ν_μ CCQELike IN MINERvA

Amit Bashyal for MINERvA Collaboration
Oregon State University

Motivation

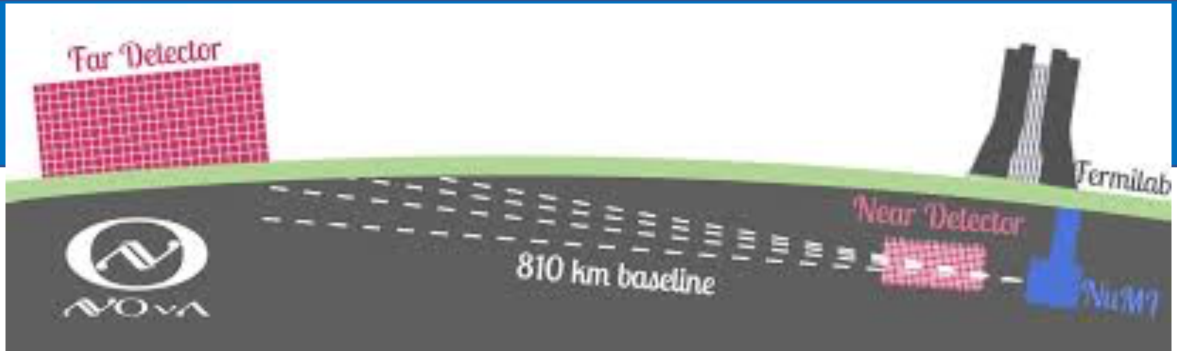
- Why do we need a CCQELike neutrino nucleus cross section measurement?

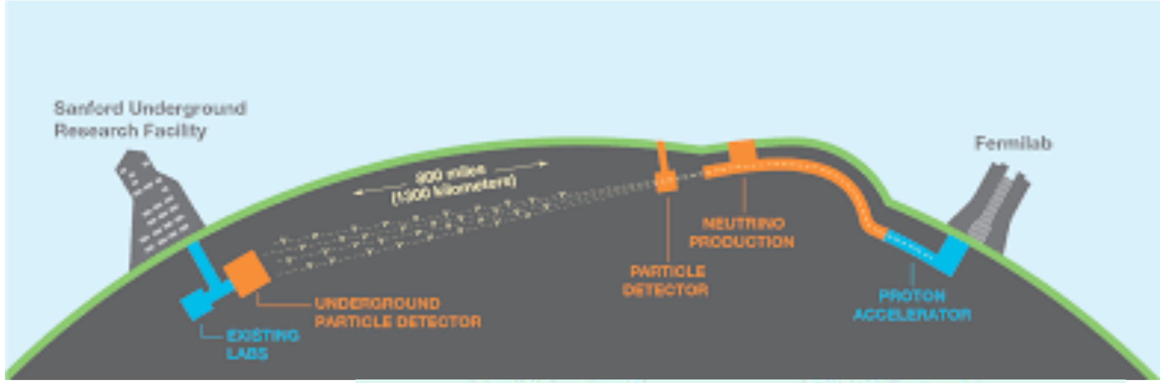
Motivation

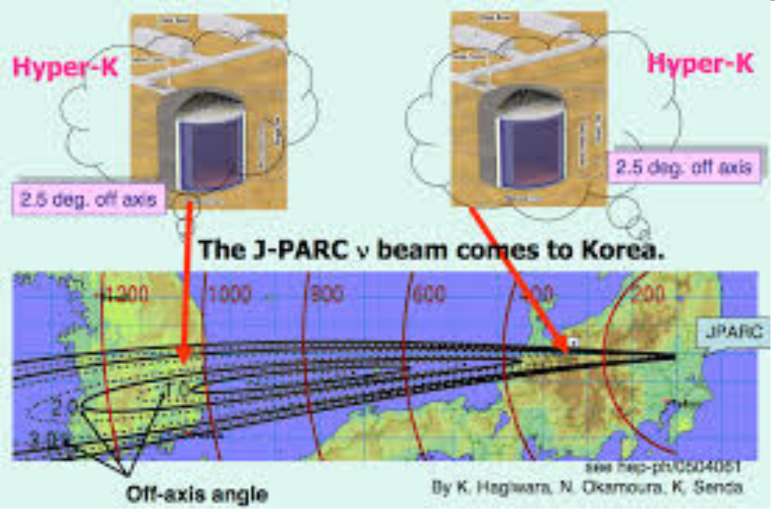
- **Current experiments like NoVA and future experiment like DUNE and HK**
- **Long Baseline experiments trying to search for answers:**
- **Matter anti matter asymmetry in the universe**
- **Neutrino mass**
- **4th kind of neutrino (sterile)…**

All experiments do their measurements on targets heavier than hydrogen **(DUNE→Liquid Argon, NoVA→Mineral oil, Hyper K →Water).**

Need to understand neutrino scattering in a complex nuclear environment.

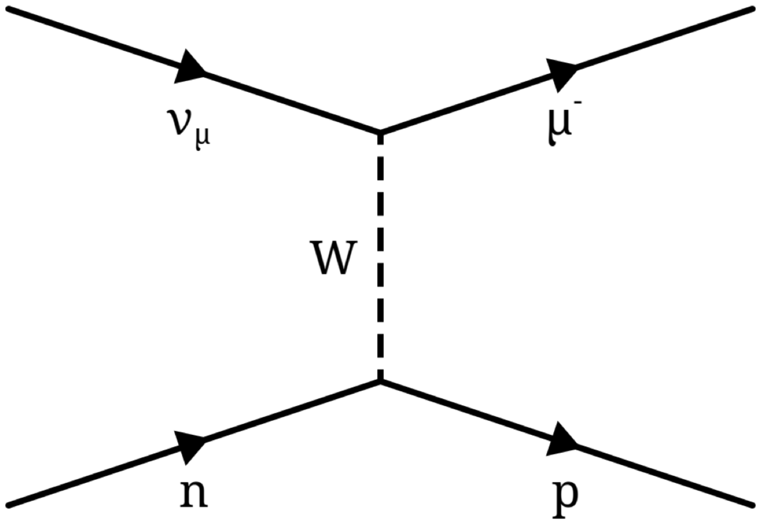




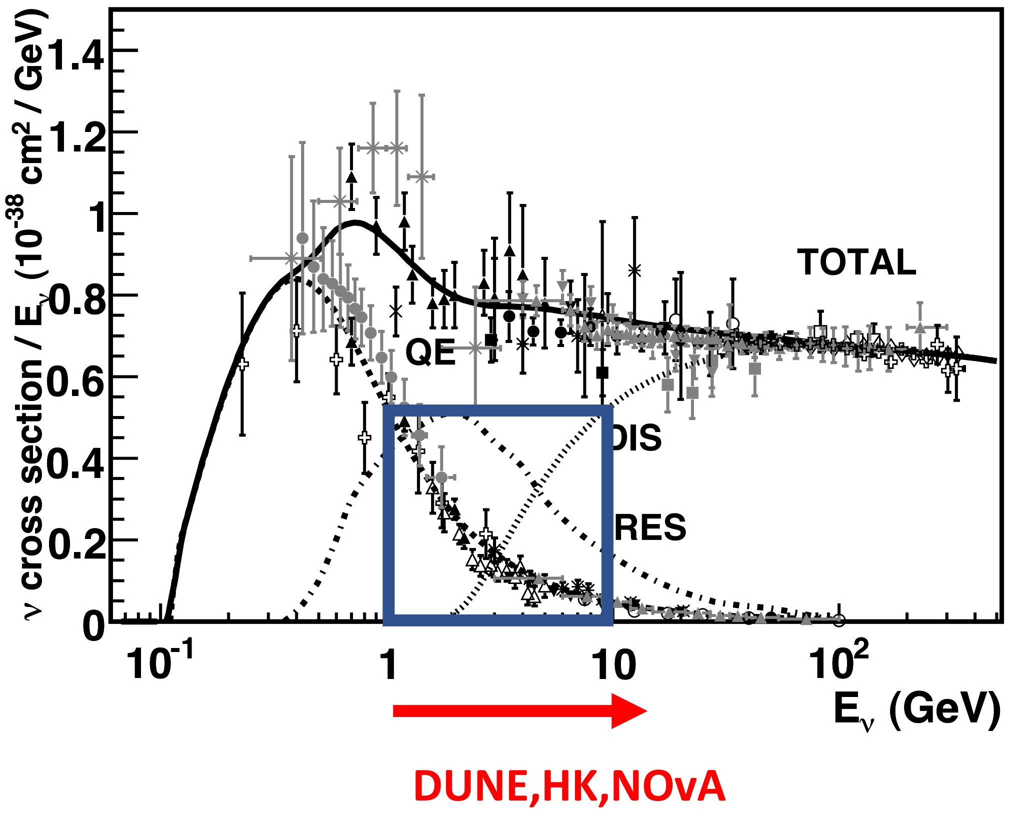


Motivation

All the mentioned experiments will do their measurements at neutrino energies in few GeV energy range.
CCQE events dominate this energy range.



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



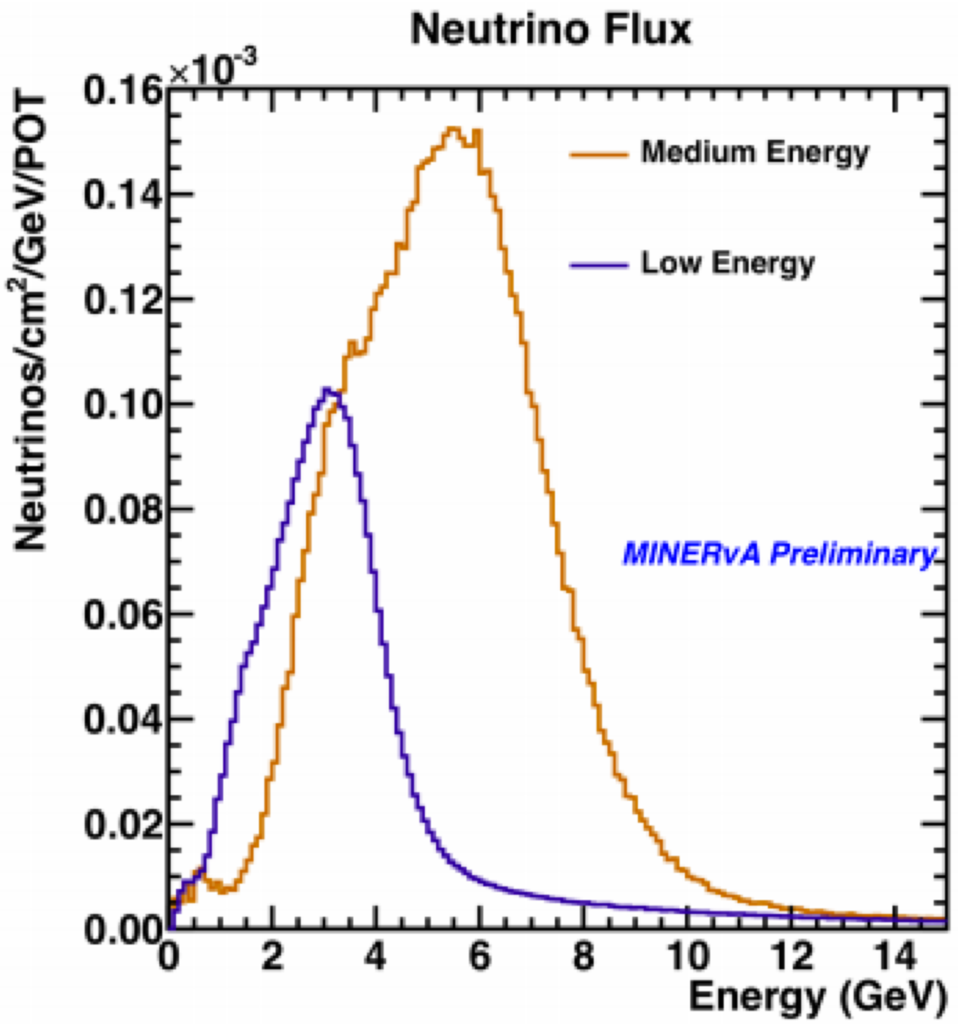
Various process contributing to the total charged current inclusive cross section in neutrino[1].

