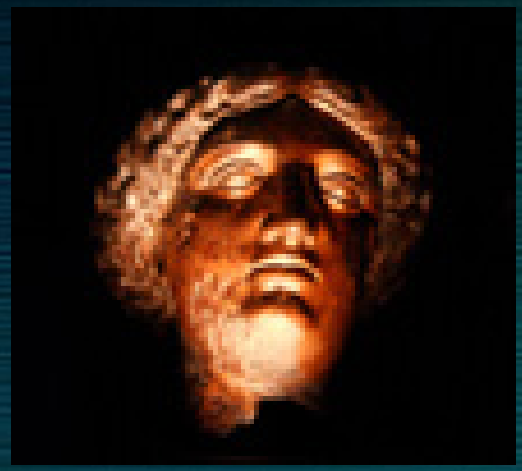
Low Energy (3.5 GeV) CCQE Results from MINERvA



Mehreen Sultana

New Perspectives @ Fermilab

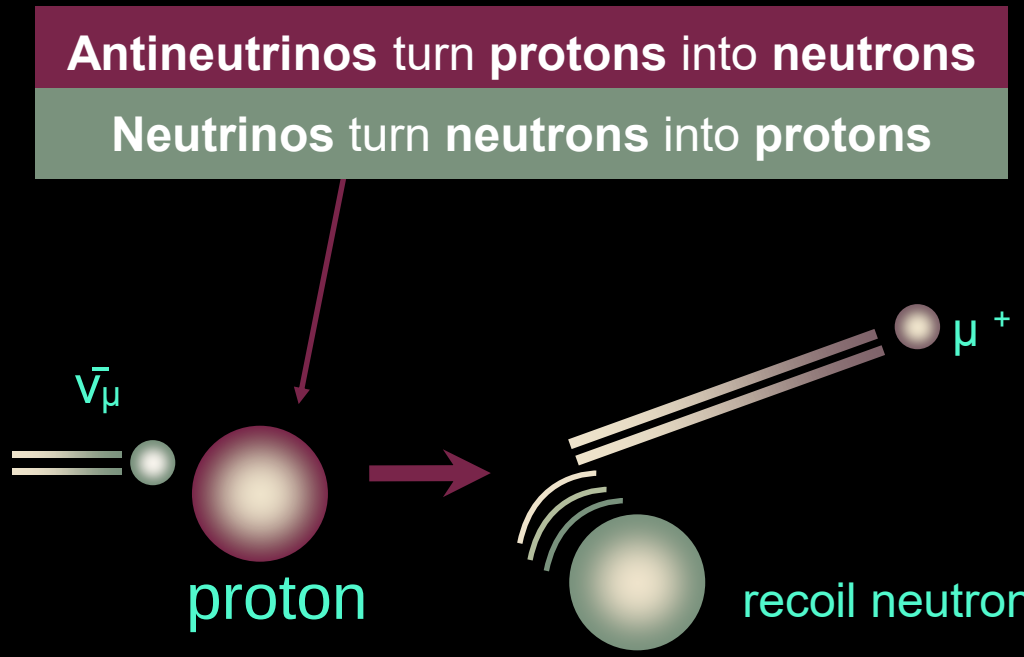
June 5th, 2017

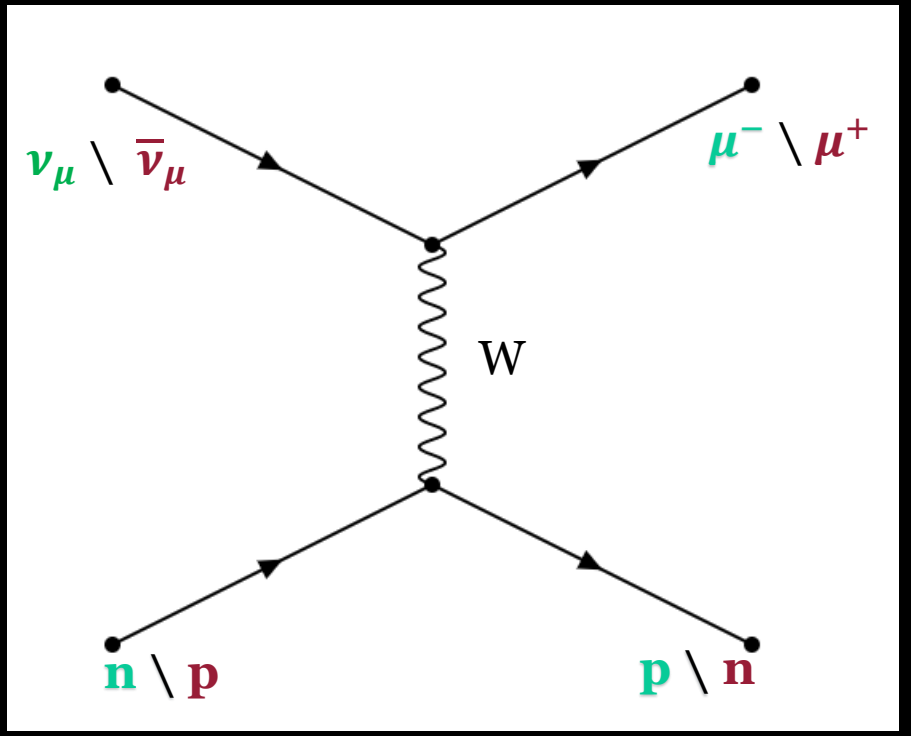
UNIVERSITY of ROCHESTER

What is CCQE? Charged Current Quasi-Elastic Scattering from nucleons

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

A relatively "simple" interaction process





Assumes elastic scattering from a free, stationary nucleon

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

WHY CCQE?

Some oscillation experiments **reconstruct the neutrino energy and 4-momentum transfer Q^2** from just the **muon kinematics**

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

Some experiments have to assume these kinematics.
(T2K, Not much information from protons)

DUNE will be able to see more details.

MINERvA can measure model independent observables to tune current nuclear models.

SIMULATION: GENIE 2.8.4 (Tweaked)

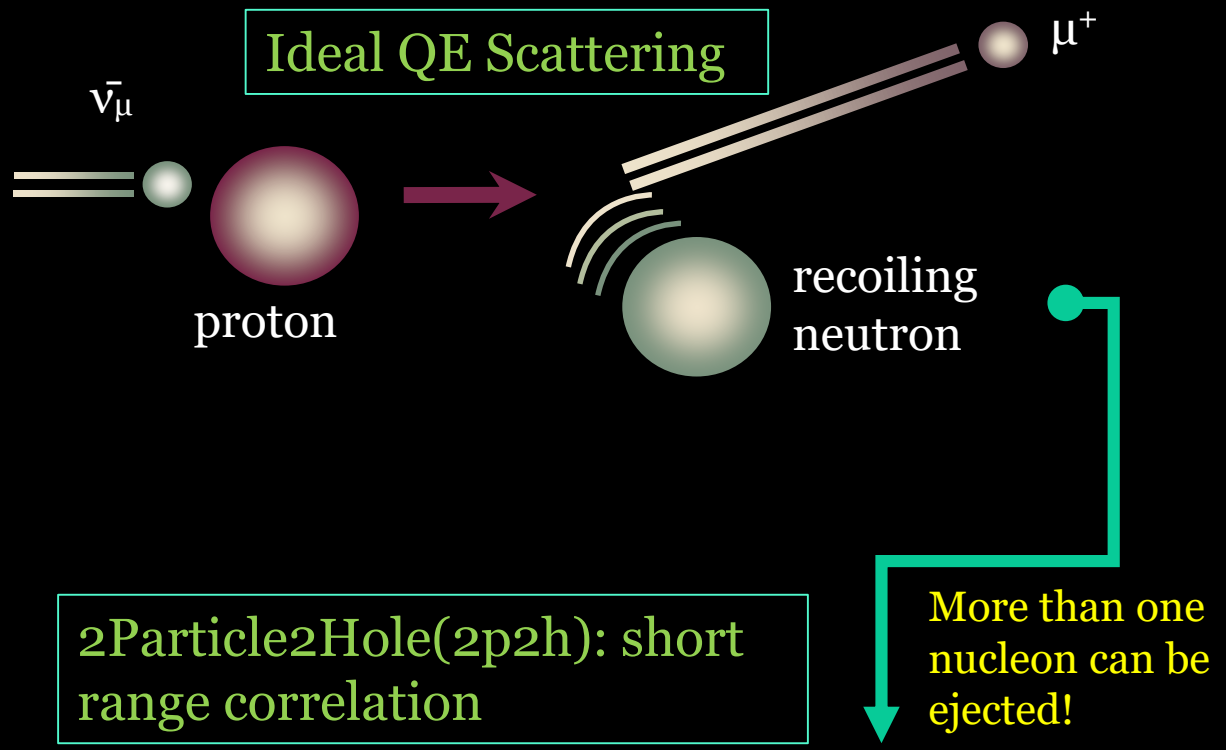
Quasi-elastic scattering from nuclei is simulated using:

- Relativistic Fermi Gas model with Bodek-Ritchie tail
- Axial mass M_A=0.99 GeV
- Fermi momentum k_F=221MeV

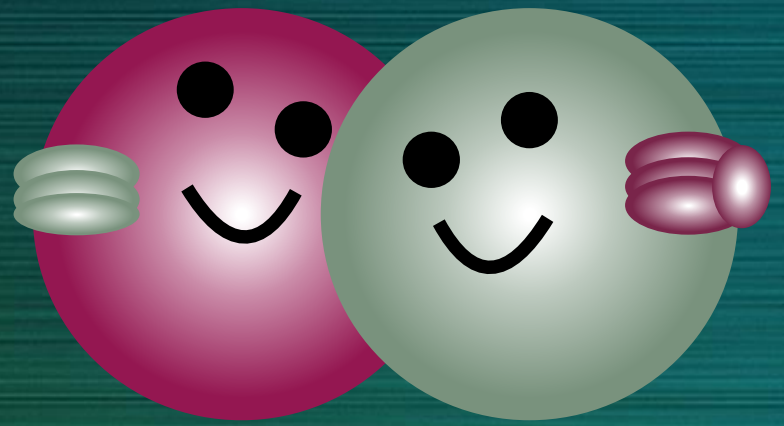
But there are more nuclear effects that we need!

