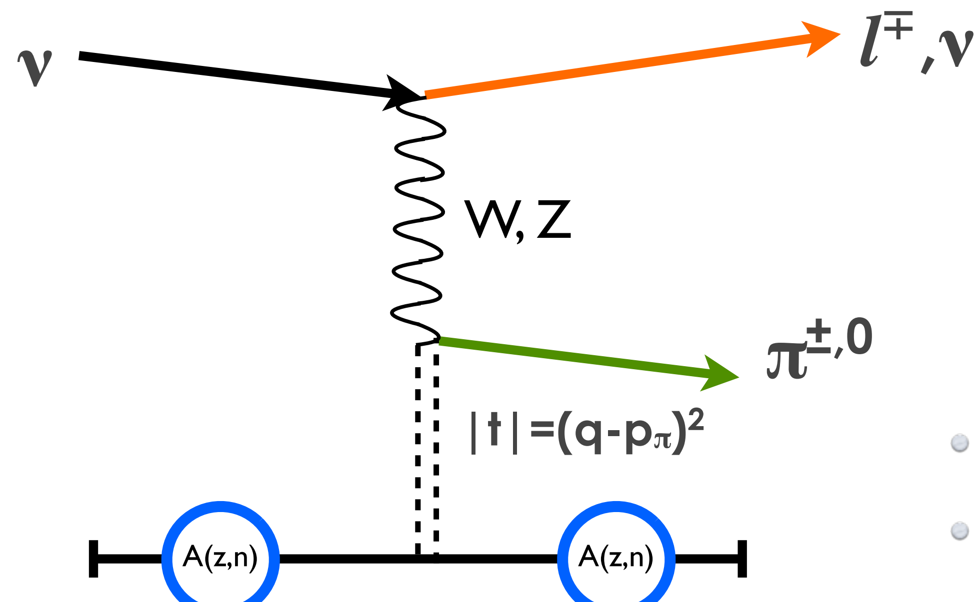
- In 1978 the Aachen-Padova measured the ν+A→ν+A+ $\pi^0$ for the first time
- In 1782 the coherent production of a $\pi^0$ in a neutrino interaction was proposed by D. Rein and L. Sehgal (Nucl. Pays. B223. 1983)




$$\nu_l(k) + A(p) \rightarrow l^-(k') + A(p') + \pi^+(p_\pi)$$

- Experimental signature
  - Two final state particles $l^{\mp}$+ $\pi^{\pm,0}$
  - Small transfer momentum to the nucleus,

    $|t| = (q - p_\pi)^2$
  - No visible recoil



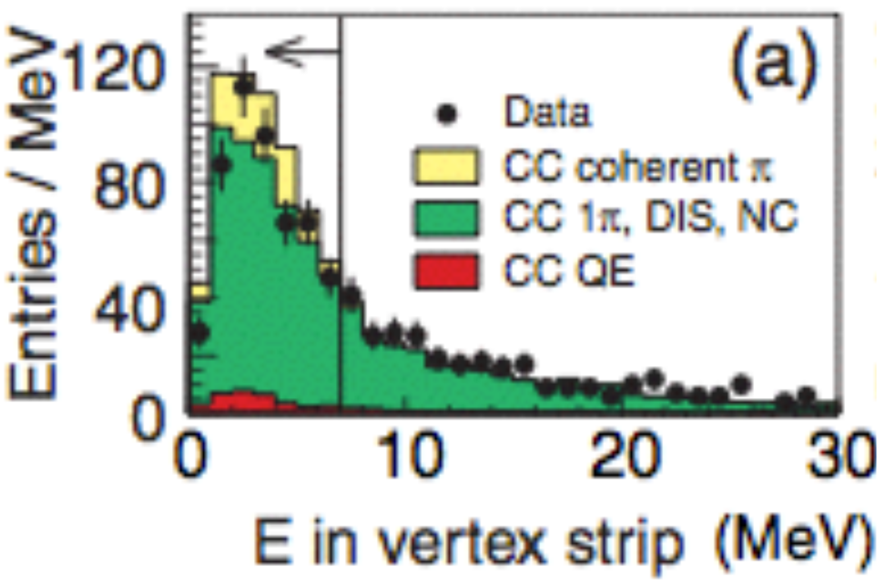
# Coherent Pion Production Previous Measurements

