Exclusive Muon and Proton Quasielastic-like Scattering at MINERvA

Joint Experimental-Theoretical Physics Seminar

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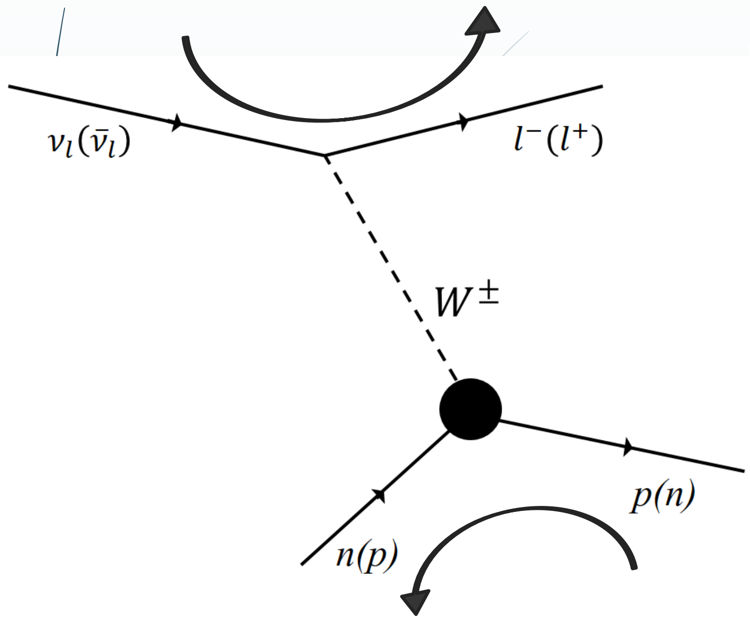
May 9, 2014

Outline

- Physics Introduction and Motivation
  - Charged Current Quasi-elastic scattering and Final State Interaction Effects
  - Neutrino Oscillation Experiments
- MINERvA Detector
- Event Reconstruction
- Quasielastic-like (QE-like) Analysis
- Results
- Future Analyses/Conclusions

Neutrino-Nucleon Quasi-elastic Scattering

Charged Current Quasi-elastic (CCQE) Scattering



Scattering from a free nucleon

Lepton Conservation – emit a charged lepton and knock out a different flavor nucleon

first derived by C.H. Llewellyn-Smith

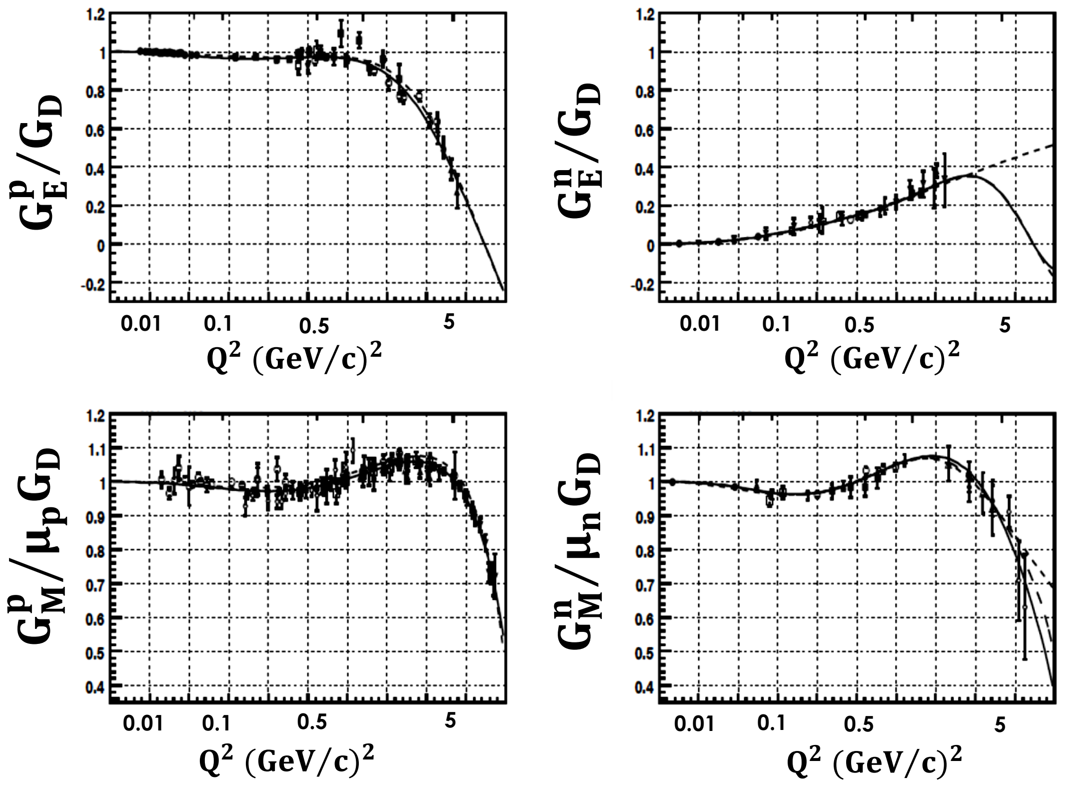
$$\frac{d\sigma}{dQ^2} = \frac{M^2 G_F^2 \cos^2\theta_C}{8\pi E_\nu^2}\left[A(Q^2) \mp B(Q^2)\frac{(s-u)}{M^2} + C(Q^2)\frac{(s-u)^2}{M^4}\right]$$

A, **B**, and **C** terms are composed of the elastic **vector**, **pseudoscalar**, **axial** form factors, which characterize the hadronic structure of the nucleon.

- Q^2 is the four momentum transfer
- M is the mass of the Nucleon
- G_F is Fermi constant
- θ_C is Cabibbo angle
- E_ν is the neutrino energy
- Mandelstam variables
  - $s = (k^\mu + p^\mu)^2$
  - $u = (k^\mu - p^\mu)^2$

CCQE Formalism for Scattering from a **free** Nucleon

arXiv:0708.1946[hep-ex]



G_E^p, G_E^n : proton and neutron electric form factors
G_M^p, G_M^n : proton and neutron magnetic form factors
μ_p, μ_n : proton and neutron magnetic moments

- The vector form factors (F_V^1 and F_V^2) can be related to the nucleon electromagnetic form factors, which are described by electron scattering data.
- A first order approximation (Goldberger-Treiman relation) relates the pseudoscalar form factor (F_P) to the axial form factor.
- The axial form factor (F_A) is approximated by the dipole form.

nuclear β-decay experiments

$$F_A(Q^2) = \frac{F_A(Q^2=0)}{\left(1+ {Q^2}/{M_A^2}\right)^2}$$

Axial Mass

Extracted from neutrino quasi-elastic cross-section measurements.

Scattering from a Nucleon in the Nucleus

Nuclear Medium

- Model by the **Relativistic Fermi Gas (RFG)** Model.

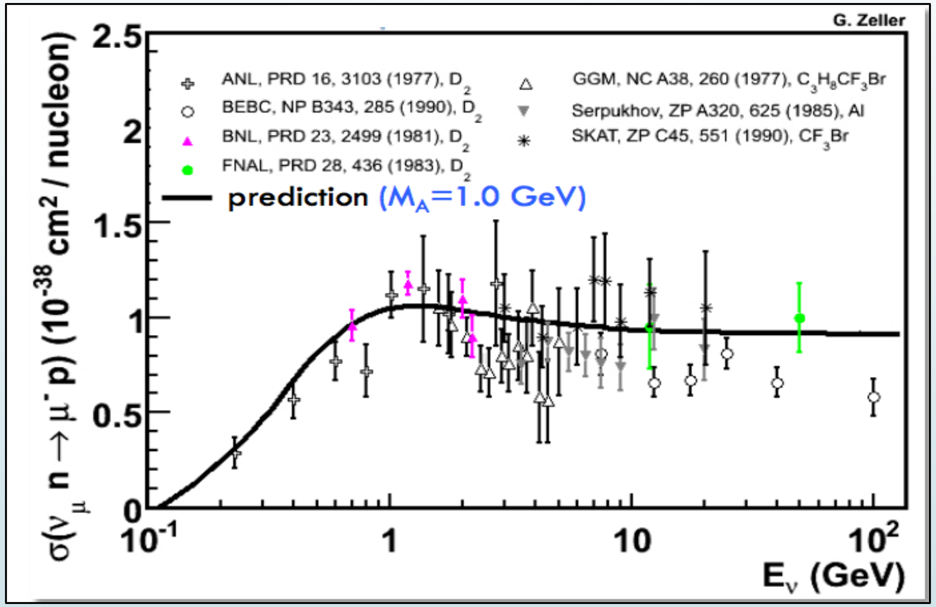
Scattering Physics

- Describe by the **Plane Wave Impulse Approximation.**
  - *Assumes scattering from independent nucleons in the nucleus.*
- Assumes the initial state nucleon is at rest.
  - Many options for calculating the event kinematics.
    - Lepton only ← the most common method.
    - Lepton and nucleon
    - Nucleon only

Nuclear Physics

- The nucleons obey Fermi statistics ⟶ implementation of Pauli blocking.
- Binding Energy ⟶ based on electron scattering data.

these ingredients plus the CCQE formalism

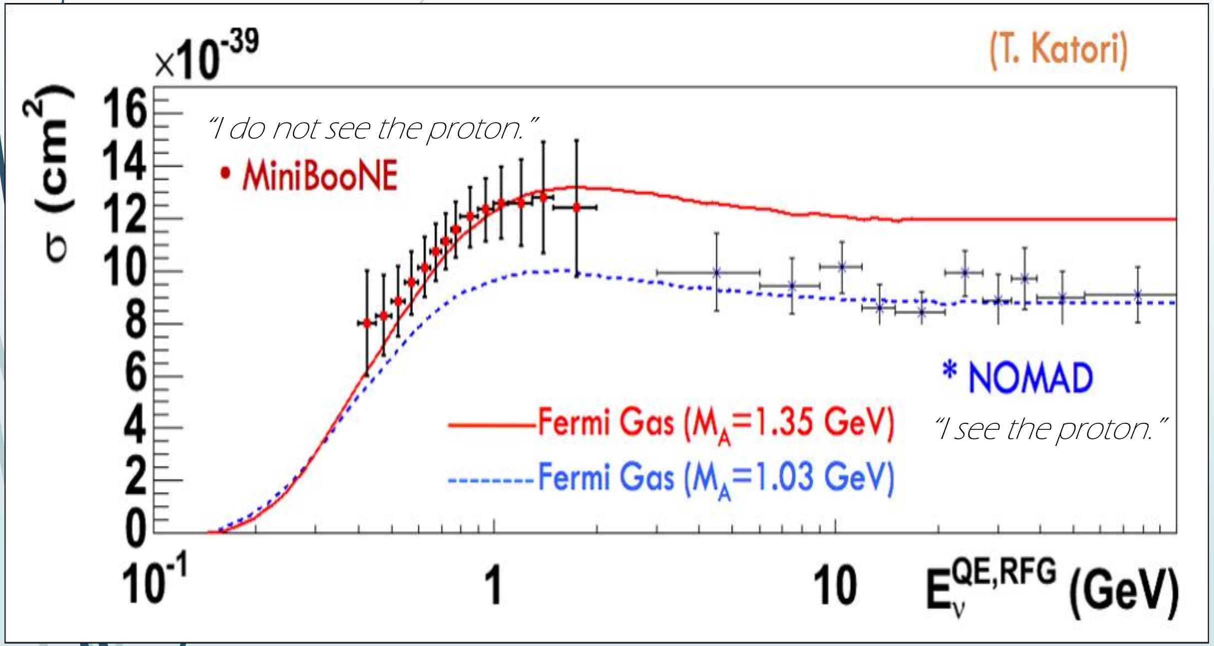


Most measurements are from $\nu - {}^2H$ scattering ⇒ treated as scattering from a *free* neutron target.

$$M_A \approx 1.0\ GeV/c^2$$

Scattering from Nuclei with $A > 2$

Scattering from heavier targets ⟶ higher event rate ☺



The dipole form does not describe the axial form factor ??

Increase M_A to account for the additional strength.

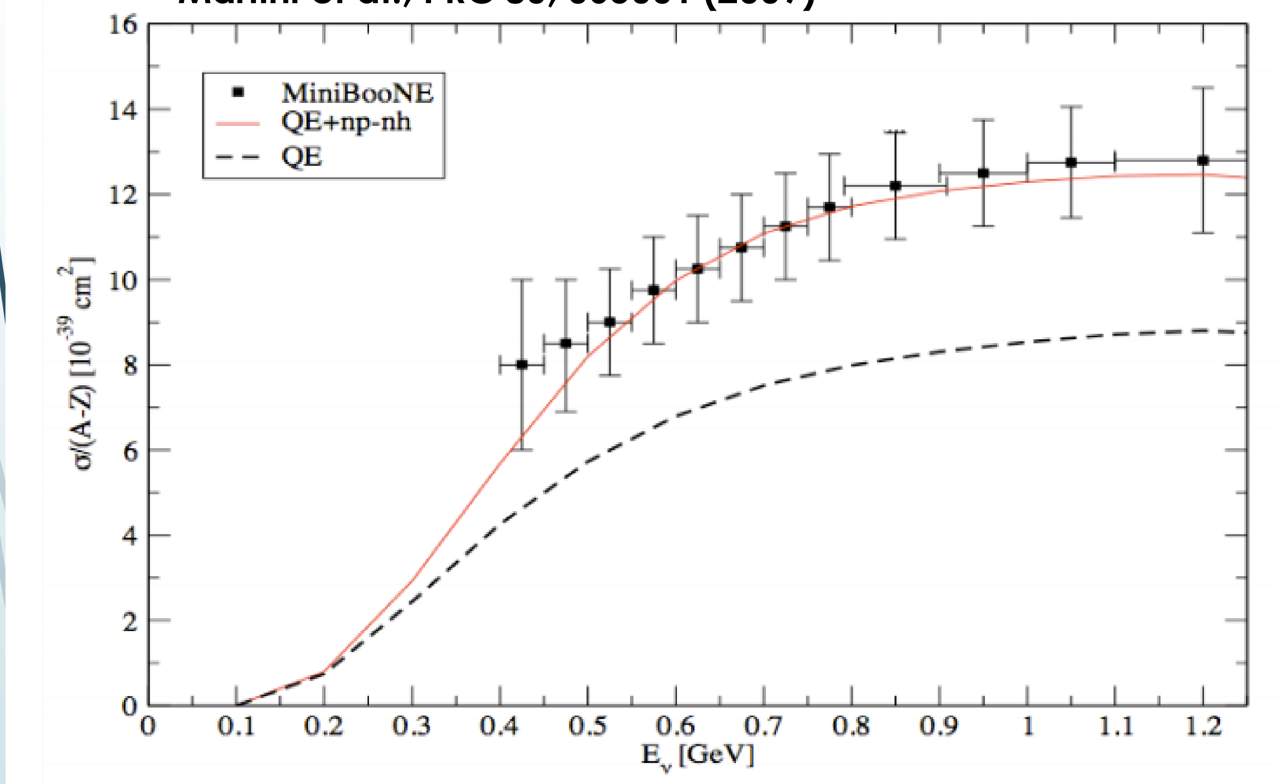
Phys. Rev. C 82:045502 (2010)

Experiment	Target	Cut in Q^2 [GeV^2]	$M_A [GeV]$
K2K	oxygen	$Q^2 > 0.2$	1.2 ± 0.12
K2K	carbon	$Q^2 > 0.2$	1.14 ± 0.11
MINOS	iron	no cut	1.19 ± 0.17
MINOS	iron	$Q^2 > 0.2$	1.26 ± 0.17
MiniBooNE	carbon	no cut	1.35 ± 0.17
MiniBooNE	carbon	$Q^2 > 0.25$	1.27 ± 0.14
NOMAD	carbon	no cut	1.07 ± 0.07

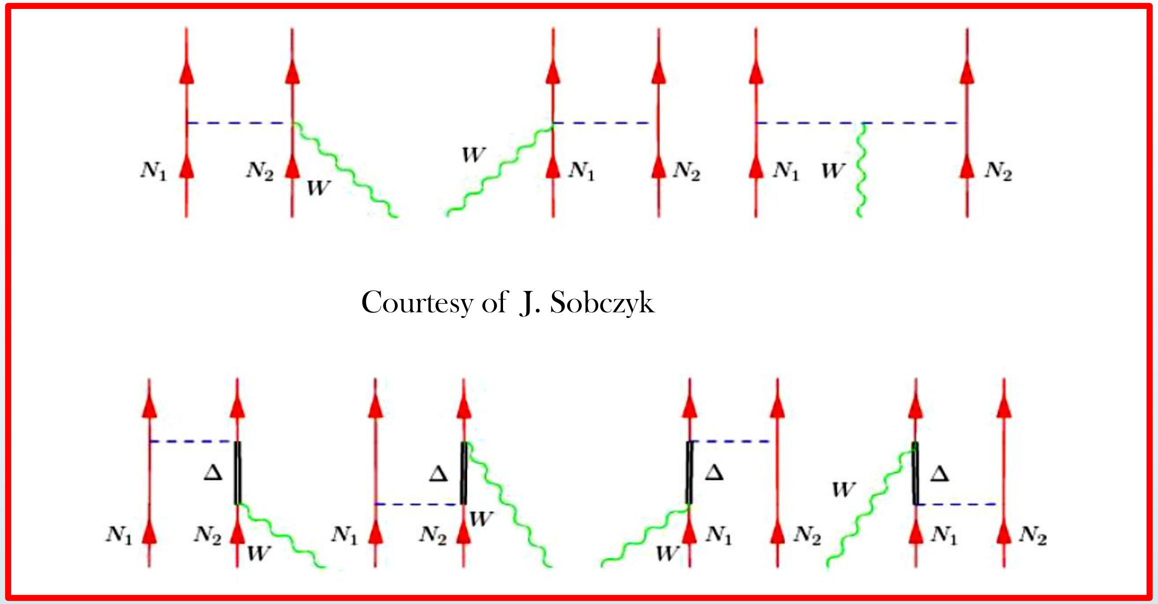
Datasets are inconsistent with the results from Deuterium!

Solving the Axial Mass Puzzle

Martini et at., PRC 80, 065001 (2009)



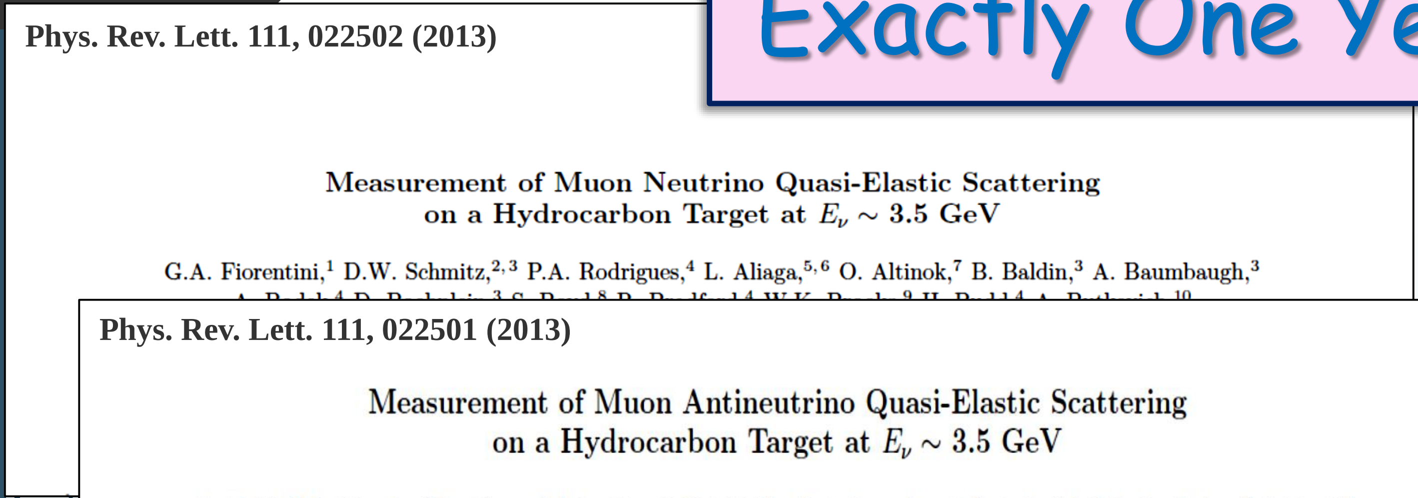
Feynman Diagrams of MEC



Enhancement in the QE cross-section is due to the meson exchange currents (MEC), which can lead to the emission of **extra nucleons at the scattering vertex**.

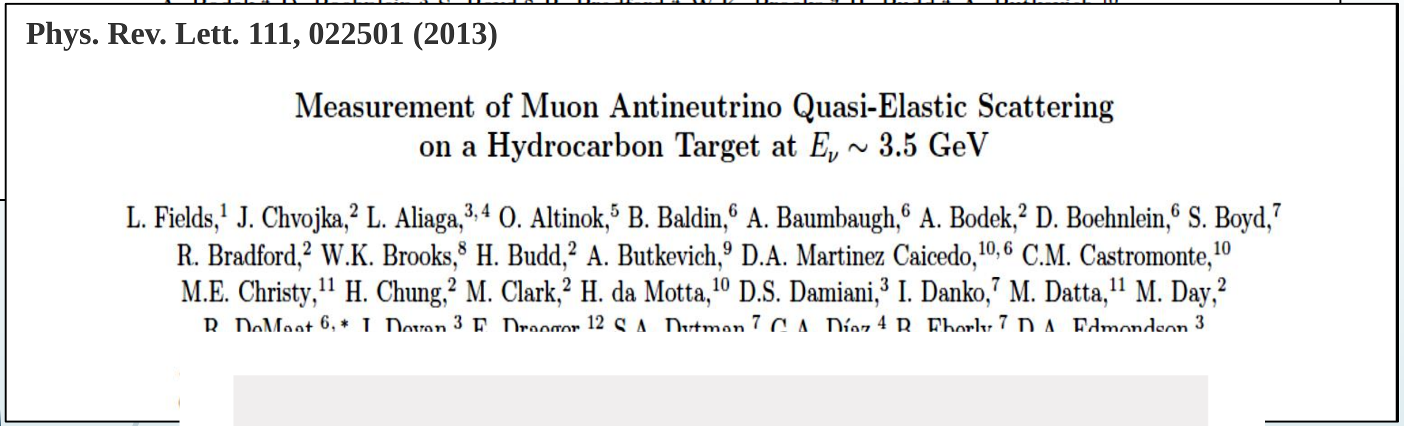
The gauge boson, W couples to a virtual meson or delta-induced virtual meson that is being exchanged between nucleons in the nucleus.

Exactly One Year Ago: QE Results!


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

Measurement of Muon Neutrino Quasi-Elastic Scattering on a Hydrocarbon Target at $E_\nu \sim 3.5$ GeV

G.A. Fiorentini,[1] D.W. Schmitz,[2,3] P.A. Rodrigues,[4] L. Aliaga,[5,6] O. Altinok,[7] B. Baldin,[3] A. Baumbaugh,[3]


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

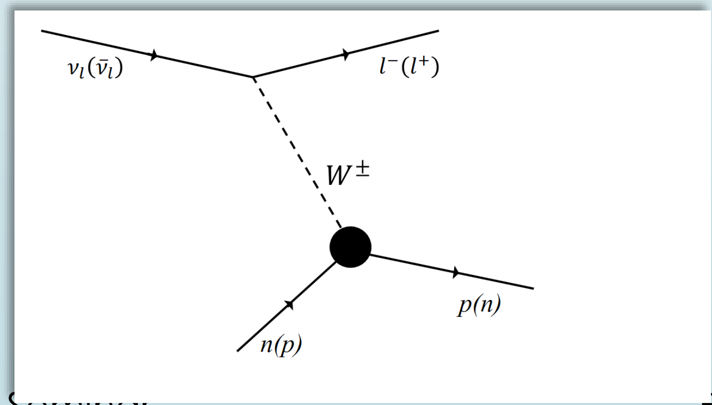
Measurement of Muon Antineutrino Quasi-Elastic Scattering on a Hydrocarbon Target at $E_\nu \sim 3.5$ GeV

L. Fields,[1] J. Chvojka,[2] L. Aliaga,[3,4] O. Altinok,[5] B. Baldin,[6] A. Baumbaugh,[6] A. Bodek,[2] D. Boehnlein,[6] S. Boyd,[7] R. Bradford,[2] W.K. Brooks,[8] H. Budd,[2] A. Butkevich,[9] D.A. Martinez Caicedo,[10,6] C.M. Castromonte,[10] M.E. Christy,[11] H. Chung,[2] M. Clark,[2] H. da Motta,[10] D.S. Damiani,[3] I. Danko,[7] M. Datta,[11] M. Day,[2]

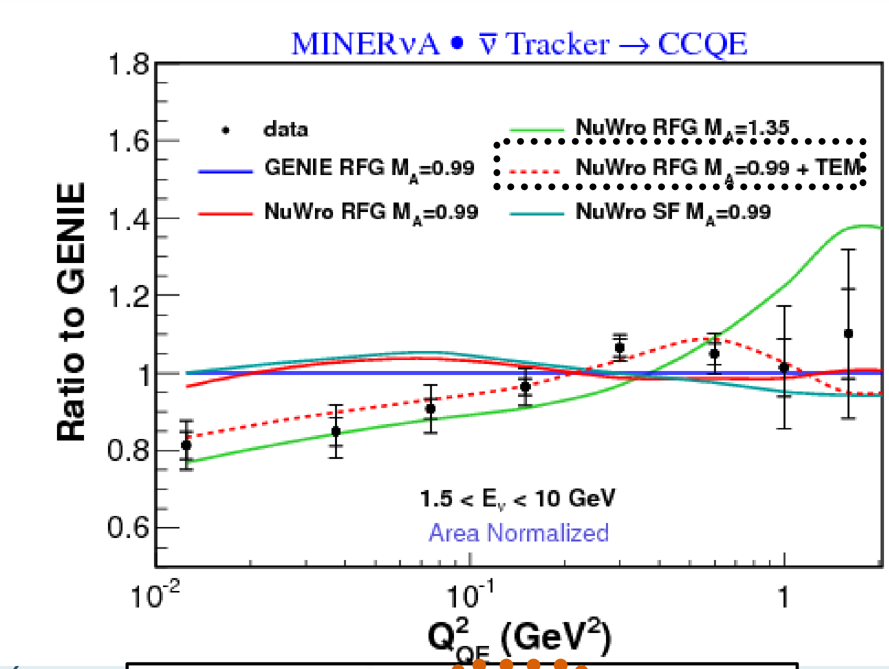
Submitted the first QE cross-section measurements to the arXiv.

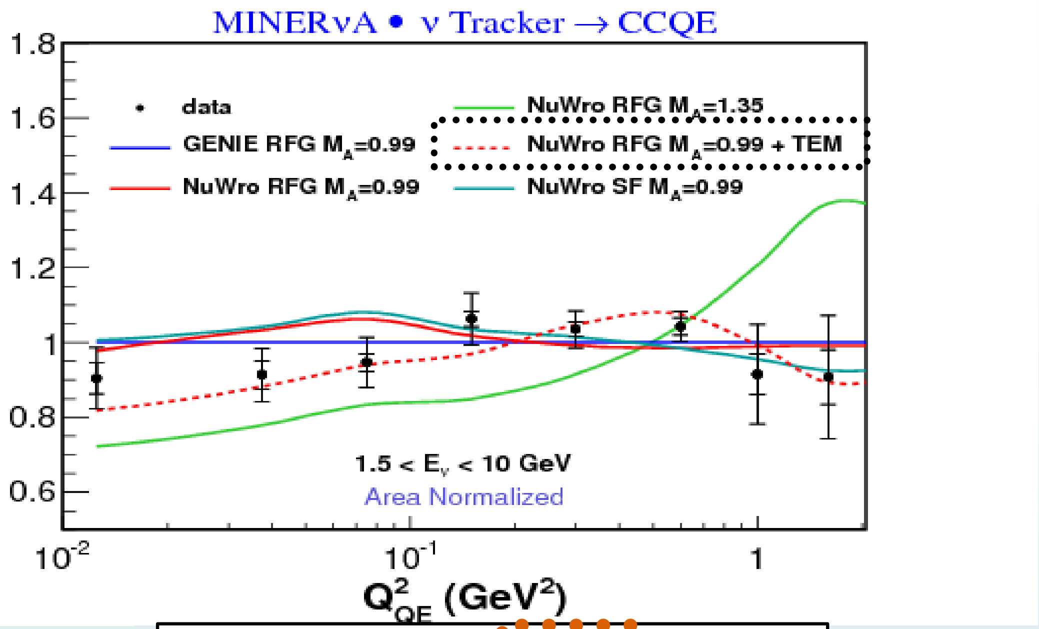
The results focus directly on quantifying the multi-nucleon contributions to the QE cross-section for both the neutrino and anti-neutrino scattering.

1. Comparing the data to various models.
2. Studying the energy around the interaction vertex.



1.) Model Comparison



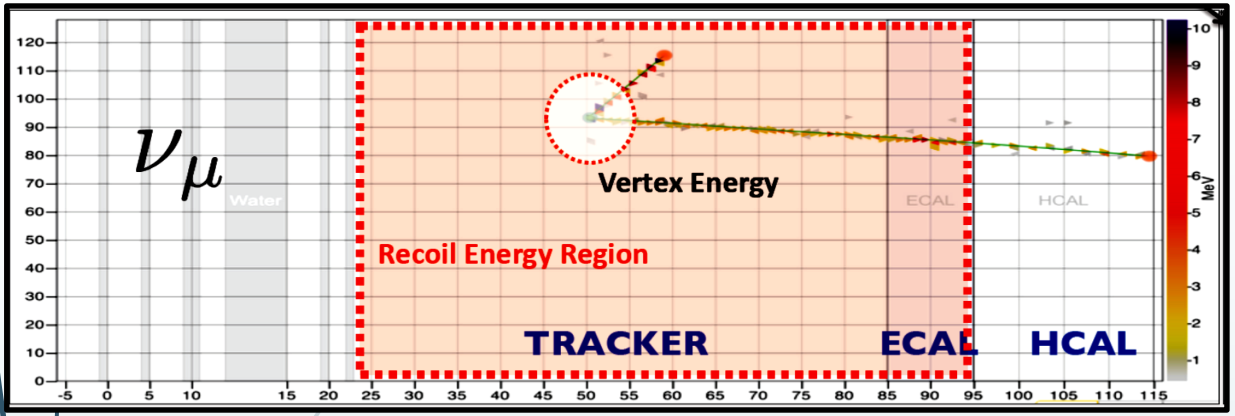


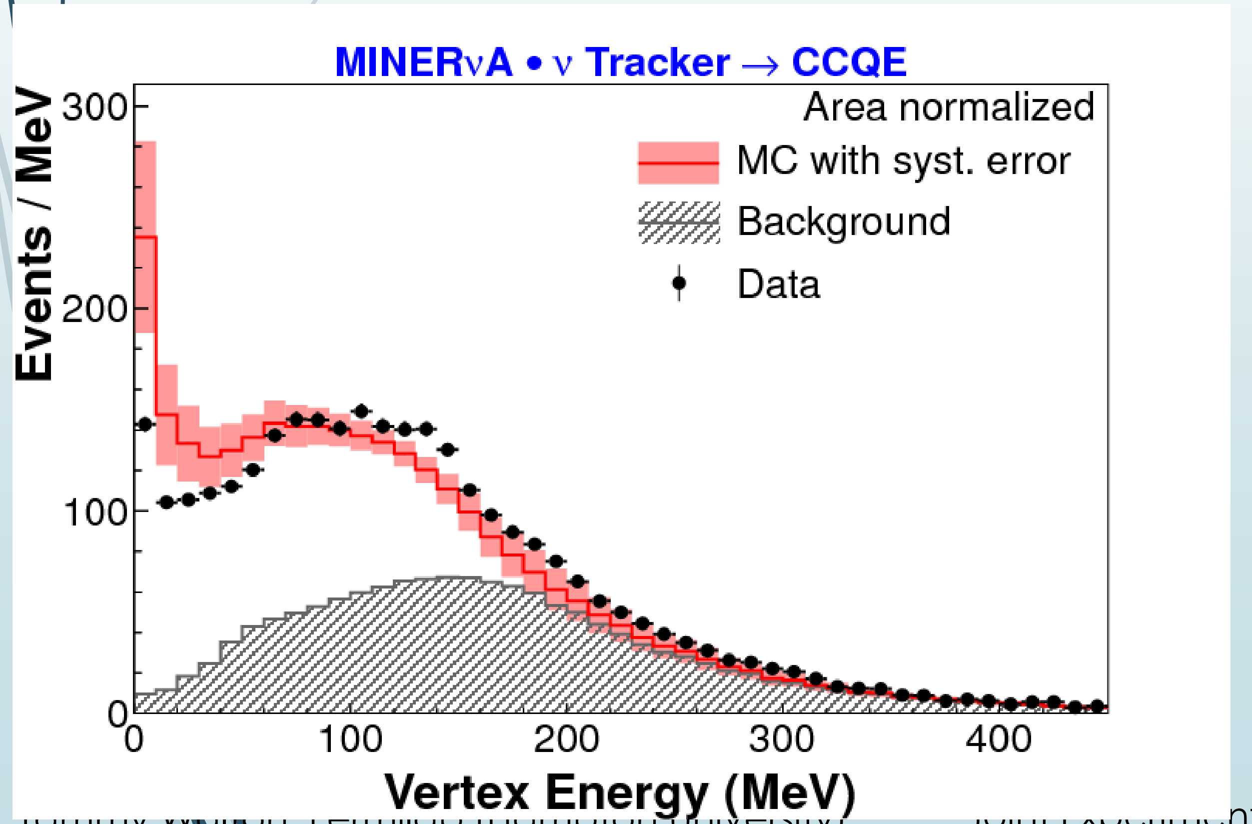
NuWro Model	RFG	RFG +TEM	RFG	SF
M_A (GeV)	0.99	0.99	1.35	0.99
Rate χ^2/d.o.f.	2.64	1.06	2.90	2.14
Shape χ^2/d.o.f.	2.90	0.66	1.73	2.99

NuWro Model	RFG	RFG +TEM	RFG	SF
M_A (GeV/c^2)	0.99	0.99	1.35	0.99
Rate χ^2/d.o.f.	3.5	2.4	3.7	2.8
Shape χ^2/d.o.f.	4.1	1.7	2.1	3.8

Datasets are best described by the **RFG with the Transverse Enhancement Model,** an empirical model (based on electron scattering data) that accounts for the **additional strength** observed in the QE cross section due to contributions from both **nucleon-nucleon interactions** and **two body currents (MEC)**.