(add in Valencia 2p2h model)

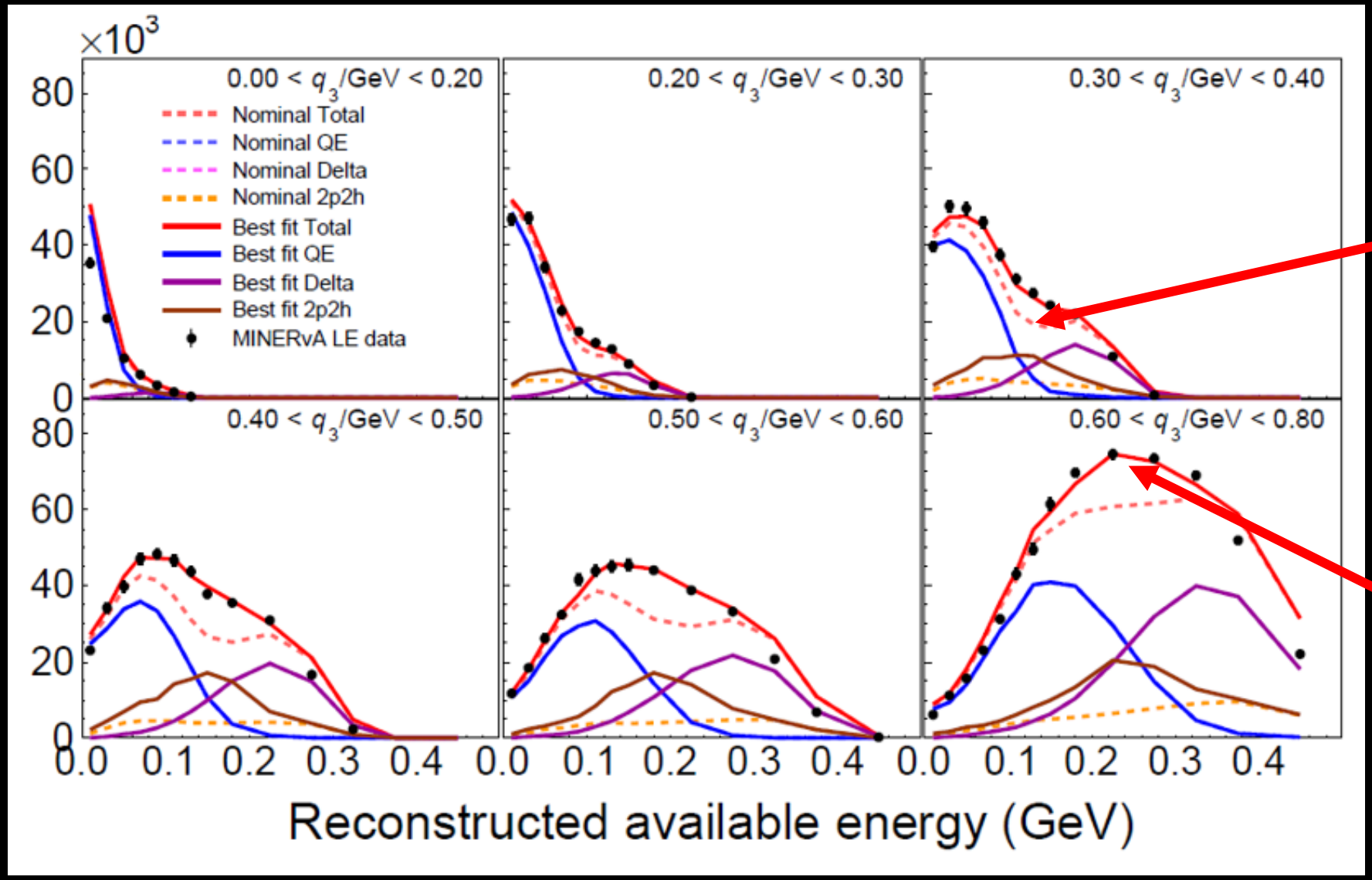
What are these effects?



Additional nuclear interactions due to correlated nucleon pairs!



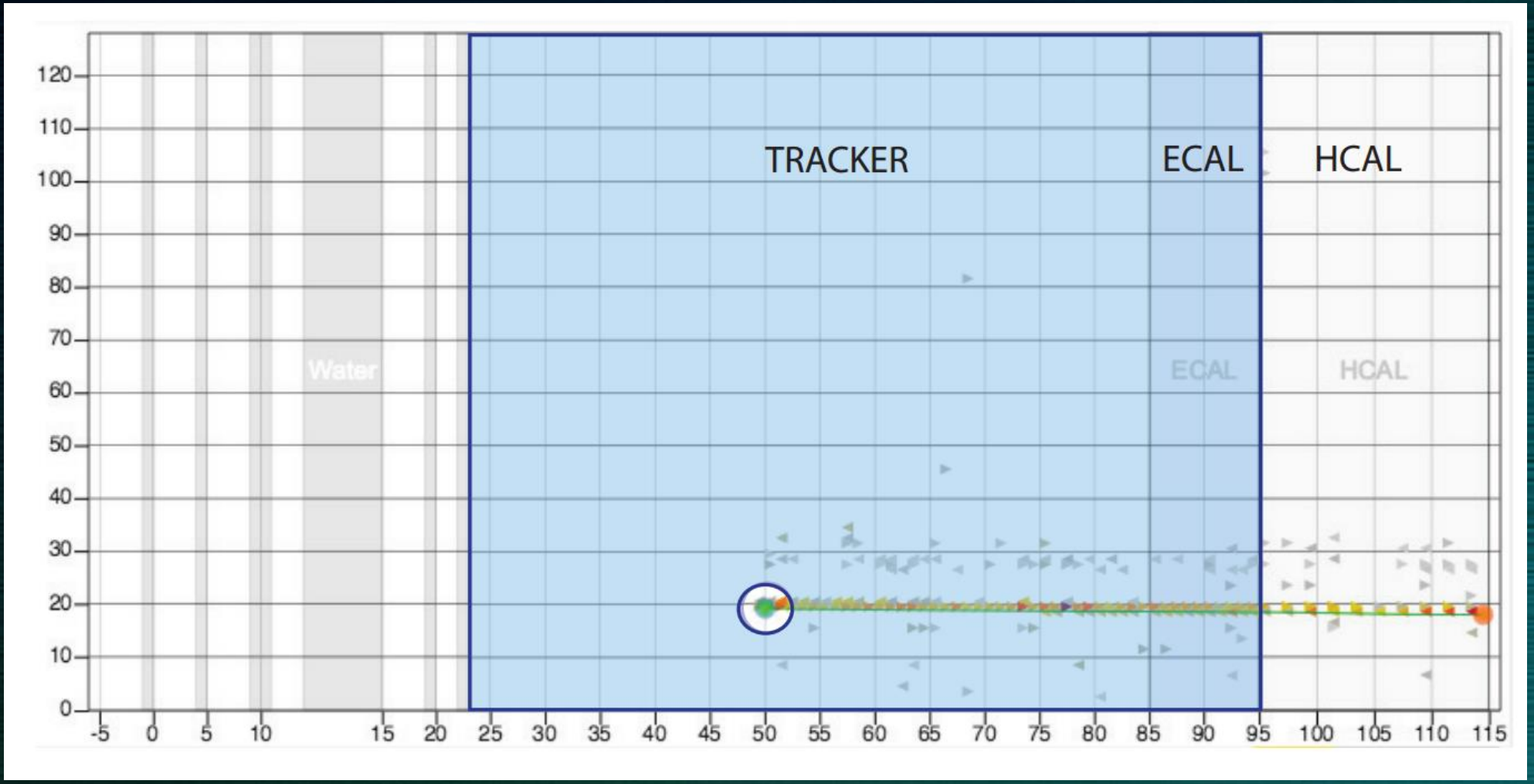
2p2h nuclear effects to our GENIE Modification: Neutrinos



Nominal 2p2h is not enough

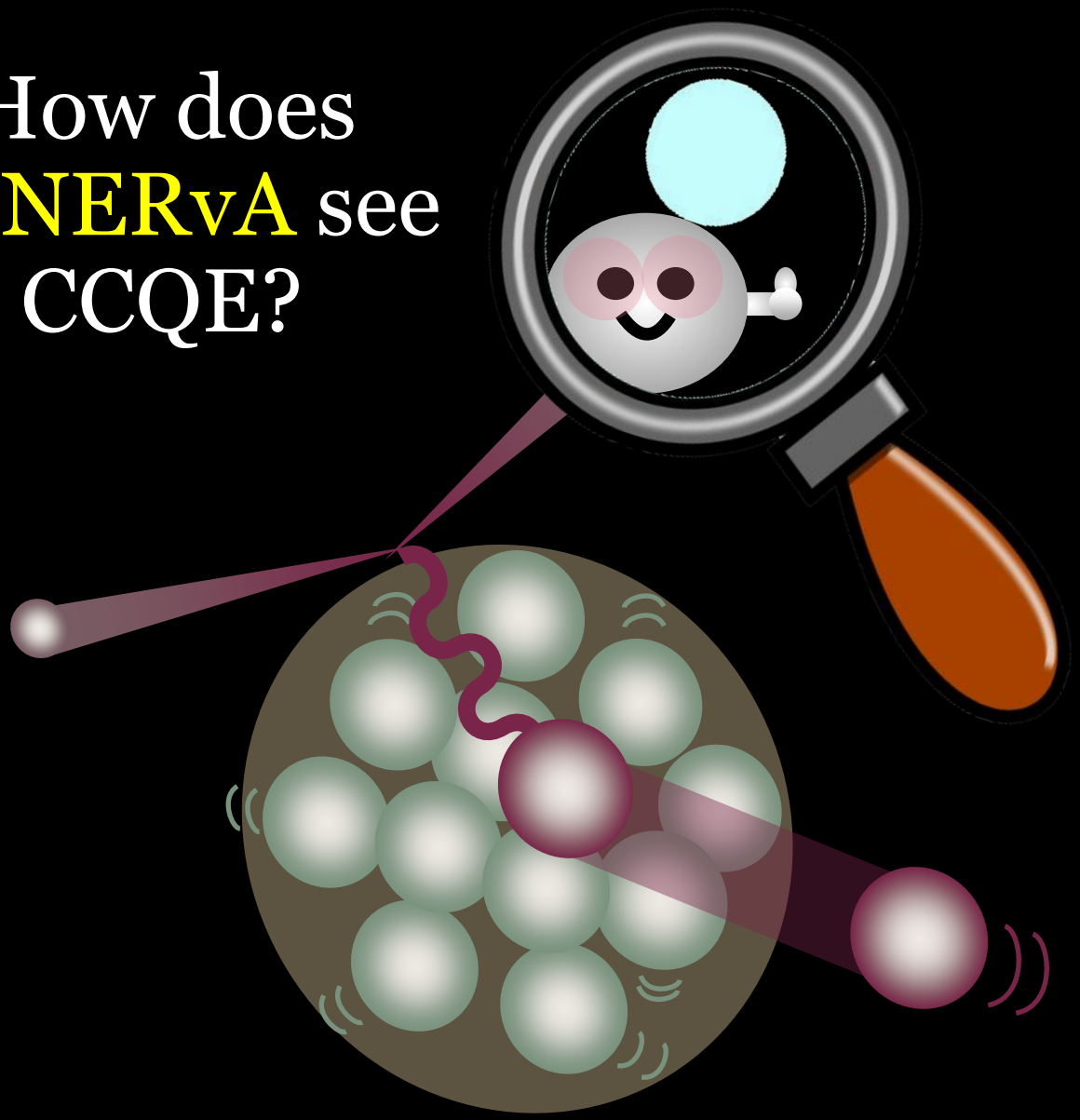
Low energy recoil fit applied to match data

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



Recoil energy region is shown in blue
Defined as reconstructed energy from clusters not in the muon track (and are not low activity/crosstalk)

How does MINERvA see CCQE?

