High Statistics Quasielastic AntiNeutrino Scattering at MINERvA

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For the MINERvA Collaboration

10th March, 2023

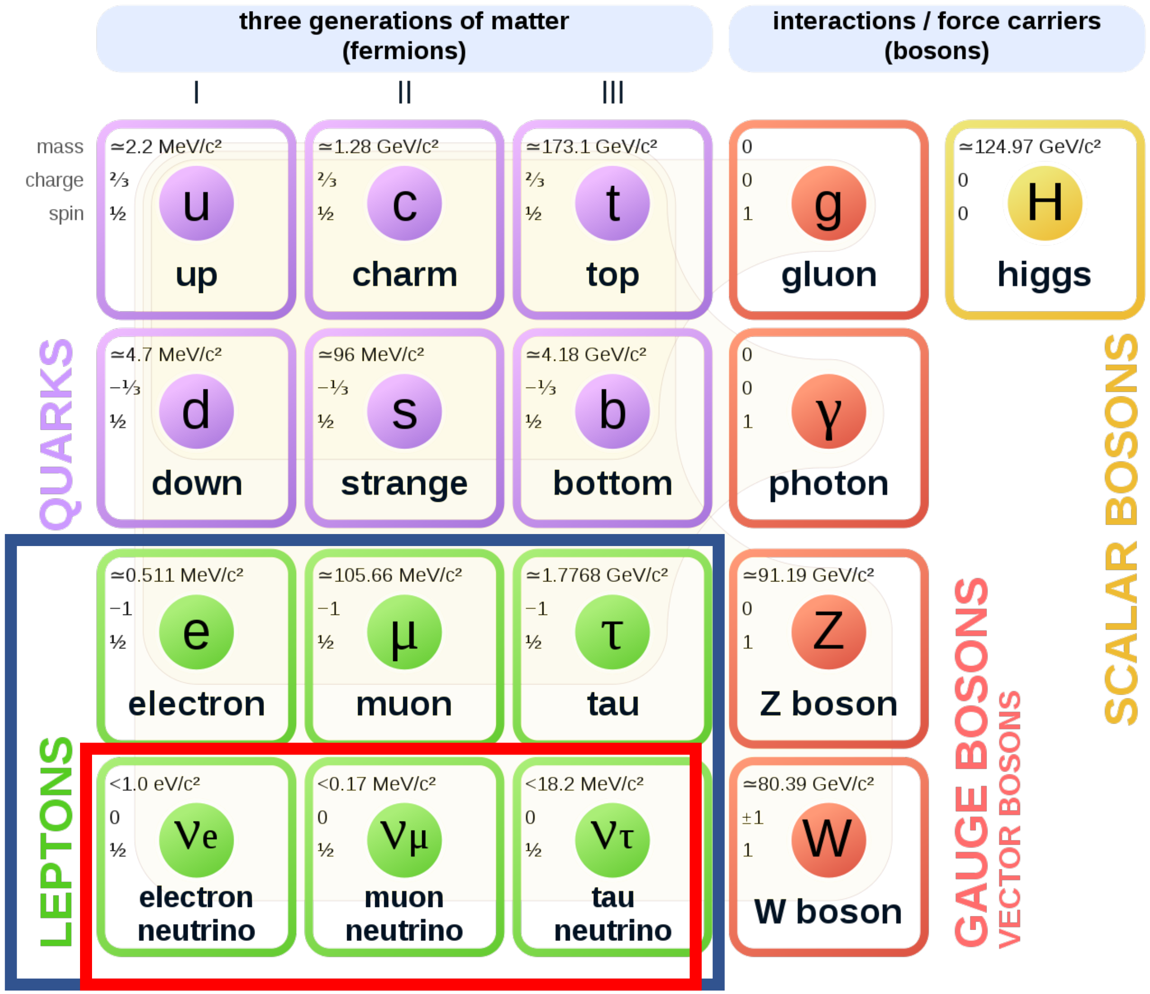
arxiv.org/abs/2211.10402

Oregon State University

**Now at Argonne National Lab*

Neutrinos In Standard Model

Standard Model of Elementary Particles



Neutrinos are electrically neutral leptons.

3 Generations of charged leptons —>3 generations of neutral massless neutrinos

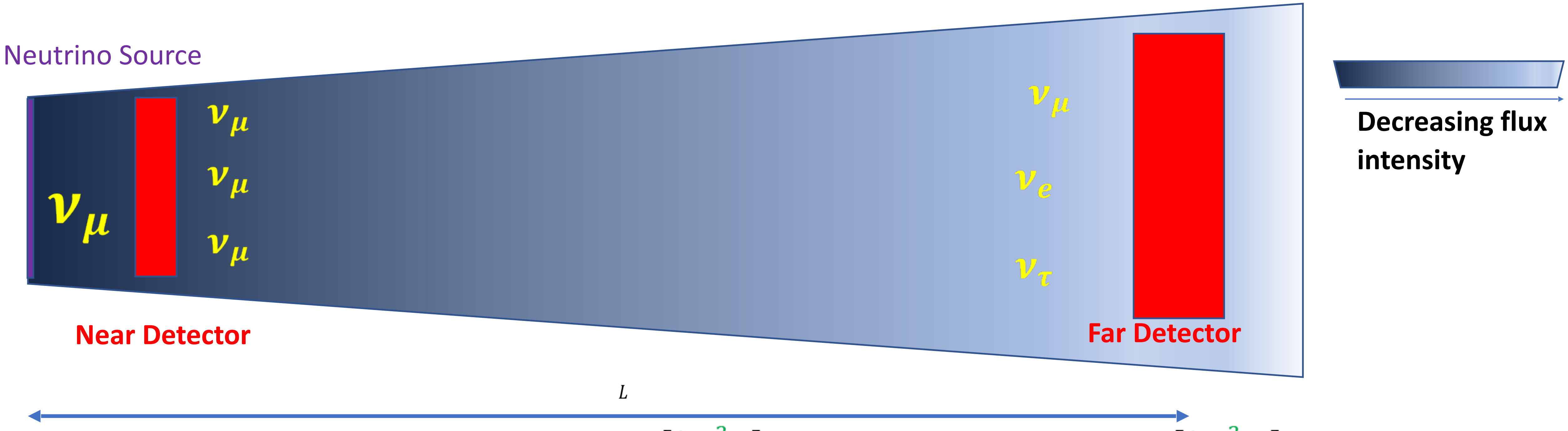
$$W^+ \rightarrow e^+ + \nu_e \qquad W^- \rightarrow e^- + \bar{\nu}_e$$

$$W^+ \rightarrow \mu^+ + \nu_\mu \qquad W^- \rightarrow \mu^- + \bar{\nu}_\mu$$

$$W^+ \rightarrow \tau^+ + \nu_\tau \qquad W^- \rightarrow \tau^- + \bar{\nu}_\tau$$

- ν_e, ν_μ, ν_τ are only interact through weak force.

Neutrino Oscillation Experiments



$$P(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} Re\,(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin\left[\frac{\Delta m^2_{ij}L}{4E}\right] + 2\sum_{i>j} Im(U^*_{\alpha i}U_{\beta i}\;U_{\alpha j}U^*_{\beta j})\,sin\left[\frac{\Delta m^2_{ij}L}{2E}\right]$$

L→ Distance Between neutrino source and far detector

E → Energy of the neutrino

$U_{\alpha i}, U_{\beta j}$ →Mixing matrix elements ($\alpha, \beta \rightarrow \nu_e, \nu_\mu, \nu_\tau$ & $i, j \rightarrow \nu_1, \nu_2, \nu_3$)

$\Delta m^2_{ij} = m^2_i - m^2_j$ →Difference of mass of eigenstates ν_i, ν_j

Neutrino Oscillation: Measurement

In a $\nu_\mu \rightarrow \nu_e$ oscillation experiment, quantity we want to measure is:

$$P_{\nu_\mu \rightarrow \nu_e}(E, L) \propto \frac{\Phi_{\nu_e}(E, L)}{\Phi_{\nu_\mu}(E, 0)}$$

$\Phi_{\nu_e}(E, L) \rightarrow$ Electron neutrino flux measured at distance L from the source

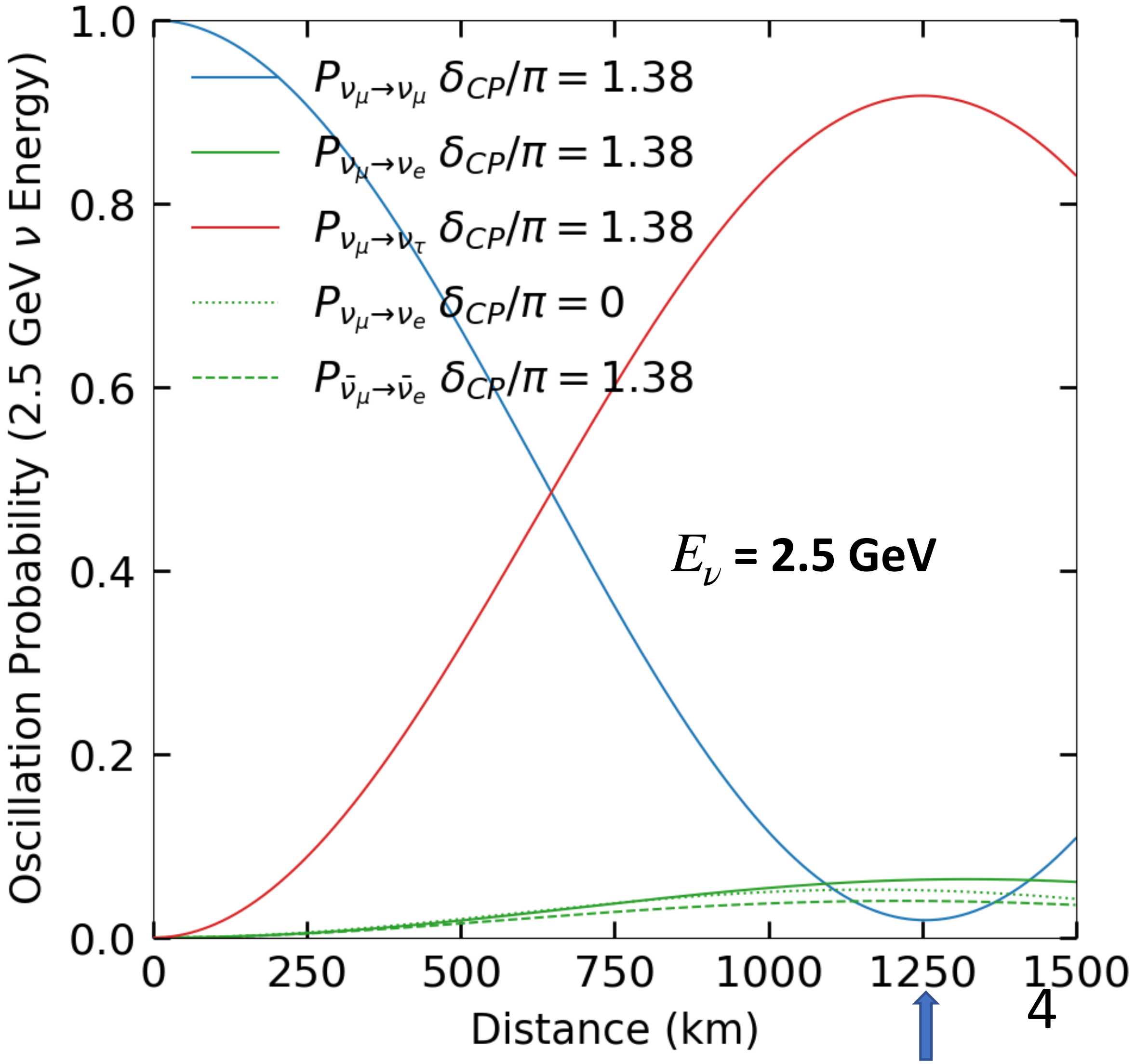
$\Phi_{\nu_\mu}(E, 0) \rightarrow$ Muon neutrino flux measured at the source

One of the goals of current oscillation experiments is to measure how much CP violation happens in lepton sector

$\delta_{CP} = 0 \rightarrow$ No CP Violation $\quad P(\nu_\mu \rightarrow \nu_e) = P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

$\delta_{CP} \neq 0 \rightarrow$ CP Violation $\quad P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

Neutrino experiments don't measure flux directly.
They measure the number of events **N** as a function of reconstructed neutrino energy $\boldsymbol{E_{rec}}$.



Neutrino Oscillation: Measurement

$[\sigma(E_\nu) * \theta(E_\nu)]$

Cross section is convoluted by nuclear effects $(\theta(E_\nu))$

$$N_e(E_{rec}, L) \propto \sum_i \Phi_e(E, L)\sigma_i(E) f_{\sigma i}(E, Erec) dEdM$$

Estimation of neutrino flux: MINERvA employs various methods to accurately estimate neutrino flux and constrain flux related uncertainties.

Neutrino Interaction Cross section: Cross section measurements improve our neutrino interaction models

Smearing of true neutrino energy (E): Limitation on how accurately neutrino energy can be reconstructed (E_{rec})

Smearing of true (E) to reconstructed (E_{rec}) depends upon detector properties.

(Accelerator neutrino) oscillation experiments like **NOvA, DUNE, T2K,HK** need accurate estimations of **neutrino flux ($\Phi(E)$)** and **cross section ($\sigma(E)$)** to extract the oscillation parameters accurately.

Nuclear effects complicate the cross-section measurements.

Neutrino Oscillation: Measurement

$$N_e(E_{rec}, L) \propto \sum_i \Phi_e(E, L)\sigma_i(E) f_{\sigma i}(E, Erec) dE dM$$

i : neutrino-nucleus interaction channel

Estimation of neutrino flux: MINERvA employs various methods to accurately estimate neutrino flux and constrain flux related uncertainties.

Neutrino Interaction Cross section: Cross section measurements improve our neutrino interaction models

MINERvA was designed to study the poorly understood neutrino-heavy nucleus interactions

- MINERvA has developed a comprehensive flux strategy to constrain the neutrino flux uncertainties.
- MINERvA has provided cross section measurements of various neutrino scattering processes over a wide neutrino energy range.
- Measurements in various target materials has helped us to understand nuclear effects in neutrino-heavy nucleus interactions.
- Neutrino oscillation experiments often use heavy target material detectors. Understanding nuclear effects is crucial to reconstruct neutrino energy in near and far detectors.

Neutrino Production in NuMI Beamline

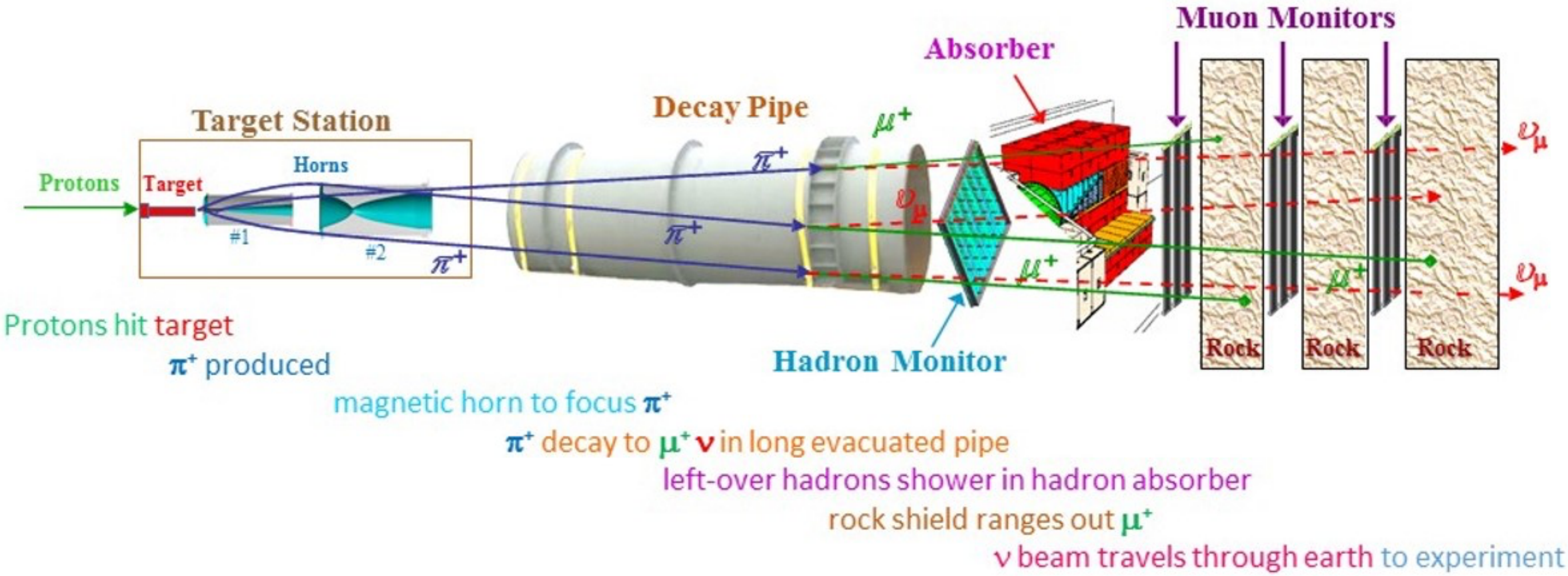
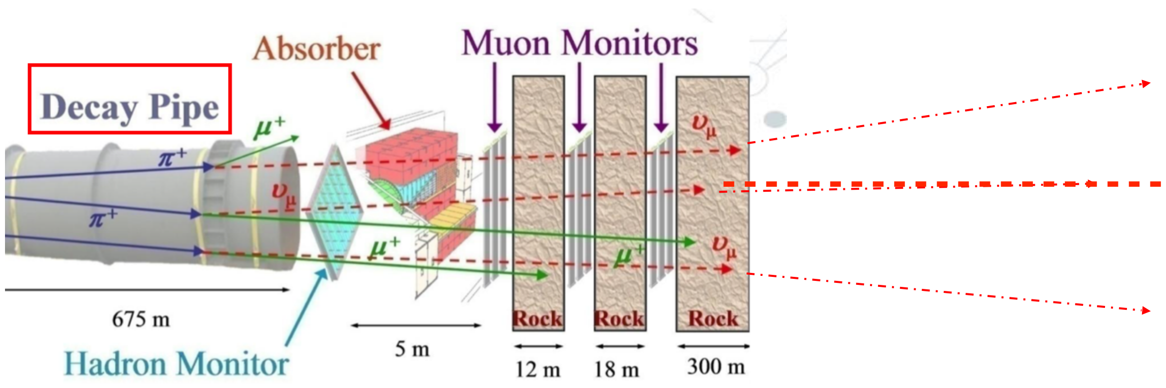
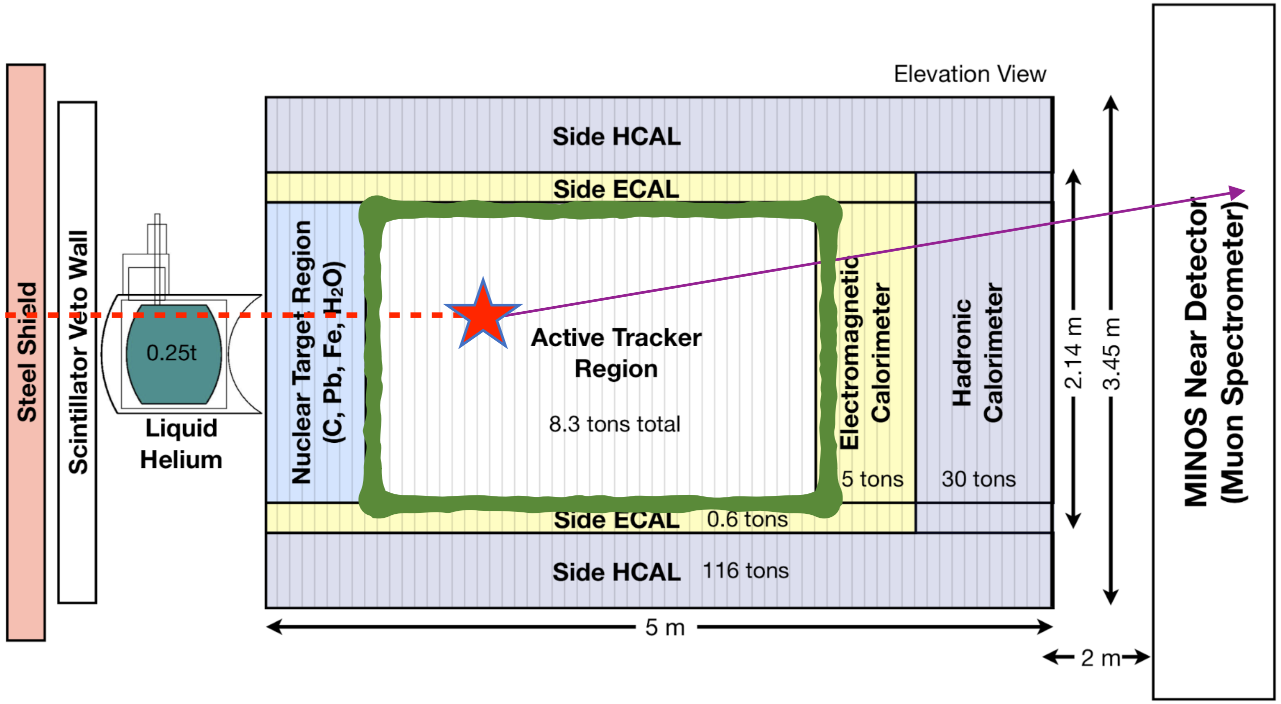


Image Credit: Fermilab

Many thanks to Accelerator Division for the awesome neutrino beam!

MINERvA Experiment



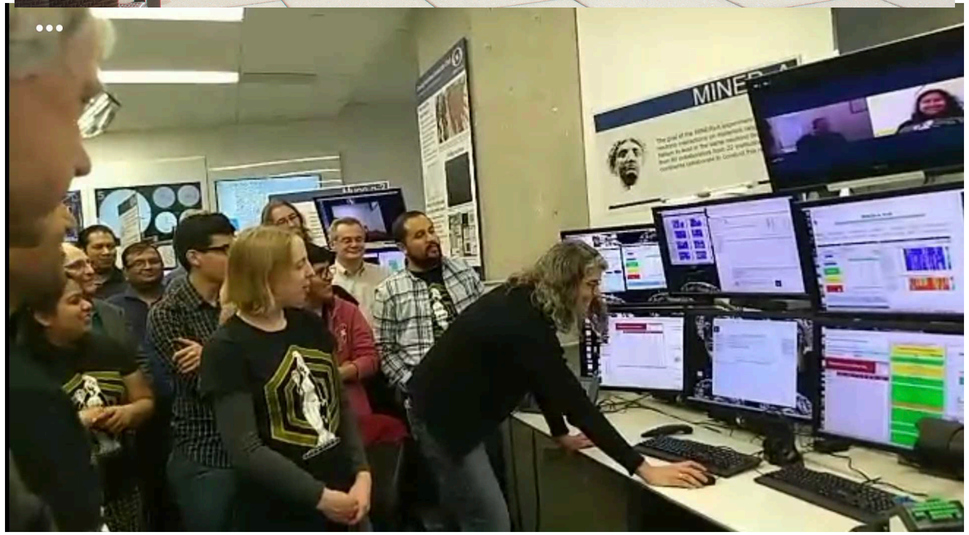


- **M**ain **I**njector **Neutrino** Nucleon (**A**) experiment
- MINERvA is a neutrino cross-section measurement experiment
- Downstream of the NuMI beam line

- MINERvA detector→1.032 km from the NuMI target
- MINOS near detector →1.04 km from the NuMI target
  - MINOS near detector is magnetized.
  - Identify charge of muon from interaction

MINERvA Experiment

The MINERvA Collaboration

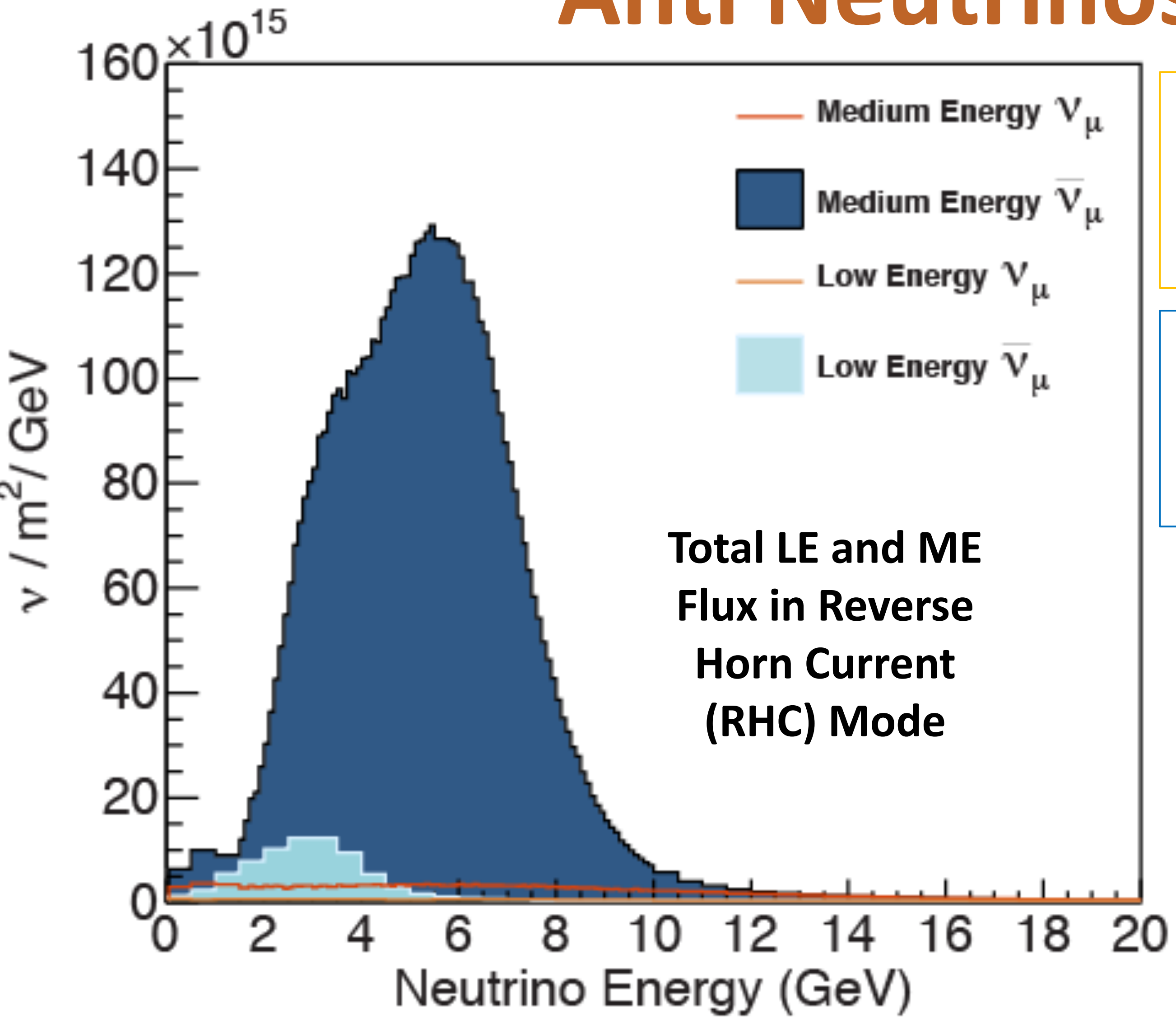


Detector shutting down for the last time.

Front face of the MINERvA detector

Celebrating for collecting 30e20 POT

Anti Neutrinos in MINERvA



ME (Medium Energy) = 6 GeV Neutrino Energy Focusing Peak Run

LE (Low Energy) = 3 GeV Neutrino energy Focusing Peak Run

LE ν POT: 4.0×10^{20}

LE $\bar{\nu}$ POT: 1.7×10^{20}

ME $\nu POT \sim 3 \times LE\ \nu\ POT$

ME $\bar{\nu}\ POT \sim 7 \times LE\ \bar{\nu}\ POT$

LE → 2 years run

ME →5.5 years run

ME data:

- High Statistics+ High Energy

RHC: Focusing Horns magnetic field to focus π^- which in turn decay to give $\bar{\nu}_\mu$.

MINERvA Flux Strategy

- Focusing Uncertainties
- Hadron Production Correction
  [PRD 94, 092005]

GEANT4 simulated Neutrino Flux

GEANT4 [version 4.9.3p6]
G4numi-v2

a priori Neutrino Flux

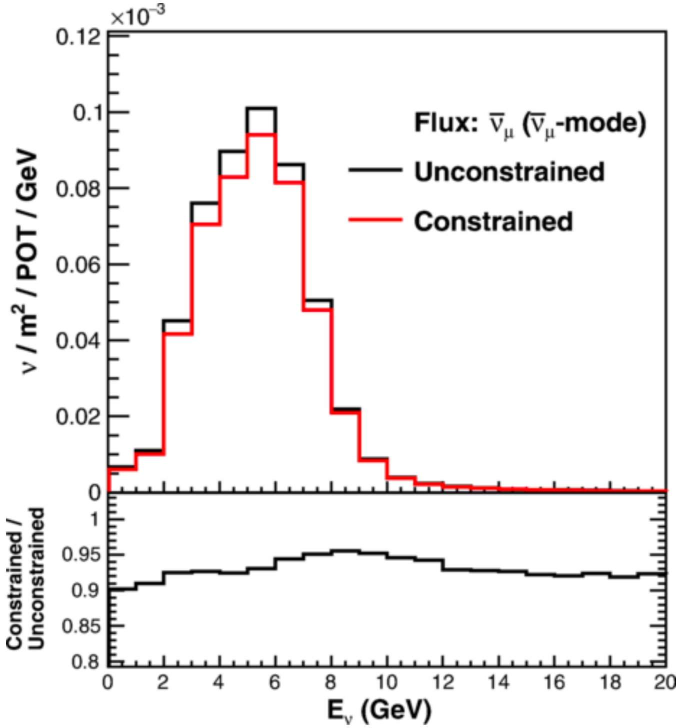
Insitu Correction

- ν+e constraint **[L. Zazutsa, PRD 107,012001]**
  - $\nu e \rightarrow \nu e$
- Inverse Muon Decay **[D. Ruterbories, PRD 104,092010]**
  - $\nu_\mu e^- \rightarrow \mu^- \nu_e$
- **Combined Fit of (FHC+RHC νe scattering)+ IMD Data**
- Uncertainty reduced from 7.8% to 4.7% ($\bar{\nu}_\mu$ Flux)

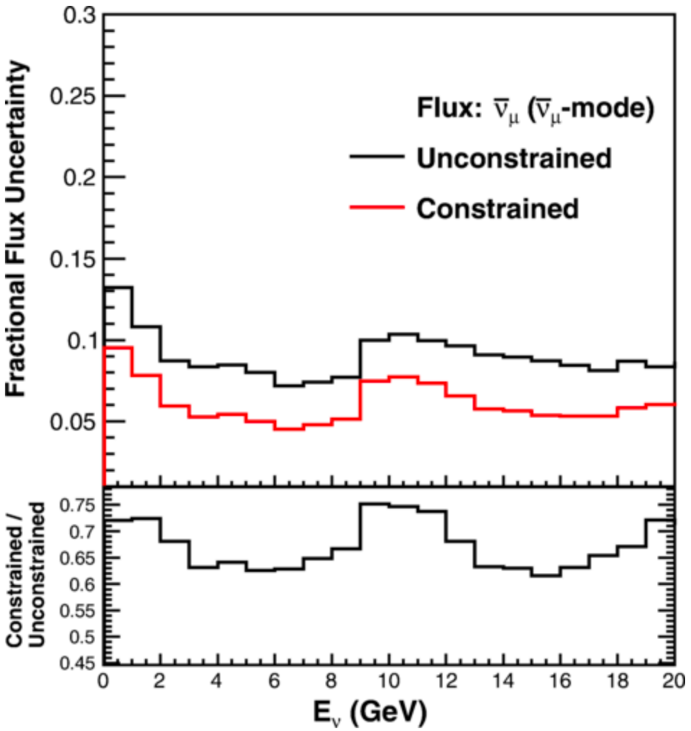
- G4numi simulated Flux Using FTFP_BERT Hadronic Model
  - GEANT4 model dependent

- Hadron Production Corrections using Thin Target Datasets [Na49, Barton]

Insitu correction on the Flux

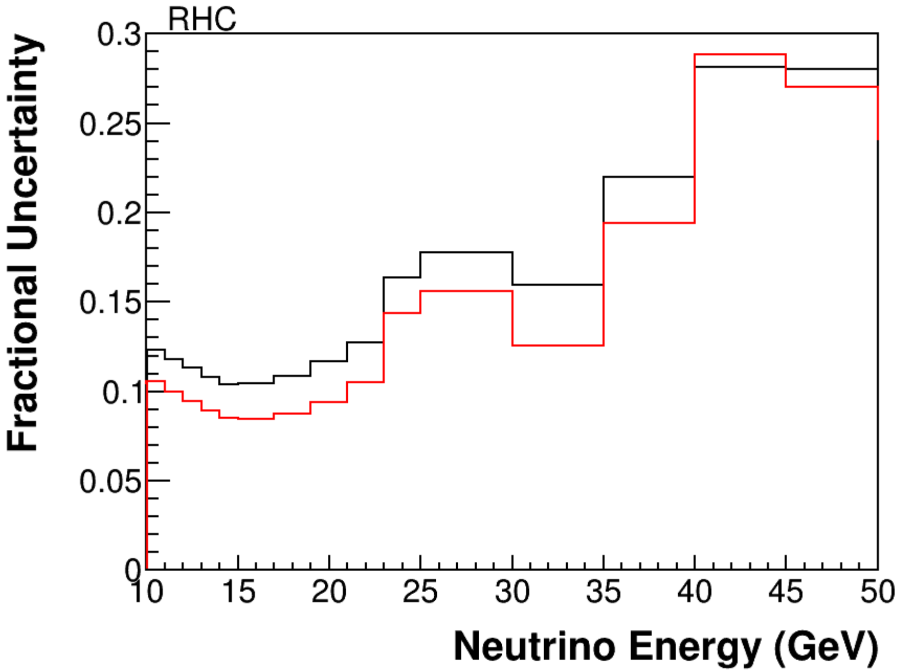


a priori anti neutrino Flux before and after constrained by *ν*e scattering data



Uncertainty on predicted anti neutrino flux before and after constrained by *ν*e scattering data

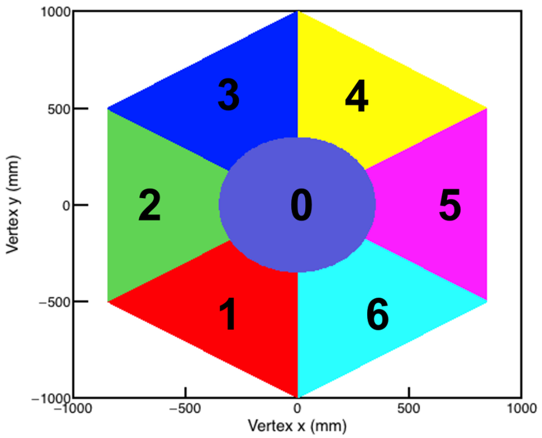
- ***ν***+e constraint [L. Zazueta, PRD 107,012001]
  - ***ν*e → *ν*e**
- Inverse Muon Decay [D. Ruterbories, PRD 104,092010]

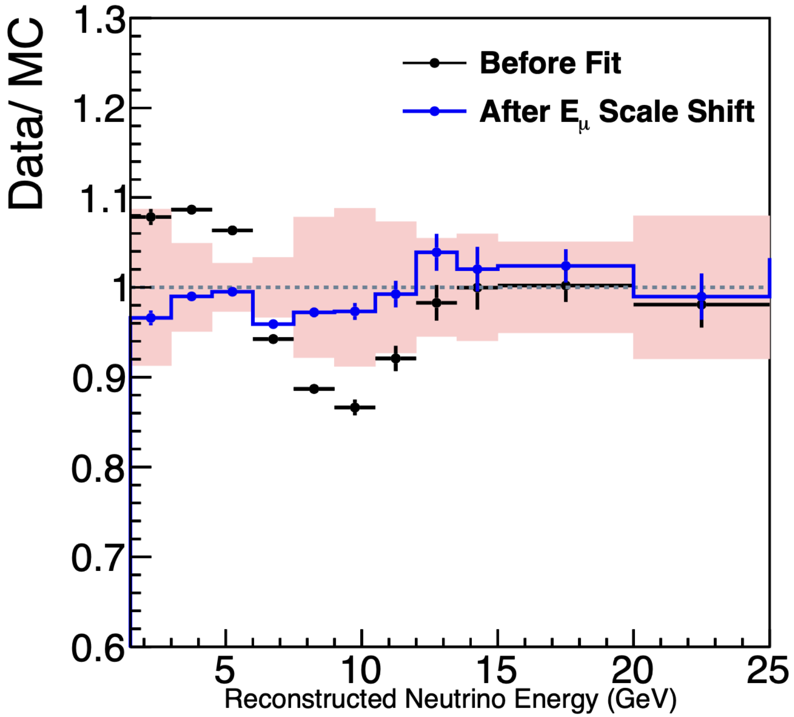


Combined Fit of (FHC+RHC νe scattering) + IMD Data
Uncertainty reduced from 7.8% to 4.7% ($\bar{\nu}_\mu$ Flux)