2.) Vertex Energy





Both nucleon-nucleon interactions and meson exchange currents result in the emission of multi-nucleons at the scattering vertex.

The energy around the interaction vertex is analyzed.

The excess energy in data suggests that there are additional nucleons in the final states.

For the neutrino scattering, this says that these initial state nucleons are predominately in a p-n state configuration.

Nuclear Physics is **NOT** that Simple

"Mystery solved!"
"What's left to uncover?"

To better model the event kinematics due to various multi-nucleon processes ⇒ understand the kinematic distributions of the N-N states ⇒ reconstruct the hadron final state system.

Need to understand hadron propagation through the nucleus!

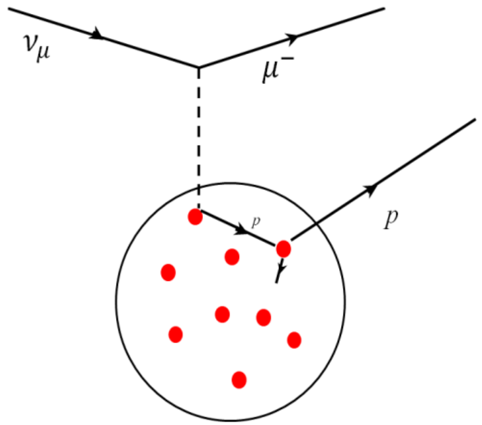
For scattering from heavier nuclei, we must be able to decouple **nuclear effects that occur at the scattering vertex** from the **nuclear processes that affect the final state system**.

More knowledge about the dynamics of the nuclear medium ⟹ better understanding of the neutrino-nucleus scattering!

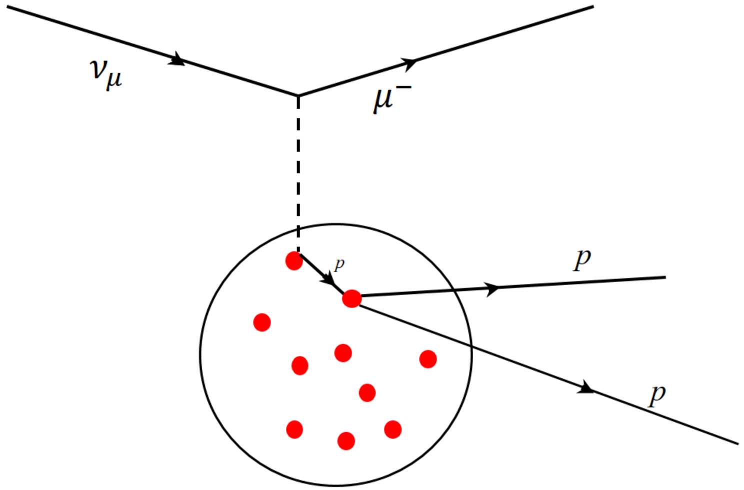
Let's focus on the final state interaction effects.

The Nuclear Environment Makes Detecting the Correct Neutrino Process Not so Easy

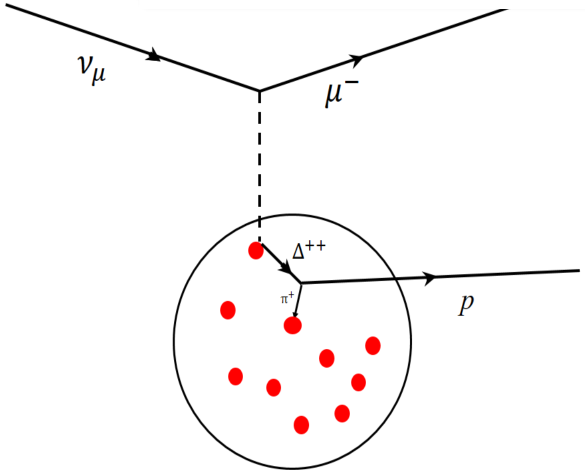
Final state interactions (FSI) alter the kinematic distributions of the recoil nucleon.



FSIs can lead to many nucleons in the final state. Looks like a 2particle 2hole excitation.

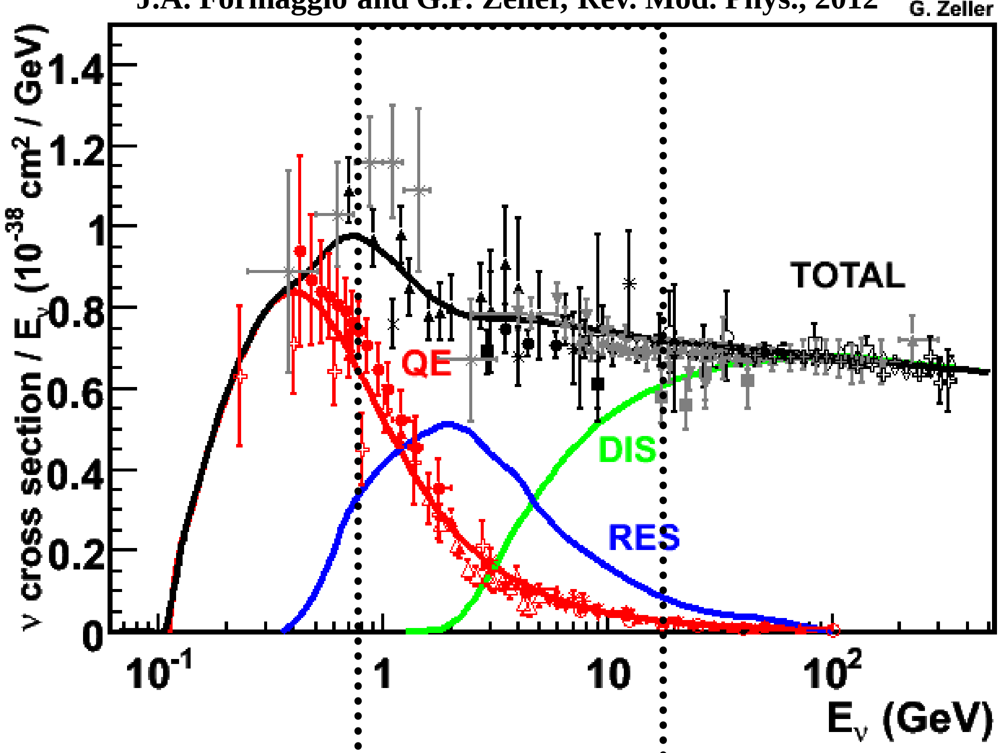


Non-QE neutrino scattering processes can look like a QE process ⇒ QE-like.



Interplay Between Nuclear and Neutrino Physics

J.A. Formaggio and G.P. Zeller, Rev. Mod. Phys., 2012



T2K, LBNE, NOνA

Event kinematic cuts are likely to introduce biases and are more sensitive to the models.

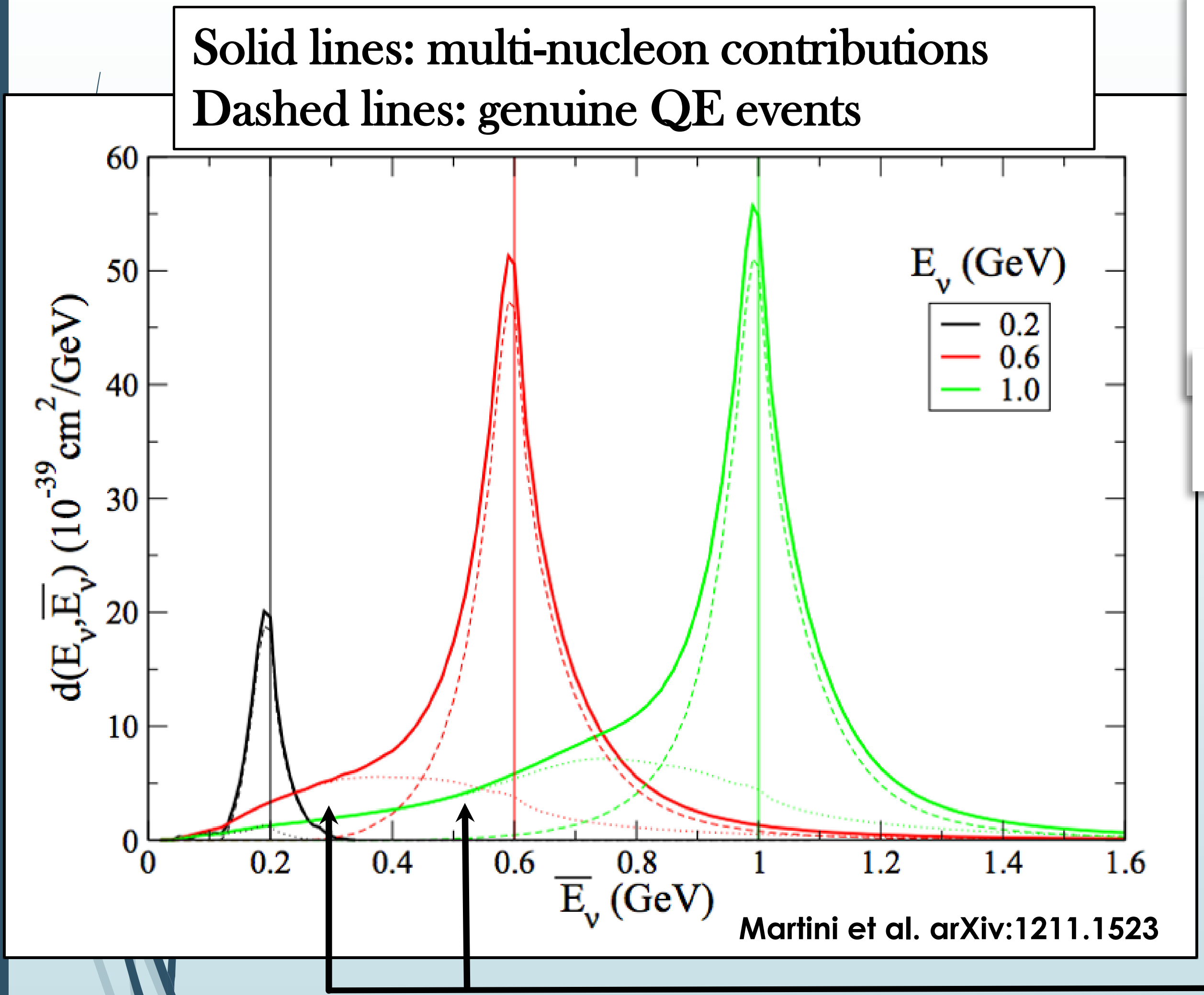
Need more cross-section measurements on heavier nuclei!

Neutrino energy is unknown. Must reconstruct the energy from the *detected* particles in the final state.

Many neutrino-interaction processes occur in this energy regime.

Must rely on neutrino event generators for modeling the final state particles.

Nuclear Physics and the Neutrino Energy



$$E_\nu^{QE} = \frac{2(M_n - E_B)E_\mu - \left[(M_n - E_B)^2 + m_\mu^2 - M_p^2\right]}{2\left[M_n - E_B - E_\mu - p_\mu \cos\theta_\mu\right]}$$

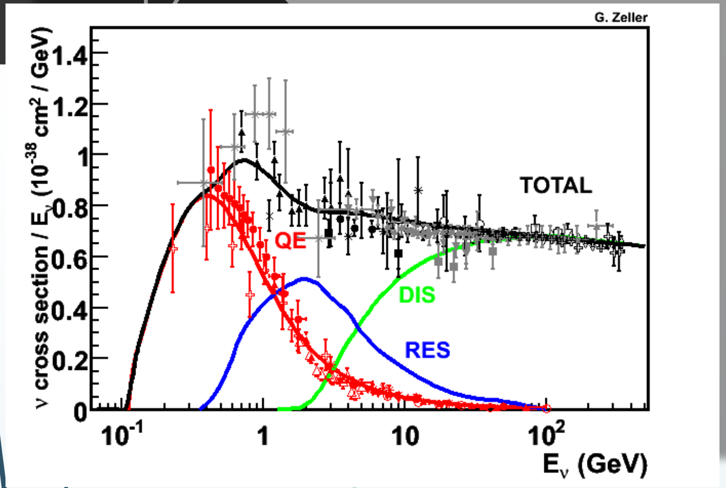
M

Equation uses only the muon kinematics ⟹ insensitive to the Fermi motion and FSIs.

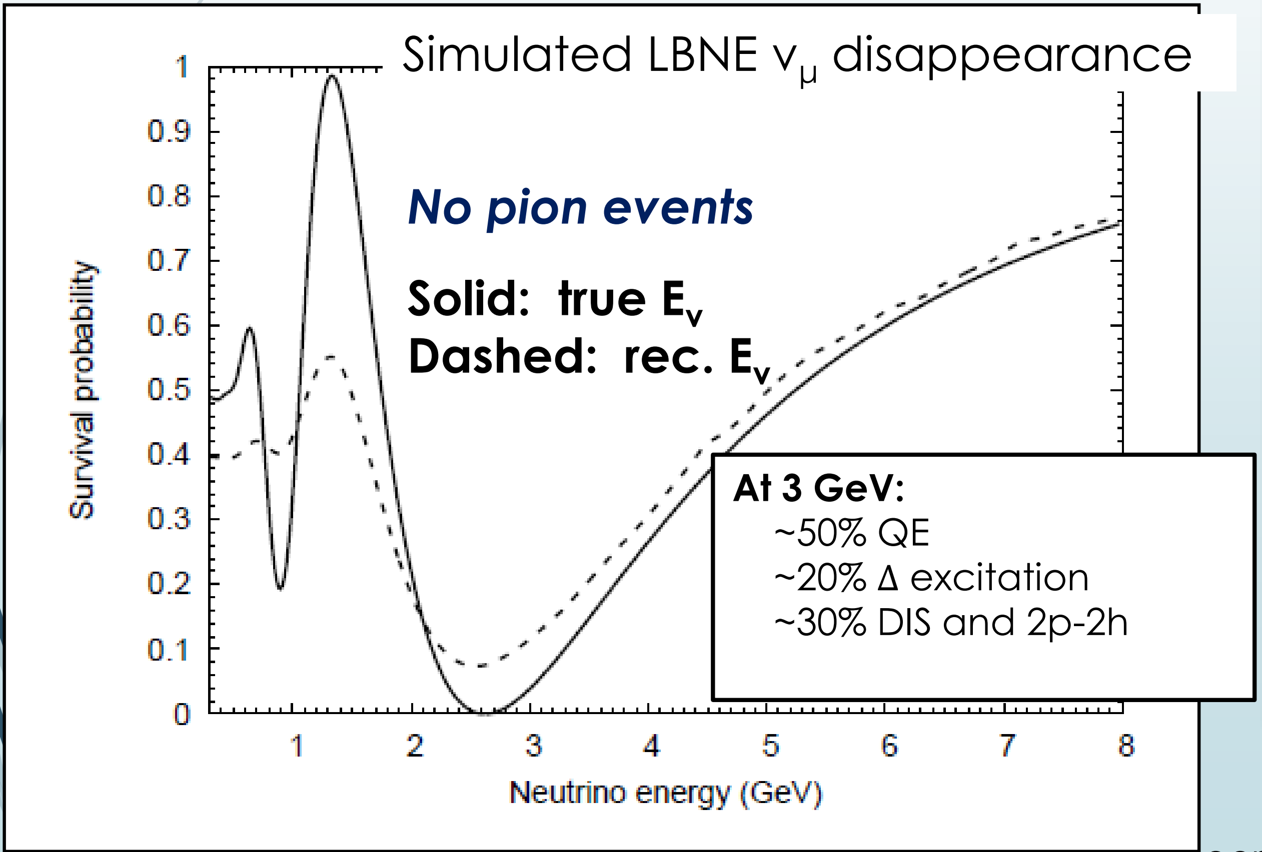
Meson exchange current processes smear the reconstructed neutrino energy.

Using the QE hypothesis which describes the scattering from a single nucleon bound in the nucleus, does not precisely describe scattering processes that are beyond the description of the plane wave impulse approximation.

Nuclear Physics and the Neutrino Energy



Mosel *et al*: arxiv 1311.7288



At 3 GeV:
- ~50% QE
- ~20% Δ excitation
- ~30% DIS and 2p-2h

Final state interactions influence the neutrino interaction channel that the experiment is measuring.

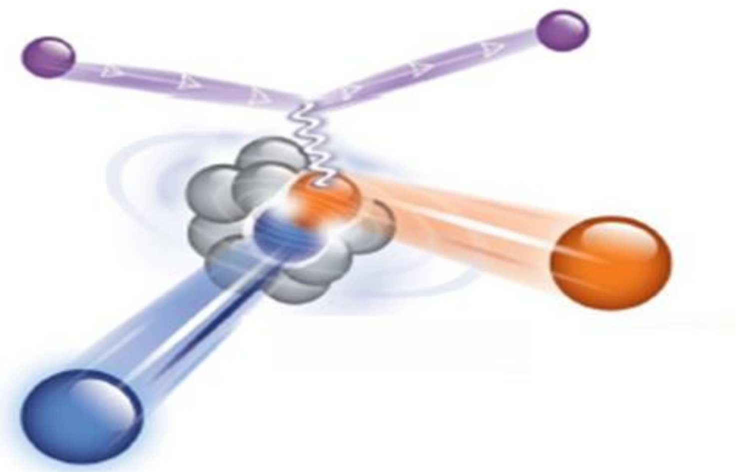
The extraction of the CP-violating phase factor is highly sensitive to the reconstruction of the neutrino energy.

Non-QE events smear the reconstructed neutrino energy.

It is critical that effects of FSI are better understood.

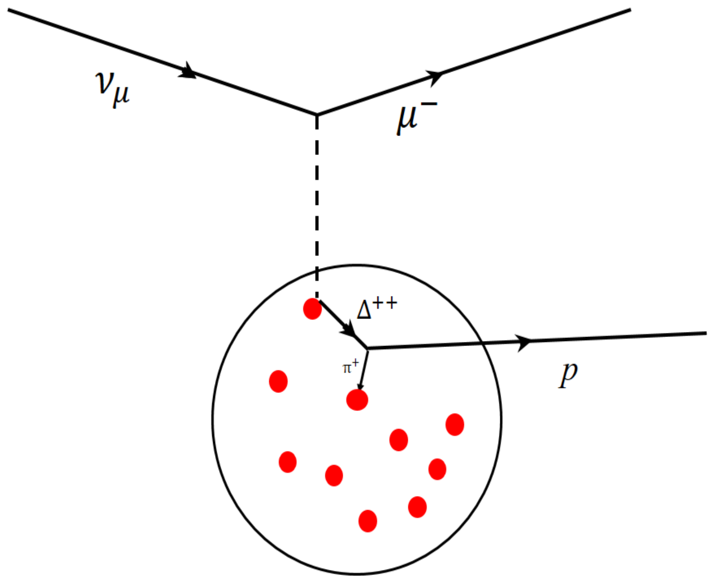
Why is νN QE Scattering **NOT** so Simple?

- **The initial state nucleons in the nucleus are interacting, therefore they are off-shell.**
  - Contributions from nucleon-nucleon correlated pairs and meson exchange currents. **Directly impacts the reconstruction of the neutrino energy when using only the lepton kinematics.**



Why is νN QE Scattering **NOT** so Simple?

- **Hadrons that are produced from a primary interaction can interact with the residual nucleus.**
  - Contributions from inelastic processes. In these processes, the pion does not escape the nucleus. **Directly impacts the reconstruction of the neutrino energy when using only the lepton kinematics.**

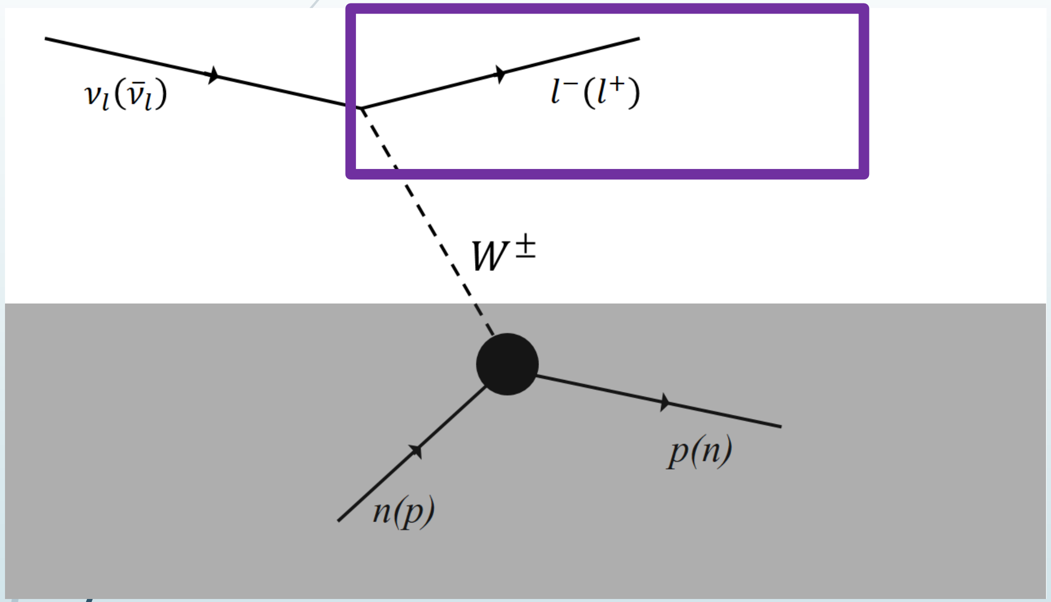


Nuclear Effects and Final State Interactions

- **Produce a measurement that is insensitive to the modeling of the neutrino scattering process.**
  - Define a signal based on the event topology. Therefore, various neutrino interactions enter into the event selection.
  - QE $\Longrightarrow$ QE-like: **muon**, **at least one proton**, **no pions**
- **Just because the event kinematics are reconstructed from the muon observables, DOES NOT imply that the measurement is insensitive to FSI. In addition, the muon alone DOES NOT provide enough information in order to decouple nuclear effects from final state interactions.**
  - Reconstruct both the lepton and hadron final states.
  - more information $\Longrightarrow$ more constraints.
- **To understand the nuclear environment, we also need measurements from the hadron system. Different observables have different sensitivities to the modeling of the nuclear environment, which directly impacts the reconstruction of the neutrino energy.**

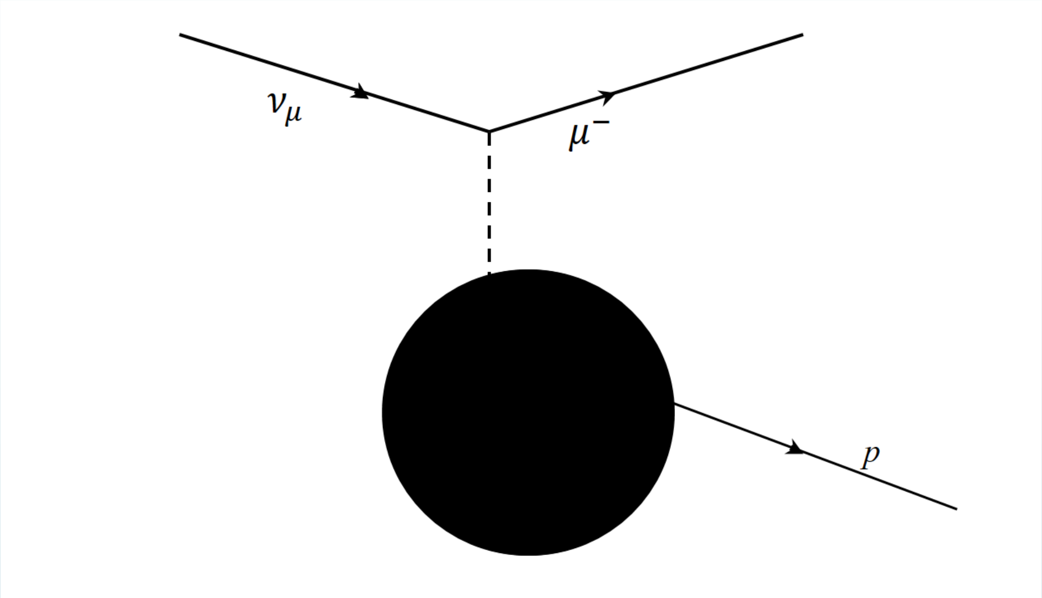
Nuclear Effects and Final State Interactions

Previous QE Measurements



- Use only the **muon** to characterize the nuclear effects at the scattering vertex for the quasi-elastic scattering.

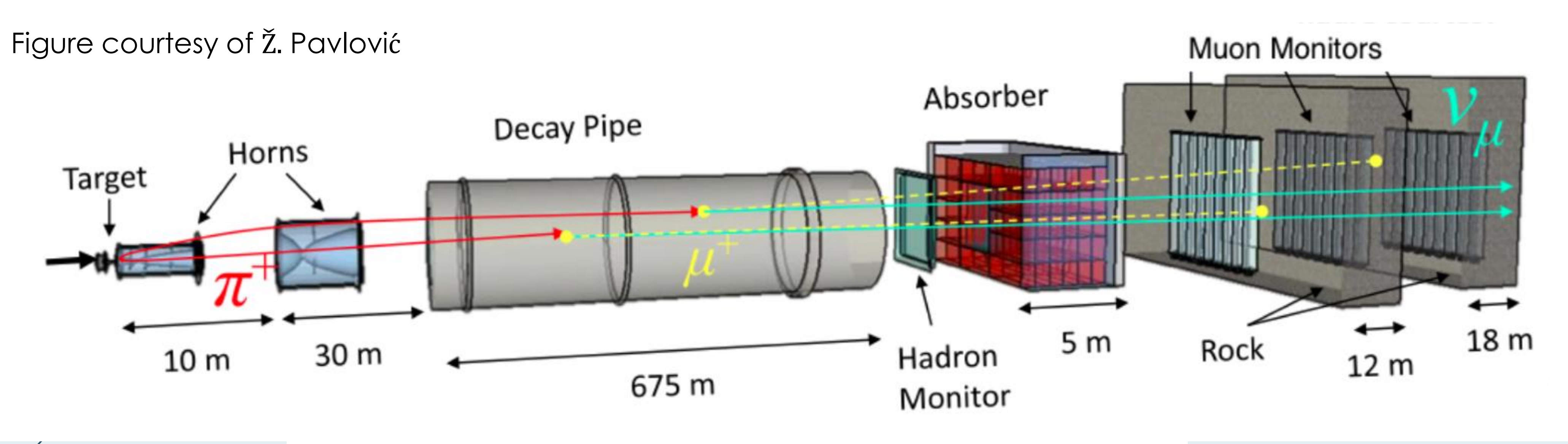
QE-*like* Measurement



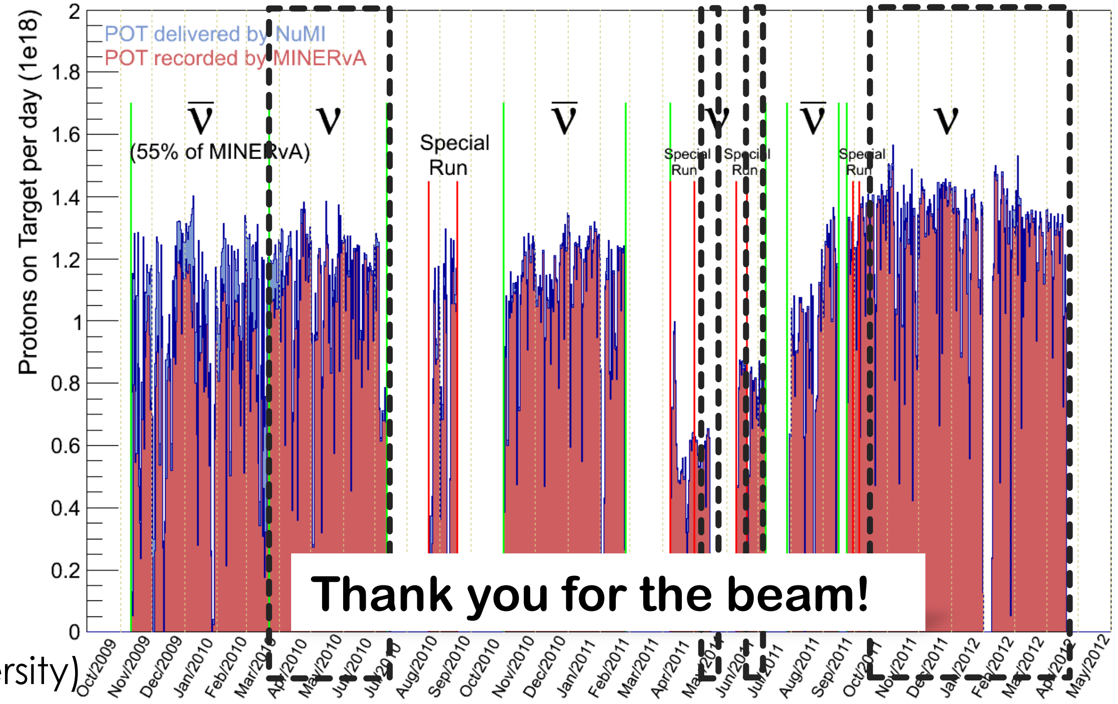
- Use both the **muon** and **proton** to characterize both the nuclear effects that occur at the scattering vertex and inside of the nuclear medium for all events that **look like** a quasi-elastic process.

The NuMI Beam and MINERvA Experiment

The NuMI Beam Line

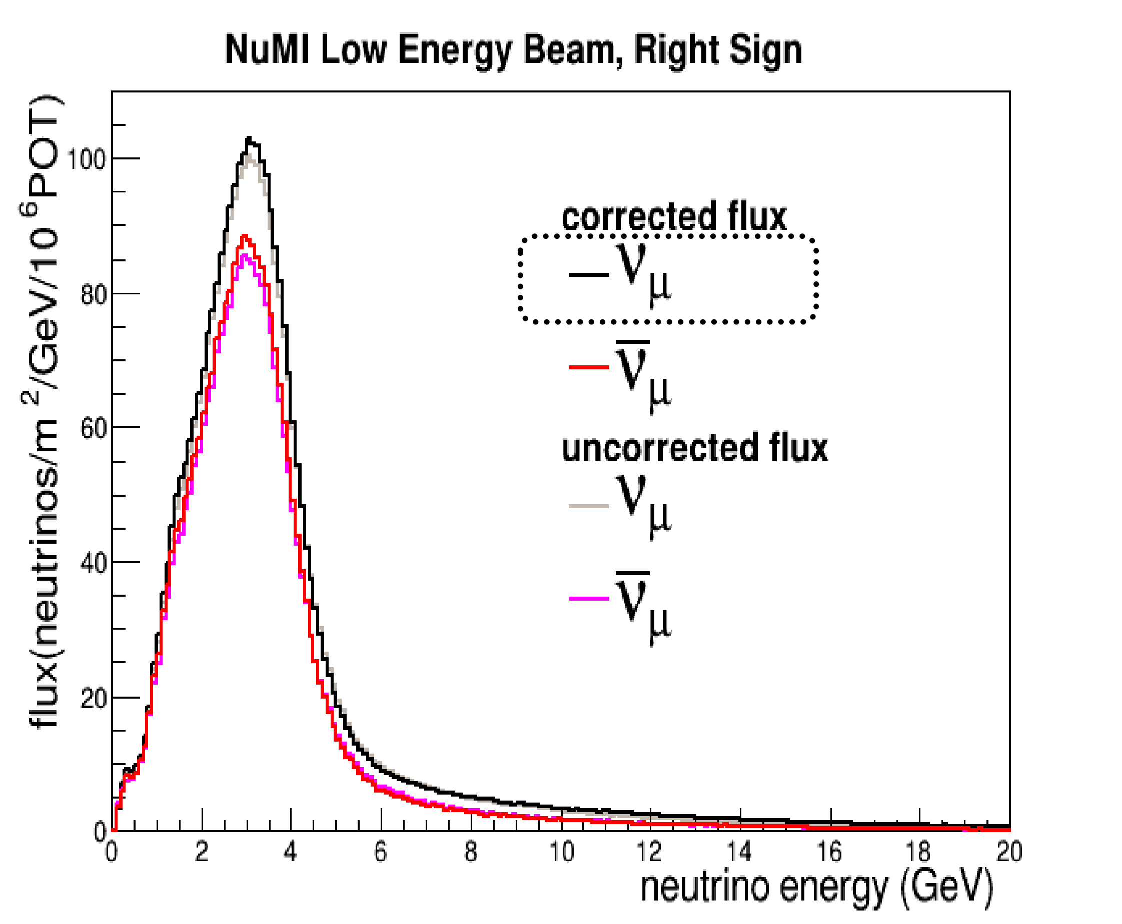


The LE ν_μ-beam comes from 3.98e+20 Protons on Target.