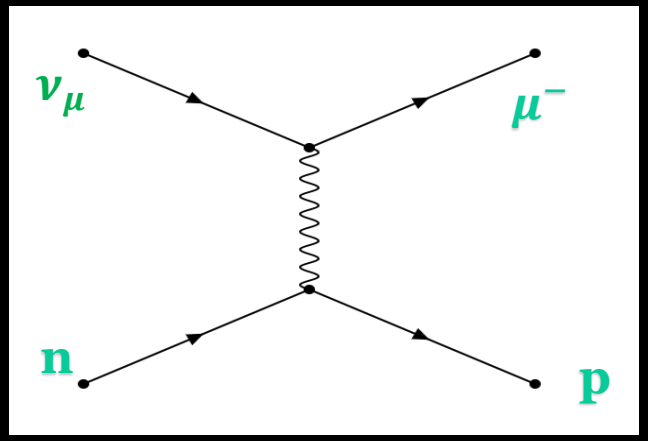


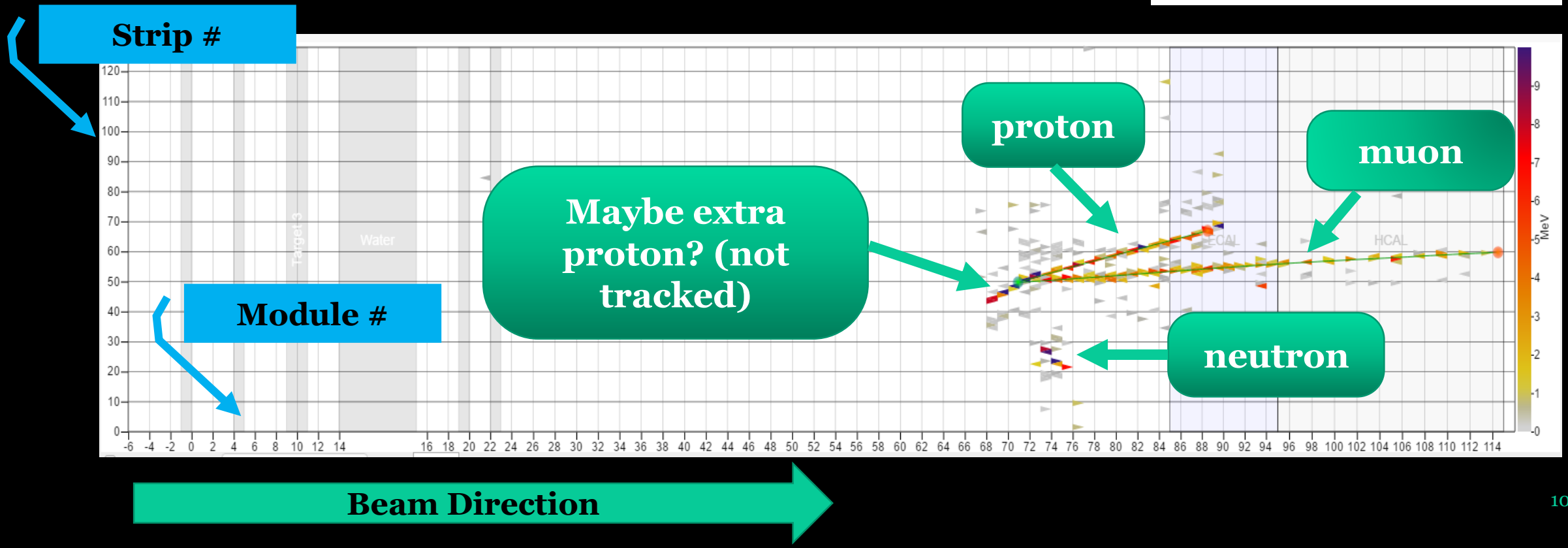
- Find muons
  - MINOS matched
- Any number of neutrons.
- No pions!
- Try not to remove events with neutrons

Event Selection: Neutrinos

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

- Muon matched in MINOS as μ-
- Track protons and pions
  - No Michel electrons
- Only 1 isolated energy deposit
- Protonlike tracks (no charged pions)



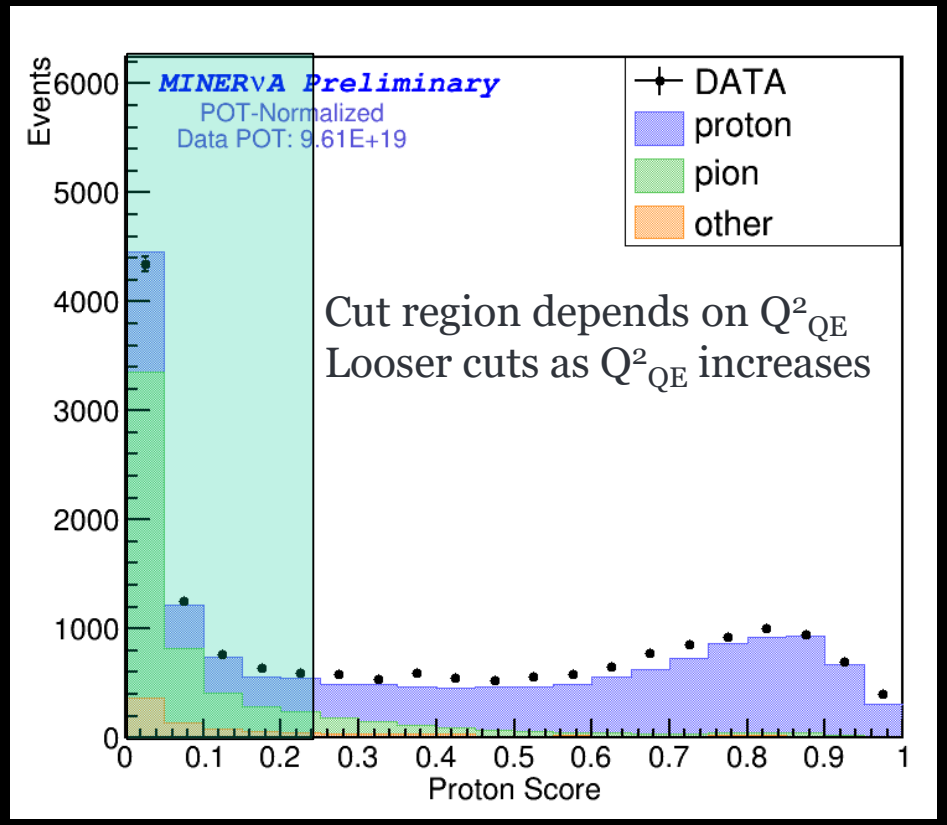


Examples of Cuts

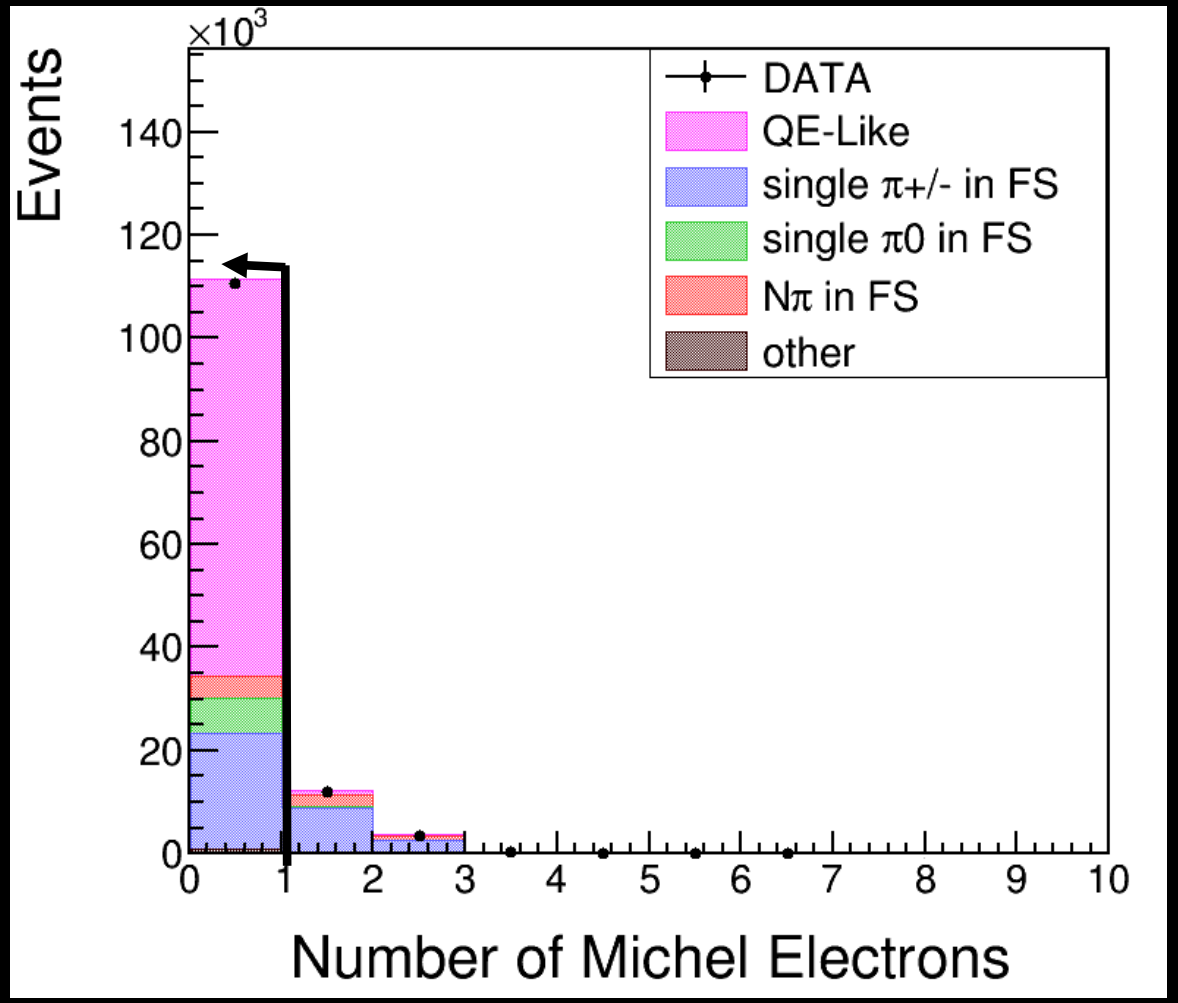
- This is how events with pions are removed
- Energy deposited by the particle long the track in the detector

