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Muon Removed Electron Added Studies for the $\bar{\nu}_e CC$ Cross Section Analysis in the NOvA Near Detector

Ayşe BAT, Erciyes University

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ERCIYES NEUTRINO RESEARCH GROUP

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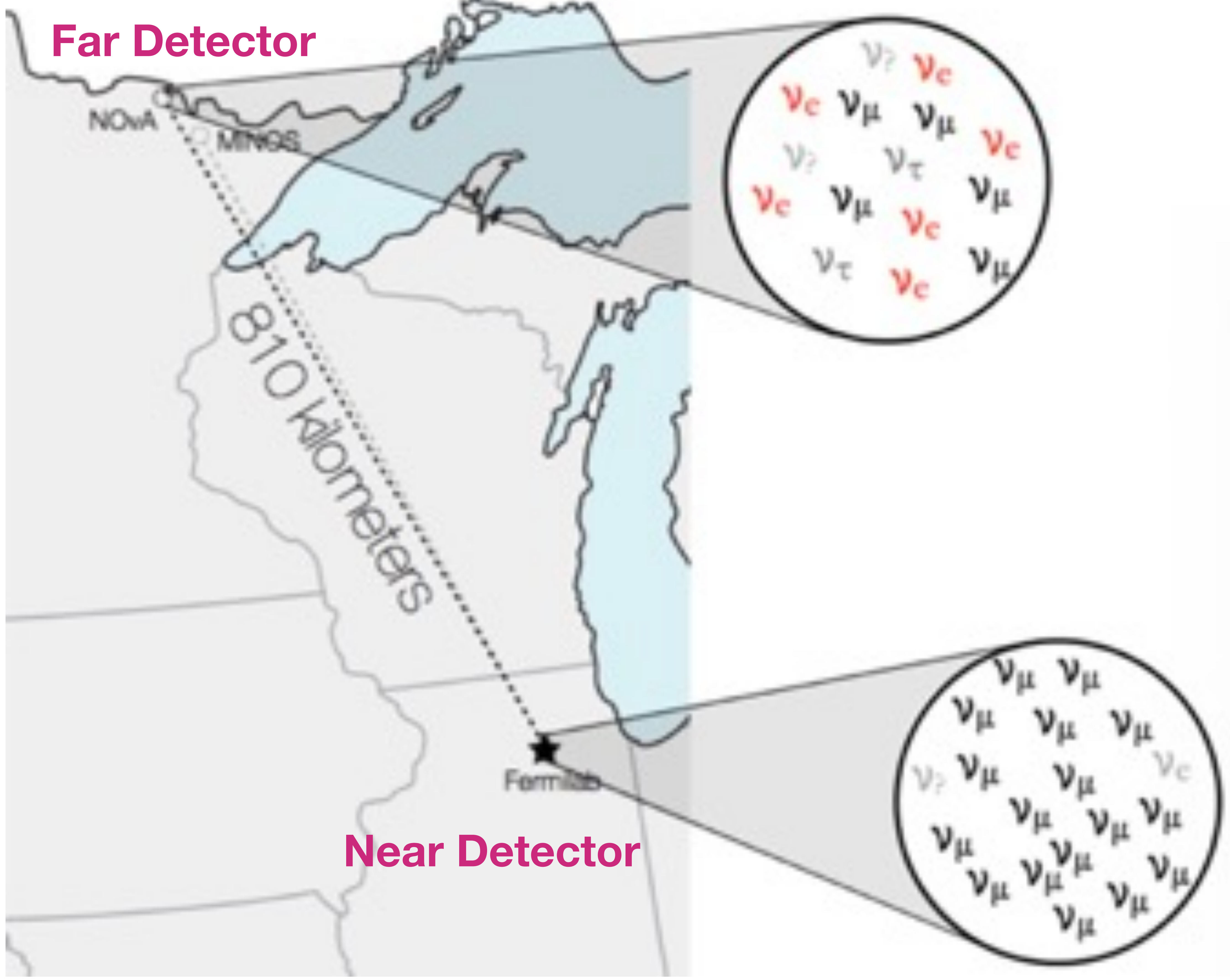
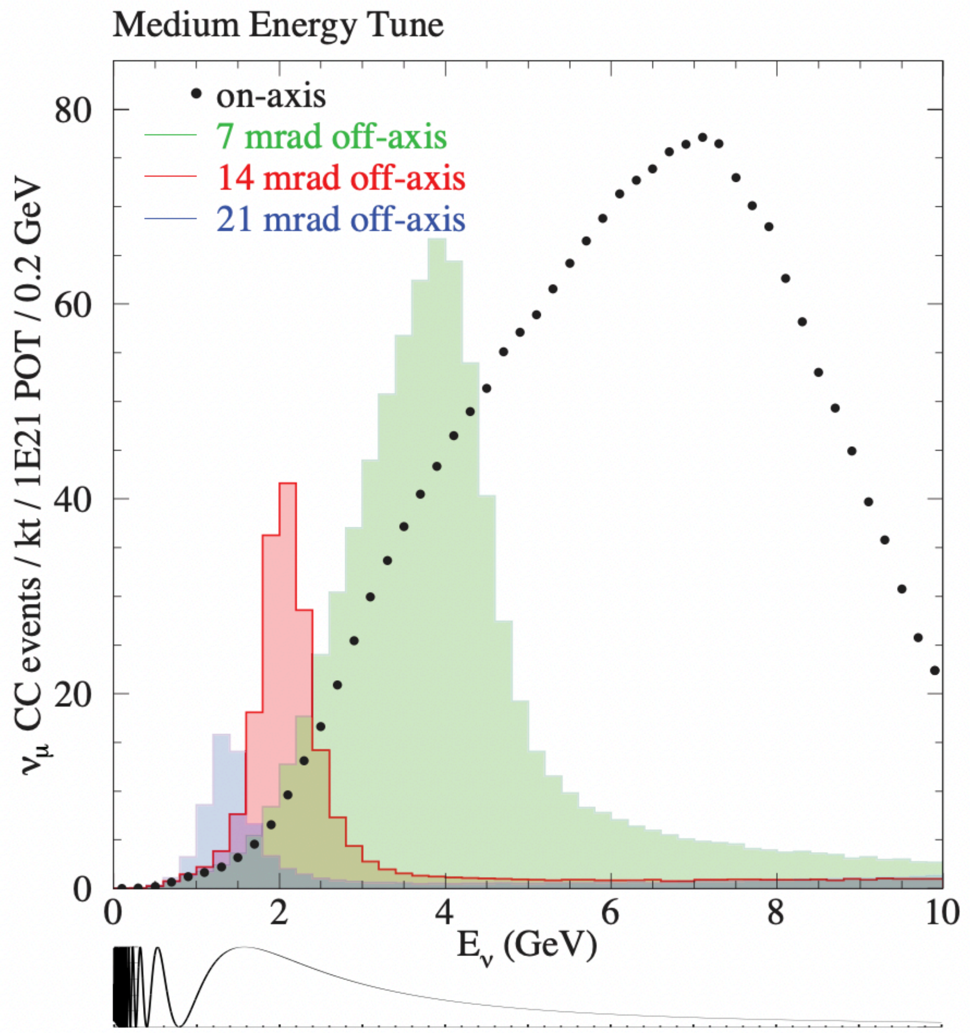
NuMI Off-Axis ν_e Appearance Experiment ($NO\nu A$)



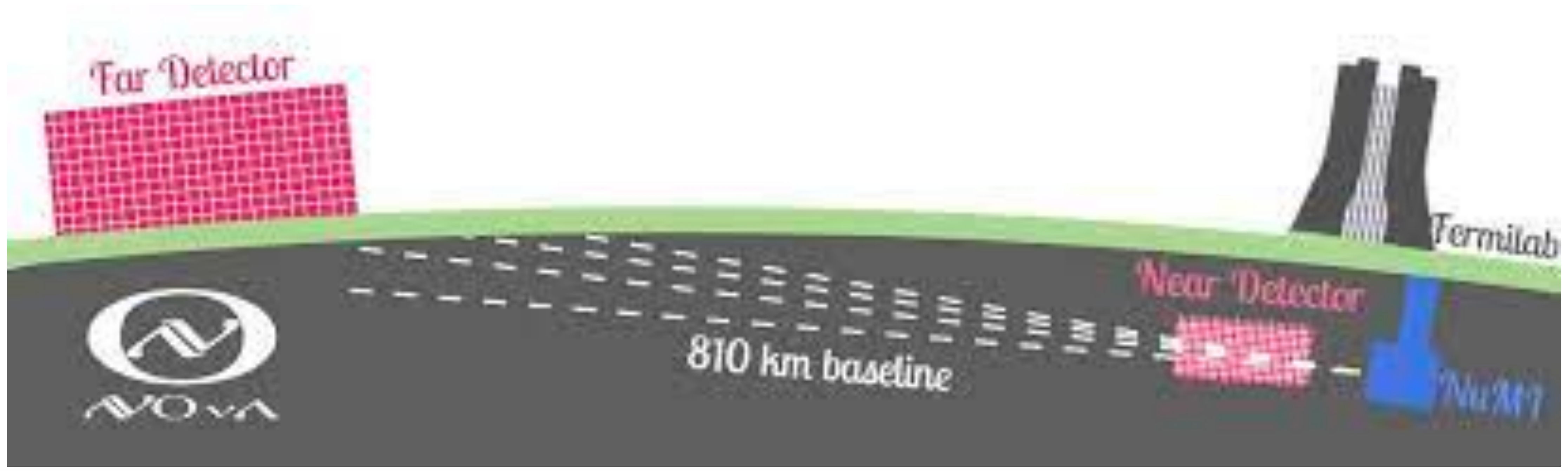
- NuMI Off-Axis ν_e Appearance Experiment (NOvA) is a 2-detector neutrino oscillation experiment.
- NOvA uses the NuMI muon neutrino beam at Fermilab as its neutrino source
- 14 kt liquid scintillator far detector at a distance of 810 km (Ash river, Minnesota) to detect the oscillated beam