This analysis uses all of the neutrino analyzable data.

The Neutrino Flux

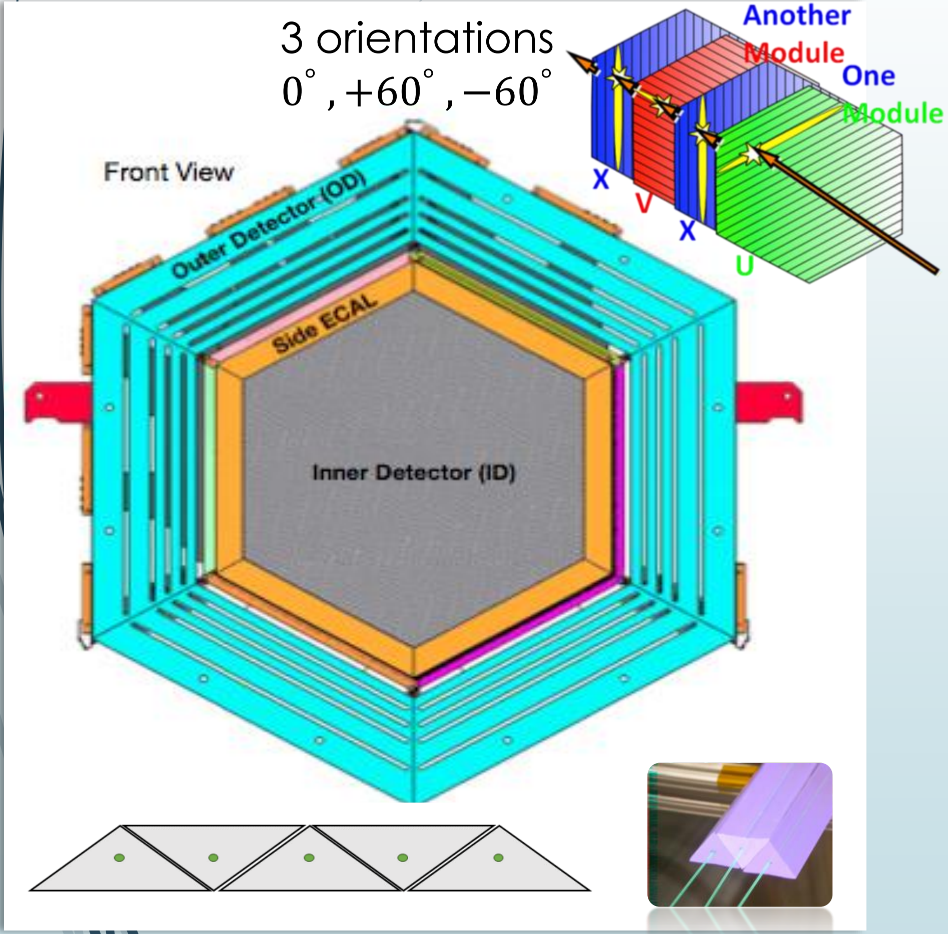


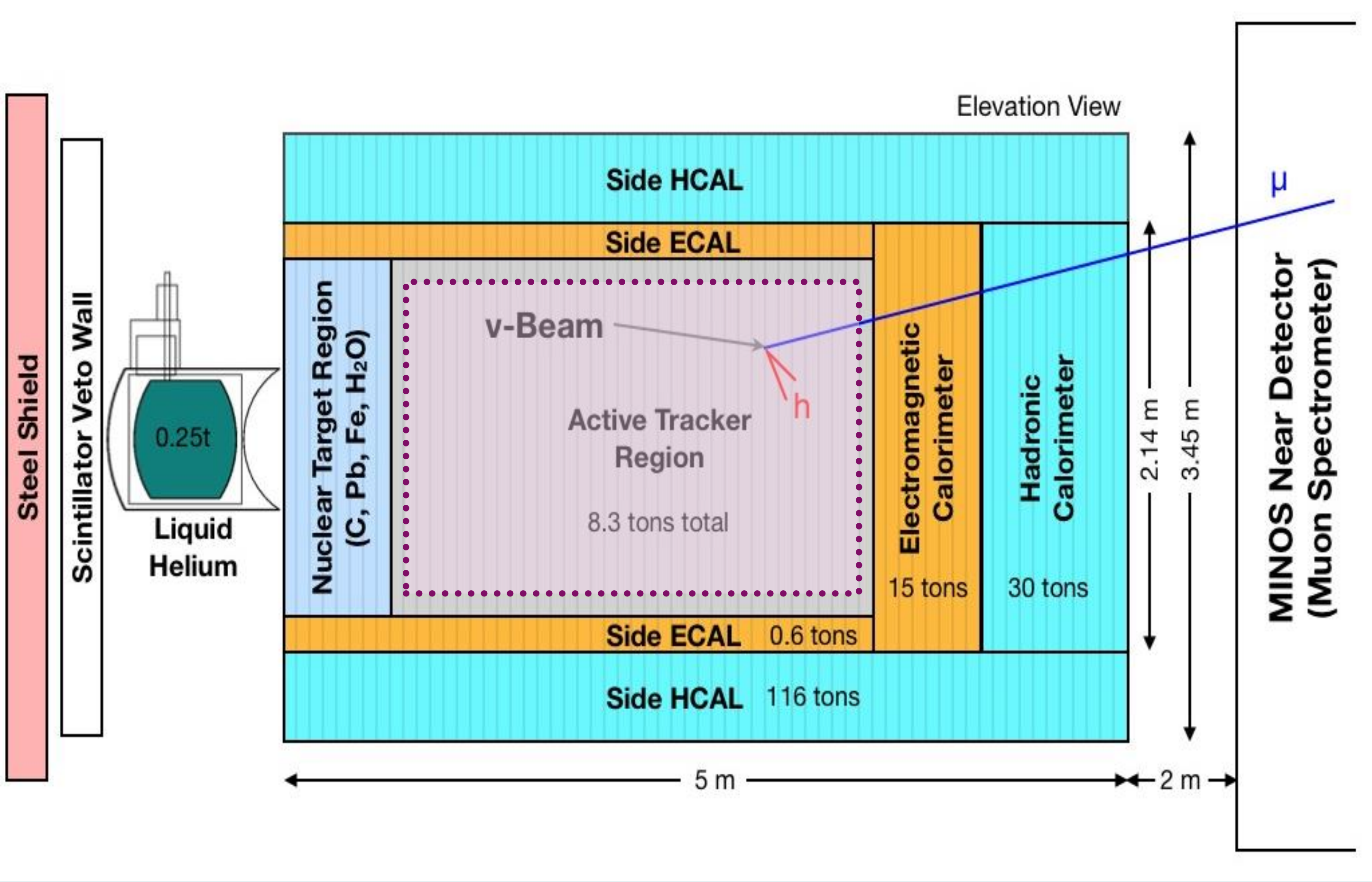
- The presented analysis uses only the neutrino energy spectrum.
- The shape analysis is insensitive to the neutrino flux (the modeling of the neutrino event rate).
- The differential cross section that is produced for this analysis, integrates over all neutrino energies.

The MINERvA Detector

Composed of 120 modules stacked along the beam direction.
Fine-grained scintillator core surround by electromagnetic and hadronic calorimeters.
MINOS near detector serves as the muon spectrometer.

3 orientations
$0^{\circ}, +60^{\circ}, -60^{\circ}$

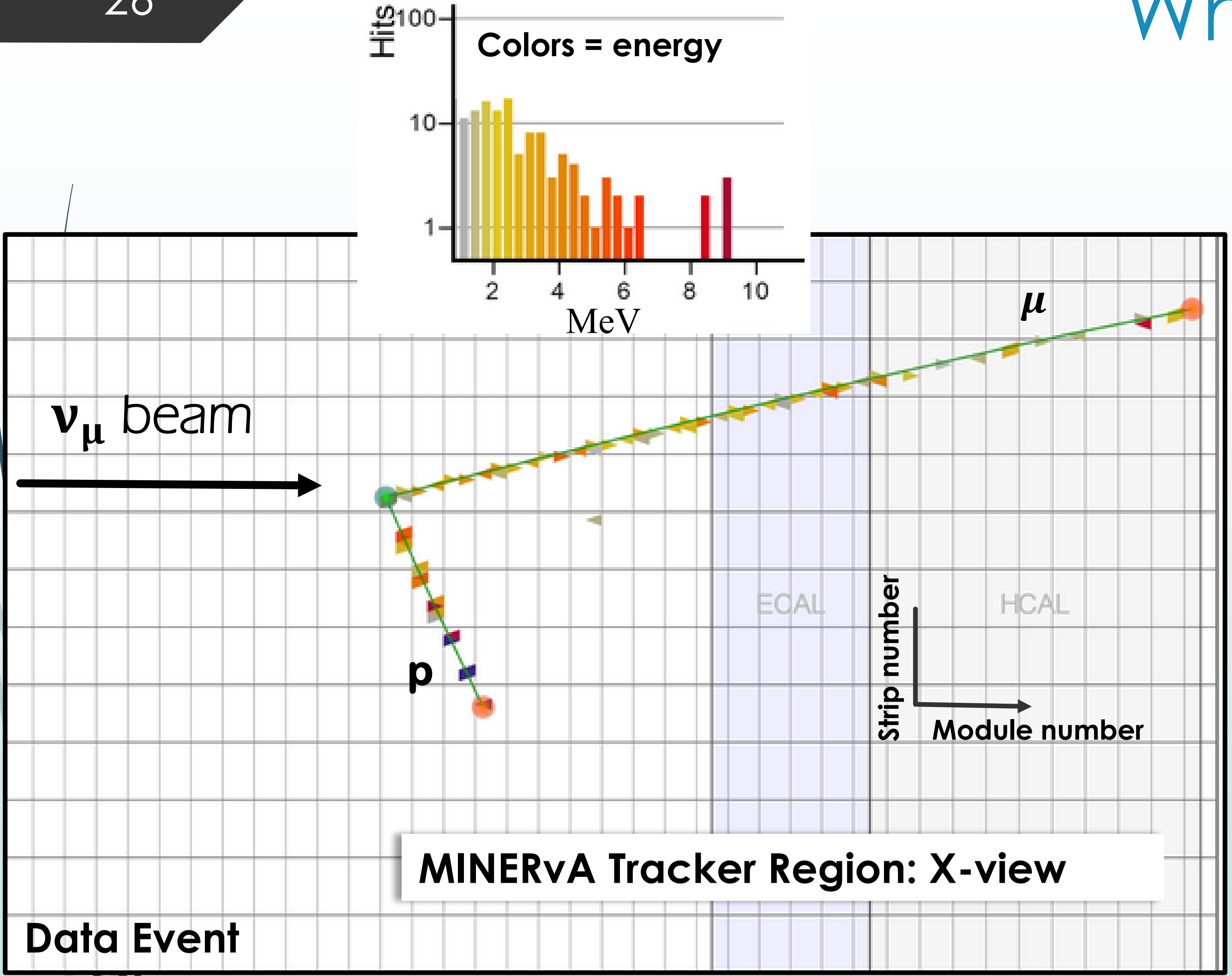




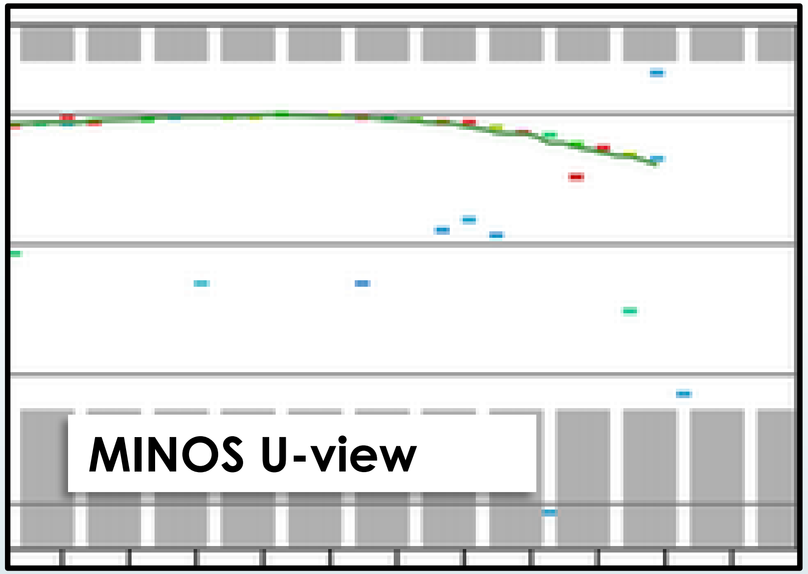
Event Reconstruction

- Searching for events with one muon track and *at least* one proton track.
- Event kinematics can be reconstructed from the **muon**, **muon and leading proton**, or **leading proton**.
- All events with a muon that **exits** the Inner part of the detector are KEPT.

Where do the muons go?



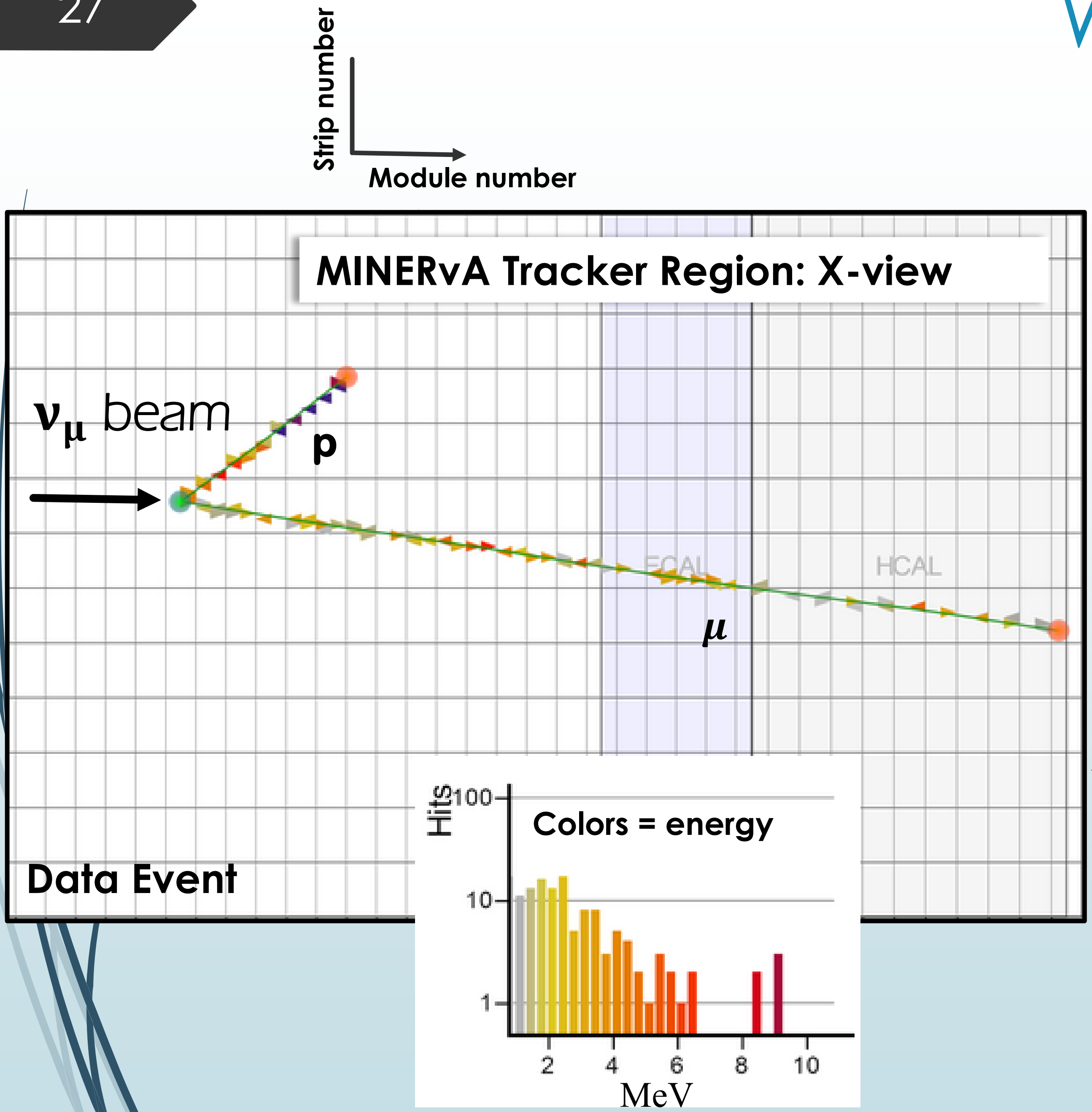
2m



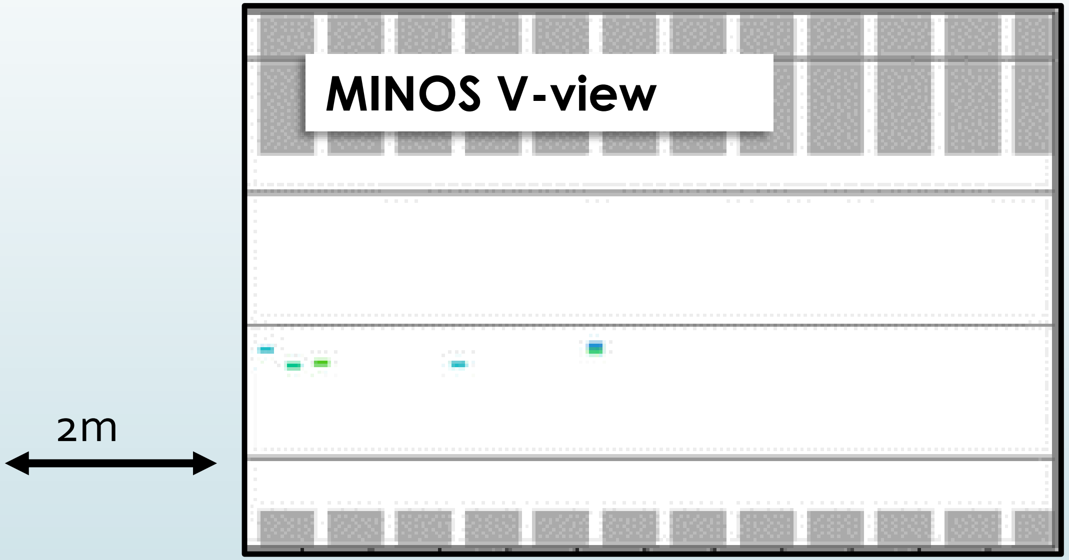
Strip: view from the top of the detector

Muon exits the Tracker Region and is track matched by MINOS.

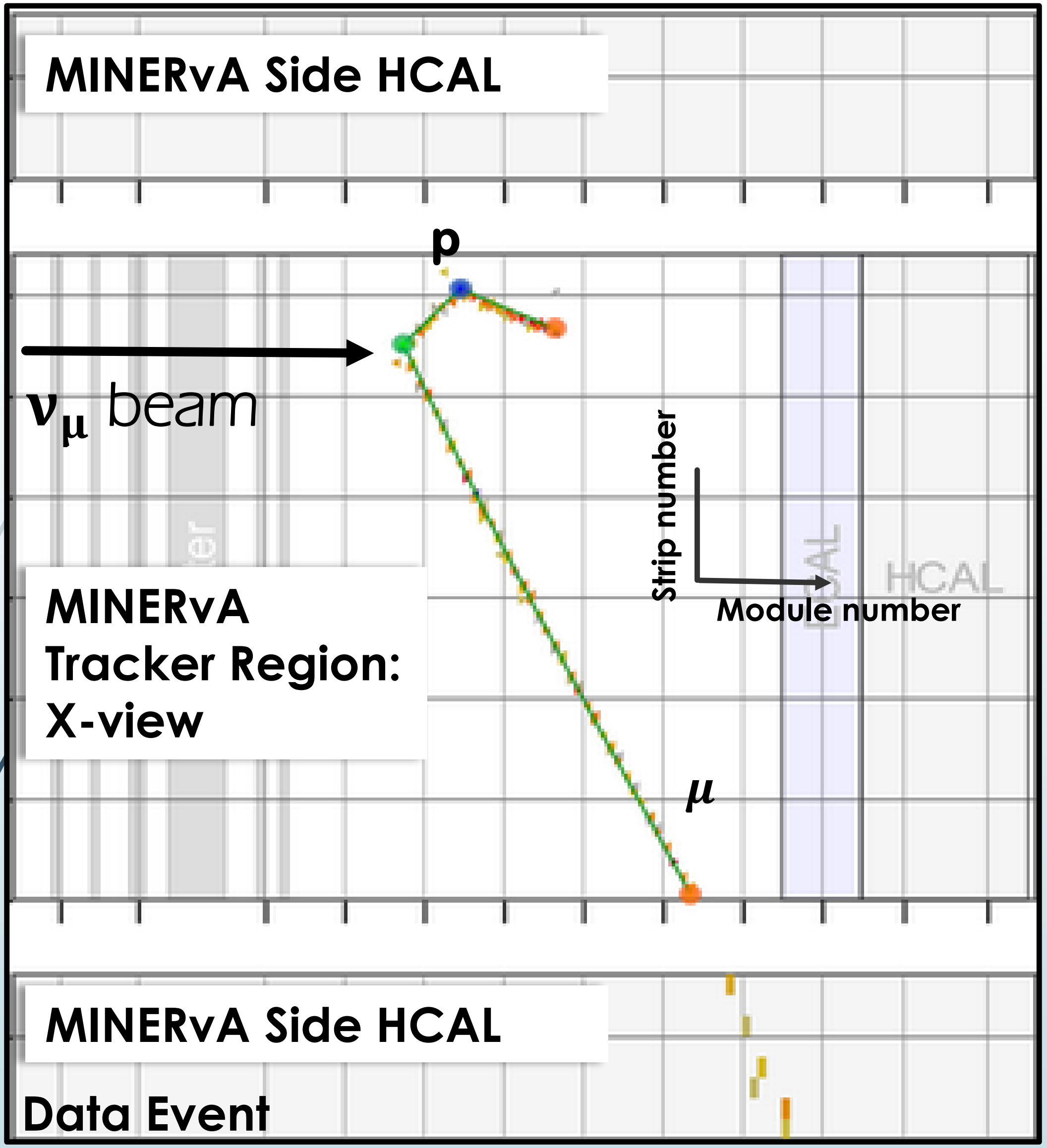
Where do the muons go?

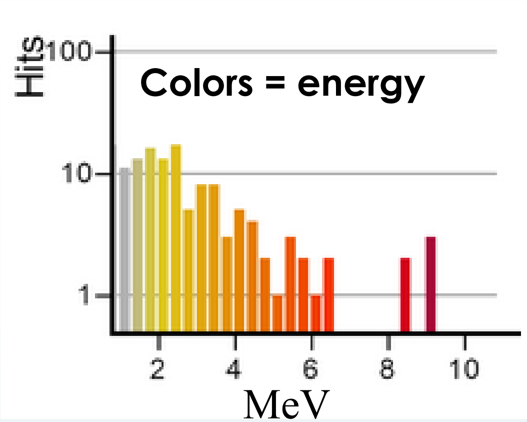


Muon exits the Tracker Region and the MINERvA track is matched to hits in MINOS.



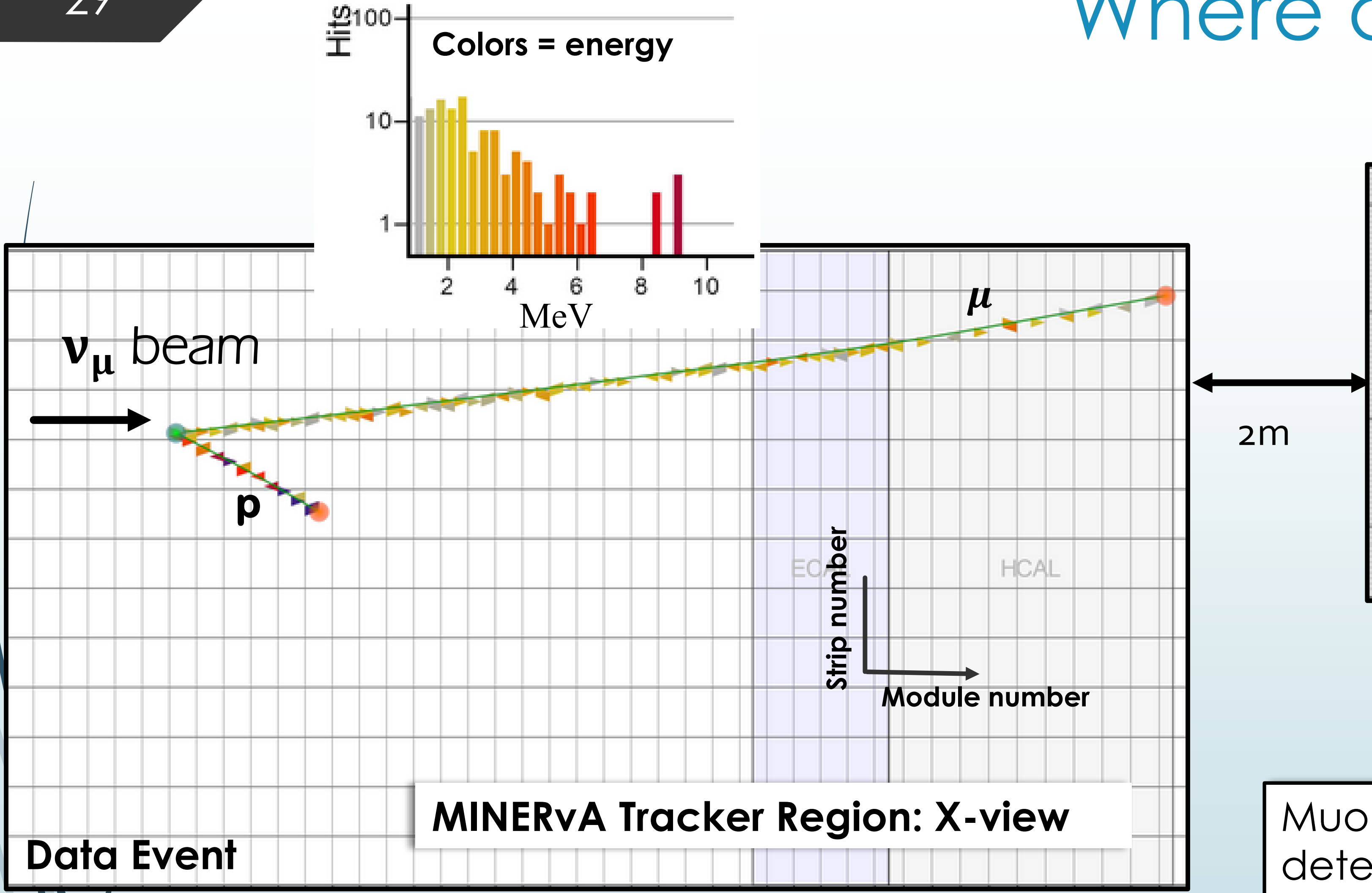
Where do the muons go?

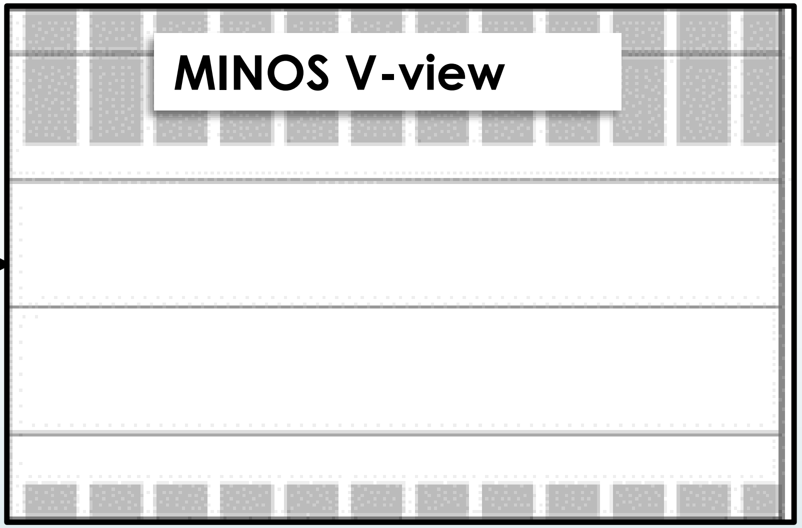




Muon exits the Tracker Region of the detector and is matched to hits in the Side HCAL region.

Where do the muons go?





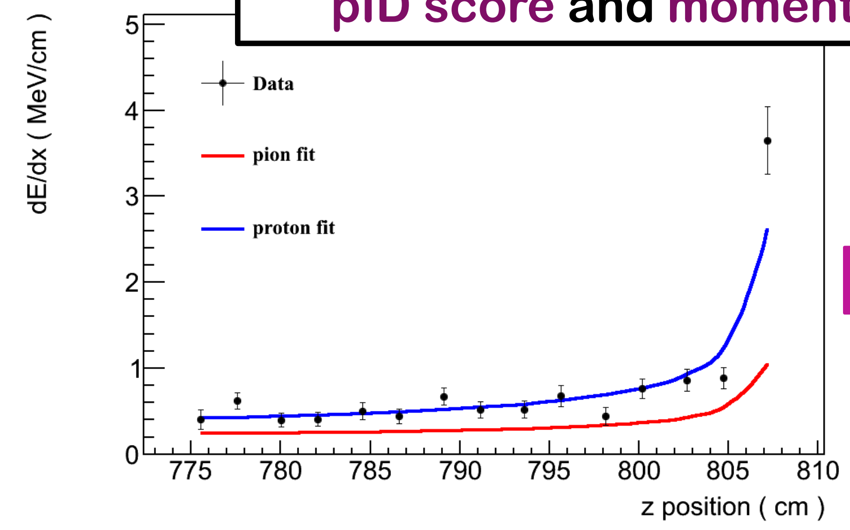
Muon exits the Tracker Region of the detector and is NOT matched to MINOS or to the Side HCAL.

Isolating the QE-like Events

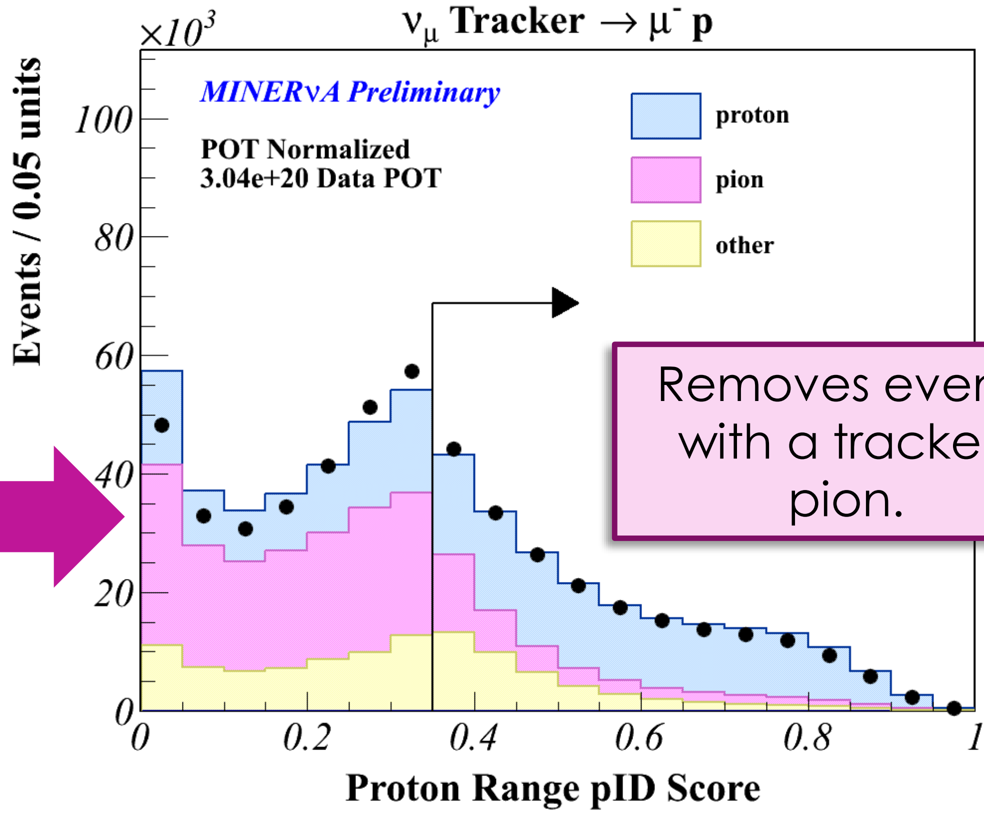
- **Event Selection**
  - Select events with two or more tracks, where one track is the muon and the other tracks are protons.
- **Signal Definition**
  - One negatively charged muon
  - At least one proton with $p_p > 450$ MeV/c. → Tracking Threshold
  - No pions

Identifying the Protons

- Requires that all of the hadron candidates resemble a proton.
- Fit each hadron track energy loss, *dE/dx* profile to both a pion and proton energy loss profile for particle identification and momentum reconstruction.
- Uses the χ^2/d.o.f values from both the pion and proton fits to create a score and momentum.