This is applied to all tracks which are not the muon

Integrated over Q^2_{qe}

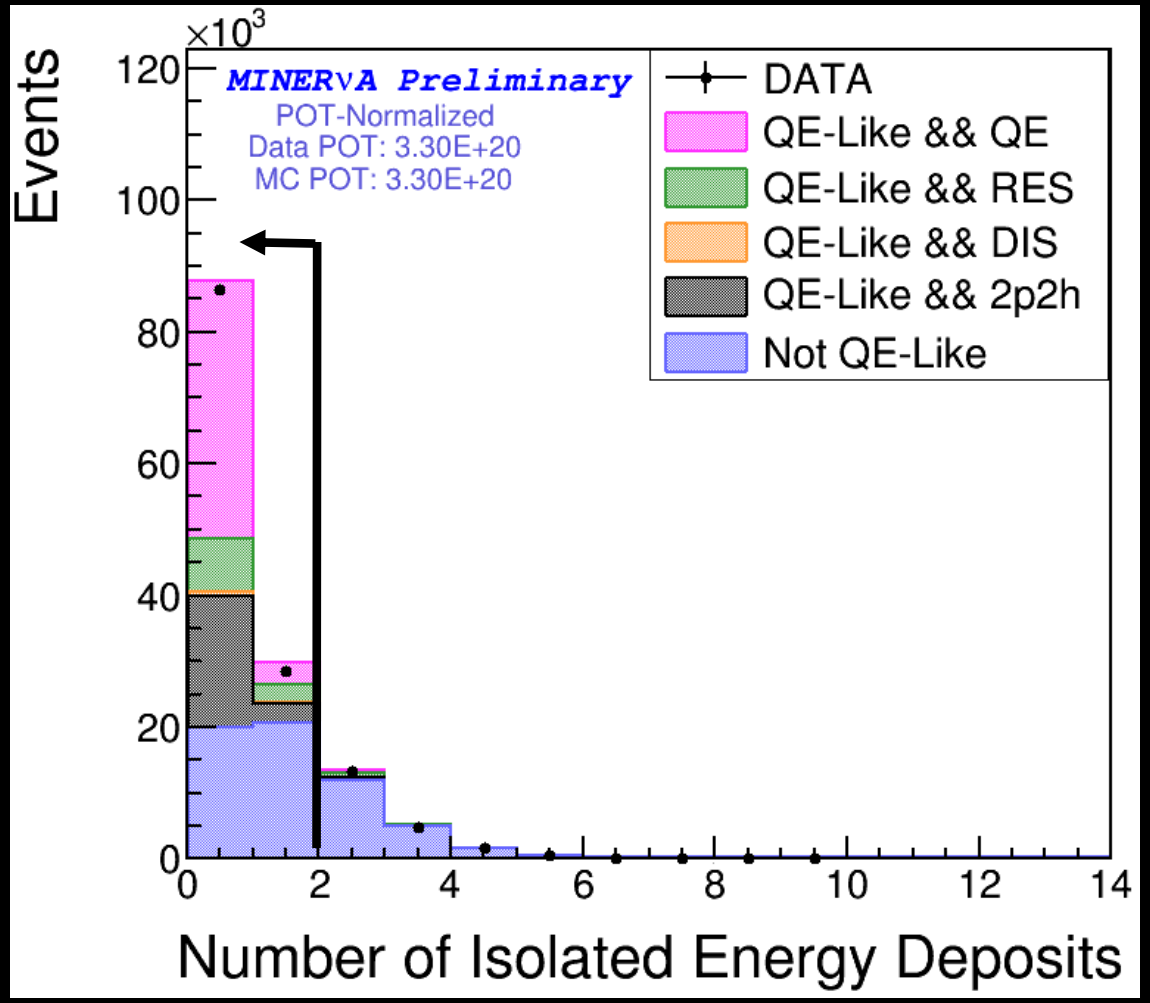


Examples of Cuts



Reject events with Michel electrons

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



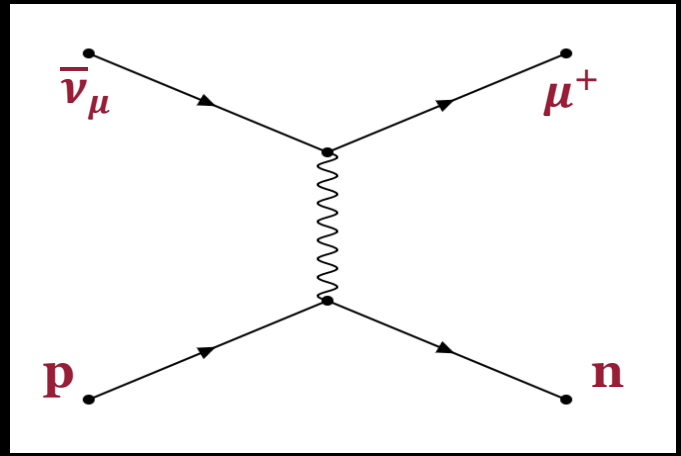
Reject events with 2 or more isolated clusters

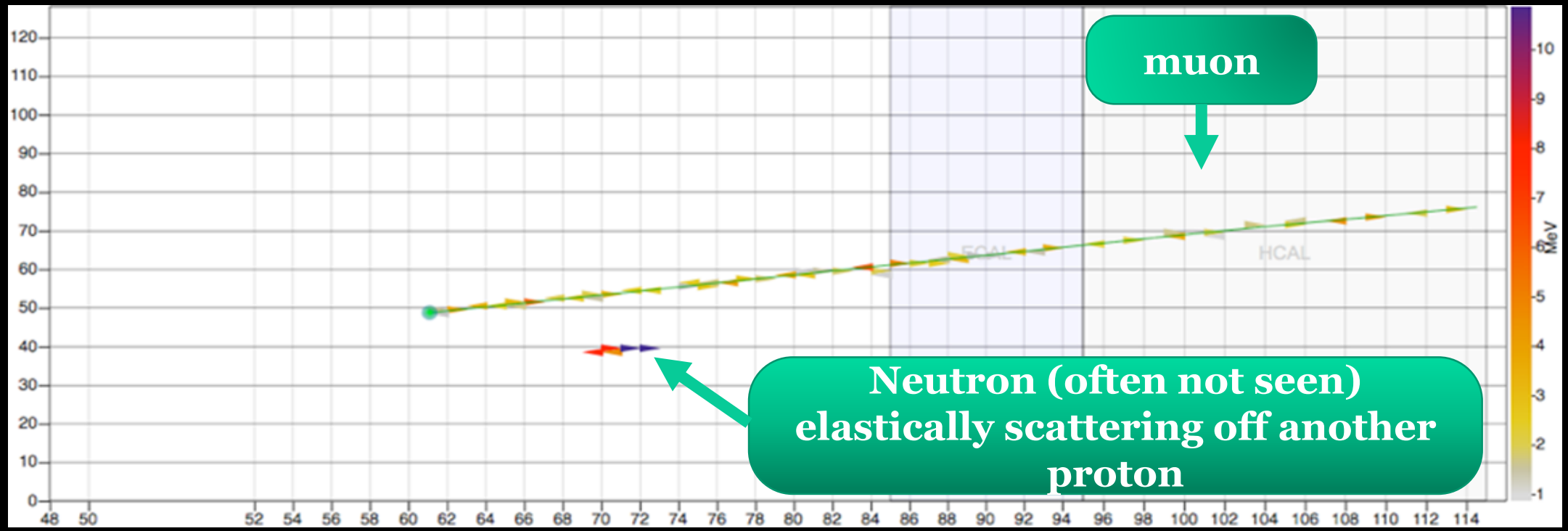
$\pi^0 \rightarrow \gamma\gamma$

Event Selection: Anti-Neutrinos

$$\overline{\nu_\mu} + p \longrightarrow \mu^+ + n$$

- No additional tracks at vertex
- Muon track matched in MINOS as μ+
- Ejected neutron won't make track from vertex
- Proton recoil energy > 120 MeV (cannot reconstruct well below this energy)





Double differential cross section $\frac{d^2\sigma}{dxdy}$

Generated in true bins *(i,j)*, from data in reconstructed bins *(α,β)*:

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

HOW?

1. Plot the **reconstructed event distribution** with selection cuts

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HOW?

1. Plot the **reconstructed event distribution** with selection cuts
2. Subtract **backgrounds**

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3. **Unfold** data to move events from reconstructed to true bins

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HOW?

1. Plot the **reconstructed event distribution** with selection cuts
2. Subtract **backgrounds**
3. **Unfold** data to move events from reconstructed to true bins
4. Correct for **efficiency** and acceptance

Double differential cross section $\frac{d^2\sigma}{dxdy}$

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HOW?

1. Plot the **reconstructed event distribution** with selection cuts
2. Subtract **backgrounds**
3. **Unfold** data to move events from reconstructed to true bins
4. Correct for **efficiency** and acceptance
5. Divide by neutrino **flux** and number of **targets**

Double differential cross section $\frac{d^2\sigma}{dxdy}$

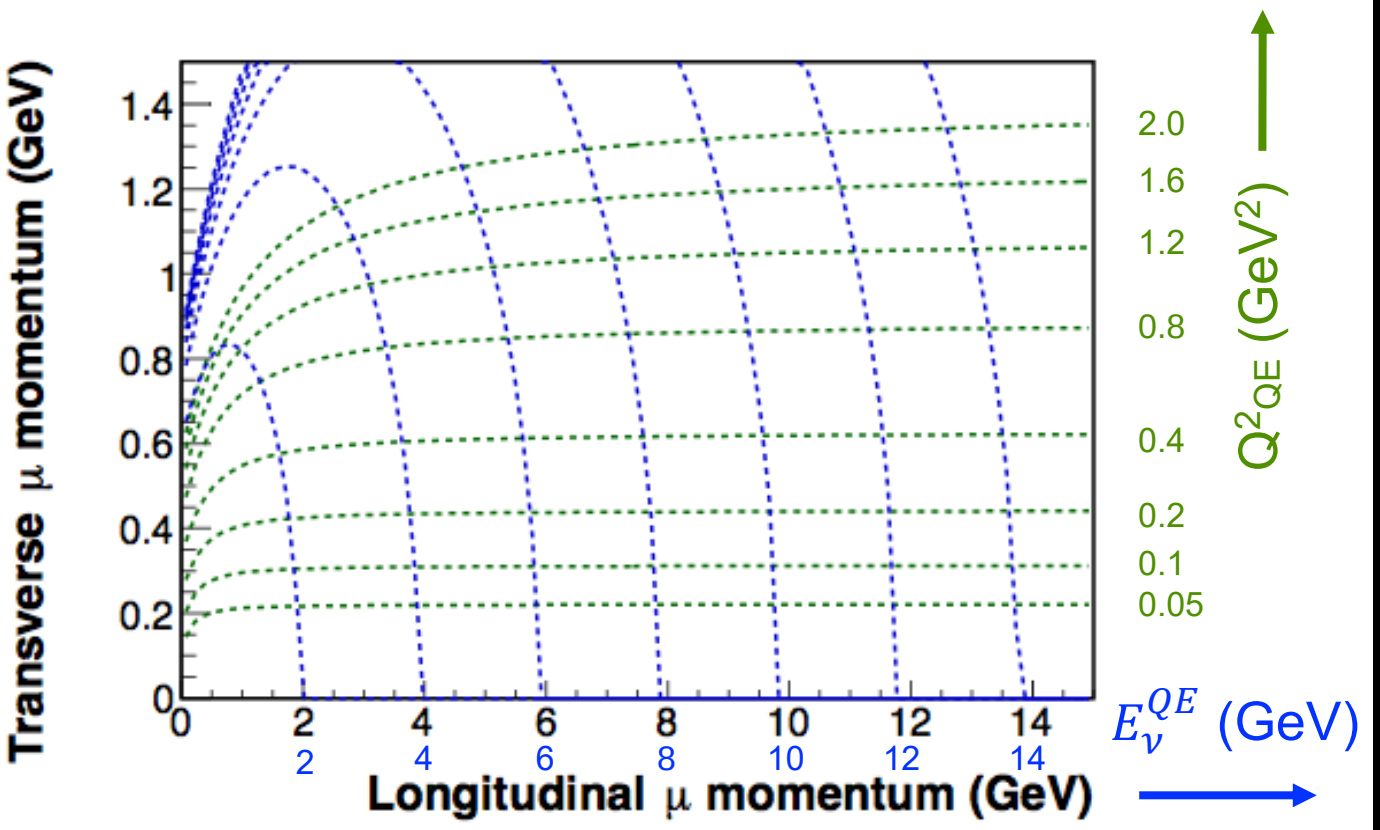
Generated in true bins *(i,j)*, from data in reconstructed bins *(α,β)*:

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

HOW?

1. Plot the **reconstructed event distribution** with selection cuts
2. Subtract **backgrounds**
3. **Unfold** data to move events from reconstructed to true bins
4. Correct for **efficiency** and acceptance
5. Divide by neutrino **flux** and number of **targets**
6. Present **bin-width normalized**

How does interaction probability vary in two dimensions?