MINERvA Experiment

- Study of neutrino cross sections in different nucleus.
- 1 to 10 GeV neutrino energy range
- Study of nuclear effects and A (atomic number) dependence of the neutrino nucleus scattering
- Results from MINERvA will be useful in current and future oscillation experiments

MINERvA = Main INjector ExpeRiment on nu (v) A (nucleus)

MINERvA Experiment



- LE ν POT: 4.0e20
- LE $\bar{\nu}$ POT: 1.7e20
- ME ν POT: 12.1e20
- ME $\bar{\nu}$ POT: 12.4e20

ME = 6 GeV Neutrino Energy Focusing Peak Run

LE = 3 GeV Neutrino energy Focusing Peak Run

LE → 2 years run

ME →5.5 years run

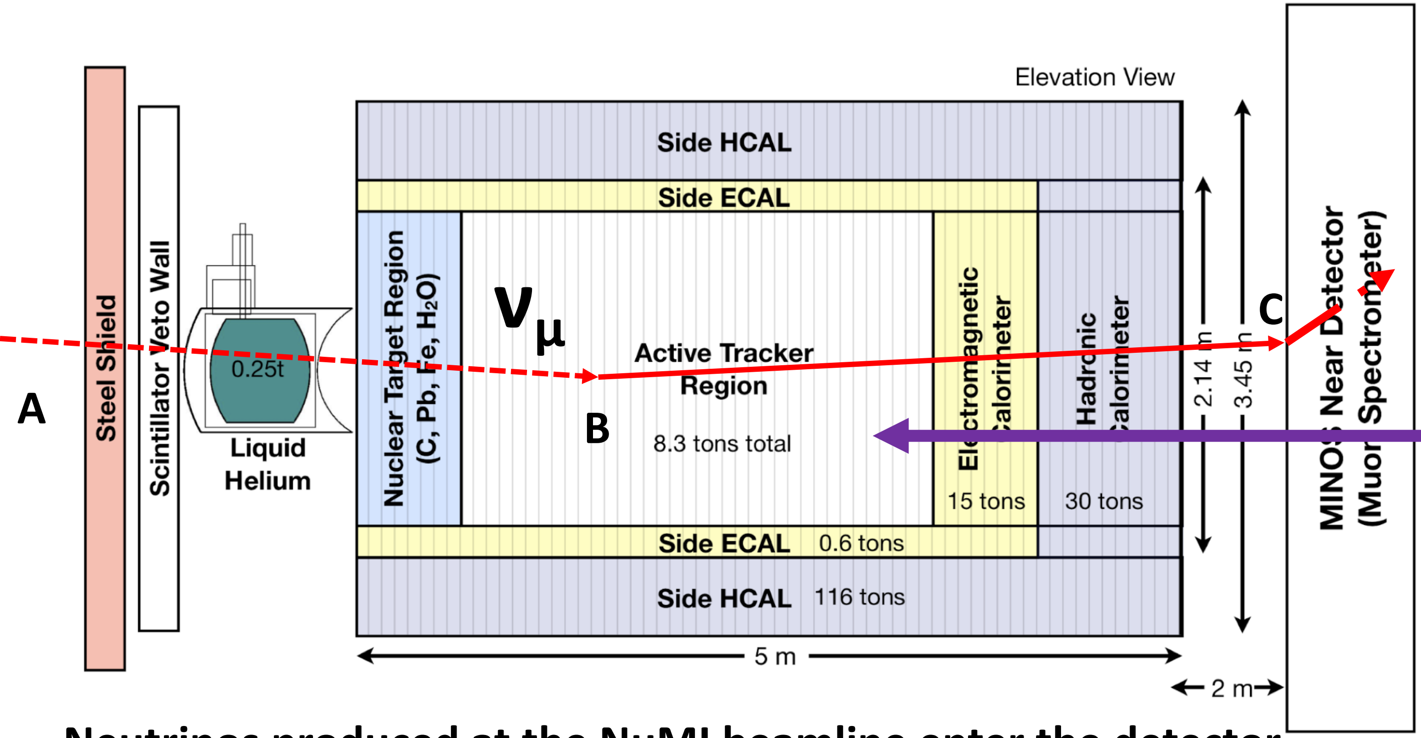
35 papers using LE Data
1 paper on ME Data

ME data:

- **High Statistics+ High Energy**

This analyses uses ME data and this talk gives an overview of the soon to be published results on CCQELike measurement.

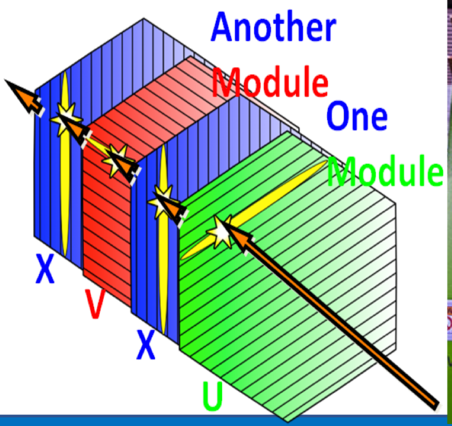
The MINERvA Detector



→Active Segmented polystyrene scintillator strips.

→ Passive nuclear targets of He,C,Water, Fe and Pb

*This analysis is fully done in the active tracker region.



Neutrinos produced at the NuMI beamline enter the detector from the left.

In the above schematic diagram:

A. a muon neutrino interacts with a nucleon.

B. Muon is produced in the detector which leaves a long track.

C. Enters the MINOS detector which is magnetized. Muon bends in the B field of the MINOS detector.

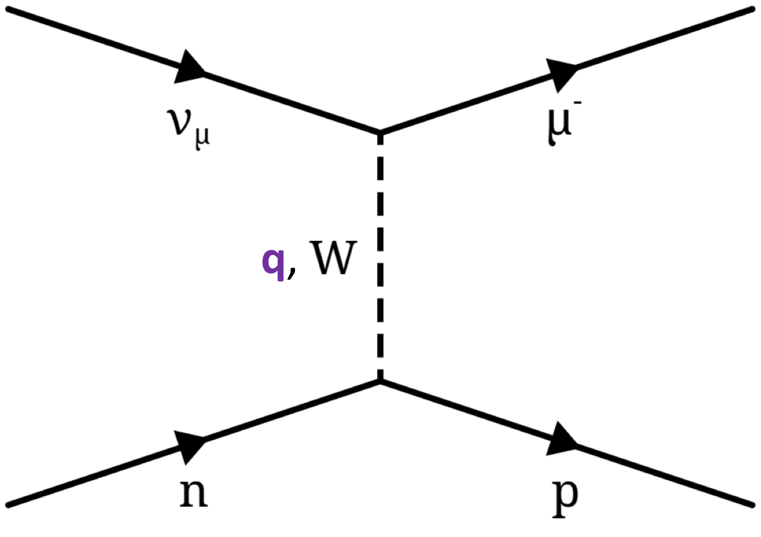
Charged Current Quasi Elastic Interactions on Nucleus

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

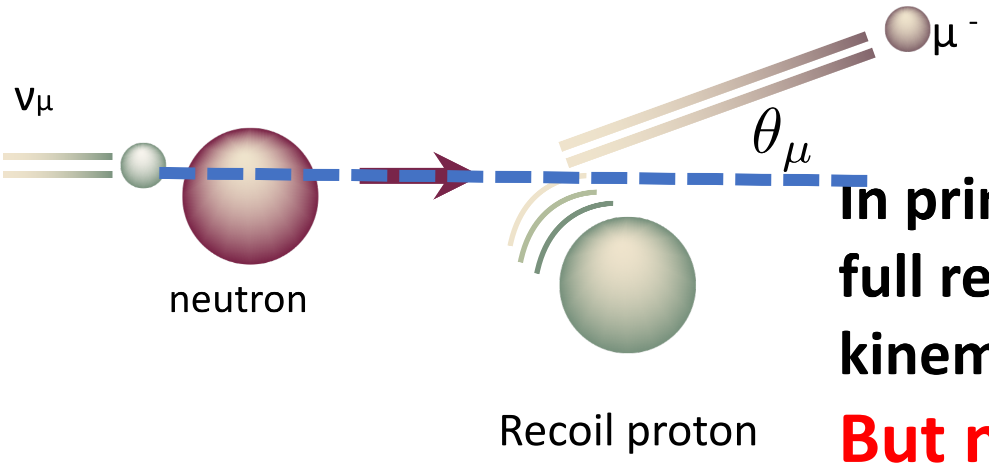
$$Q^2_{QE} = 2E_\nu^{QE}(E_\mu - p_\mu \cos\theta_\mu) - m_\mu^2$$

θ_μ Angle between incoming neutrino and outgoing muon

$Q^2_{QE} = -q^2$ Four Momentum Transfer Squared from lepton to hadron system



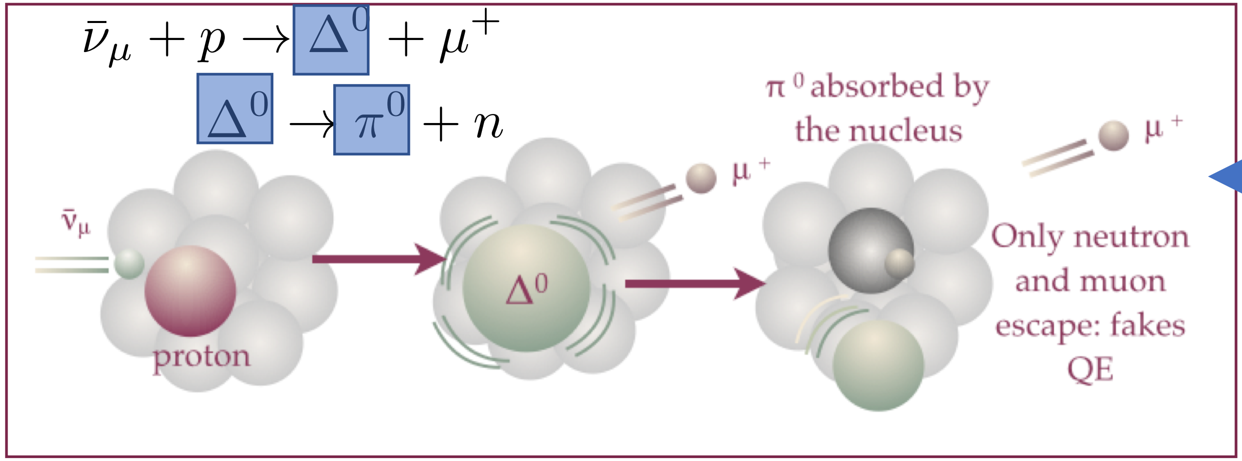
$$\nu_\mu + n \to \mu^- + p$$



In principle 2-body scatter from a nucleon at rest allows full reconstruction of the neutrino energy from muon kinematics alone.

But nuclear effects complicate this picture…

Nuclear Effects

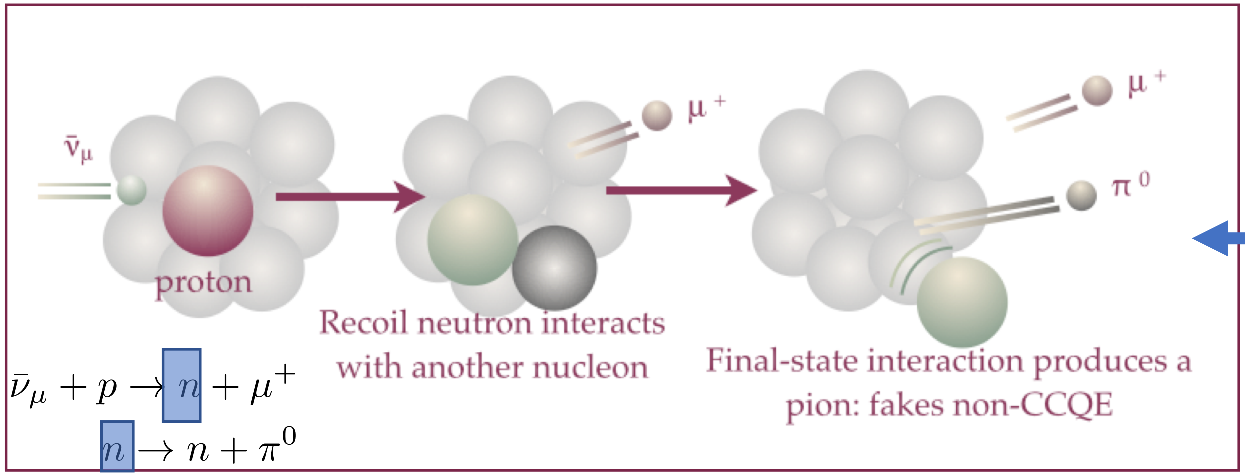


$$\bar{\nu}_\mu + p \to \mu^+ + n$$ Anti neutrino CCQE

Initial Interaction is not CCQE but the observed event looks like CCQE

Final State Interactions

Interactions inside the nucleus can fake the events we want or don't want

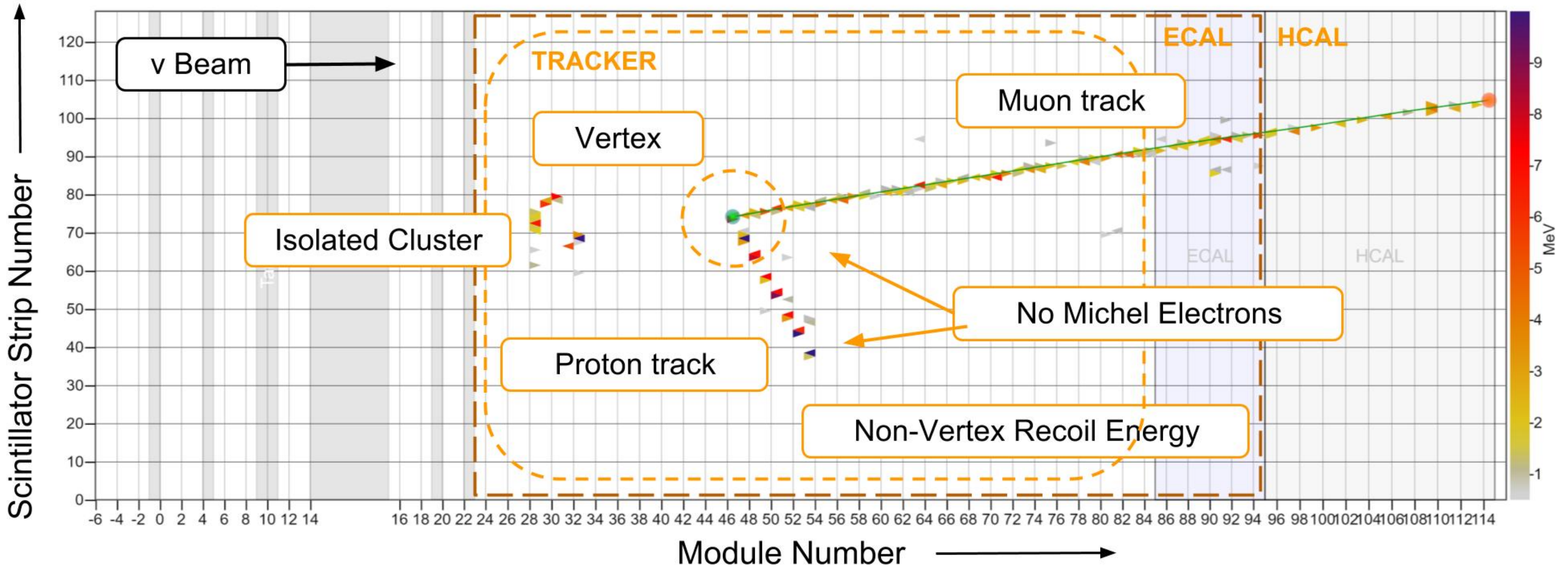


Initial Interaction is CCQE but the observed event looks like non CCQE.