The far detector is sited 14 mrad off-axis to produce a narrow-band beam around the oscillation maximum region (~2 GeV)



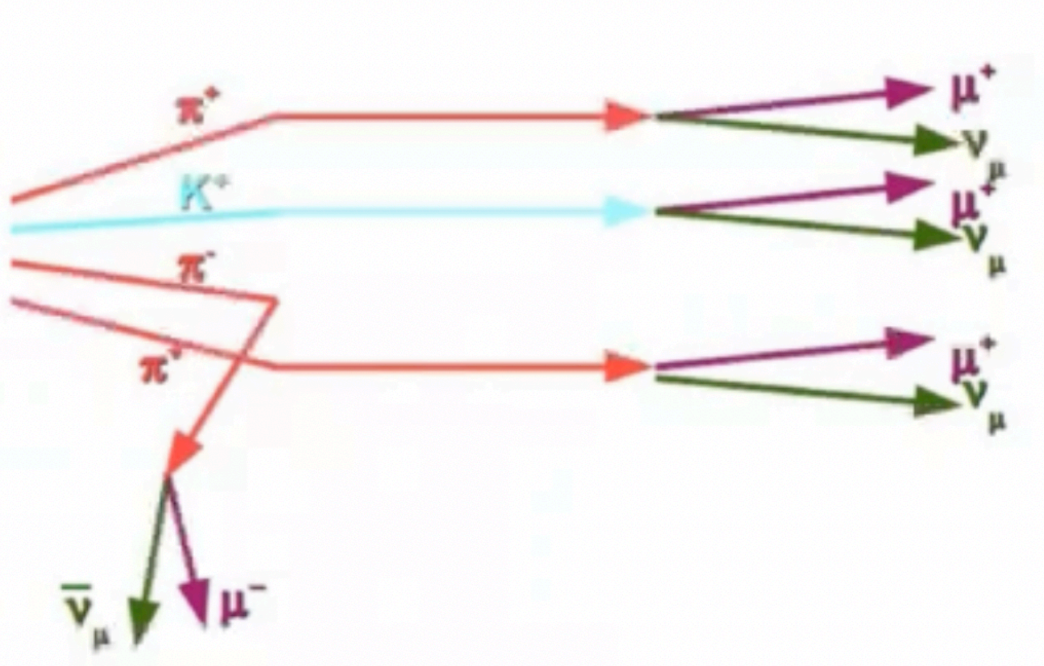
The NOvA experiment is designed to answer three fundamental questions in neutrino physics:

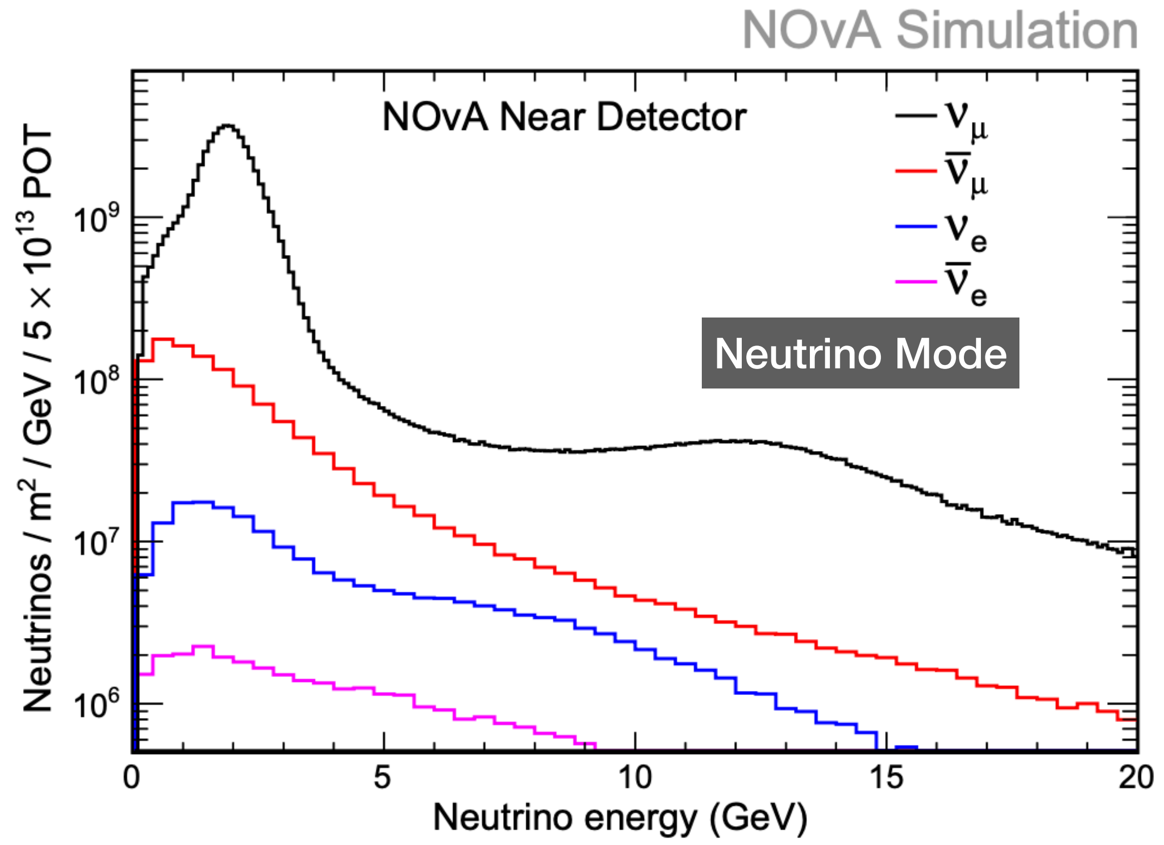
1. Can we observe the oscillation of muon neutrinos to electron neutrinos?
2. What is the ordering of the neutrino masses?
3. What is the symmetry between matter and antimatter?