IMD constrains Flux with E_ν>10 GeV

Low nu Fit to resolve discrepancy





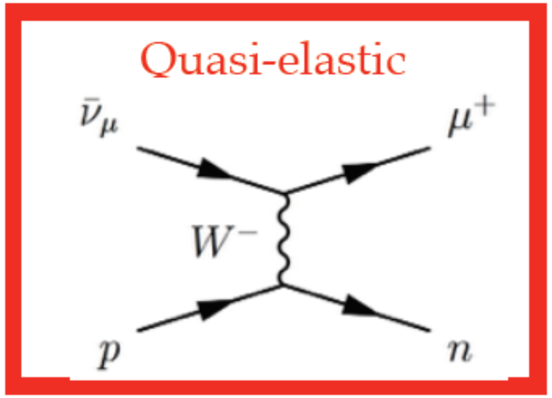
- MINERvA saw discrepancy between its data and simulated sample.
- Discrepancy due to shift in energy spectrum
- A multi parameter fit
  - Fit done with Low recoil sample
    - Cross-section independent of E_ν —> Shape depends on Flux
  - Focusing parameters and MINOS muon energy scale as fit parameters
- Shift of MINOS muon energy scale by 1.8 σ to resolve discrepancy

[A. Bashyal,arXiv:2104.05769]

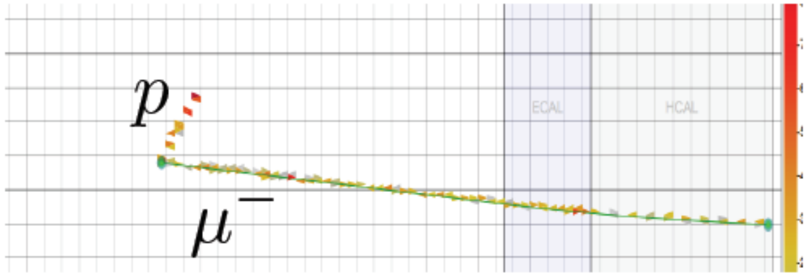
Parameter	Nominal	Best Fit (No Prior)	Best Fit (Prior)
Beam Position (X)	0.0 mm	$-0.3 \pm 0.3 \pm 0.1$ mm	$-0.3 \pm 0.2 \pm 0.1$ mm
Beam Position (Y)	0.0 mm	$0.8 \pm 0.3 \pm 0.3$ mm	$0.7 \pm 0.2 \pm 0.2$ mm
Target Position (X)	0.0 mm	$-0.8 \pm 0.3 \pm 0.1$ mm	$-0.8 \pm 0.3 \pm 0.1$ mm
Target Position (Y)	0.0 mm	$2.3 \pm 0.7 \pm 1.2$ mm	$1.7 \pm 0.6 \pm 0.8$ mm
Target Position (Z)	-1433 mm	$-1432.4 \pm 2.4 \pm 0.3$ mm	$-1431 \pm 1.8 \pm 0.3$ mm
Horn 1 Position (X)	0.0 mm	$-0.3 \pm 0.4 \pm 0.5$ mm	$-0.1 \pm 0.3 \pm 0.1$ mm
Horn 1 Position (Y)	0.0 mm	$0.1 \pm 0.5 \pm 0.5$ mm	$0.0 \pm 0.3 \pm 0.3$ mm
Beam Spot Size	1.5 mm	$1.41 \pm 0.09 \pm 0.03$ mm	$1.32 \pm 0.09 \pm 0.03$ mm
Horn Water Layer	1.0 mm	$1.2 \pm 0.3 \pm 0.05$ mm	$1.3 \pm 0.25 \pm 0.1$ mm
Horn Current	200 kA	$198.0 \pm 1.4 \pm 1.4$ kA	$199.1 \pm 0.7 \pm 0.5$ kA
Muon Energy Scale	1.0	$1.032 \pm 0.004 \pm 0.008$	$1.036 \pm 0.004 \pm 0.006$

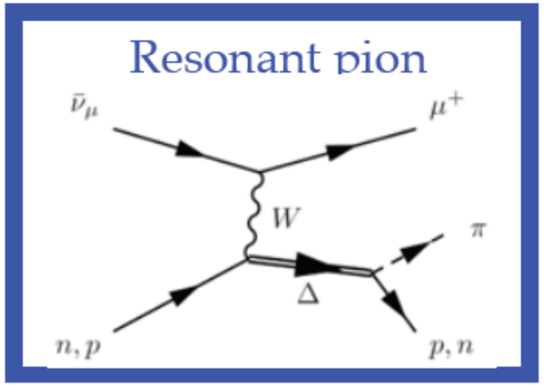
$\bar{\nu}_{\mu}$ Charged Current Quasi Elastic Cross-section Measurement in CH Target

General Neutrino Nucleon Interactions in MINERvA

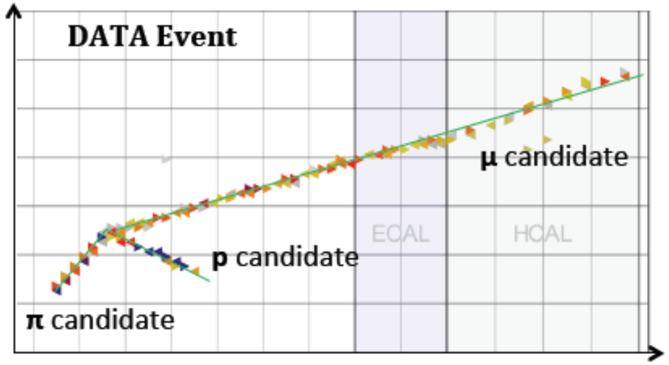


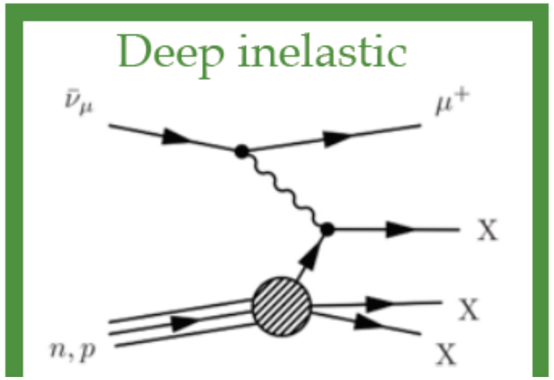
QE



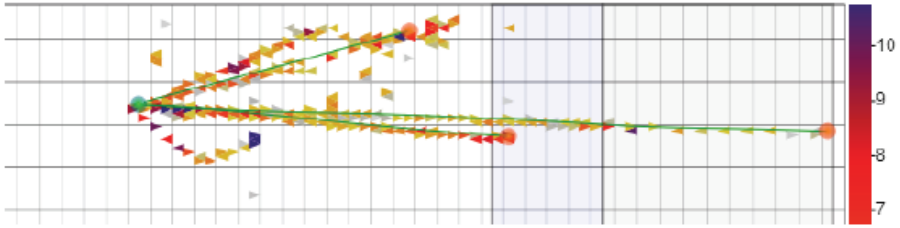


RES

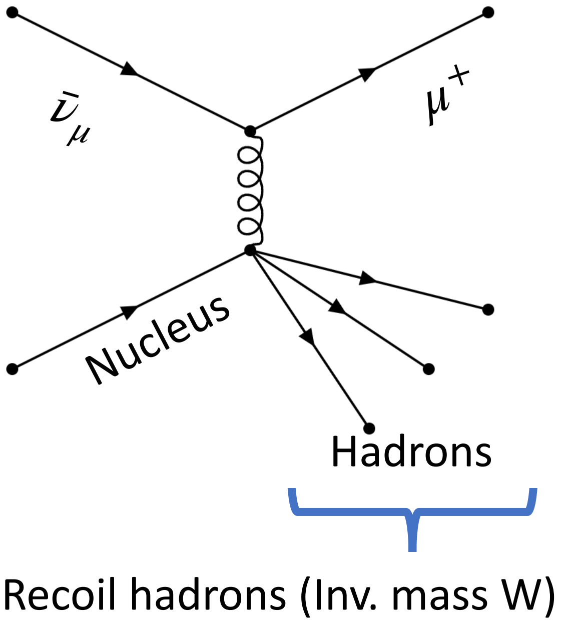




DIS

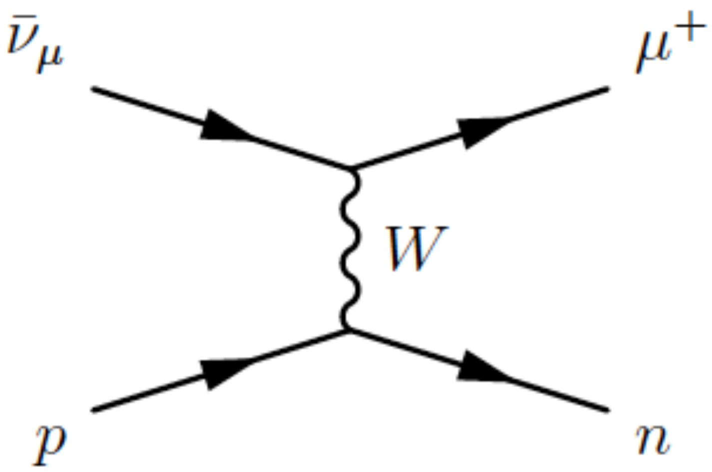


Increasing invariant mass of recoil system

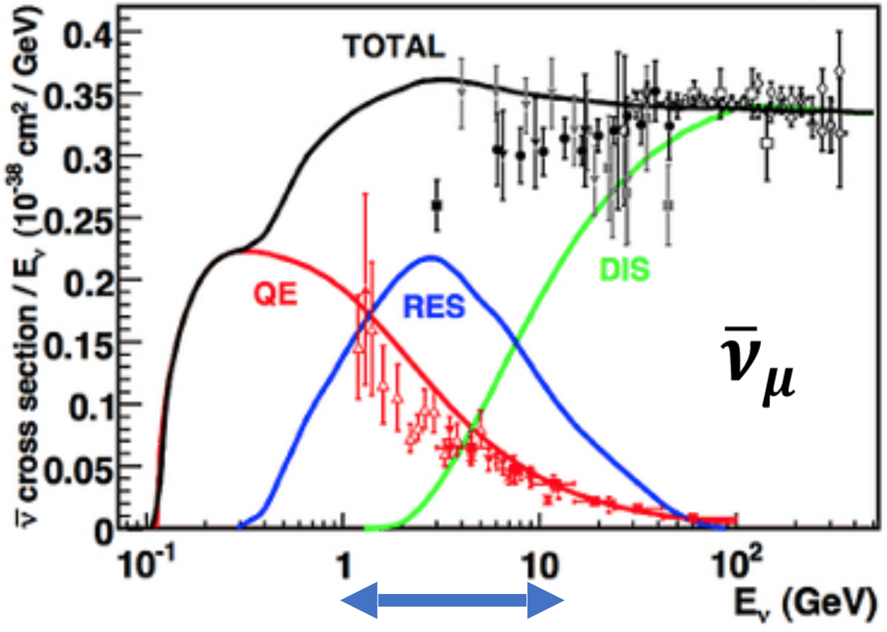


$$W^2 = M^2 + 2M\nu - Q^2$$

CCQE Interactions



Feynman diagram of an anti muon neutrino CCQE interaction



MINERvA, DUNE,NOvA

Oscillation experiments like **NOvA and DUNE** (will) see **CCQE** interactions as one of the **major** interactions.

CCQE cross-section measured by MINERvA will help oscillation experiment to understand their data.

Z.A Formaggio and Z.P. Zeller, Rev. Mod. Phys. 84, 1307-1341, 2012

CCQE Processes

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

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

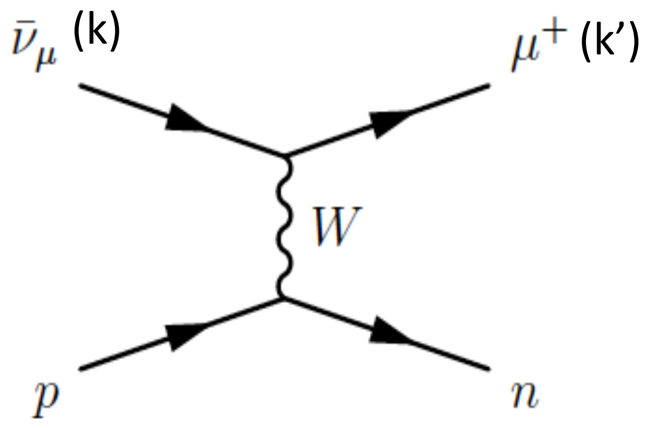
$l \rightarrow e, \mu, \tau \quad n \rightarrow neutron \quad p \rightarrow proton$

Anti-neutrino nucleon cross-section (per nucleon) for different interaction channels.

Red: QE cross-section

Neutrino Nucleon QE Scattering

- CCQE : Relatively clean process
- Assuming the nucleon is at rest, the energy of the incoming neutrino can be reconstructed using the kinematics of outgoing muon.

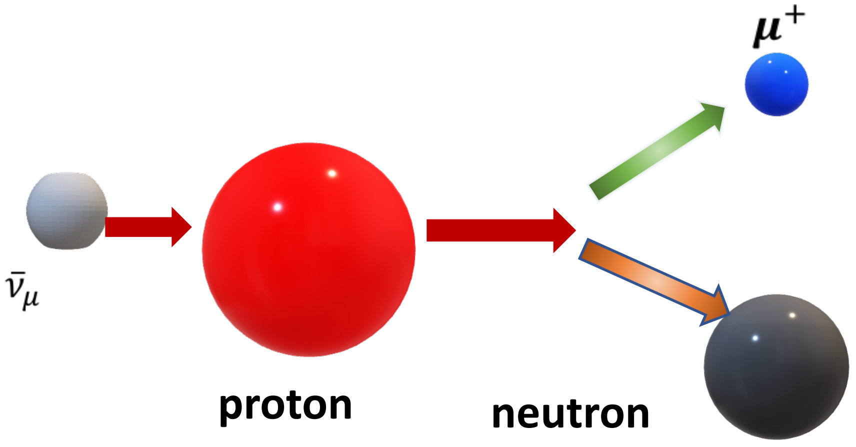


$$Q^2 = -\boldsymbol{q}.\boldsymbol{q}$$
$$q = k - k'$$

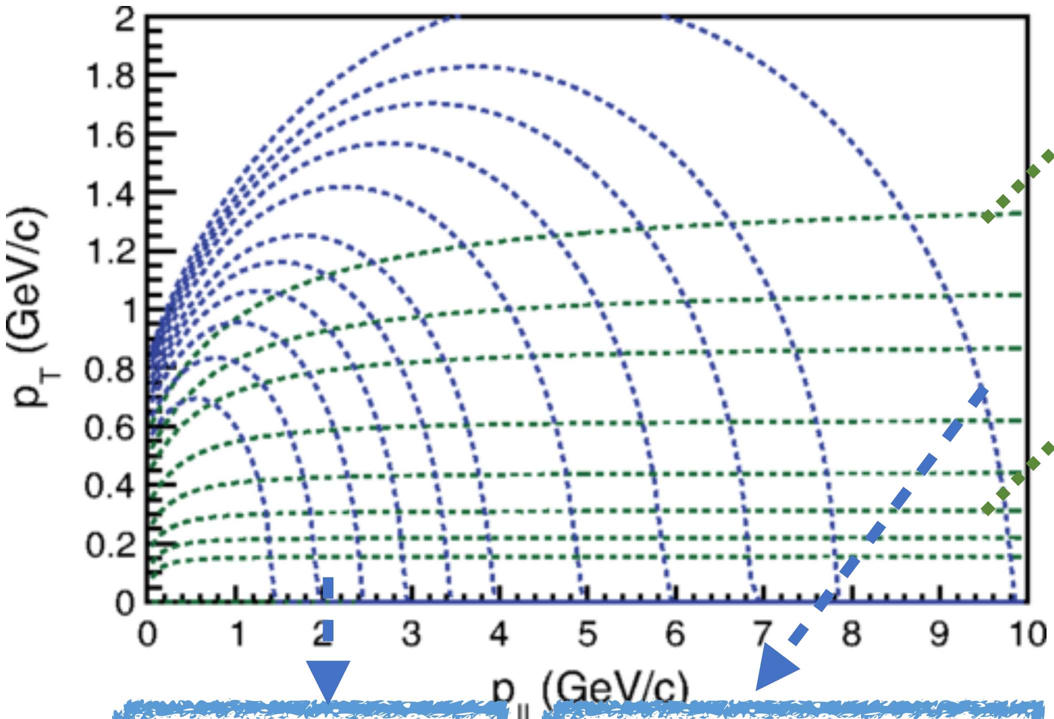
$$E_\nu^{QE} = \frac{m_n^2 - (m_p - E_b)^2 - m_\mu^2 + 2(m_p - E_b)E_\mu}{2(m_p - E_b - E_\mu + p_\mu \cos\theta_\mu)}$$

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

$m_p \rightarrow$ *mass of proton*
$m_n \rightarrow$ *mass of neutron*
$E_b \rightarrow$ *Binding Energy of the neutron in nucleus*
$E_\mu \rightarrow$ *Energy of the outgoing muon*
$p_\mu \rightarrow$ *Momentum of the outgoing muon*
$Q^2 \rightarrow$ *Four momentum transferred squared*



Cross section Measurement Variables



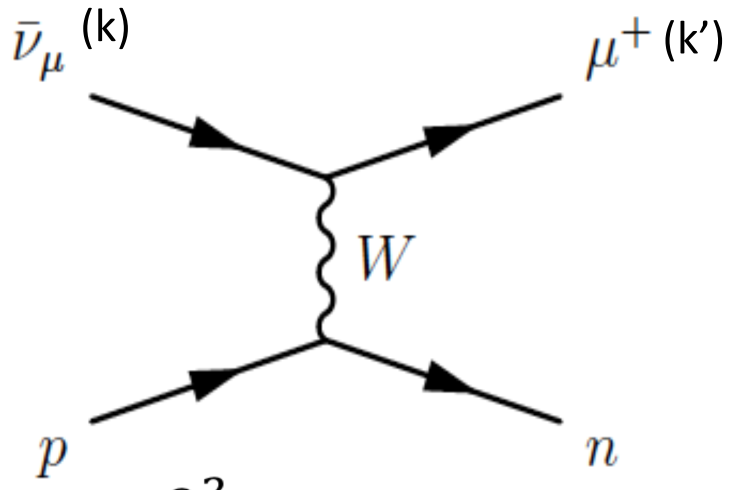
$Q^2_{QE} = 2.0\ GeV/c^2$

$Q^2_{QE} = 0.1\ GeV/c^2$

$E_{\nu QE} = 2.0\ GeV$

$E_{\nu QE} = 10.0\ GeV$

$E_{\nu QE}$: Blued Dotted Lines

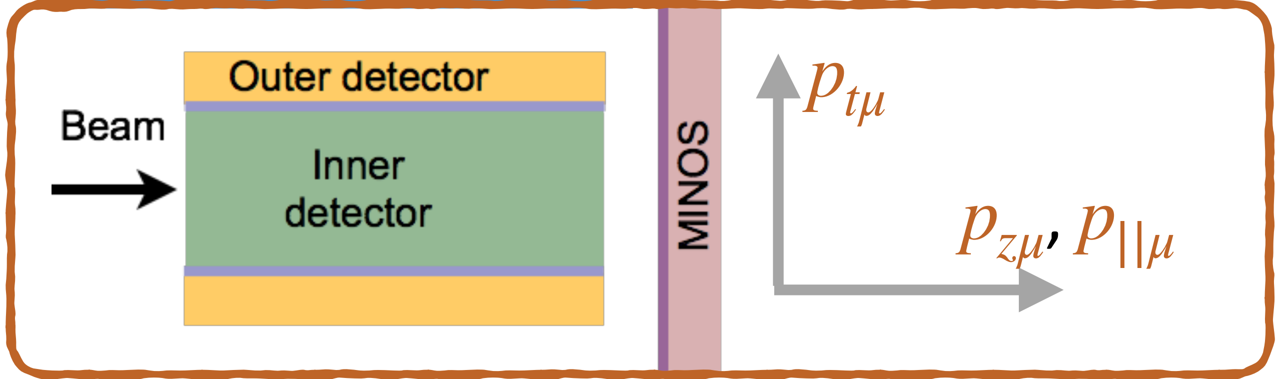


$Q^2 = -\boldsymbol{q}.\boldsymbol{q}$

$q = k - k'$

Q^2_{QE} : Green Dotted lines

Measures momentum transferred from leptonic to hadronic system.



Variables:

Kinematics ($p_{t\mu}$,$p_{z\mu}$)

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

$\bar{\nu}_\mu$ CCQELike (CH Target) Measurement in MINERvA

Measurement of Muon Antineutrino Quasielastic Scattering on a Hydrocarbon Target at Eν~3.5 GeV

MINERvA Collaboration • L. Fields (Northwestern U.) et al.

Published in: Phys.Rev.Lett. 111 (2013) 2, 022501

LE Beam

$\frac{d\sigma}{dQ^2}_{QE}$

Indication of multi-nuclear effects in CCQE processes

Measurement of the Muon Antineutrino Double-Differential Cross Section for Quasielastic-like Scattering on Hydrocarbon at $E_\nu \sim 3.5$GeV

LE Beam

MINERvA Collaboration • C.E. Patrick (Northwestern U.) et al.

Published in: Phys.Rev.D 97 (2018) 5, 052002

$\frac{d^2\sigma}{dp_z dp_t}, \frac{d^2\sigma}{(dE_\nu dQ^2)_{QE}}$

Incorporation of 2p2h (multi nuclear) process

High-Statistics Measurement of Antineutrino Quasielastic-like scattering at $E_\nu \sim$ 6~GeV on a Hydrocarbon Target

ME Beam

MINERvA Collaboration • A. Bashyal (Argonne and Oregon State U.) et a

e-Print: 2211.10402 [hep-ex] **Submitted to the PRD (This Talk)**

$\frac{d^2\sigma}{dp_z dp_t}, \frac{d^2\sigma}{(dE_\nu dQ^2)_{QE}}$

Higher Statistics, improved background constrain and measurement in previously unexplored region

3 D $\bar{\nu}_\mu$ CCQELike Cross section Measurement

Ongoing Work

ME Beam

$\frac{d^3\sigma}{dR dp_z dp_t}$

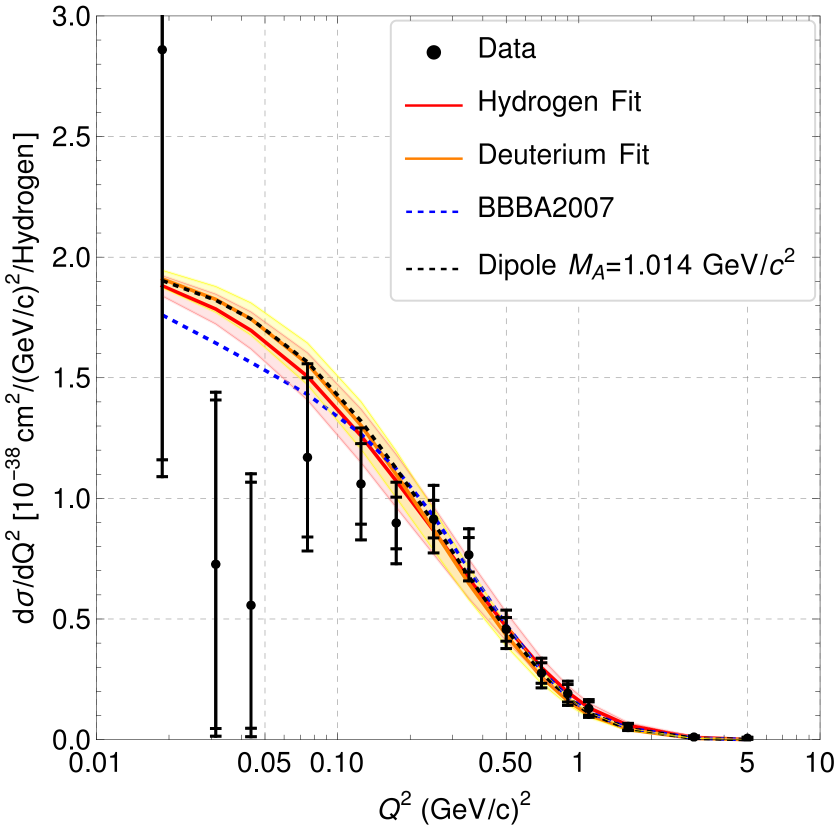
Measurement of visible energy (needed to measure E_ν^{reco}) in different μ^+kinematic bins

Measurement of the axial vector form factor from antineutrino-proton scattering in MINERνA

Tejin Cai

University of Rochester
York University

Joint Experimental-Theoretical Physics Seminar, Feb 1, 2023



Article | Open Access | Published: 01 February 2023

Measurement of the axial vector form factor from antineutrino–proton scattering

T. Cai, M. L. Moore, A. Olivier, S. Akhter, Z. Ahmad Dar, V. Ansari, M. V. Ascencio, A. Bashyal, A. Bercellie, M. Betancourt, A. Bodek, J. L. Bonilla, A. Bravar, H. Budd, G. Caceres, M. F. Carneiro, G. A. Díaz, H. da Motta, J. Felix, L. Fields, A. Filkins, R. Fine, A. M. Gago, H. Gallagher, ... L. Zazueta

+ Show authors

Nature **614**, 48–53 (2023) | Cite this article

Signal of above analysis is subset of this analysis' Signal.

Simulation of Neutrino Nucleon Interaction in MINERvA

GENIE 2.12.6 [*arXiv:1510.05494 [hep-ph]*]is our neutrino MC generator:

- ❑ Nuclear Model (initial state) → Relativistic Fermi Gas (RFG) Model for initial nuclear state with an additional high energy tail as prescribed by Bodek and Ritchie [*A. Bodek and J. Ritchie, Phys. Rev. D 23, 1070 (1981)*].
- ❑ Final State Interaction of hadrons →INTRANUKE h-A model
- ❑ QE Process → **Llewellyn-Smith formalism** + BBA05 with M_A = 0.99 GeV
  C.H. Llewellyn Smith, Phys. Rept. 3C, 261 (1972)
- ❑ Resonance π production → Rein Sehgal model with M_A= 1.12 GeV
- ❑ Deep Inelastic Scattering→ Bodek- Yang Model **[A. Bodek,arXiv:hep-ph/0411202 [hep-ph] .]**

Full Detector Simulation (GEANT4) to simulate the response of the detector for particles that interact with the detector.

Simulated Neutrino Flux

↓

WE COVERED THIS

GENIE

Tunes

GENIE+Tunes →MINERvA Tune

Referred as MINERvA Tune v1 in this Talk

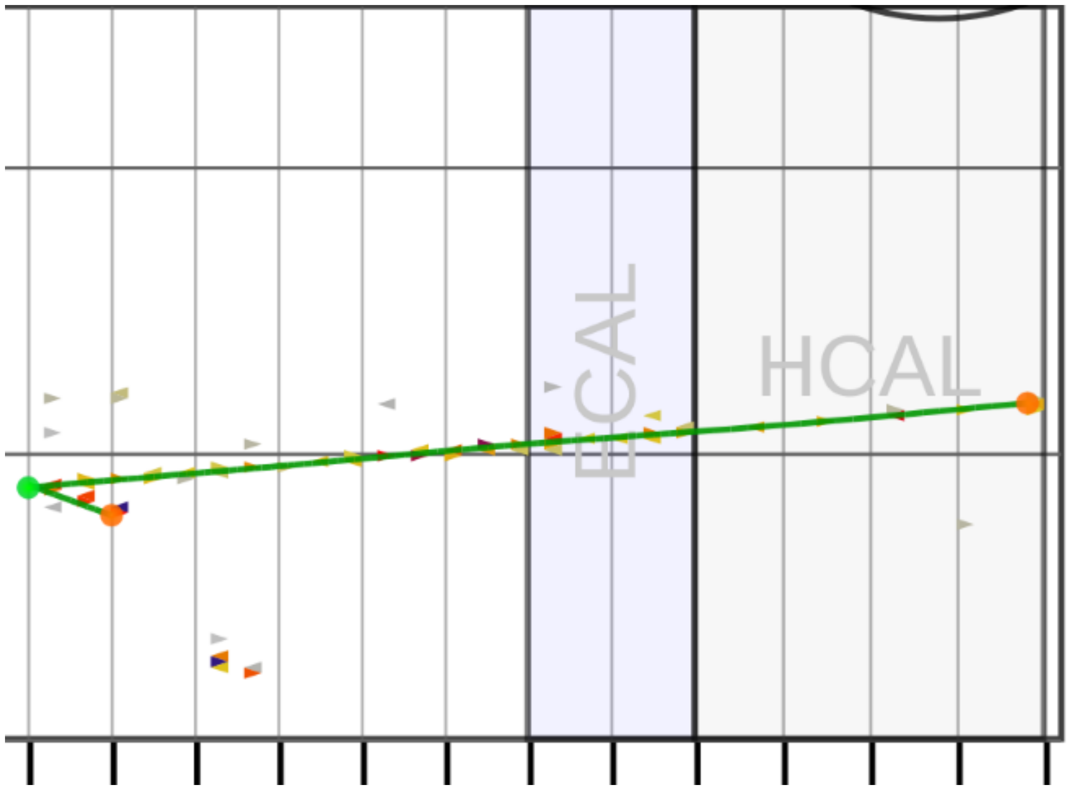
Various corrections to the GENIE generated events.

- ❑ QE events at Low Q^2 modified using Valencia RPA model
- ❑ Multi nuclear effects (2p2h) added based on Nieves Valencia model *[Phys. Rev. D 88, 113007 (2013), arXiv:1307.8105 [hep- ph]*.
- ❑ 2p2h processes are enhanced based on a fit to MINERvA Low energy Inclusive data *[P. Rodrigues et al. (MINERvA), Phys. Rev. Lett. 116, 071802 (2016)]*
- ❑ Non resonant pion production suppressed by 40% based on re-analysis of bubble chamber data *[P. Rodrigues, EPhys. J. C 76, 474 (2016), arXiv:1601.01888 [hep-ex]]*.

MINERvA Detector Simulation

GENIE Generated Neutrino Interactions

Full Detector Simulation (GEANT4) to simulate the response of the detector for particles that interact with the detector.



- **Data Overlay is done on the detector simulated events.**
- **Simulate pileup effect from other interactions (upstream and in the target) in the simulated interactions.**

CCQE Cross-section

- CCQE Cross-section is generally expressed in Llewellyn Smith formalism:

$$\frac{d\sigma}{dQ^2}\begin{pmatrix}\nu n \to l^- p \\ \bar{\nu} p \to l^+ n\end{pmatrix} = \frac{M^2 G^2 \cos^2\theta_c}{8\pi E_\nu^2}\left[A(Q^2) \mp B(Q^2)\frac{(s-u)}{M^2} + C(Q^2)\frac{(s-u)^2}{M^4}\right] \quad (1)$$

$$M = \frac{m_p + m_n}{2}$$

$$s - u = 4ME - Q^2 - m_l^2$$

$$G_F^2 = 1.18 \times 10^{-5} GeV^{-2} \; (Fermi\ Coupling\ constant)$$

$$\theta_C = 0.974$$

CCQE Cross-section

$$A(Q^2) = 4\frac{Q^2}{4M^2}|F_A|^2(1+\frac{Q^2}{4M^2}) - |F_V^1|^2(1-\frac{Q^2}{4M^2}) + |\xi F_V^2|^2\frac{Q^2}{4M^2}(1-\frac{Q^2}{4M^2}) + 4F_V^1\xi F_V^2\frac{Q^2}{4M^2}] \quad (1)$$

Valid for ν_μ, ν_e

$$B(Q^2) = 4\frac{Q^2}{4M^2}[F_A(F_V^1 + \xi F_V^2)] \quad (2)$$

$$C(Q^2) = \frac{1}{4}|F_A|^2 + |F_V^1|^2 + \frac{Q^2}{4M^2}|\xi F_V^2|^2] \quad (3)$$

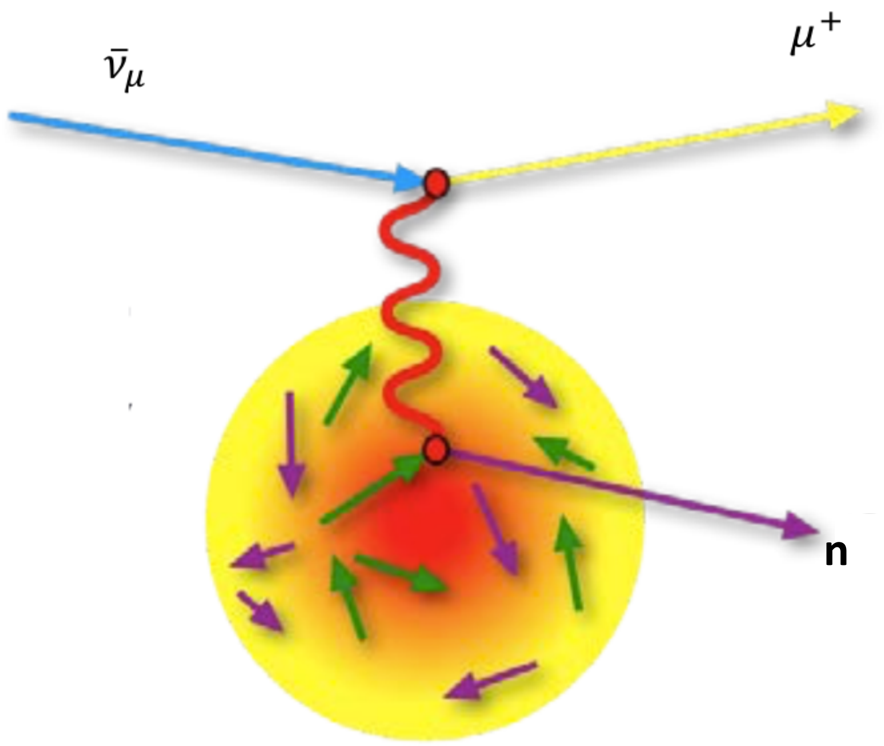
$F_A \rightarrow$ **Axial Form Factor**

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

- $M_A \sim$ 0.99 GeV (Axial Mass)
- **Based on bubble chamber** (hydrogen targets) measurements
- Measurements in **heavier target** report slightly **higher axial mass**
  - **Nuclear Effects**
- Dipole Form Factor approximation breaks at high Q^2

Neutrino Nucleon Cross-section Modeling

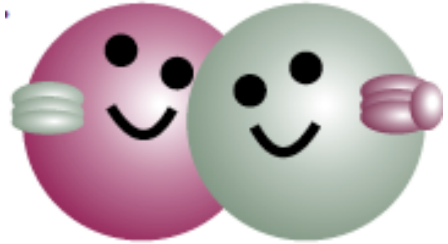
- CCQE cross-section model based on the Llewellyn Smith formalism.



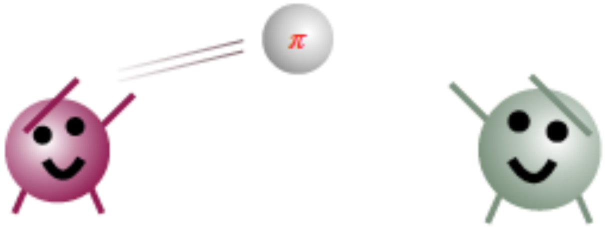
- Cross-section models are based on neutrino interaction with the free nucleons.

- In heavy targets like **carbon** (this analysis) , argon, etc., the final state particle (that exits the nucleus) can be changed due to nuclear effects that are not **modeled by the Fermi Gas Model**.