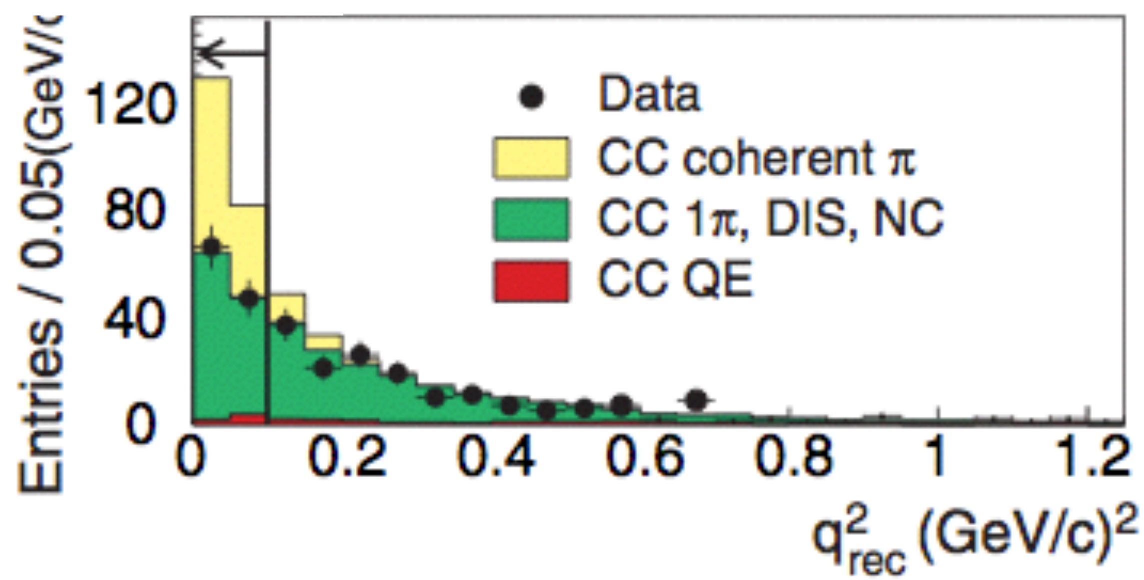
K2K experiment (CH) <E$_\nu$> = 1.3 GeV

**No evidence for coherent pion production**

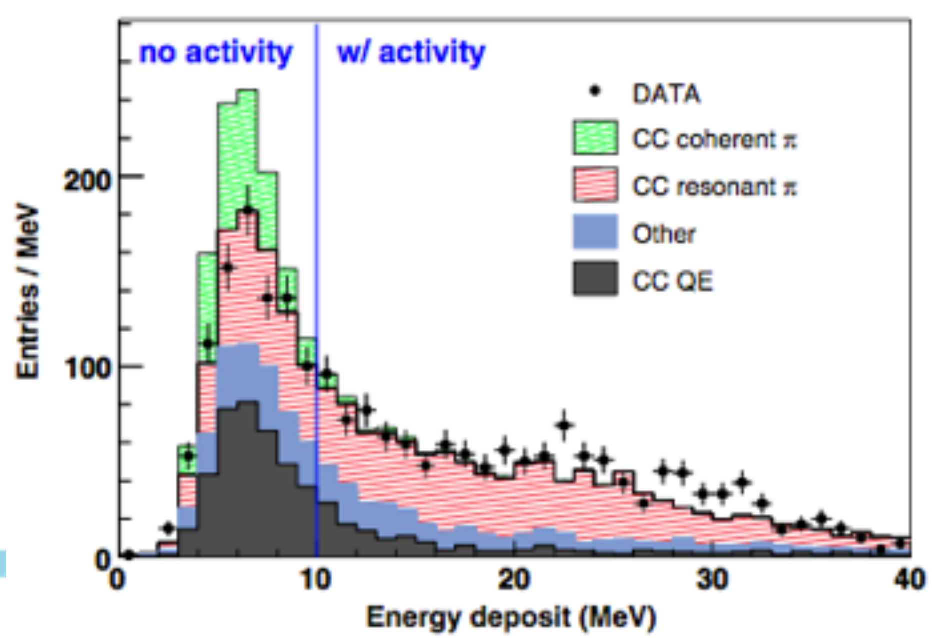
$$q^2_{rec} = 2E_\nu^{rec}(E_\mu - p_\mu cos\theta_\mu),$$

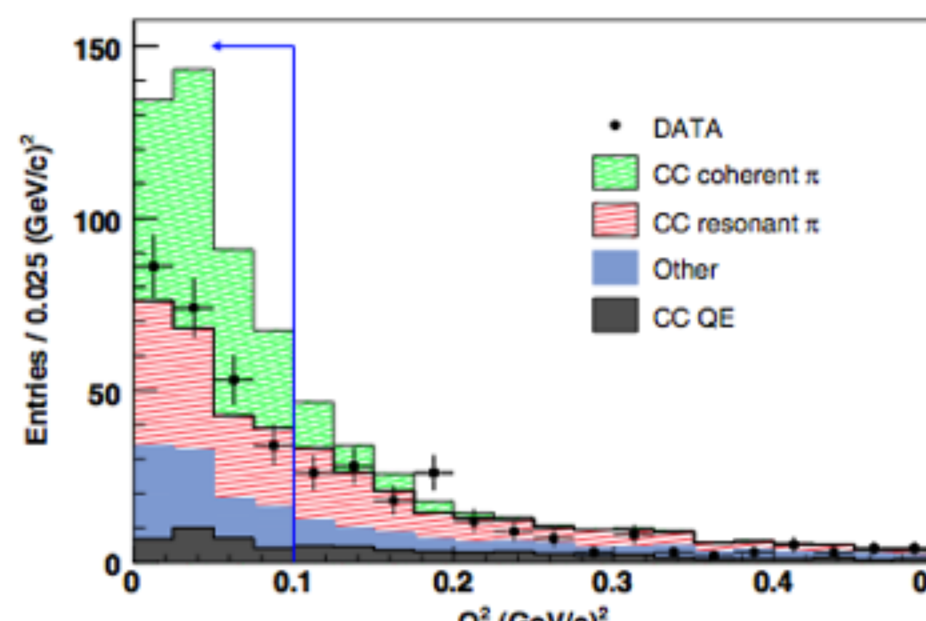
$$E_\nu^{rec} = \frac{M_p^2 - m_\mu^2 + 2E_\mu(M_n - V) - (M_n - V)^2}{-E_\mu + (M_n - V) + p_\mu cos\theta_\mu}$$