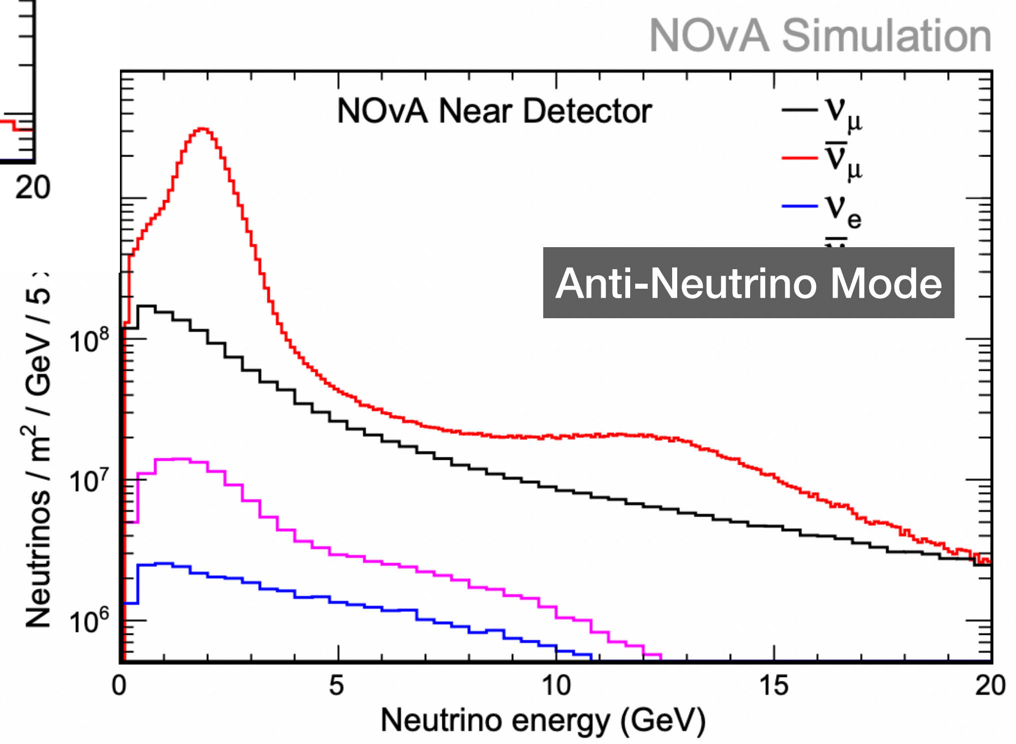
NUMI Beam at FERMILAB

120 GeV protons strike a graphite target and hadronic cascade is created.





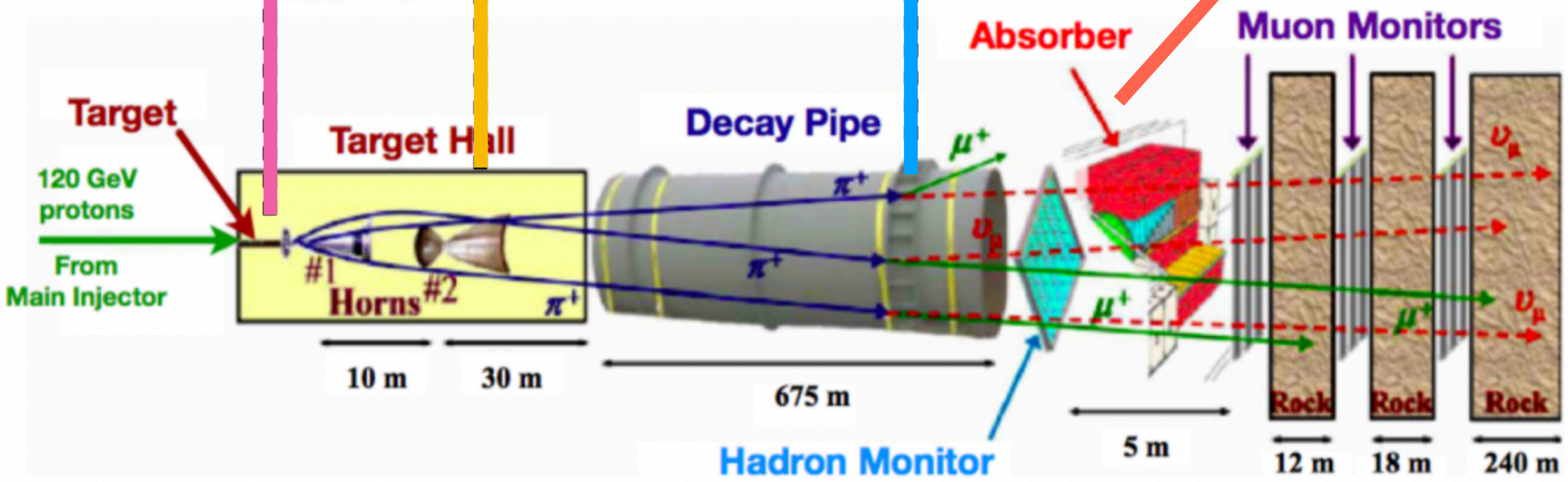
Magnetic Horn used for making a ν beam (FHC) or $\bar{\nu}$ beam (RHC).



Pions and Kaons are focused by 2 magnetic horns.

Pions and Kaons decay

Remaining μ and hadrons are absorbed.



14.6 mrad off-axis

NOvA

on-axis

MINERvA

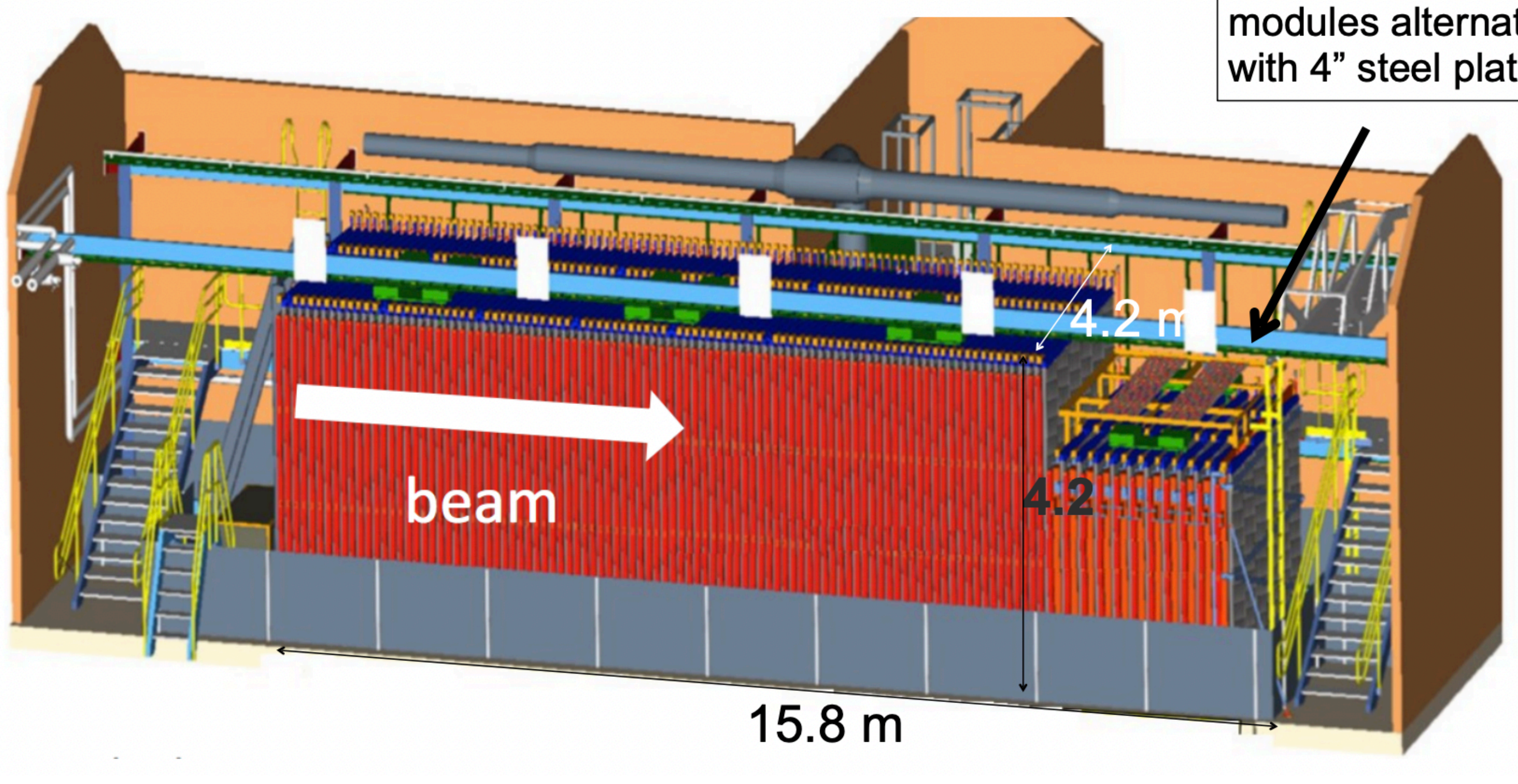
MINOS

$$\pi^{\pm} \rightarrow \mu\nu_\mu$$

$$K^{\pm} \rightarrow \mu\nu_\mu$$

$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_\mu(\bar{\nu}_\mu)$	99.987
$\pi^{\pm} \rightarrow e^{\pm} + \nu_e(\bar{\nu}_e)$	0.0123