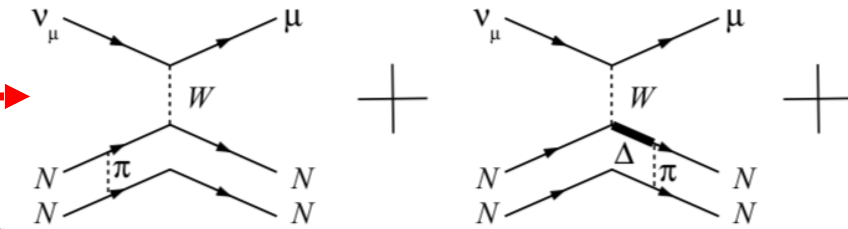
Nuclear Effects: nucleon-nucleon correlation



Short Range correlations modeled by Bodek Ritchie Tail added in RFG and Spectral Functions

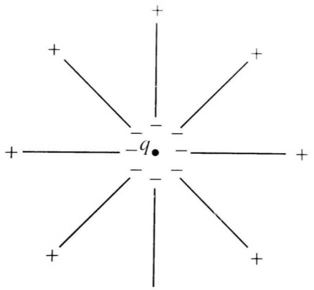


Medium Range correlations modeled by Meson Exchange current and Transverse Enhancement model



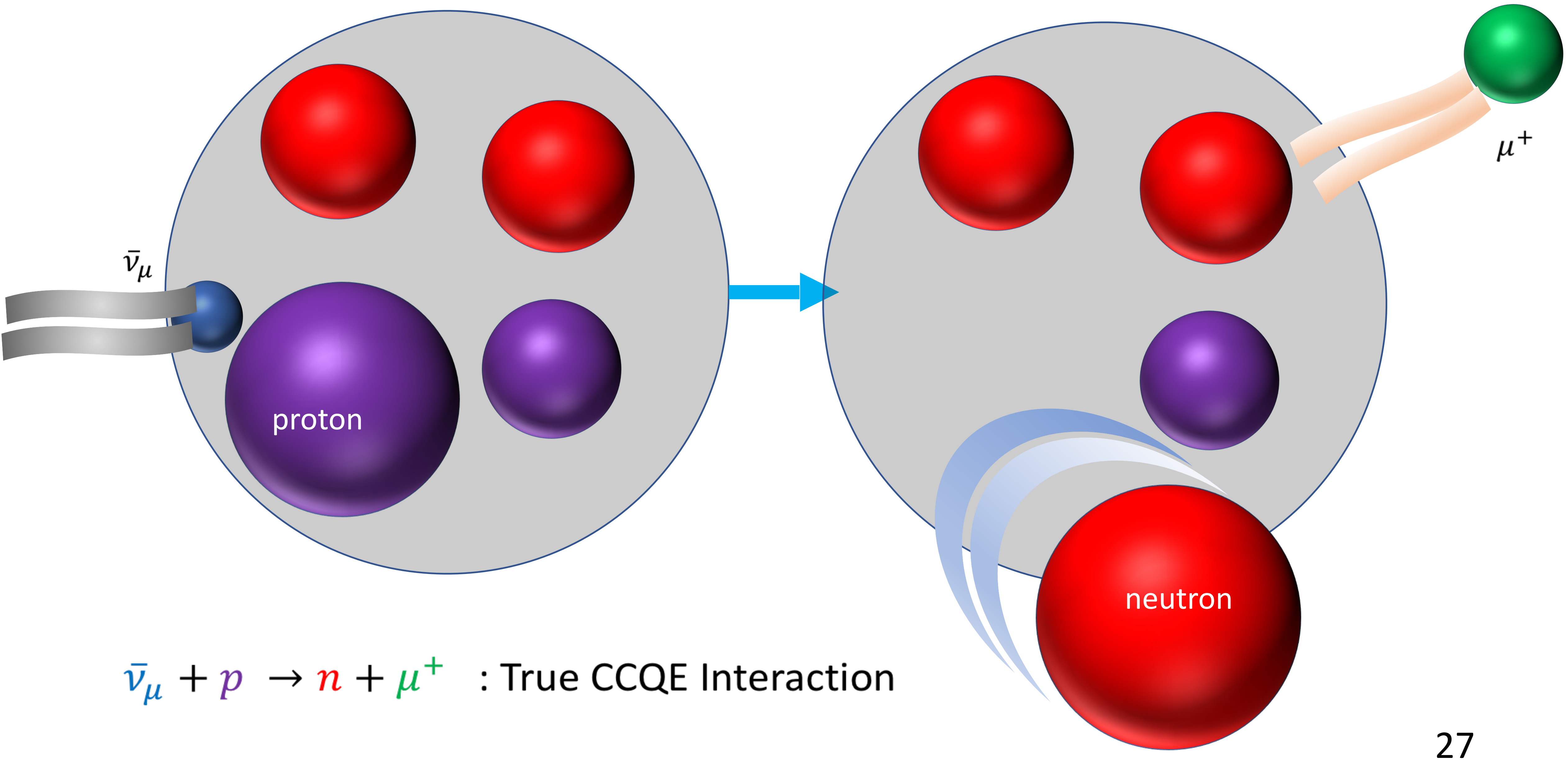
Valencia 2p2h model for MEC effects

Long Range Correlations Random Phase Approximation



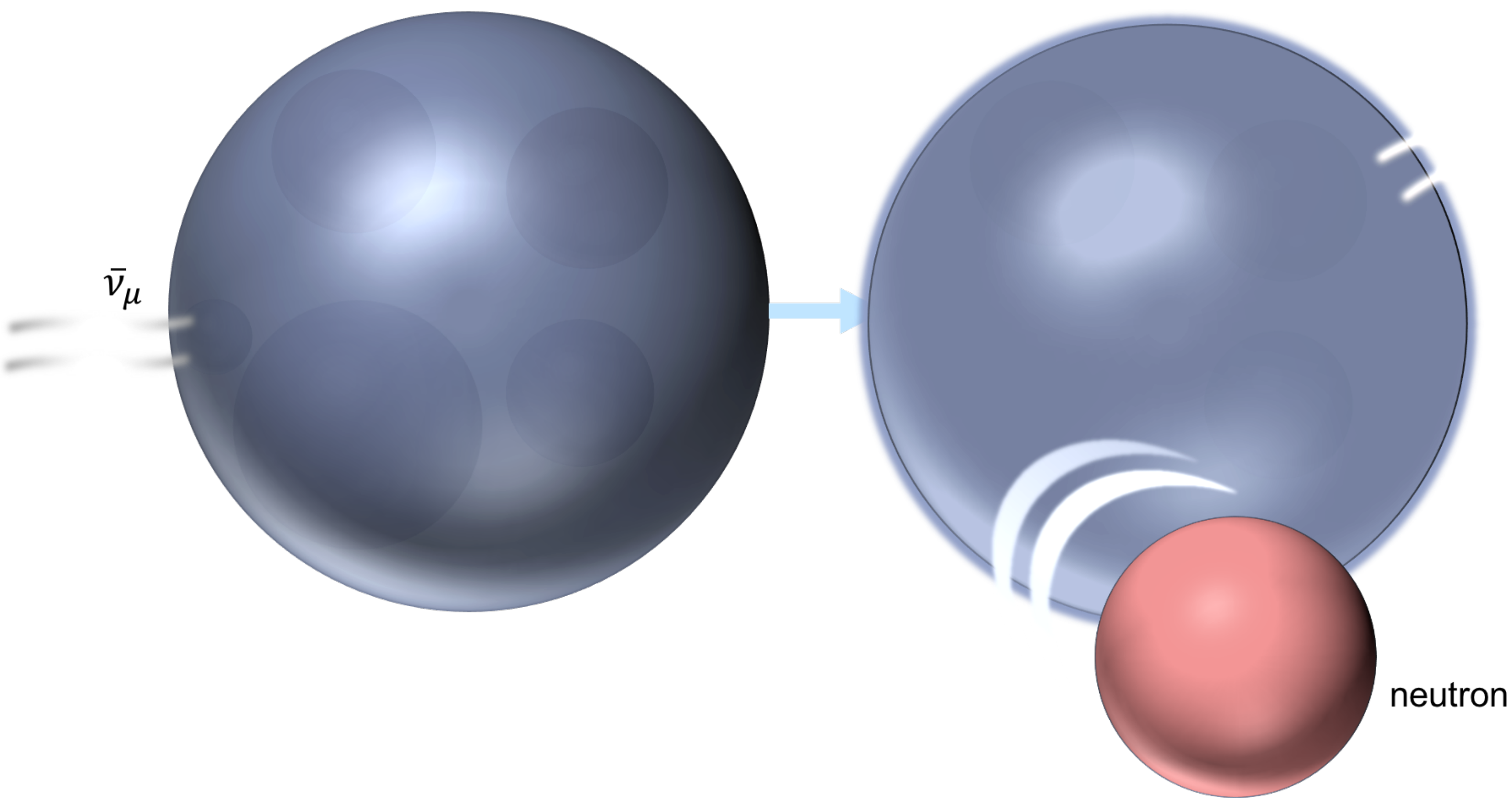
RPA: Like dielectric effect in EM interaction. Polarization of nucleus screens the coupling of W boson. Suppression of cross-section at low Q^2.

Nuclear Effects: Final State Interactions



$\bar{\nu}_\mu + p \rightarrow n + \mu^+$: True CCQE Interaction

Nuclear Effects: Final State Interactions



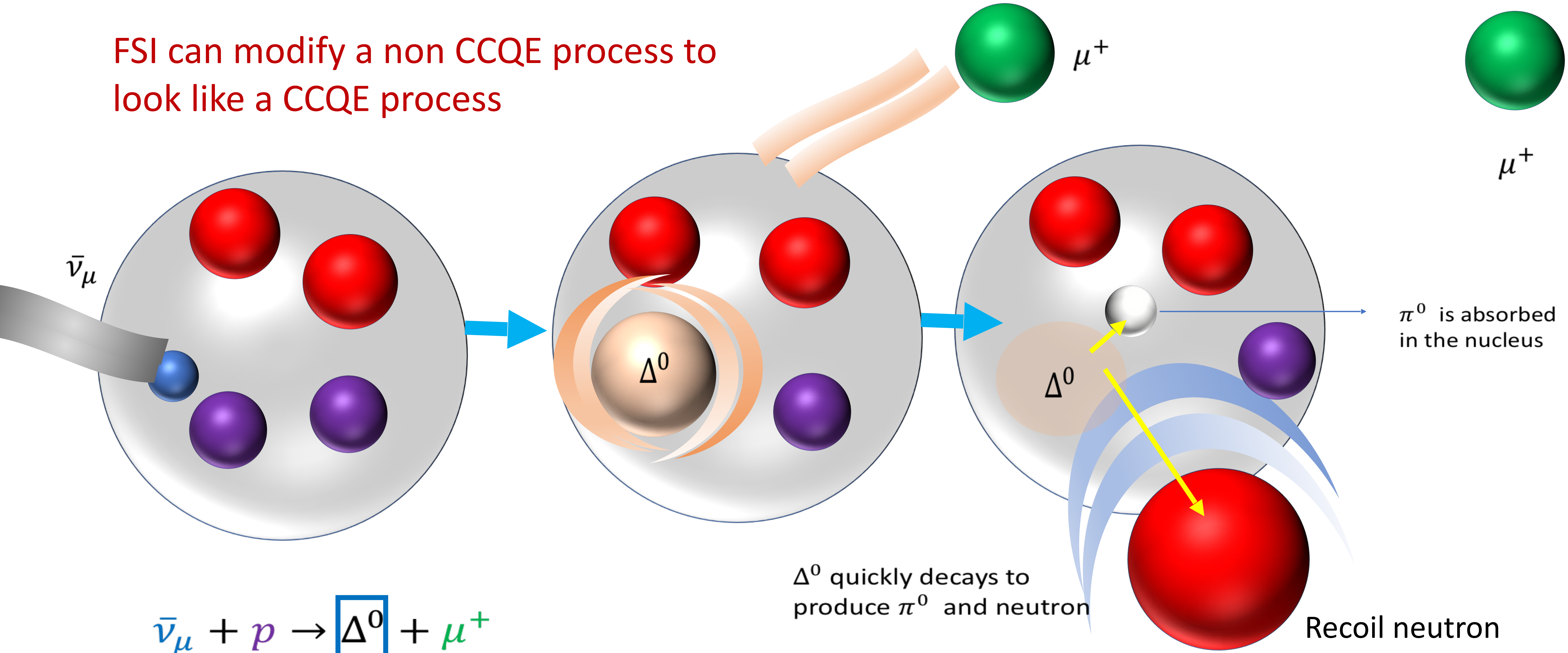
But we don't know what happens inside the nucleus.

We can only see the final state particles in the detector.

$\bar{\nu}_\mu + p \rightarrow n + \mu^+$: True CCQE Interaction

Nuclear Effects: Final State Interactions

FSI can modify a non CCQE process to look like a CCQE process

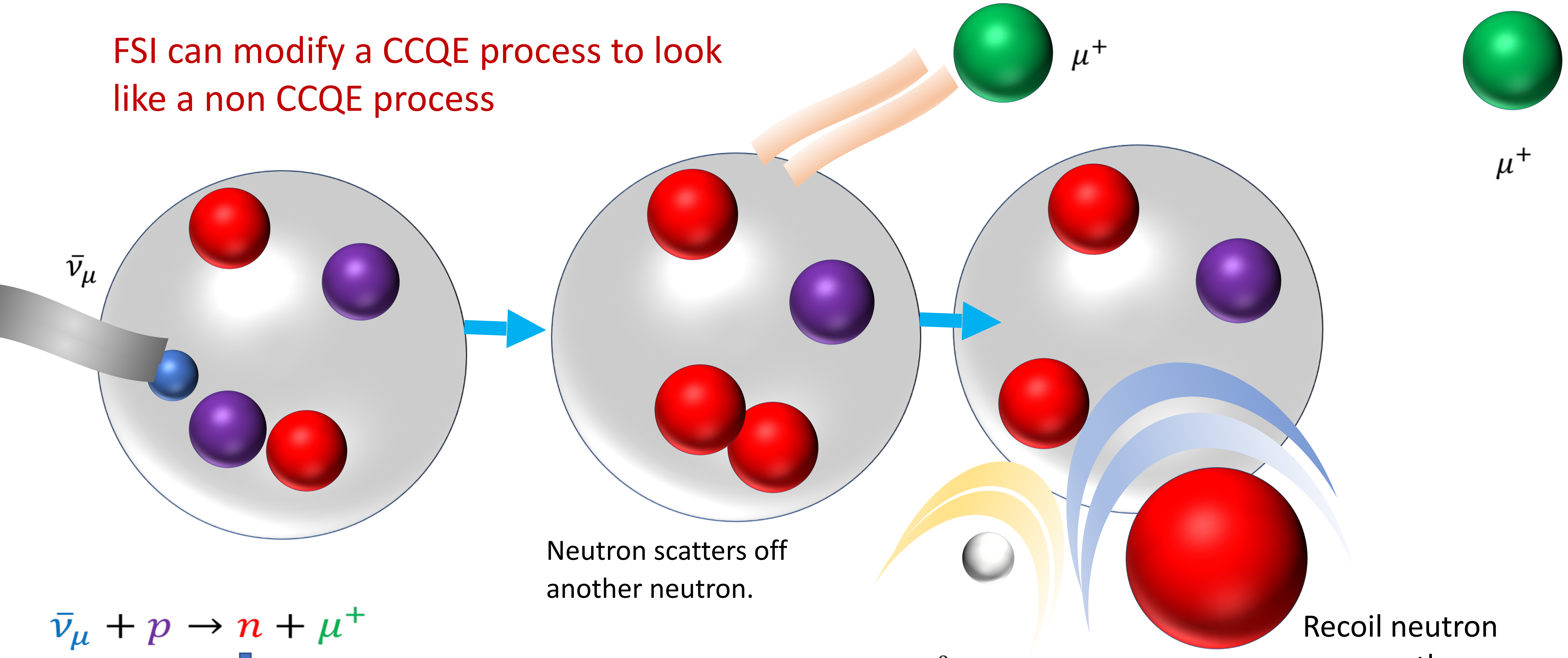


$$\bar{\nu}_\mu + p \rightarrow \Delta^0 + \mu^+$$

$$\Delta^0 \rightarrow \pi^0 + n$$

Nuclear Effects: Final State Interactions

FSI can modify a CCQE process to look like a non CCQE process

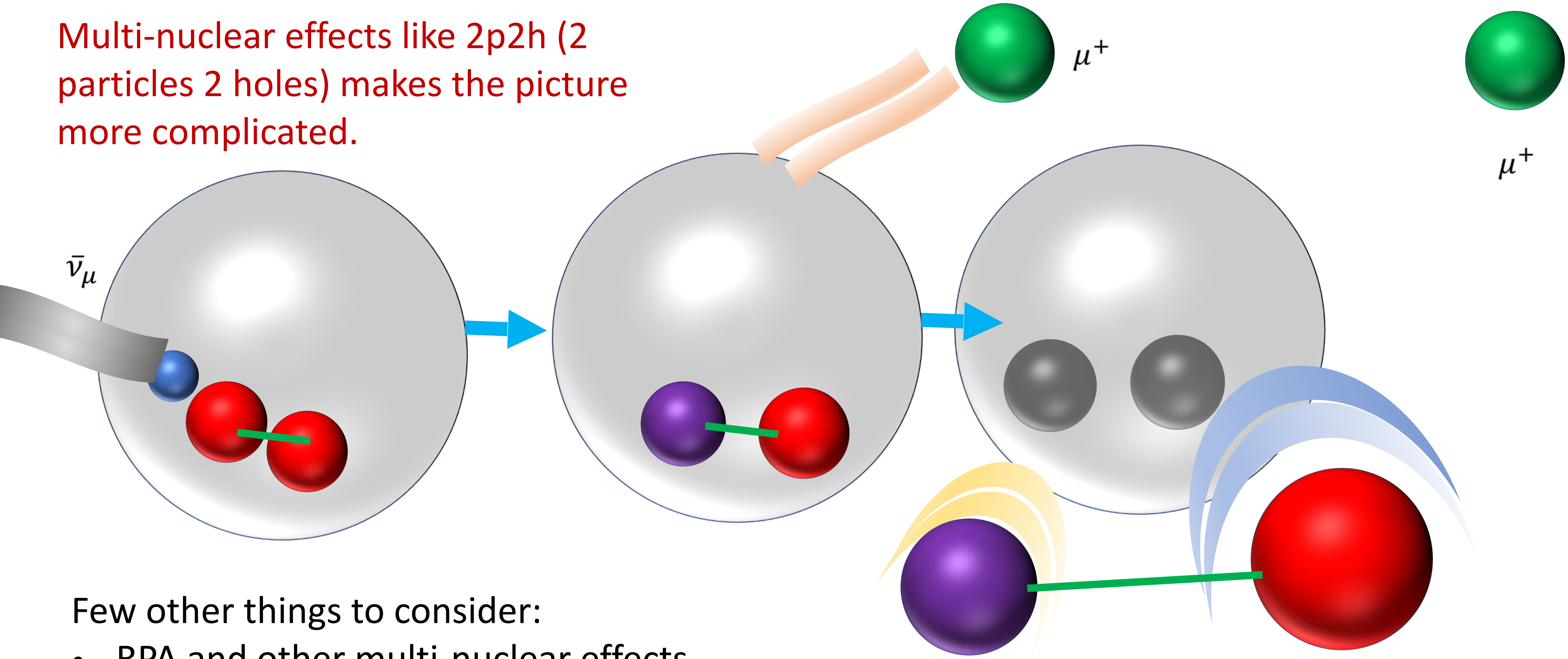


$$\bar{\nu}_\mu + p \rightarrow n + \mu^+$$

$$n \rightarrow \pi^0 + n$$

Nuclear Effects: Final State Interactions

Multi-nuclear effects like 2p2h (2 particles 2 holes) makes the picture more complicated.



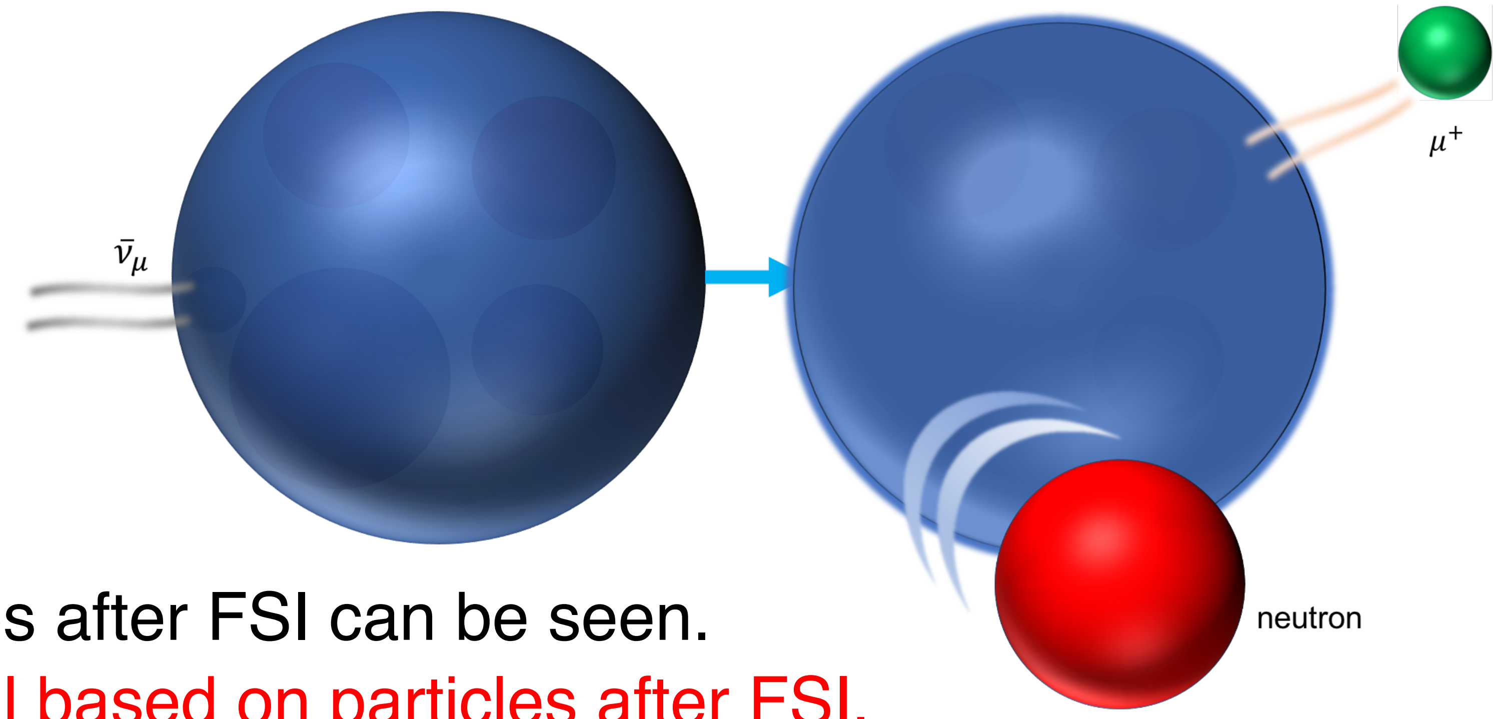
Few other things to consider:

- RPA and other multi-nuclear effects
- Nucleons are not at rest

Multi Nuclear effect ejects the nucleon with its correlated partner

CCQE-Like Event

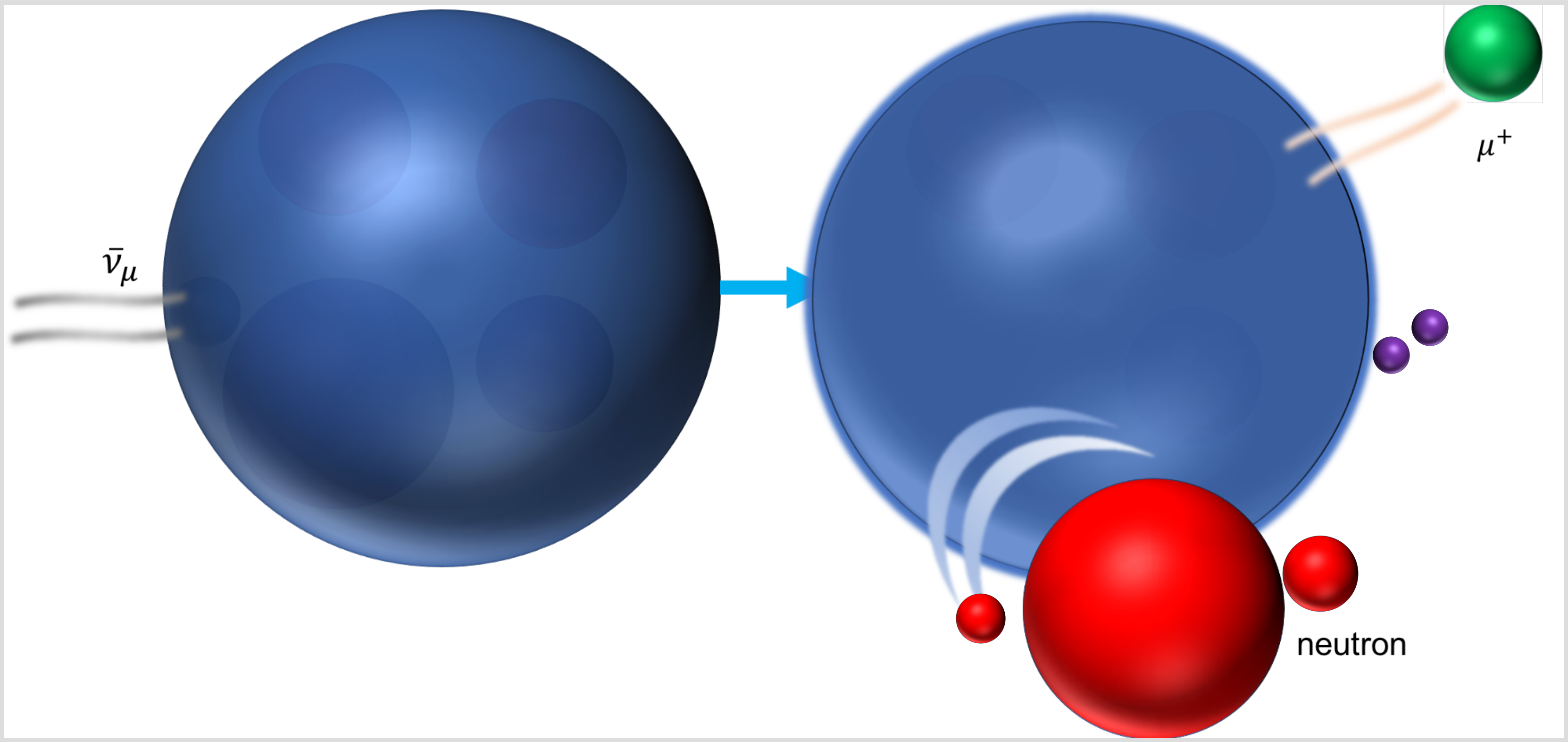
- FSI can fake a CCQE process to look like a non CCQE process.
- FSI can fake a non CCQE process to look like a CCQE process.



Only particles after FSI can be seen.

- Define signal based on particles after FSI.
  - CCQELike processes

Signal Definition: CCQELike Process



1 μ^+

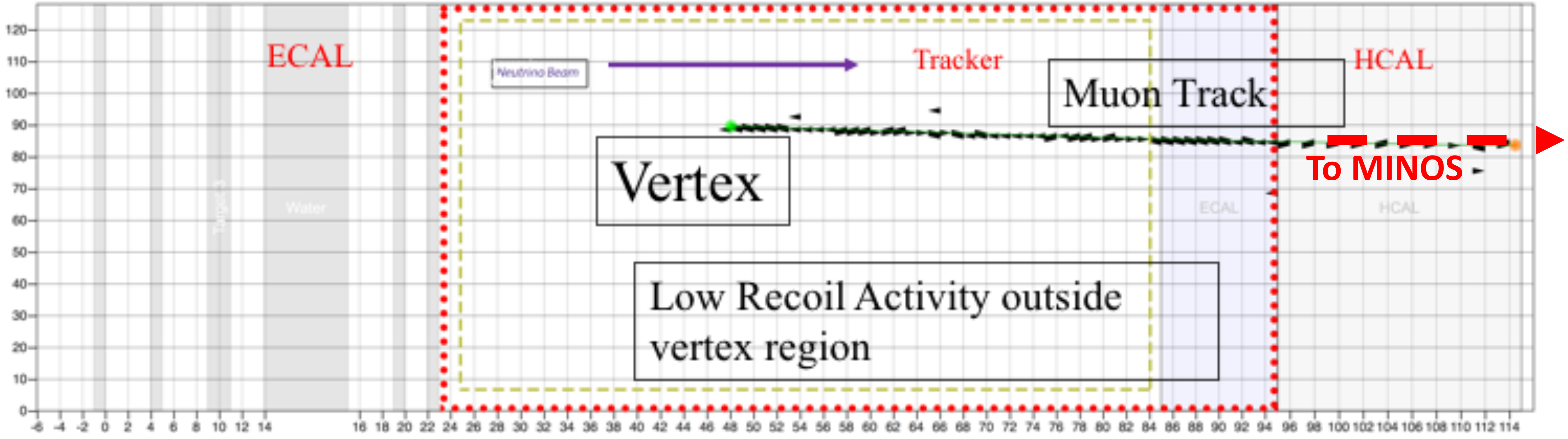
Protons below 120 MeV are allowed

Any number of neutrons are allowed.

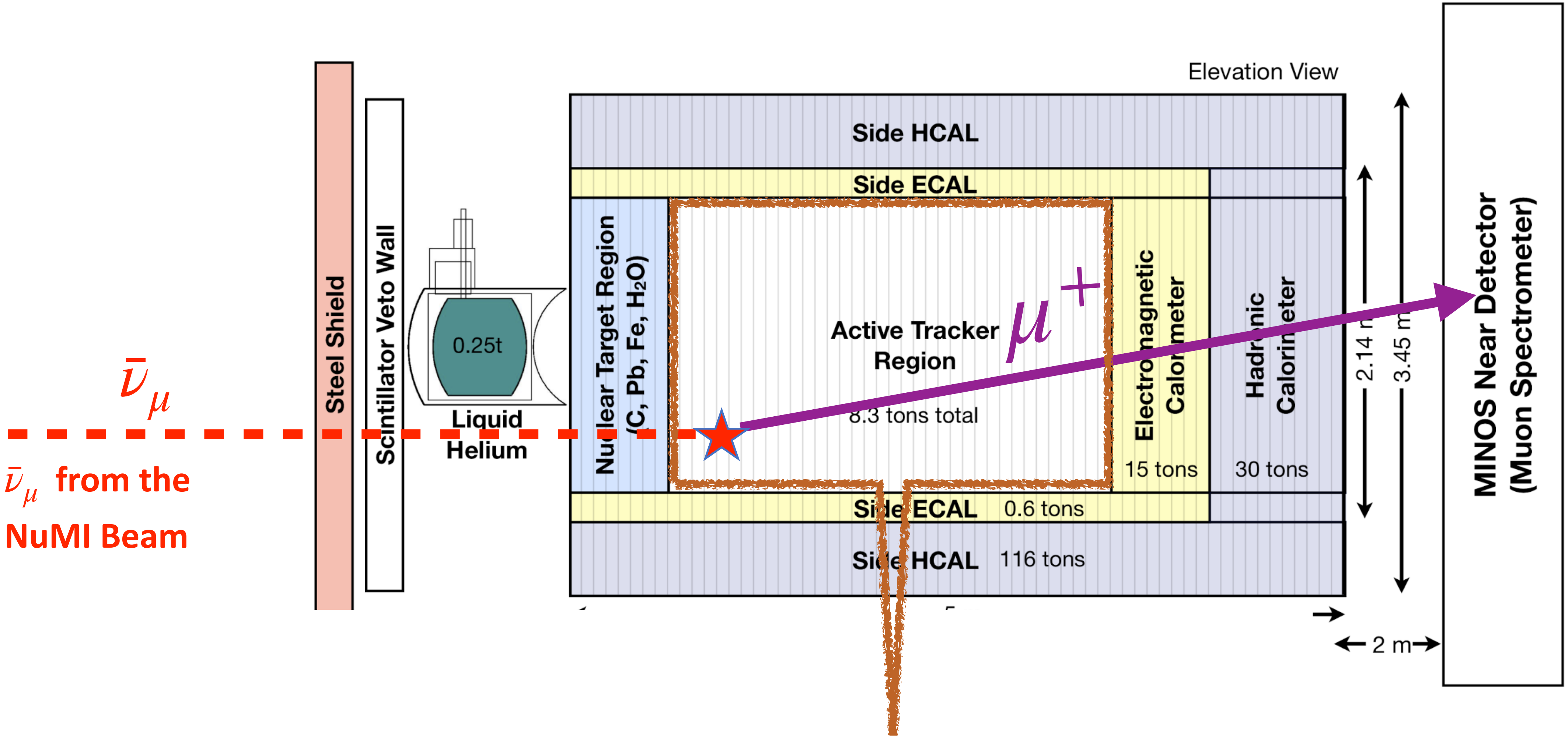
Signal Definition based on Final State Particles

- **1 positive muon (μ^+)**
- **Any number of neutrons**
- **Any number of Protons below 120 MeV Kinetic Energy**
- **No mesons (particles like $\pi^\pm$ which are produced in Resonance processes)**

Event Reconstruction:CCQELike Process

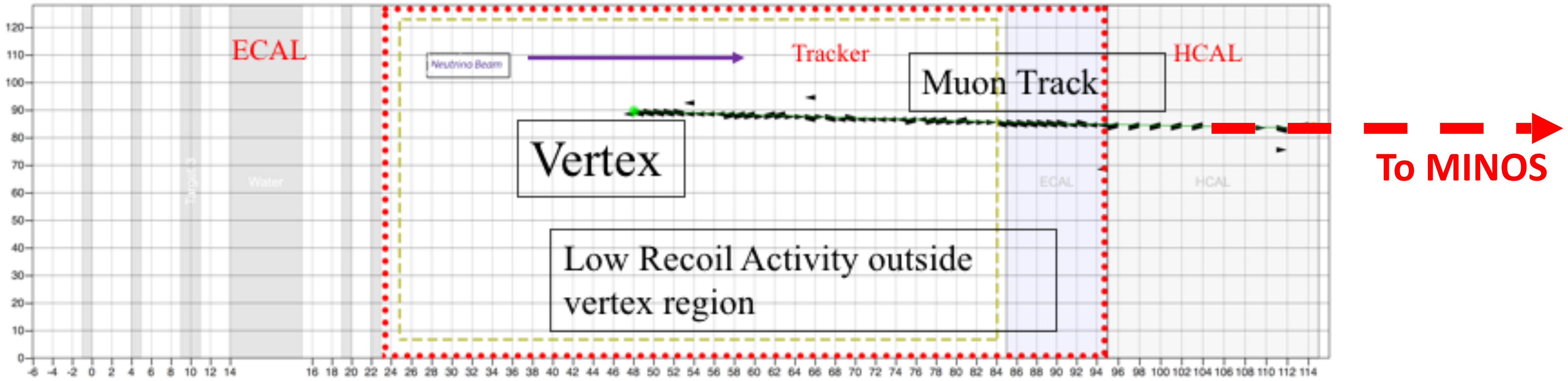


Event should be in the **Tracker (CH)** region of the detector. We are interested in the cross-section in CH target.



Tracker Region of of the MINERvA Detector

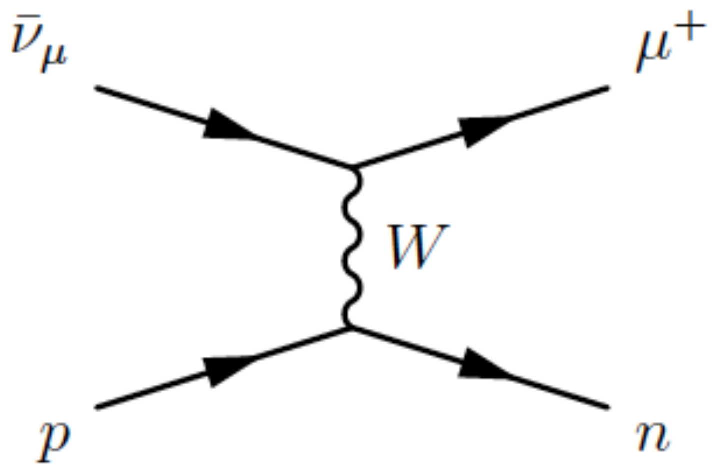
Event Reconstruction:CCQELike Process

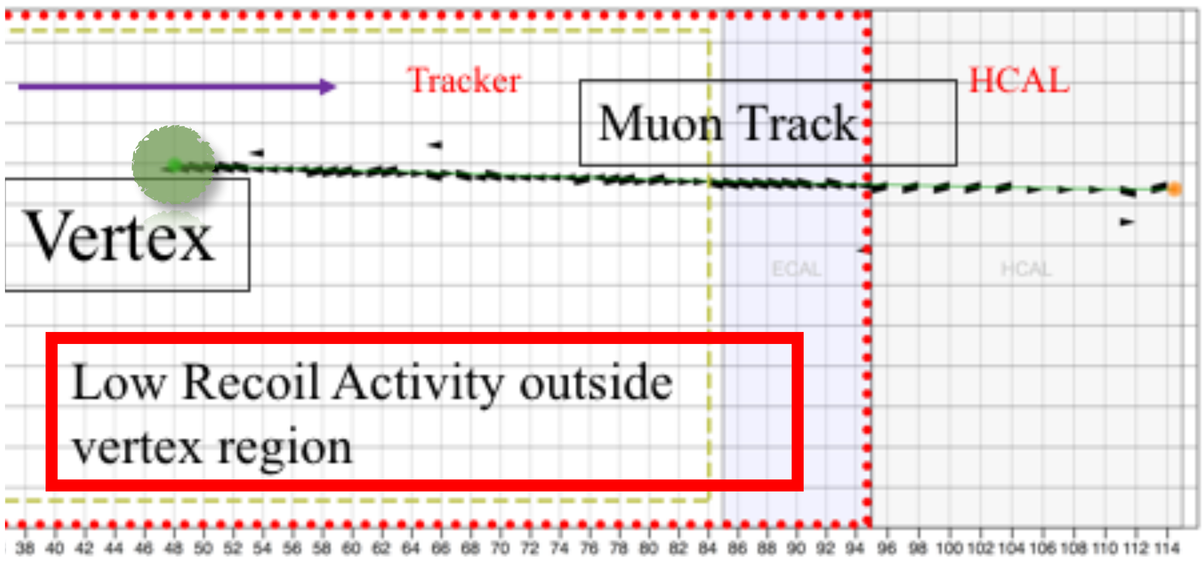


Signal Definition
Event should have 1 positive muon in the final state.