Add in the fact that nucleons are never at rest, charge screening effects etc (backup slide).

CCQELike Event

- **IDEAL CCQE**
- One charged muon
- One proton
- No neutron
- No mesons
- Low recoil activity

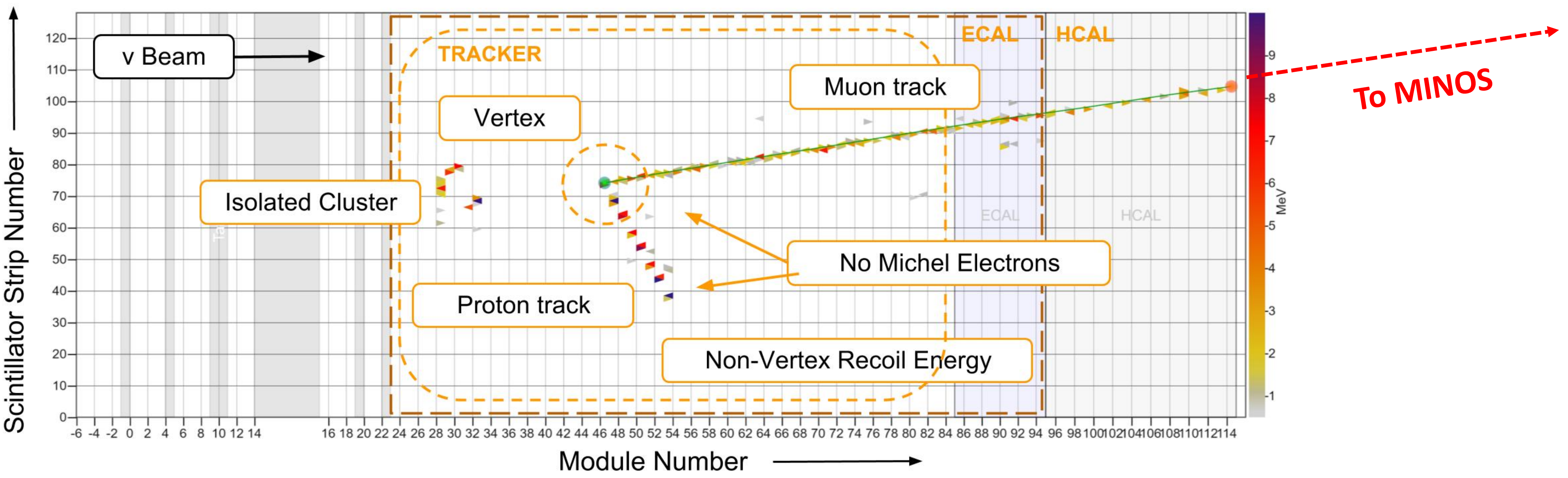


Construct a CCQELike Signal based on final state particles only.

Non CCQE interactions that fake similar Final State Particles needs to be accounted for.

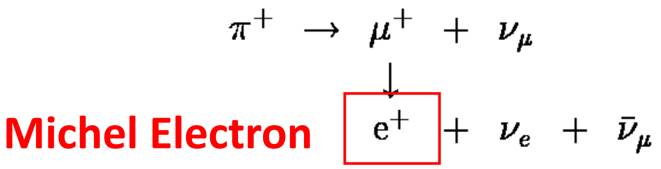
$$\nu_\mu + n \rightarrow \mu^- + p$$

Signal Definition

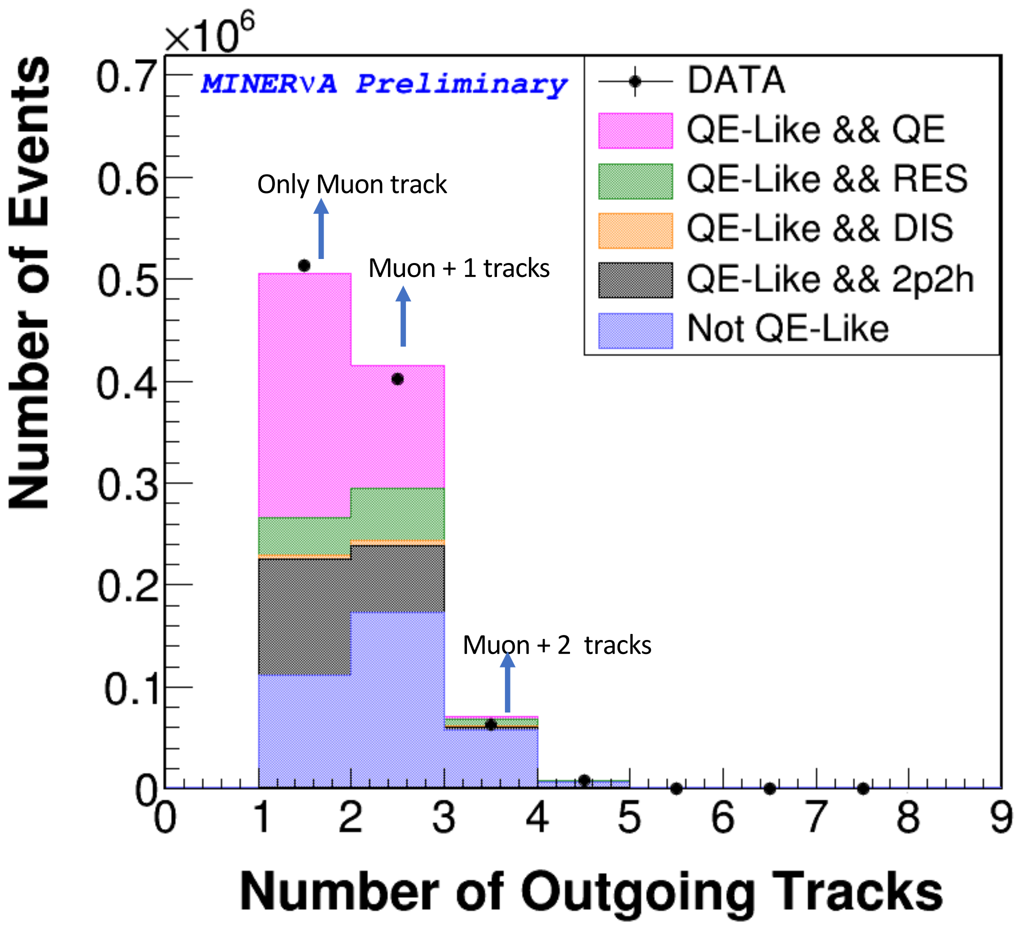


CCQELike signal definition can be constructed based on Final State Particles.

→1 charged muon
→ Any number of proton or neutron
→ No mesons
→ Low recoil Activity



Sample

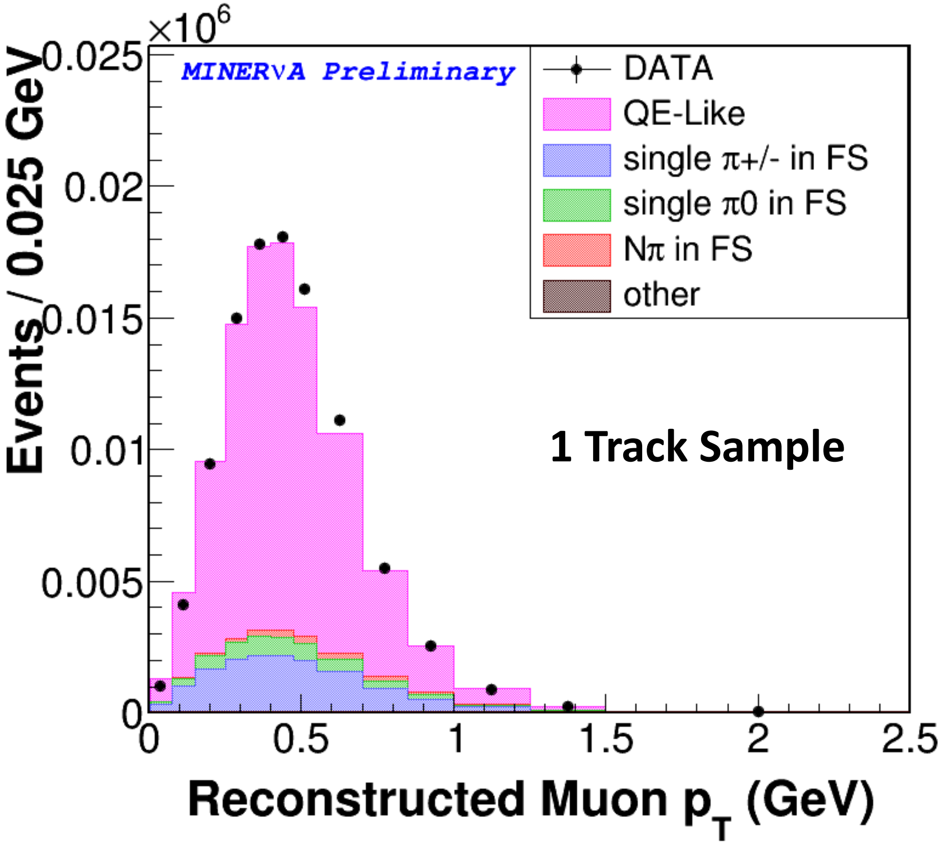


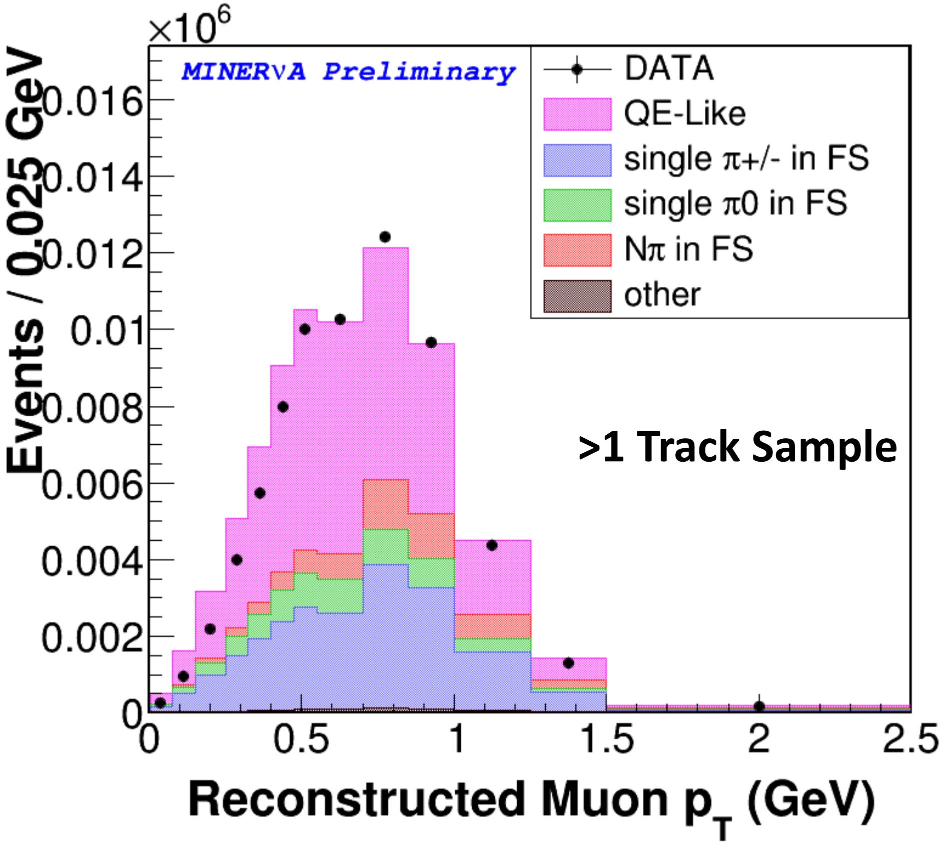
Analysis uses 8.25E20 protons on target (POT) Data.