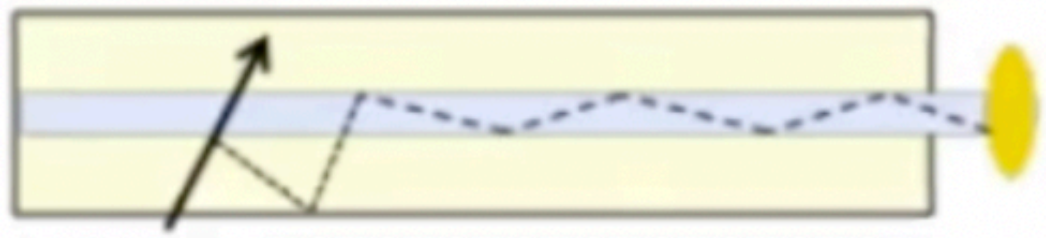
NOνA Near Detector



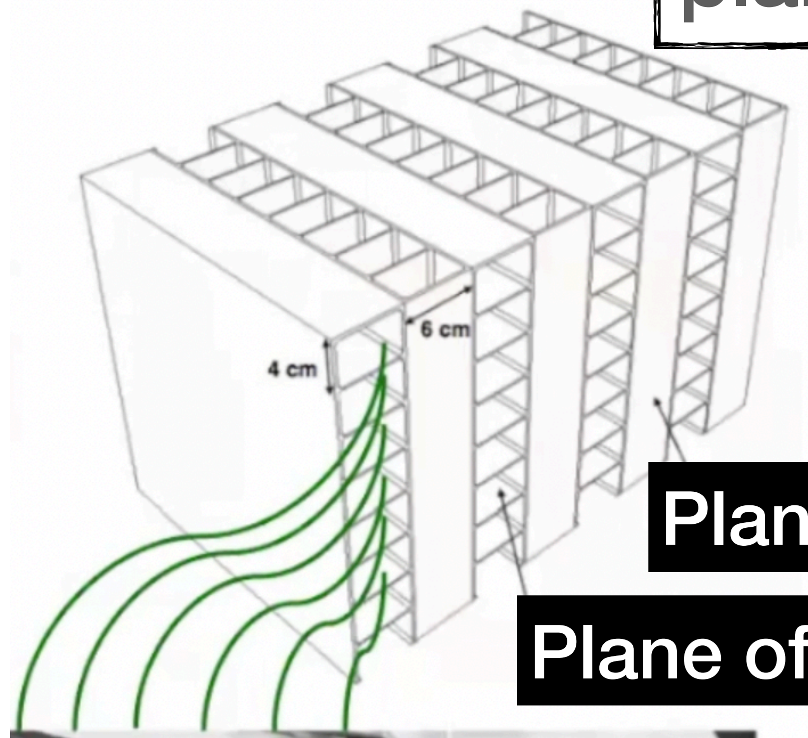
semi-active region, modules alternated with 4” steel plates

Photosensors is coupled to wavelength Sifting fiber embedded in scintillator

Fiber
(not to scale)

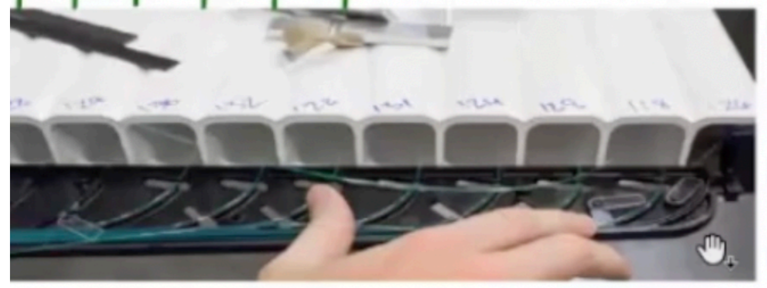


***NOνA, MINERνA, MINOS, SciBar* and others use this technique.**



Plane of vertical cells

Plane of horizontal cells

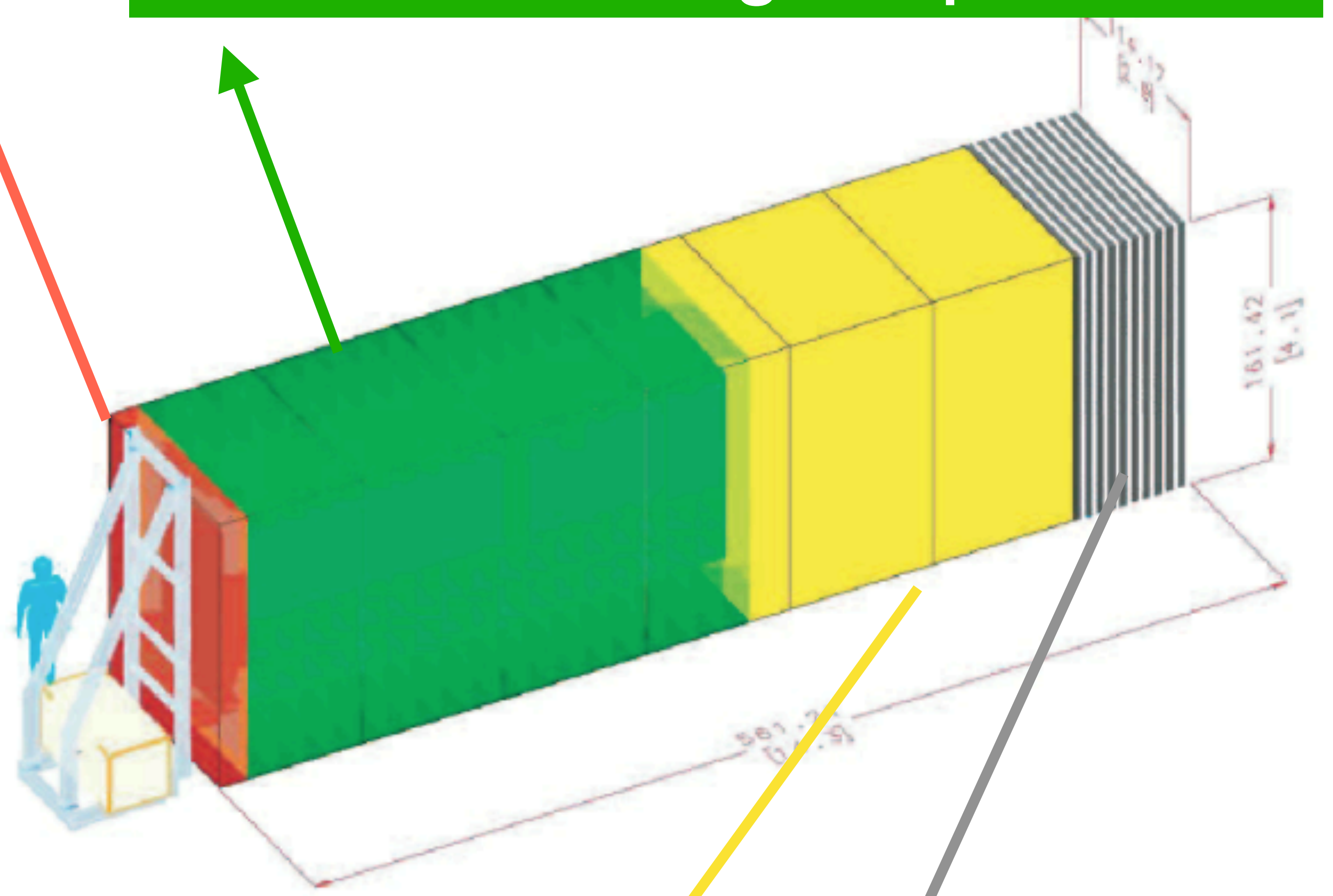


The detector is split into four logical regions.

The first 6 planes from the upstream surface of the detector is used as veto counter

Near Detector
Location: Fermilab
Weight : ~300 Ton
Width : 4.1 m
Hight : 4.1 m
Depth : 15.8 m
Medium : Liquid Scintillator
Cells : 20,192 cells in 192 planes (with muon catcher)

20 ton fiducial volume is centered in the following 108 planes.