- **1 MINOS matched muon track** (to identify the charge of the muon)
  - **Apply a 20^o angle cut on muon track** (with respect to the $\bar{\nu}_\mu$ beam)
- **No Additional tracks** (in next few slides)

Event Reconstruction:CCQELike Process

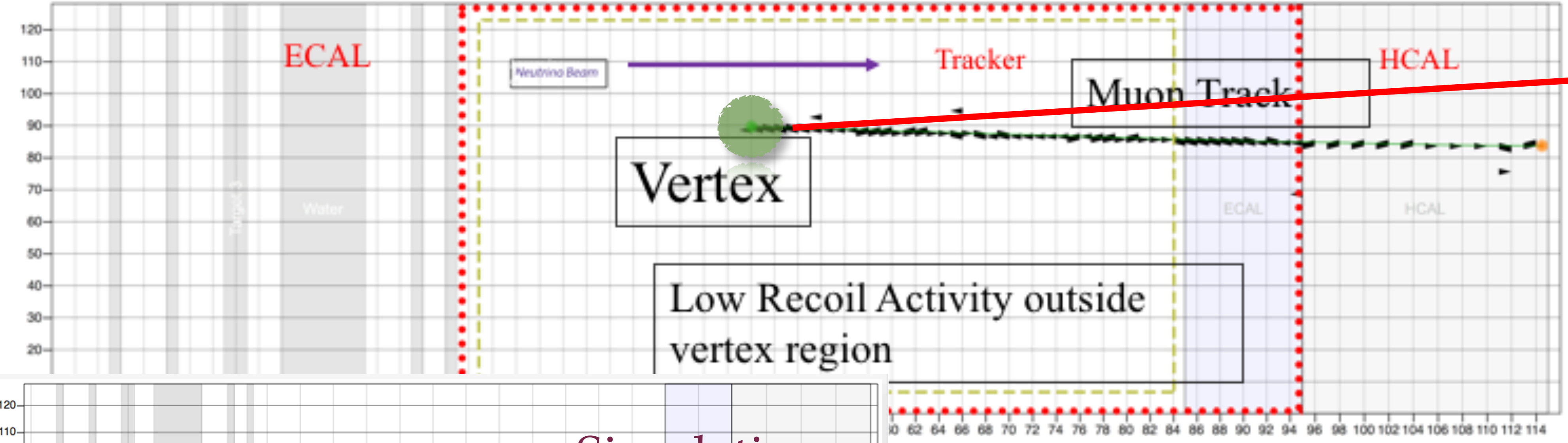




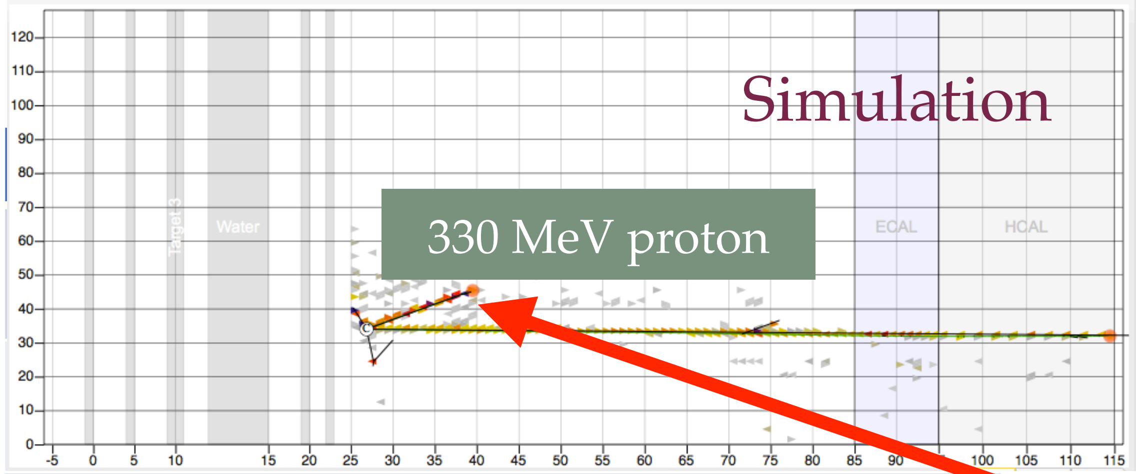
Signal Definition
Event should have 1 positive muon in the final state.
Event can have any number of neutrons in the final state.

- **Low Recoil Activity outside the vertex region**
  - Most of the energy from the interaction carried away by the muon
  - **Recoil Activity** → **Isolated clusters** outside the vertex region
  - **High recoil activity** events are dominated by **resonance and Deep Inelastic** events.

Event Reconstruction:CCQELike Process



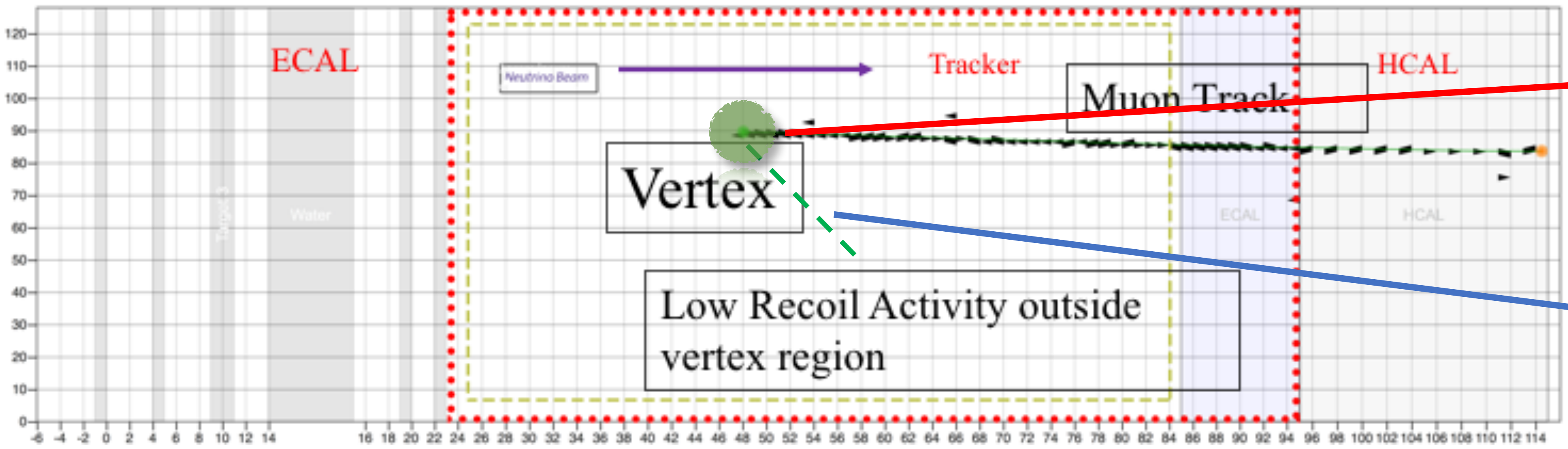
Vertex region of radius 100 mm to exclude recoil activity inside it.



Event can have any number of final state protons less than 120 MeV.

- **Exclude a region of 100 mm radius around the interaction vertex for recoil energy.**
- **Low energy proton** can come from **2p2h** and **other multi nucleon processes**. We want to keep them.
- **Very low energy protons** cannot be tracked and resolved and **deposit energy near the vertex**.
- **High Energy Protons → Additional tracks.**

Event Reconstruction:CCQELike Process



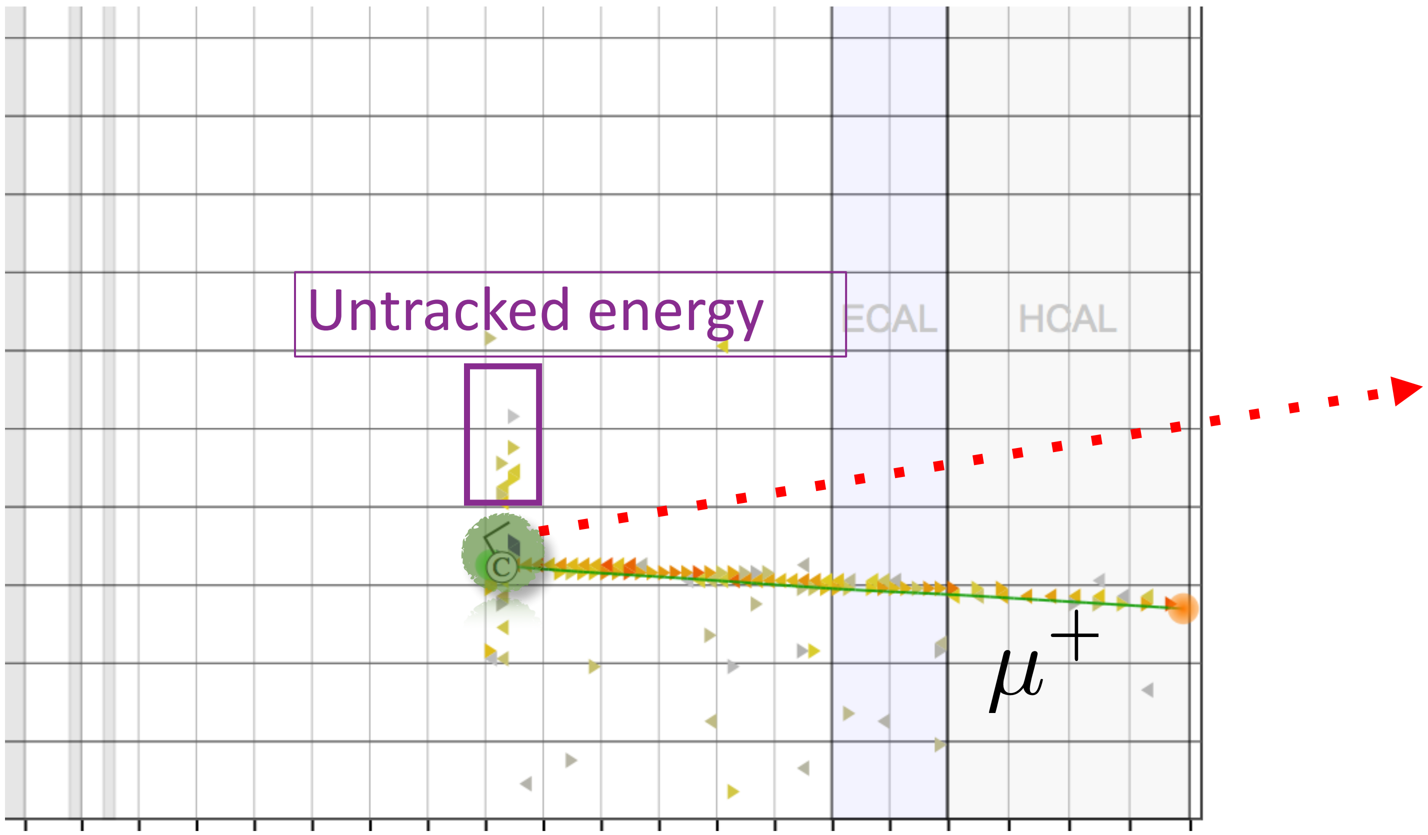
Vertex region of radius 100 mm to exclude recoil activity inside it.

Pions with high enough energy can be tracked in MINERvA detector.

Signal Definition
Event should have 1 positive muon in the final state.
Event can have any number of neutrons in the final state.
Event can have any number of final state protons less than 120 MeV.
Event cannot have any mesons in the final state.

- **Only 1 track events (track being muon track) are selected.**
- **Additional tracks → charged pions** are rejected.
  - Remember protons with high Kinetic Energy also make tracks [and (>120 MeV) rejected]

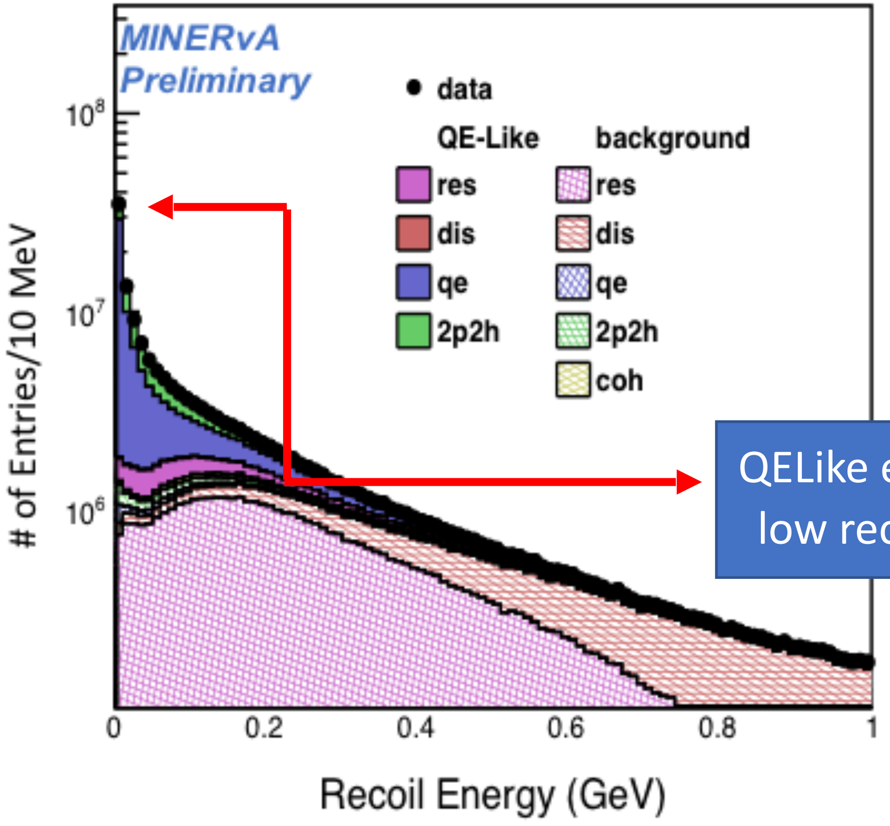
Recoil Energy Definition

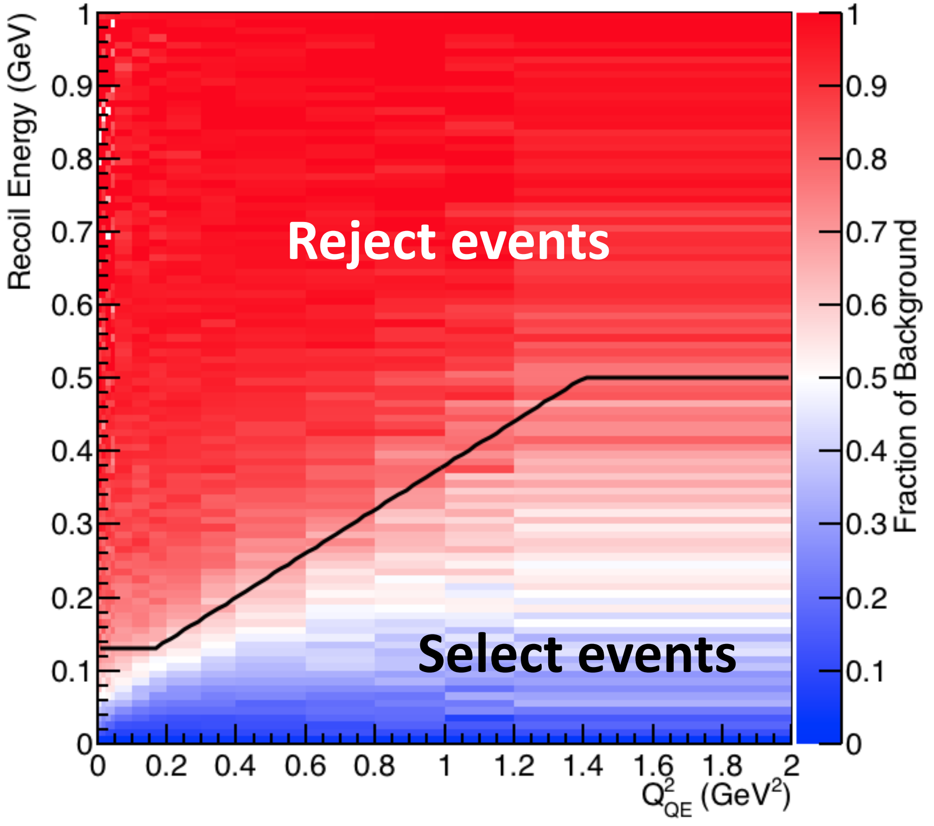


All the untracked energy outside the spherical blob of radius 100 mm outside the interaction vertex.

Untracked energy is the energy of the clusters that are not part of the μ^+ track.

Recoil Energy





- **Distribution of Recoil Energy with Data and Various MC components.**

- Recoil Energy cut based on the previous iteration of this analysis [Phys.Rev.D 97 (2018) 5, 052002]
- **Optimized** for signal selection efficiency+purity of selected sample.
- **Loose cut at high Q^2_{QE}** region
  - **Keep 2p2h events** in this region that is not well-understood.

Extraction of Cross-section

$$\left(\frac{d^2\sigma}{dxdy}\right)_{ij} = \frac{\sum_{\alpha\beta ij} U_{\alpha\beta ij}(N_{data,\alpha\beta} - N^{bkg}_{data,\alpha\beta})}{\epsilon_{ij}\Phi T \Delta x_i \Delta y_j}$$

- This analysis measures cross section (σ) as a function of 2 variables x and y.
- Event reconstruction in (α, β) bins.
- Want to measure in true bins (i, j) bins.
- More on this later.

- $\left(\frac{d^2\sigma}{dp_z dp_t}\right) \rightarrow$ Cross section as a function of muon kinematics
- $\left(\frac{d^2\sigma}{dE_\nu dQ^2}\right)_{QE} \rightarrow$ Cross section as a function of E_ν and four momentum transferred (Q^2) based on QE hypothesis

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

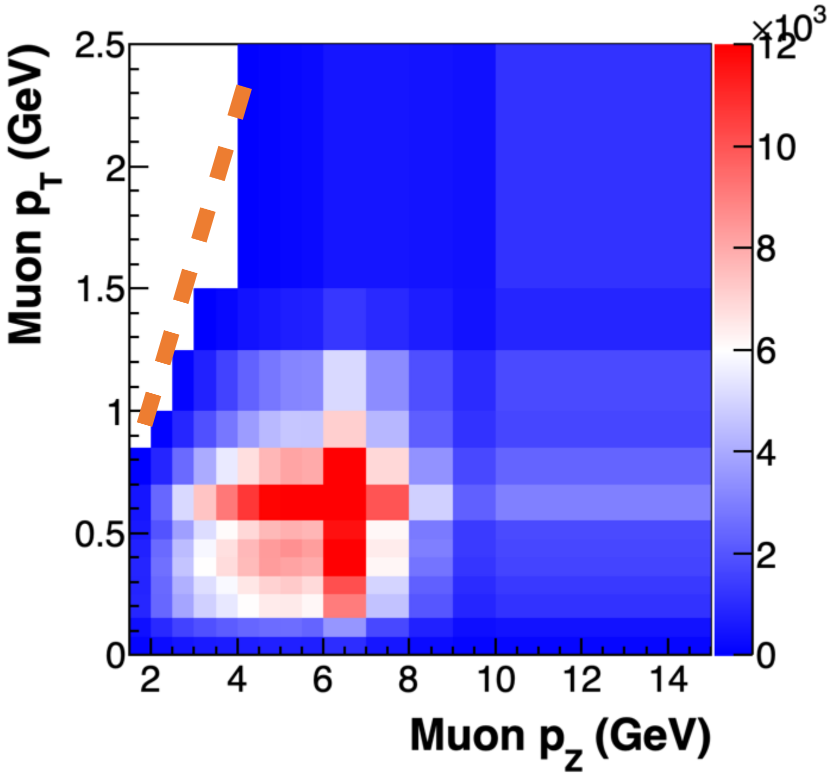
$$Q^2_{QE} = 2E_\nu^{QE}(E_\mu - p_\mu \cos\theta_\mu) - m_\mu^2$$

Event Reconstruction

$$\left(\frac{d^2\sigma}{dxdy}\right)_{ij} = \frac{\sum_{\alpha\beta ij} U_{\alpha\beta ij}\left(N_{data,\alpha\beta} - N^{bkg}_{data,\alpha\beta}\right)}{\epsilon_{ij}\Phi T \Delta x_i \Delta y_j}$$

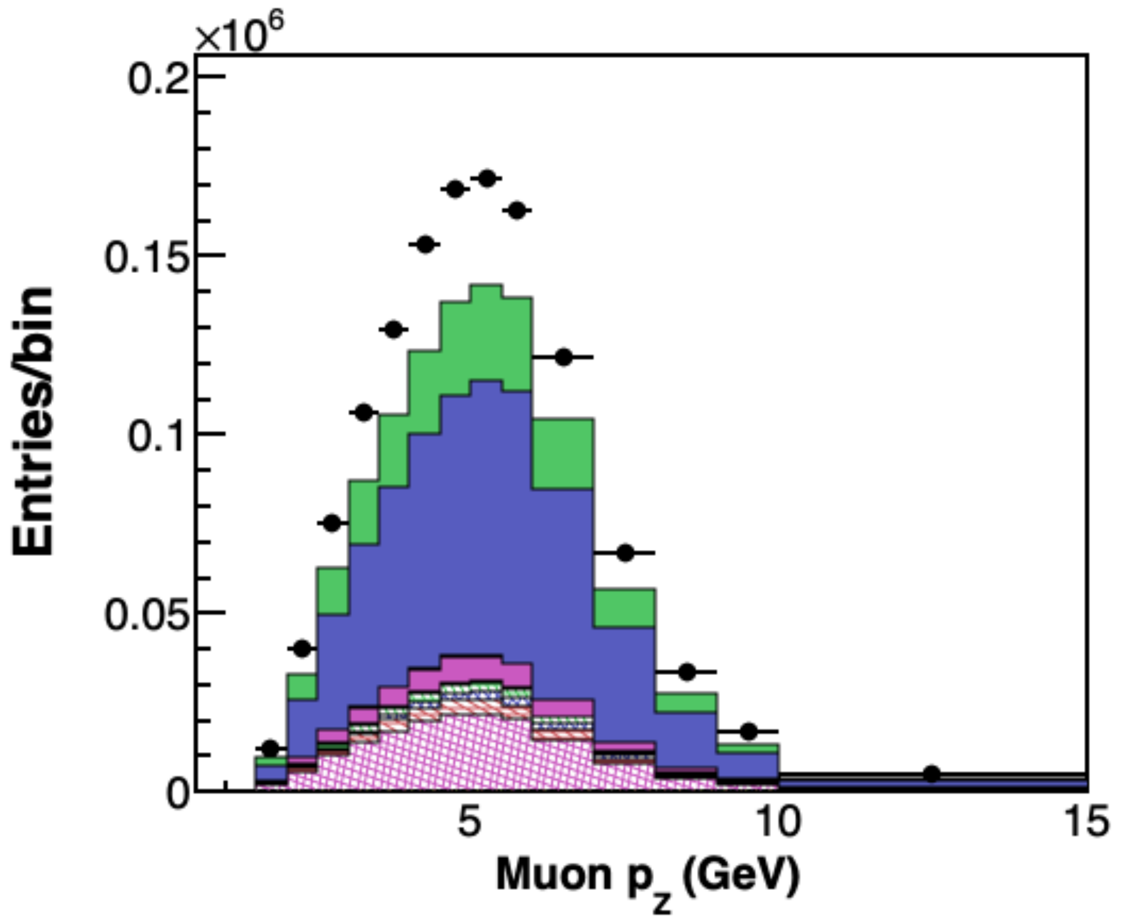
Raw Event Reconstruction

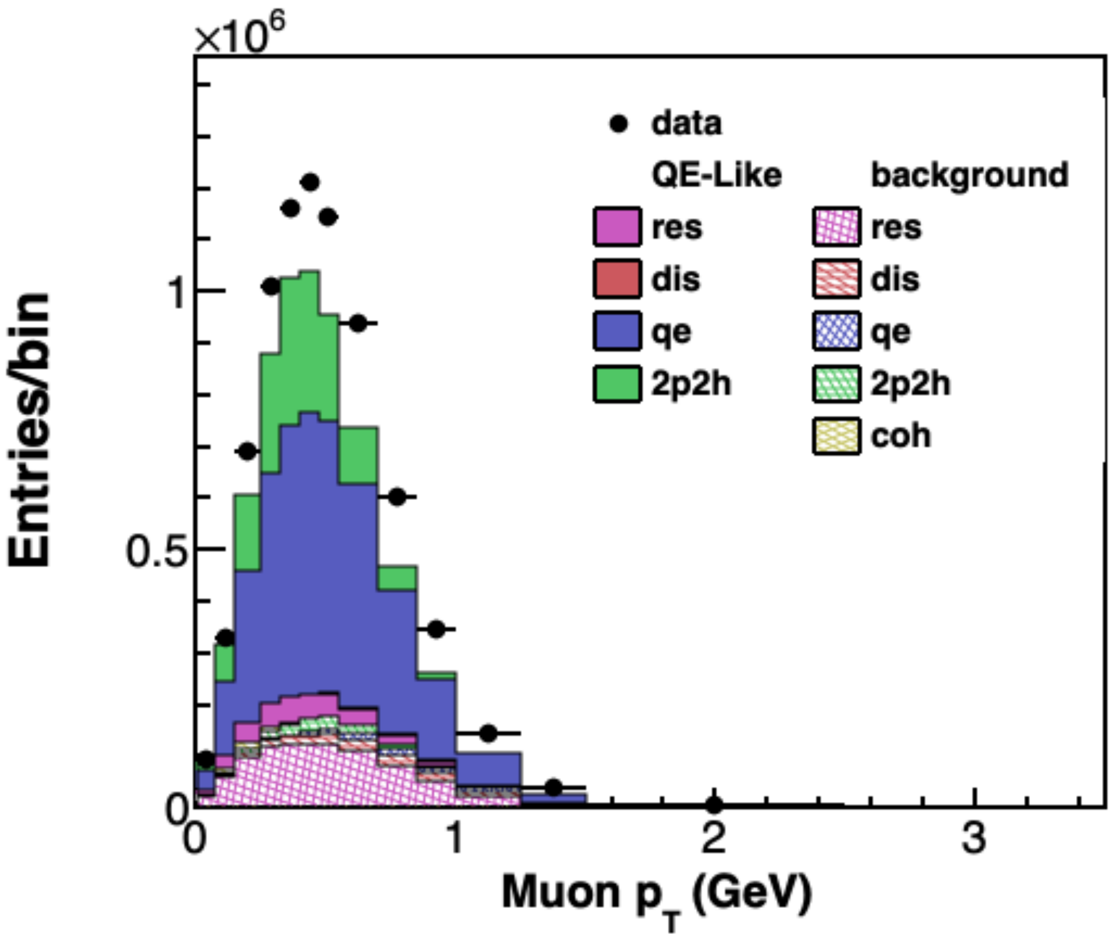
$$\left(\frac{d^2\sigma}{dxdy}\right)_{ij} = \frac{\sum_{\alpha\beta ij} U_{\alpha\beta ij}\left(N_{data,\alpha\beta} - N^{bkg}_{data,\alpha\beta}\right)}{\epsilon_{ij}\Phi T \Delta x_i \Delta y_j}$$



- **Apply the selection conditions on the data and simulated sample to select the CCQE Like candidate events.**
- **Requiring muon track angle to be less than 20 degrees rejects events at high p_T and low p_Z phase space.**

Raw Event Selection

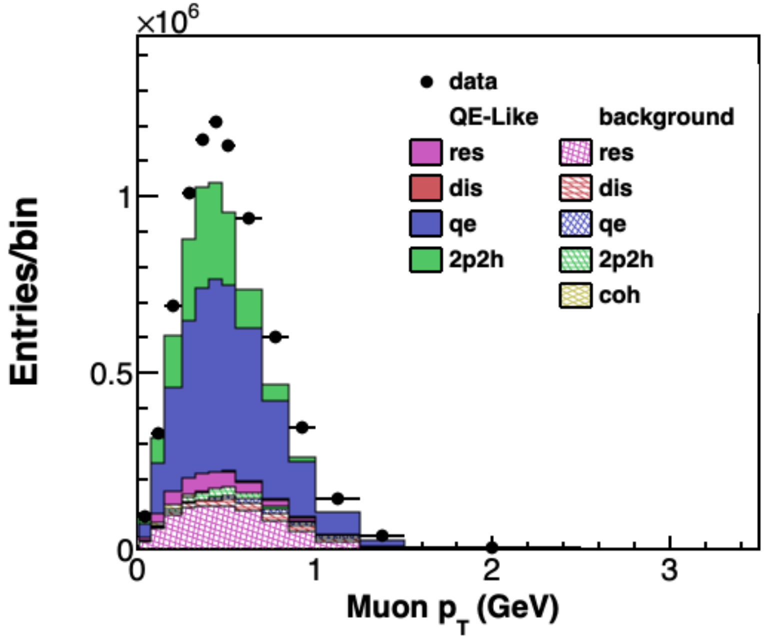




We look at our simulated sample to estimate the types of events we select in our data.
*1 D are the projections from 2 D distributions.

Muon p_z || Neutrino Beam

Selected Events (Signal)

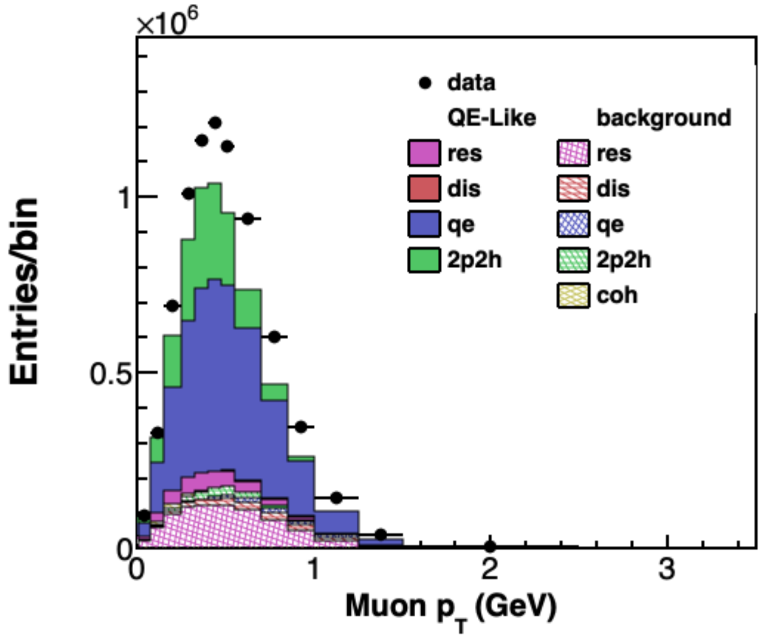


Signal Components	Fraction of Total MC Events
QE	**0.54**
RES	0.05
DIS	0.003
2p2h	0.193
Total	0.786

Signal (QE-Like)

- res→ Events that produced pions initially but go through FSI to produce neutron in the final state.
- dis→ Events where the neutrino completely breaks the nucleon and creates high recoil activity but only neutron is the Final State Particle (very rare)
- qe→ True QE events. Recoil neutrons do not go through FSI and escape the nucleus.
- 2p2h →Events in which the neutrino interacts with a correlated pair of nucleons and both nucleons exit the nucleus.

Selected Events (Background)



Background Components	Fraction of Total MC Events
RES	**0.151**
DIS	0.029
QE	0.012
2p2h	0.016
COH	0.006
Total	0.214

Background

res→ Events that produce pions in the final state.

dis → Events where the nucleon is completely broken apart and has various hadrons in the final state.

qe→ QE events where the neutron goes through FSI and produce other particles (like pions, or protons that can be tracked).

2p2h →correlated pair of nucleons are produced initially but go through FSI to produce mesons.

coh (coherent)→ pion is produced through coherent process (initial state of the nucleon is not modified).

$$\bar{\nu}_\mu + A \rightarrow \mu^+ + \pi^- + A$$

A is the target nucleus.

Background

$$\left(\frac{d^2\sigma}{dxdy}\right)_{ij} = \frac{\sum_{\alpha\beta ij} U_{\alpha\beta ij}(N_{data,\alpha\beta} - N^{bkg}_{data,\alpha\beta})}{\epsilon_{ij}\Phi T \Delta x_i \Delta y_j}$$

- Our selected data has both signal and background contribution.
- We need to subtract the background from our selected sample.
- Cannot rely on MC completely to estimate the background in the data.
  - Pion production may be over predicted by our simulation.
  - Nuclear effects have significant uncertainties.
  - We want to improve simulation models from our data after all.
- Use Data driven method to subtract the background from the data.

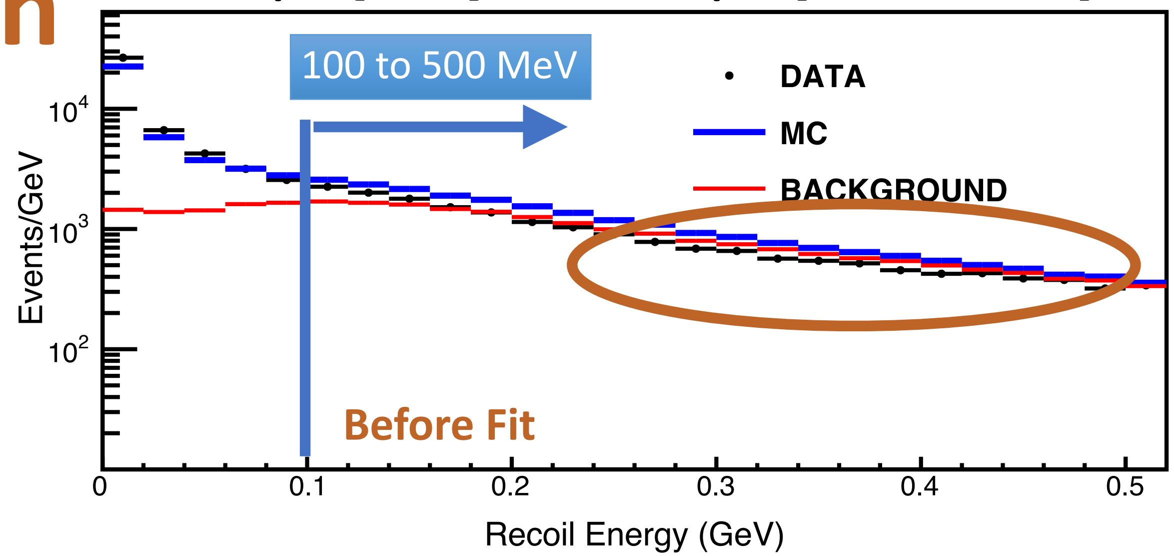
Background Subtraction

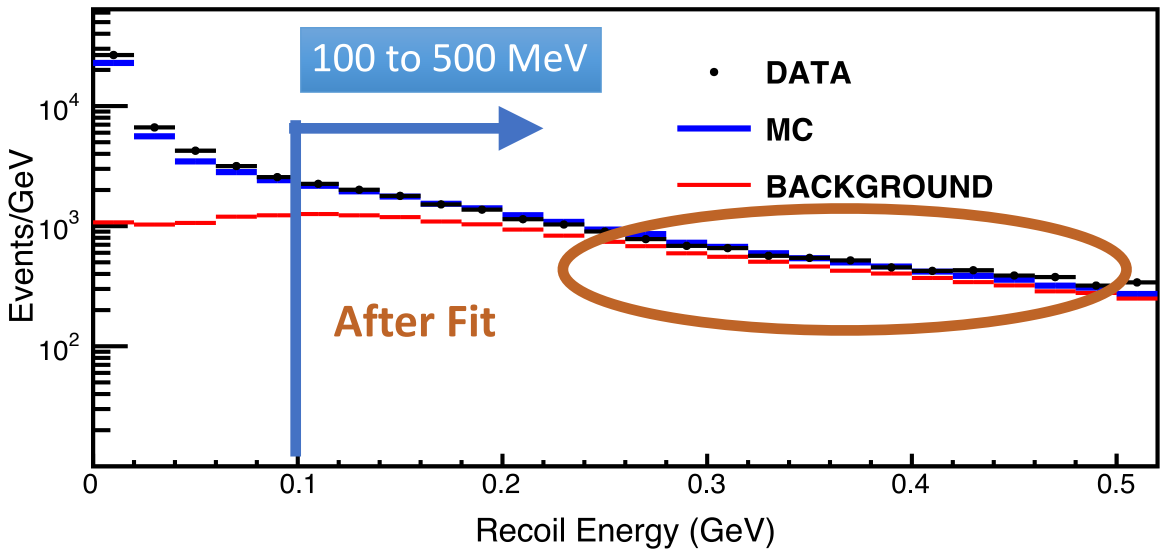
- We look at our recoil energy distribution **in 14 different bins of muon p_T and p_z .**

- Fraction fit of data with simulated signal and background recoil energy distribution shapes.
  - ROOT::TFractionFitter [root.cern.ch]
  - Fit done between 100 to 500 MeV recoil energy region.
    - Background rich region

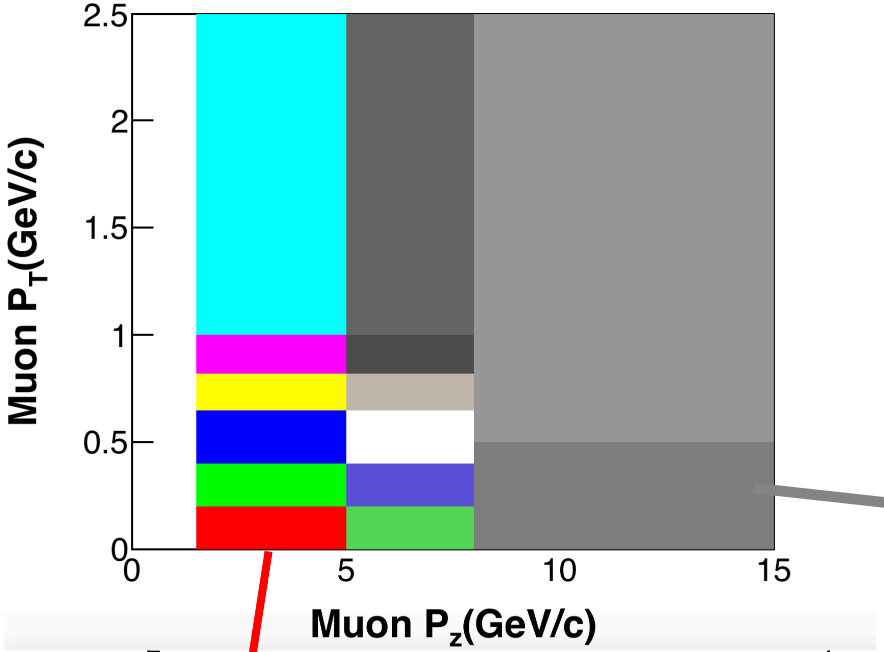
- Fit gives the best estimation of signal and background fraction in our data.
  - Efficiency correction to get the signal fraction in each fit region.