Analysis is done by dividing the events into two categories:

1. **Events with one reconstructed outgoing muons (1 Track)**
2. **Events with at least one reconstructed muon and one proton track. (>1 Track)**

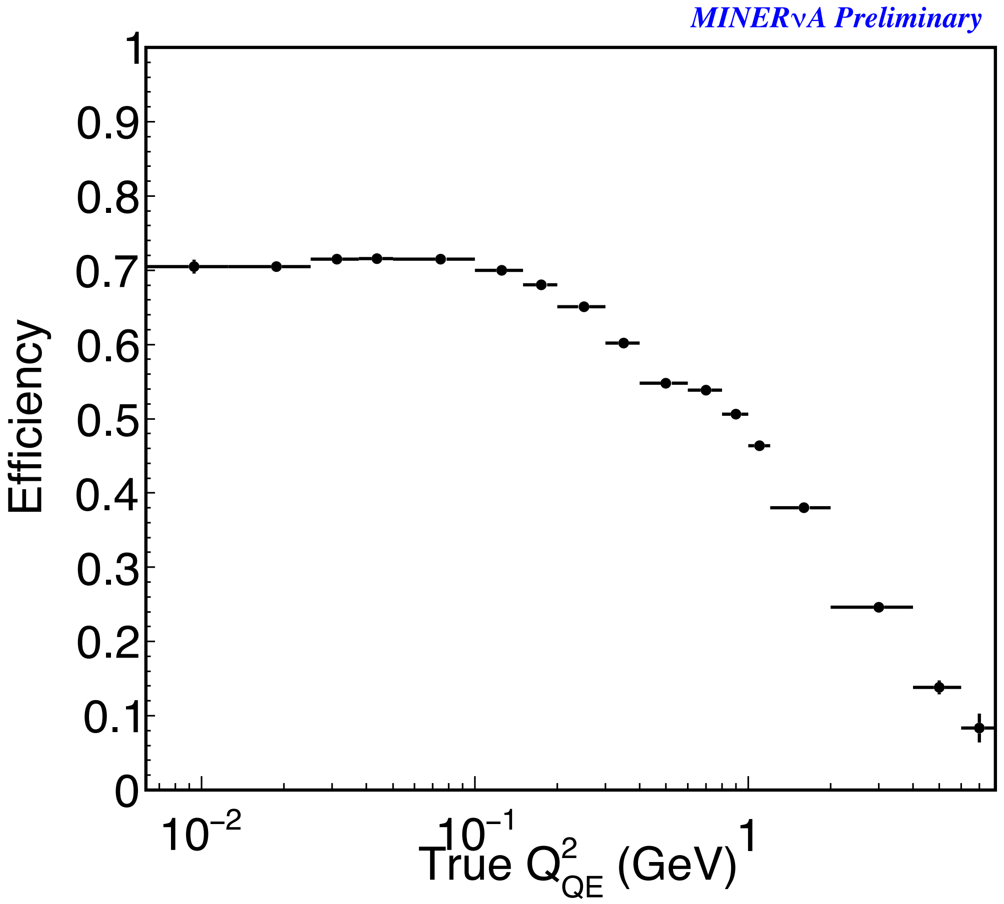
CCQELike Events Distribution





*In both sample, dominant backgrounds are FinalState (FS) pions.

Signal Selection Efficiency for both samples



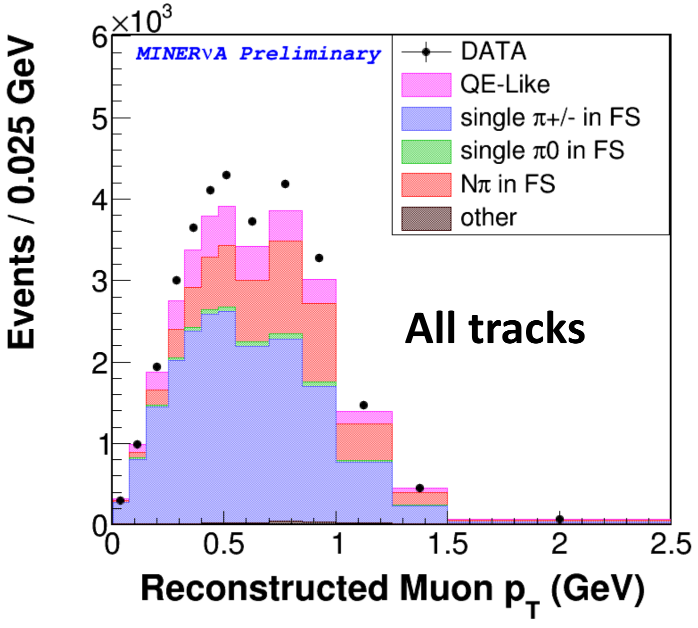
→**Signal Selection efficiency goes down at higher Q2 (Q2>1 GeV²).**

→**Muons are required to go through MINOS detector for energy and charge reconstruction. High Q2 events (higher pT) do not make it to MINOS detector.**

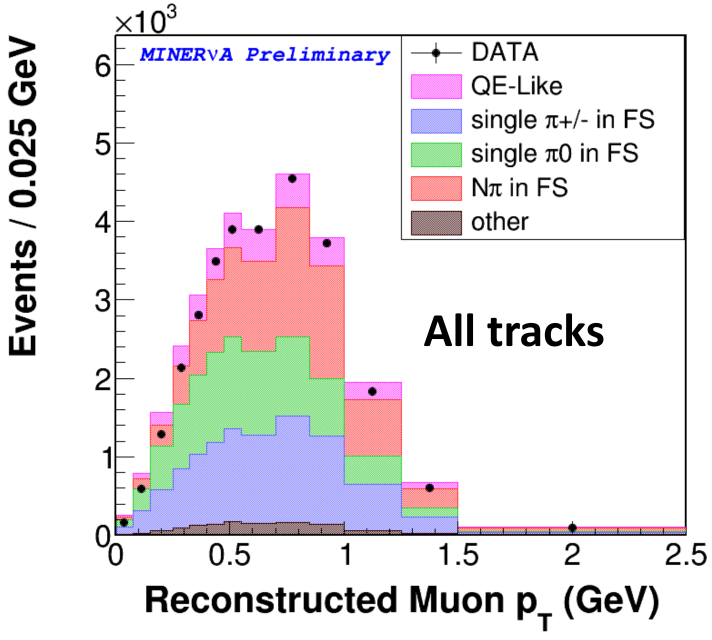
→**Particle identification cut (differentiating proton from pion) performs poor at high Q2.**

Background Constraint

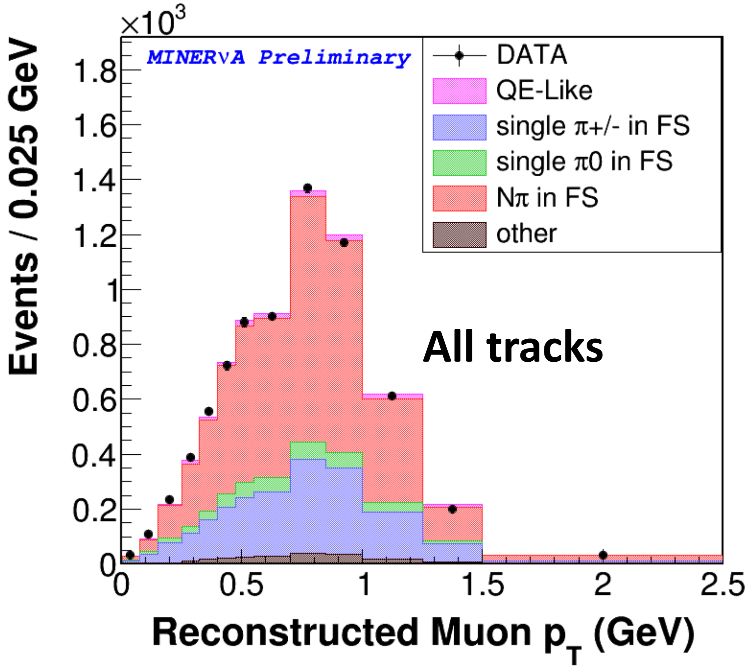
- Pion backgrounds are constrained by looking at three different independent samples for 1 track and >1 track samples separately..



Sample to constrain **pi+ backgrounds**



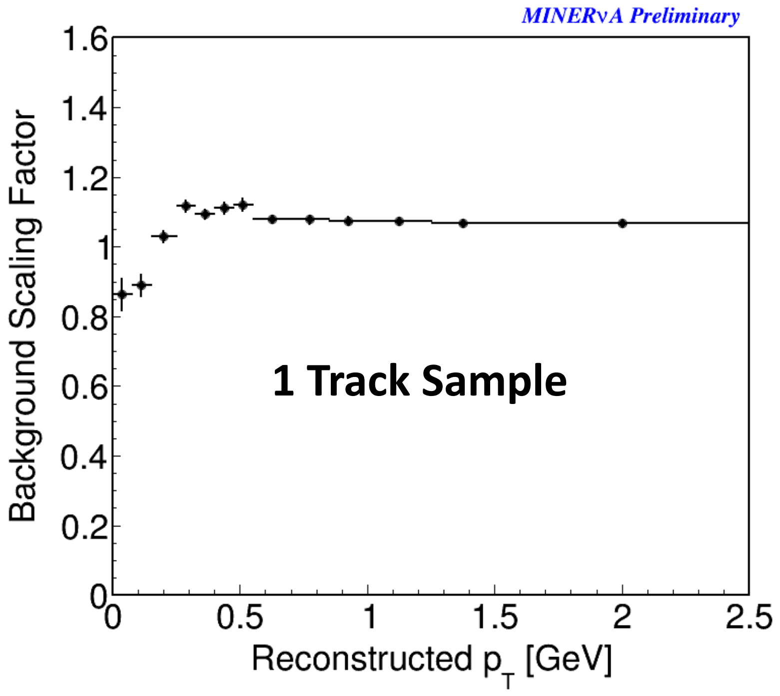
Sample to constraint **pi0 backgrounds**

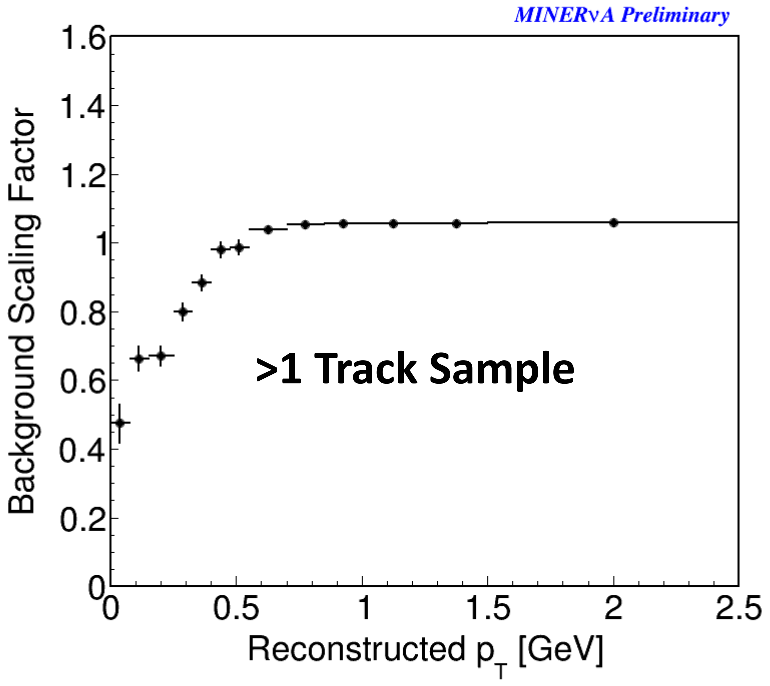


Sample to constrain **multi pion backgrounds**

Background Constraint

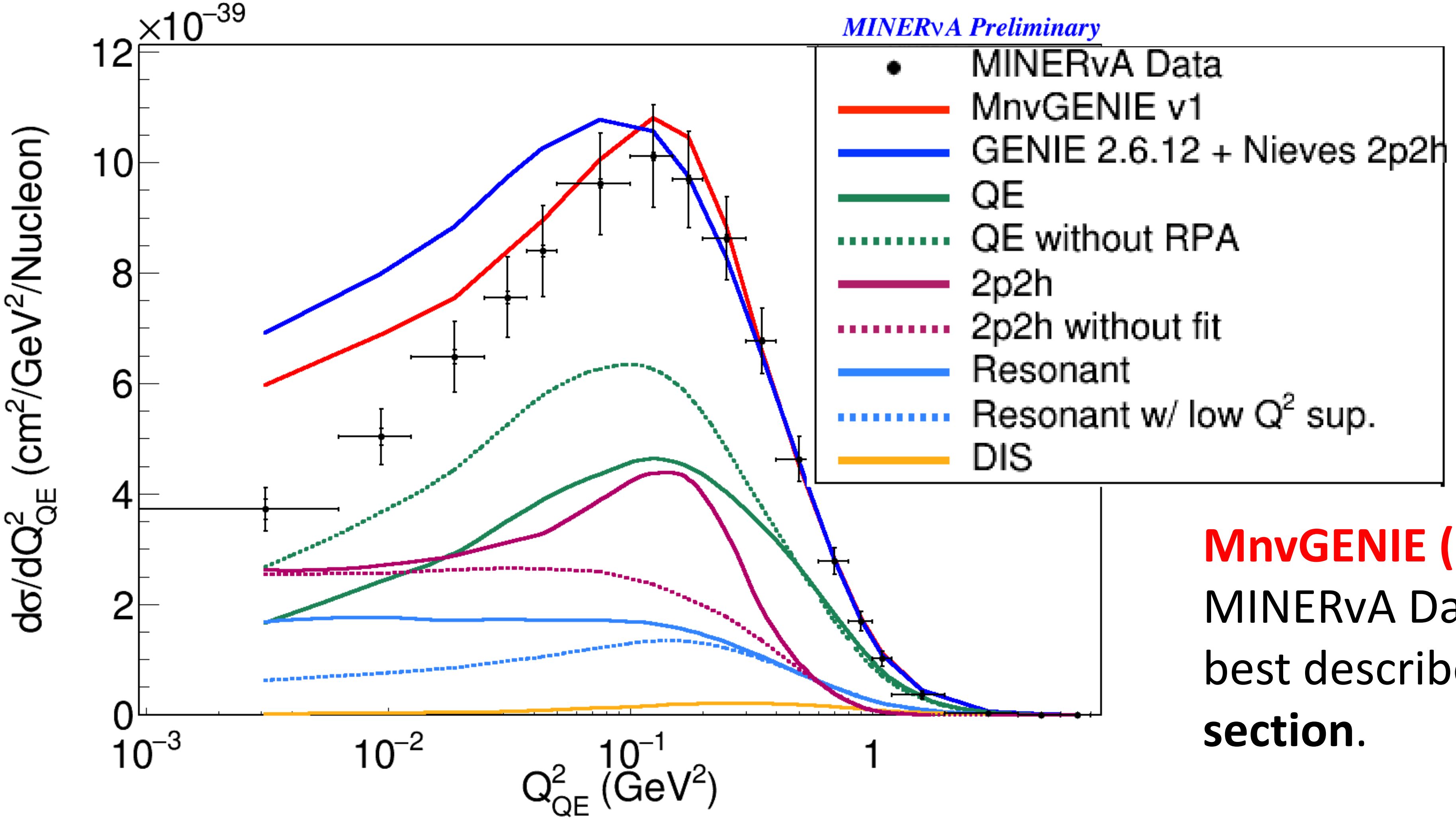
- Background scale factors are extracted by doing a χ^2 fit between data and simulated events simultaneously in all 3 sample regions.
- Scale factors extracted for 1 track and >1 track samples separately.