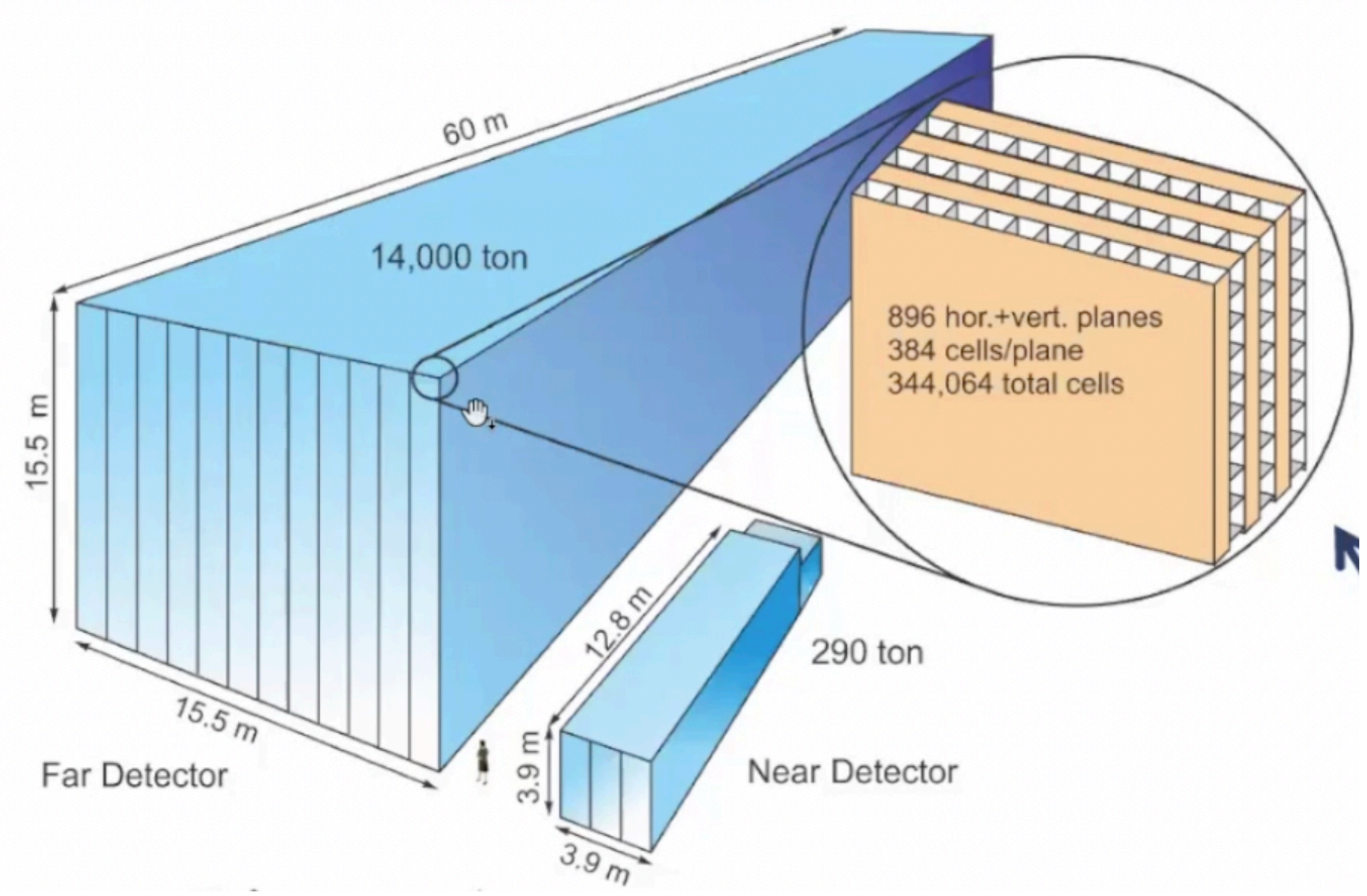


Electron showers of a few GeV from $\nu_e CC$ interactions are contained in 72 planes

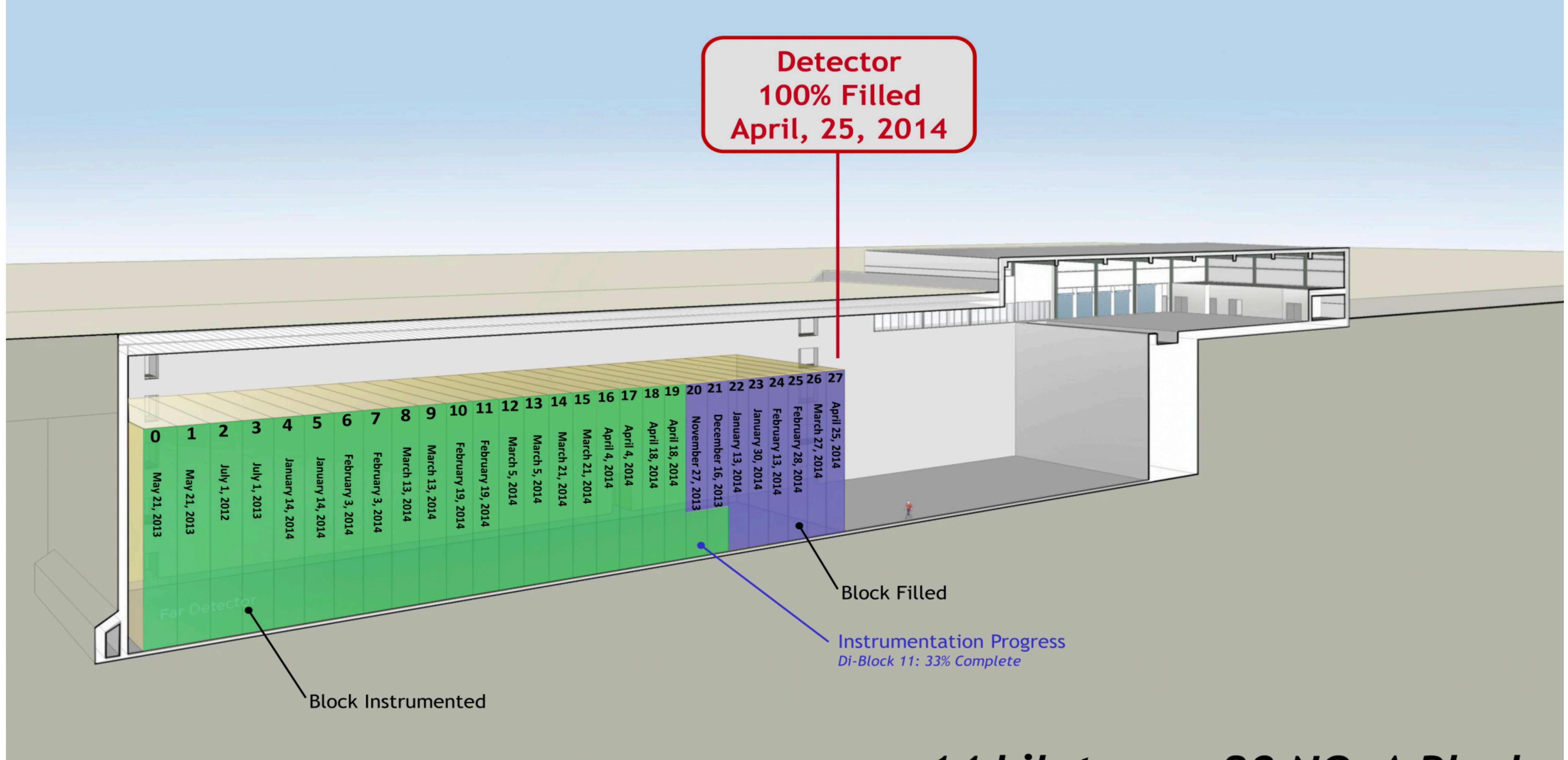
The active detector sections are followed by a muon catcher composed of ten scintillator planes with inter-spaced 10 cm thick steel planes.

NOνA Far Detector

Far Detector
Location: Ash River, Minnosata
Weight : 14 kTon
Width : 15.5 m
Hight : 15.5m
Depth : 60m
Medium : Liquid Scintillator
Cells : 344,000 scintillator in 896 planes



810 km away from each others.

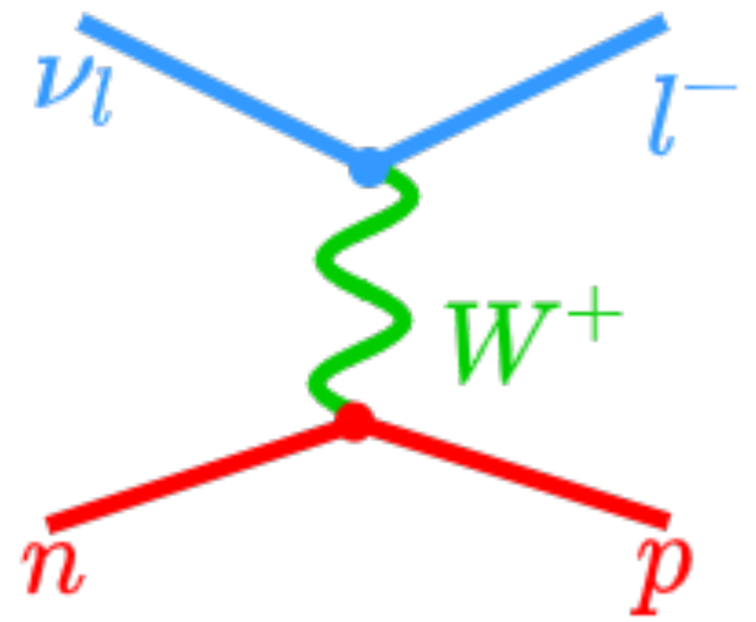


14 kilotons = 28 NOvA Blocks
28 blocks of PVC modules are assembled and installed in place
28.0 blocks are filled with liquid scintillator
20.66 blocks are outfitted with electronics

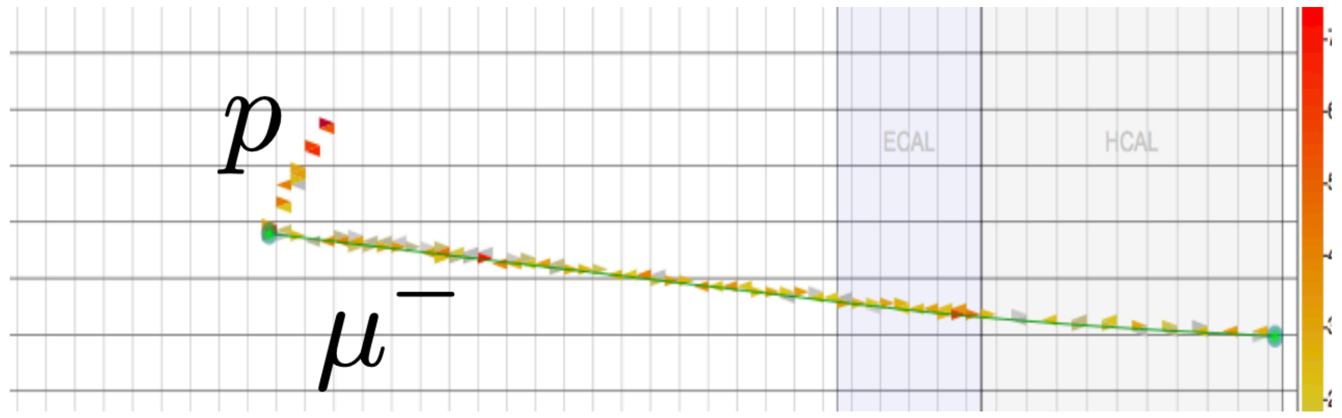
Near Detector nearly has quarter of the size of the far detector.