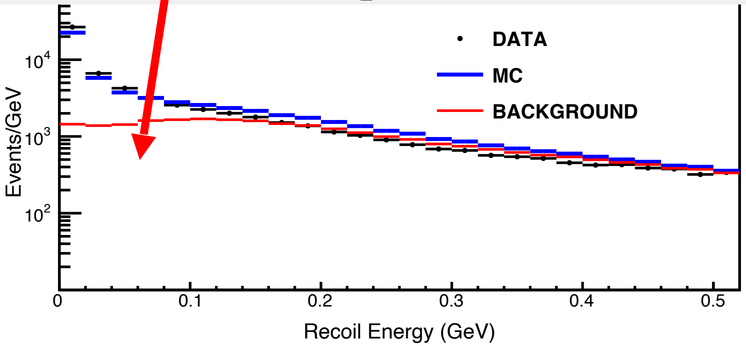
pz =[1.5-5] GeV/c and p_t = [0.2-0.4 GeV/c]

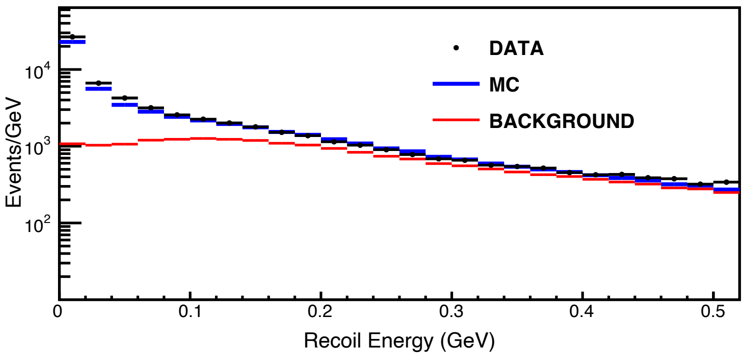


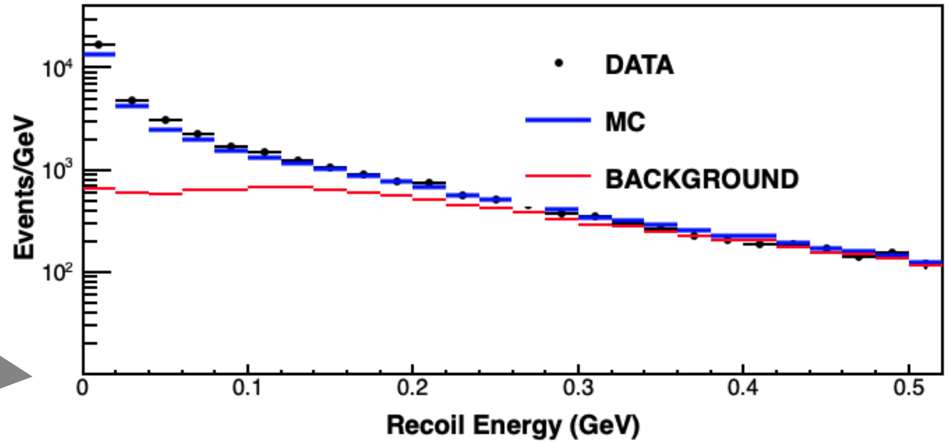


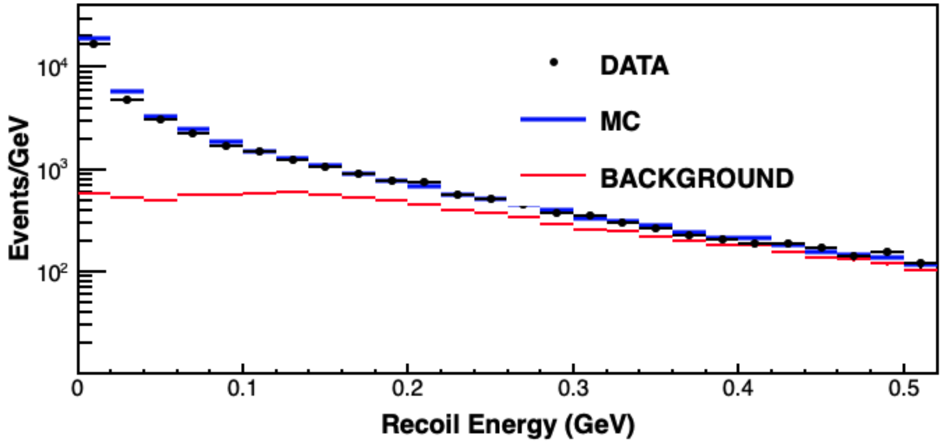
Background Subtraction











Fit Done in all 14 bins to extract the signal fraction in the data.

635,592±1,251 (stat.) ± 13,850 (syst.) events after **background subtraction.**

p_T GeV/c	p_z Gev/c	Signal Before	Signal After	Signal Efficiency	Efficiency Corrected Signal	χ^2/NDF
0.0 - 0.2	1.5 - 5.0	0.56	0.610 ± 0.027	0.901	0.78	18.12/19
0.2 - 0.4	1.5 - 5.0	0.62	0.700 ± 0.011	0.905	0.86	26.82/19
0.4 - 0.65	1.5 - 5.0	0.61	0.673 ± 0.008	0.901	0.84	16.08/19
0.65 - 0.82	1.5 - 5.0	0.59	0.622 ± 0.012	0.922	0.75	5.96/19
0.82 - 1.0	1.5 - 5.0	0.59	0.582 ± 0.0188	0.951	0.66	14.74/19
1.0 - 2.5	1.5 - 5.0	0.0.59	0.597 ± 0.0373	0.988	0.61	16.44/19
0.0 - 0.2	5.0 - 8.0	0.62	0.788 ± 0.0367	0.923	0.89	11.43/19
0.2 - 0.4	5.0 - 8.0	0.67	0.772 ± 0.015	0.922	0.89	16.64/19
0.4 - 0.65	5.0 - 8.0	0.67	0.719 ± 0.010	0.918	0.85	26.45/19
0.65 - 0.82	5.0 - 8.0	0.65	0.700 ± 0.0119	0.930	0.80	21.69/19
0.82 - 1.0	5.0 - 8.0	0.64	0.638 ± 0.0166	0.952	0.71	11.33/19
1.0 - 2.5	5.0 - 8.0	0.62	0.615 ± 0.026	0.983	0.63	19.48/19
0.0 - 0.5	8.0 - 15.0	0.69	0.778 ± 0.026	0.926	0.89	18.86/19
0.0 - 0.5	8.0 - 15.0	0.66	0.69 ± 0.0156	0.950	0.77	11.87/19

Signal fraction in the simulated sample (100 to 500 MeV recoil energy)

Signal fraction predicted by the fit (100 to 500 MeV recoil energy)

Fraction of signal in the data sample that passes the recoil cut

Unsmearing the reconstructed events

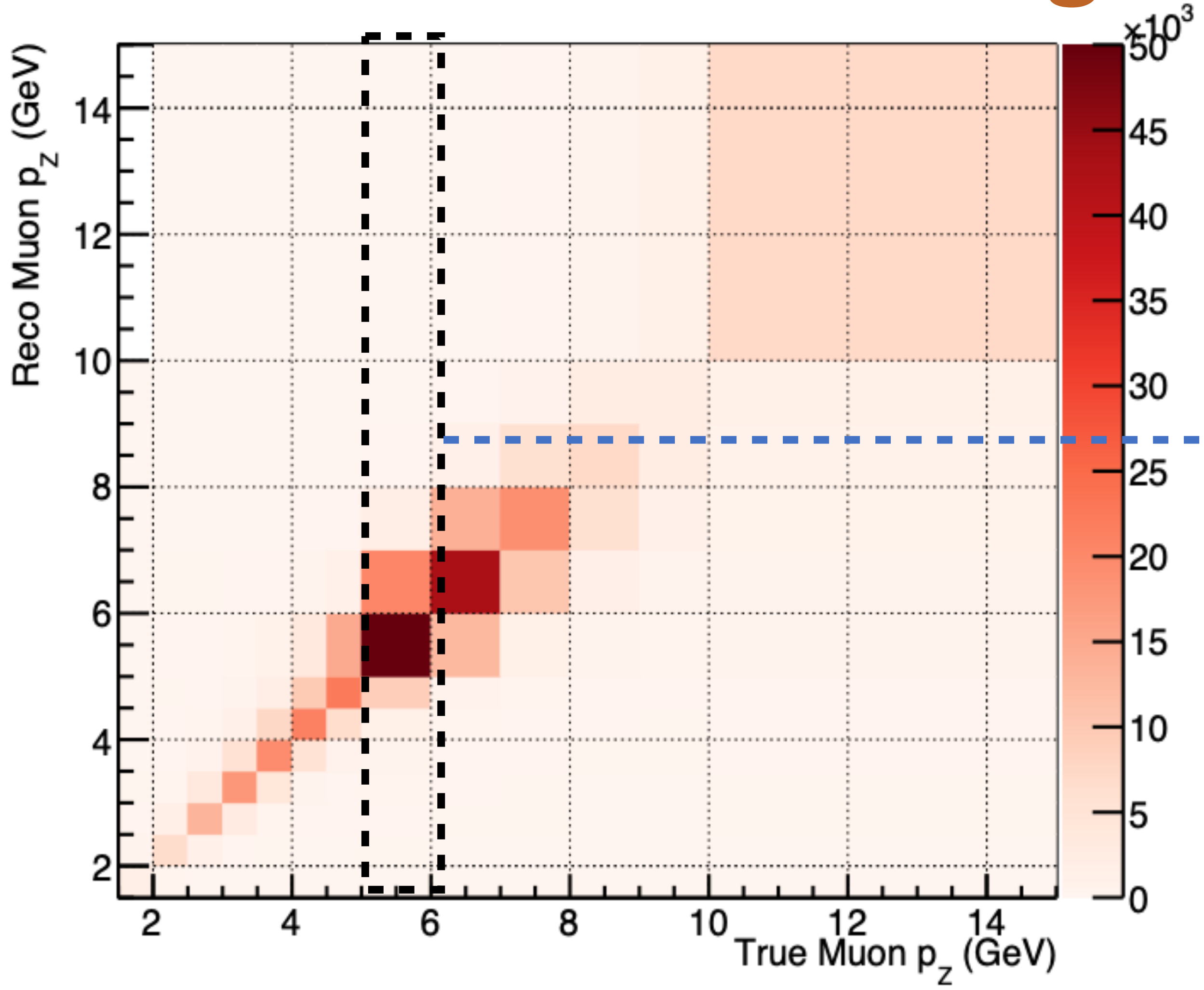
$$\left(\frac{d^2\sigma}{dxdy}\right)_{ij} = \frac{\sum_{\alpha\beta ij} U_{\alpha\beta ij}\left(N_{data,\alpha\beta} - N^{bkg}_{data,\alpha\beta}\right)}{\epsilon_{ij}\Phi T \Delta x_i \Delta y_j}$$

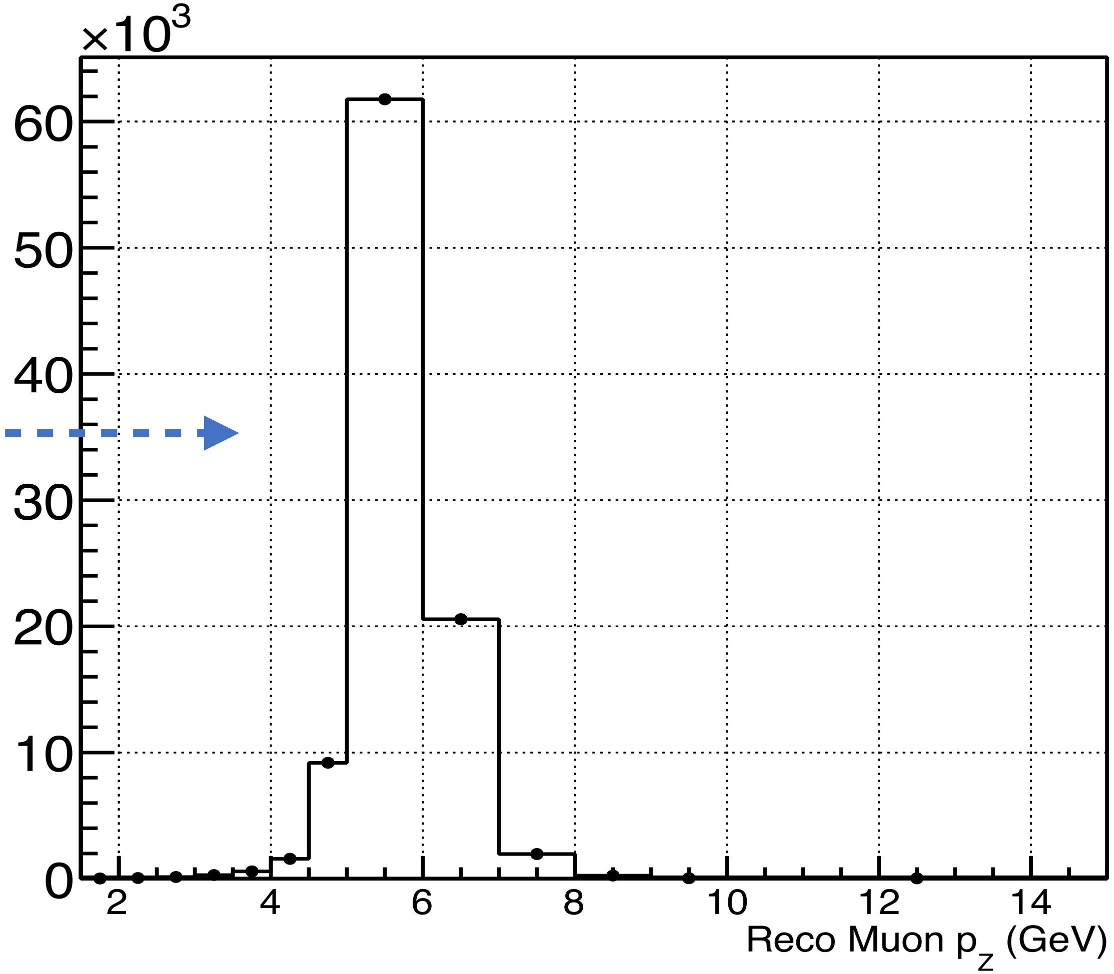
- We look in our data as a **function of reconstructed quantities** $[(p_z, p_t)_\mu, (E_\nu, Q^2)_{QE}]$.
- **Cannot measure these quantities perfectly**
  - Limitation of our detector resolution
  - Reconstruction algorithms

- **Example**
  - A μ^+ whose **actual (true) momentum** is **5 GeV** could be reconstructed as 4 GeV sometimes or 3 GeV sometimes.

- Called the **smearing of the events** from true bin to the reconstructed bins.
- We want to **test models against our measurements**
  - **Models are based on True Variables**
- **Need to correct our reconstructed events to their true phase space.**
- $U_{\alpha\beta ij} \rightarrow$ Matrix that contain **the smearing information** of events in **true bins** ij to reconstructed bins $\alpha\beta$
- We use **Iterative Bayesian Unfolding** method [cite]to **unfold our reconstructed data into the true bins**.

Smearing of Events

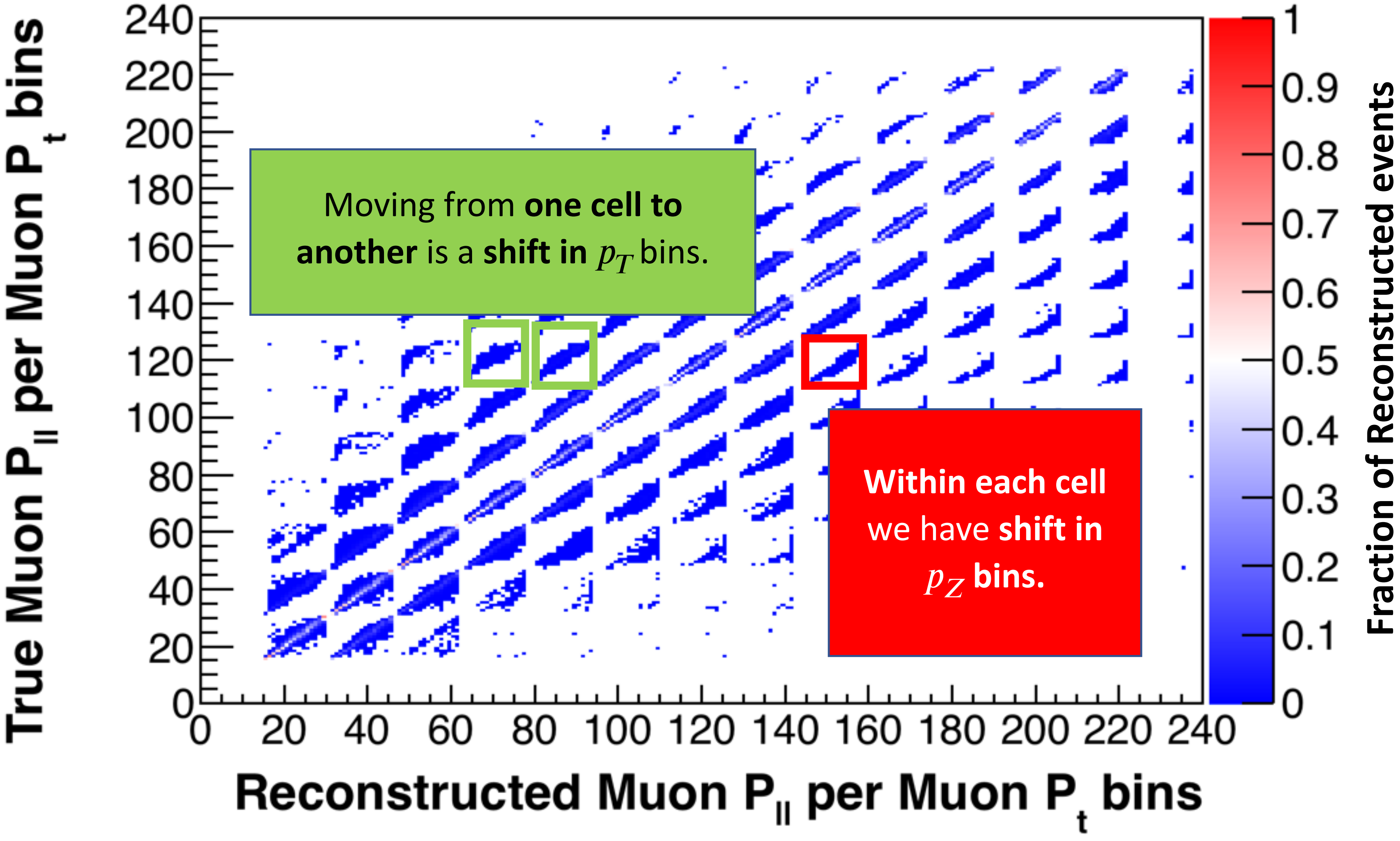


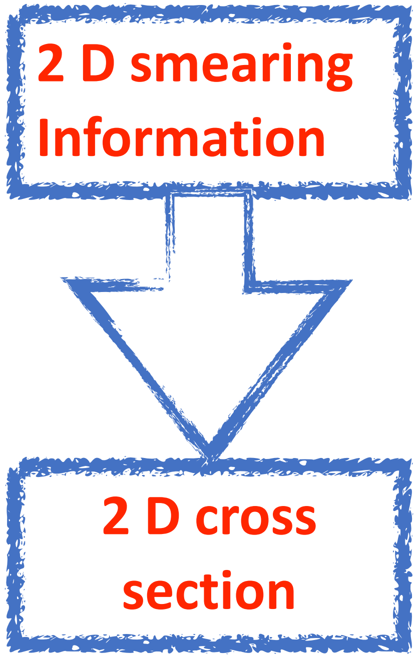


Smearing of events from their true p_z bins to reconstructed p_z bins.

Smearing of 5 to 6 GeV (true) events in different reconstructed bins

Unfolding Matrix





Unfolding of the Event

- Background subtracted sample is unfolded to the the true kinematic variables.
  - Iterative Bayesian Unfolding [G. D' Agostini, Nuclear Instrument Method]
  - Based on RooUnfold Algorithm.
- Unfolding studies done with various model predictions.
  - Find Optimum number of iteration needed to unfold
  - Test the stability of the unfolding matrix
- $(p_z, p_t)_\mu$ = 4 iterations
- $(E_\nu, Q^2)_{QE}$ = 8 iterations

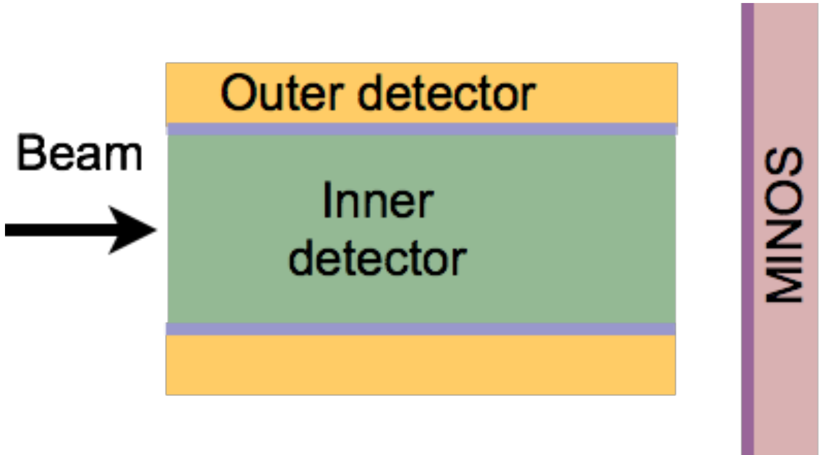
Signal Selection Efficiency Correction

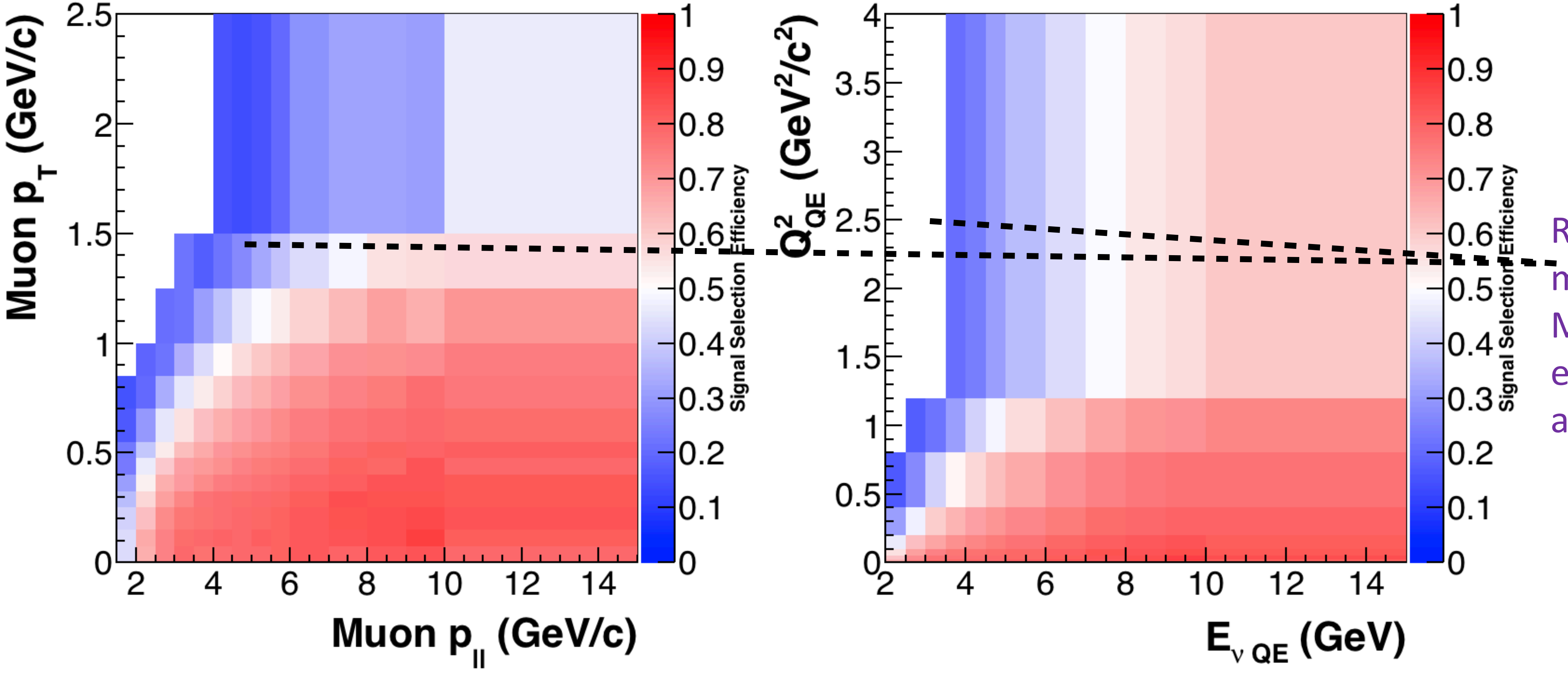
$$\left(\frac{d^2\sigma}{dxdy}\right)_{ij} = \frac{\sum_{\alpha\beta ij} U_{\alpha\beta ij}\left(N_{data,\alpha\beta} - N^{bkg}_{data,\alpha\beta}\right)}{\boxed{\epsilon_{ij}}\,\Phi T \Delta x_i \Delta y_j}$$

$$\boxed{\epsilon = \frac{N^{Pass\ Cut}_{QELIKE}}{N^{Total\ Events}_{QELIKE}}}$$

- We fail to reconstruct some signal events due to:
  - Detector acceptance
    - Remember MINOS acceptance requirement?
  - Reconstruction Efficiency
    - Our algorithms are not 100% perfect.

- Correct for the fraction of events that we failed to reconstruct.





Requirement to match muons at MINOS drops our efficiency for high angle muons.

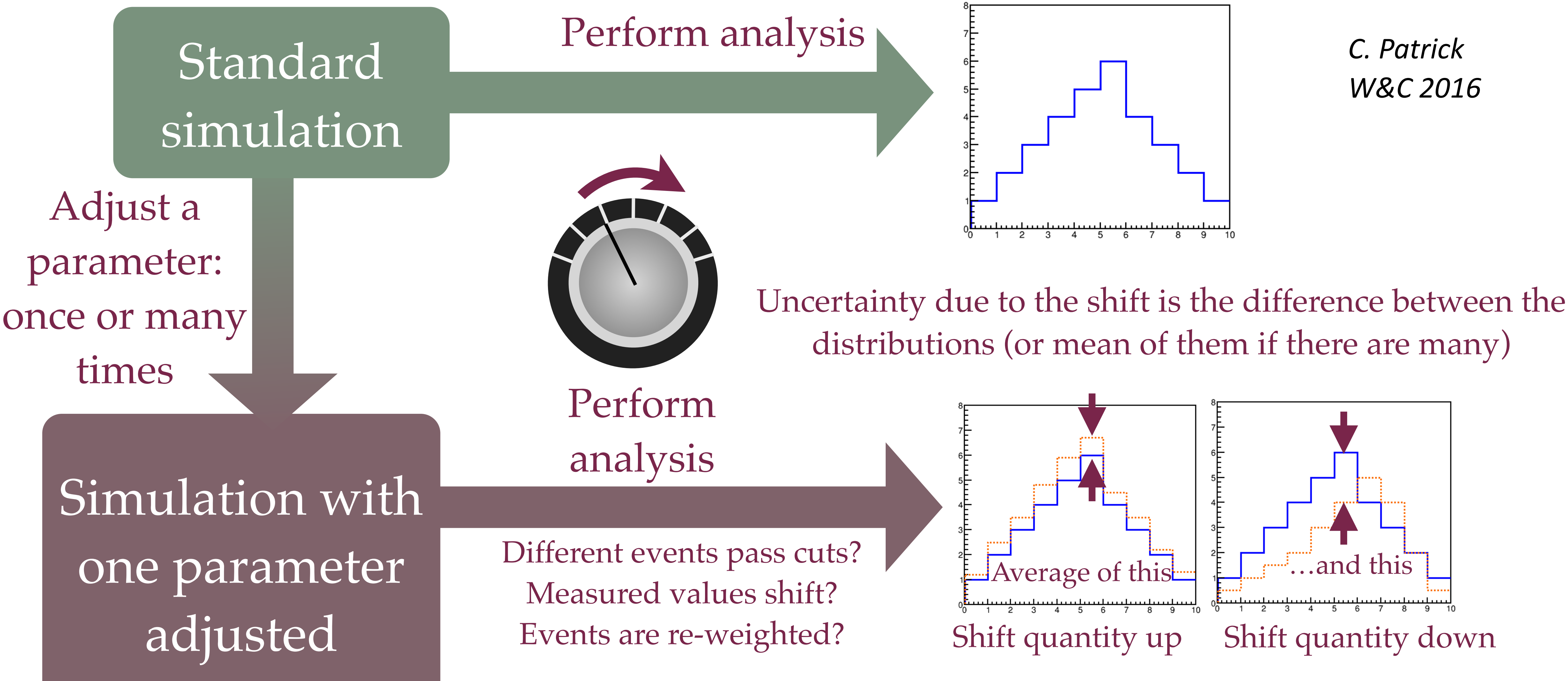
Signal Selection Efficiency ≈ 70% to 80%

Flux And Target Normalization

$$\left(\frac{d^2\sigma}{dxdy}\right)_{ij} = \frac{\sum_{\alpha\beta ij} U_{\alpha\beta ij}(N_{data,\alpha\beta} - N^{bkg}_{data,\alpha\beta})}{\epsilon_{ij}\Phi T \Delta x_i \Delta y_j}$$

- Muon P_z *vs*. P_T: We use the integrated neutrino flux for normalization.
- E_ν *vs*. Q^2: distribution is normalized by neutrino flux of corresponding E_ν to get the neutrino cross-section independent of the shape of the flux.
- T →Total number of nucleons in the tracker region.
- 3.23×10^{30} nucleons (protons+neutrons) in the tracker region.
- Φ (Flux) integrated from 0 to 120 GeV to obtain the differential cross section

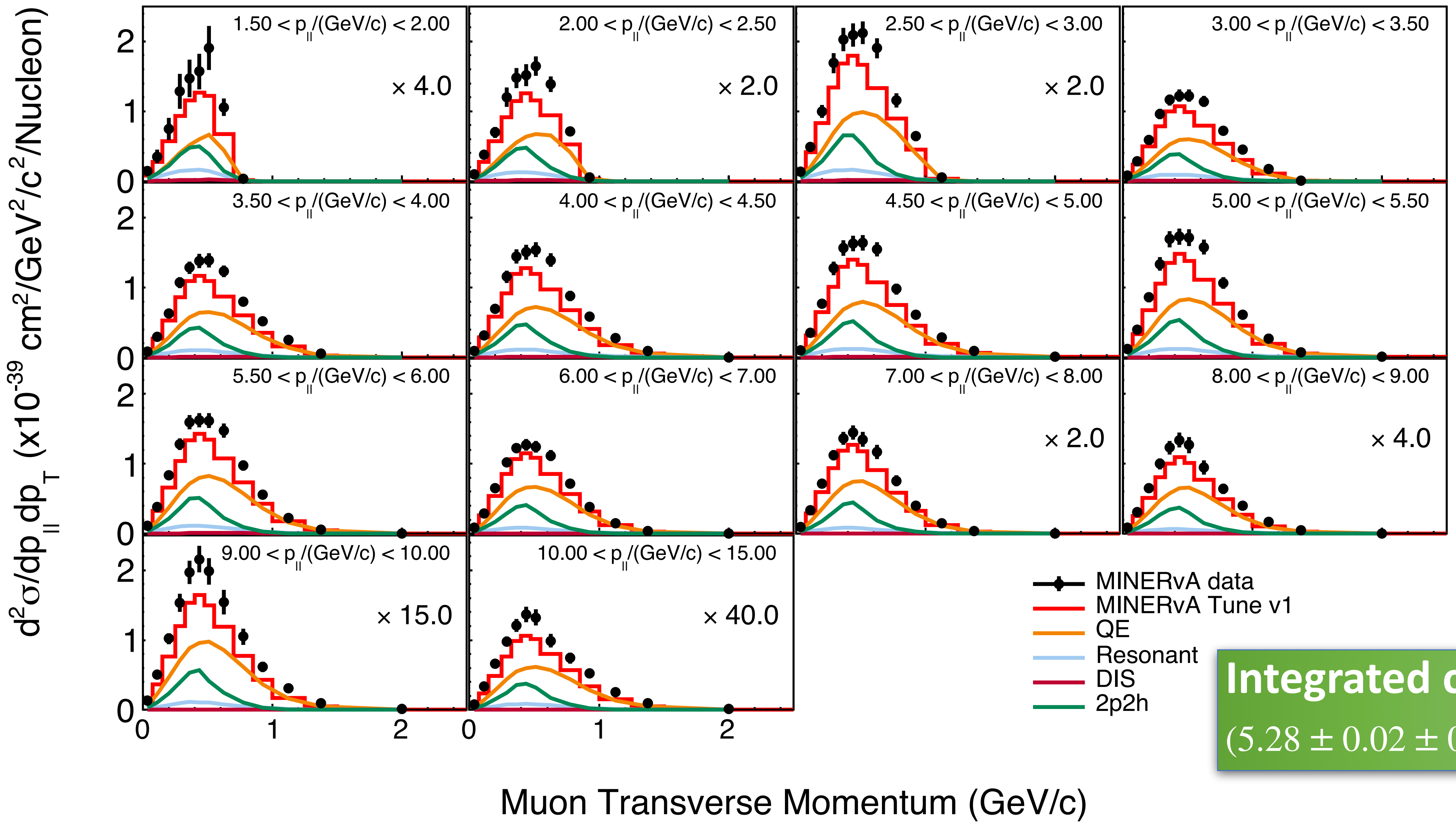
Systematic Uncertainties



Examples: increase resonant cross section by 10% OR 500 "universes" of flux changes

Cross section Results

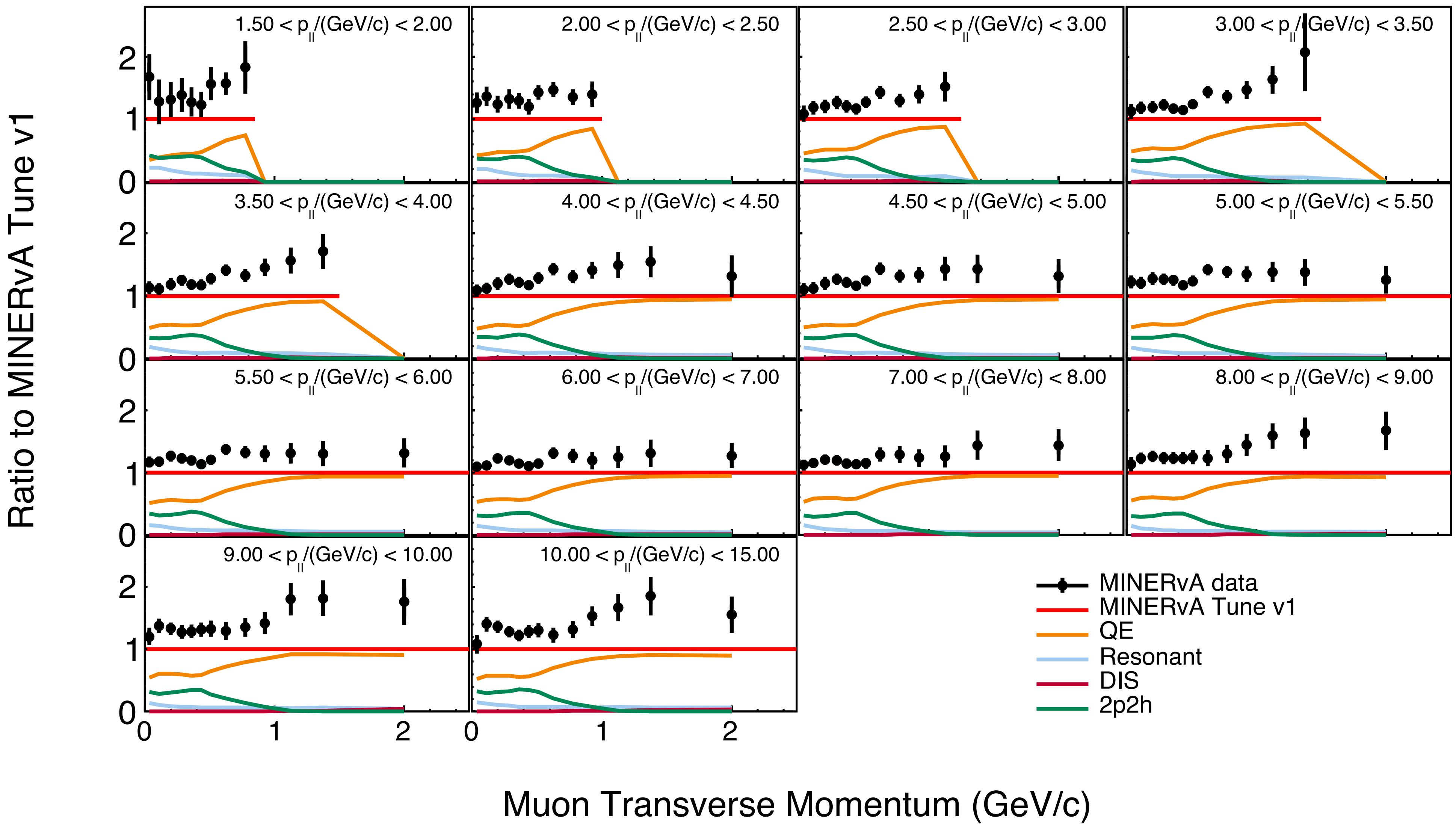
p_t cross section in the bins of p_z



Integrated cross section:

$(5.28 \pm 0.02 \pm 0.35) \times 10^{-39} cm^2/nucleon$

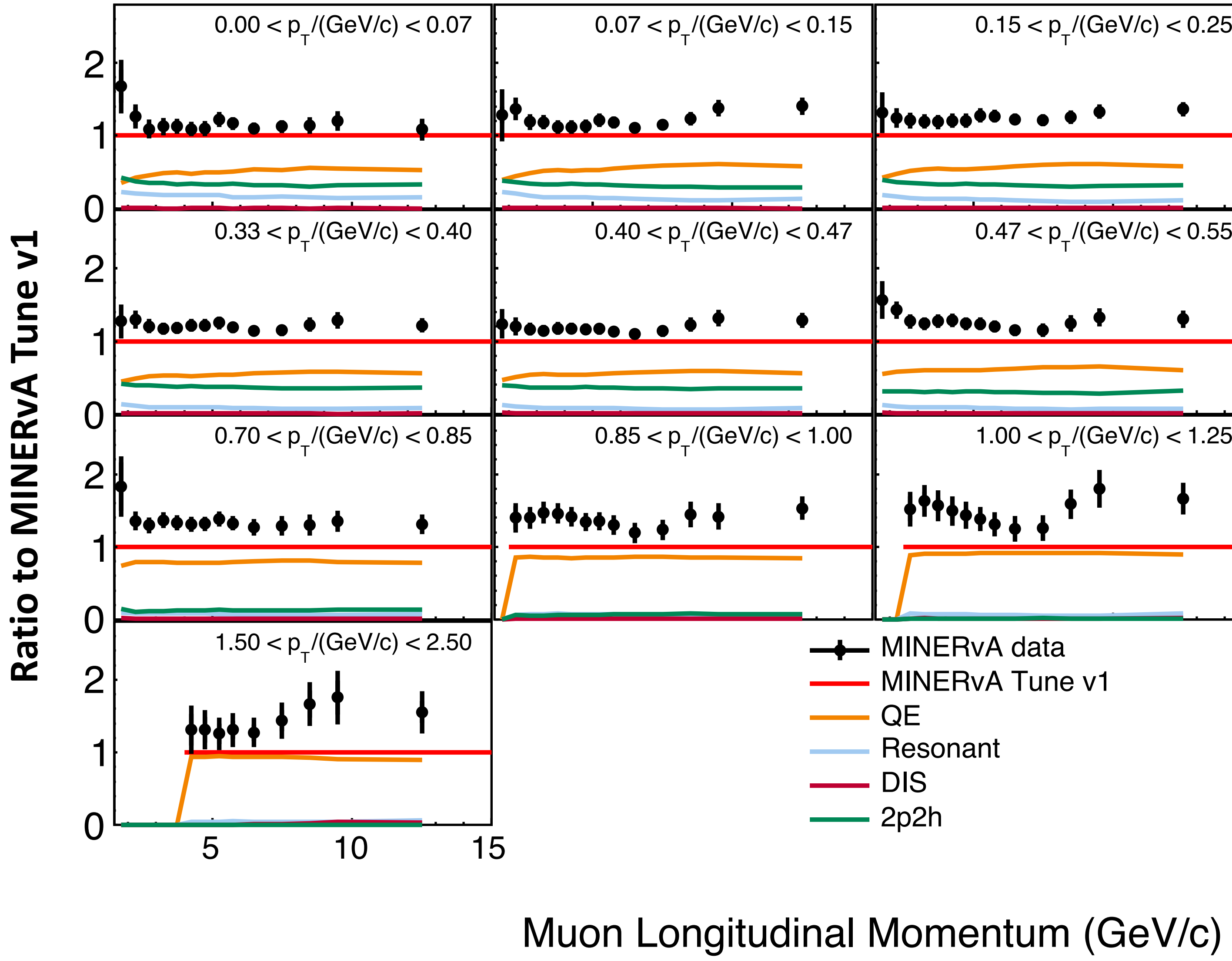
Cross section Ratio (p_t in the bins of p_z)



Across all bins the model under predicts our measured cross section.

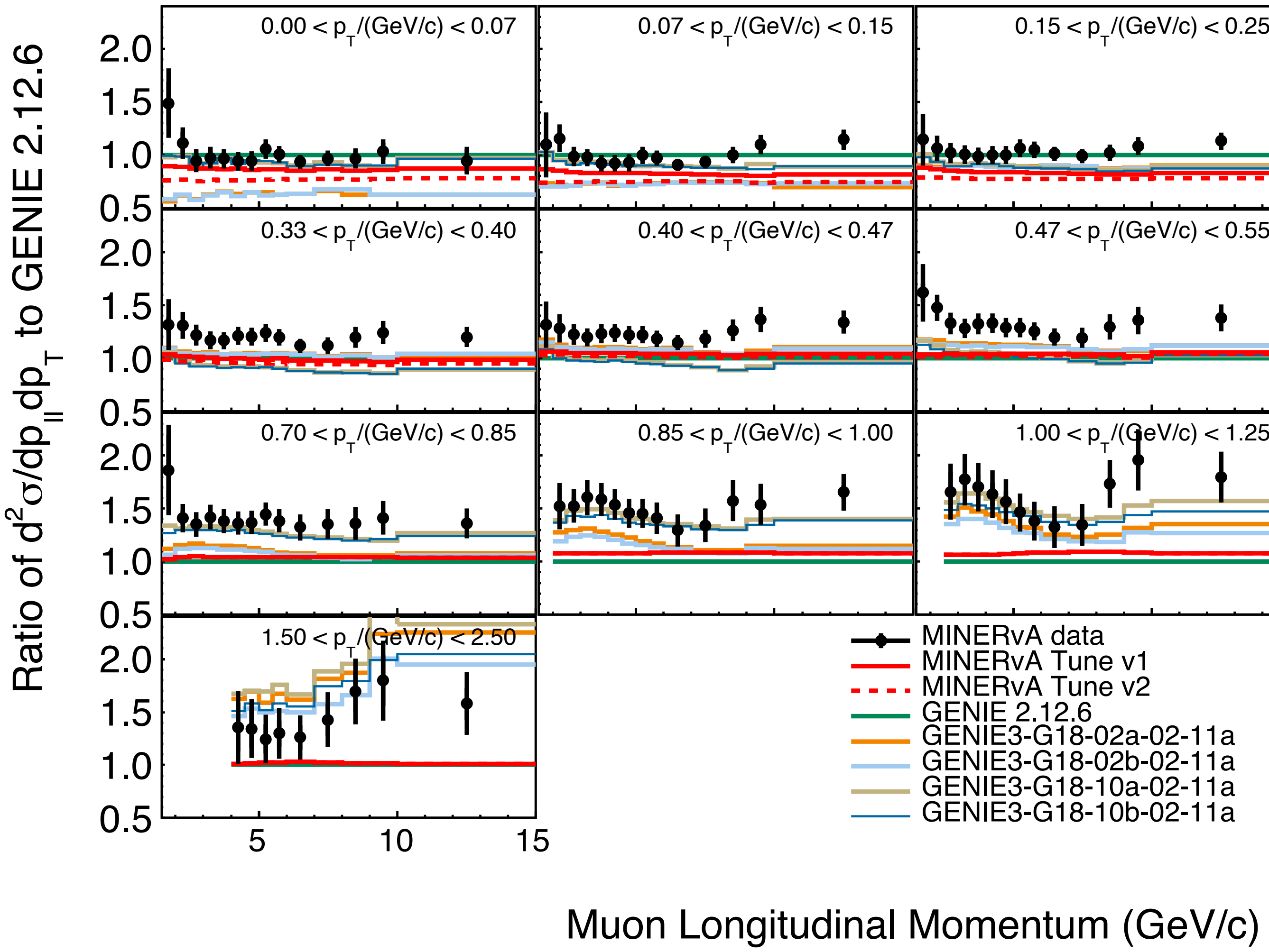
CCQE Like Cross section dominated by QE processes followed by 2p2h.

Cross section ratio (p_z in the bins of p_t)



QE (1p1h) and 2p2h processes dominate the low transverse region whereas the higher transverse region is dominated by QE processes entirely.

Comparison with GENIE 3 models



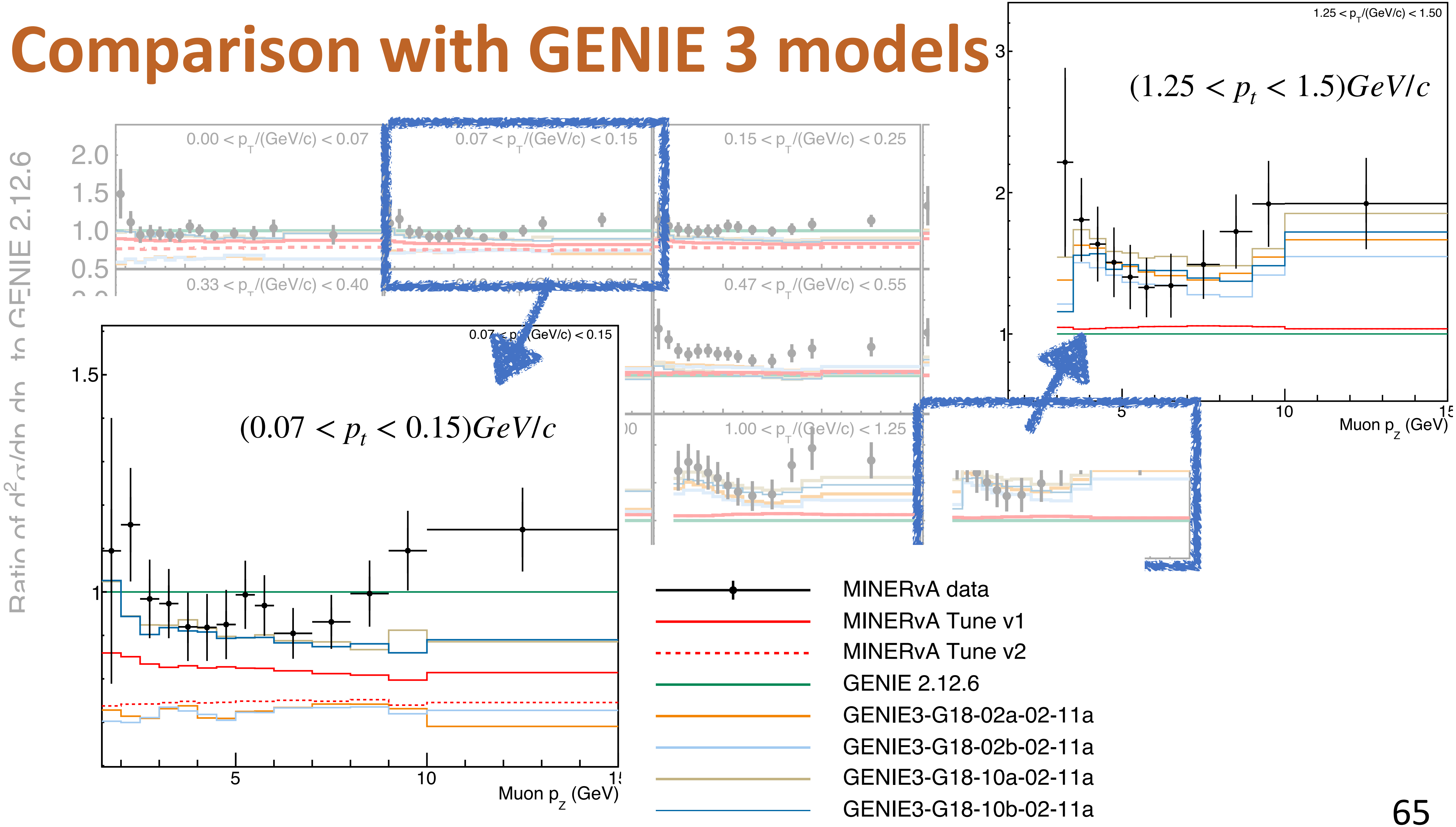
GENIE 3 model **G18-10x-02-11a** agrees better with our data compared with **G18-02x-02-11a**
(x = a,b)
10x: incorporates Valencia model.
02x: GENIE ver2 2p2h model

GENIE 3 : GENIE 3.0.6

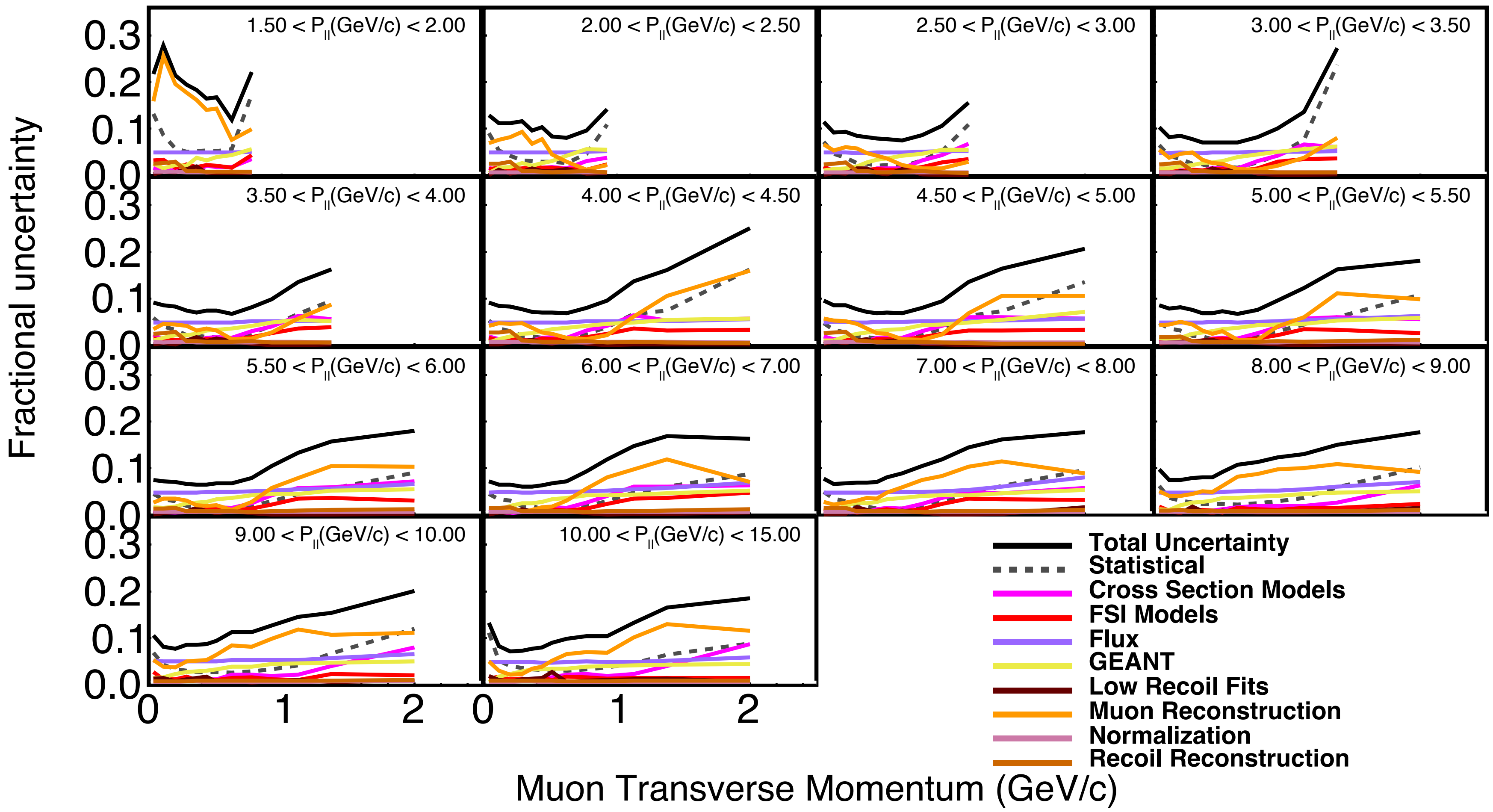
Out of the box GENIE (2.12.6) does not describe our data well.
We need more than our LE tunes to describe our ME data.

MnvTune v2 = **MnvTune v1**+ Pion Production suppression Low Q^2
[*P. Stowell*, arXiv:1903.01558.]

Comparison with GENIE 3 models



Error Summary on the data



- Uncertainty is dominated by the muon reconstruction.
- Flux contribution is around 5%.
- Neutron related error dominates the GEANT category and contribute unto 5% in some regions.
- GENIE cross section models and FSI contribute contribute less than 5% overall.

χ^2 comparison

Model	χ^2 - linear	χ^2 - log
GENIE 2.12.6 Tunes		
MINERvA Tune v1	362.6	580.4
MINERvA Tune v2	364.4	601.4
GENIE w/o 2p2h	226.5	473.2
GENIE (Default)	346.4	550.6
GENIE+πtune	354.3	568.5
GENIE+RPA	230.0	406.7
GENIE+RPA+πtune	231.7	414.6
GENIE+Low Recoil Tune	755.4	1059.4
GENIE+Low Recoil Tune+RPA	361.2	570.0
GENIE+Low Recoil Tune+πtune	760.6	1081.8
GENIE 3.0.6 Tunes		
GENIE 3.0.6 G18_02a_02_11a	602.9	865.0
GENIE 3.0.6 G18_02b_02_11a	586.9	878.3
GENIE 3.0.6 G18_10a_02_11a	353.1	447.5
GENIE 3.0.6 G18_10b_02_11a	312.8	421.7

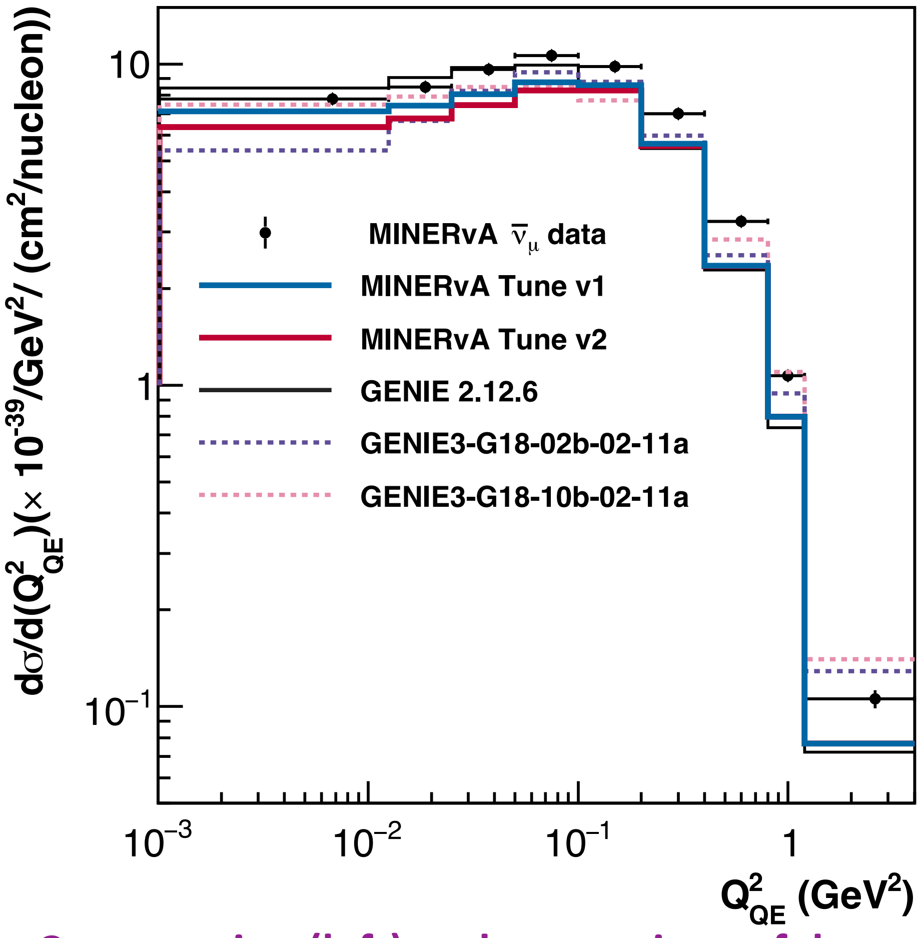
TABLE II. $p_{||} - p_{\perp}$ χ^2 between data and model variants derived from GENIE. The number of degrees of freedom is 171. Both the χ^2 between the values and between the logs of the values are listed.

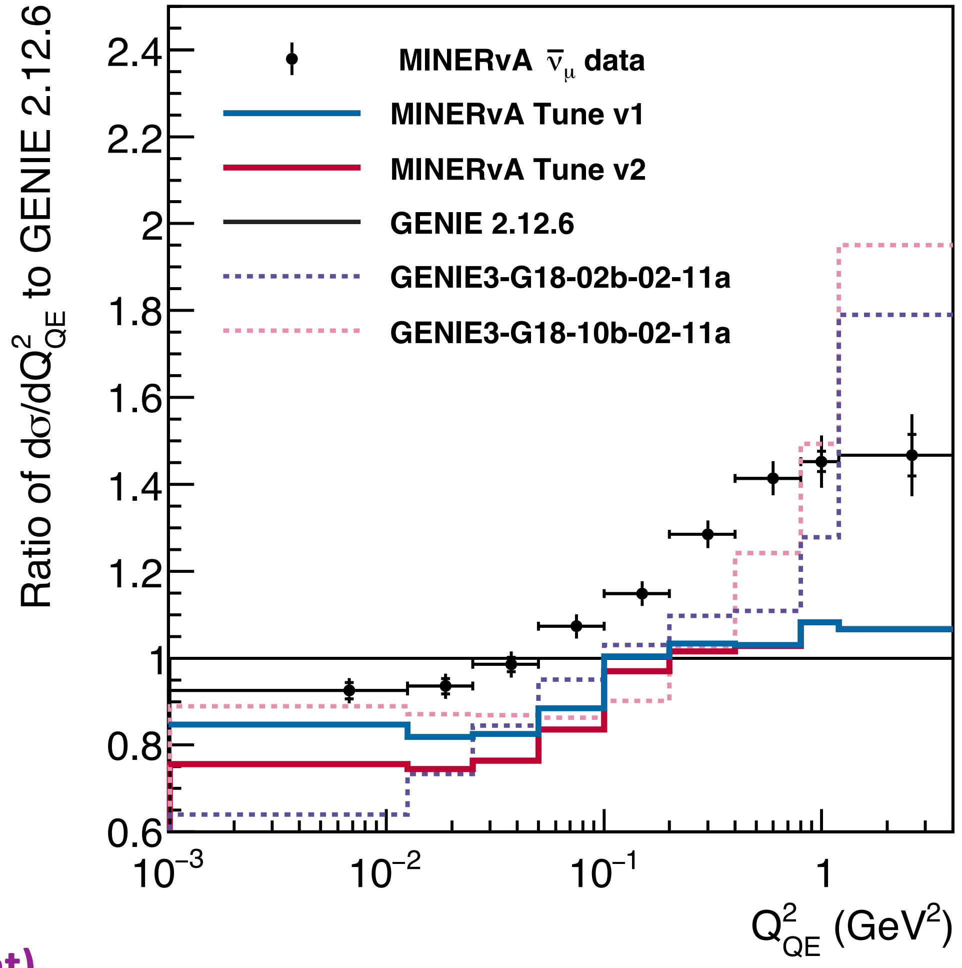
- **Full systematic and bin to bin correlations are treated to calculate the χ^2 between data and models.**
- **χ^2 tells us that GENIE 2 variations that were based on low energy data are not sufficient to describe our Medium Energy data.**
- **GENIE 3 models with Nieves 2p2h implementation performs better than GENIE 2 like 2p2h models.**

1 D projections from $(E_\nu, Q^2)_{QE}$ measurements

Cross section (Q^2_{QE}) : MINERvA Tune and GENIE 3

MINERvA Tune v2 = MnvTune v1+Pion Production suppression Low Q^2 based on P. Stowell, arXiv:1903.01558.



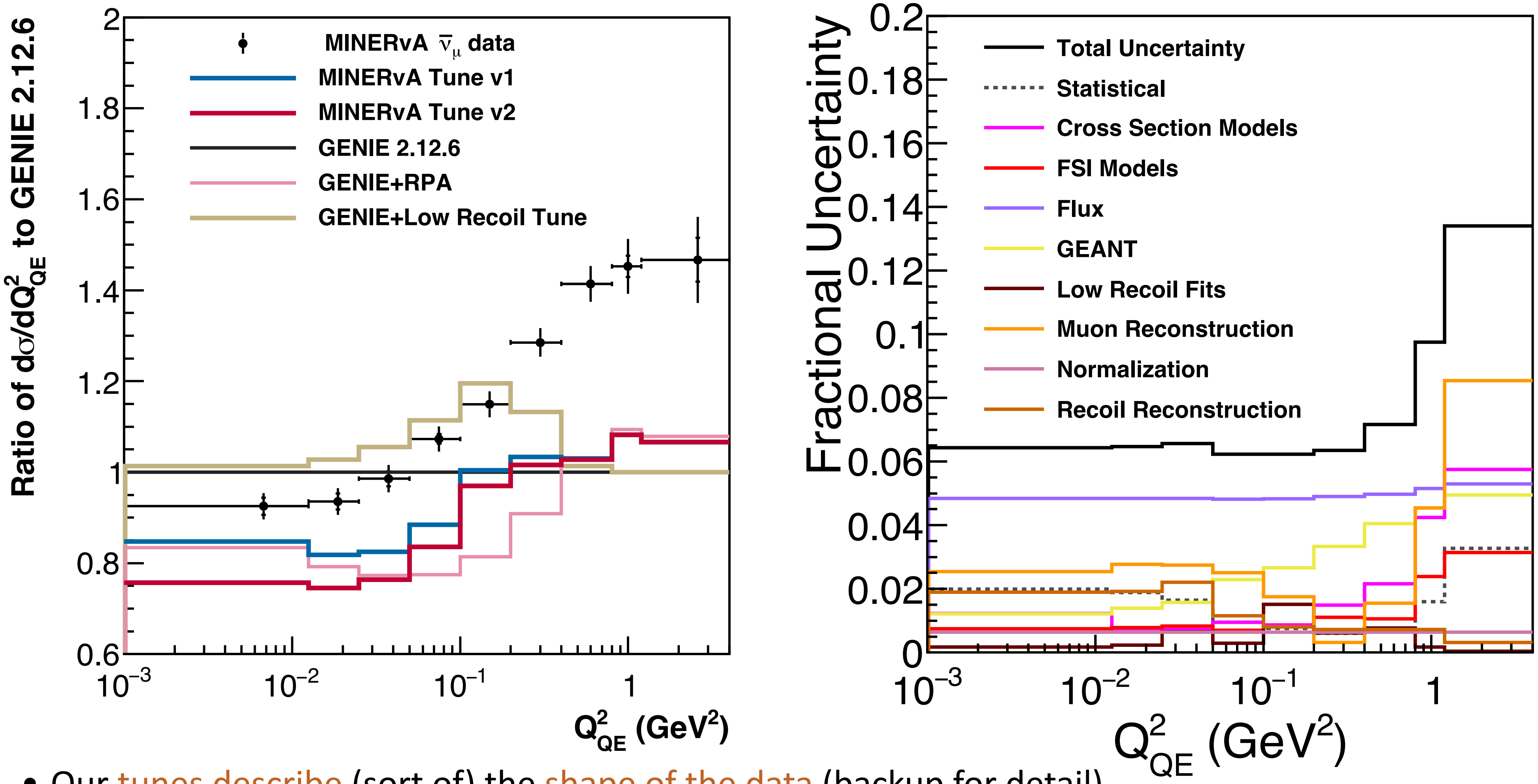


Cross section (left) and comparison of data and models (right).

GENIE 3 model with Nieves and hN (G18-10b series) describes data better at high Q^2_{QE} than older models.

None of the models agree with the data at highest Q^2_{QE} bin

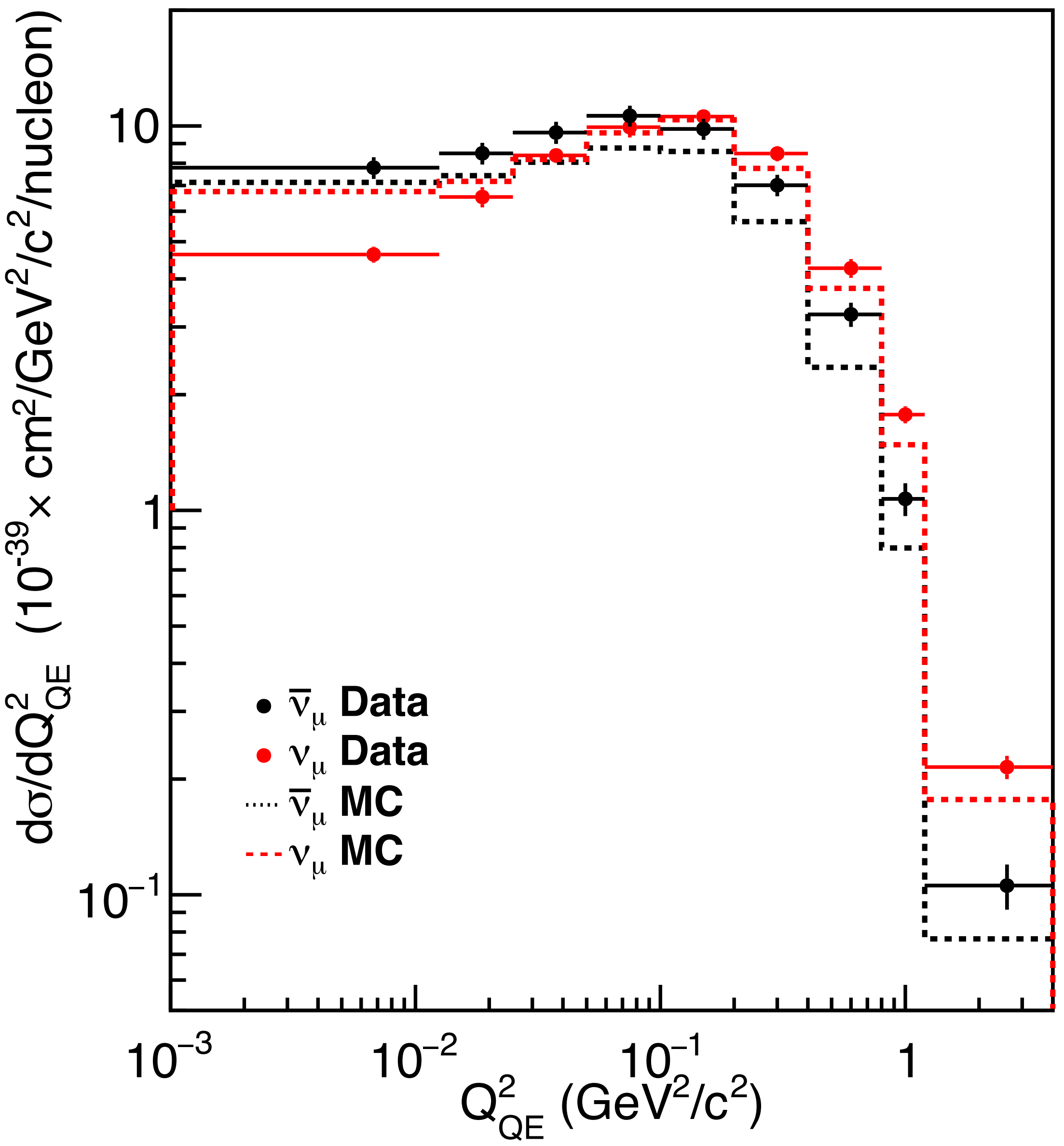
Cross section (Q^2_{QE}) : MINERvA Tunes



MnvTune v2 =
MnvTune v1
+
Pion Production
suppression Low Q^2

- Our tunes describe (sort of) the shape of the data (backup for detail) .
  - But needs more than LE tunes to describe our ME data
- Uncertainties on Q^2_{QE} cross section (right) are dominated by Flux, Muon reconstruction.
- GEANT4 uncertainties are dominated by neutron related interactions.

Comparison with MINERvA ME ν_μ CC0pi measurement



$\nu_\mu + n \to \mu^- + p$ [*M. Carniero*, PRL 124,121801]

$\bar{\nu}_\mu + p \to \mu^+ + n$ [This Talk]

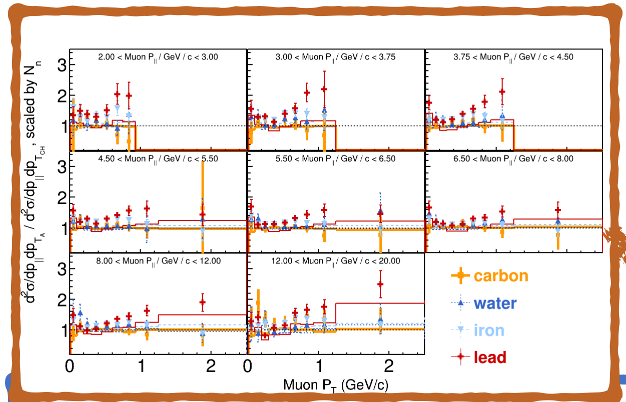
- **Not one to one comparison but can show the agreement with data and our model for CCQELike cross section measurements for both neutrinos (black) and anti neutrinos (red)**

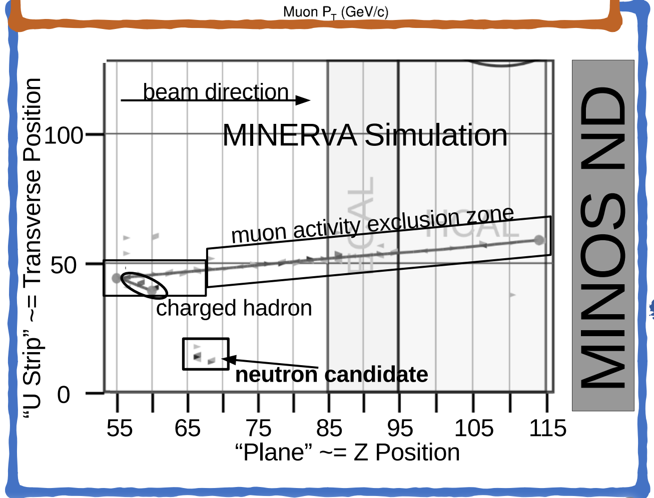
Conclusions

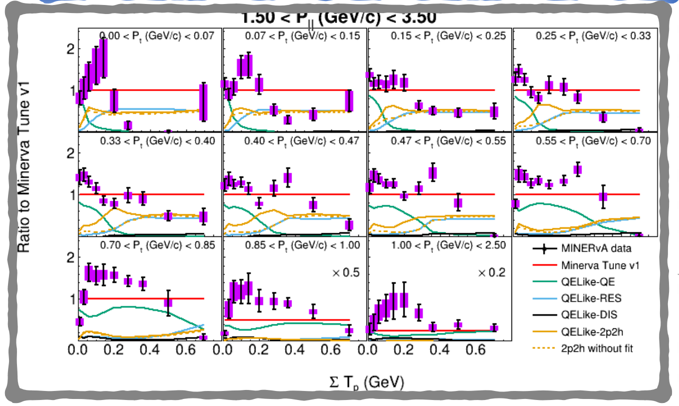
Conclusions

- This analysis provides high statistics cross section measurement of anti neutrinos CCQE like process.
- Extends measurements to previously unexplored kinematic regions.
- More than LE tunes are needed to describe our ME data.
- Models under predict the data
  - Similar to the LE era analysis
- Higher Statistics, better constrained flux systematics
  - Valuable information for upcoming oscillation experiments.