Muon transverse/longitudinal momentum

- Muon p_T and $p_{||}$ are measurable quantities
- Good phase space coverage

Measuring A Double Differential Cross Section

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

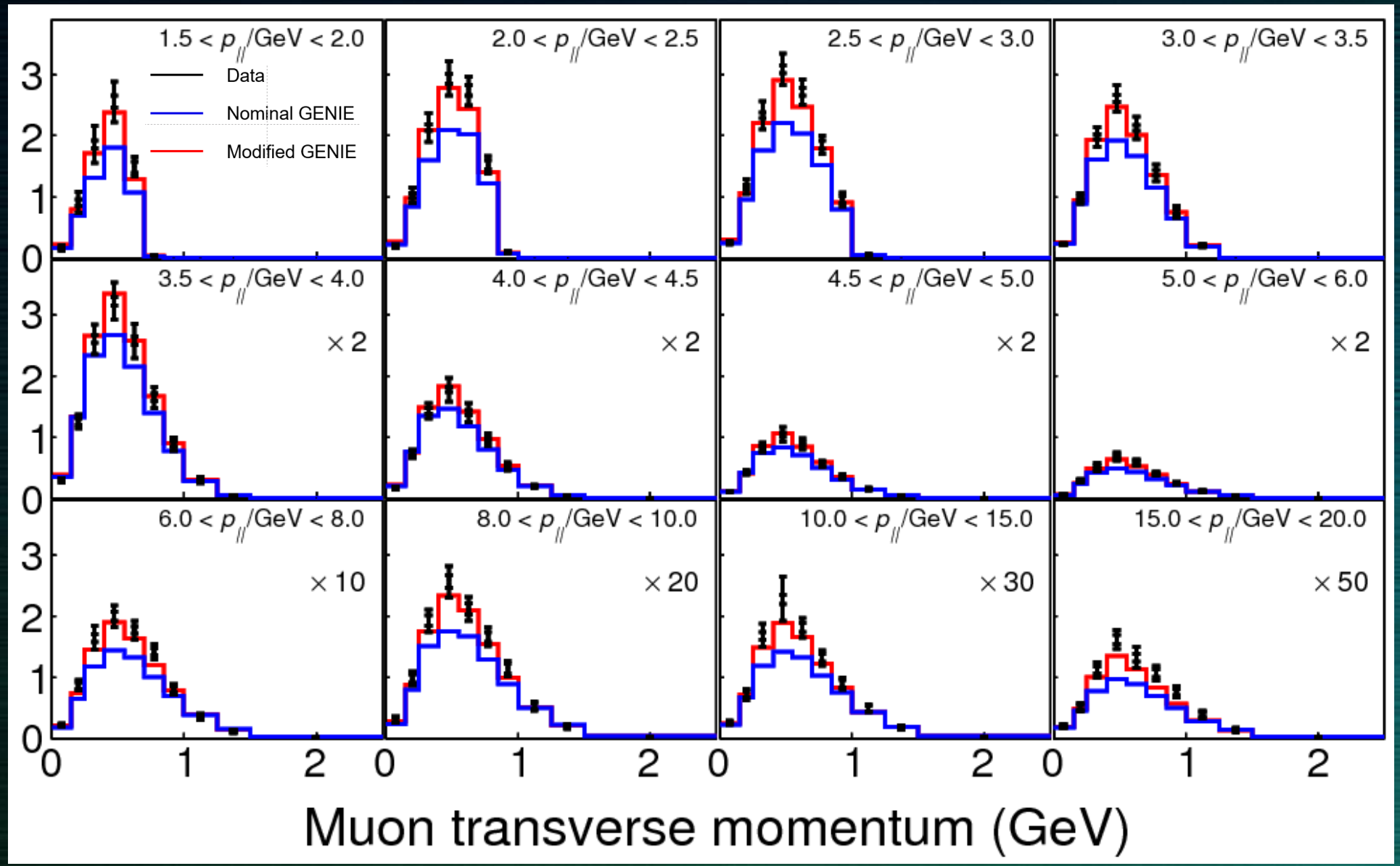
$$E_\nu^{QE} = \frac{m_n^2 - (m_p - E_b)^2 - m_\mu^2 + 2(m_p - E_b)E_\mu}{2(m_p - E_b - E_\mu + p_\mu \cos\theta_\mu)}$$

With MINERvA's energy acceptance, we can approximate to the model independent observables p_T and $p_{||}$

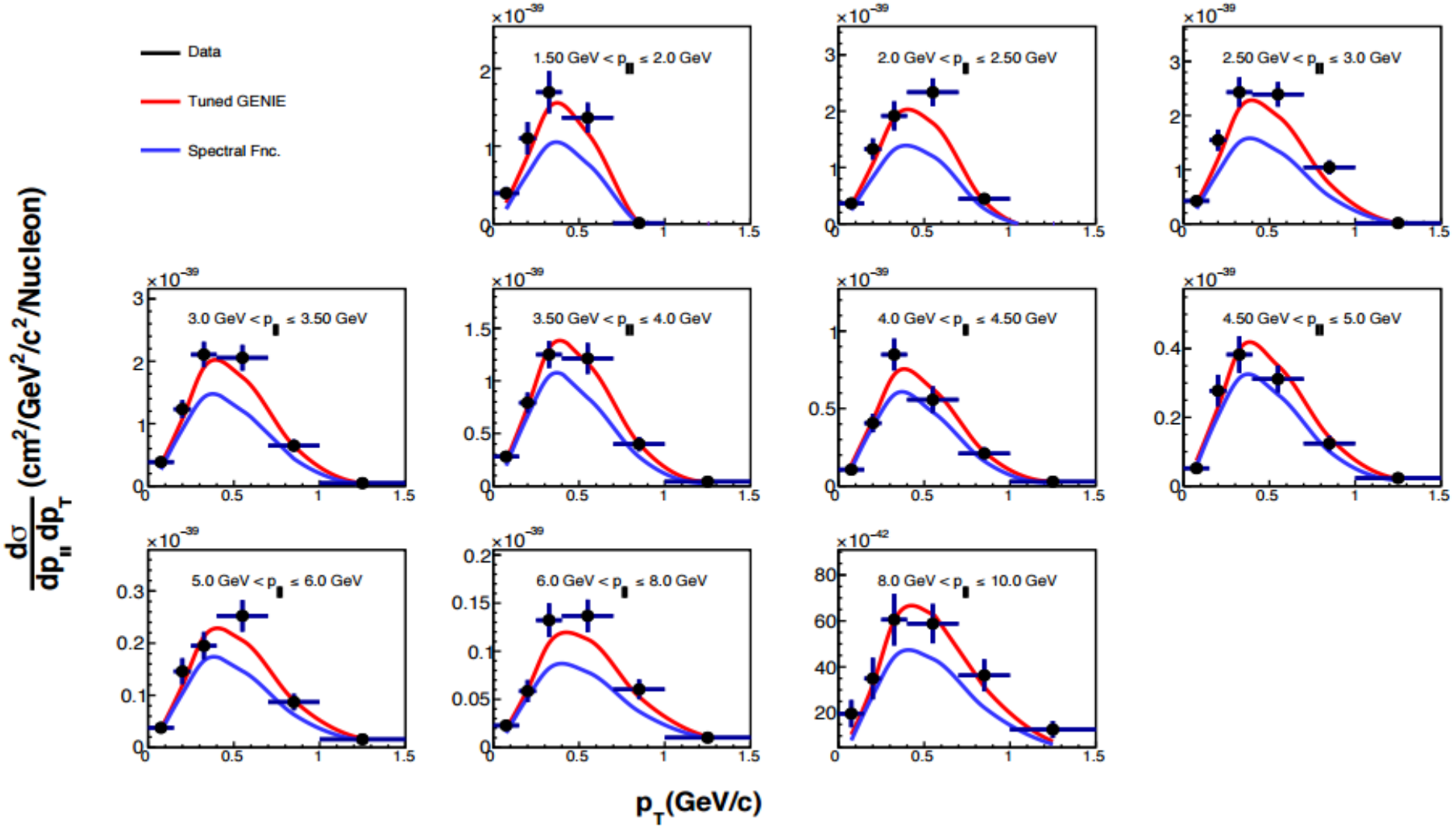
$$Q^2_{QE} \sim p_T^2$$

$$E_\nu \sim p_{||}$$

Neutrinos: Double Differential Cross Sections in Muon Kinematics



Anti-Neutrinos: Double Differential Cross Section in Muon Kinematics



Summary and Outlook

Need 2p2h and RPA models in our simulation for constraining uncertainties!

We have a model + ad hoc corrections to describe the inclusive data

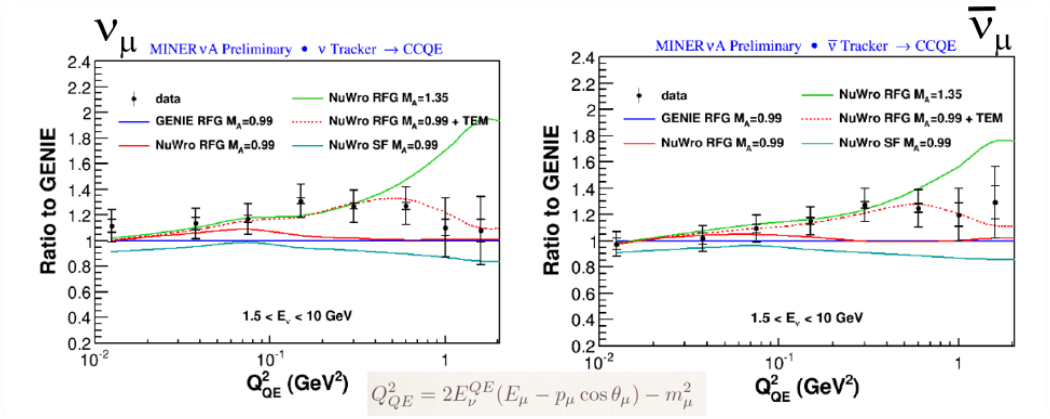
Genie tuned in Neutrino but works for both neutrino and anti-neutrino channels!

Other experiments needs our enhancements to 2p2h.

THANKS MINERvA! ESPECIALLY DAN, CHERYL, AND MINERBA.

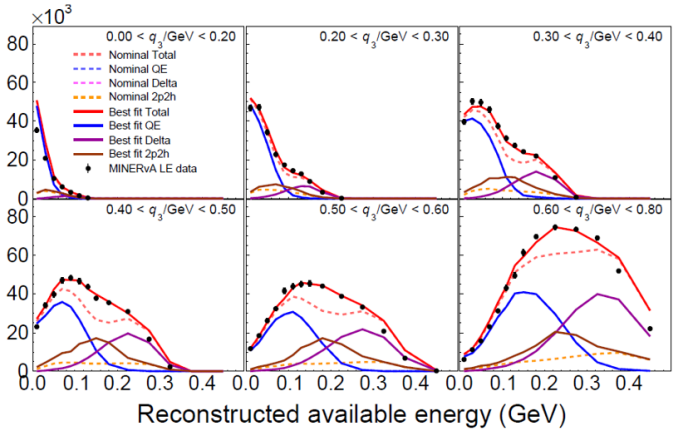
Backup.