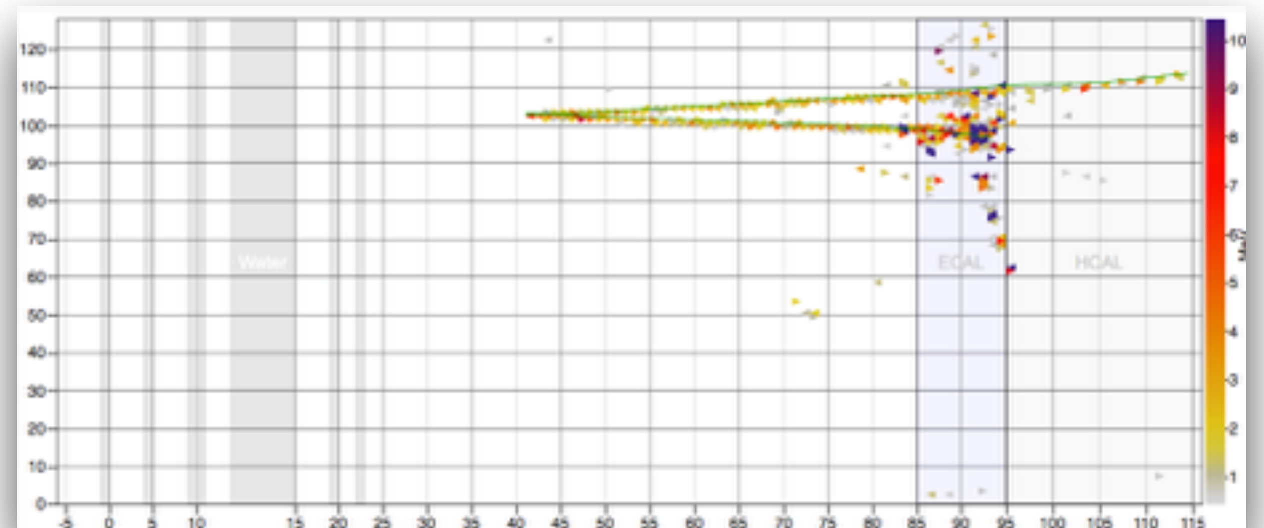

SciBooNE experiment (CH) <E$_\nu$> =1.1 GeV, 2.2 GeV



# Coherent Pion Production at MINERvA

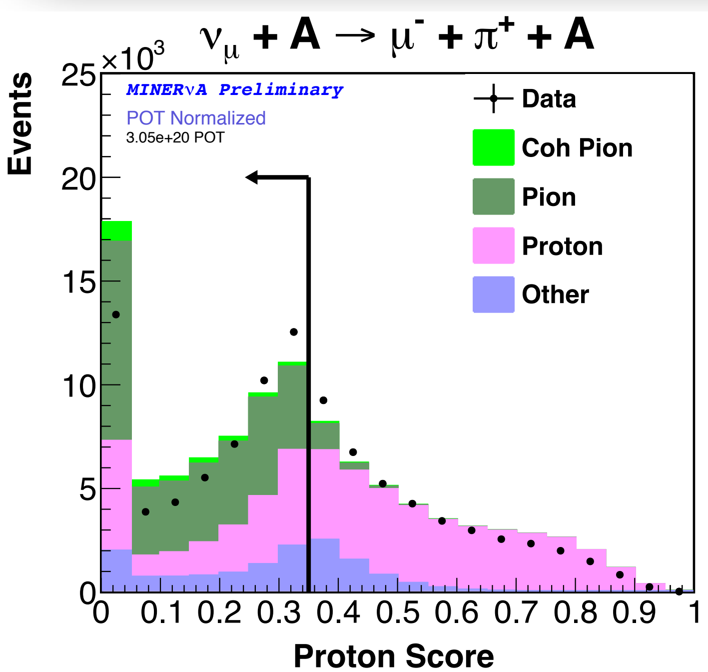
- Two final state particles $\mu^{\mp} + \pi^{\pm}$