Reduction in overall pion background.
→ Moderate reduction of background at low pT
→ low reduction at high pT.
→ Consistent with LE result[6].

CCQELike Cross-section



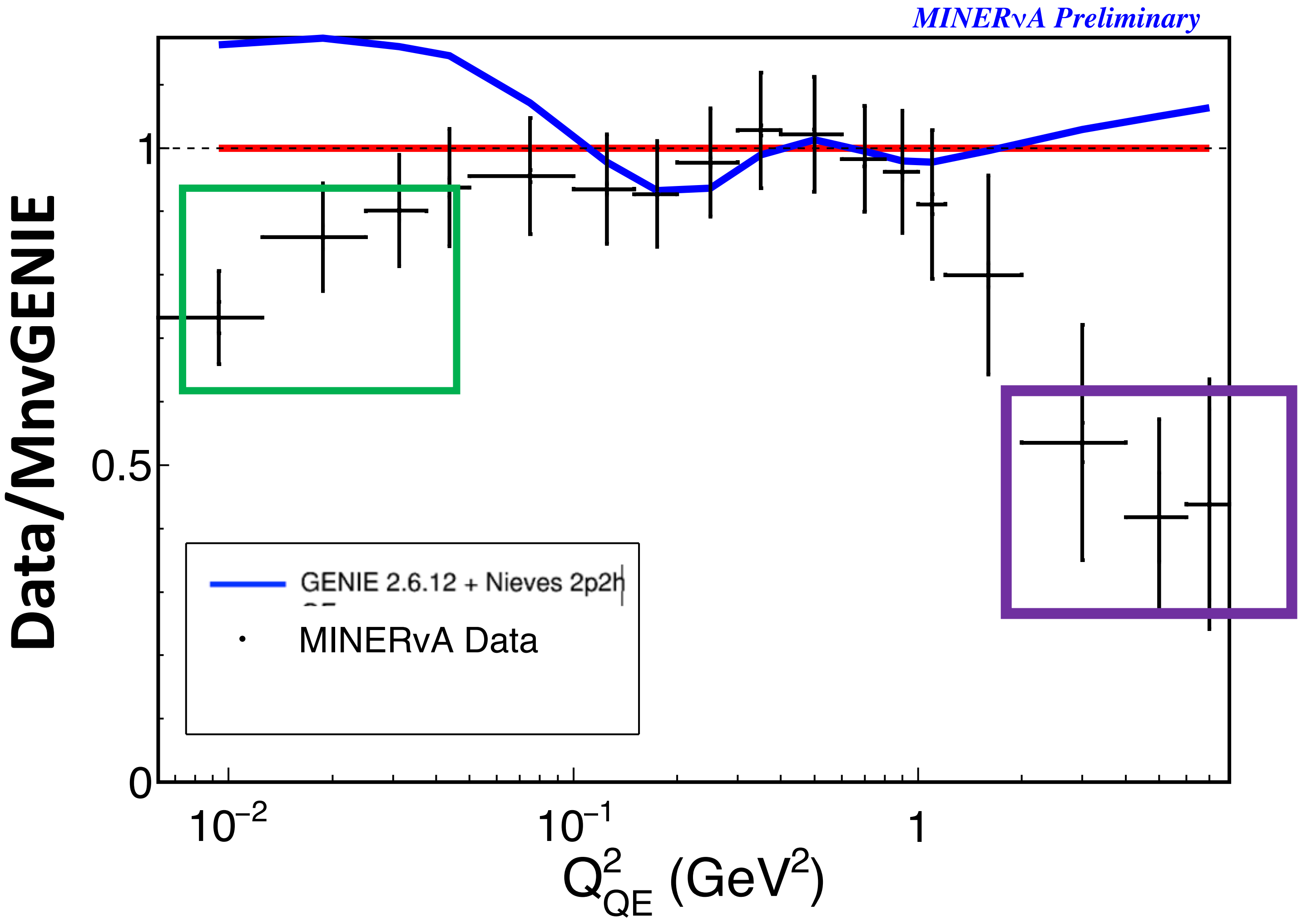
Solid lines are various components of MnvGNIE (see back up slide for more info).

Dotted lines are tweaks to those components.

MnvGENIE (red) is tuned to MINERvA Data and hence best describes the **data cross section**.

(More info on MnvGENIE on backup slide)

CCQELike Cross-section



At low Q2, more qelike resonant pion events.

In low Q2 region, deficit of pion production is favored. This was reported by MINOS[3] and also observed in MINERvA's CC1pi analysis [4].

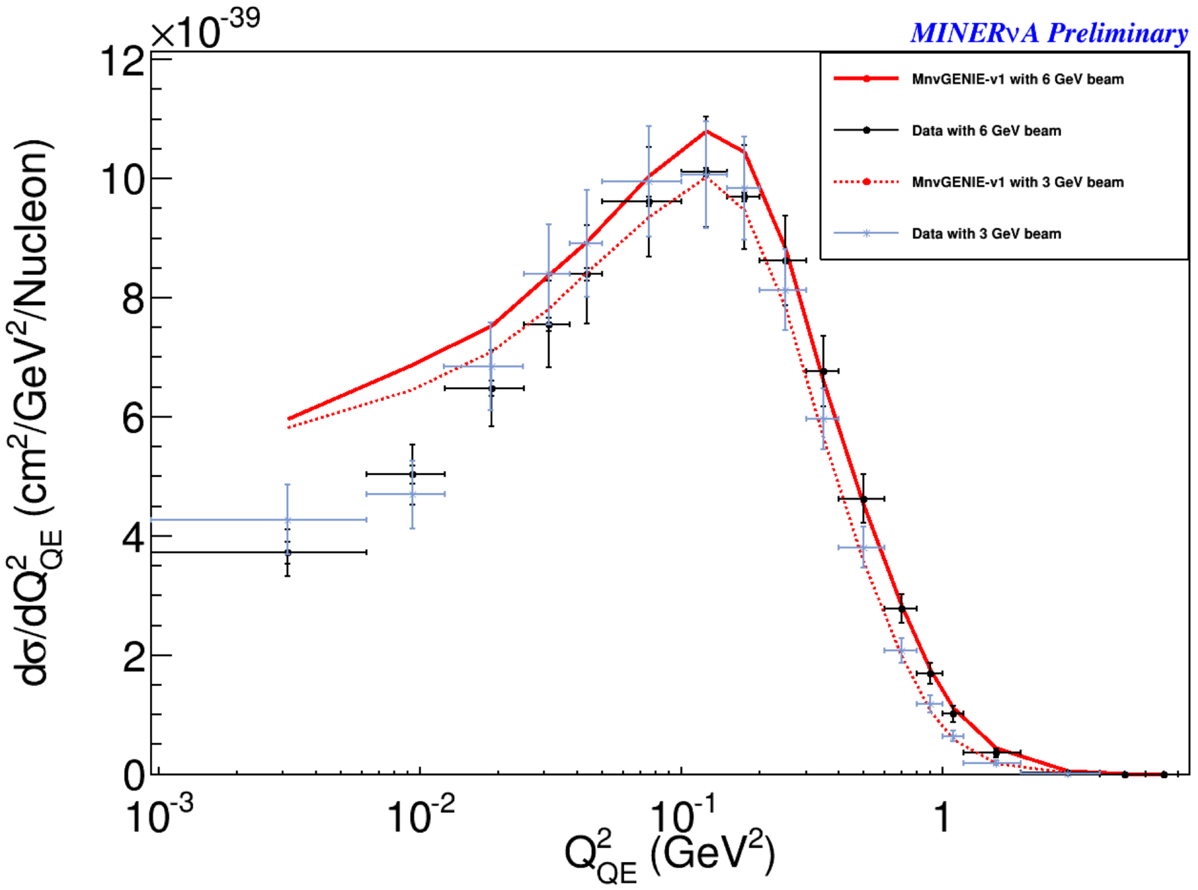
At high Q2, GENIE over predicts the cross sections.
→This is the region where we might be pushing the limit of dipole approximation in our CCQE cross section model.

$$\frac{d\sigma}{dq^2} \propto (F_1, F_2, F_A)$$

$$F_A(Q^2) = \frac{F_A(0)}{(1 - \frac{q^2}{M_A^2})^2}$$

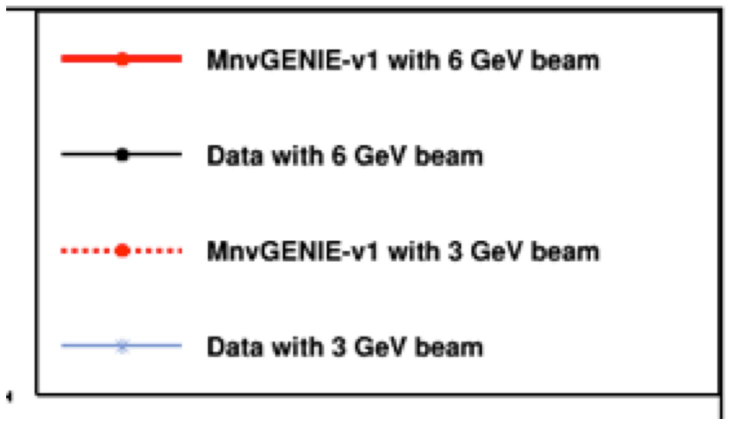
Dipole Axial Form Factor

Comparison to LE Data

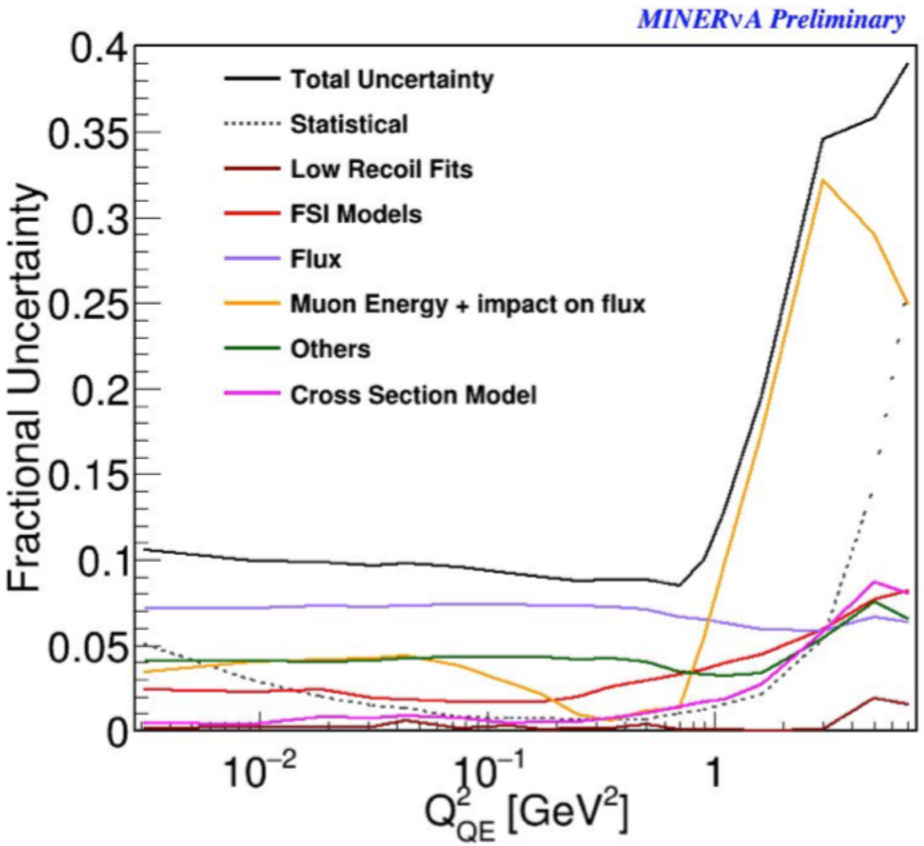


→ME data and LE data results agree well with one another.

→As ME data has larger peak neutrino energy, it will be used to probe into higher Q2 regions with better accuracy.



Systematics on Cross Section



Statistical uncertainty is less than 5 %.