Conclusions

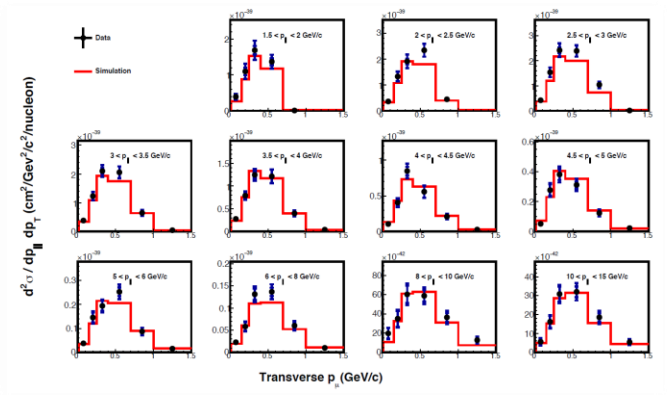


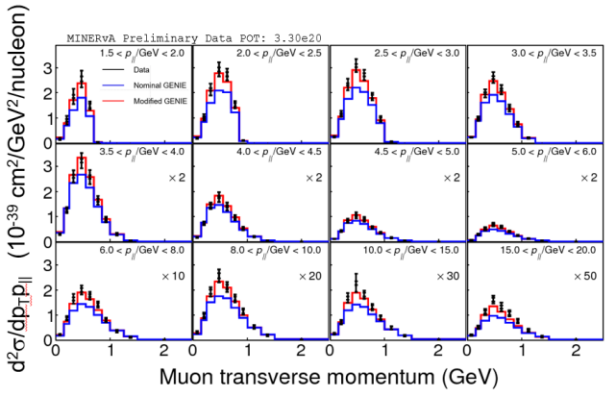
$$Q^2_{QE} = 2E^{QE}_{\nu}(E_\mu - p_\mu \cos\theta_\mu) - m^2_\mu$$

We need 2p2h-like models in our simulation!



We have a model + ad hoc corrections to describe the inclusive data



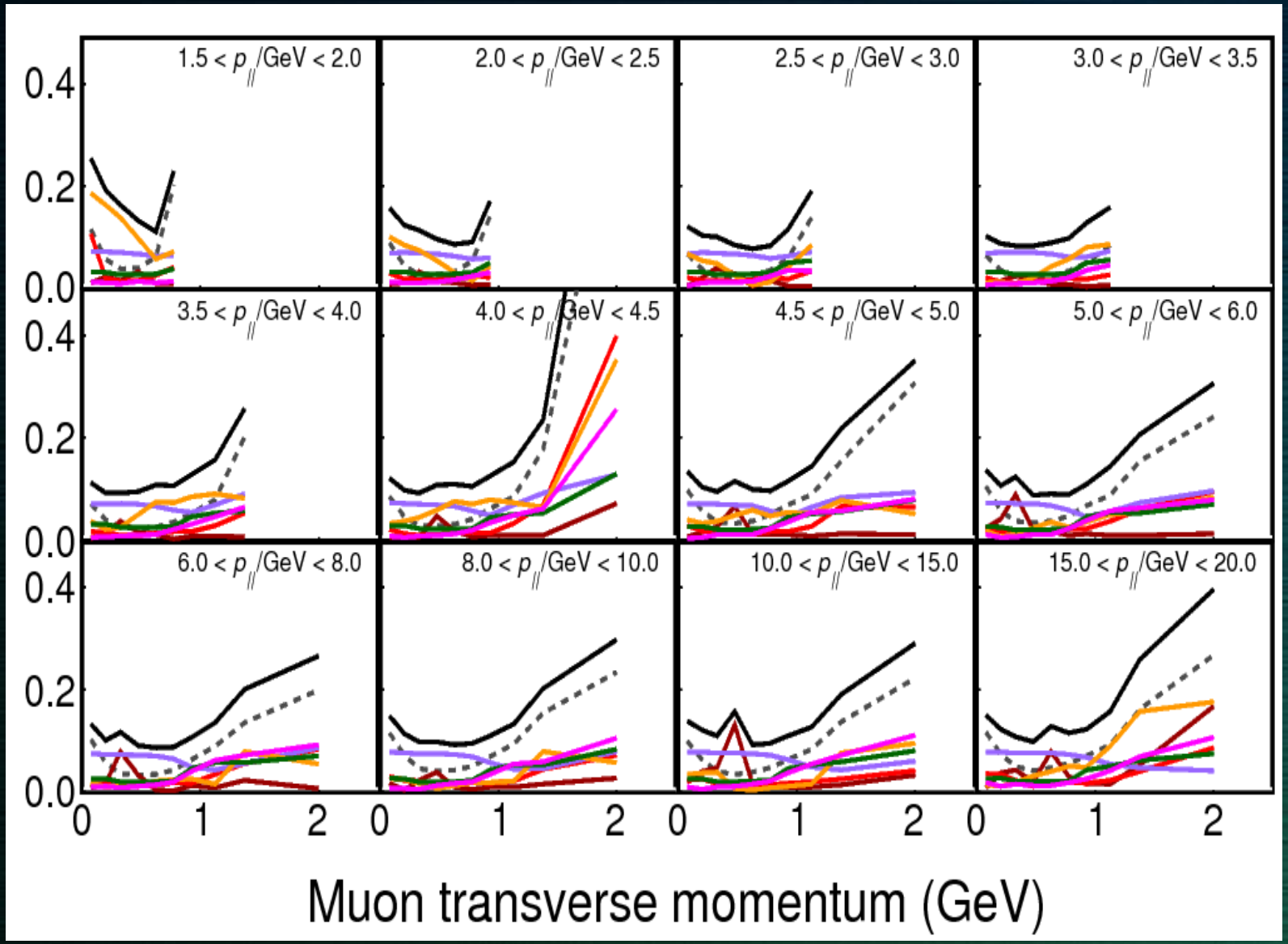


Works on neutrino ***AND*** antineutrino exclusive channels!

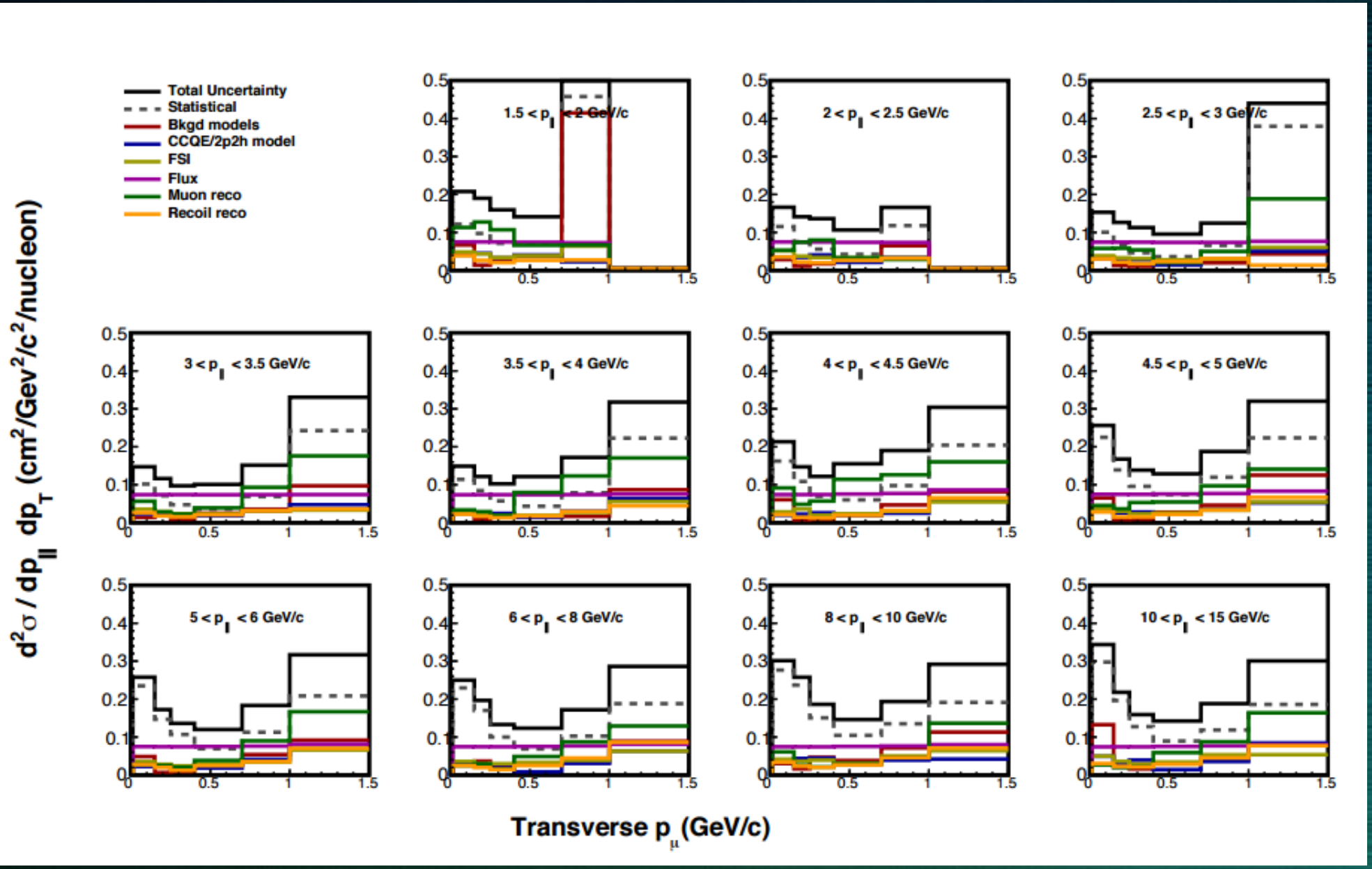
This is CC0π – just like the primary signal region in T2K

We have a prescription which can be directly applied to oscillation experiments.

Neutrinos: Systematic Uncertainties (In Muon Kinematics binned by transverse momenta)

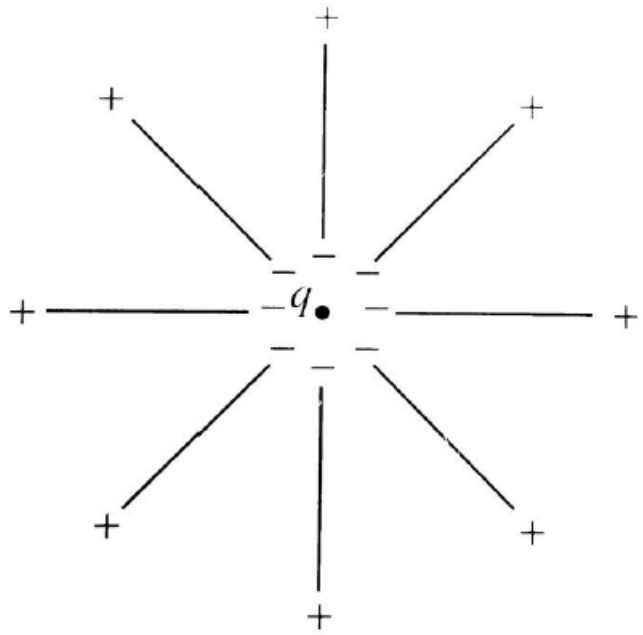


Anti-Neutrinos: Systematic Uncertainties (In Muon Kinematics)