Neutrino Interactions

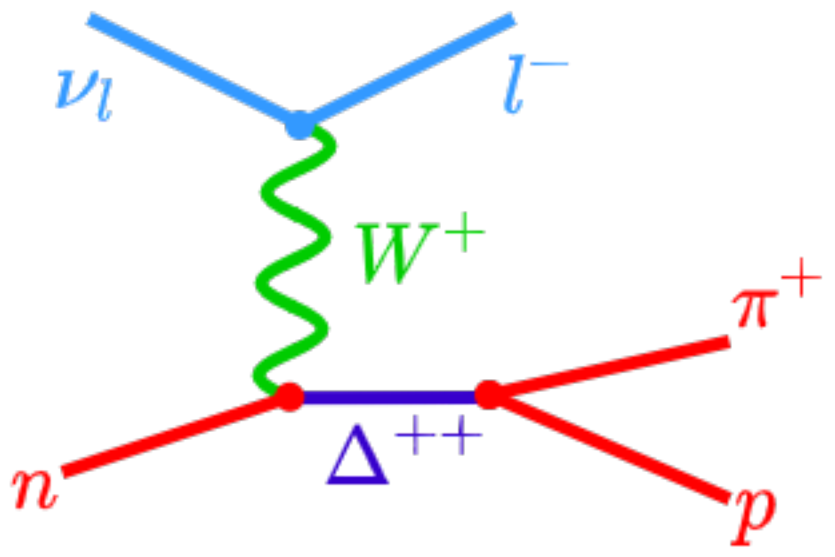
Quasi-Elastic (QE) Scattering



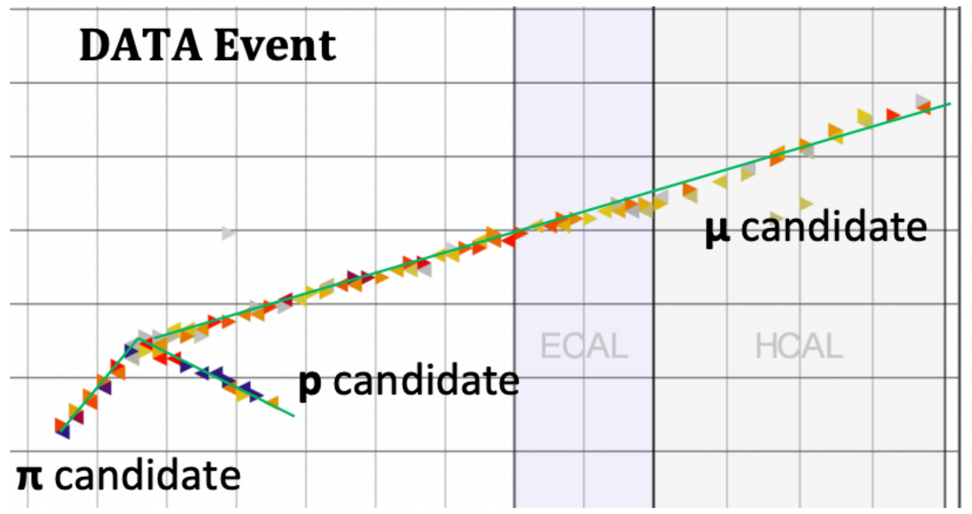
The neutrino scatters elastically off the nucleon ejecting a nucleon from the target



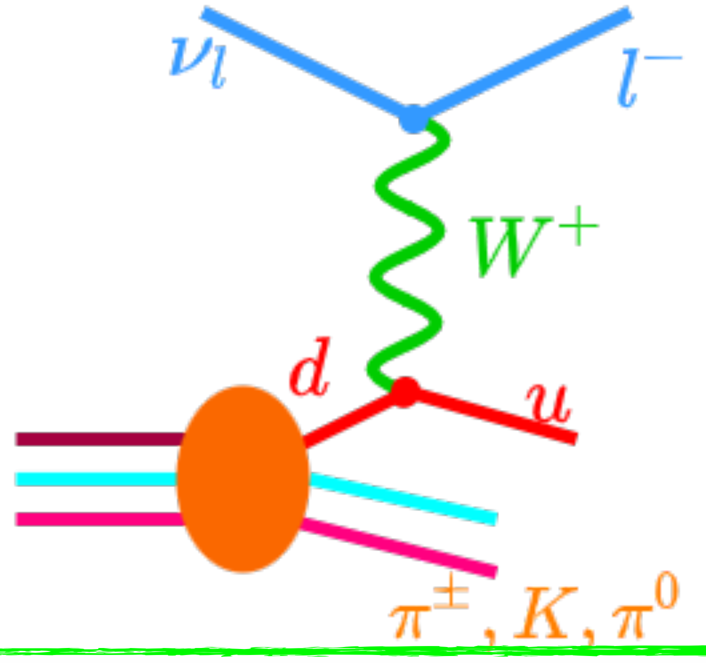
Resonance Production (RES)



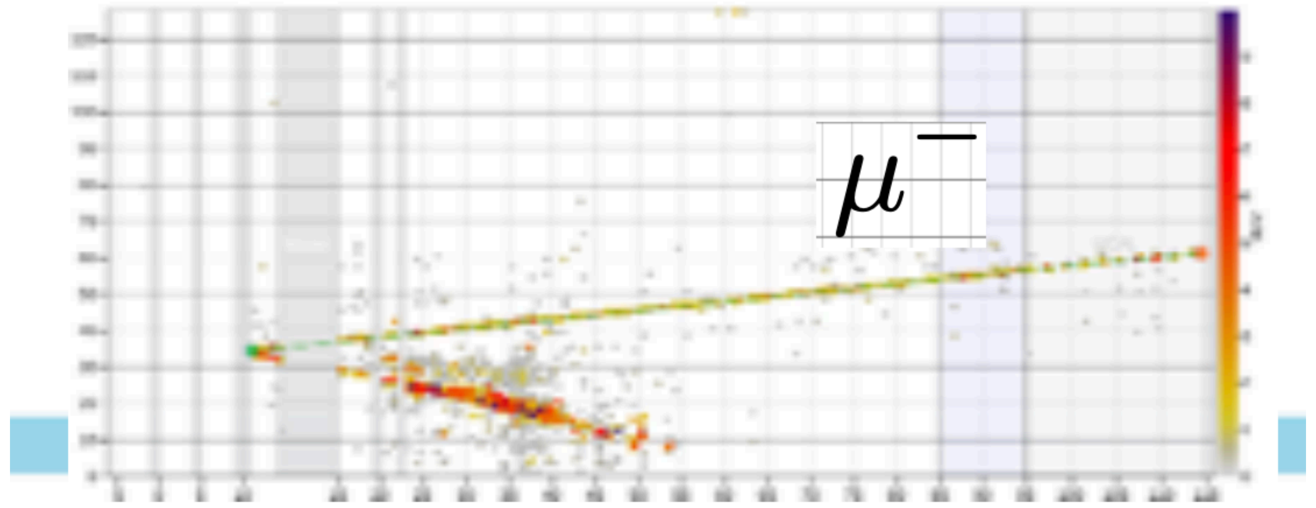
The neutrino can excite the target nucleon to a resonance state