CCQELike LandScape



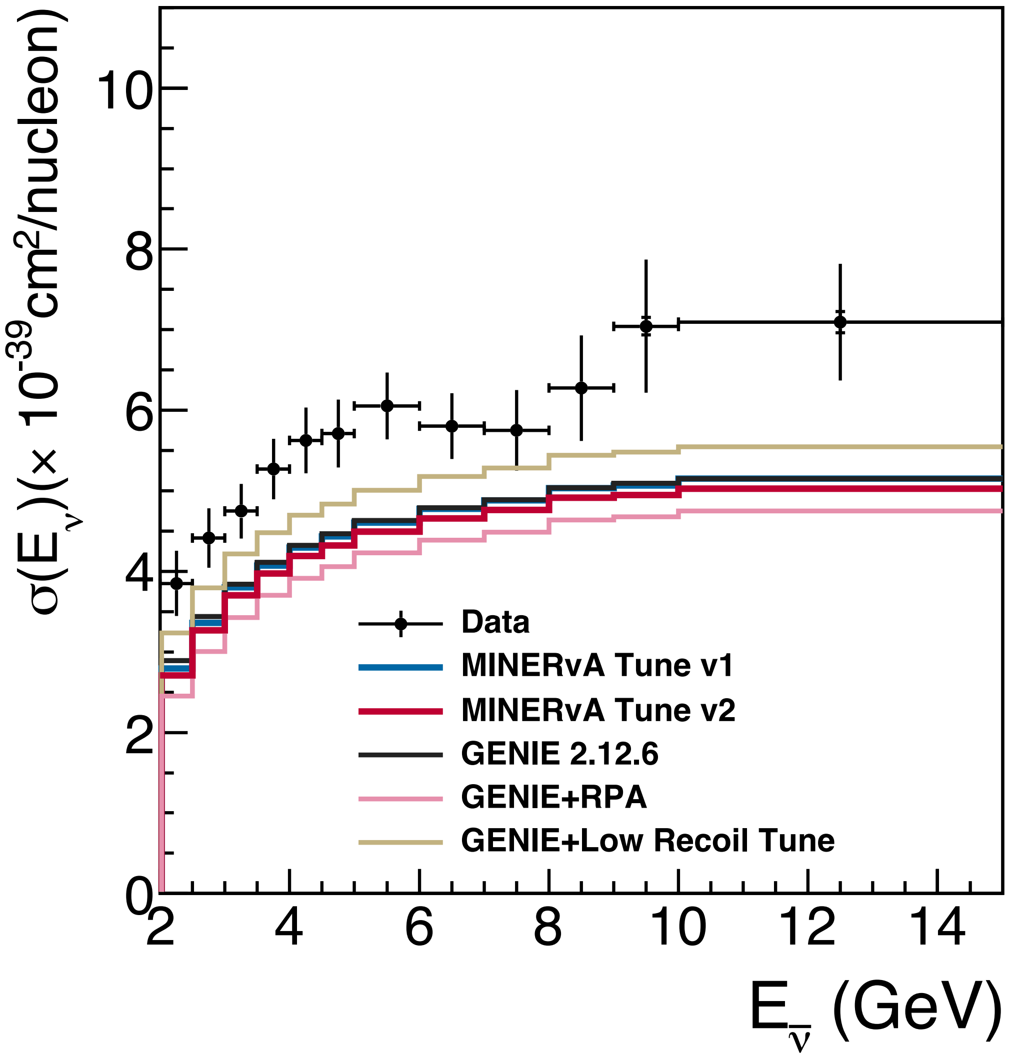


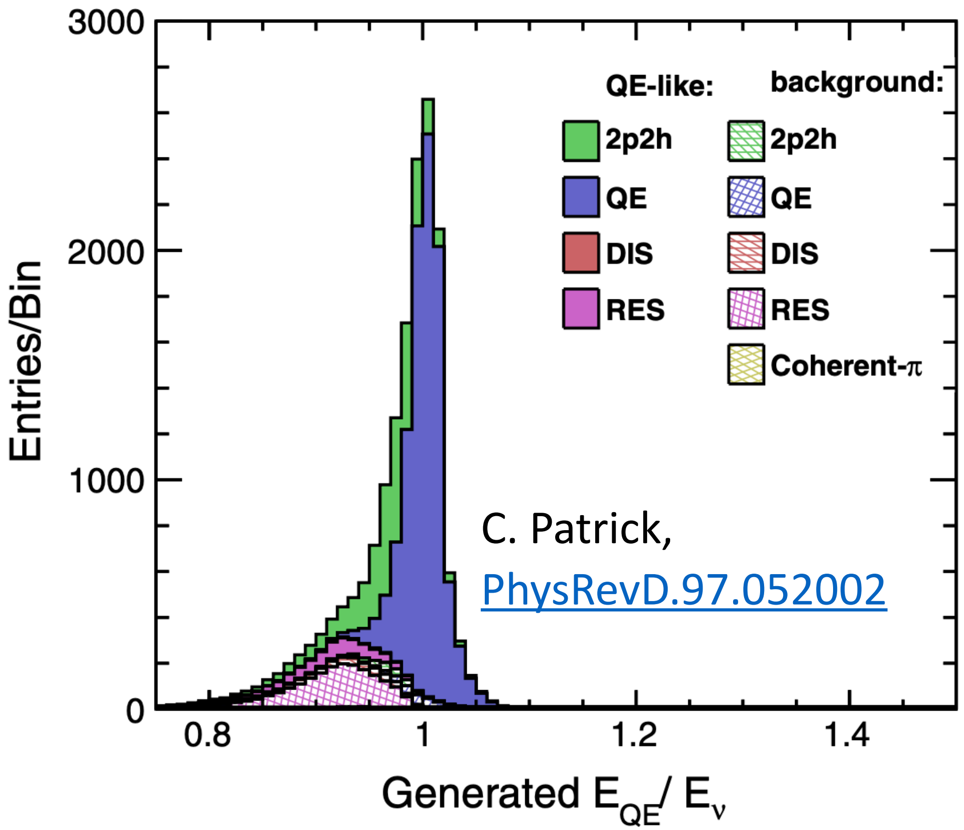


- High Statistics results ν_μ [*M. Carneiro*, PhysRevLett.124.121801] **and $\bar{\nu}_\mu$ CCQELike are published**.
- $\left(\frac{\sigma_{\nu_\mu}}{\sigma_{\bar{\nu}_\mu}}\right)_{CH}$ analysis with full treatment of systematics and correlations is ongoing.
- $(\sigma_{\nu_\mu})_A, (\sigma_{\nu_\mu})_{CH}$ and ratios **where A is** C, H_20, Fe, Pb [*J, Kleykamp*, arxiv: 2301.02272]
- Neutrons are the Final State particles of this analysis.
  - Paper being prepared on cross section with 2 or more neutrons in final state.
- $\bar{\nu}_\mu$ CCQELike cross section measurement in heavier target (ongoing)
- $\bar{\nu}_\mu$ CCQELike cross section as a function of recoil energy in muon kinematic bins (ongoing)
  - ν_μ CCQELike version of this analysis published [*D. Ruterbories*, arxiv 2203.08022]

Back up

Cross section (E_ν)

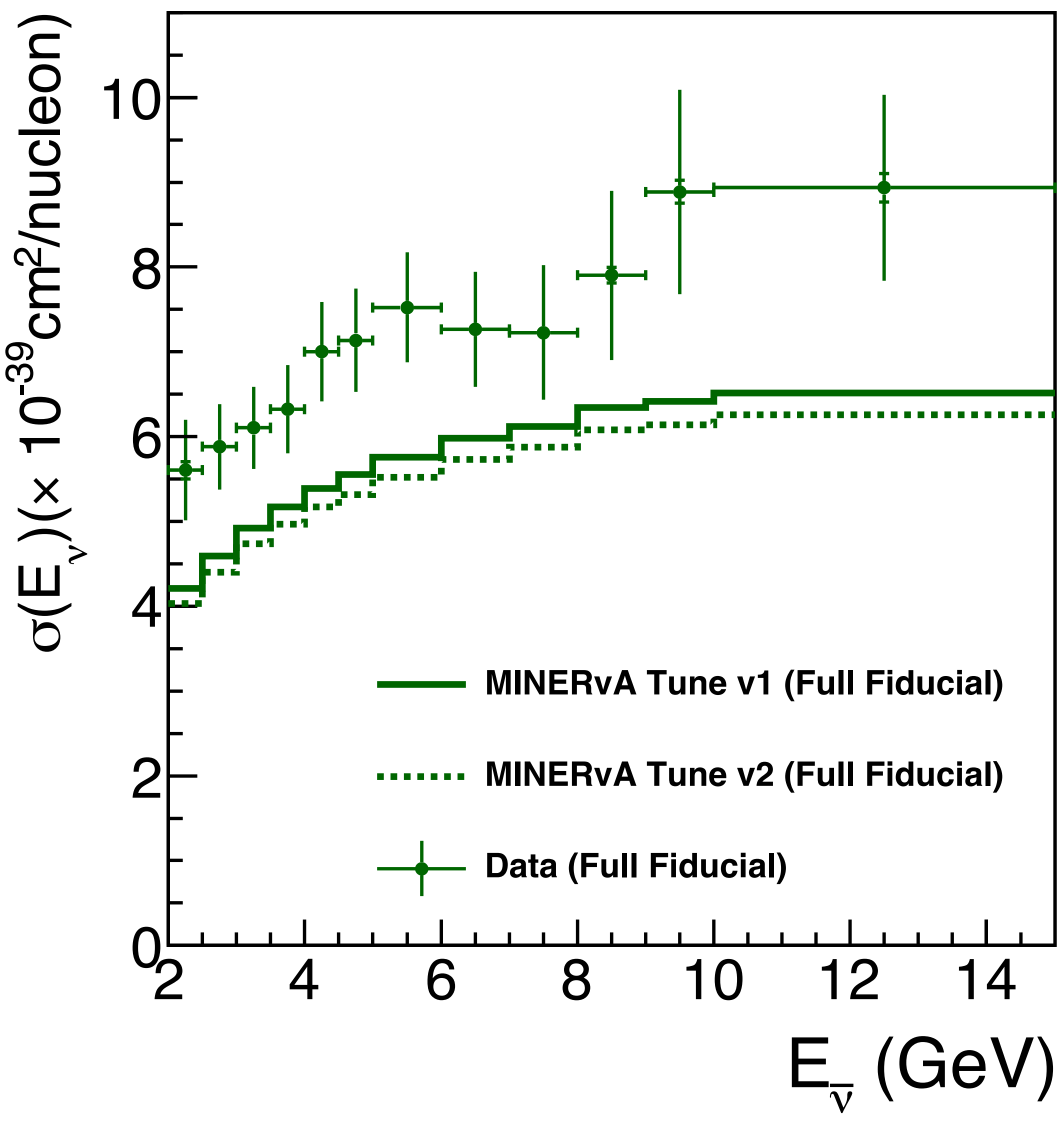




$$E_\nu^{QE} \neq E_\nu$$

- Since the **flux is estimated** in the bins of **true neutrino energy**, $E_{\nu QE}$ cross section is **corrected** to E_ν (true neutrino energy).
- Correction introduces model dependency but allows (qualitative) comparison with other results and theoretical models.

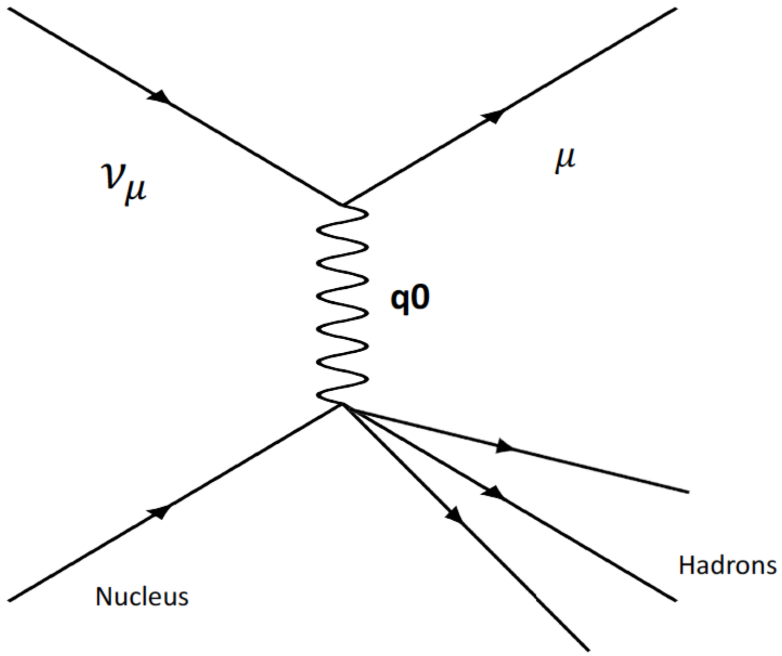
Full Fiducial Cross section (E_ν)



Signal Definition includes events with proton KE less than 120 MeV.
Remember that our selection criteria requires a 20% angle cut.

Removing the proton KE threshold and correcting for the angle cut gives the full fiducial cross section.
Allows closer comparison with other results.

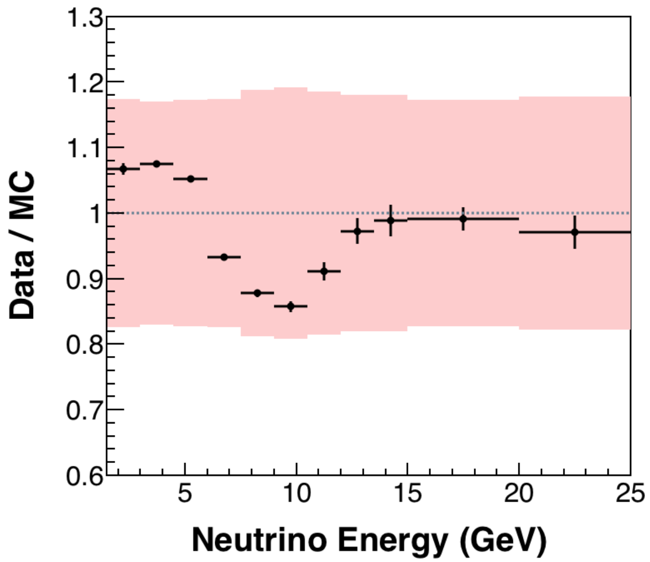
Low nu Fit to resolve Data/MC discrepancy

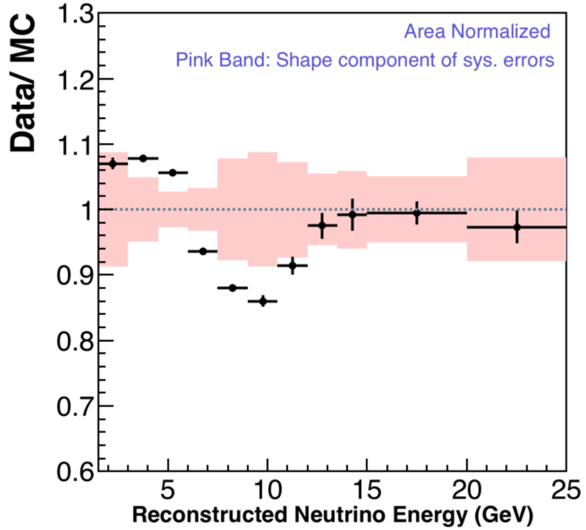


Charged Current Inclusive Event

$\boldsymbol{\nu_\mu + N \rightarrow \mu^+ + Hadrons}$

- $\boldsymbol{\nu}$ (nu) → Energy transferred (q_o) to the recoil system
- Low nu Events → $q_o << E_\nu$
- **Cross section Independent of incoming neutrino energy →Shape of Low nu distribution depends on flux shape only.**



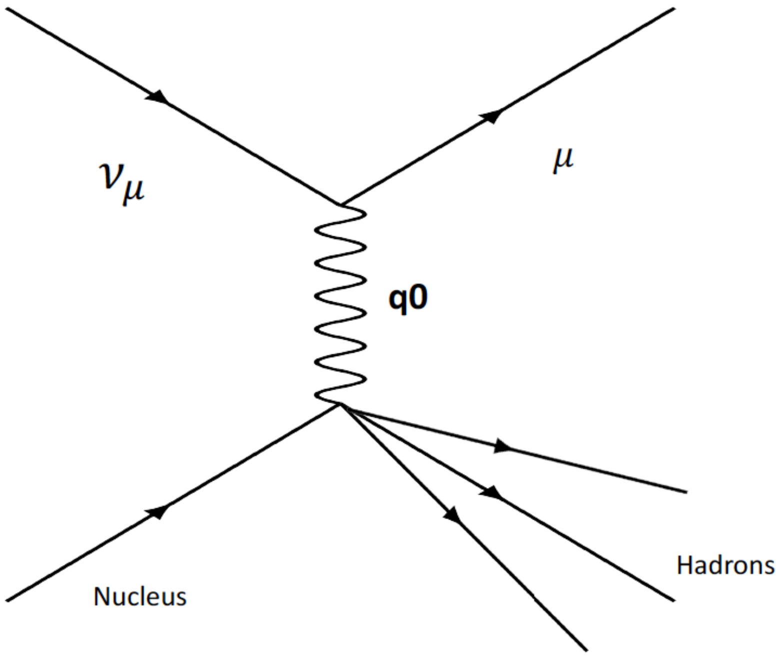


Ratio between MINERvA low nu data and simulated sample. The pink shade shows shape+normalization coverage (left) and shape coverage (right) by the systematic errors. This excludes cross section mismodeling as a candidate cause of discrepancy.

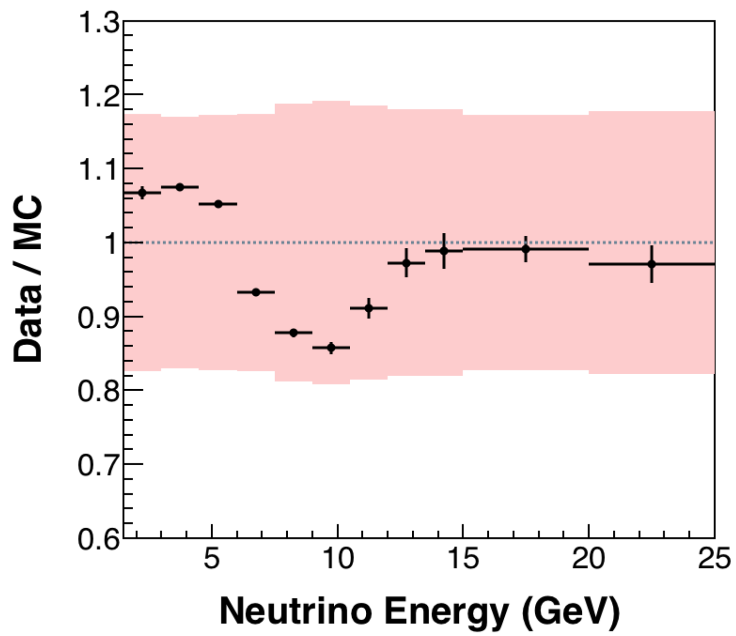
$$\frac{d\sigma}{d\nu} = \frac{G_F^2 M}{\pi} \int_0^1 \left(F_2 - \frac{\nu}{E_\nu}[F_2 \pm xF_3] + \frac{\nu}{2E_\nu^2}\left[\frac{Mx(1-R_L)}{1+R_L}F_2\right] + \frac{\nu^2}{2E_\nu^2}\left[\frac{F_2}{1+R_L} \pm xF_3\right]\right)dx$$

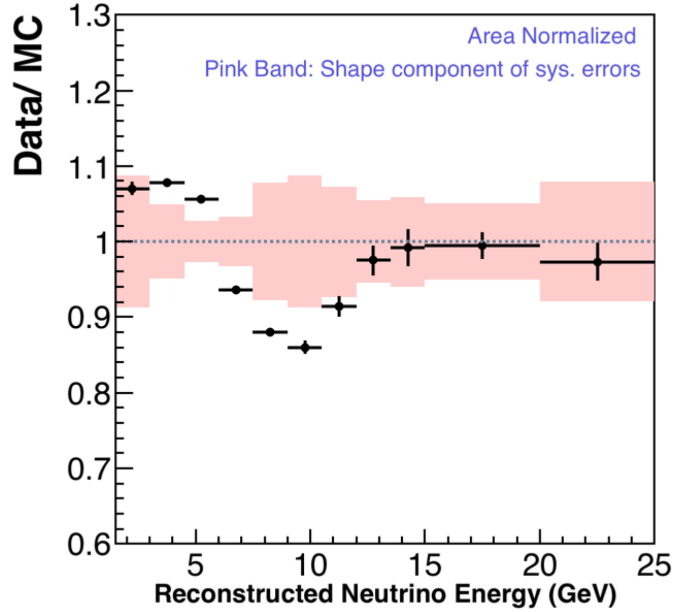
$$\frac{d\sigma}{d\nu} \approx \frac{G_F^2 M}{\pi} \int_0^1 (F_2)dx$$

Low nu Fit to resolve Data/MC discrepancy



Charged Current Inclusive Event
$\boldsymbol{\nu_\mu + N \rightarrow \mu^+ + Hadrons}$





- **Ratio between MINERvA low nu data and simulated sample.**
- **Left**: Pink shade shows shape+normalization coverage by systematic errors.
- **Right**: Pink shade shows shape coverage by systematic errors.

- Low nu Events → $q_o << E_\nu$
- **Cross section Independent of incoming neutrino energy →Shape of Low nu distribution depends on flux shape only.**

$$\frac{d\sigma}{d\nu} \approx \frac{G_F^2 M}{\pi} \int_0^1 (F_2) dx$$

CCQE Cross-section

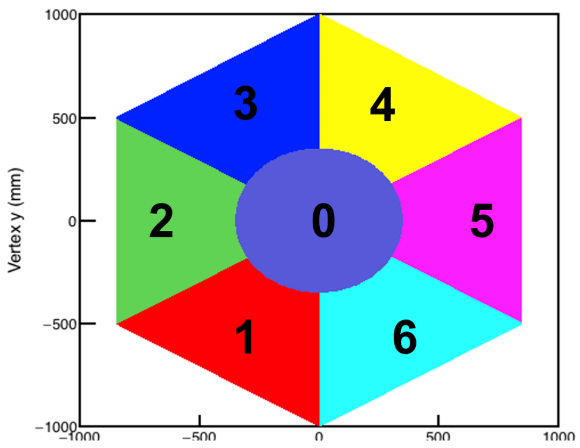
$$\frac{d\sigma}{dQ^2}\begin{pmatrix}\nu n \to l^- p \\ \bar{\nu} p \to l^+ n\end{pmatrix} = \frac{M^2 G^2 \cos^2\theta_c}{8\pi E_\nu^2}\left[A(Q^2) \mp B(Q^2)\frac{(s-u)}{M^2} + \frac{C(Q^2)(s-u)^2}{M^4}\right] \quad (1)$$

$$A(Q^2) = 4\frac{Q^2}{4M^2}\Big[|F_A|^2\left(1+\frac{Q^2}{4M^2}\right) - |F_V^1|^2\left(1-\frac{Q^2}{4M^2}\right) + |\xi F_V^2|^2\frac{Q^2}{4M^2}\left(1-\frac{Q^2}{4M^2}\right) + 4F_V^1 \xi F_V^2 \frac{Q^2}{4M^2}\Big] \quad (1)$$

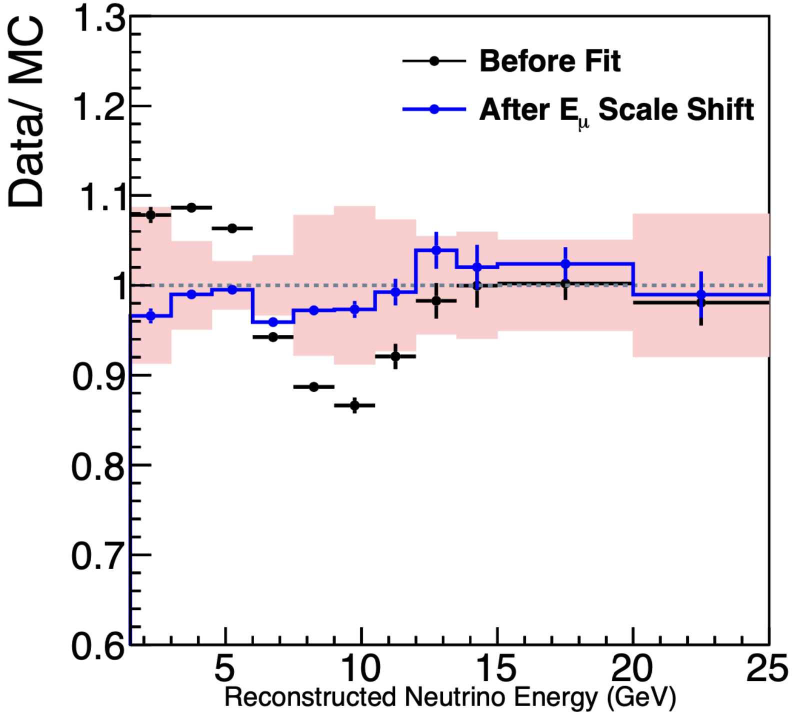
$$B(Q^2) = 4\frac{Q^2}{4M^2}\left[F_A\left(F_V^1 + \xi F_V^2\right)\right] \quad (2)$$

$$C(Q^2) = \frac{1}{4}\left[|F_A|^2 + |F_V^1|^2 + \frac{Q^2}{4M^2}|\xi F_V^2|^2\right] \quad (3)$$

Low nu Fit to resolve discrepancy



- Transverse face of the MINERvA detector was divided into 7 different areas and a multi parameter fit with the low nu sample was performed.
- Focusing + MINOS Muon energy scale as fit parameters
- Fit with and without prior uncertainty taken into account on each parameter
- Fit with (out) preferred a 3.2 (3.6)% shift in muon energy scale.
- MINERvA shifted muon energy scale by 3.6% for all sample (bottom left plot)



Parameter	Nominal	Best Fit (No Prior)	Best Fit (Prior)
Beam Position (X)	0.0 mm	$-0.3 \pm 0.3 \pm 0.1$ mm	$-0.3 \pm 0.2 \pm 0.1$ mm
Beam Position (Y)	0.0 mm	$0.8 \pm 0.3 \pm 0.3$ mm	$0.7 \pm 0.2 \pm 0.2$ mm
Target Position (X)	0.0 mm	$-0.8 \pm 0.3 \pm 0.1$ mm	$-0.8 \pm 0.3 \pm 0.1$ mm
Target Position (Y)	0.0 mm	$2.3 \pm 0.7 \pm 1.2$ mm	$1.7 \pm 0.6 \pm 0.8$ mm
Target Position (Z)	-1433 mm	$-1432.4 \pm 2.4 \pm 0.3$ mm	$-1431 \pm 1.8 \pm 0.3$ mm
Horn 1 Position (X)	0.0 mm	$-0.3 \pm 0.4 \pm 0.5$ mm	$-0.1 \pm 0.3 \pm 0.1$ mm
Horn 1 Position (Y)	0.0 mm	$0.1 \pm 0.5 \pm 0.5$ mm	$0.0 \pm 0.3 \pm 0.3$ mm
Beam Spot Size	1.5 mm	$1.41 \pm 0.09 \pm 0.03$ mm	$1.32 \pm 0.09 \pm 0.03$ mm
Horn Water Layer	1.0 mm	$1.2 \pm 0.3 \pm 0.05$ mm	$1.3 \pm 0.25 \pm 0.1$ mm
Horn Current	200 kA	$198.0 \pm 1.4 \pm 1.4$ kA	$199.1 \pm 0.7 \pm 0.5$ kA
Muon Energy Scale	1.0	$1.032 \pm 0.004 \pm 0.008$	$1.036 \pm 0.004 \pm 0.006$

Low-nu Fit with Focusing Parameters only

Parameter	Nominal Value	New Value
Beam Position (X)	0 mm	-0.2 ± 0.12 mm
Beam Position (Y)	0 mm	-0.53 ± 0.14
Beam Spot Size	1.5 mm	1.22 ± 0.14 mm
Horn Water Layer	1 mm	0.895 ± 0.16 mm
Horn Current	200 kA	197.41 ± 0.76 kA
Horn 1 Position (X)	0 mm	0. ± 0.17 mm
Horn 1 Position (Y)	0 mm	-0.39 ± 0.17 mm
Target Position (X)	0 mm	-0.32 ± 0.17 mm
Target Position (Y)	0 mm	1.65 ± 0.5 mm
Target Position (Z)	-1433 mm	-1419.44 ± 1.83 mm

MINERvA Flux Strategy

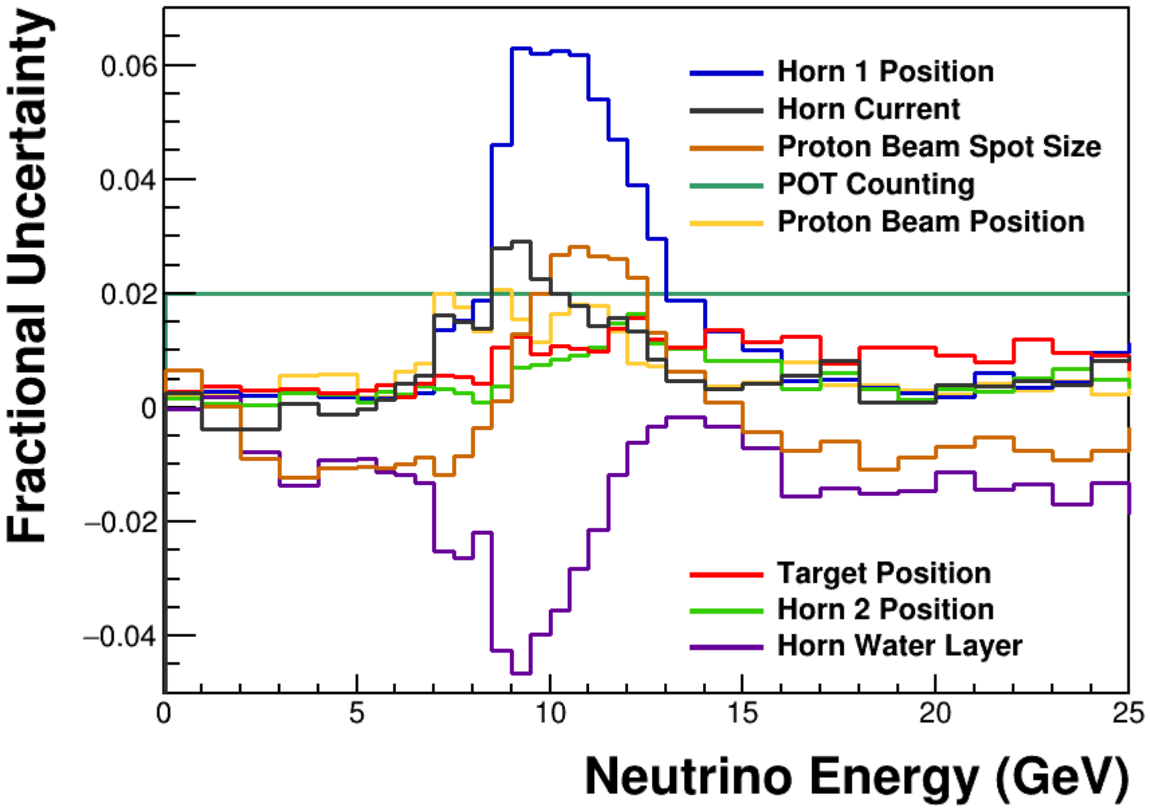
- **Focusing Uncertainties**
- Hadron Production Correction [PRD 94, 092005]

↓

a priori Neutrino Flux

Parameter	Nominal Value	Final 1 σ shifts used in MINERvA analyses
Beam Position (X)	0 mm	0.4 mm
Beam Position (Y)	0 mm	0.4 mm
Beam Spot Size	1.5 mm	0.3 mm
Horn Water Layer	1.0 mm	0.5 mm
Horn Current	200 kA	1 kA
Horn 1 Position (X)	0 mm	1 mm
Horn 1 Position (Y)	0 mm	1 mm
Horn 1 Position (Z)	30 mm	2 mm
Horn 2 Position (X)	0 mm	1 mm
Horn 2 Position (Y)	0 mm	1 mm
Target Position (X)	0 mm	1 mm
Target Position (Y)	0 mm	1 mm
Target Position (Z)	-1433 mm	1 mm
POT Counting	0	2% of Total POT
Baffle Scraping	0	0.25% of POT

Table of Beam Parameters and their values at their nominal and shifted position.

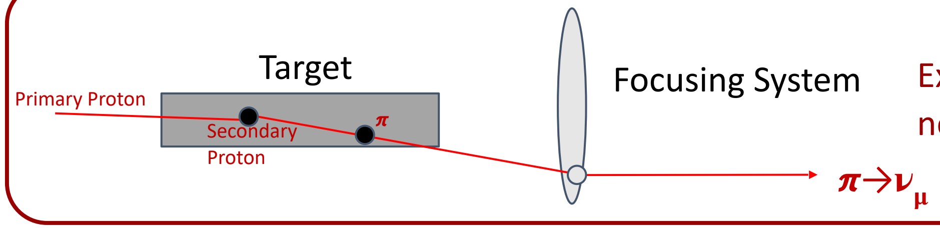


Focusing Uncertainties in the Medium Energy neutrino Flux. Each uncertainty is the ratio of neutrino flux due to shifted beam parameter (by +1 σ) to the nominal neutrino flux.