Nuclear Screening

- Polarization of the nucleus screens electroweak coupling of the W

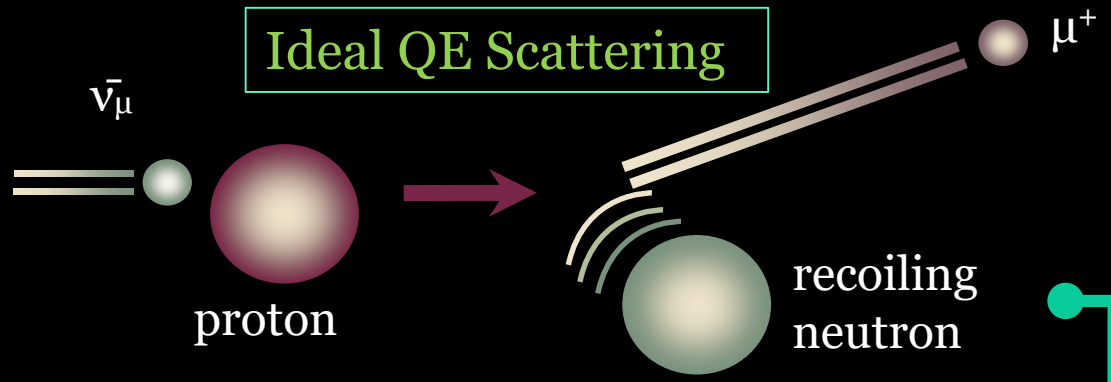


Griffiths, *Introduction to Electrodynamics*

- A common analogy is screening of electric charge in a dielectric
- Calculated using **R**andom **P**hase **A**pproximation (RPA)
- Effect on cross section: Suppression at low four momentum transfer Q^2

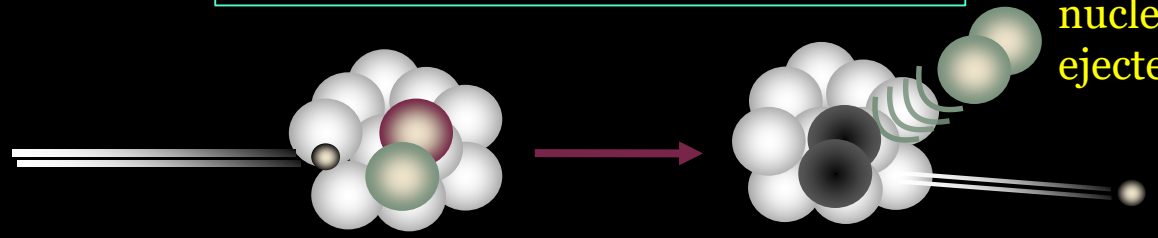
What are these effects?

Ideal QE Scattering



2Particle2Hole(2p2h): short range correlation

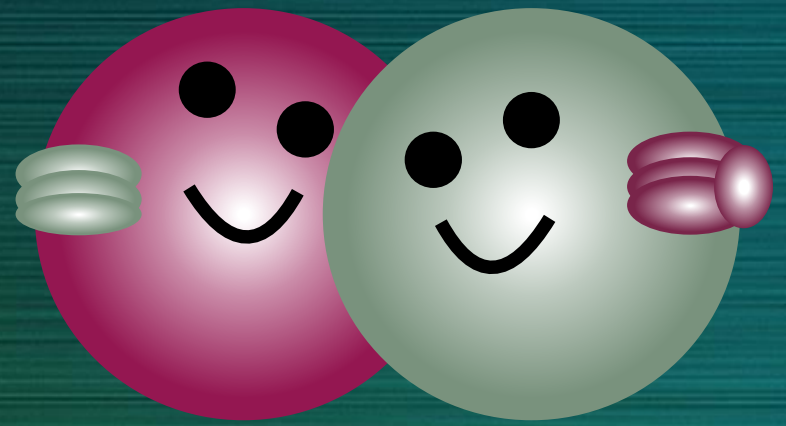
More than one nucleon can be ejected!



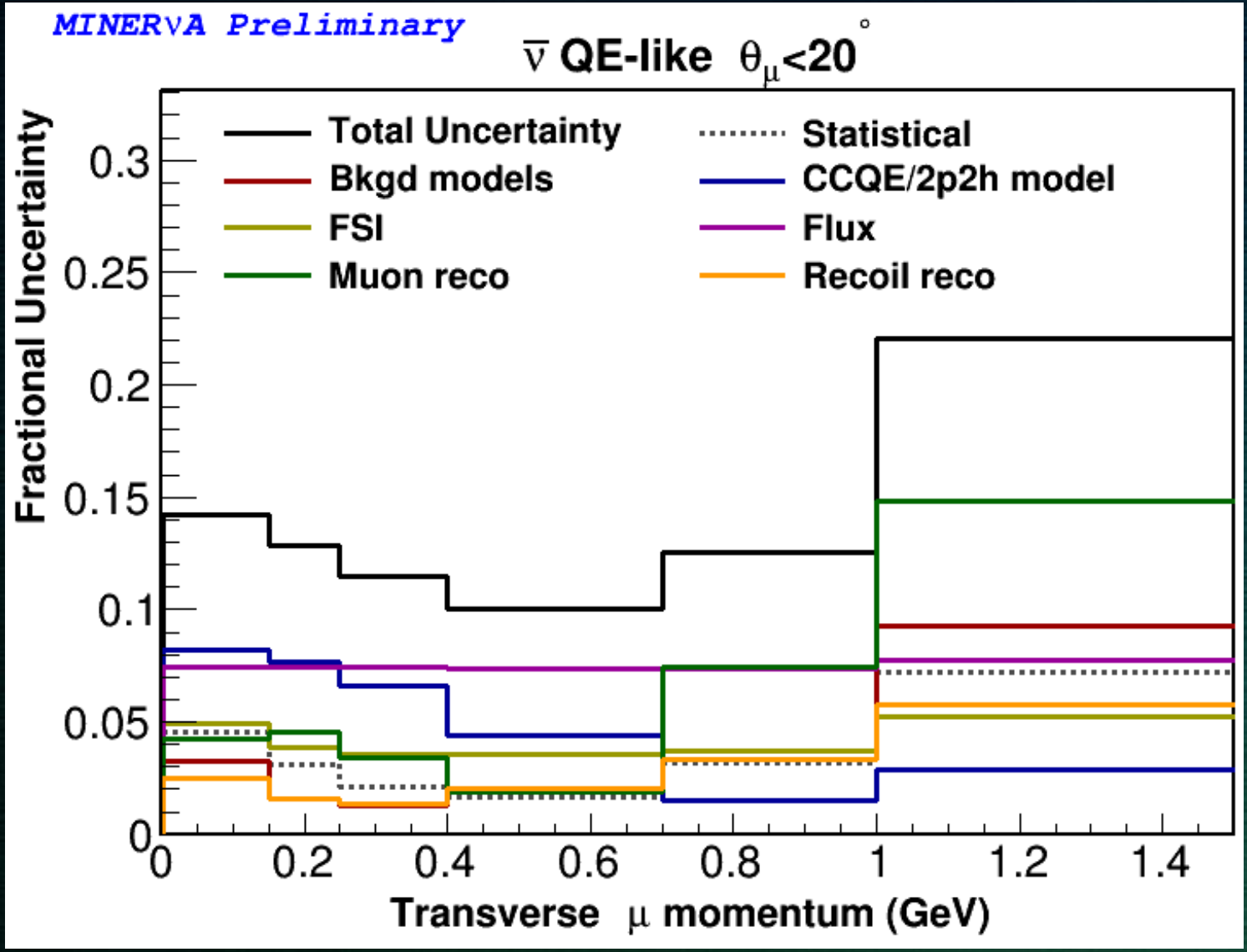
Long range correlation through electroweak interactions

Random phase approximation (RPA)

Additional nuclear interactions due to correlated nucleon pairs!



Anti-Neutrinos: Systematic Uncertainties (In Muon Kinematics)



Statistical uncertainty

Background models

- **resonant** interactions affect background subtraction

CCQE / 2p2h model

- dominated by uncertainty in **correlation effect strength**

Final-state interactions

- **pion absorption** dominates

Flux

- beam focusing
- tertiary hadron production
- reweight to other experiments

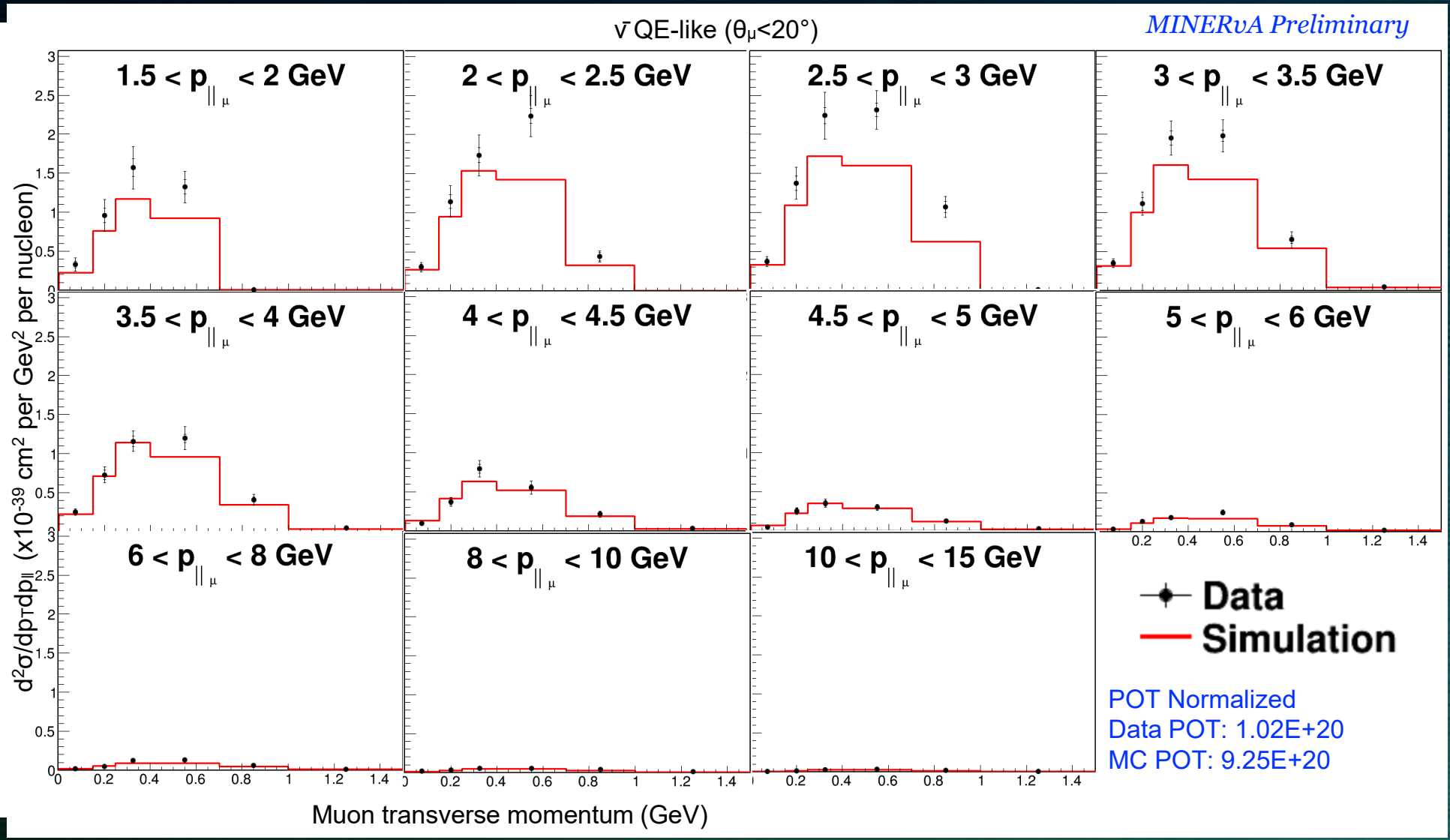
Muon reconstruction

- **muon energy scale** dominates
- tracking efficiency
- muon angle and vertex position