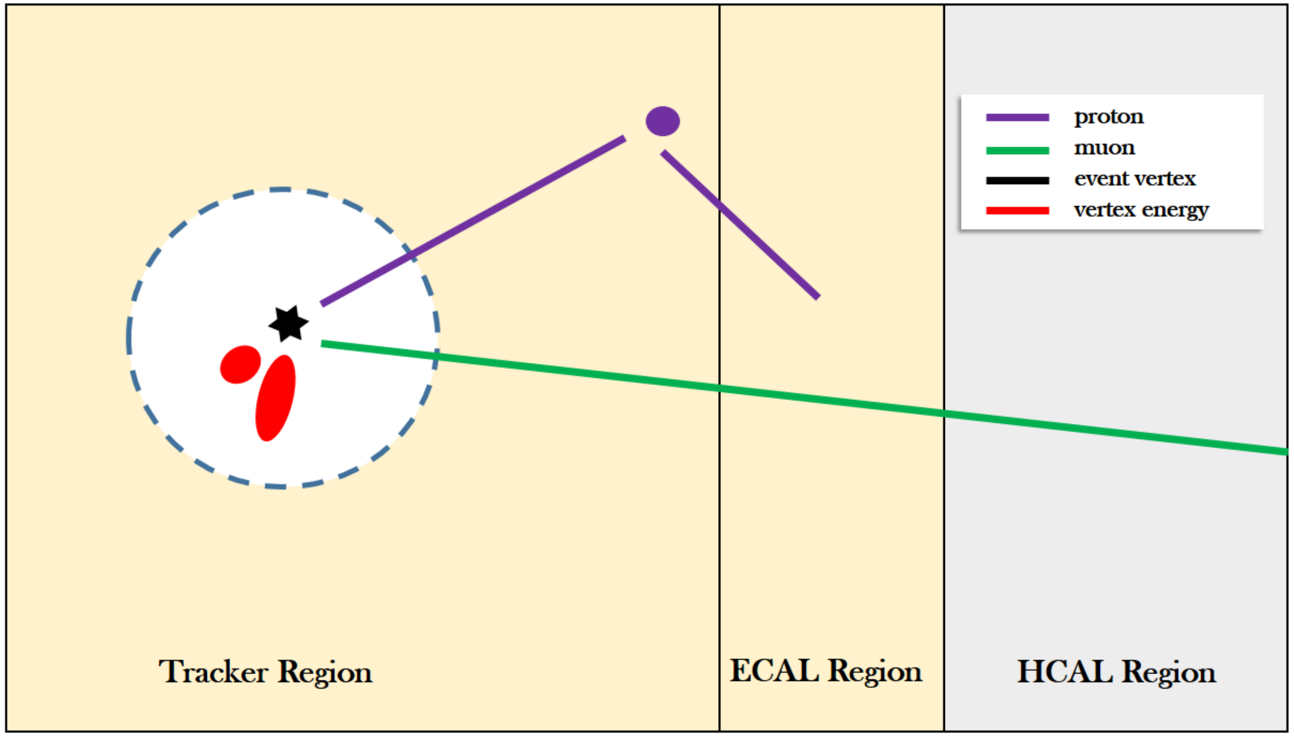
For each track, gives both the pID score and momentum!



Removes events with a tracked pion.

Removing Events Beyond the Quasi-elastic Region

Topological observable is defined as **unattached visible energy**.



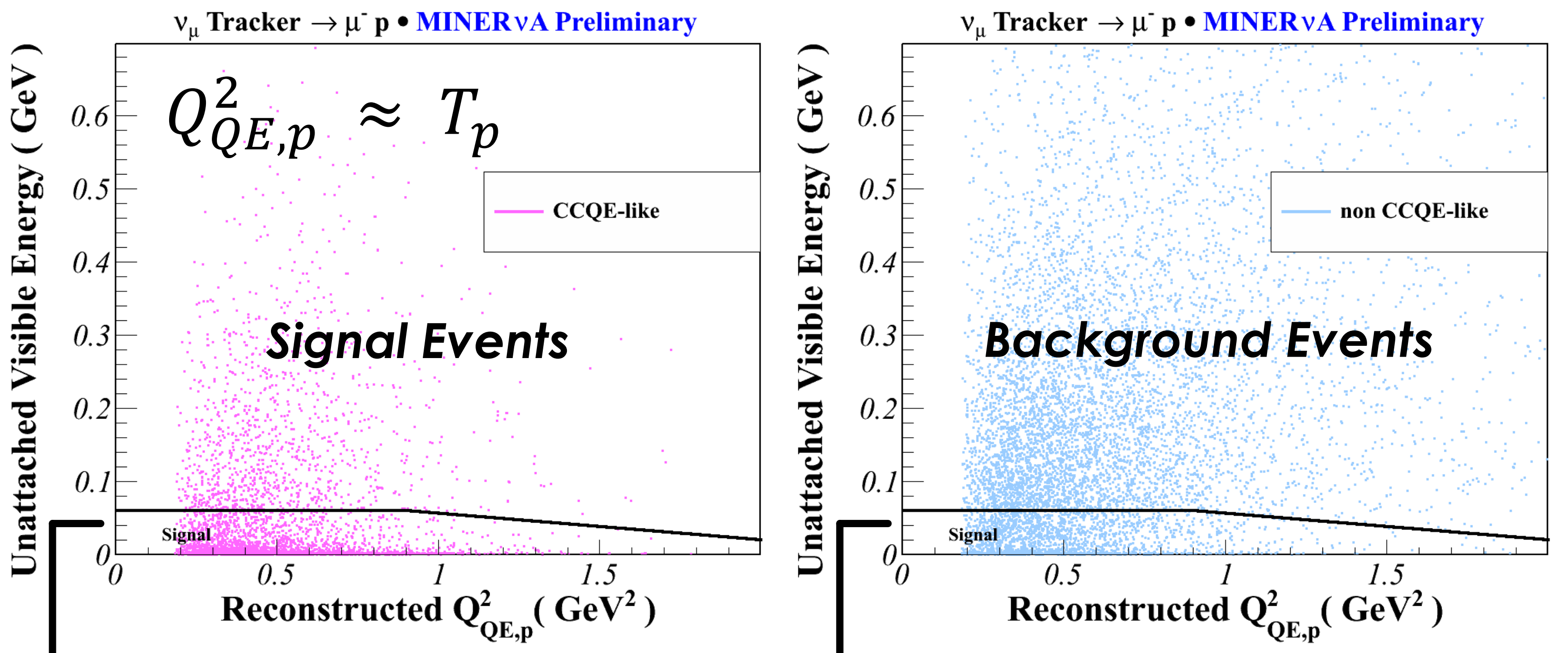
- **The hadronic invariant mass $W \gg M_p$ for the non QE-like events, where the proton is tracked in this analysis. Events with $M_p^2 \leq W^2 \leq M_{\Delta^{++}}^2$ most likely leave little or no extra energy.**

- **Very large amounts of extra energy which is not on the muon or proton track, most likely corresponds to final state particles that were not tracked. NOT a signature of a neutrino-nucleus interaction in the quasi-elastic or transition region.**

Removing Events Beyond the Quasi-elastic Region

$Q^2_{QE,p}$: four momentum transfer for QE scattering from a nucleon at rest, using only the proton kinematics

T_p : the proton kinetic energy



Signal Region

Higher energy protons are more likely to re-scatter.

The kinetic energy of those protons is reconstructed too low.

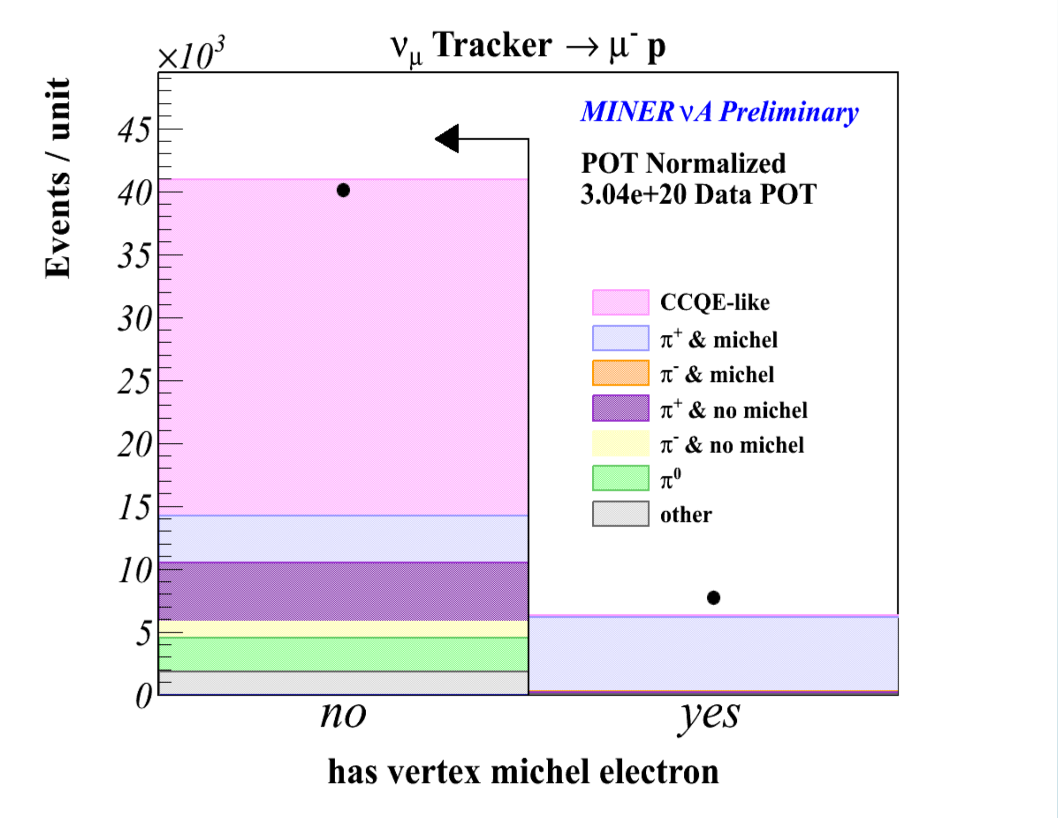
Higher energy protons migrate to lower bins, while leaving large amounts of energy depositions which correspond to their secondary scattered products.

Removing Events with Soft Pions

$$\pi^{\mp} \rightarrow \mu^{\mp} + \nu_\mu(\bar{\nu}_\mu)$$
$$\mu^- \longrightarrow e^- \bar{\nu}_e \nu_\mu$$
$$\mu^+ \longrightarrow e^+ \nu_e \bar{\nu}_\mu$$

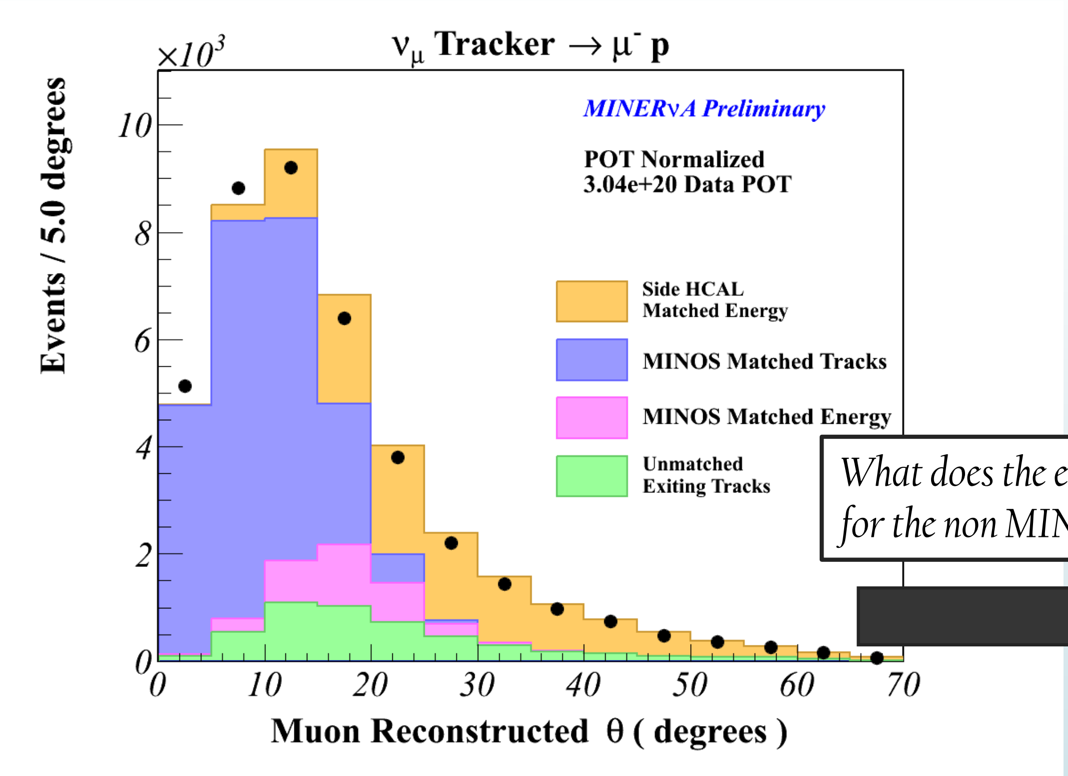
Veto events with a Michel electron found near the interaction vertex.

Removes events with low energy pions that stop and decay in the detector.

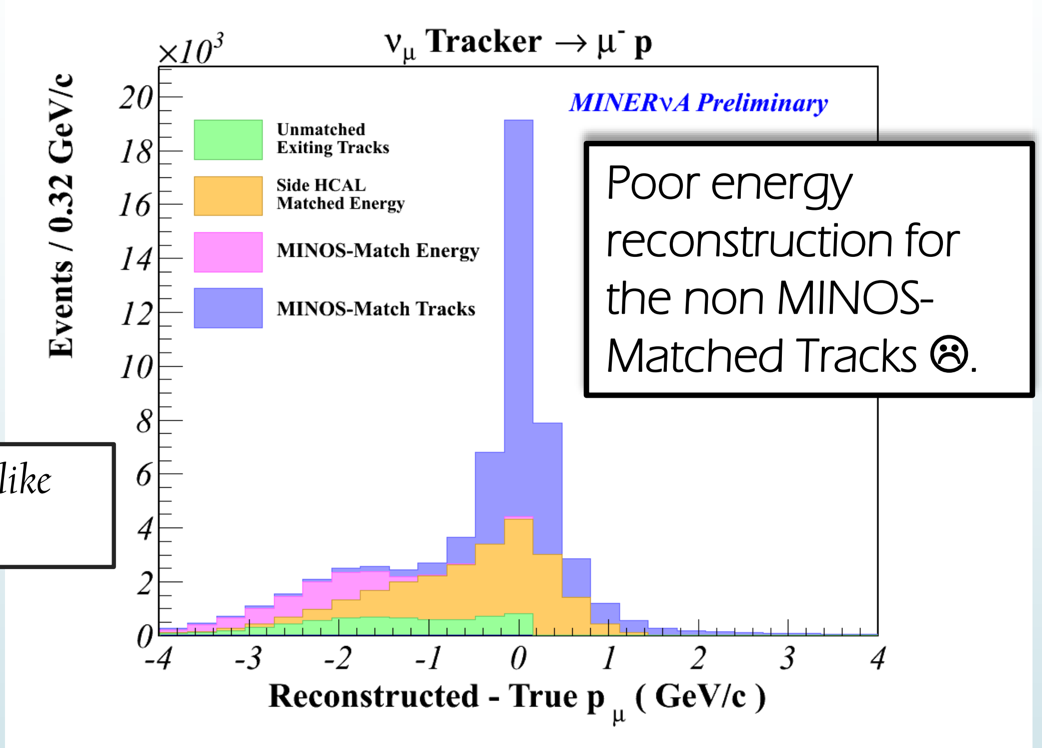


Muon Topology of the QE-like Candidates

Include ALL muons ⟹ more statistics ☺



What does the energy resolution looks like for the non MINOS-Matched tracks?



Poor energy reconstruction for the non MINOS-Matched Tracks ☹.

Include tracks matched to hits in the Side HCAL ⇒ broader scattering θ_μ acceptance.

For the entire sample, we cannot use the muon kinematics to reconstruct the event kinematics.

Reconstruction of the Event Kinematic

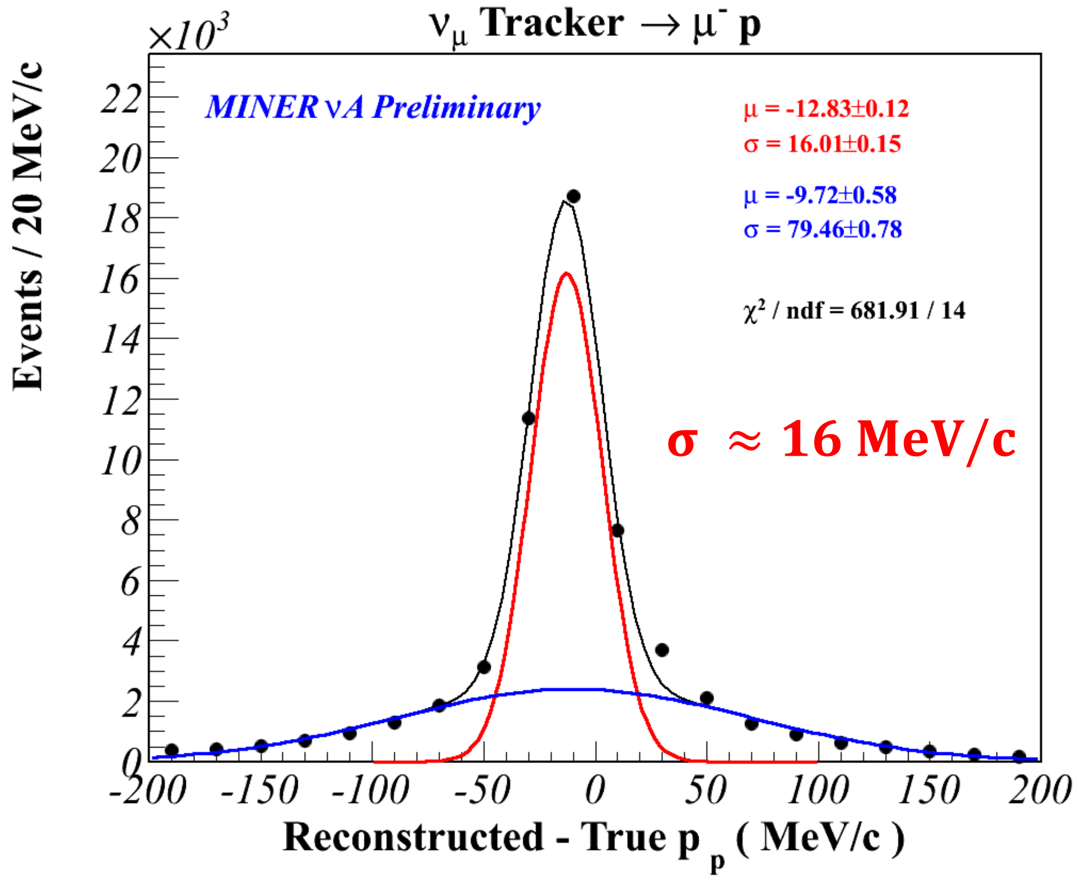
- Reconstruct Q^2 using kinetic energy of the leading proton.

- Use the QE hypothesis.

- Assume scattering from a free nucleon at rest.

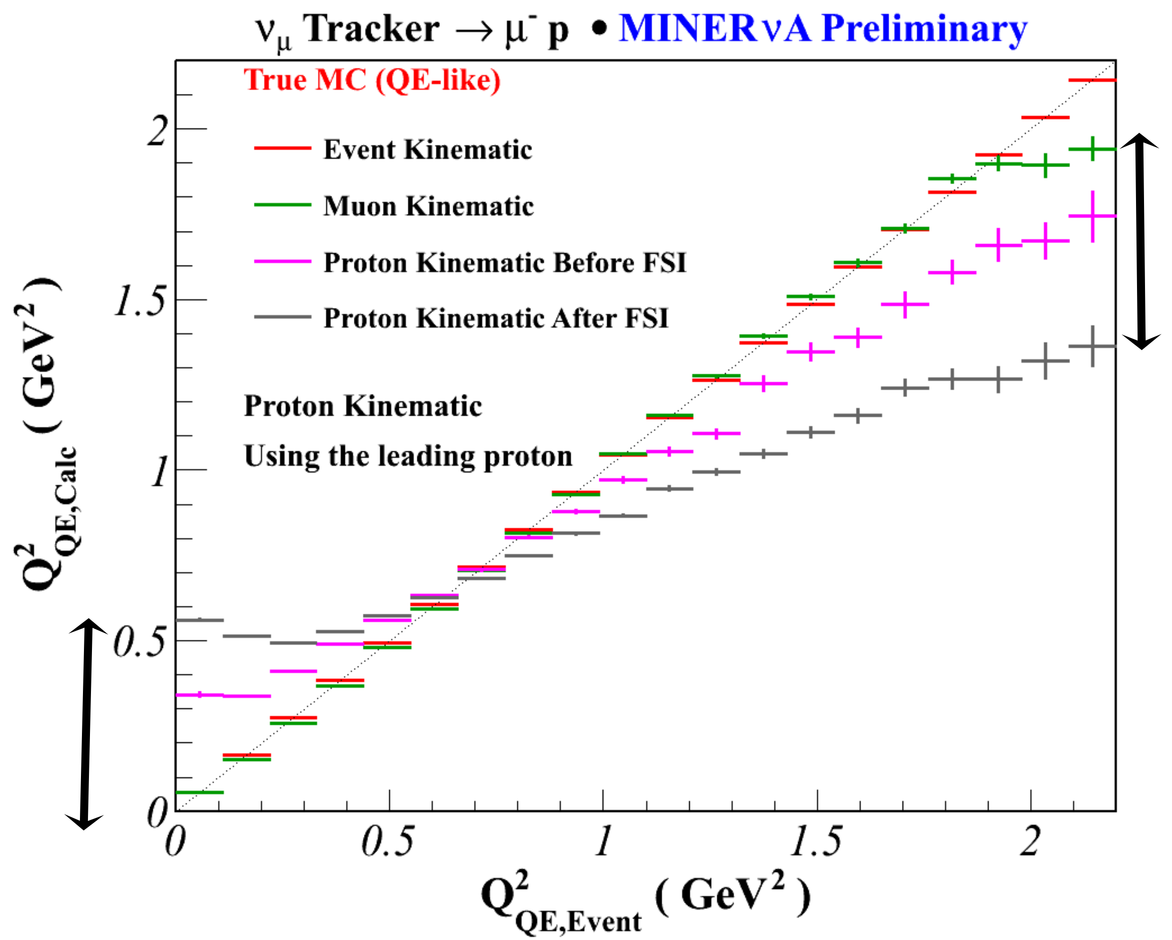
  - $Q^2_{QE,p} = (M')^2 - M_p^2 + 2M'(T_p + M_p - M'),$

    - $M' = M_n - E_{bind}$
    - E_{bind} is the binding energy
    - T_p is the proton kinetic energy
    - M_n is the mass of the neutron
    - M_p is the mass of the proton



p_p is the proton momentum

Reconstructing Q^2 from the Muon vs. Proton

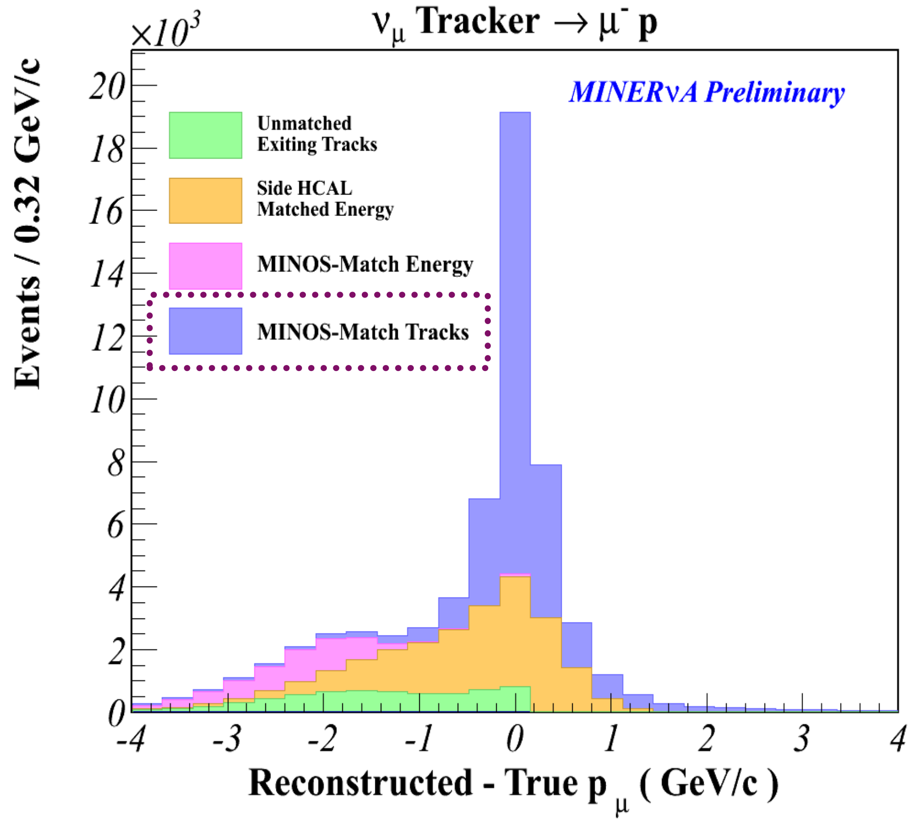


The primary message:

The Q^2 is smeared at all values when calculating Q^2 from the proton kinematics.

This smearing is due to not accounting for the Fermi motion and FSIs.

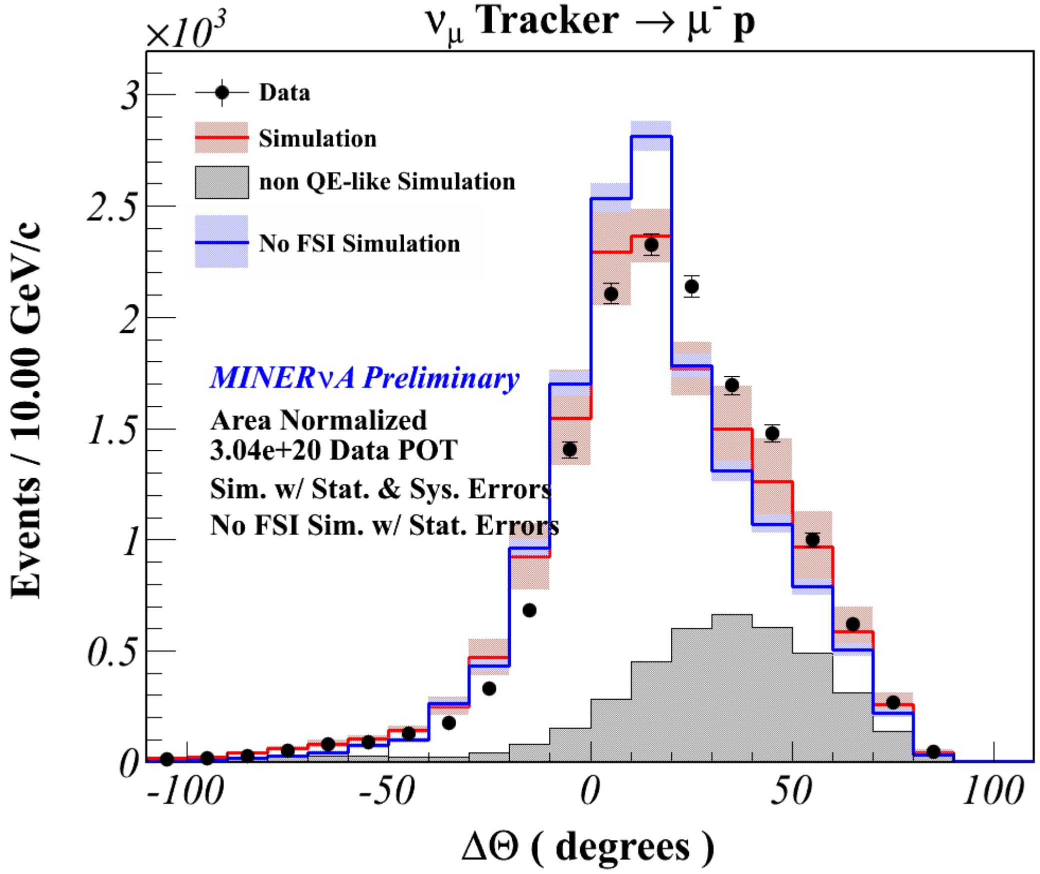
How well does GENIE Model the Nuclear Environment?



- Use the MINOS-Match Tracks sample.
- Both the muon and leading proton have a well-reconstructed energy.

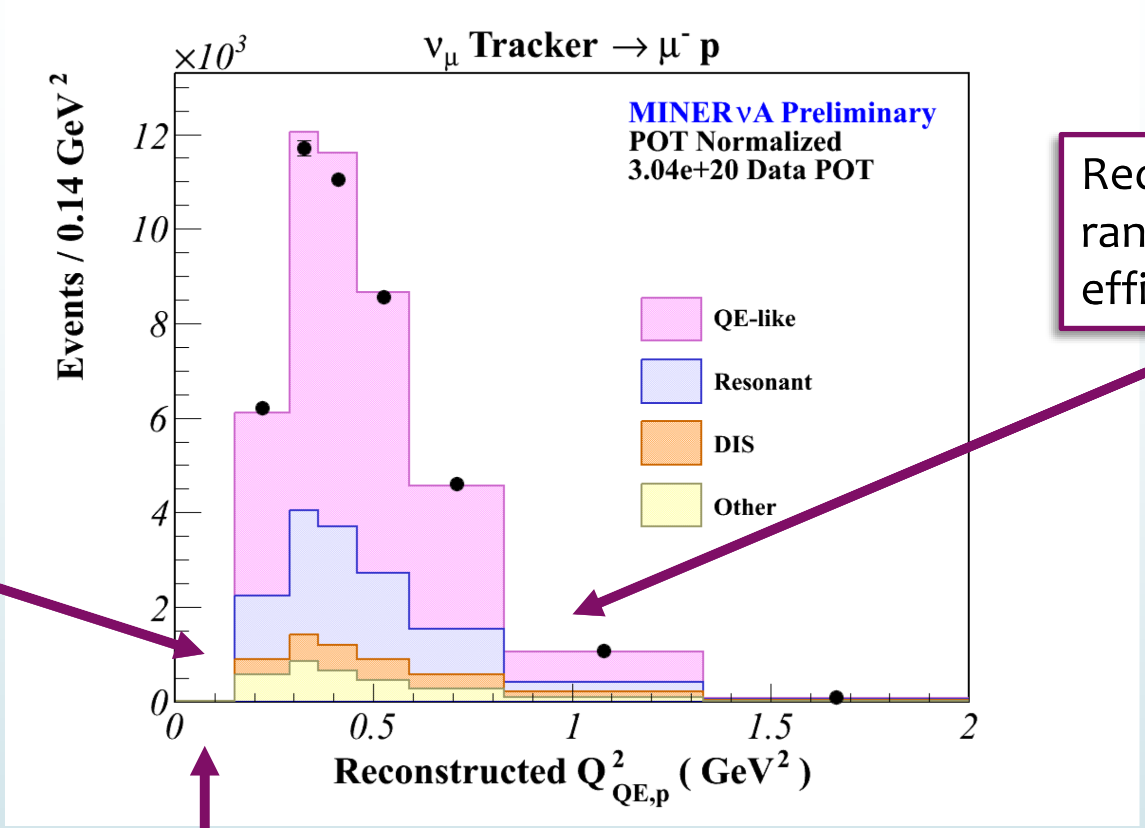
$$\Delta\theta = \theta_{proton}^{predict} - \theta_{proton}^{reco}$$

$$\theta_{proton}^{predict} = \cos^{-1}\left(\frac{E_{\nu}^{QE} - p_{\mu}\cos\theta_{\mu}}{p_{proton}}\right)$$



QE-like Candidates

Data Candidates = 40,102



Requiring the hadron to resemble a ranging out proton ⟶ drop in the efficiency.

Resonant Production with a pion in the final state dominant background.

Tracking threshold prevents the reconstruction of events in the first bin.

The QE-like signal is predicted to consists of:

QE = 72.3 %

Res = 23.9%

DIS = 3.8%

Differential cross section vs. four-momentum transfer calculated for QE scattering from a free nucleon at rest.

Function to convert from Q^2_{reco} to Q^2_{true} using the leading proton kinematics.