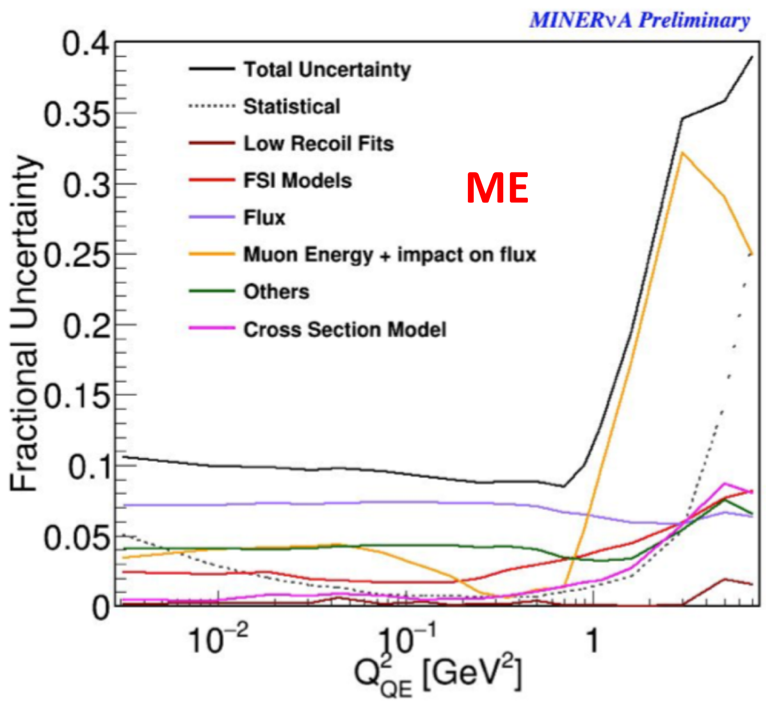
Flux →Dominant uncertainty at 8%.

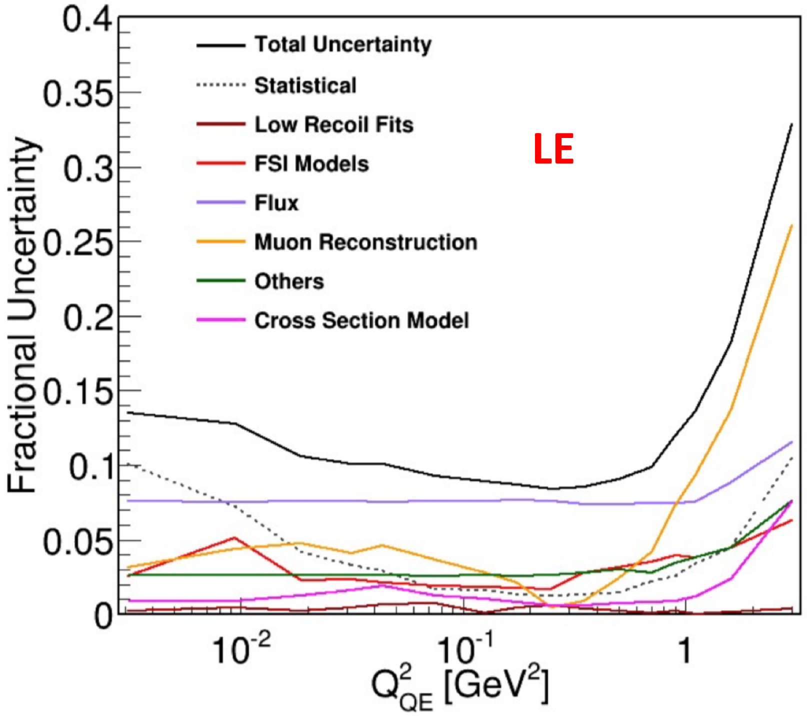
FSI models contributes 4 % uncertainty.

Model dependence systematics (cross section) is less than 1 % at low to moderate Q2.

Less than 10% total uncertainty on cross section.

Systematics on Cross Section



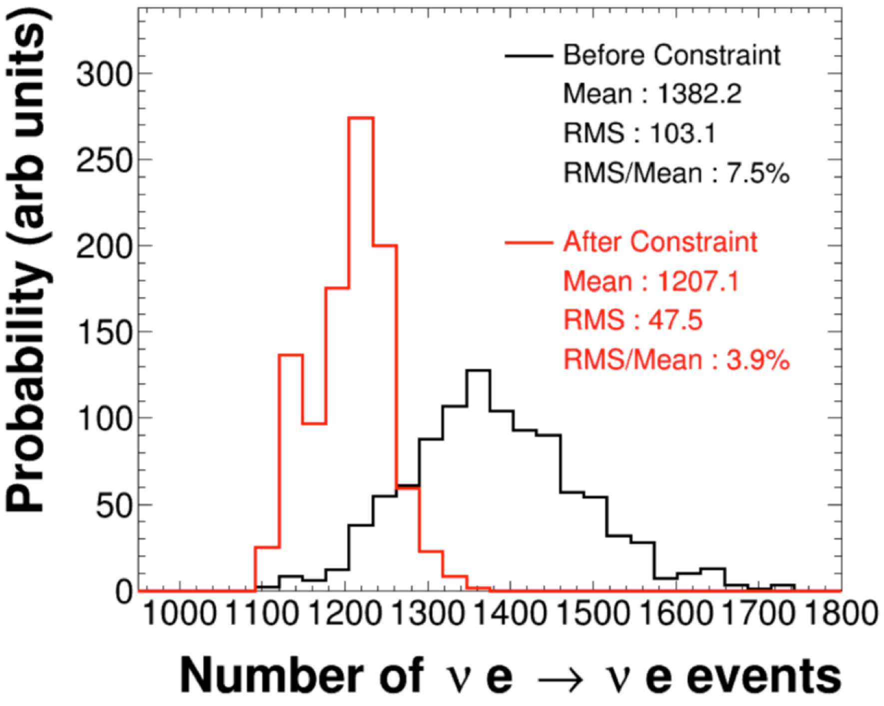


With higher statistics, the ME result has smaller statistical uncertainties.

→Less than 5 at low Q2 for ME vs 10 % for LE at same region.

High Energy ME run has enabled this analysis to probe into higher Q2.

Systematics on Cross Section (Flux)



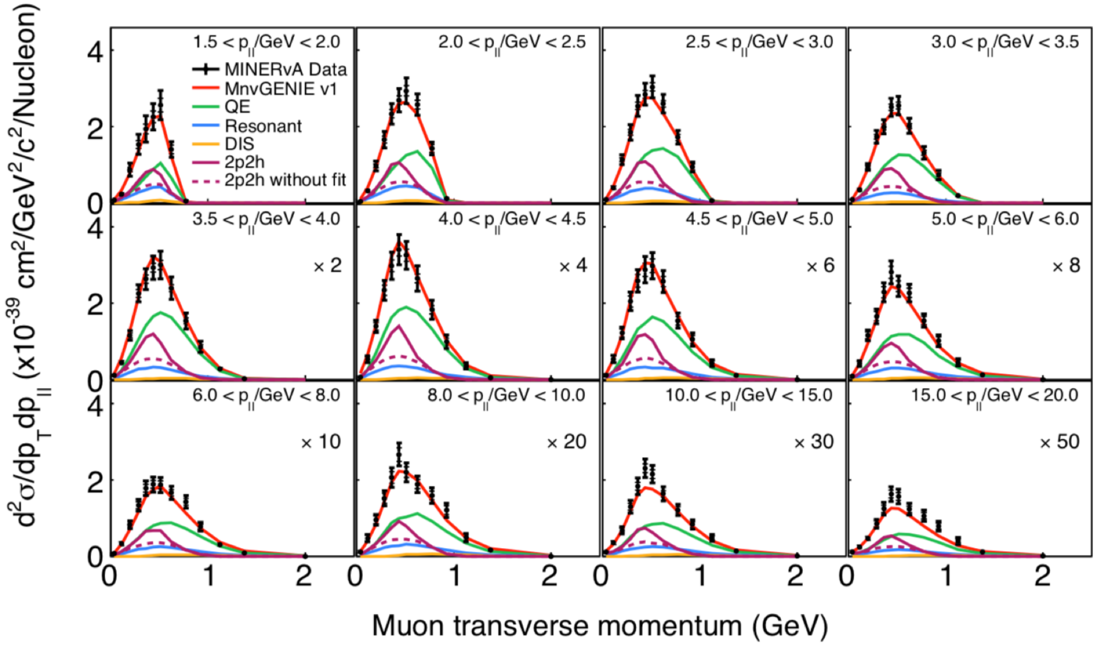
MINERvA has just published a nu+e scattering result (first ME paper) which can be used to further constrain the flux uncertainties [4].

Conclusions

- Ultimate goal (coming soon) of this analysis is to publish cross section results in 2D in the bins of muon pT and pZ as done with the **LE data**.

Coming Soon!

2D Cross section (neutrino nucleus) ME



2D Cross section (neutrino nucleus) LE [6]

Conclusions

- Our Q2 results agrees with LE data at the region of interest.
- Verifies that the tweaks motivated from other MINERvA studies applied works on ME data as well.
- Larger Statistics has enabled to reduce the uncertainties on the final cross section
- Wide beam neutrino energy data will extend this analysis in larger Q2 regions.
  - Further test of CCQE model (dipole approximation).

Citations

[1]. From eV to EeV: Neutrino Cross sections Across Scales (arXiv:1305.7513 [hep-ex])

[2]. R. Subedi et al. Science, 320(5882):1476–1478, 2008

[3]. arXiv: 1410.8613

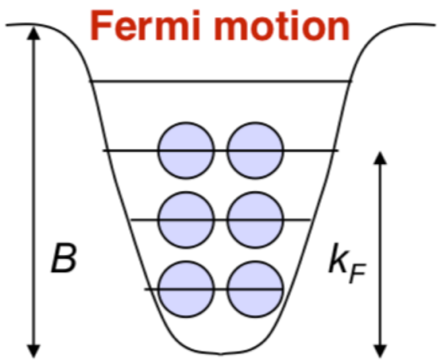
[4]. Phys.Rev. D94 (2016) 052005

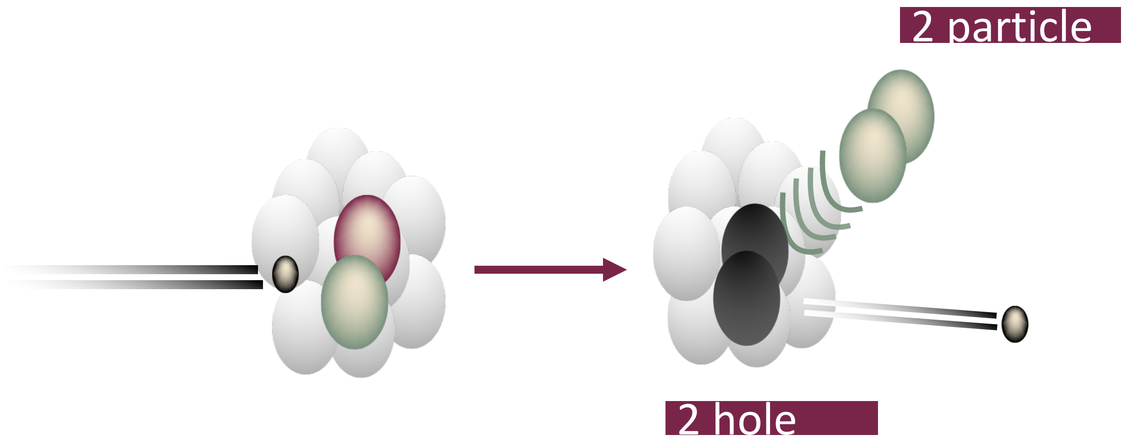
[5]. Constraint of the MINERvA Medium Energy Neutrino Flux using Neutrino-Electron Elastic Scattering" arXiV:1906.00111

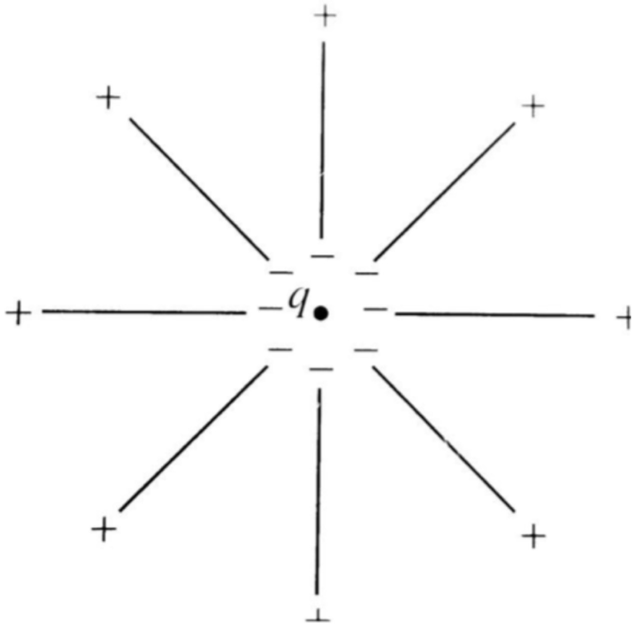
[6]. Phys. Rev. D 99, 012004 (2019)

Back Up

Nuclear Effects







Fermi Motion
Nucleus can be modeled as fermi gas and the nucleons will have fermi momentum (nucleons are never at rest).