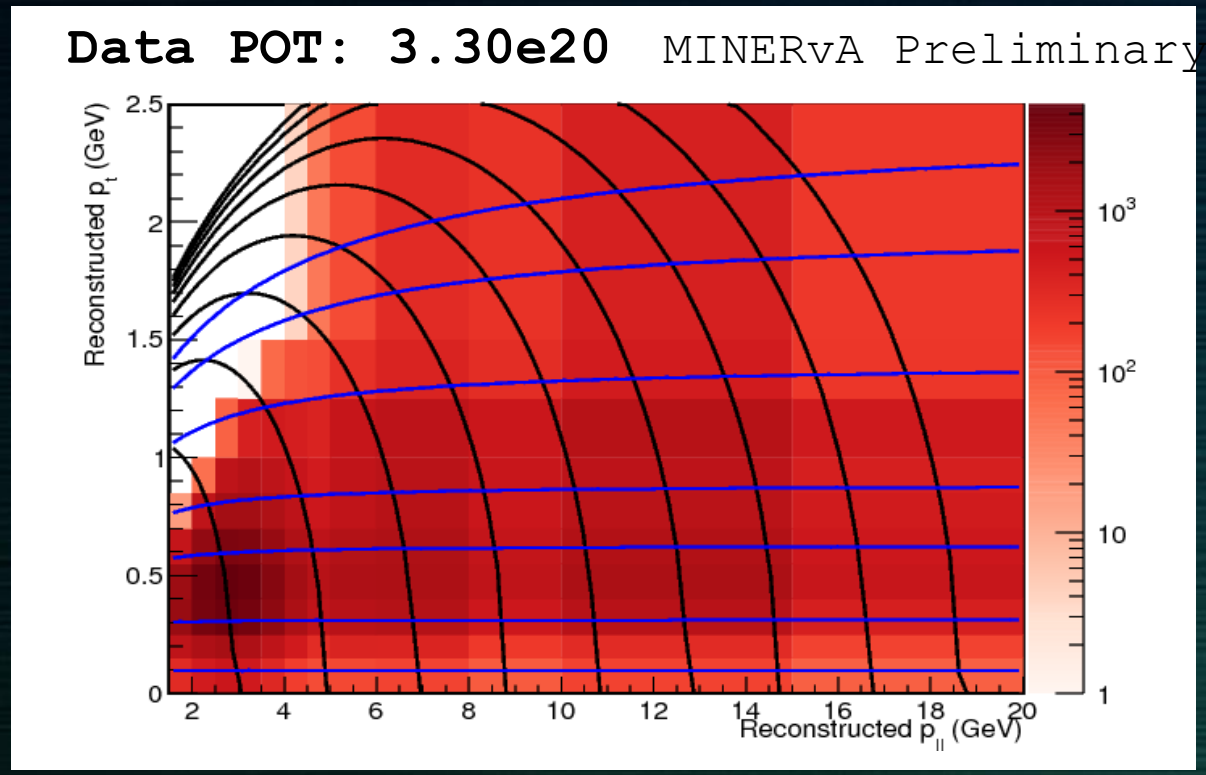
Recoil reconstruction

- detector response to different particles - **neutron** dominates

Anti-Neutrinos: Double Differential Cross Section in Muon Kinematics

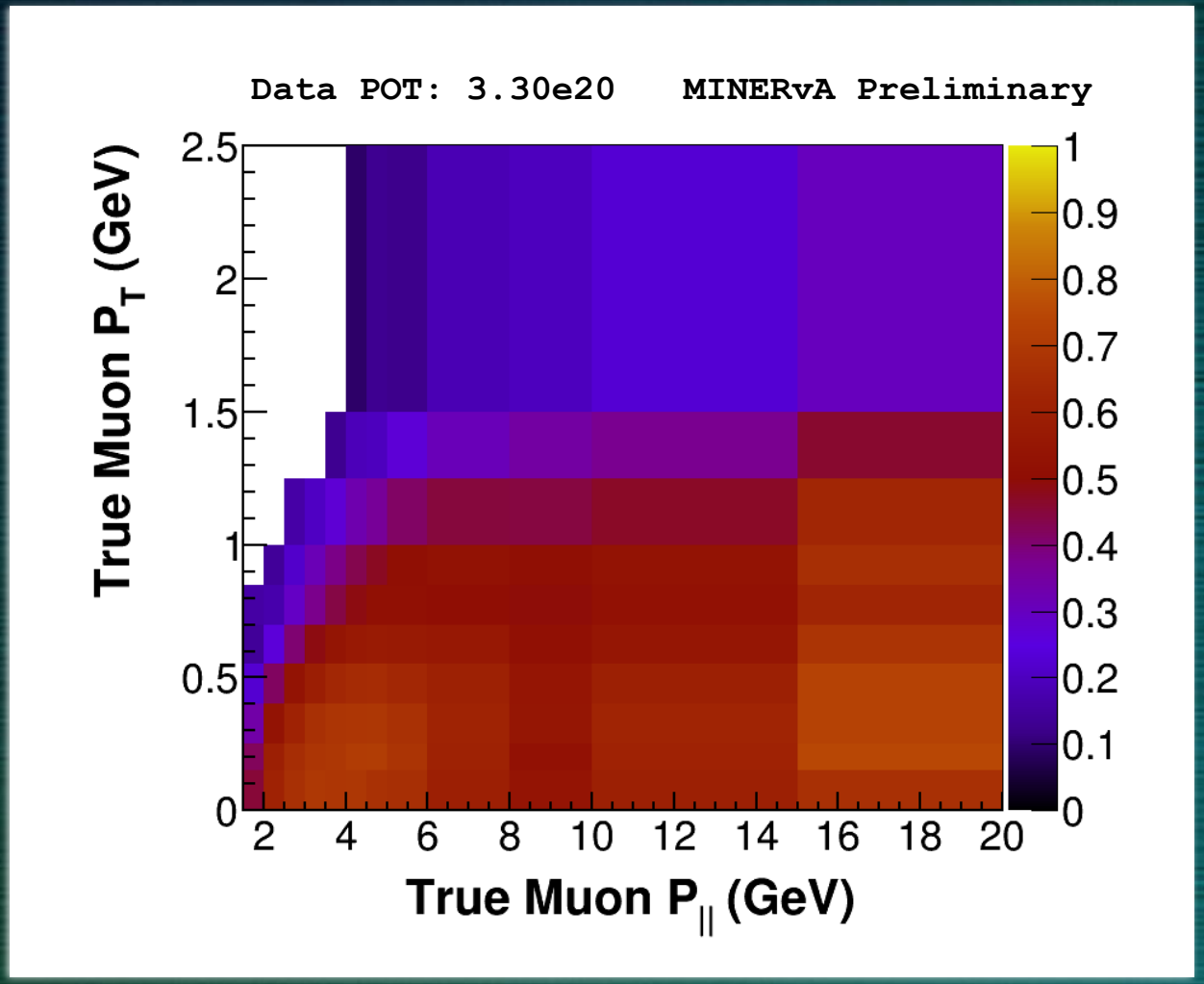


Neutrinos: Final Selected Sample Momenta

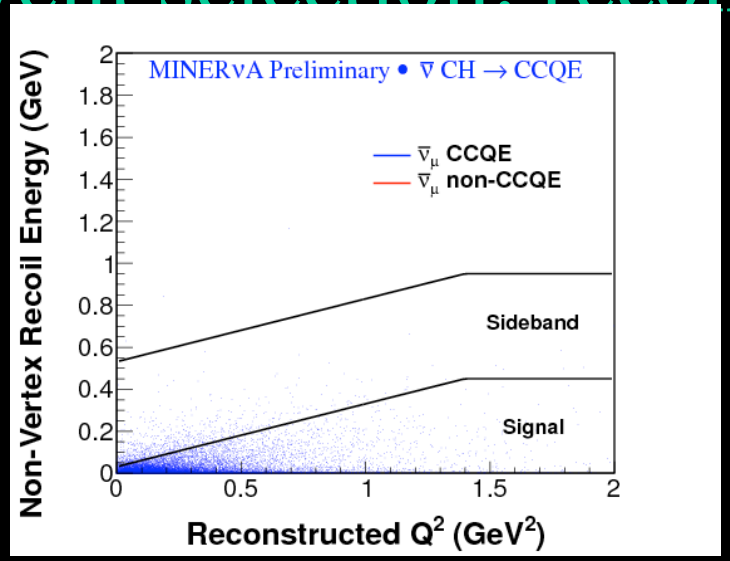


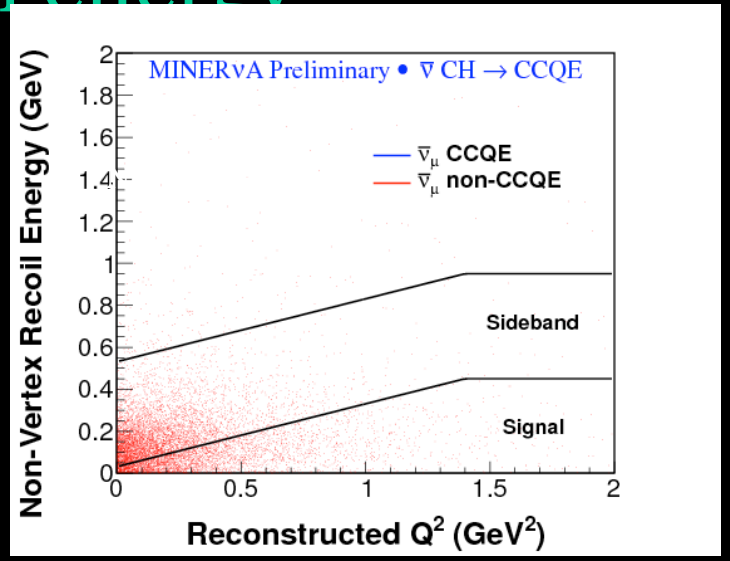
Lines of constant $E_{\nu,qe}$ [3,7,11,15,19]

Lines of constant Q^2_{qe} [0.01,0.1,0.4,0.8,2.0,4.0,6.0]



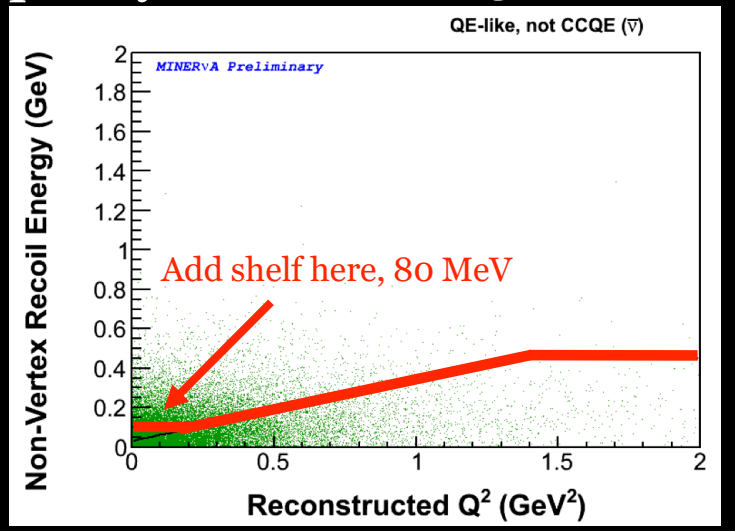
Event selection: recoil energy





- This cut optimizes efficiency times purity for true CCQE events

- But it does a poor job (17% efficiency) of accepting CC0π events that are not CCQE
- We can improve efficiency by relaxing the cut at low Q^2, but will sacrifice purity



Anti-Neutrinos: Final Selected Sample Momenta