Background constrained by the data

$$\left(\frac{d\sigma}{dQ^2_{QE,p}}\right)_i = \frac{1}{\Phi T}\frac{1}{\Delta Q^2_{QE,p}}\frac{\sum_j U_{ij}\left(N_j^{data} - N_j^{bkgd}\right)}{\varepsilon_i}$$

Integrated neutrino flux and number of nucleons

Bin width

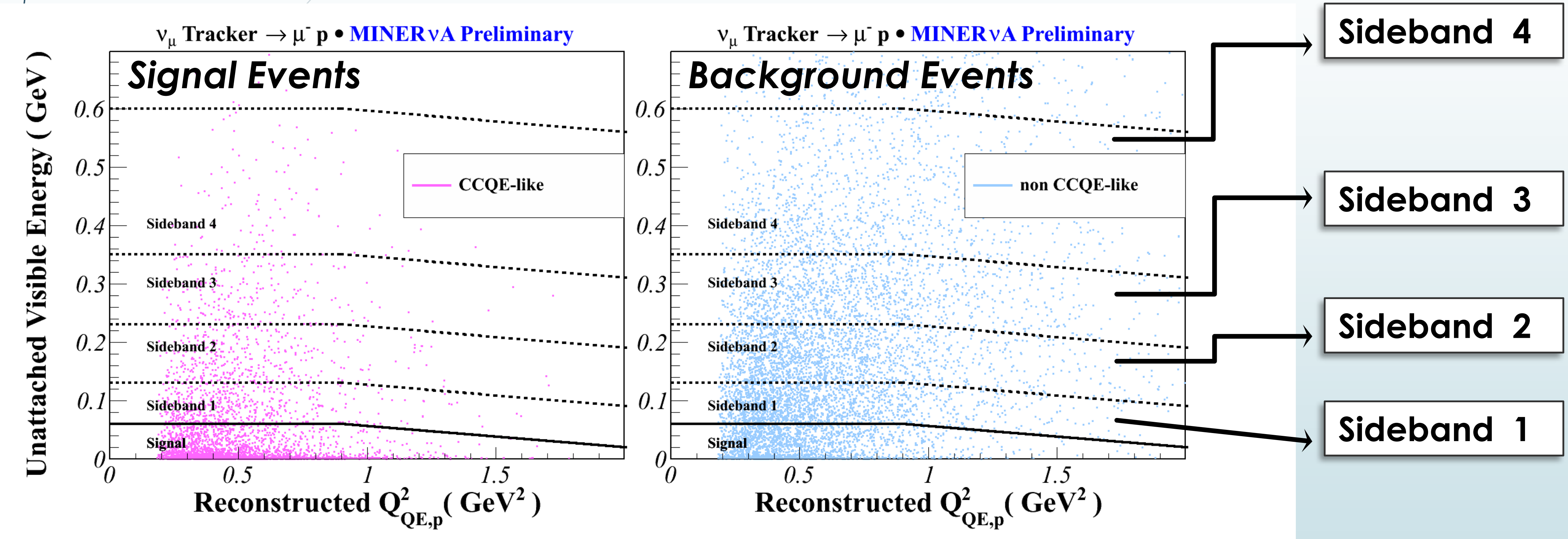
Product of the selection efficiency and acceptance

The non QE-like Backgrounds

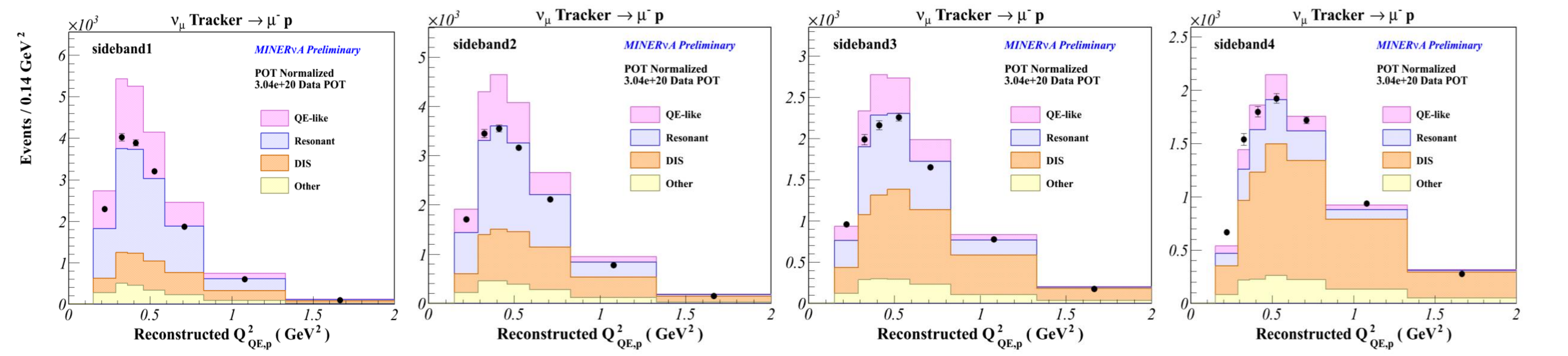
- **Largest background**: Resonant (primary from the Δ^{++} production) with a pion in the final state **(~20%).**
- Deep Inelastic Scattering makes up about **~6%** of the background.
- Neutrino cross-sections have large uncertainties $\Rightarrow$ use the ***data*** to tune the background.
- Resonant and DIS are the largest contributions $\Rightarrow$ backgrounds are separated into ***"two-components"***: **Resonant** and **DIS plus others**.
- Use a multi-sideband procedure to obtain the ***"two-component"*** background scales.

Tuning the non QE-like Backgrounds

- Step1: **Select four consecutive sidebands outside of the signal region.**

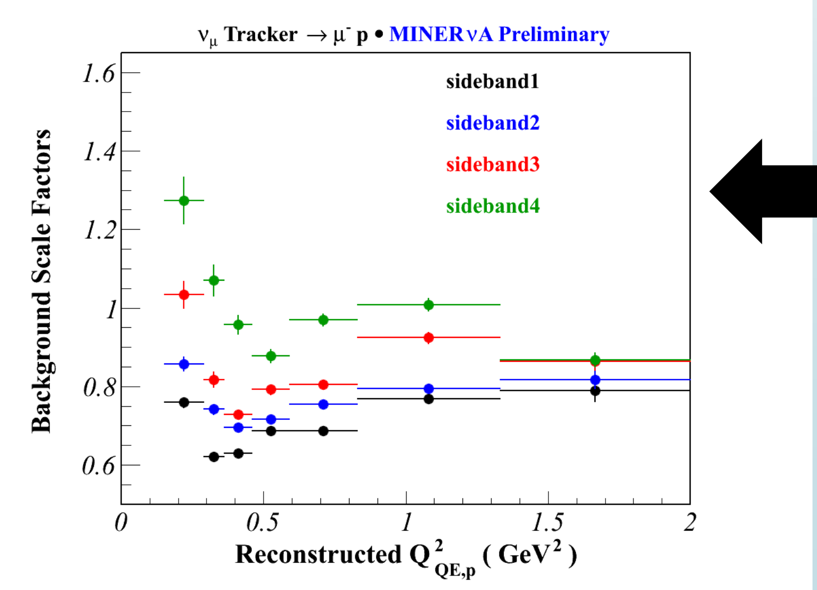


➨ Step 2: **For each sideband, extract weights that force the data and simulation to match perfectly.**

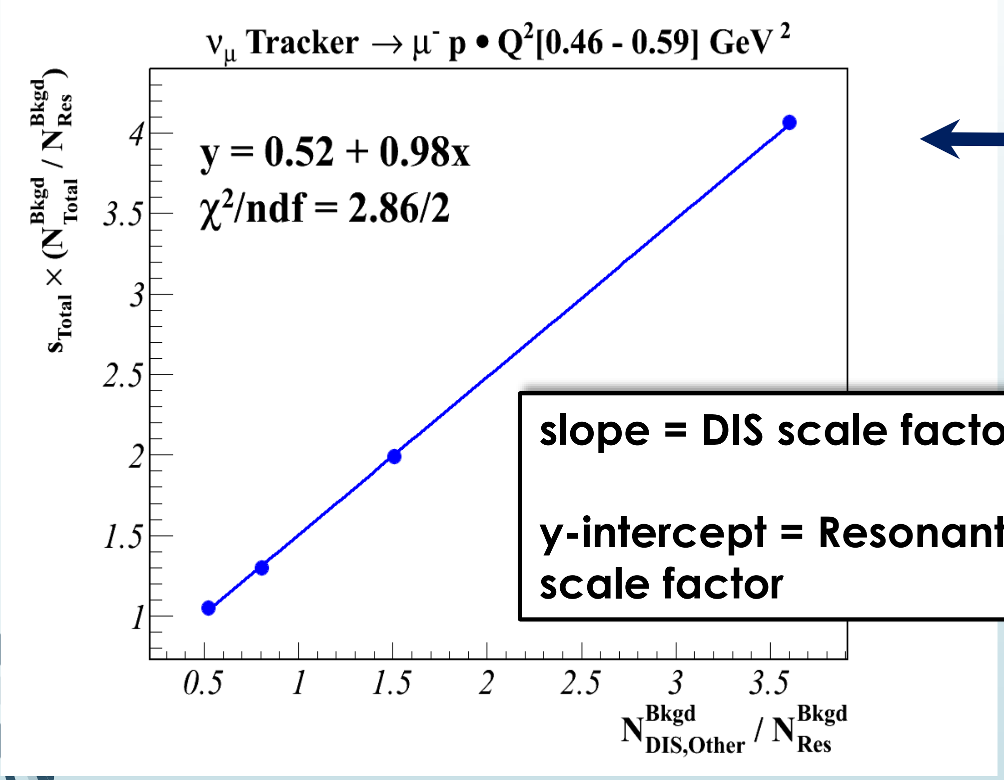


sideband 1 ⟶ sideband 4

- The fraction of signal events decreases.
- The relative fraction of Resonant to DIS events changes.
- The agreement between the data and simulation becomes much better.

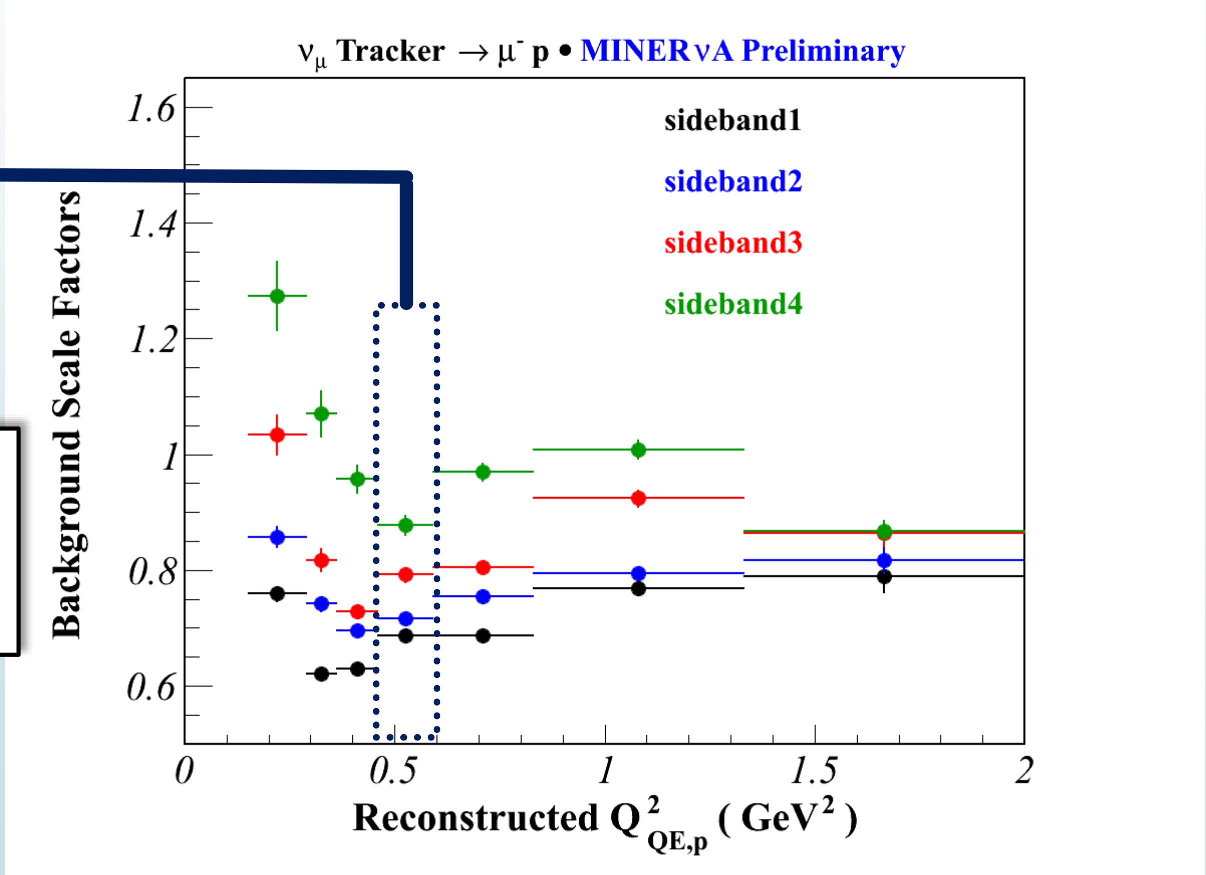


➨ Step 3: **Fit each $Q^2_{QE,p}$ bin to a line. The fit extracts scale factors simultaneously for the *Resonant* and *DIS plus Other* components, with the assumption that all of the sidebands are perfectly aligned.**

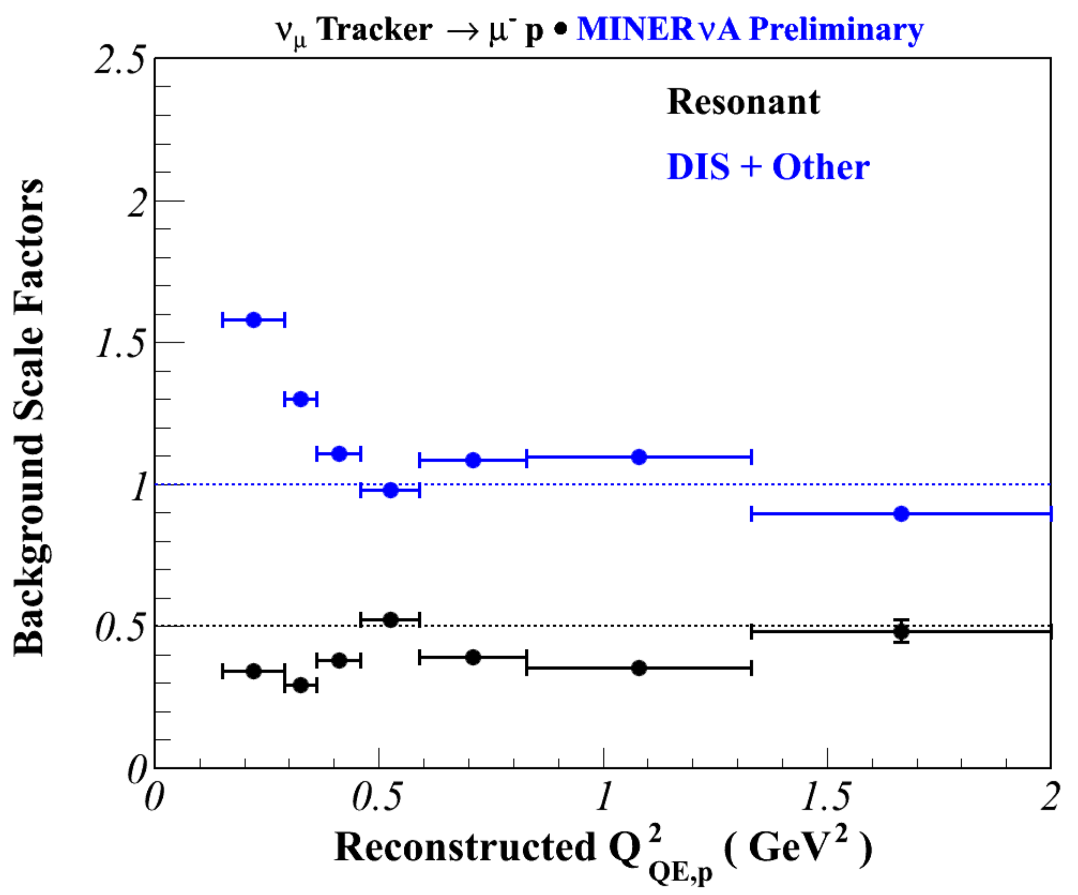


slope = DIS scale factor

y-intercept = Resonant scale factor



The Background Scale Factors



The results show that GENIE overestimate the Resonant production.

These scale factors are convolution of the modeling of the neutrino primary interactions and final state interactions.

Systematic Uncertainties

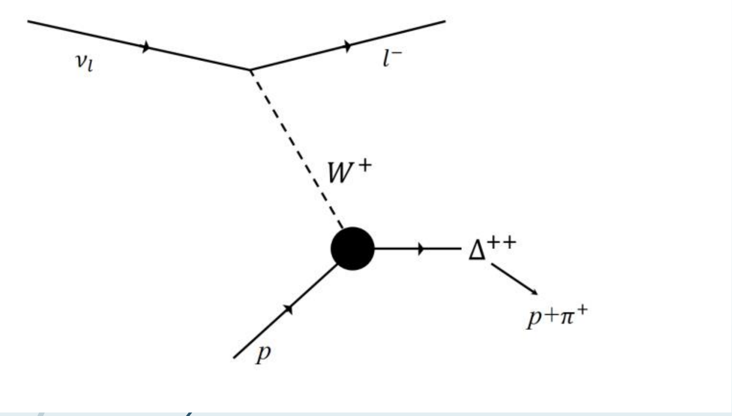
Primary Contributors to the total Systematic Uncertainty

- Neutrino Flux
- Proton Response (Detector Response of the Reconstructed Protons)
- Geant4 Response (Detector Modeling of the Hadron Inelastic Cross-section)
- Neutrino Cross section Models
- FSI Models

Will focus only on these sources.

Systematic Errors: Cross-section Model

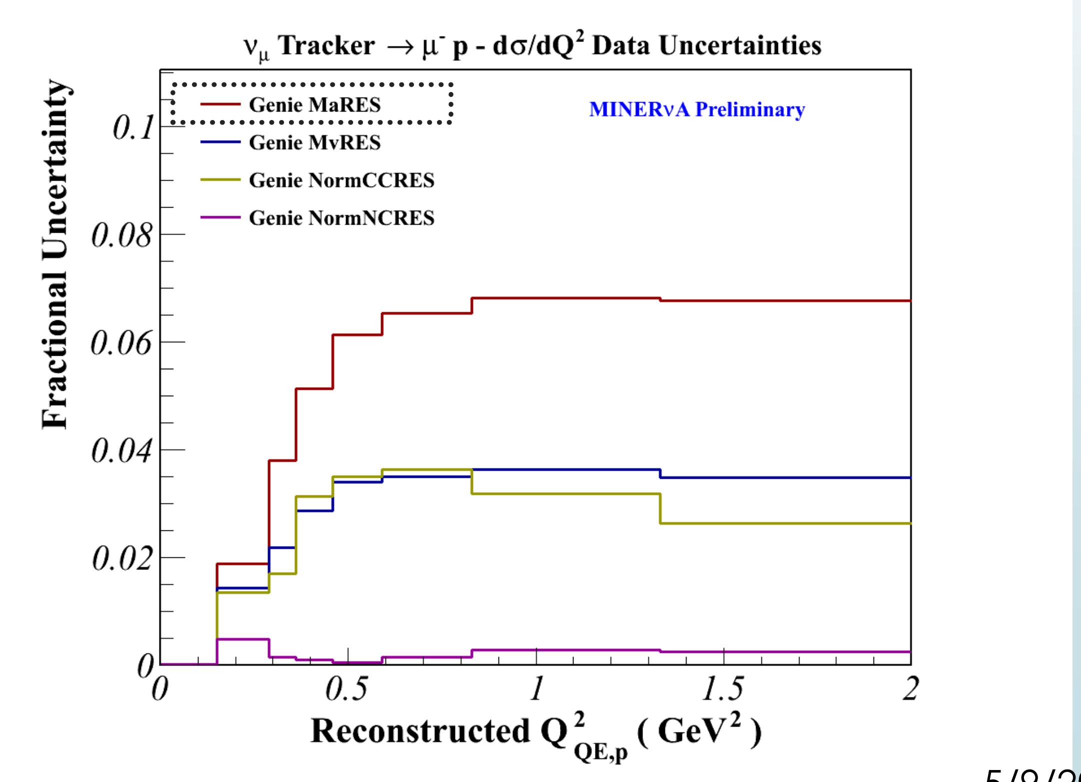
GENIE 2.6.2



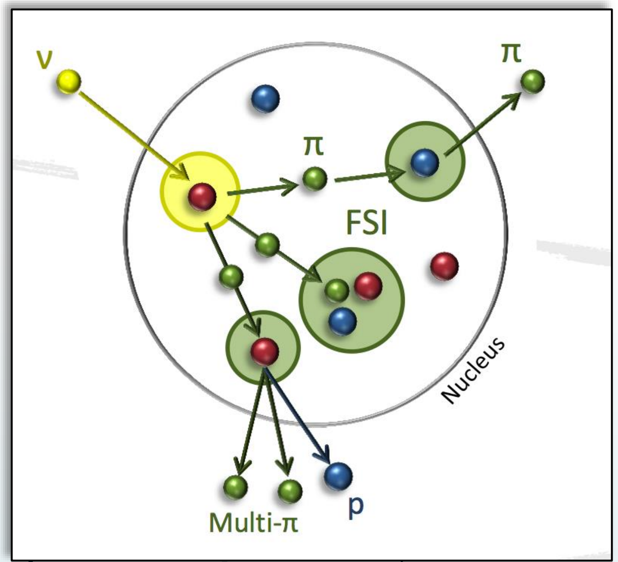
Model parameter	Uncertainty
CC resonance prod. normalization	±20%
Resonance model parameter (M_A)	**±20%**
Non-resonance pion production	±50%

Primary background is from the Resonant production.

Uncertainties on the cross-section models enter through the efficiency-correction.



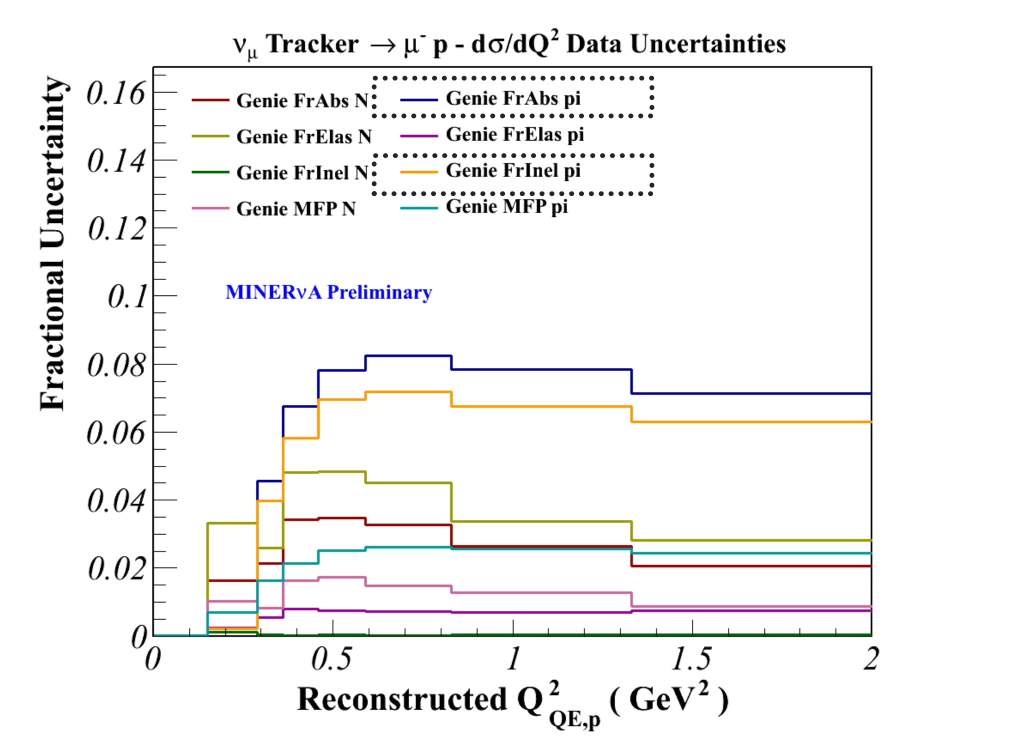
Systematic Errors: FSI Model



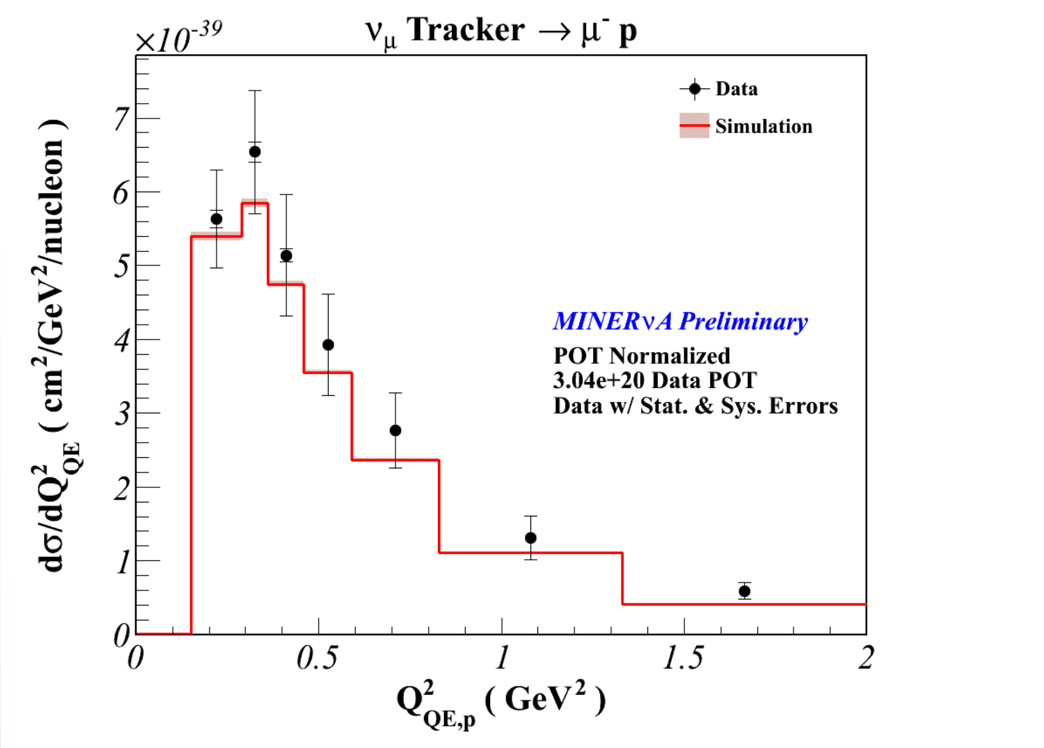
Model parameter	uncertainty
pion/nucleon mean path	±20%
pion/nucleon charge exchange	±50%
pion absorption	**±30%**
pion/nucleon **inelastic cross-section**	**±40%**
elastic cross sections	±10-30%

The uncertainties on the FSI also enter into the analysis at the efficiency correction.

The modeling of the kinematic correlation between the pion and proton for the Resonant production, causes the uncertainties on the GENIE pion production models to become significant in this analysis.



Cross-section Results



Before interpreting these results, we will focus on the pure QE component of this QE-like cross-section.

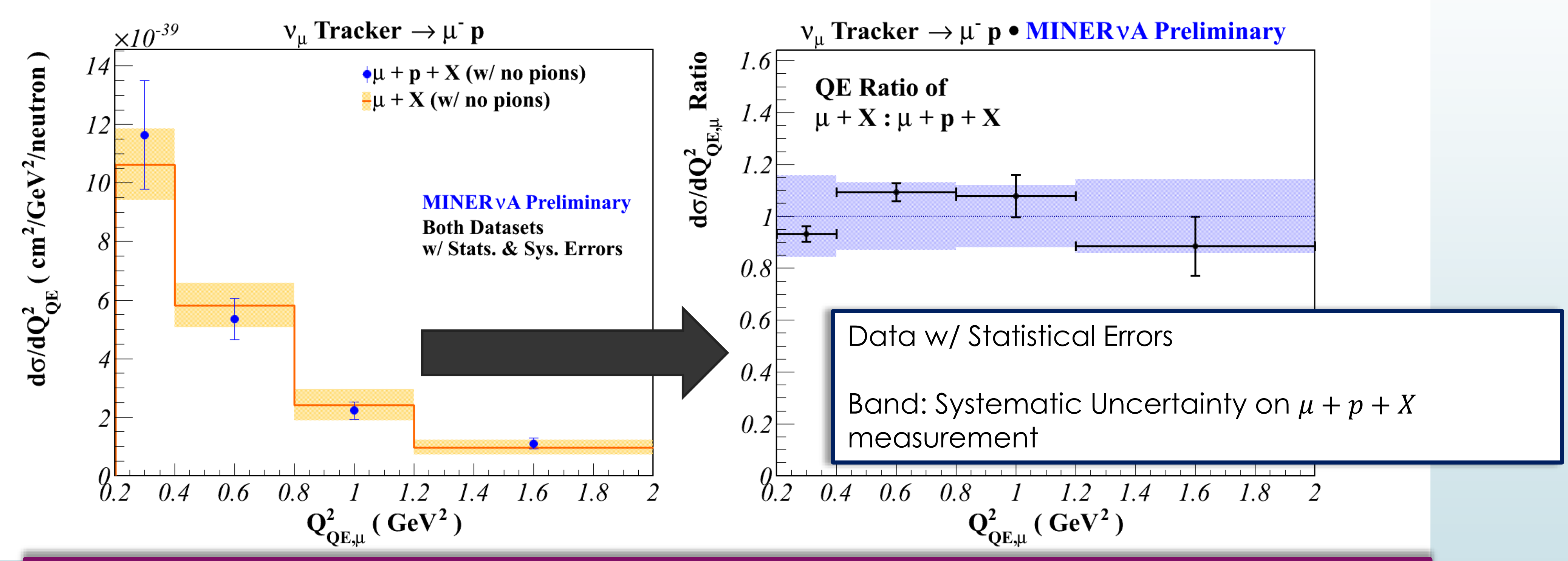
To interpret these results, we will focus on the shape analysis.

Comparing the pure QE Cross-sections

- This QE-like cross section consists of a **pure QE component** with a muon track-matched by MINOS.
- We can compare this subset to the published QE cross section.
- Recall that the published QE measurement is best described by **RFG+TEM**, which says that our data sees evidence of "two-body" currents. Furthermore, the shape analysis shows that **RFG does NOT best interpret the QE regime**.
- Note that the common systematic uncertainties are not canceled due to the differences in the software versions that were used to produce each result.

Comparing the pure QE Cross-sections

QE Analysis	P.O.T
$\mu + p + X$	~1e20
$\mu + X$	~3e20



Although, the recoil system and background tuning procedure are treated completely different per analysis, we see consistency between the measurements.

Interpreting the total QE-like cross-section

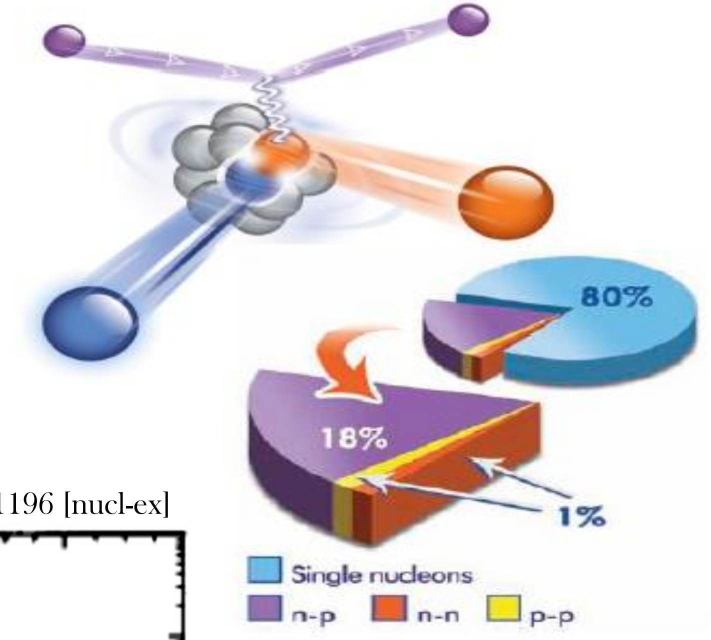
- QE-like cross section consists of both the **Quasi-elastic** and **Inelastic** components.
- First we will evaluate how the neutrino event generators describe each component.
  - This is critical for understanding the primary results.

Modeling the Momentum Distribution of the Initial State Nucleons

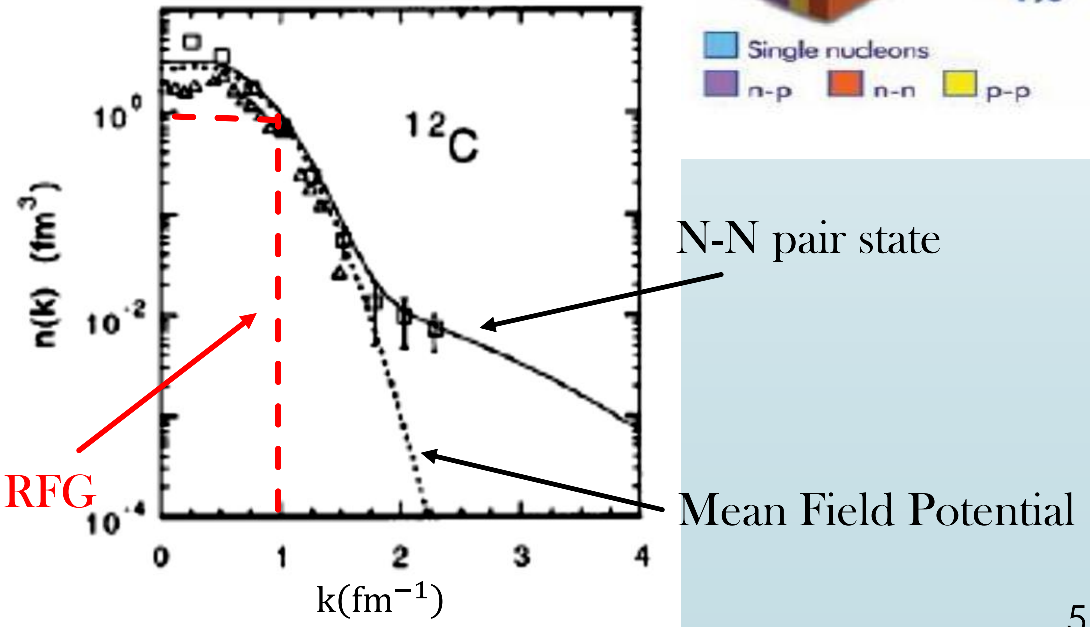
Short Range Correlations

- Nucleons in the nucleus come very close ⟶ interact strongly ⟶ undergo hard collisions.
- Gauge boson, W is absorbed by the nucleon-nucleon correlated pair.
- Electron-carbon exclusive scattering experiments at Jlab observed nucleons in a N-N correlated pair approximately 20% of the time.
- GENIE models **only the high momentum tail** of these correlated N-N states via the prescription of Bodek-Ritchie model. Bodek and Ritchie Phys. Rev.D23 (1981)1070.