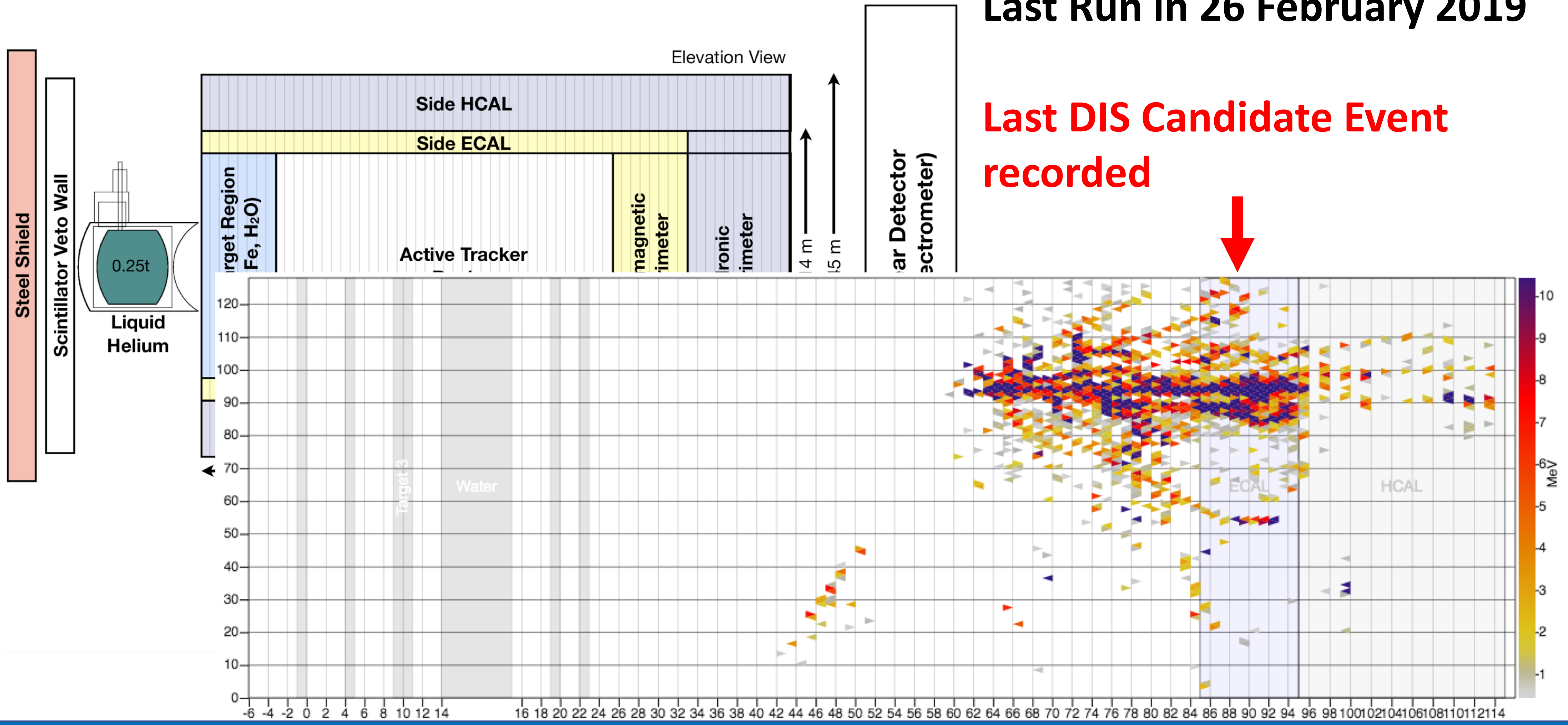
Multi Nucleon interaction (2p2h):
Sometimes a correlated pair of nucleons are produced. Mostly the pairs are protons and neutrons [1].

Screening Effect : W boson will polarize the target nucleus producing a screening effect Analogous to screening effect of electric charge in charge medium.

MnvGENIE v1

- Analysis is based on MnvGENIE v1.
- MnvGENIE v1 = GENIE 2.12.6 + Nieves 2p2h + Non Resonant Pion Reduction + Neutrino Low Recoil Fit + Valencia RPA applied to QE
  - Start with GENIE 2.12.6 (Relativistic Fermi Gas)
  - Add 20% 2p2h effects based on electron scattering data using Nieves Model.
  - Suppress non-resonant pion production to better agree data measured on deuterium.
  - Apply the fit based on low recoil analysis to 2p2h events in [q0,q3] phase space.
  - Reduce cross section of QE events as a function of Q^2 based on Valencia Model.

The MINERvA Detector



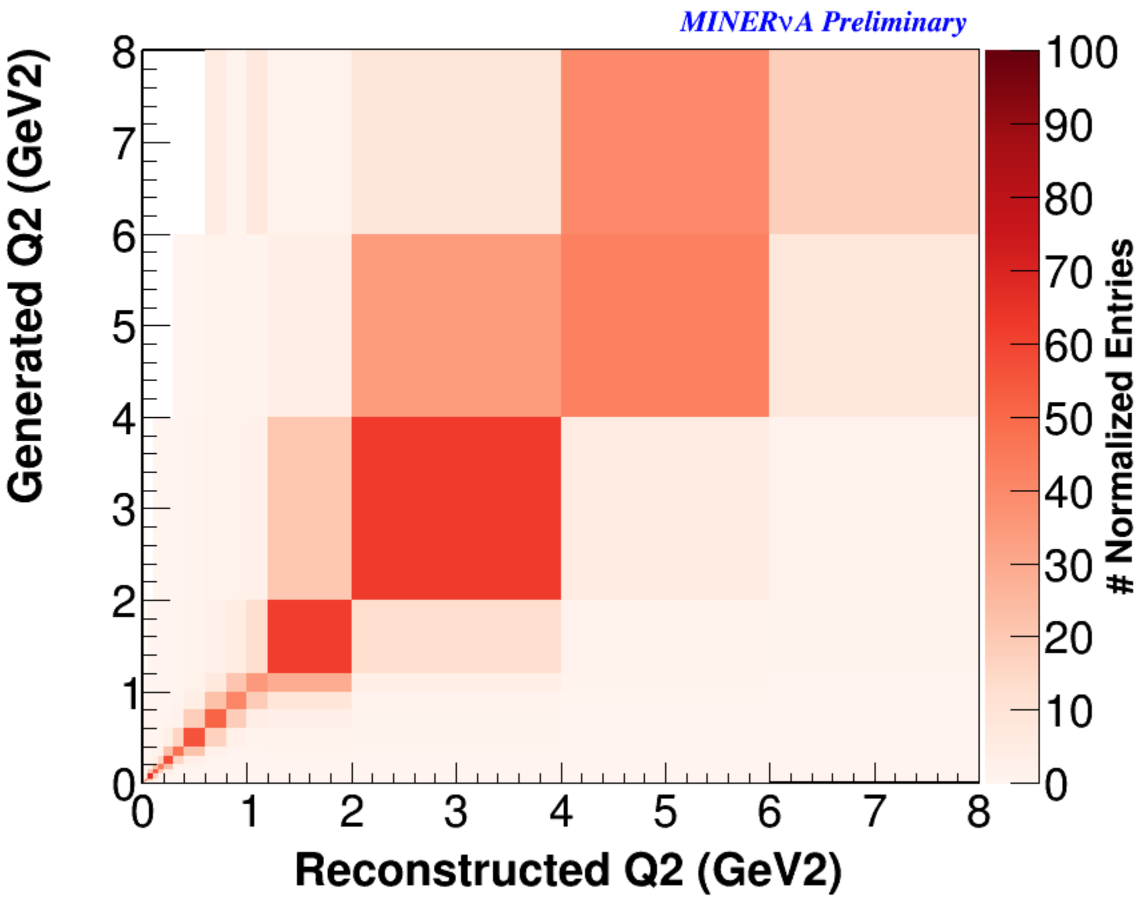
Last Run in 26 February 2019

Last DIS Candidate Event recorded

Unfolding

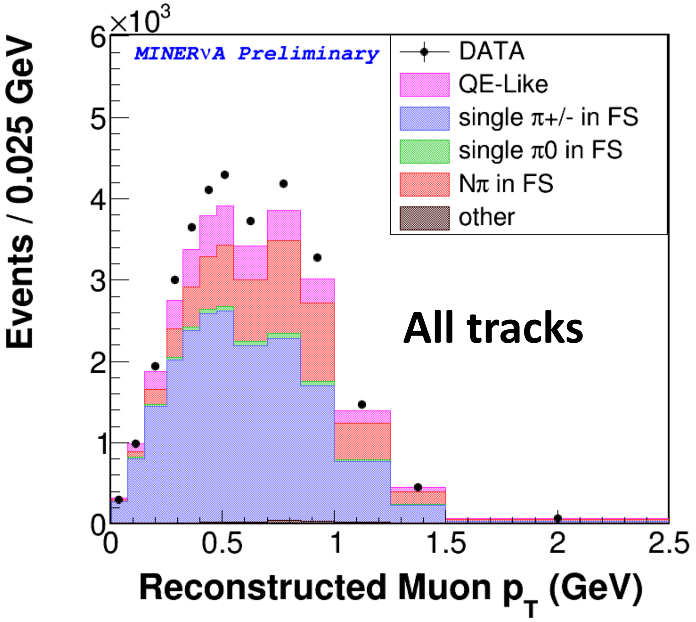
- Background subtracted Data needs to be corrected for the detector effects.
- Migration Matrix constructed using MnvGENIE in the bins of muon Q2.
- Unfolding based on Iterative Bayes unfolding.

MINERvA Preliminary

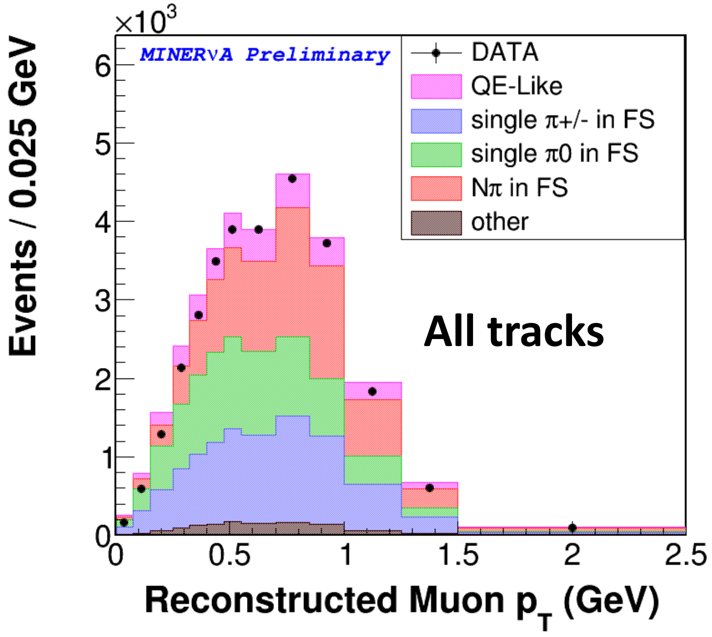


Background Constraint

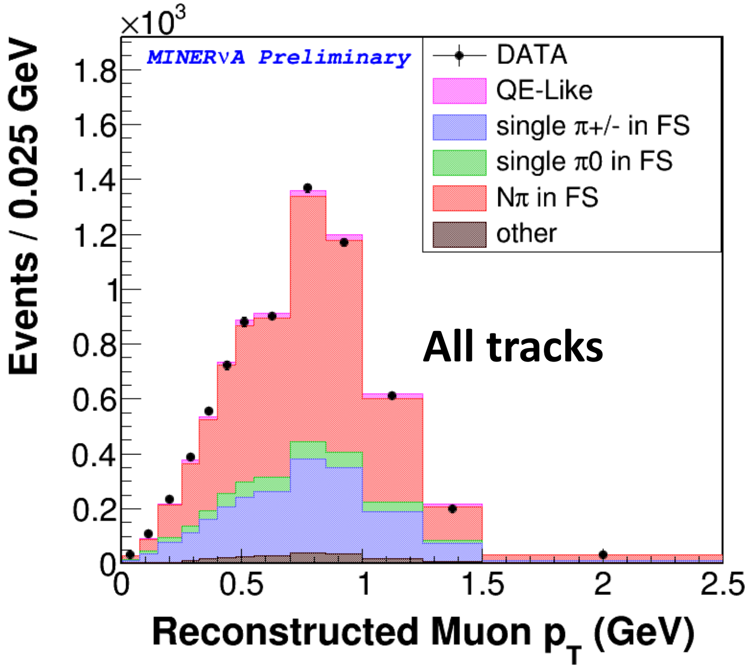
- Pion backgrounds are constrained by looking at three different independent samples for 1 track and >1 track samples separately..