MINERvA Flux Strategy

- Focusing Uncertainties
- **Hadron Production Correction** [PRD 94, 092005]

a priori Neutrino Flux

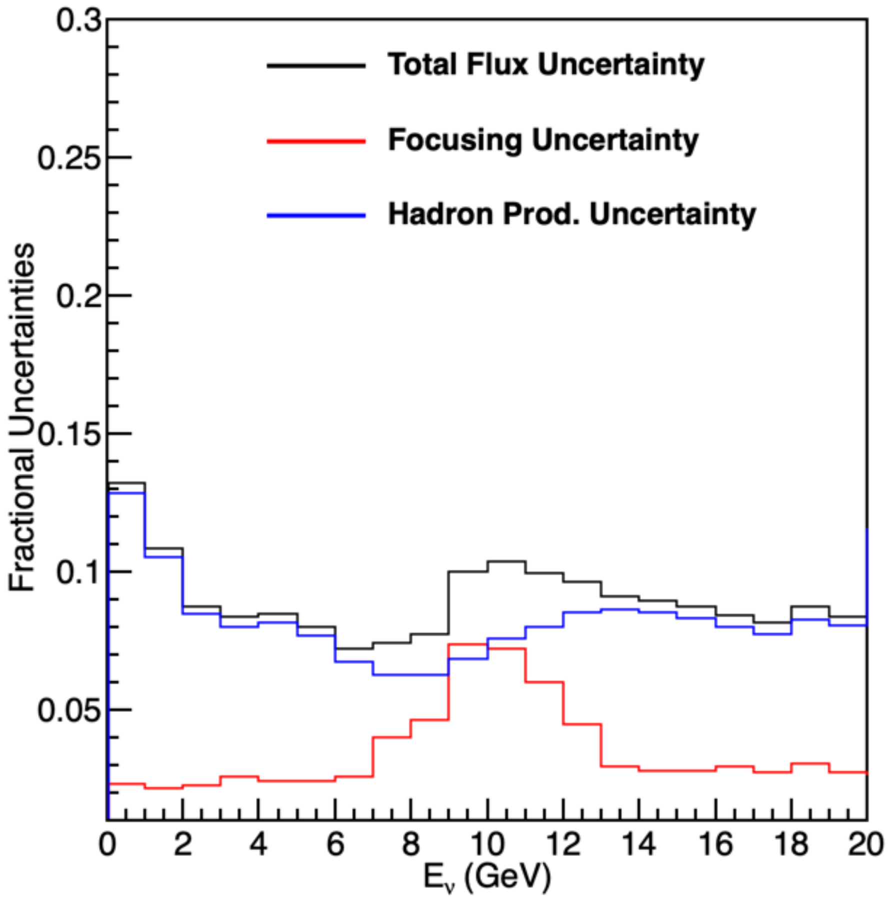


Example of a neutrino ancestry

Full Neutrino Ancestry using G4numi Simulation

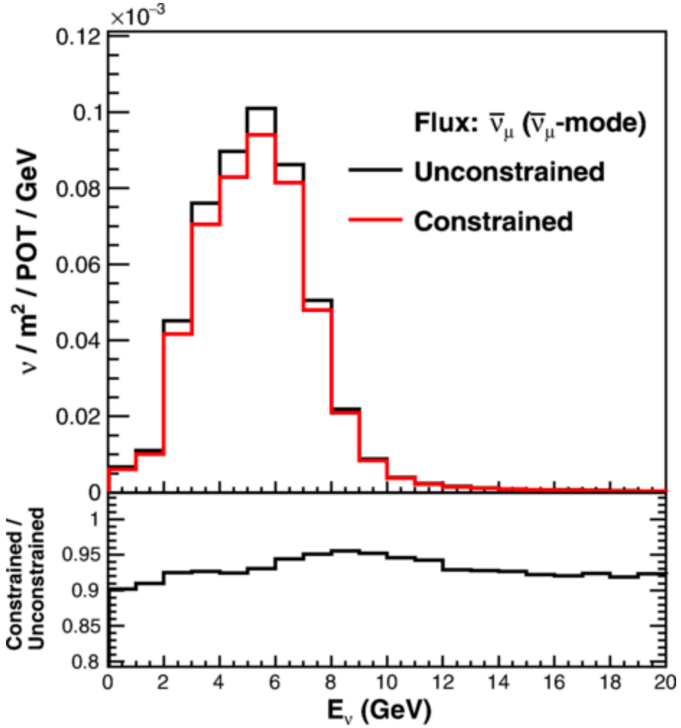
Coverage of Interactions by Existing Thin Target Datasets

- **Direct Coverage**
- **Coverage by Extension of data sets**
- **No coverage at all**

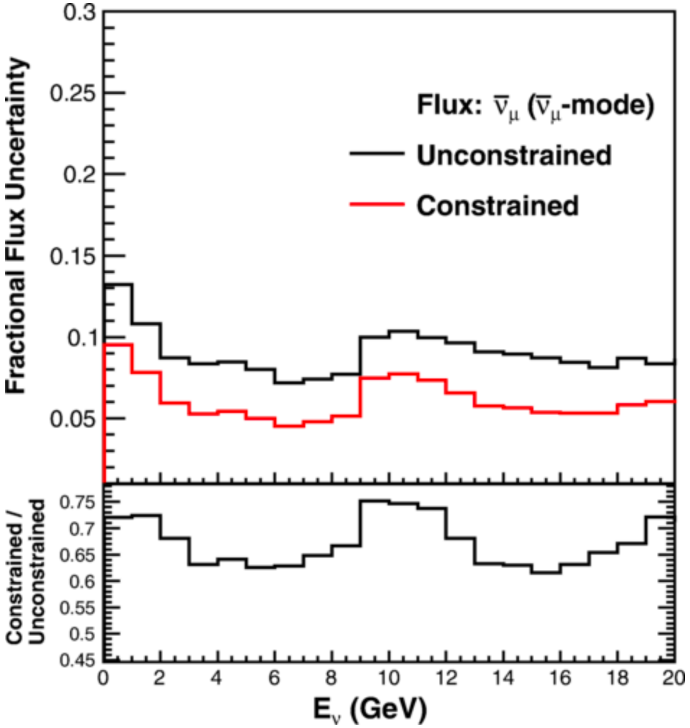


- **Thin target experiments [cite] data to correct HP processes.**
- **Uncertainty based on data applied to each interaction type.**
  - *Might need plot approval on lower plot (unc from gen2thin (-14) minervame6A)

MINERvA Flux Strategy



a priori anti neutrino Flux before and after constrained by νe scattering data



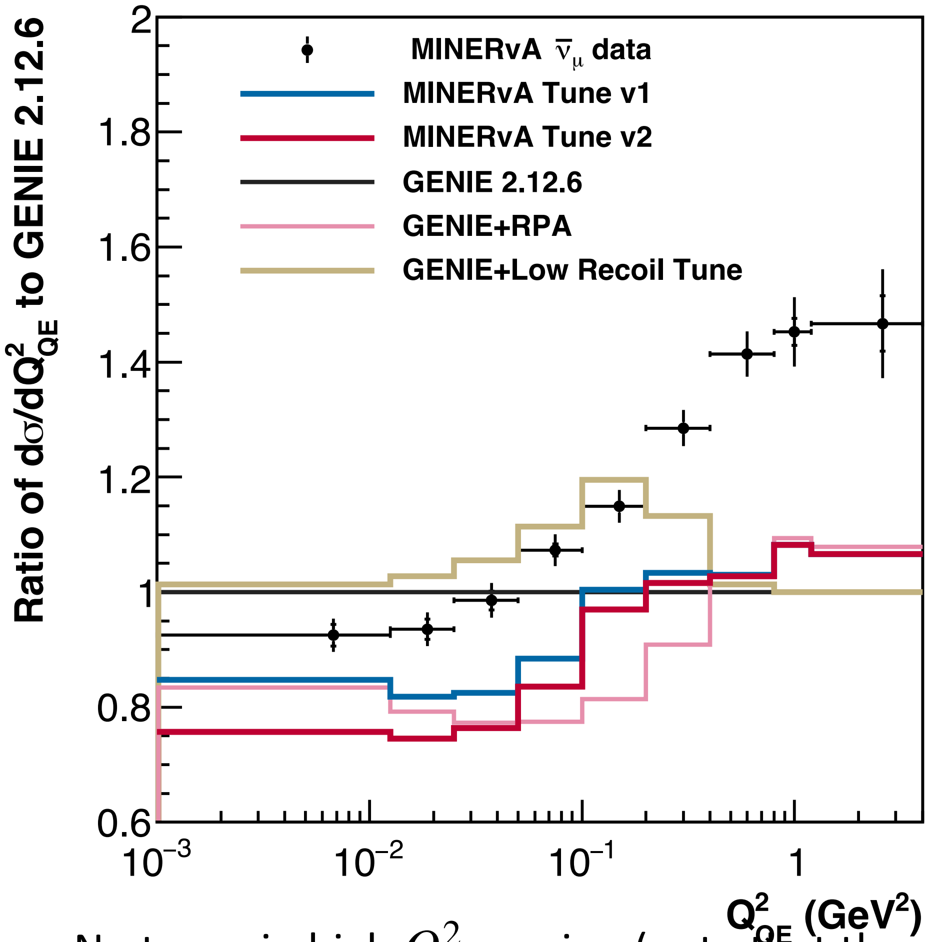
Uncertainty on predicted anti neutrino flux before and after constrained by νe scattering data

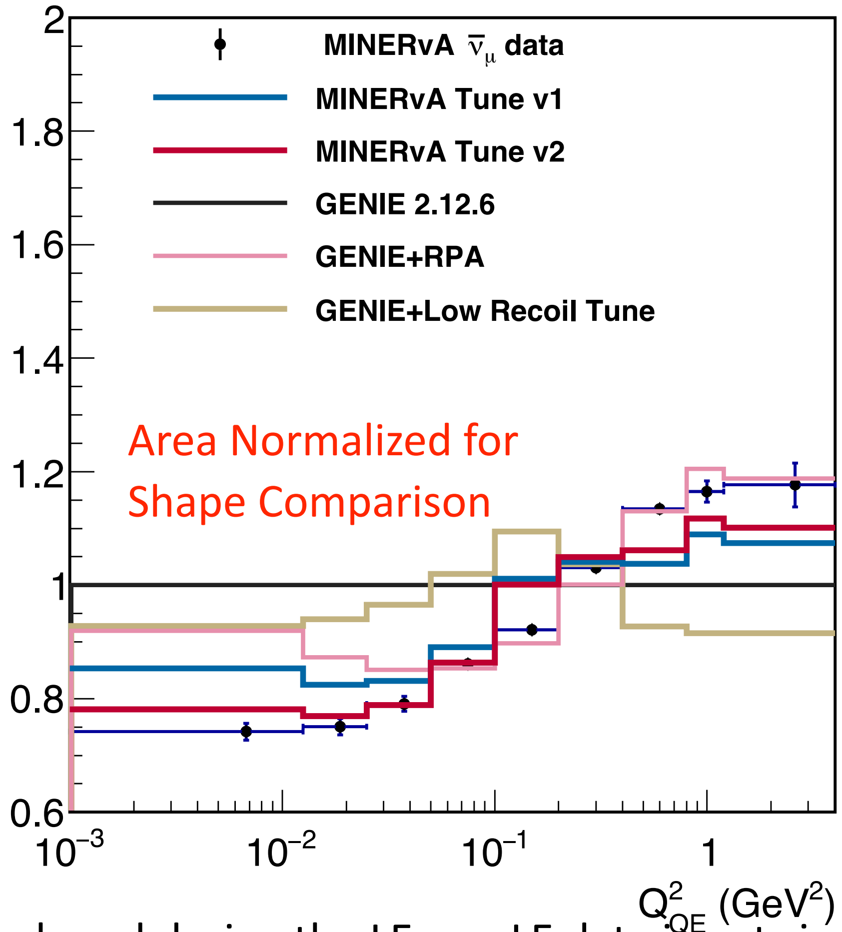
- ν+e constraint [PRD 107,012001]
  - $\nu e \rightarrow \nu e$
- Inverse Muon Decay [PRD 104,092010]
  - $\nu_\mu e^- \rightarrow \mu^- \nu_e$

Neutrino Flux (left) and uncertainty before and after IMD constraint.

Because of $E_\nu \cong 11$ GeV, only constrain high energy region.

Cross section (Q^2_{QE}) : MINERvA Tunes





MnvTune v2 = MnvTune v1 + Pion Production suppression Low Q^2 based on P. Stowell, arXiv:1903.01558.

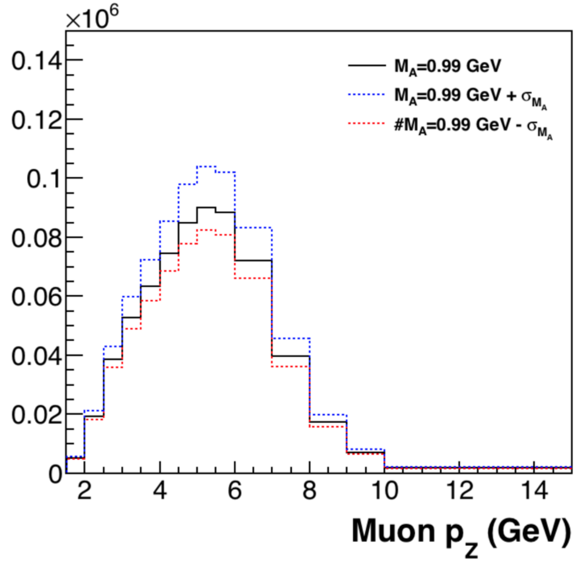
No tunes in high Q^2_{QE} region (note that they were developed during the LE era: LE data is not significant in this region).

Plots show that our tunes predict the shape of the distribution relatively well (right) compared to absolute distribution.

Systematic Uncertainties

Reconstruction Related Uncertainties:
Uncertainties related to reconstruction of blobs, tracks, PID etc

GENIE Model Related Uncertainties
Uncertainties coming from GENIE models to model neutrino interactions.
They get propagated to our data during background subtraction, efficiency correction and unfolding.



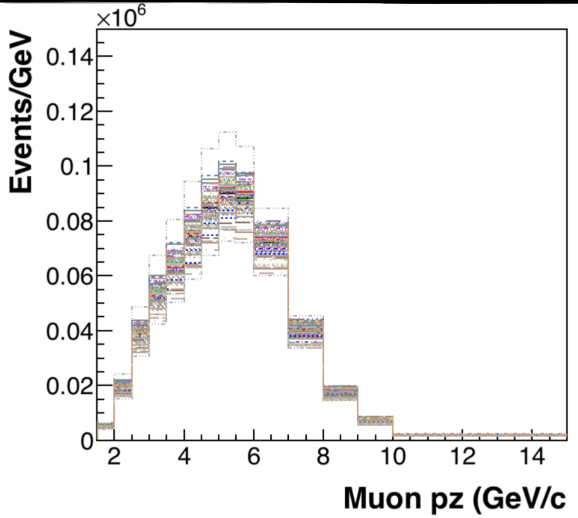
A GENIE M_A related systematic

Two Universe Method

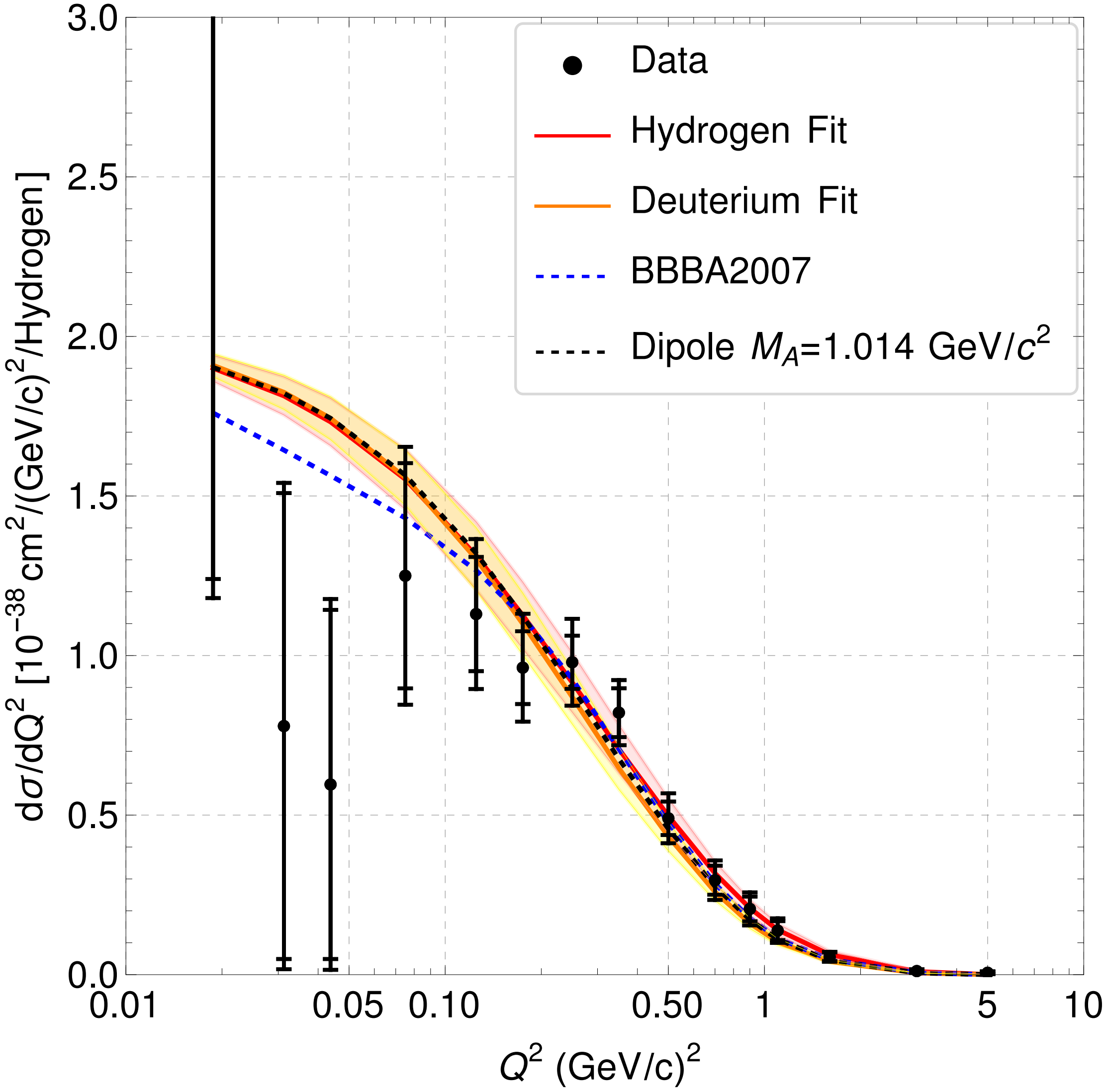
- Shift the **parameter by** $\pm 1\sigma$
- Get the alternate distributions (universe).
- Calculate uncertainty from the spread relative to central value (CV) universe.

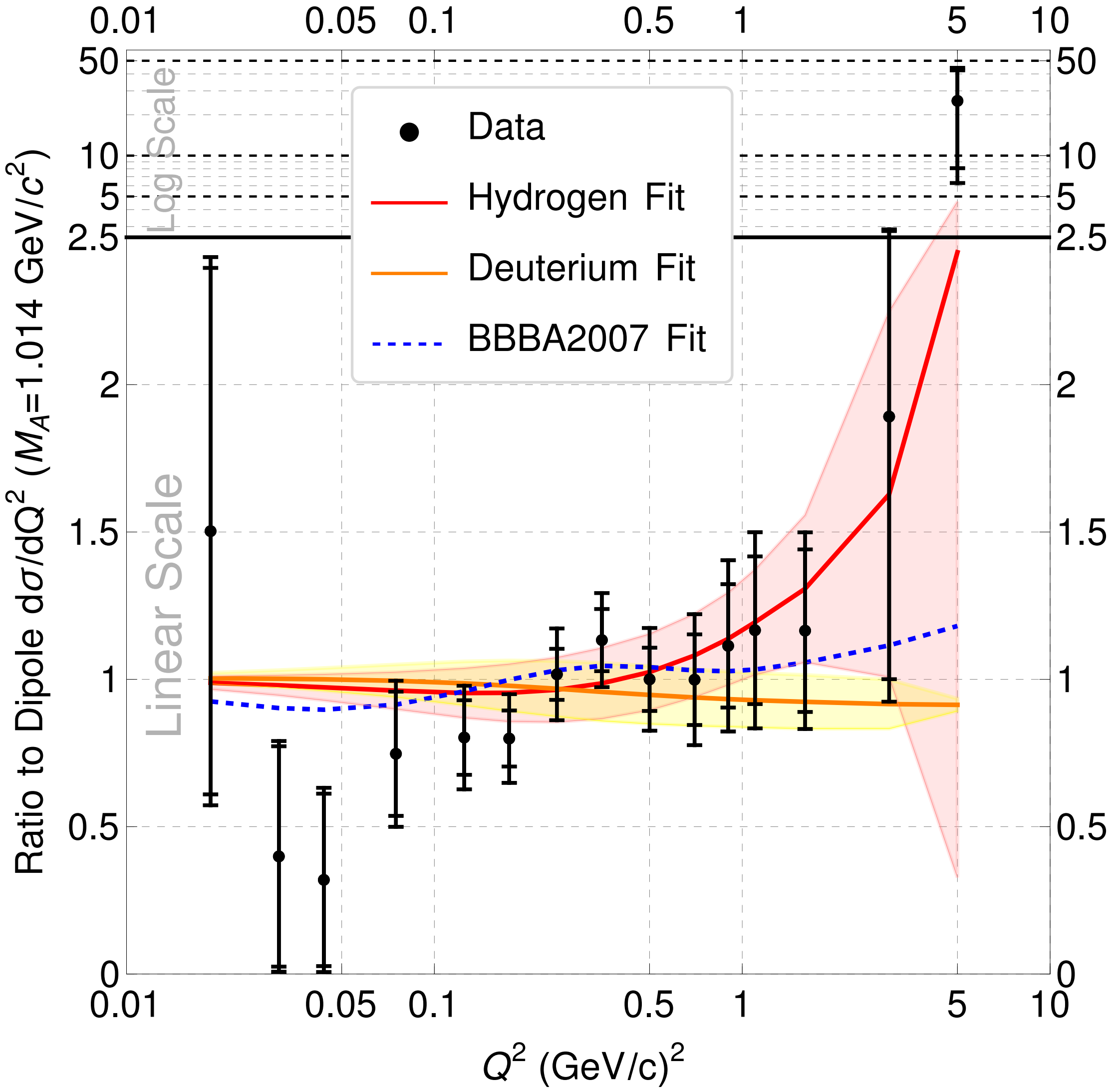
Flux Uncertainties (Already covered):
- Focusing Uncertainties
- Hadron Production Uncertainties

Multi Universe Method



- Many parameters (correlated)
- Shift parameters within $\pm 1\sigma$
- Generate **N** universes (500 in this analysis)
- Calculate uncertainty from the spread of the distribution.


Data
Hydrogen Fit
Deuterium Fit
BBBA2007
Dipole M_A=1.014 GeV/c^2
dσ/dQ^2 [10^{-38}cm^2/(GeV/c)^2/Hydrogen]
Q^2 (GeV/c)^2


Data
Hydrogen Fit
Deuterium Fit
BBBA2007 Fit
Log Scale
Linear Scale
Ratio to Dipole dσ/dQ^2 (M_A=1.014 GeV/c^2)
Q^2 (GeV/c)^2

$\bar{\nu}_\mu$ CCQE (H) Cross-section

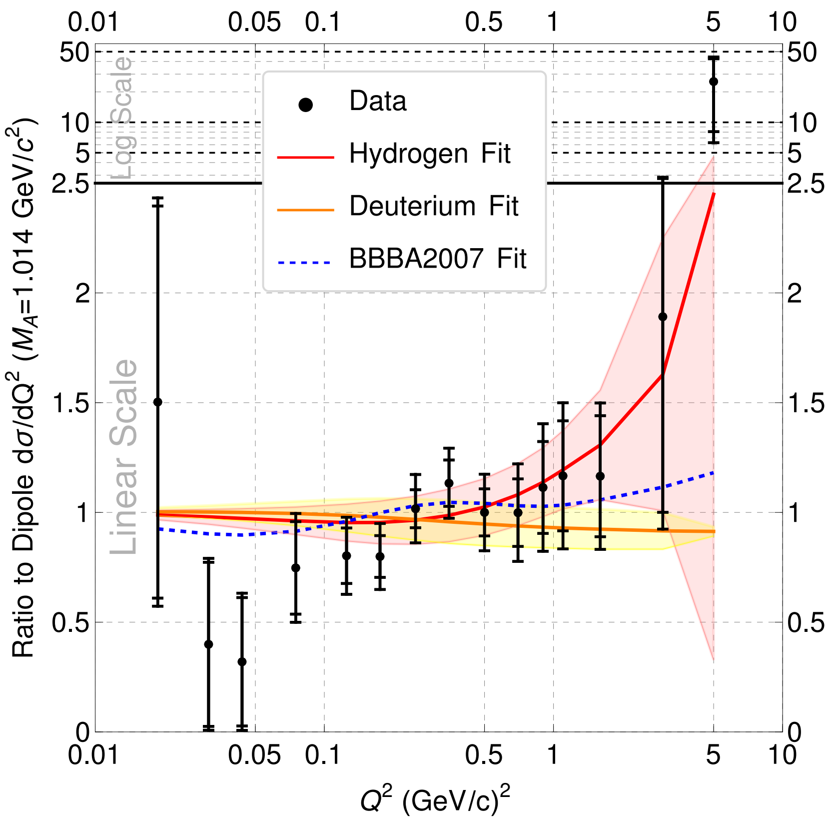
Article | Open Access | Published: 01 February 2023

Measurement of the axial vector form factor from antineutrino–proton scattering

T. Cai, M. L. Moore, A. Olivier, S. Akhter, Z. Ahmad Dar, V. Ansari, M. V. Ascencio, A. Bashyal, A. Bercellie, M. Betancourt, A. Bodek, J. L. Bonilla, A. Bravar, H. Budd, G. Caceres, M. F. Carneiro, G. A. Díaz, H. da Motta, J. Felix, L. Fields, A. Filkins, R. Fine, A. M. Gago, H. Gallagher, ... L. Zazueta

+ Show authors

Recent W&C Seminar by T. Cai on F_A extraction from Hydrogen atoms (Free Nucleon)

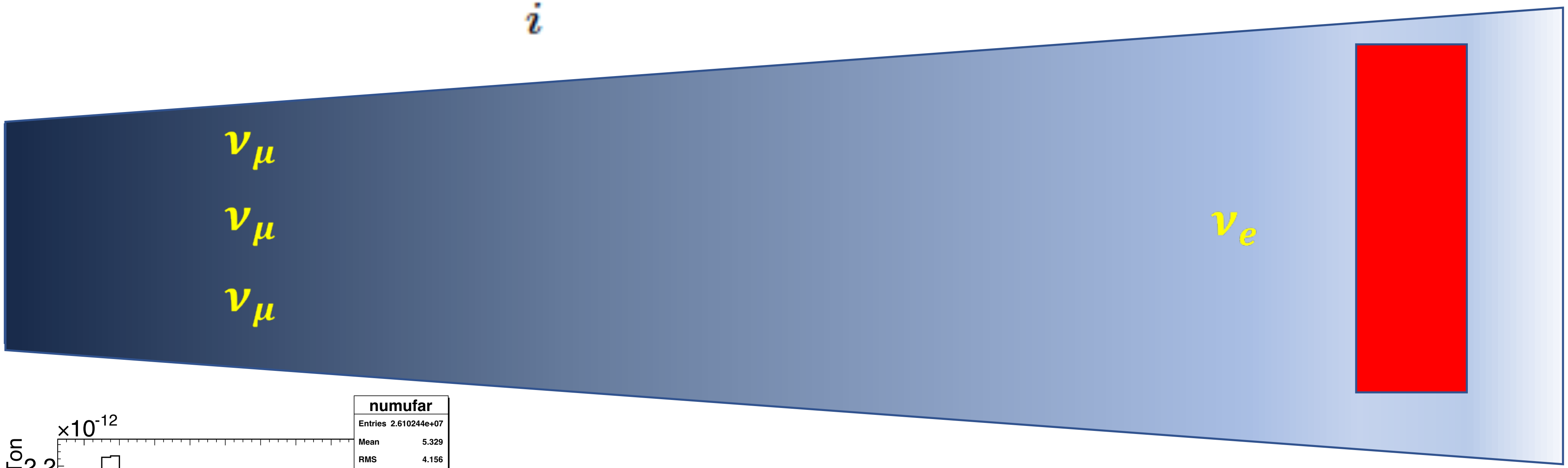


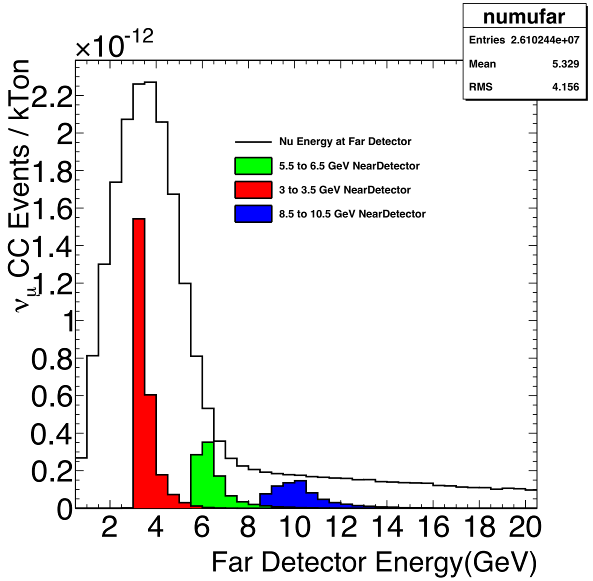
F_A → **Axial Form Factor**

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

- **Based on bubble chamber** (hydrogen targets) measurements
- Measurements in **heavier target** report slightly **higher axial mass**
  - **Nuclear Effects**
- Dipole Form Factor approximation breaks at high Q^2

$$N_e(E_{rec}, L) \propto \sum_i \Phi_e(E, L)\sigma_i(E) f_{\sigma i}(E, Erec) dEdM$$

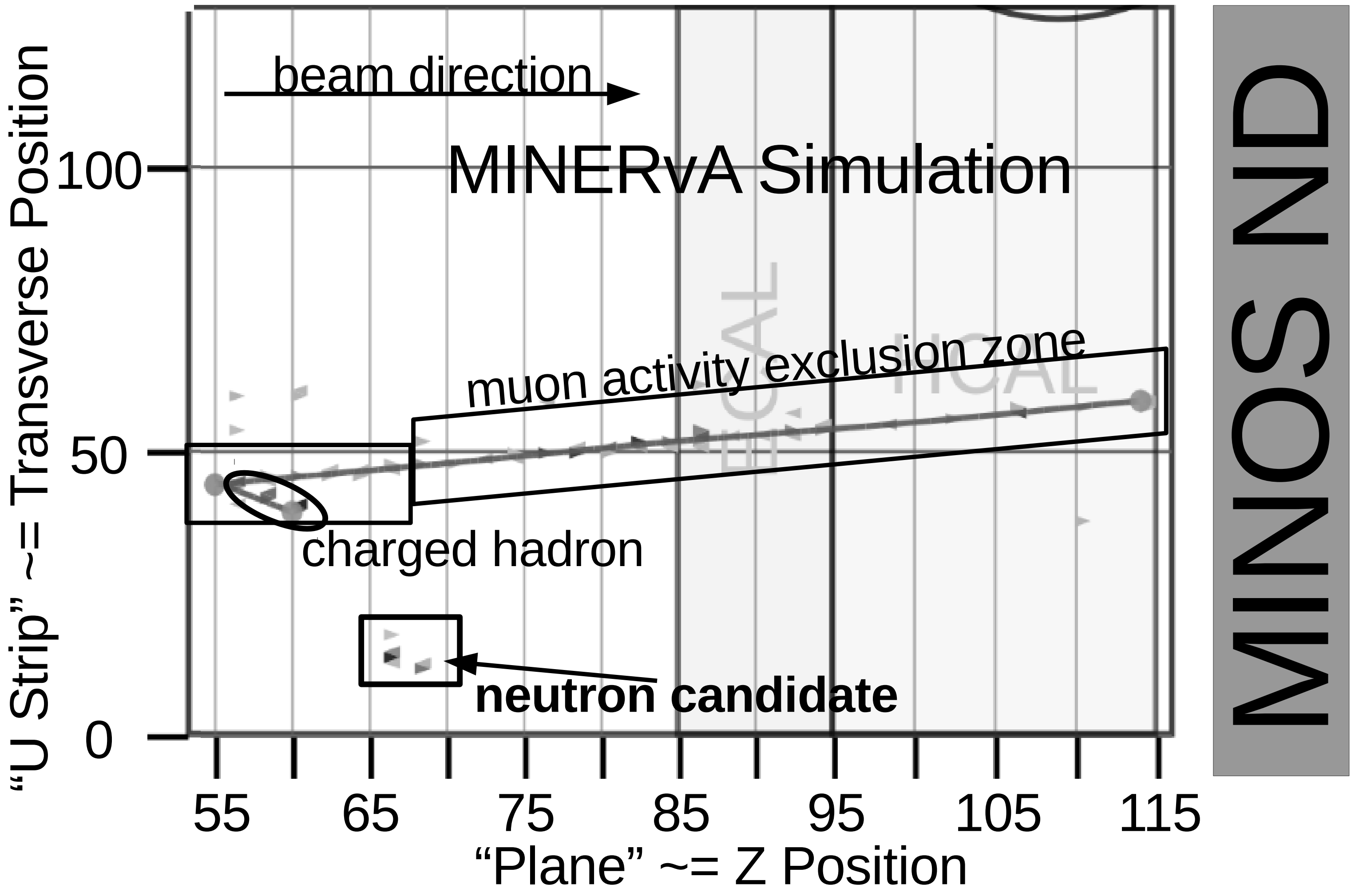




- Near and Far Detector will see different neutrino energy spectra.
- Different **nuclear effects** for same E_{rec} at Near and Far Detector.
- $\sigma_{Near} \neq \sigma_{Far}$ for the same E_{rec}
  - Need to understand the nuclear effects in heavy nucleus.

MINERvA was designed to study the poorly understood neutrino-heavy nucleus interactions

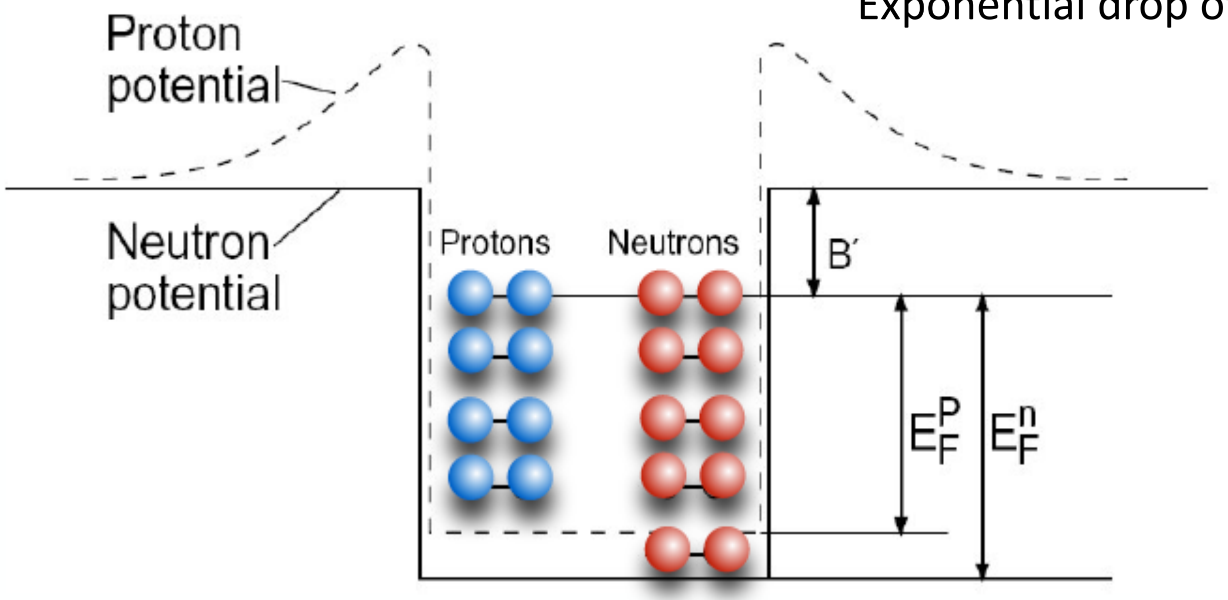
Neutron Reconstruction in MINERvA



Paper in Preparation to submit to the PRD.

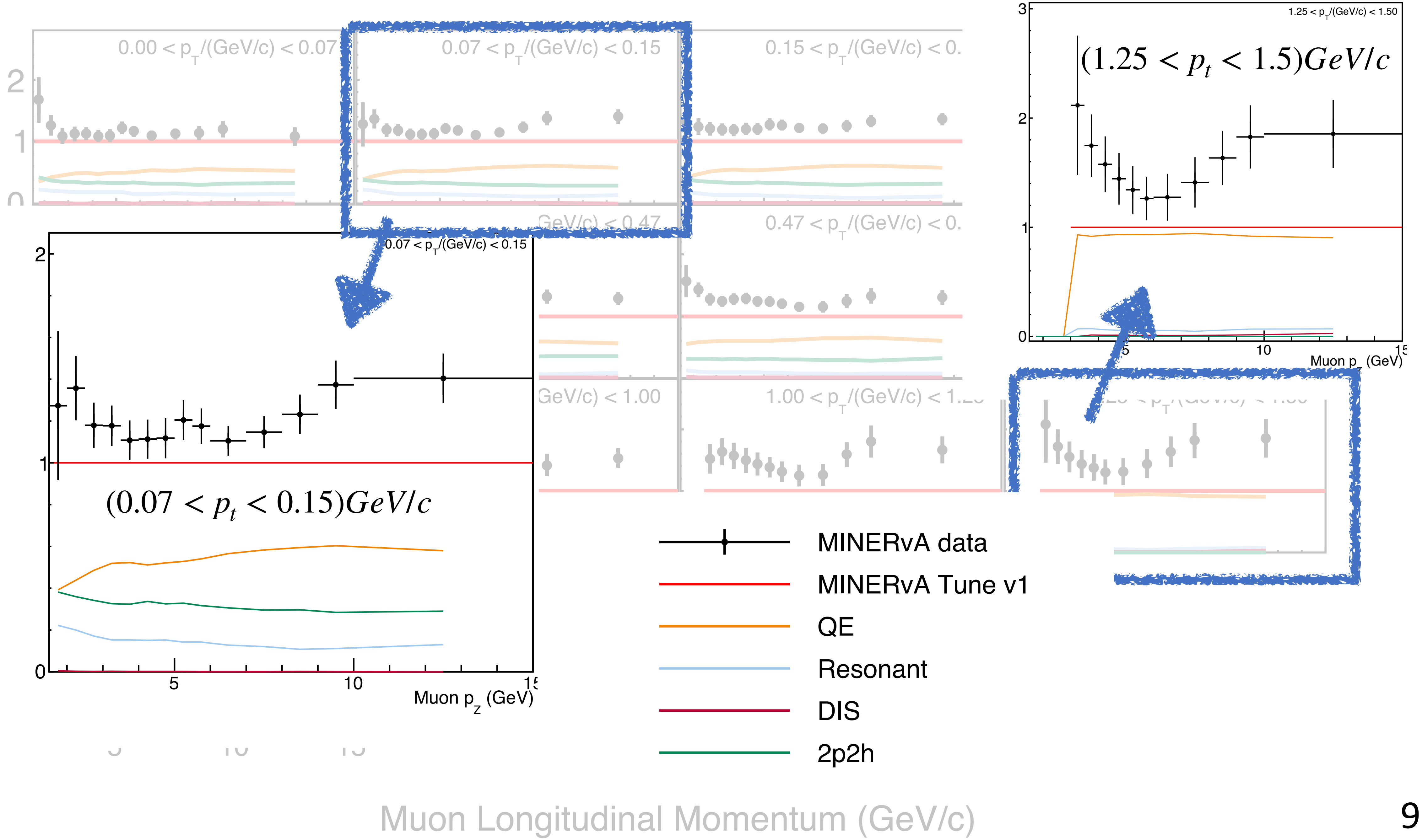
Nucleus and Nucleons: Relativistic Fermi Gas Model

Exponential drop of proton potential due to coulomb potential



Relativistic Fermi Gas:

- Nucleons as independent particles with some fermi momentum in a mean field generated by the rest of the nucleus.
- Nucleons can interact with other nucleons.


0.00 < p_T/(GeV/c) < 0.07
0.07 < p_T/(GeV/c) < 0.15
0.15 < p_T/(GeV/c) < 0.
0.47 < p_T/(GeV/c) < 0.
1.00 < p_T/(GeV/c) < 1.
1.25 < p_T/(GeV/c) < 1.50
(1.25 < p_t < 1.5)GeV/c
(0.07 < p_t < 0.15)GeV/c
Muon p_z (GeV)
MINERvA data
MINERvA Tune v1
QE
Resonant
DIS
2p2h
Muon Longitudinal Momentum (GeV/c)