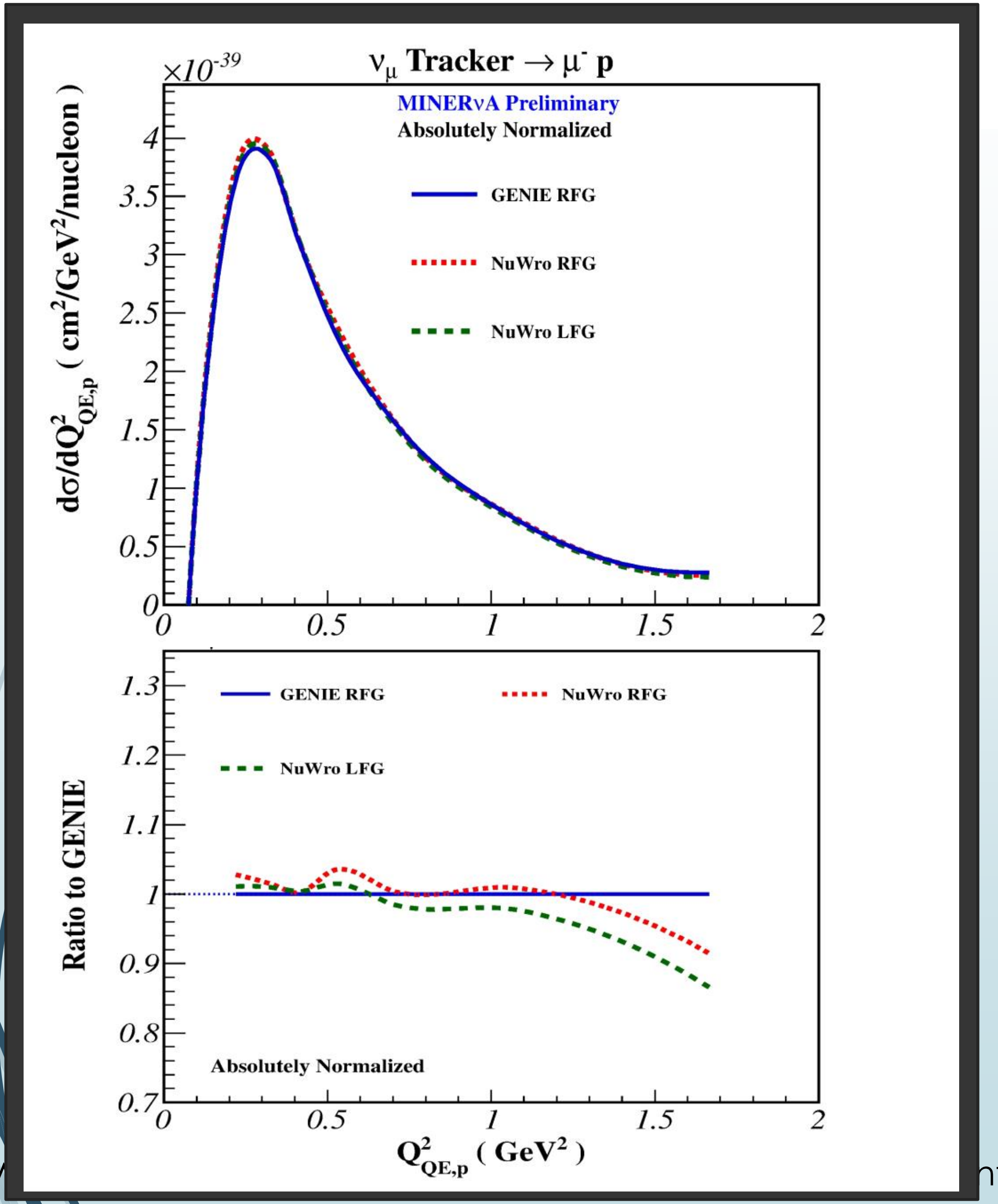
R. Subedi et at., Science 320, 1476 (2008)



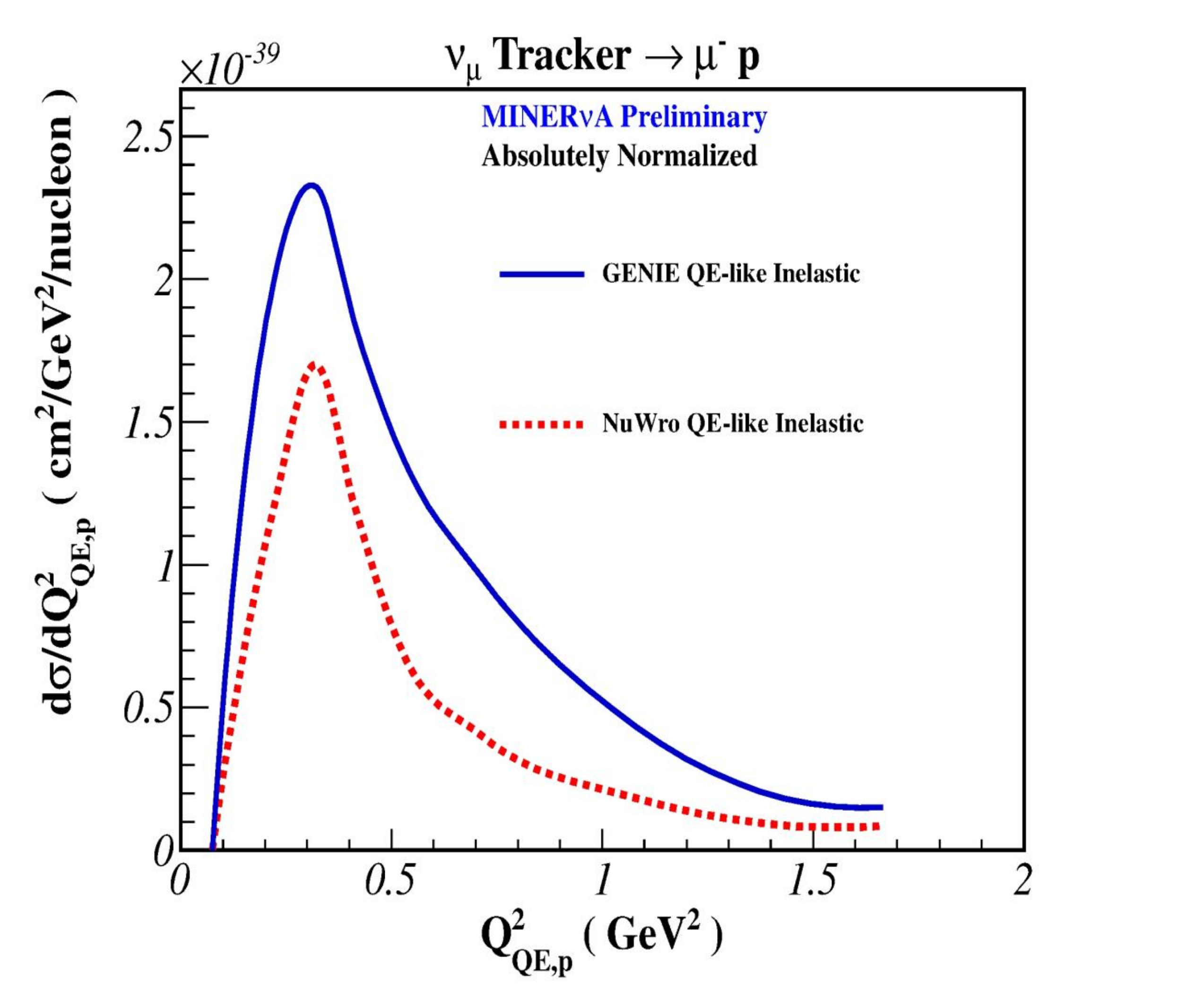
J. Arrington et al., arXiv:1104.1196 [nucl-ex]



Modeling the Nuclear Structure and QE scattering



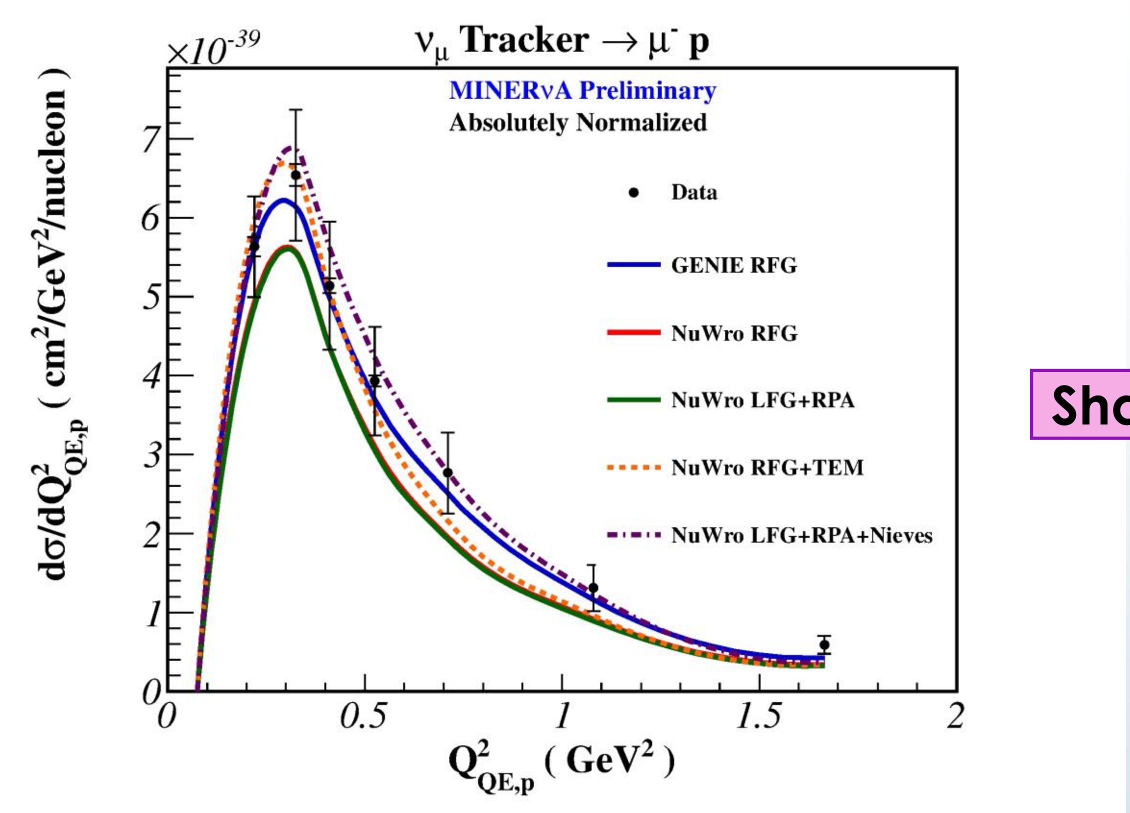
The differences between GENIE and NuWro are due to both the modeling of the momentum distribution of the initial state nucleons and FSI effects.



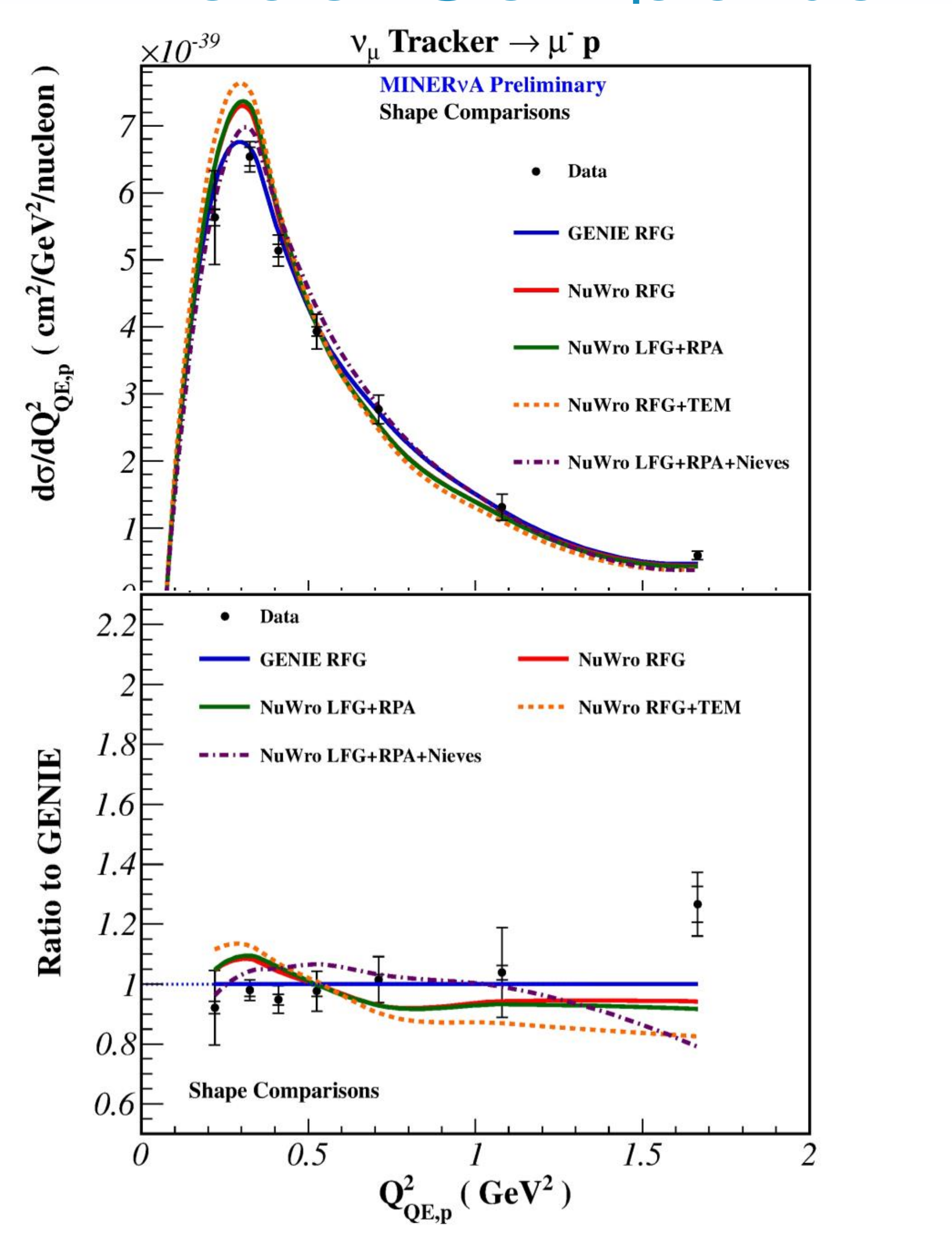
GENIE and NuWro model both the event rate and the shape differently for the inelastic component of the QE-like cross-section.

The discrepancy comes from both the modeling of the pion production cross-section and pion absorption.

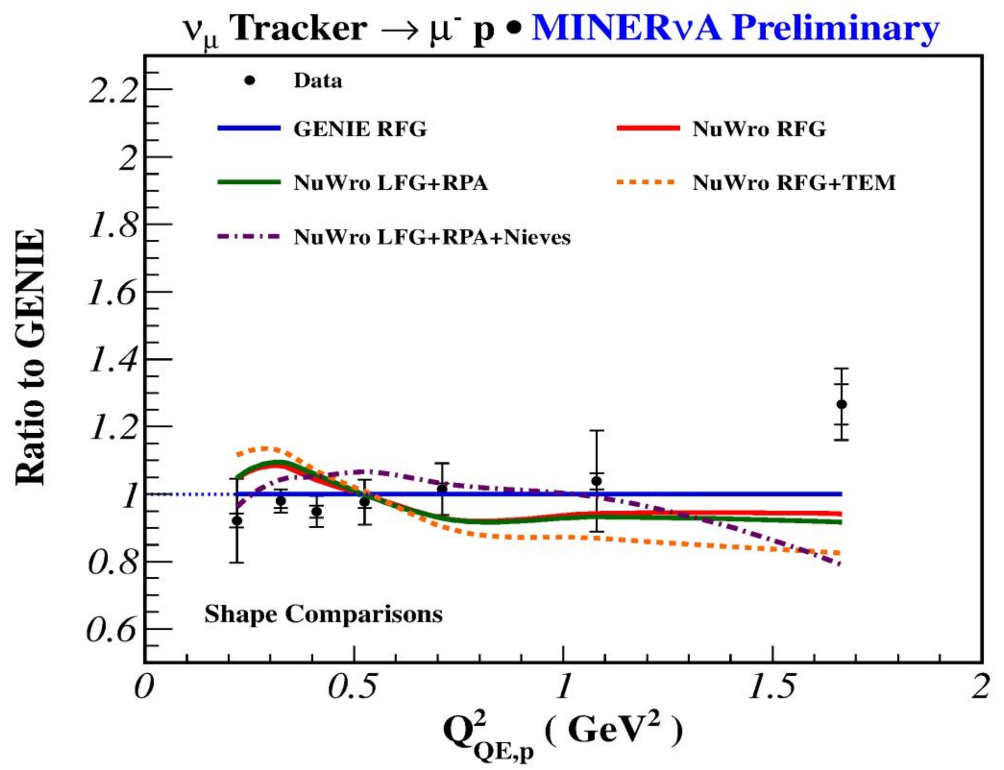
Model Comparisons



Shape



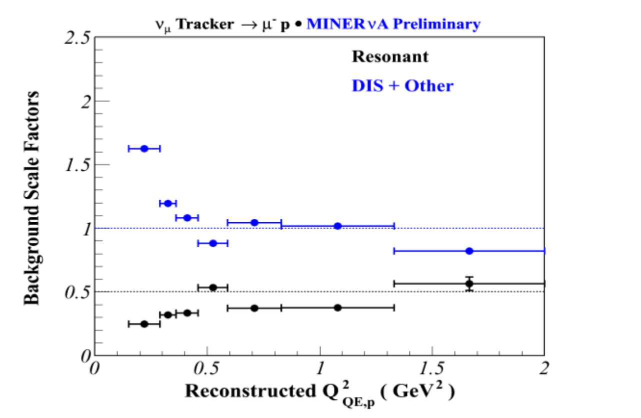
Model Comparisons

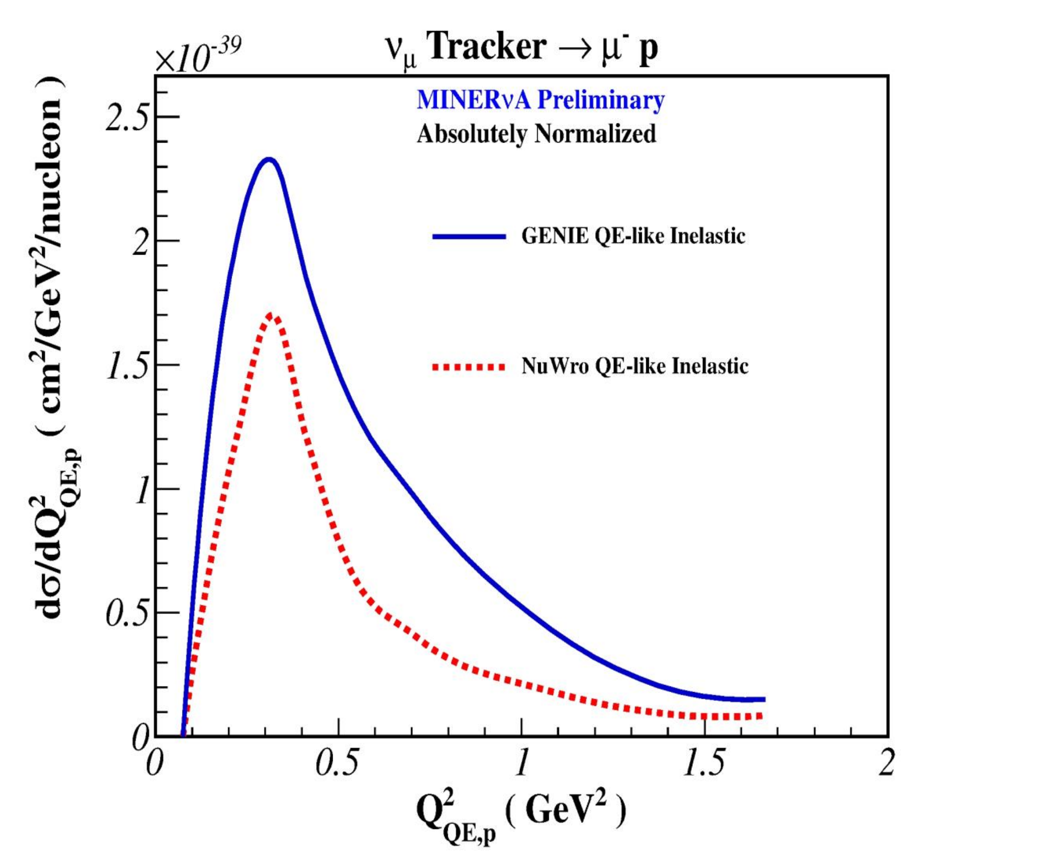


Models	Rate χ^2 (d.o.f = 7)	Shape χ^2 (d.o.f = 6)
GENIE RFG	9.05	11.1
NuWro RFG	12.88	21.25
NuWro RFG + TEM	28.49	35.76
NuWro LFG + RPA	14.49	24.54
NuWro LFG + RPA + Nieves	26.25	27.81

GENIE best describes the QE-like measurement. This is NOT the best model for the previous QE results.

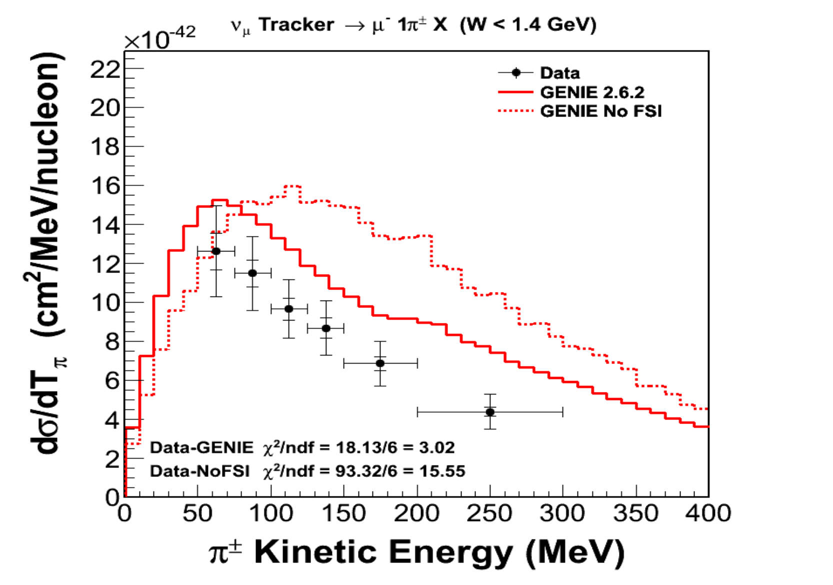
QE-like background tuning procedure shows that the event rate for the Resonant production is overestimated. Recall that these scale factors are a convolution of both the pion production event rate and pion absorption.





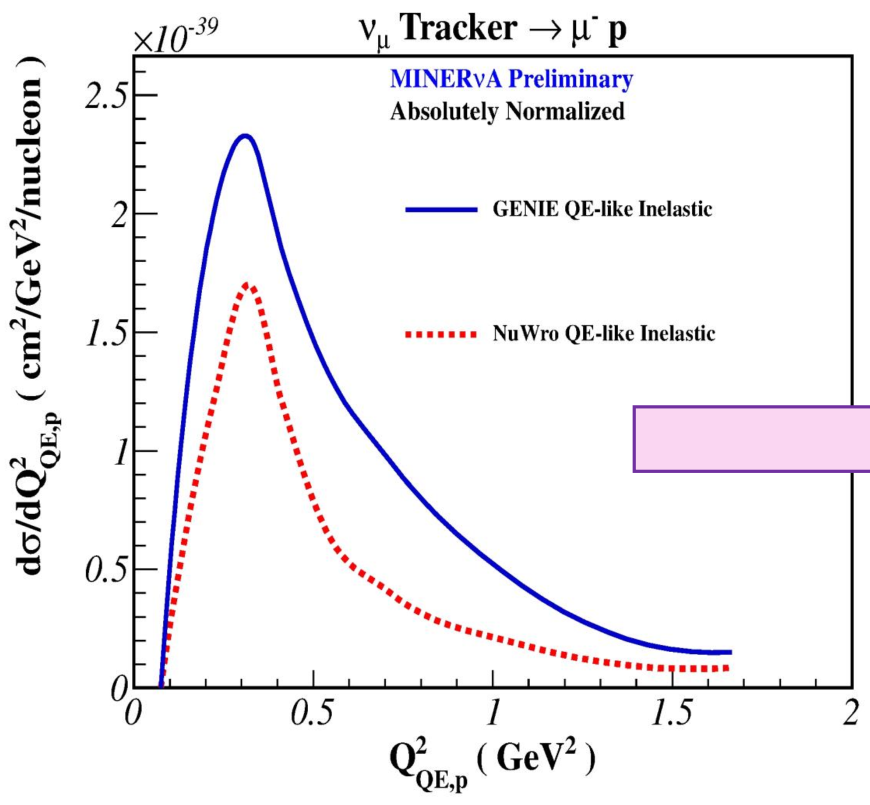
Supporting evidence from the Pion Production analysis.

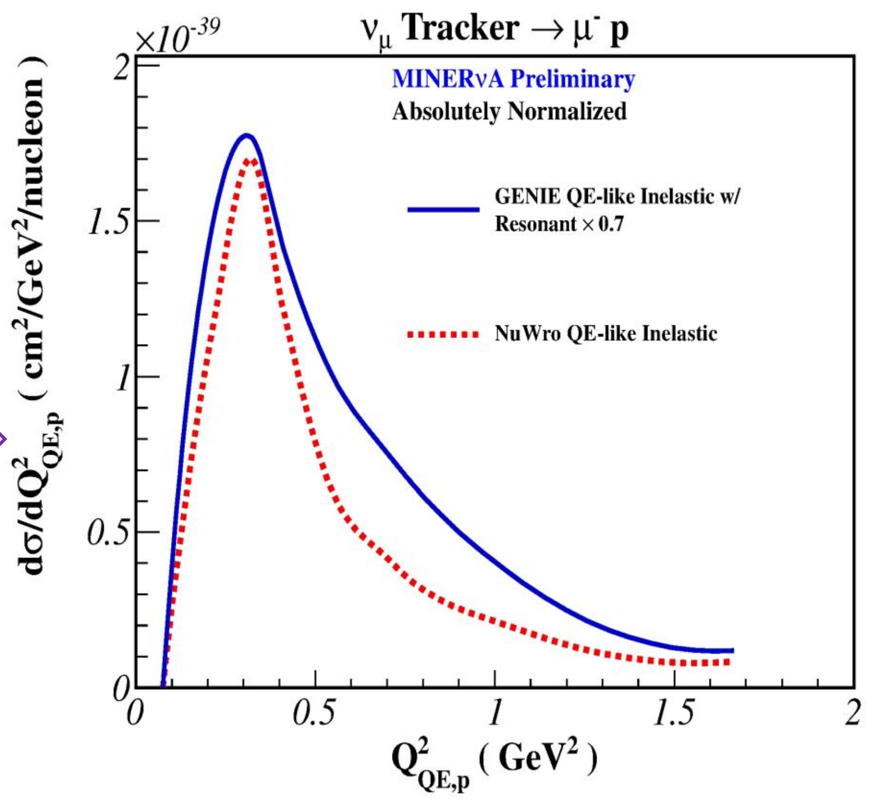
B. Eberly - Wine & Cheese (2/07/2014)

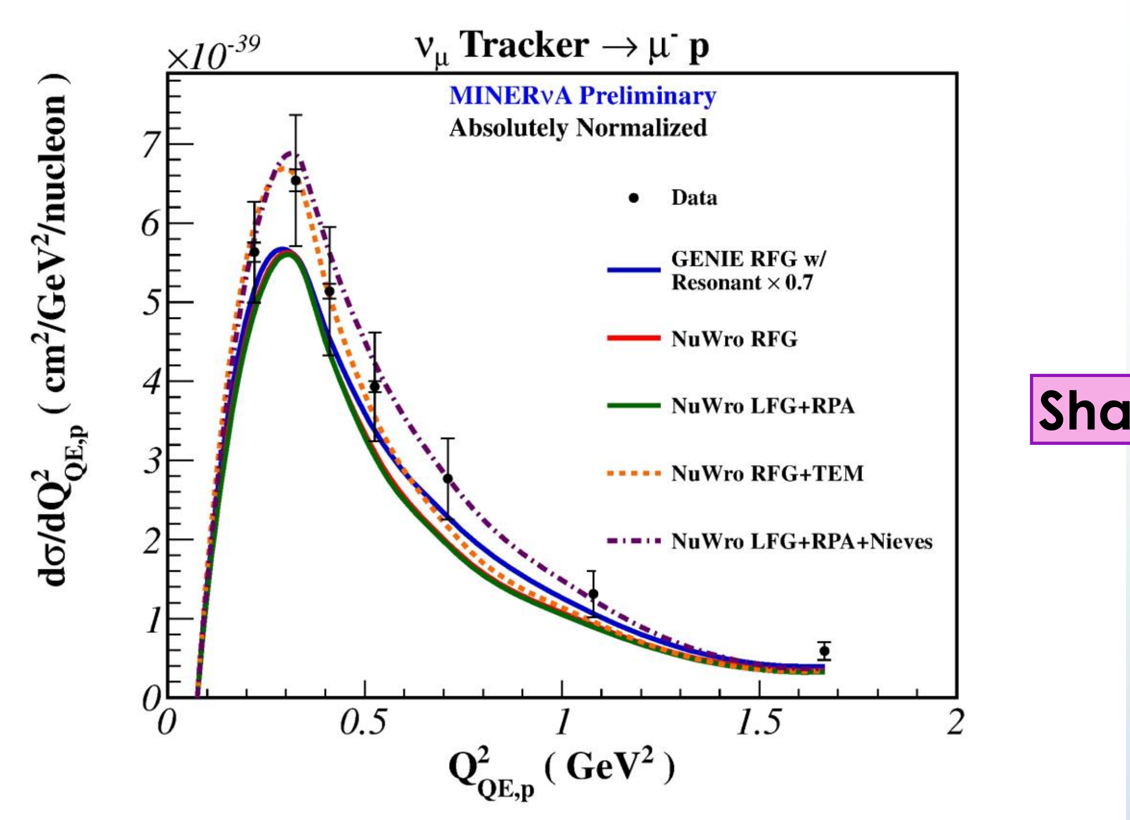


Modeling the Inelastic component

Additional interpretation of the results. We will also evaluate the results with the GENIE Resonant production scaled down by 30%.