Sample with a Michel electron only **(pi+ backgrounds)**

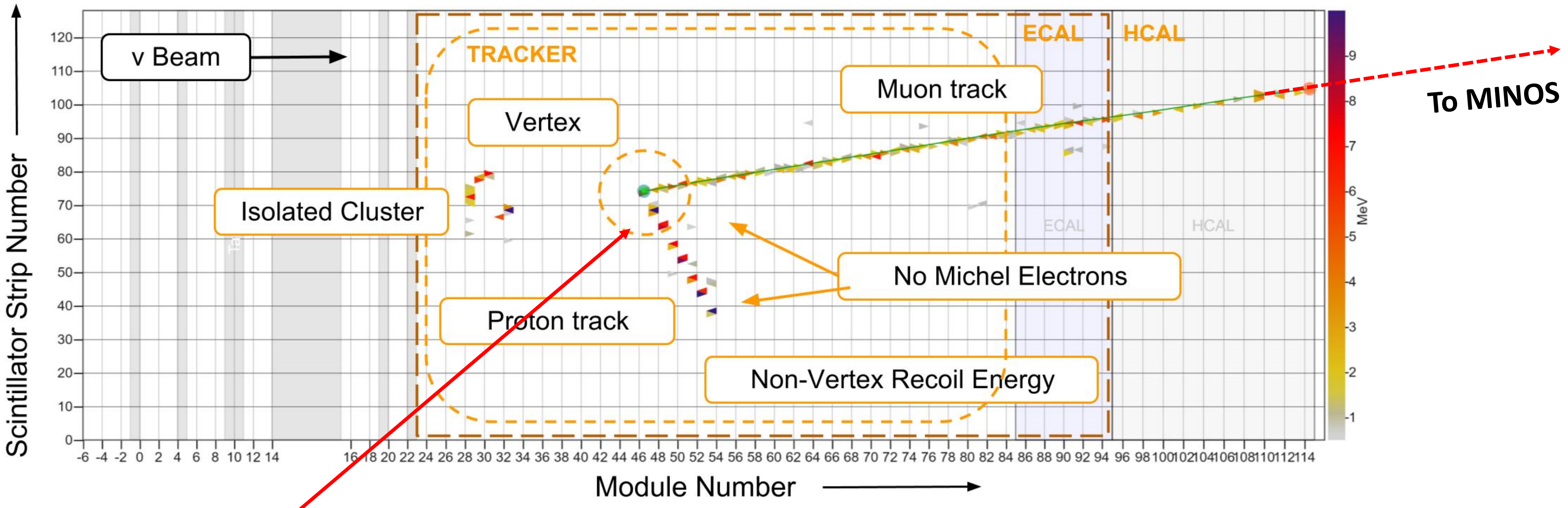


Sample with >1 isolated shower cluster **(pi0 backgrounds)**



Sample with >1 isolated shower cluster+Michel electrons **(multi pion backgrounds)**

Signal Definition

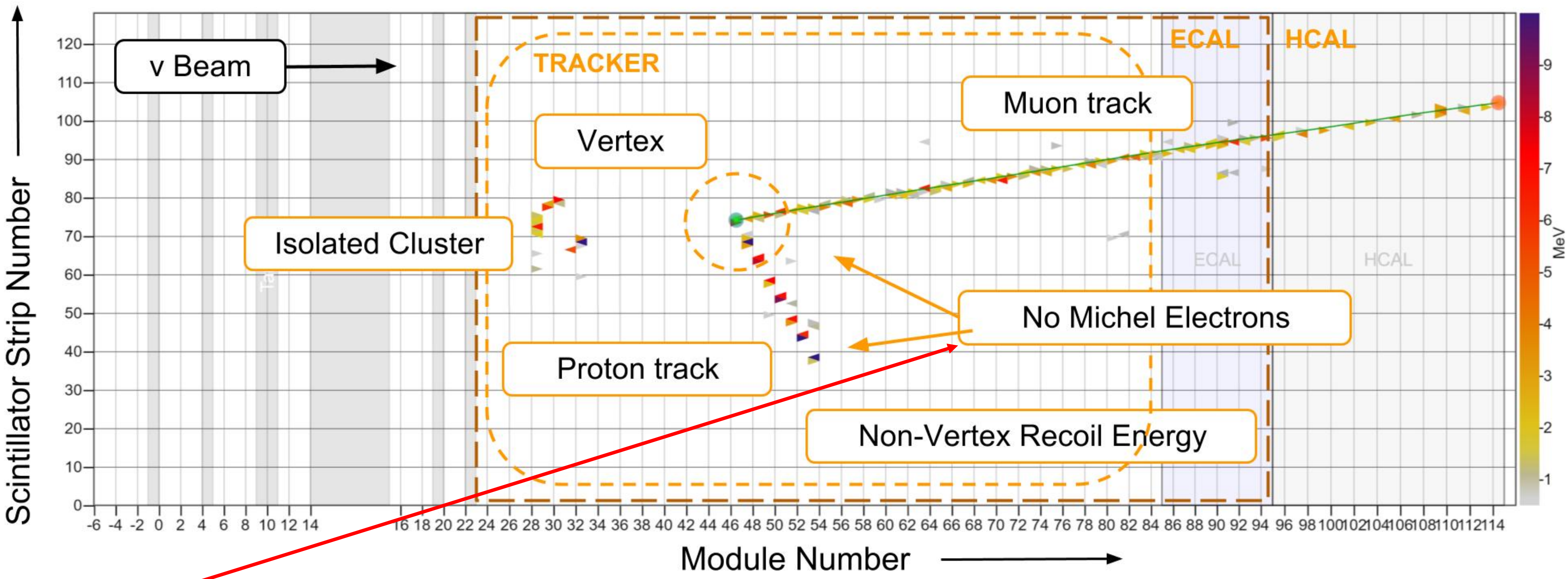


Interaction Vertex inside the fiducial volume
1 outgoing negative muon track

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

Michel Electron $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$

Signal Definition



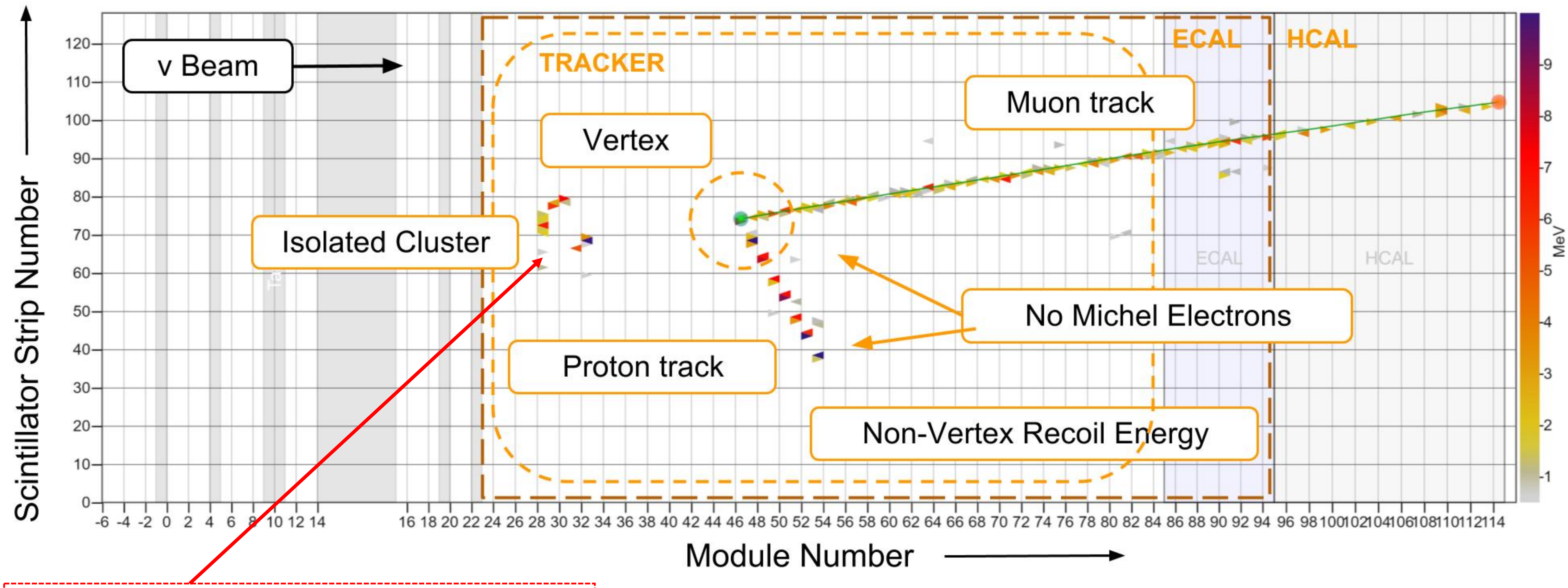
No Michel Electrons to exclude interactions that have pions as Final State

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\downarrow$$

Michel Electron $e^+ + \nu_e + \bar{\nu}_\mu$

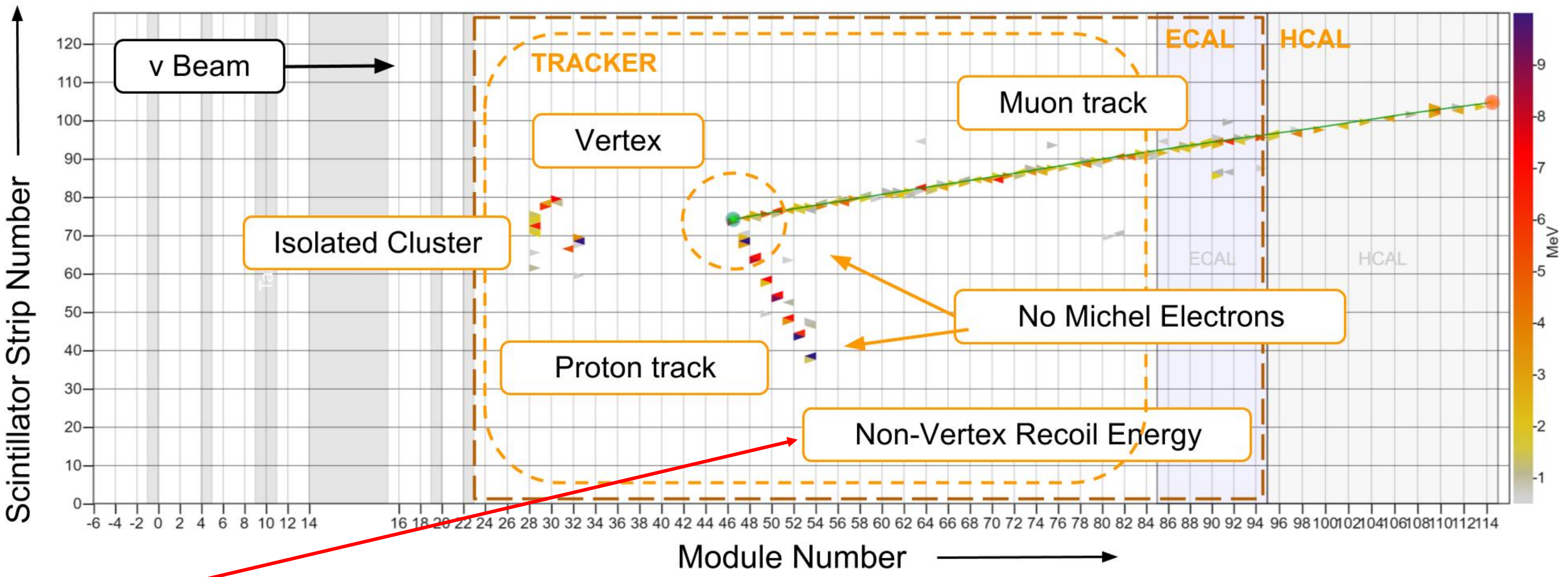
Signal Definition



Number of clusters that are not part of interaction vertex is no more than 1.

Isolated energy deposits may come from neutron or photon. Signficant CCQELike events might have 1 isolated energy deposit from neutrons.

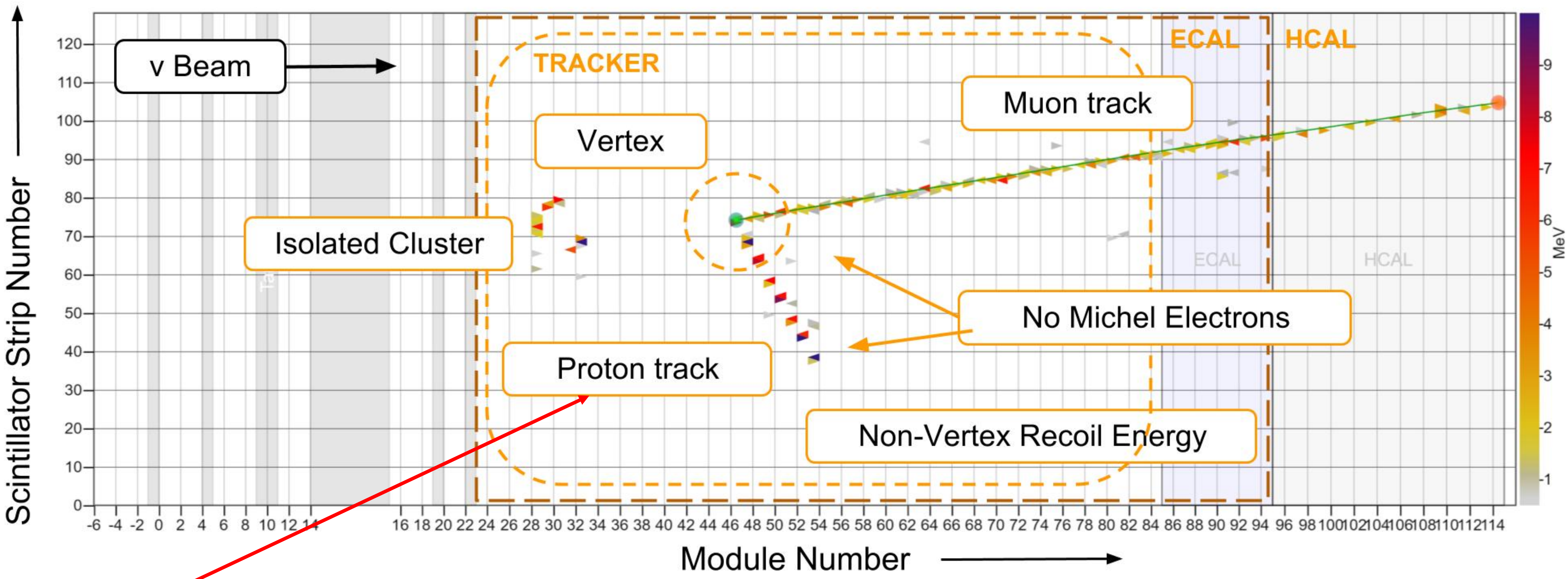
Signal Definition



Needs to have a low untracked recoil activity (<500 MeV) outside the vertex region (a sphere of 150 mm around the interaction vertex).

Untracked recoil activities→ Recoil activities coming from other particles other than muon and proton track.

Signal Definition



Can have any number of proton tracks.