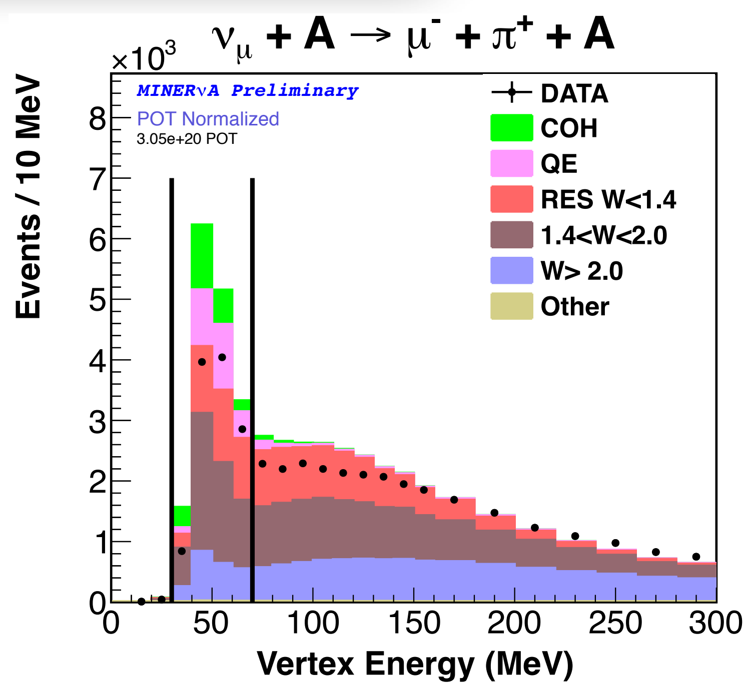


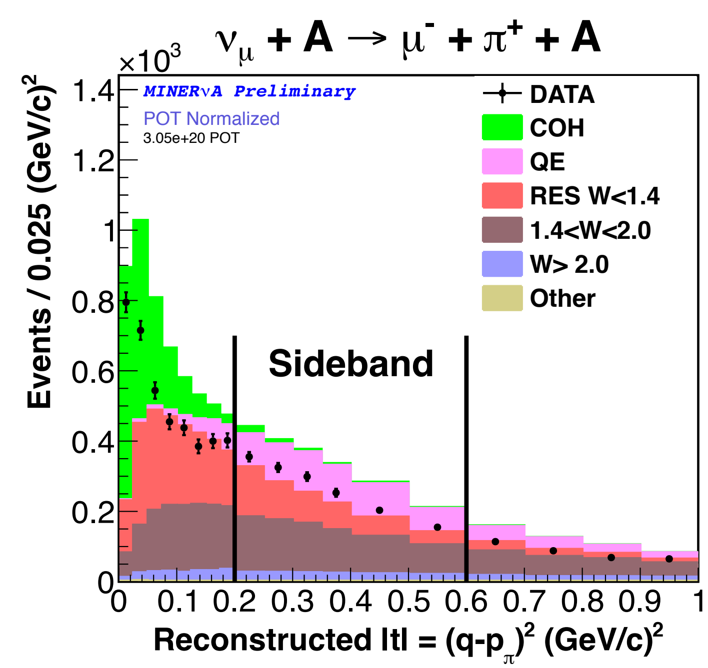
$$E_\nu = E_\mu + E_\pi$$

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

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




Requires that the hadron candidate resembles a pion

Require the total energy within a region around the vertex be consistent with a $\mu^{\mp} + \pi^{\pm}$

Low $|t|=(q-p_\pi)^2$

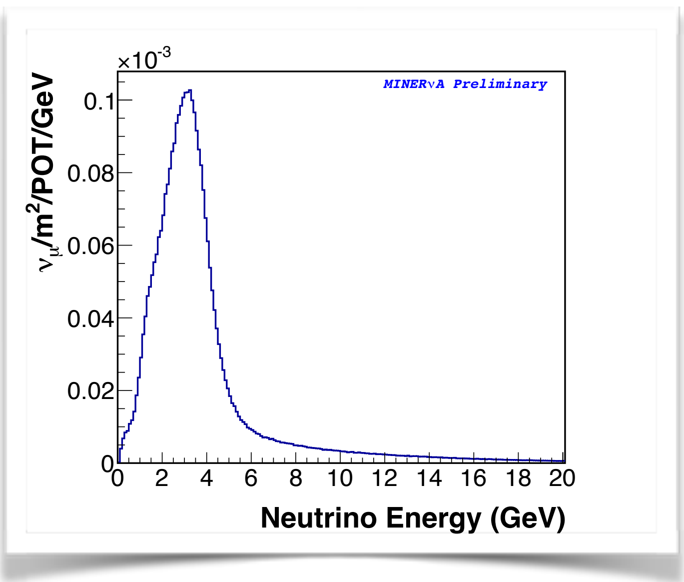
# Coherent Pion Production by Neutrinos

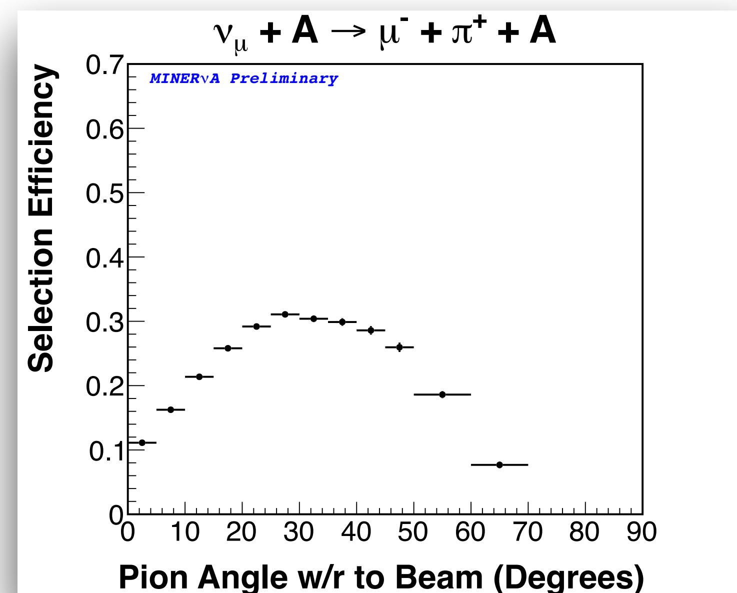
$$\left(\frac{d\sigma}{d\theta_\pi}\right)_i = \frac{1}{\Phi_\nu \times T_n} \cdot \frac{1}{(\Delta\theta_\pi)_i} \cdot \frac{\sum_j U_{ij}(N_j^{data} - N_j^{bkgd})}{\epsilon_i}$$