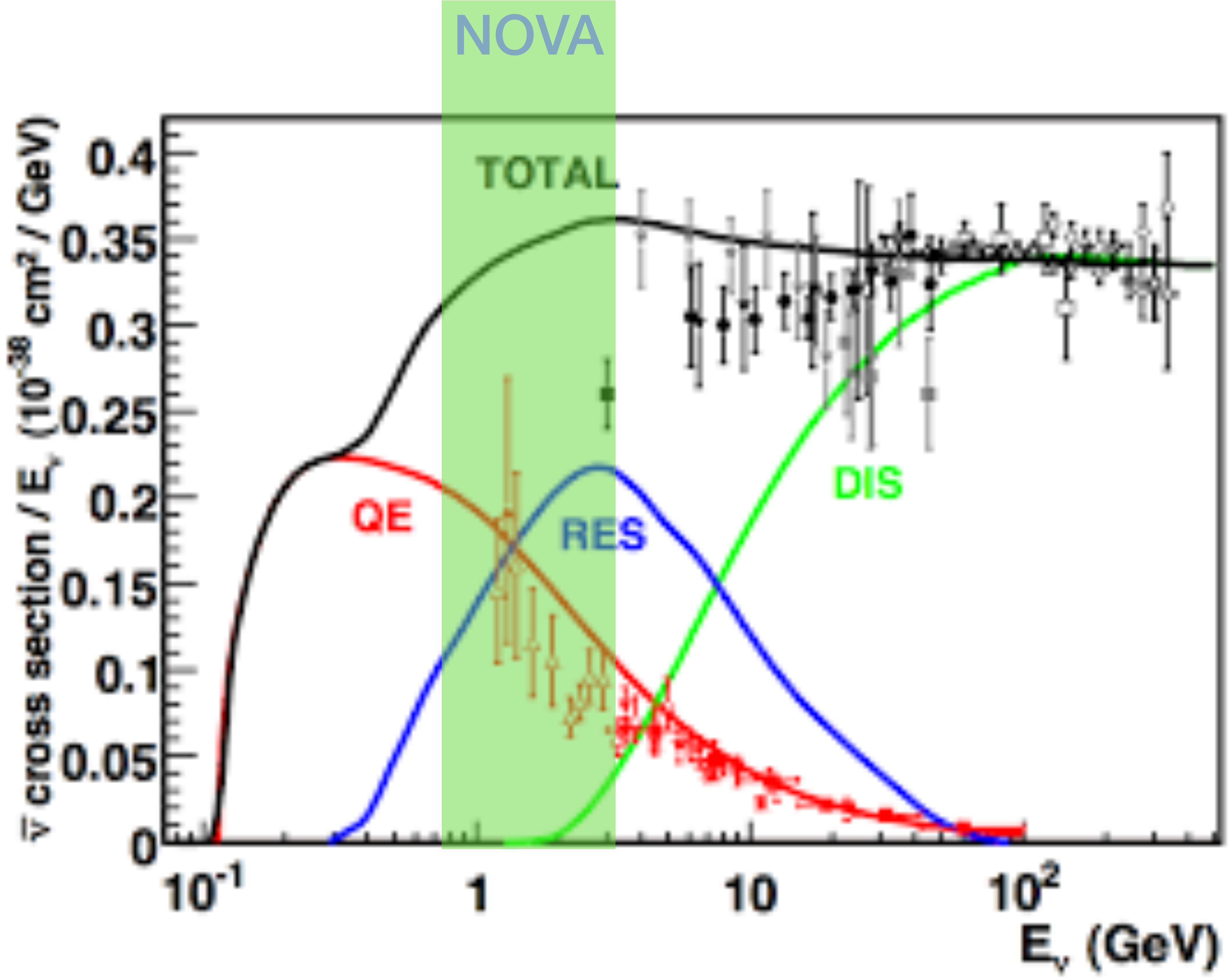


Deep Inelastic scattering (DIS)



The neutrino scatters off a quark in the nuclear producing a hadronic system in the final state.