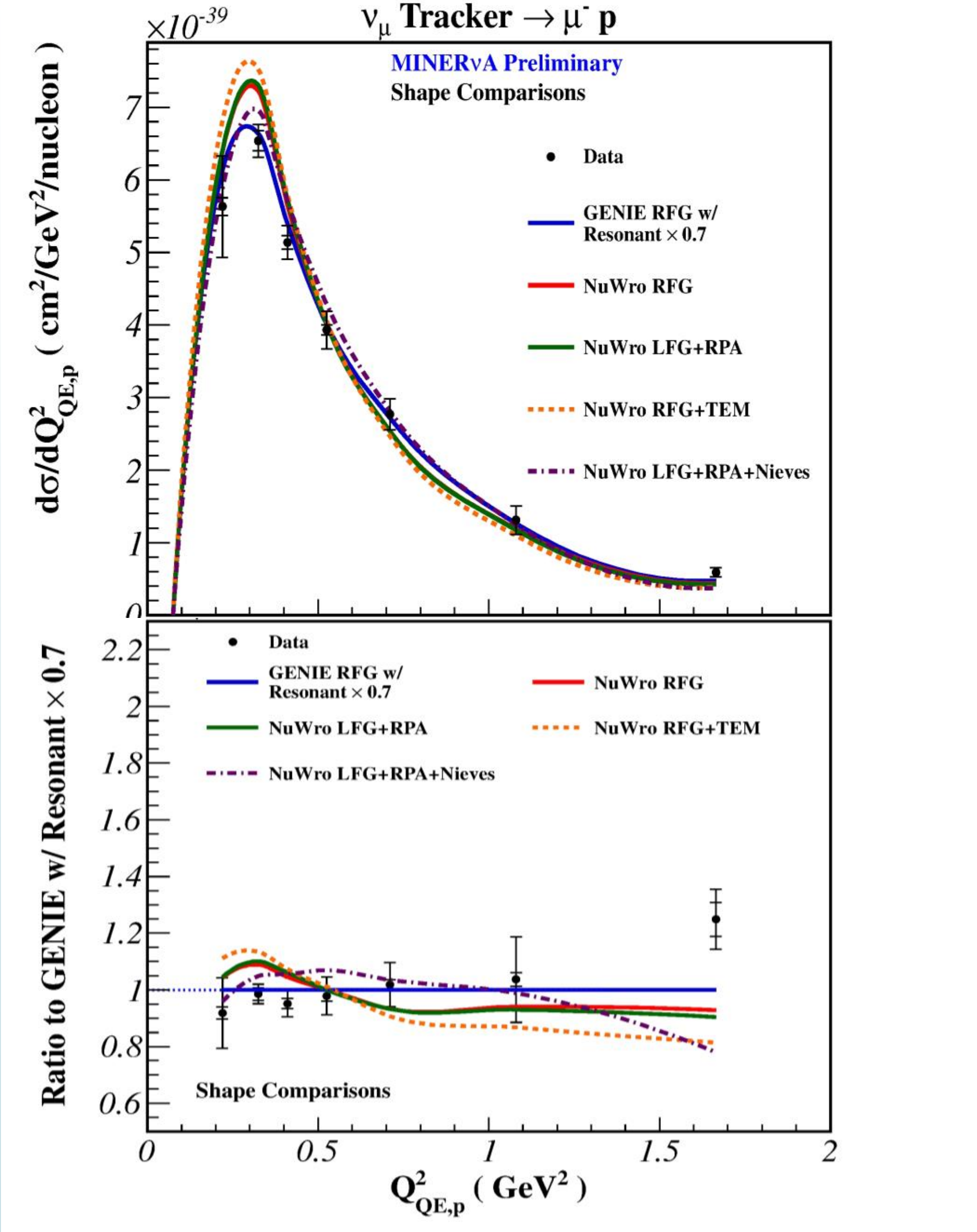




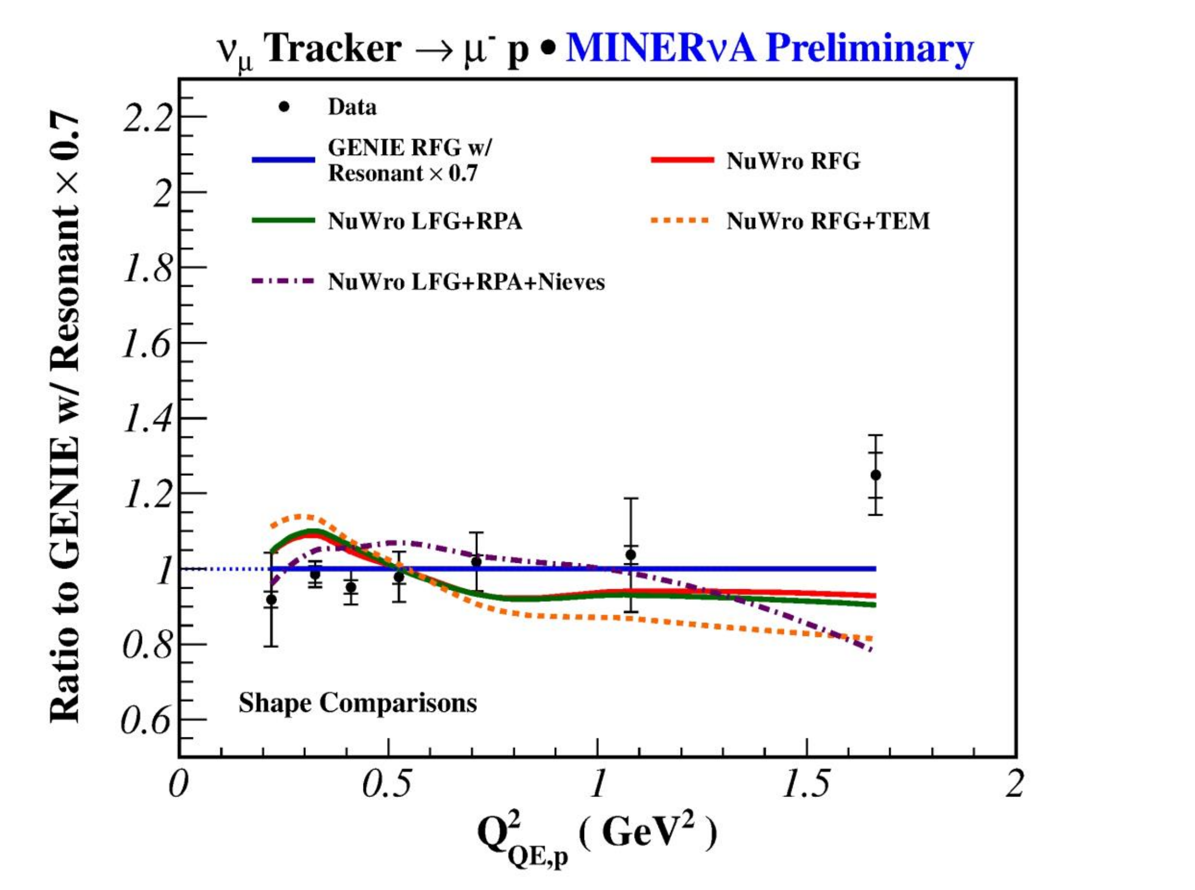


×10^-39
νμ Tracker → μ- p
MINERνA Preliminary
Absolutely Normalized
Data
GENIE RFG w/ Resonant × 0.7
NuWro RFG
NuWro LFG+RPA
NuWro RFG+TEM
NuWro LFG+RPA+Nieves
dσ/dQ²QE,p (cm²/GeV²/nucleon)
Q²QE,p (GeV²)
0
1
2
3
4
5
6
7
0.5
1
1.5
2

Shape



×10^-39
νμ Tracker → μ- p
MINERνA Preliminary
Shape Comparisons
Data
GENIE RFG w/ Resonant × 0.7
NuWro RFG
NuWro LFG+RPA
NuWro RFG+TEM
NuWro LFG+RPA+Nieves
dσ/dQ²QE,p (cm²/GeV²/nucleon)
Ratio to GENIE w/ Resonant × 0.7
Shape Comparisons
Q²QE,p (GeV²)
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
0
0.5
1
1.5
2



The conclusion remains the same with the GENIE Resonant component scaled down by 30%.

Summary

- The cross check between the published QE and pure QE component of the QE-like cross-section shows consistency between the measurements.
- From the shape analysis, GENIE best describes the ν_μQE-like data.
- There exists evidence that GENIE mis-models the pion production event rate. Therefore, an alternative interpretation was provided, where GENIE Resonant production was scaled down by 30%.
- Since GENIE models the shape of the QE and inelastic components approximately the same, the results from the alternative shape analysis **also show** that GENIE best describes the data.
- This event selection consists of various different components, which CAN be separated.
  - Pure QE component.
  - QE-like component where both the muon and proton are tagged.
- These components have different sensitivities to the modeling of nuclear effects and FSI. Along with the published QE and pion production results, this dataset has the potential to disentangle the hard scattering from FSI effects.

Future Analyses and Conclusions

Future Quasi-elastic Measurements in MINERvA

- International Workshop on Neutrino-Nucleus Interactions in the Few-Ge Region: NuInt14
  - Present *update results with new model comparisons* for both the anti-neutrino and neutrino QE cross-sections.
- Evaluating the correlations between the anti-neutrino and neutrino QE systematics.
- More results from the muon-proton QE-like portion of the presented analysis.
- The analogy of this presented QE-like analysis on the nuclear targets (C,Fe,Pb).
- Neutrino QE-like double differential cross-section measurement using either the muon or proton kinematics.
- More on the Michel electron analysis.

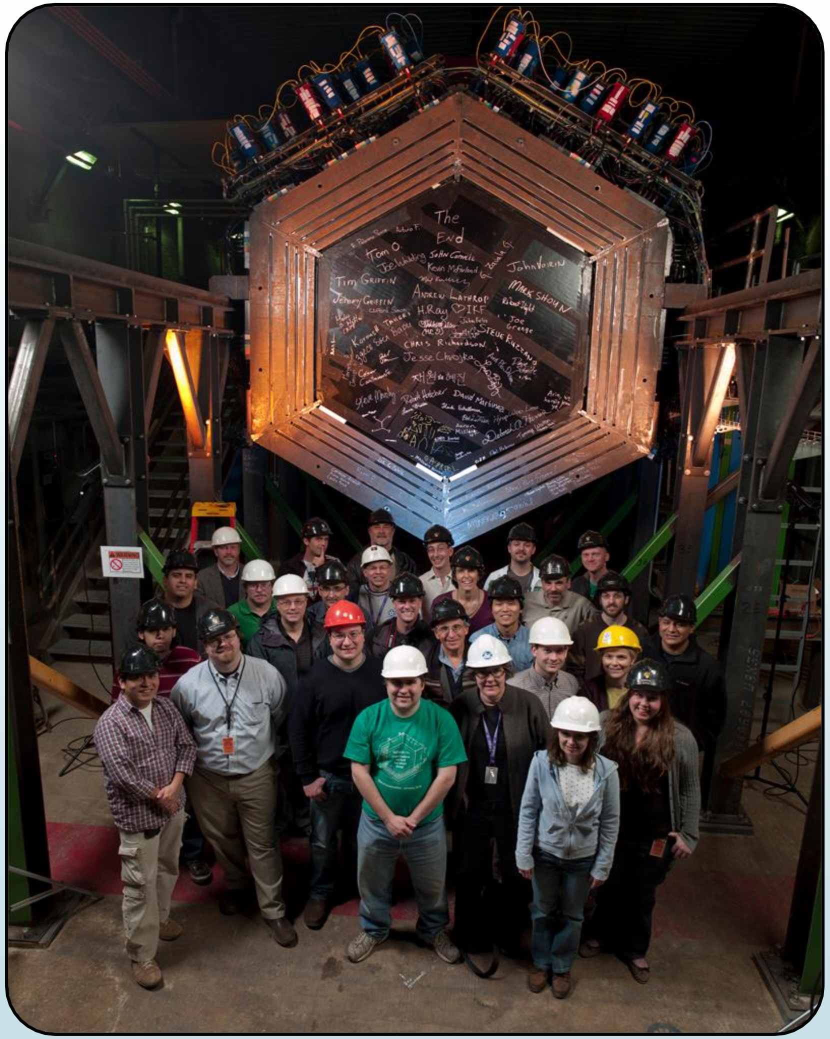
Conclusions / Final Thoughts

- Presented is the ***FIRST-EVER*** measurement of the QE-like cross section using the **proton kinematics**.
  - First muon neutrino analysis to incorporate ***ALL*** of MINERvA exiting muons.
- The modeling of both the pion production and the pion FSI has a significant impact on the interpretation of this data.
- The results show that the QE-like cross-section is best described by GENIE.
- The first published neutrino QE measurement is **NOT** best interpreted by GENIE. However, the QE component of this QE-like cross-section **is consistent** with the first published measurement.
- MINERvA recent pion production measurement also presents some tension with GENIE.
- Although the individual components are not accurately modeled by GENIE, GENIE best describes the total QE-like cross-section.
- **This analysis is a benchmark for decoupling the challenges in modeling the different components of the neutrino-nucleus interactions in the quasi-elastic/inelastic regimes and FSI effects.**

Thank You !!

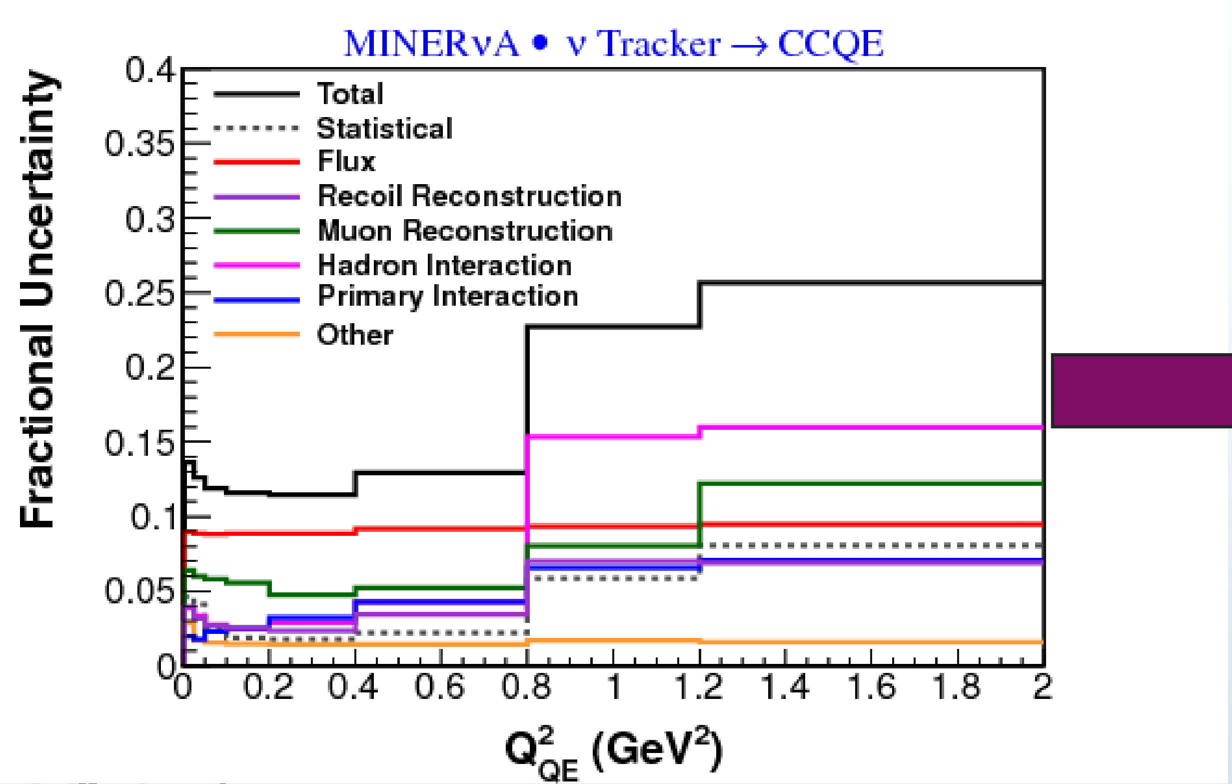
University of California at Irvine
Centro Brasileiro de Pesquisas Físicas
University of Chicago
Fermilab
University of Florida
Université de Genève
Universidad de Guanajuato
Hampton University
Inst. Nucl. Reas. Moscow
Massachusetts College of Liberal Arts
University of Minnesota at Duluth

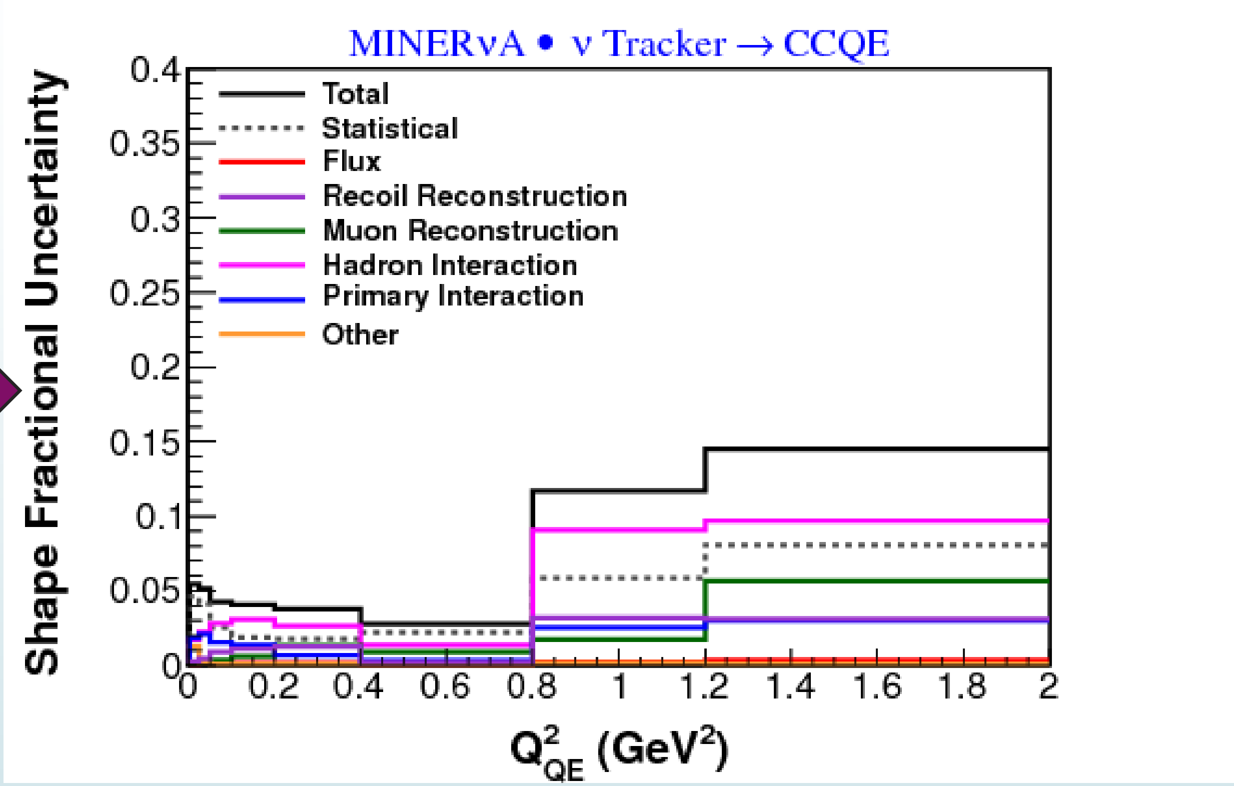
Universidad Nacional de Ingeniería
Northwestern University
Otterbein University
Pontificia Universidad Catolica del Peru
University of Pittsburgh
University of Rochester
Rutgers, The State University of New Jersey
Universidad Técnica Federico Santa María
Tufts University
William and Mary



Back-up Slides

The QE Shape Analysis

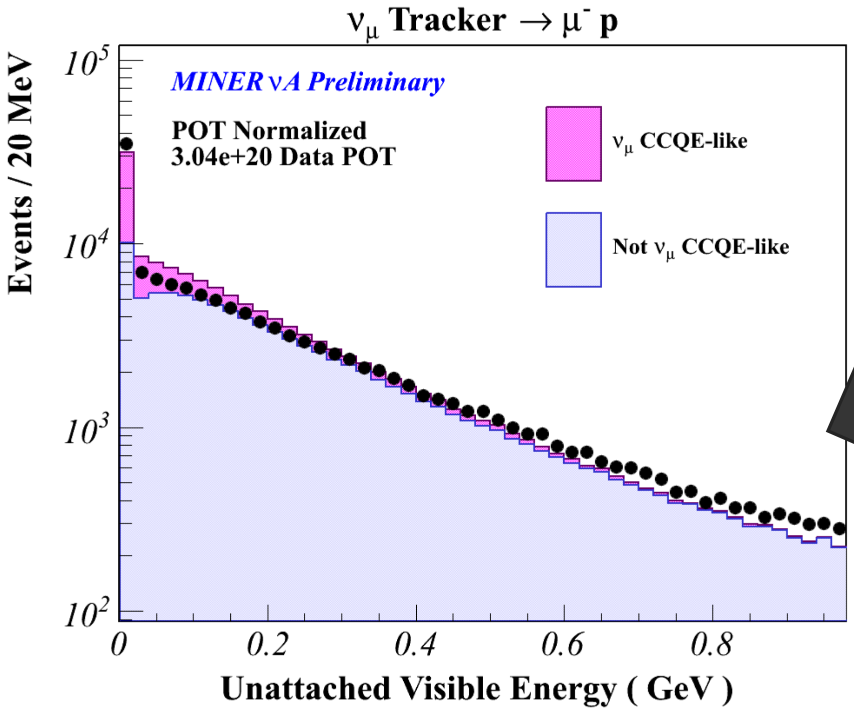




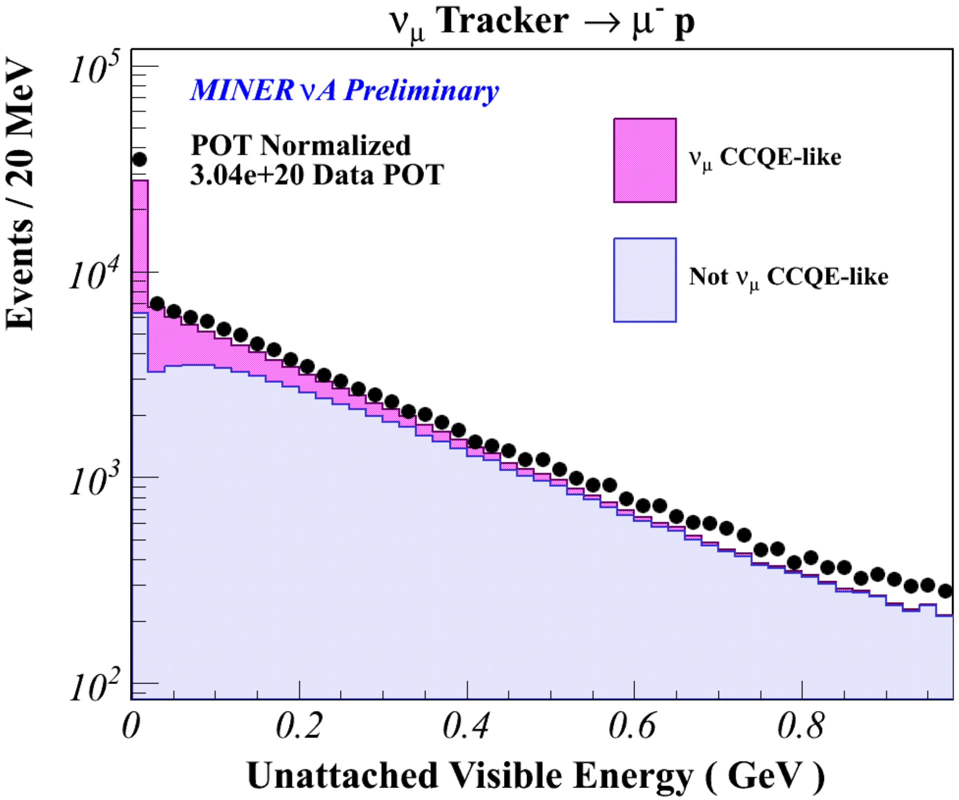
<u>Focus on the shape analysis.</u>

- Systematic errors are reduced.
- Insensitive to uncertainty on the neutrino flux ☺.

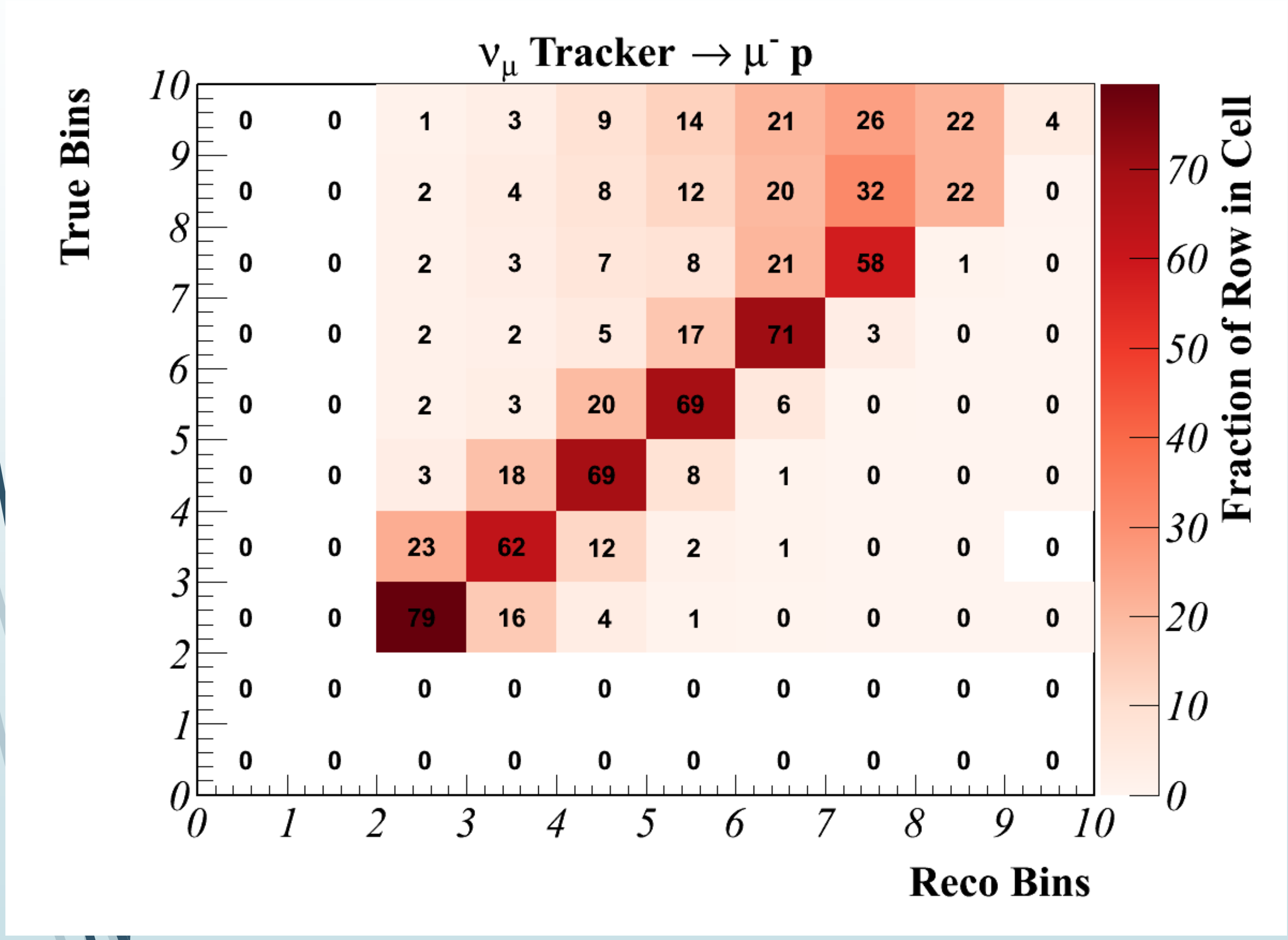
Unattached Visible Energy



Before and after tuning the backgrounds.



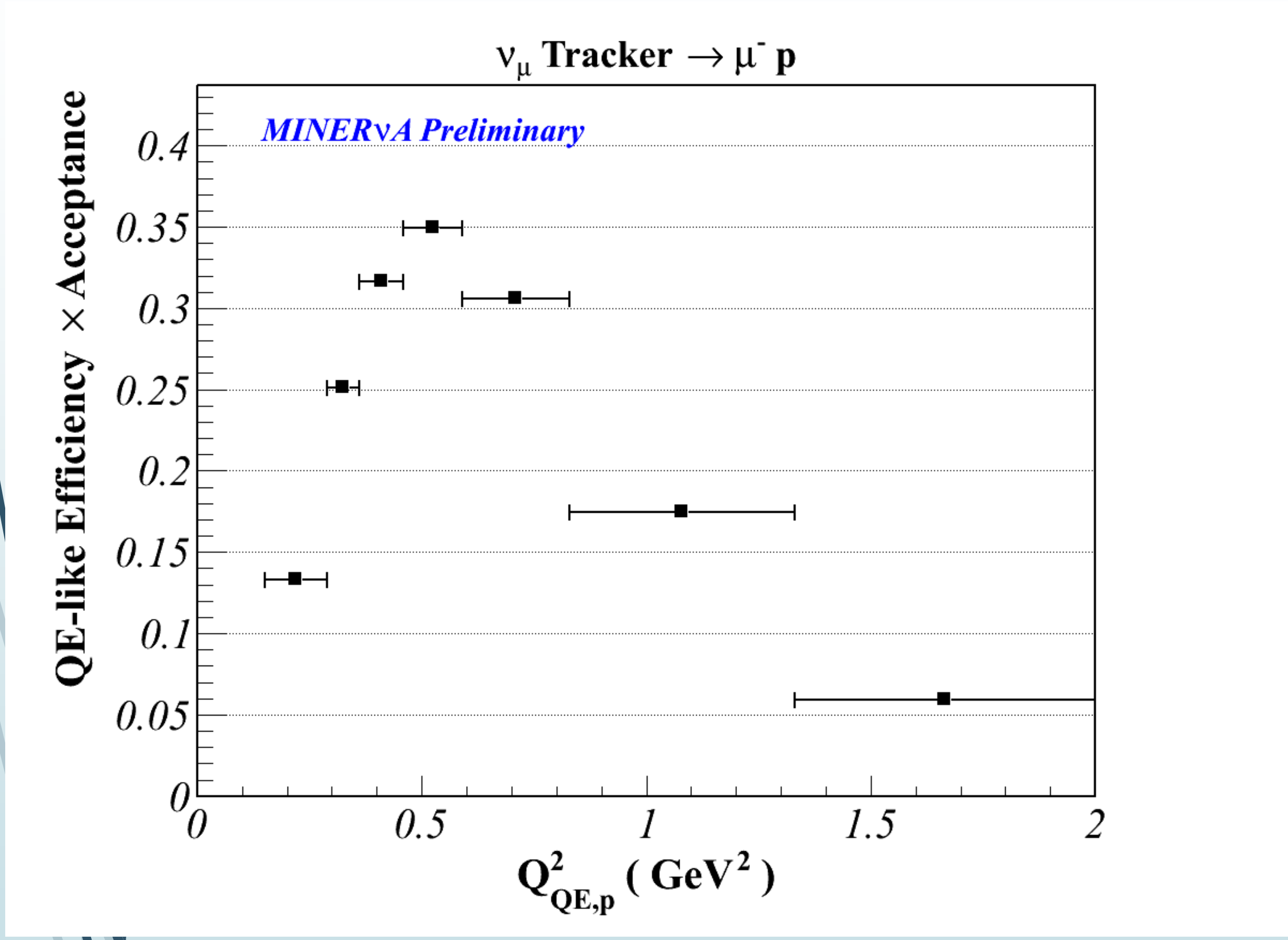
Unfolding: Bin Migration Matrix



We unfolded to a Q^2 calculated assuming QE scattering from a free nucleon at rest, using the kinetic energy of the leading proton in the final state.

The unfolding procedure is model independent.

Efficiency Correction: Efficiency Function



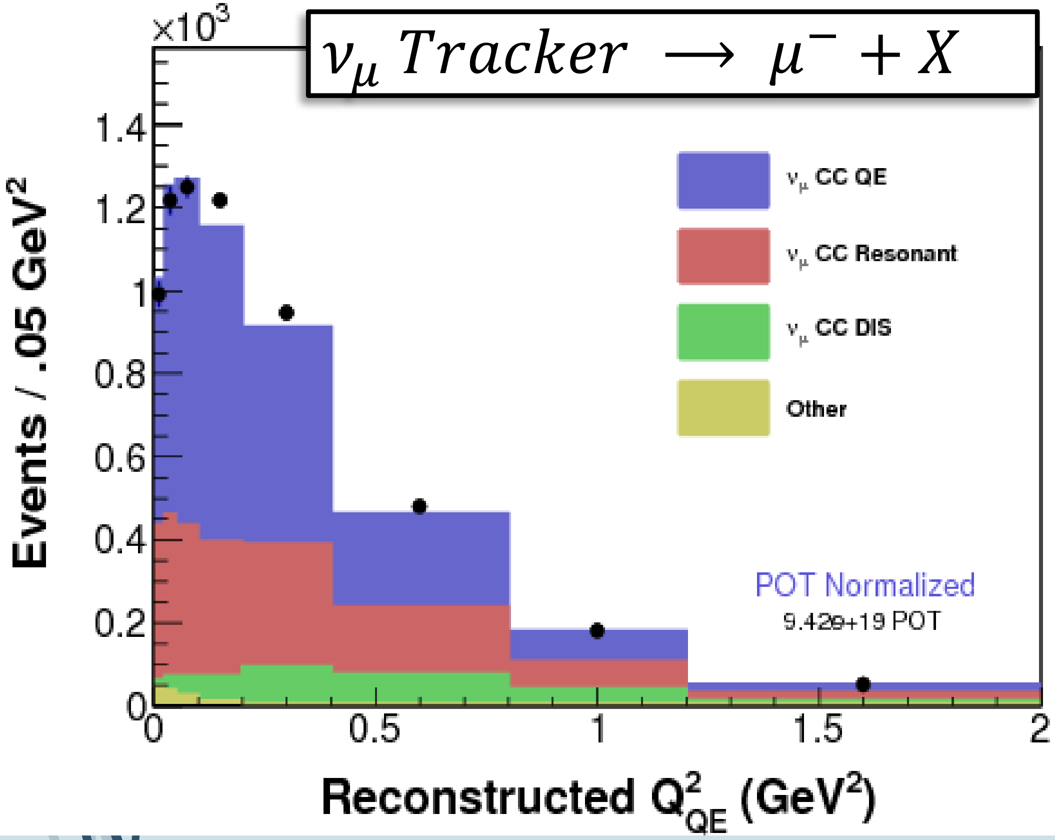
The efficiency function that is used to correct the event rate.