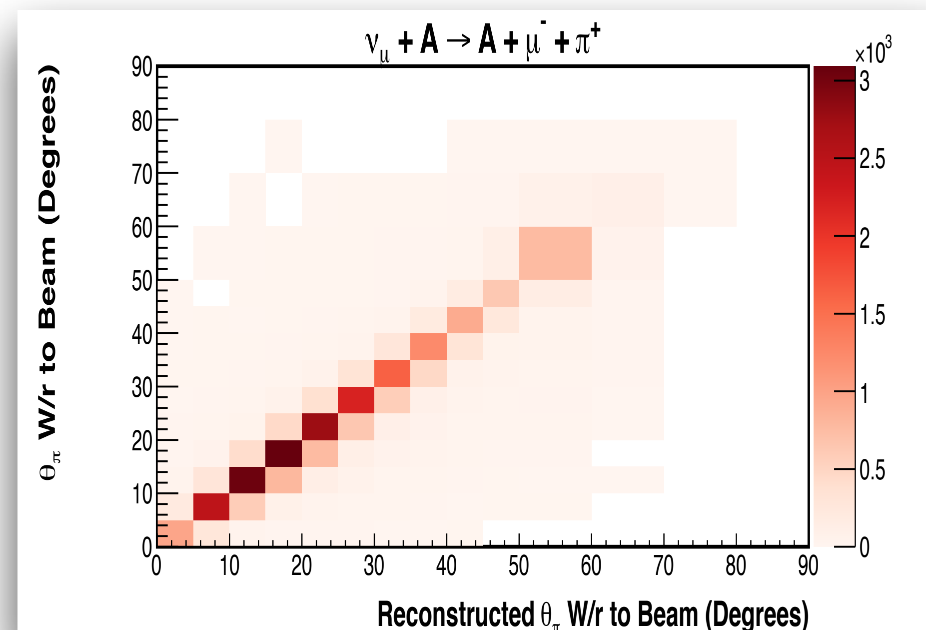
Integrated Flux

Acceptance and Efficiency

Unfolding
Migrations due to reconstruction effects

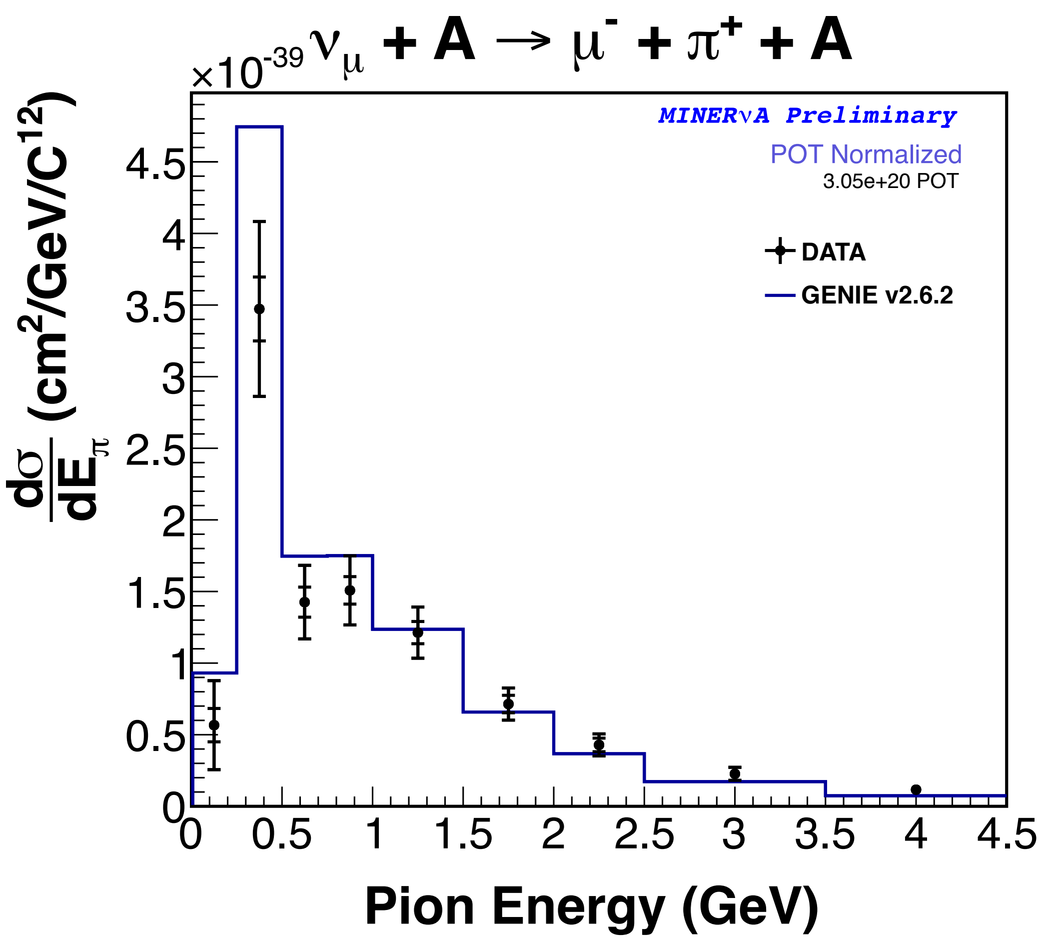


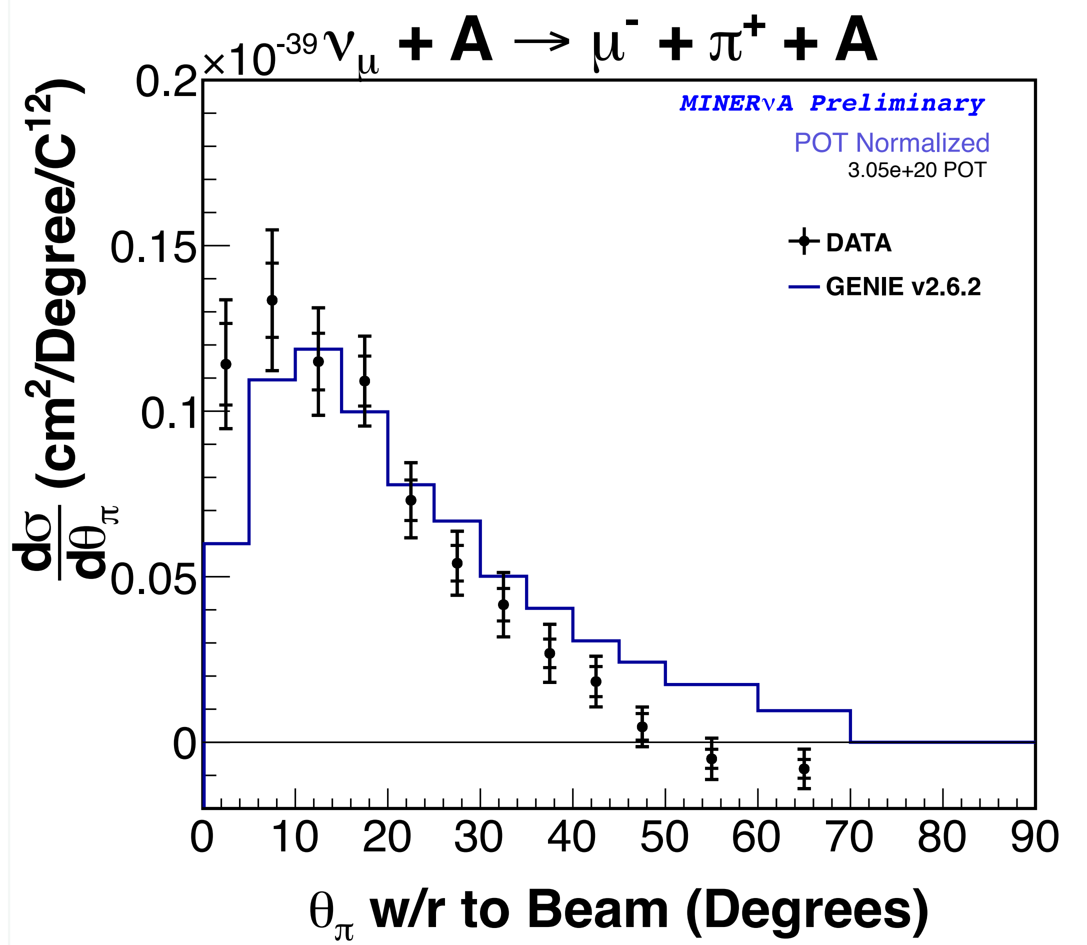



# Coherent Pion Production by Neutrinos

- By selecting low |t| events, MINERvA provides a model-independent measurement of the differential cross-section for coherent scattering of both neutrinos and anti-neutrinos on carbon



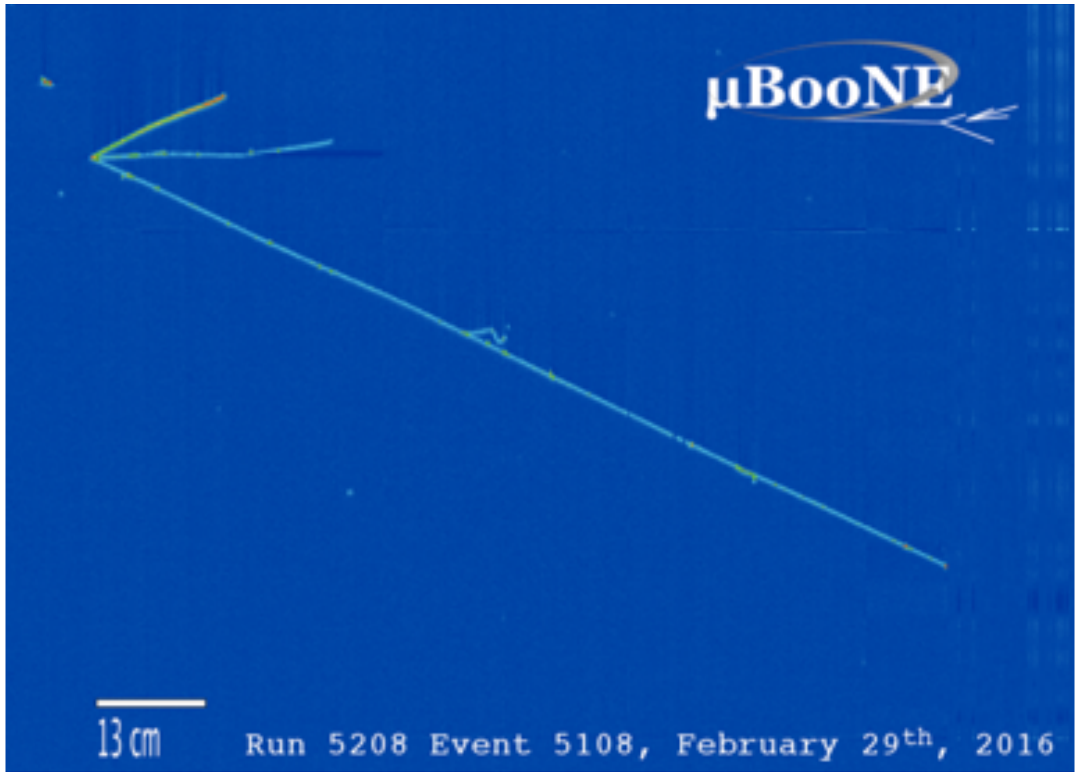




- Data prefer a more forward pion angle distribution and harder pion energy distribution

Phys.Rev. D97 (2018) no.3, 032014

# Present and Future

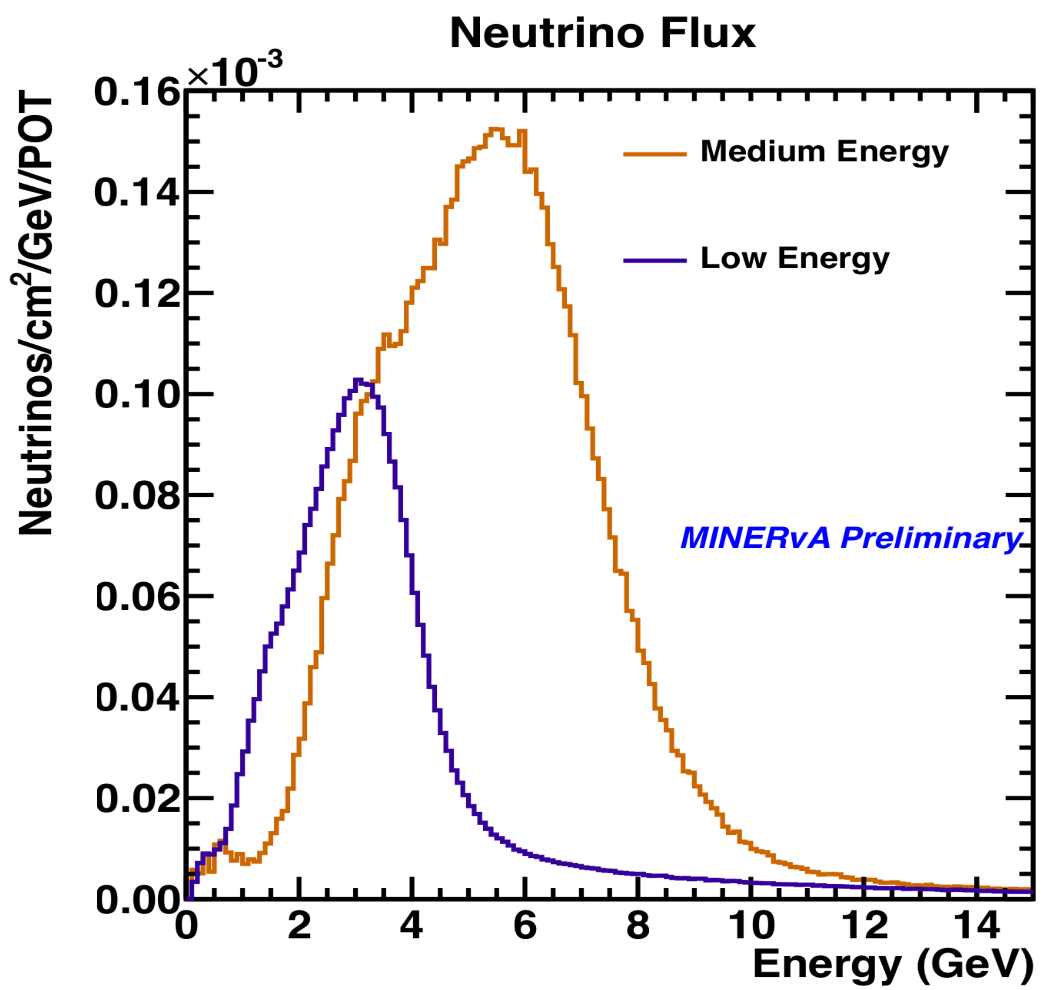
- We have several experiments studying different neutrino interactions and making precise cross section measurements
  - MINERvA, T2K, NOvA, MiniBooNE, ArgoNeut NOMAD and others..
- Future neutrino oscillation experiment (DUNE) will use new detector technology
  - New targets made of liquid argon
- Several experiments in the lab are leading the effort for the liquid argon (MicroBooNE, SBND and ICARUS)