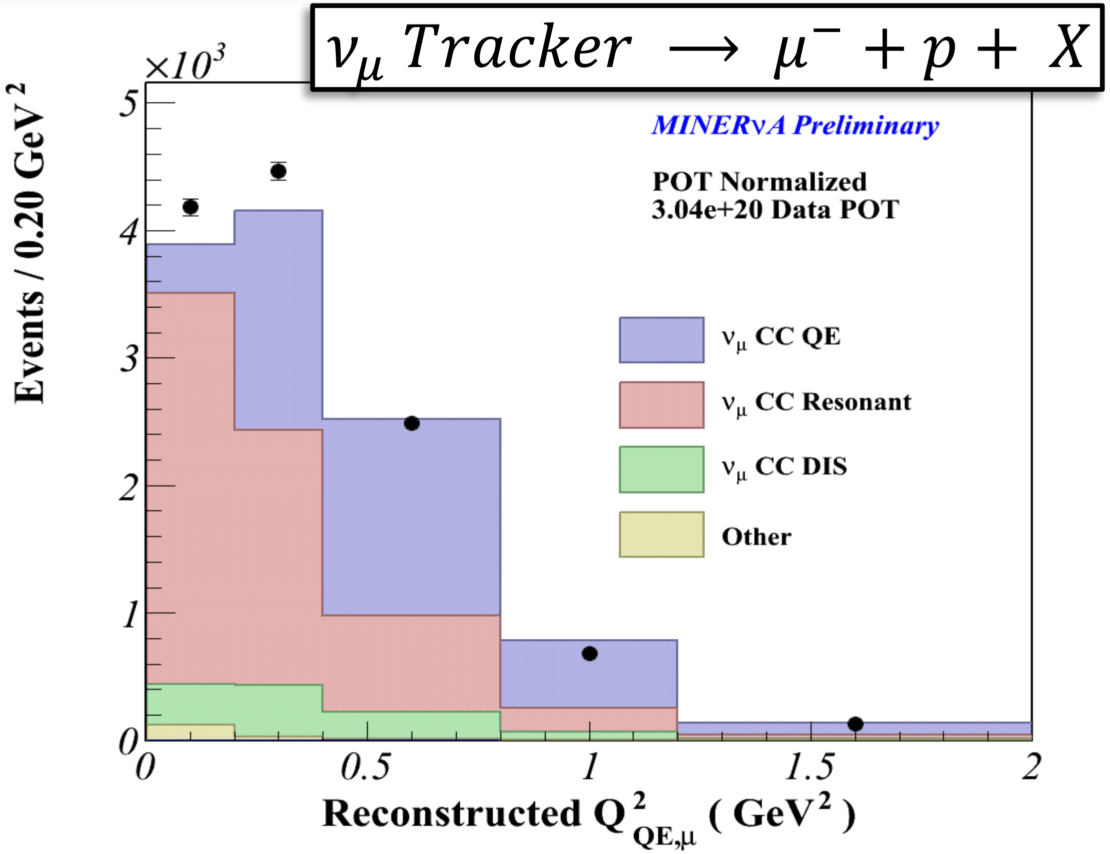
The rapid decline is due to pID consistency requirement.

The probability that the proton re-scatters in the detector increases with energy.

Interacting protons most likely have a poor proton pID score ⟶ these protons no longer resemble a ranging out proton.

Comparing the Reconstructed $Q^2_{QE,\mu}$ for the pure QE samples with MINOS-matched track.

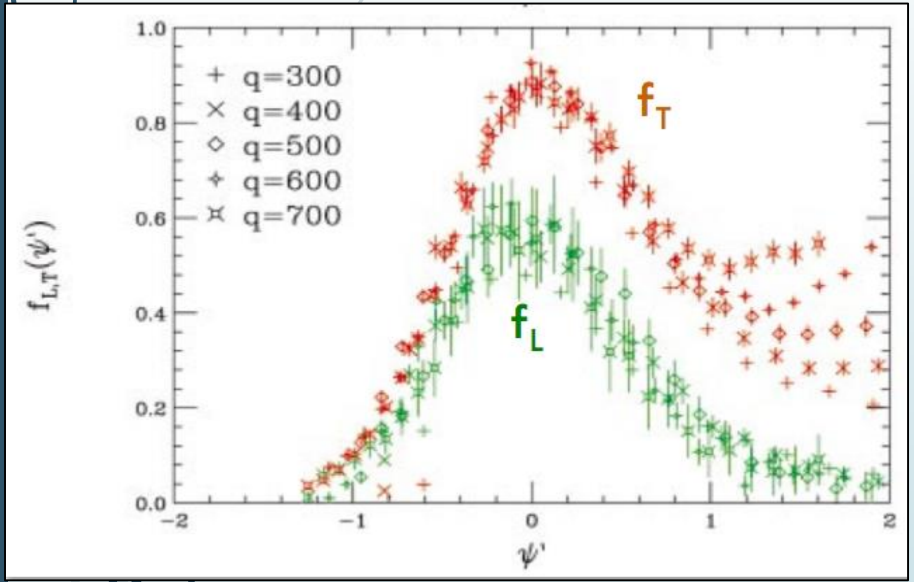




Guidance from Electron Scattering Data

- A(e,e’,p) scattering can separate the cross section into the transverse f_T and longitudinal f_L components.
- $f_T = f_T$ for the independent nucleons.

Observed additional strength in the transverse component of the cross section which is likely due to N-N correlated pairs and two-body currents (Meson exchange currents (MEC)), which can produce multinucleons at the scattering vertex.



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

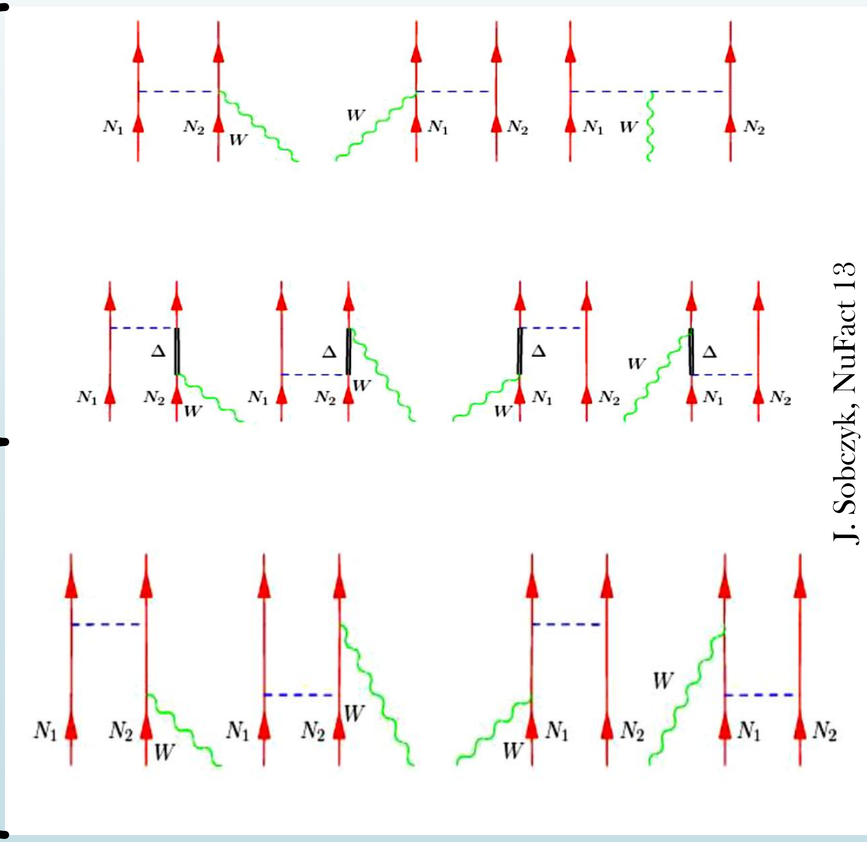
QE peak

Between the QE peak

Delta region

MEC Feynman diagrams

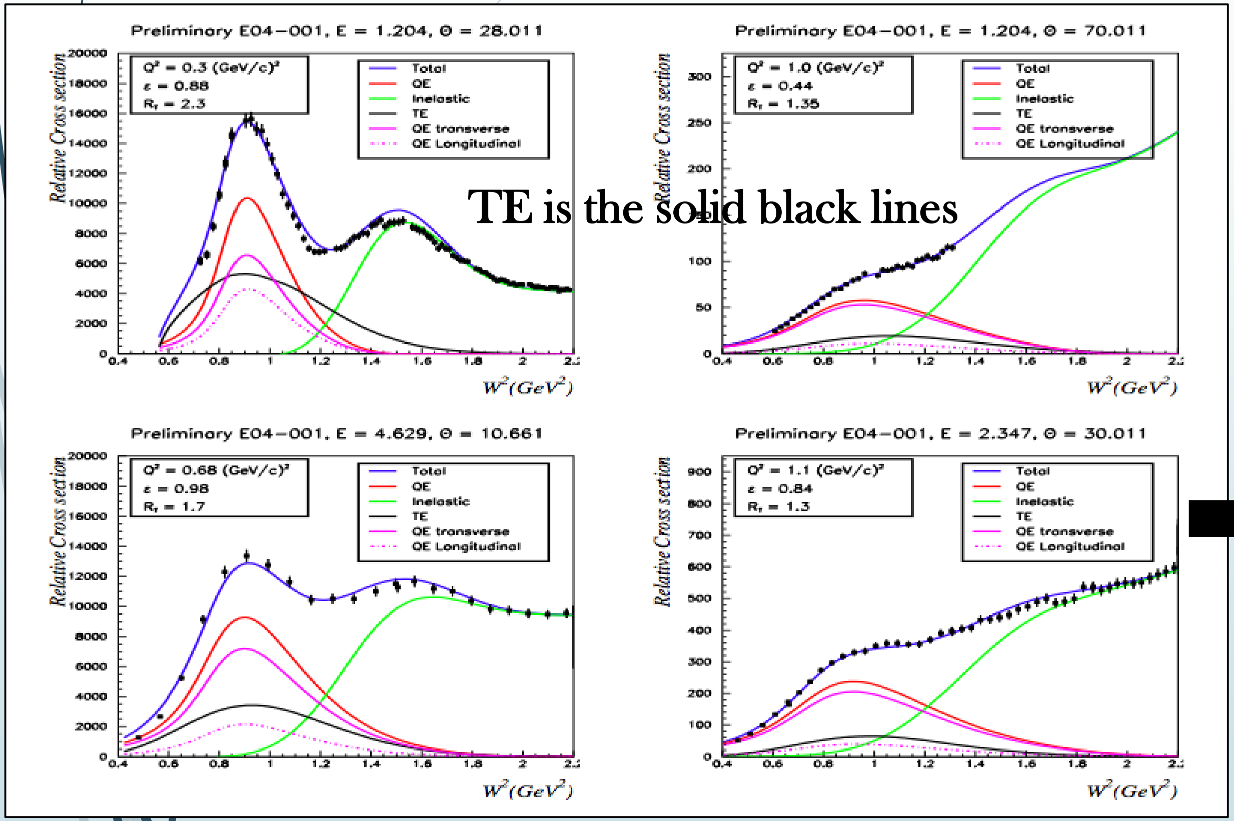
SRC Feynman diagrams



J. Sobczyk, NuFact 13

Introduce an Empirical Model: Transverse Enhancement Model (TEM)

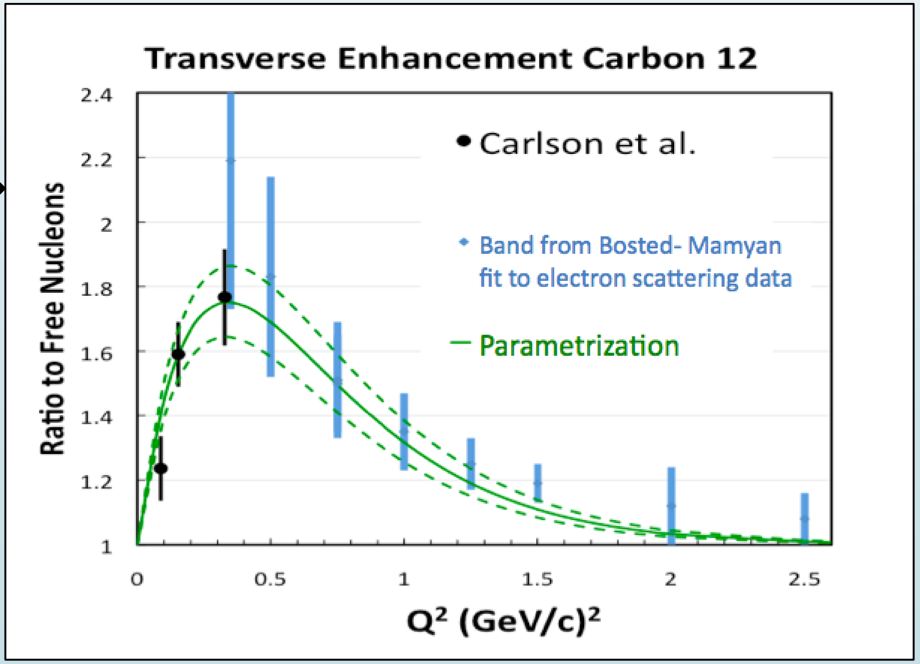
Fits for different Q^2 bins



Bodek, Budd, Christy, Eur. Phys. J. C 71:1726 (2011), arXiv:1106.0340

- Accounts for additional strength that is observed in the transverse component of the QE cross section by modifying the nucleon magnetic form factors.

$$\text{Ratio} = \frac{QE_{Total} + QE_{TE}}{QE_{Total}}$$



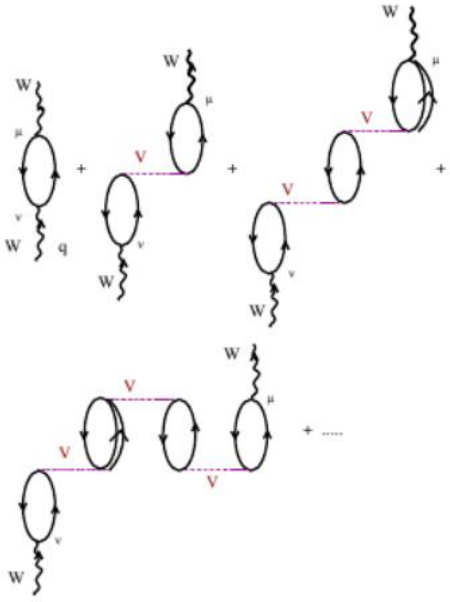
Random Phase Approximation

Slide courtesy of D. Schmitz – Wine & Cheese

Why RPA (1)

RPA (random phase approximation) are nuclear collective effects which according to Martini and Nieves are necessary to reproduce MiniBooNE CCQE data.

- Polarization (RPA) effects. Substitute the ph excitation by an RPA response: series of ph and Δh excitations.



1. Effective Landau-Migdal interaction

$$V(\vec{r}_1,\vec{r}_2) = c_0\delta(\vec{r}_1-\vec{r}_2)\left\{ \boxed{f_0(\rho)} + f_0'(\rho)\vec{\tau}_1\vec{\tau}_2 + \boxed{g_0(\rho)\vec{\sigma}_1\vec{\sigma}_2} + g_0'(\rho)\vec{\sigma}_1\vec{\sigma}_2\vec{\tau}_1\vec{\tau}_2 \right\}$$

Isoscalar terms $\boxed{}$ do not contribute to CC

2. $S = T = 1$ channel of the ph–ph interaction → s longitudinal (π) and transverse (ρ) + **SRC**

$$g_0'\vec{\sigma}_1\vec{\sigma}_2\vec{\tau}_1\vec{\tau}_2 \to [V_l(q)\hat{q}_i\hat{q}_j + V_t(q)(\delta_{ij}-\hat{q}_i\hat{q}_j)]\,\sigma_1^i\sigma_2^j\vec{\tau}_1\vec{\tau}_2$$

$$V_{l,t}(q) = \frac{f_{\pi NN,\rho NN}}{m^2_{\pi,\rho}}\left(F_{\pi,\rho}(q^2)\frac{\vec{q}^{\,2}}{q^2-m^2_{\pi,\rho}} + g'_{l,t}(q)\right)$$

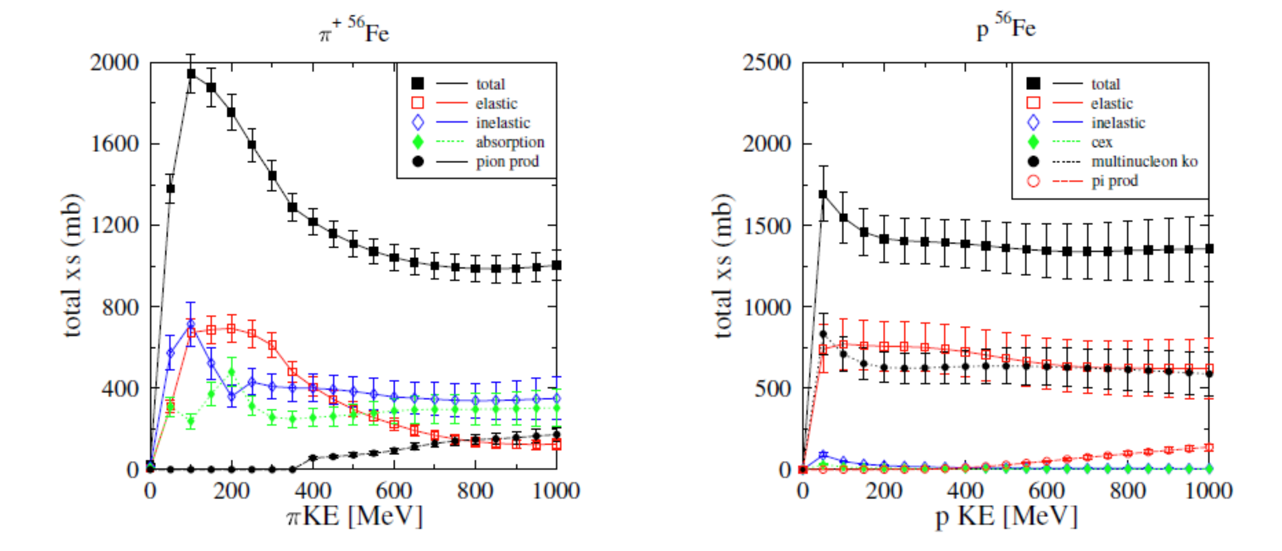
3. Contribution of Δh excitations important

- analogy: polarization effects, screening electric charge
- form factors become renormalized.

Final State Interactions

Slide courtesy of B. Eberly – Wine & Cheese

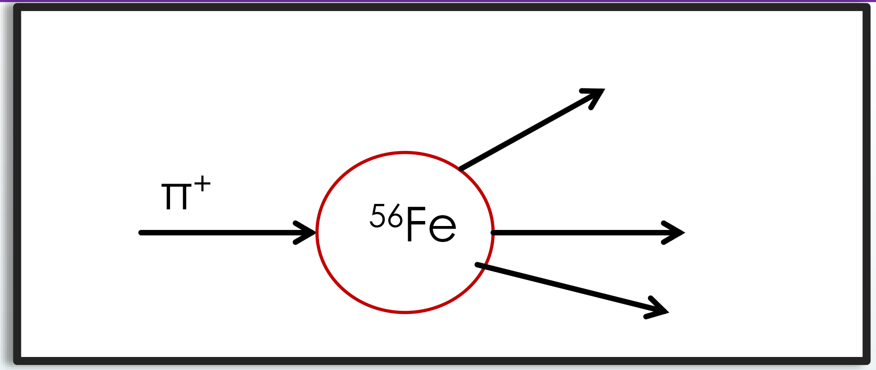
- Neutrino oscillation experiments use neutrino event generators (Monte Carlo) to understand neutrino-nucleus interactions
  - Many current and future experiments use GENIE
- GENIE has two FSI models:
  - hA – use Fe reaction cross section data, isospin symmetry, and $A^{2/3}$ scaling to predict FSI reaction rates
  - hN – step final state particles through the nucleus and simulate full particle cascade using angular distributions as a function of energy



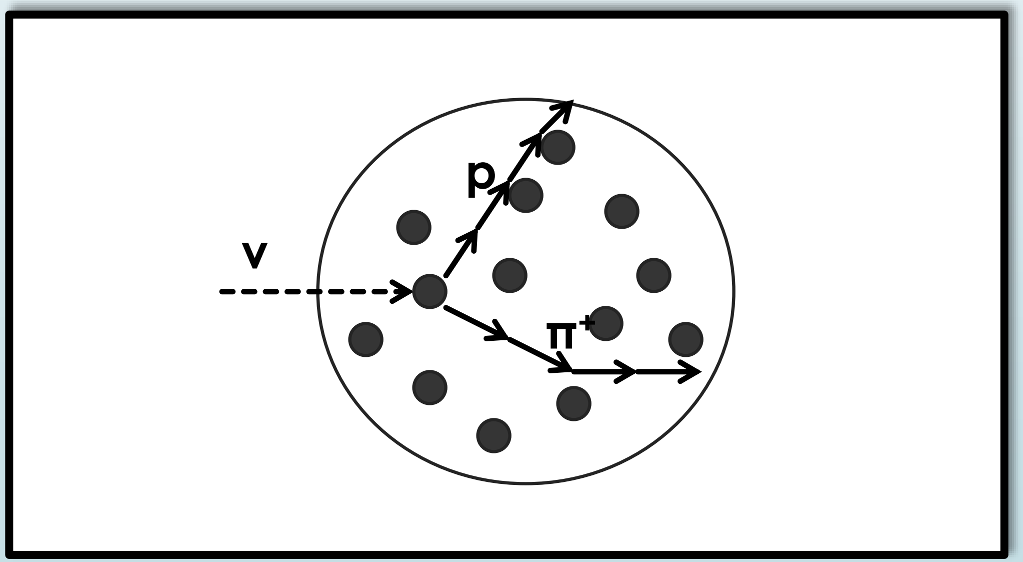
Final State Interactions

Slide courtesy of B. Eberly – Wine & Cheese

GENIE: Use p,π scattering on Fe data as basis for FSI model.



NuWro: Step interaction products through nucleus and use nucleon cross sections (Oset data).



GENIE Uncertainties

Cross Section Model Uncertainties

Uncertainty	1 σ
M_A (Elastic Scattering)	± 25%
Eta (Elastic scattering)	± 30%
M_A (CCQE Scattering)	+25% −15%
CCQE Normalization	+20% −15%
CCQE Vector Form factor model	on/off
CC Resonance Normalization	± 20%
M_A (Resonance Production)	± 20%
M_V (Resonance Production)	± 10%
1pi production from $\nu p / \bar{\nu} n$ non-resonant interactions	± 50%
1pi production from $\nu n / \bar{\nu} p$ non-resonant interactions	± 50%
2pi production from $\nu p / \bar{\nu} n$ non-resonant interactions	± 50%
2pi production from $\nu n / \bar{\nu} p$ non-resonant interactions	± 50%
Modfiy Pauli blocking (CCQE) at low Q^2 (change PB momentum threshold)	± 30%

•*Intranuclear Rescattering Uncertainties*

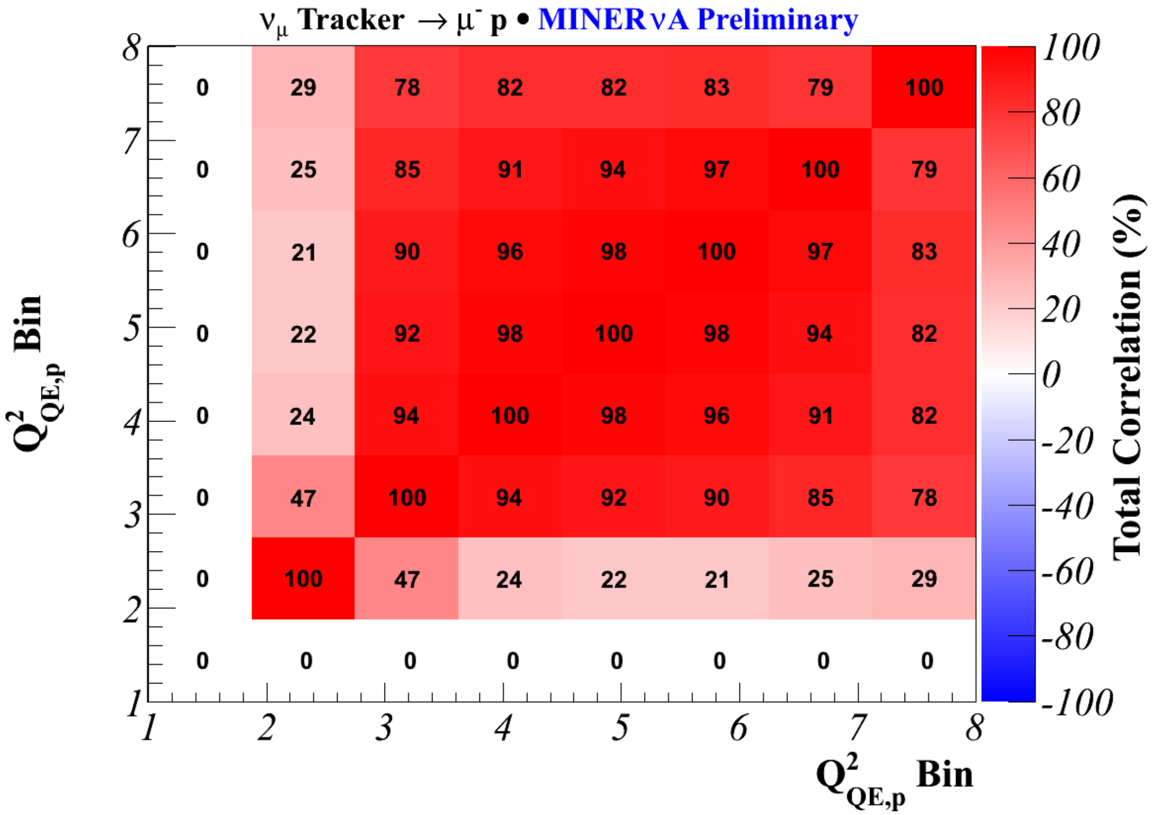
Uncertainty	1 σ
Pion mean free path	± 20%
Nucleon mean free path	± 20%
Pion fates – absorption	± 30%
Pion fates – charge exchange	± 50%
Pion fates – Elastic	± 10%
Pion fates – Inelastic	± 40%
Pion fates – pion production	± 20%
Nucleon fates – charge exchange	± 50%
Nucleon fates – Elastic	± 30%
Nucleon fates – Inelastic	± 40%
Nucleon fates – absorption	± 20%
Nucleon fates – pion production	± 20%
AGKY hadronization model – x_F distribution	± 20%
Delta decay angular distribution	On/off
Resonance decay branching ratio to photon	± 50%

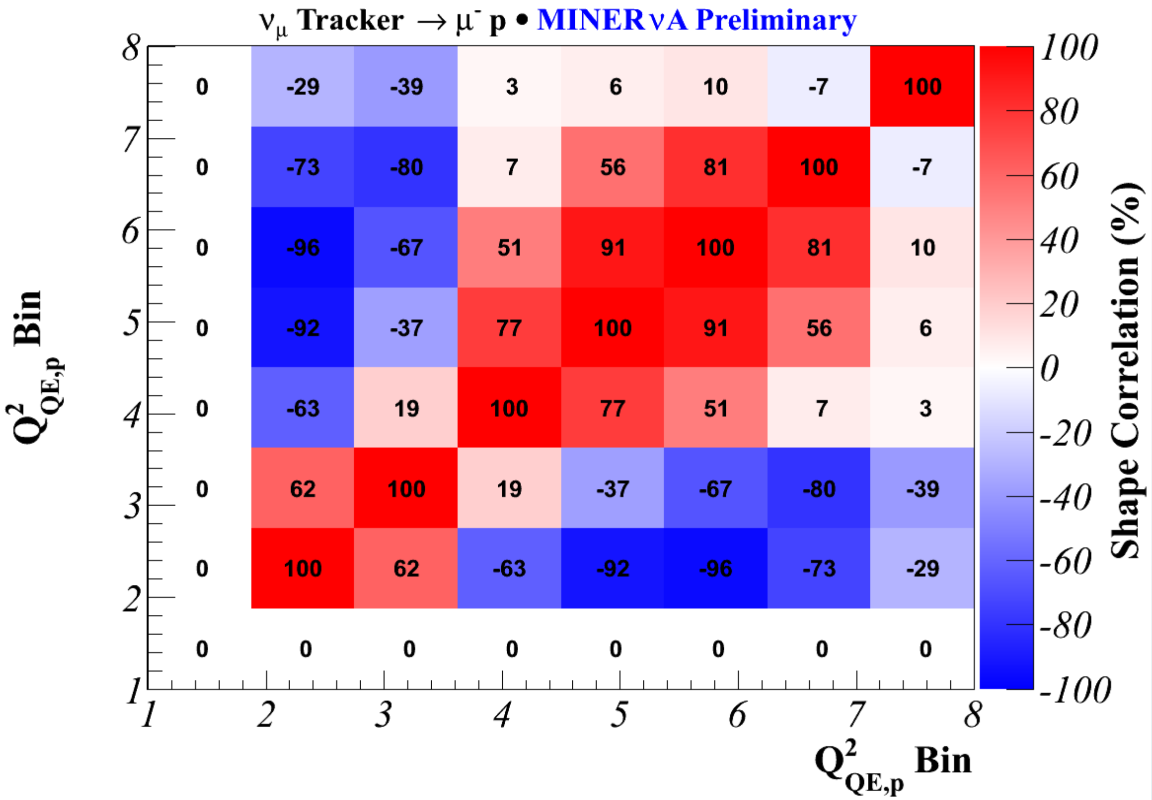
References: (1) www.genie-mc.org, (2) arXiv:0806.2119, (3) D. Bhattacharya, Ph. D Thesis (U. Pittsburgh) 2009.

Normalization Factors for the Shape Analysis

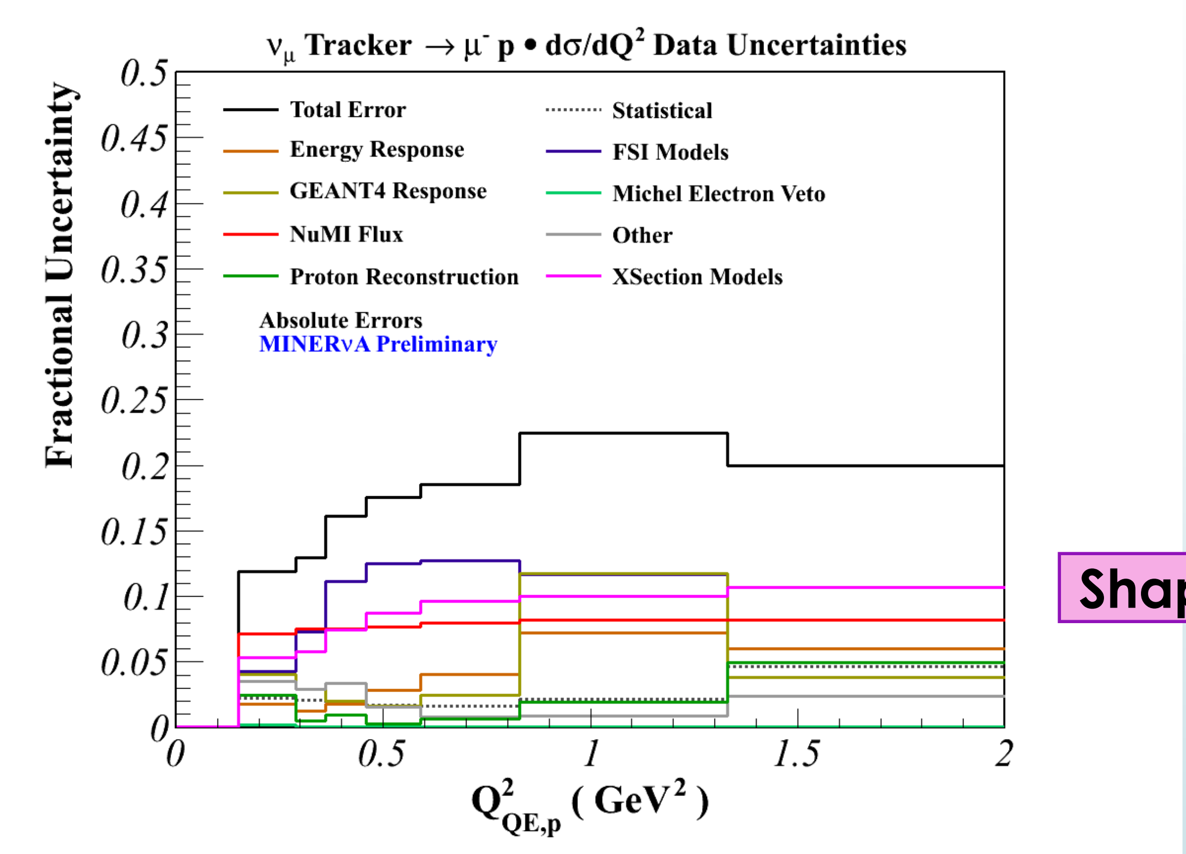
Models	Area Normalization
GENIE RFG	1.087
NuWro RFG	1.297
NuWro LFG + RPA	1.315
NuWro RFG + TEM	1.142
NuWro LFG + RPA + Nieves	1.014
GENIE RFG w/ Resonant x 0.7	1.189

Correlation Matrices





Focus on the Shape Analysis



Shape