Charged current candidate from MicrooBooNE

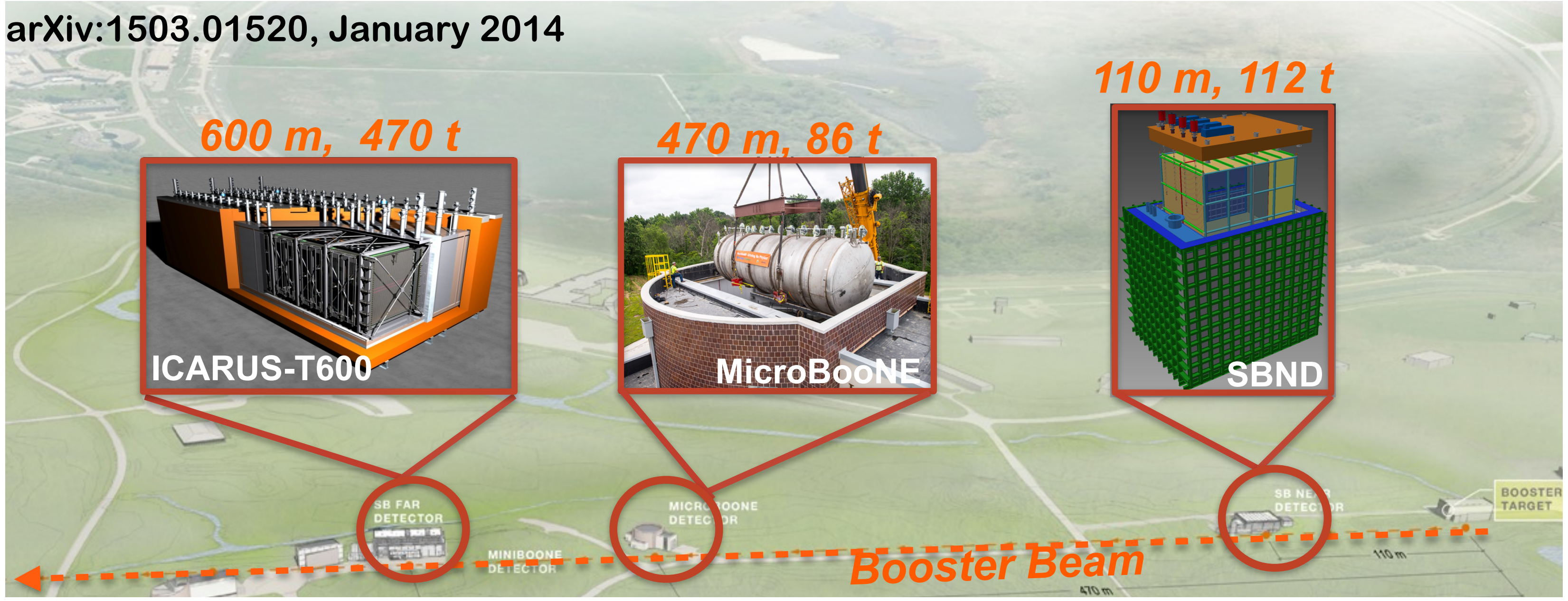
# Next From MINERvA

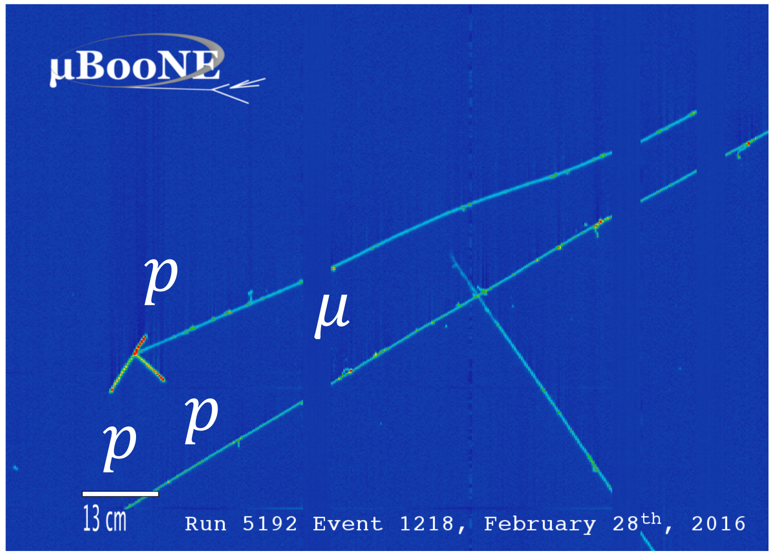
- Measurements of quasi-elastic, pion production, DIS and inclusive on iron, lead and carbon using the NuMI medium energy beam yielding high statistics
- Measurements of nuclear effects for quasi-elastic and pion production with high statistics



# Ongoing Effort with LAr

- Short-baseline neutrino program at Fermilab:
  - Search for a fourth type of neutrino (sterile neutrino)
  - Measure cross sections on liquid argon
- Three LAr Time Projection Chamber (TPC) detectors at different locations




- Liquid argon has excellent resolution for final state
  - Provide sample of events with multiple nucleons

# Summary

- Some cross section measurements are challenging because nuclear effects are not easy to disentangle
- We need to understand the interplay between nuclear effects and cross sections in neutrino nucleus interactions
- However, cross sections are very important, since they help us perfect the nuclear model we have in our event generator (GENIE)
- The nuclear model is essential to transfer information from the near detector to the far detector in oscillation experiment
- Understanding the neutrino interactions with nuclei is vital for precision oscillation measurements