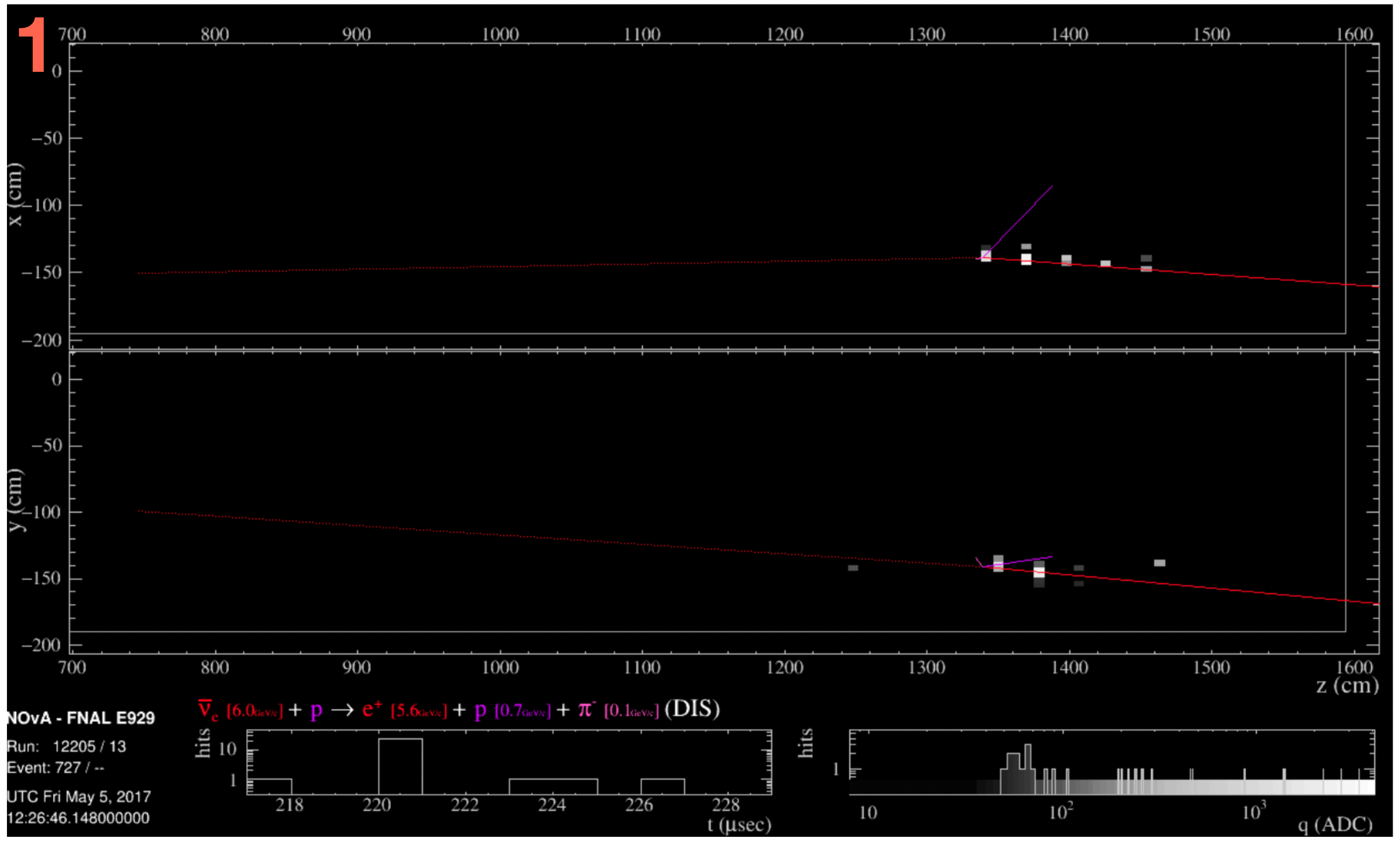


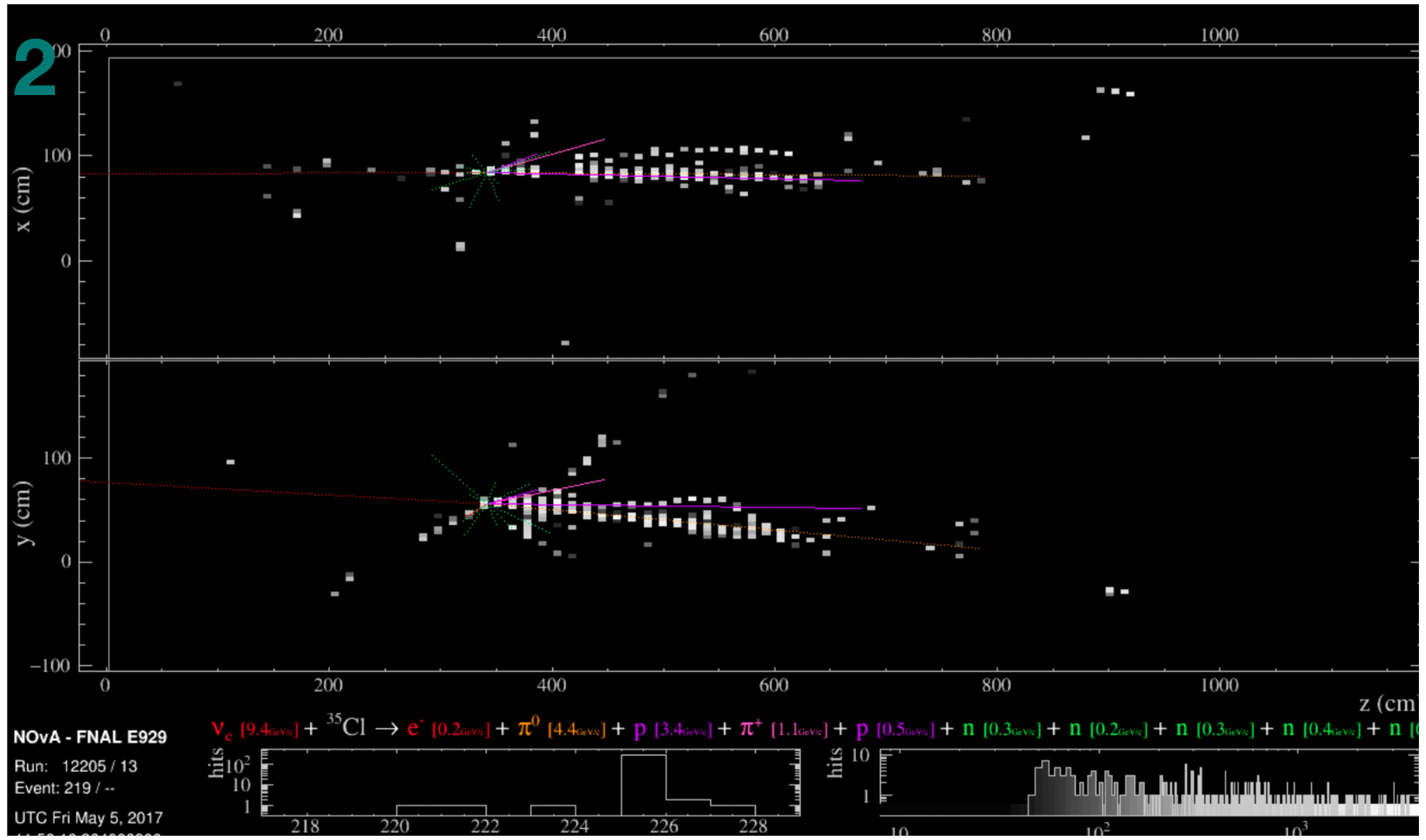


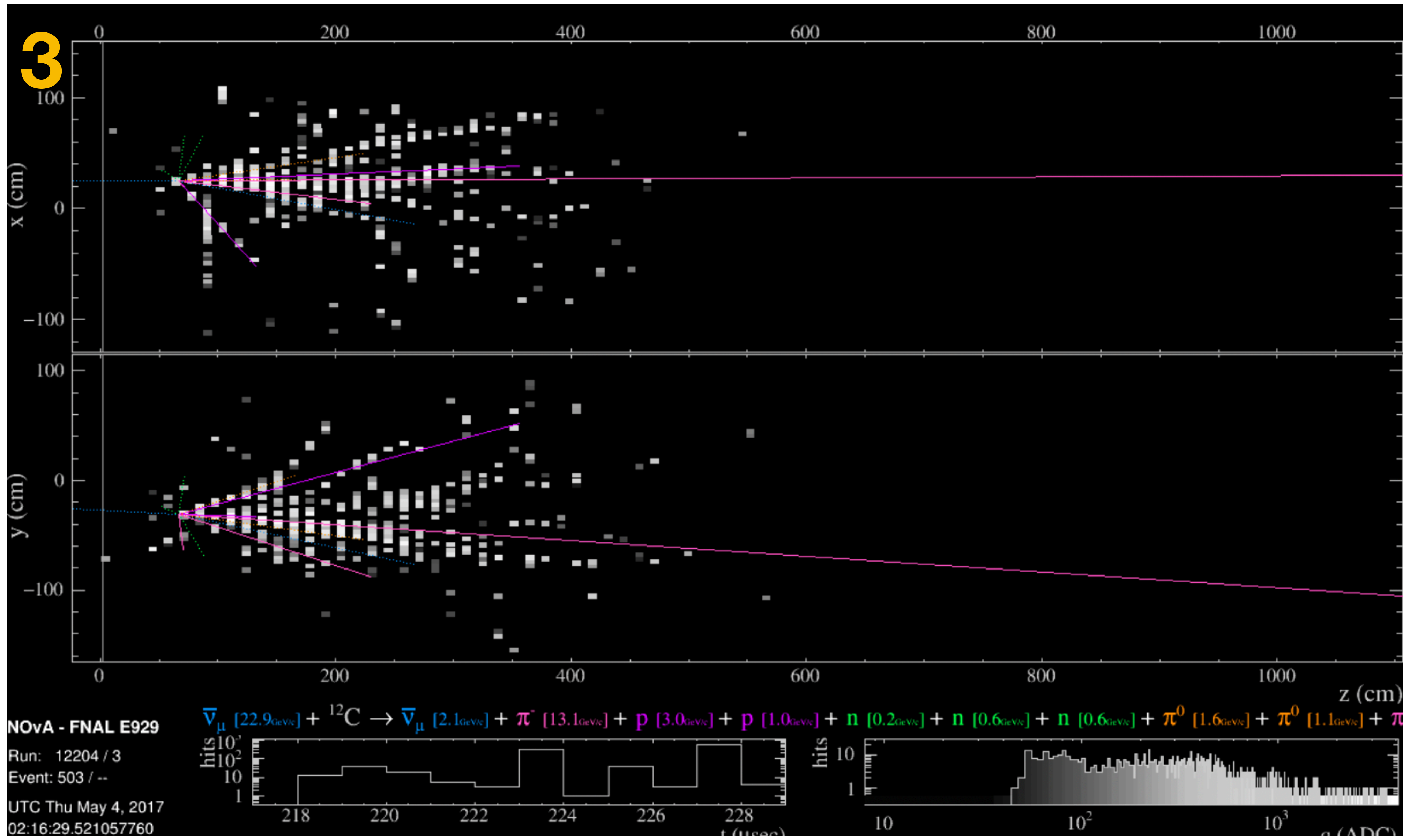
- At low energies, neutrinos interact with atomic electrons and nuclei as a whole.
- At higer energies, they interact with nucleons (n or p) inside the nucleus.
- At the highest energies, the neutrino will transfer enough energy to the nucleus to break it apart.

NOνA Experiment Event Display

1. A true $\bar{\nu}_e$ event strongly classified by ProngCVN with a score of 1.000
2. A true ν_e event strongly classified by ProngCVN with a score of 1.000
3. A true $\bar{\nu}_\mu$ event strongly classified by ProngCVN with a score of 0.916
    - The classification score from ProngCVN here is the electron score, which is why background numu events are hard to remove

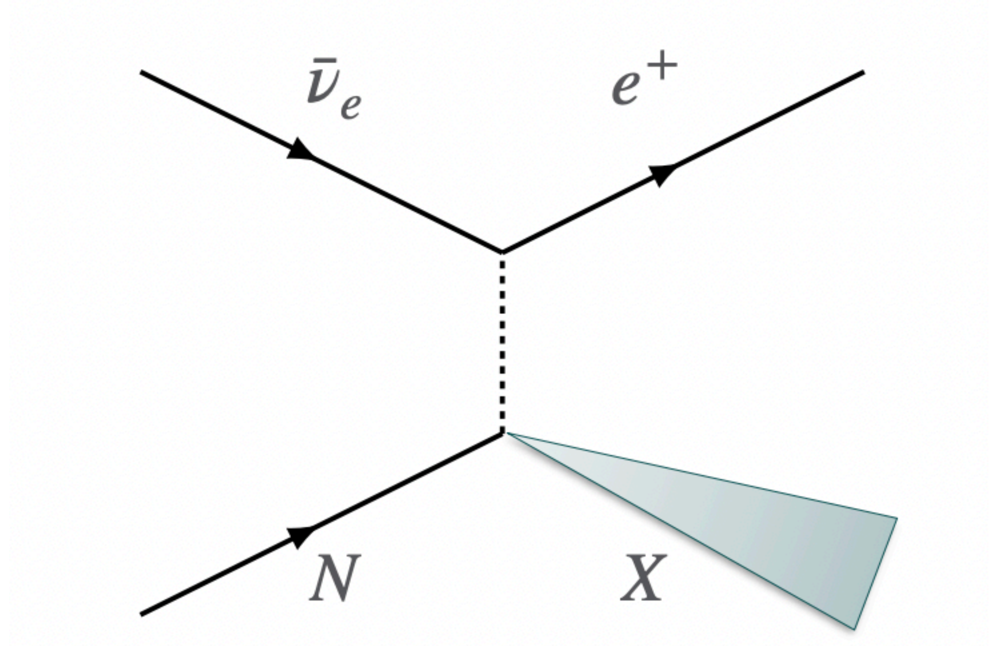






$\nu_e CC$ inclusive Measurement

$\bar{\nu}_e CC$ Signal



- This analysis will measure the $\bar{\nu}_e CC$ inclusive cross section by selecting candidate signal events, $\bar{\nu}_e + N \rightarrow e^+ + X$.

- The main deliverable of this analysis is a double-differential measurement of the $\bar{\nu}_e CC$ inclusive cross section with respect to the electron angle and electron energy.

Unfolding Matrix — **Estimated number of signal events**

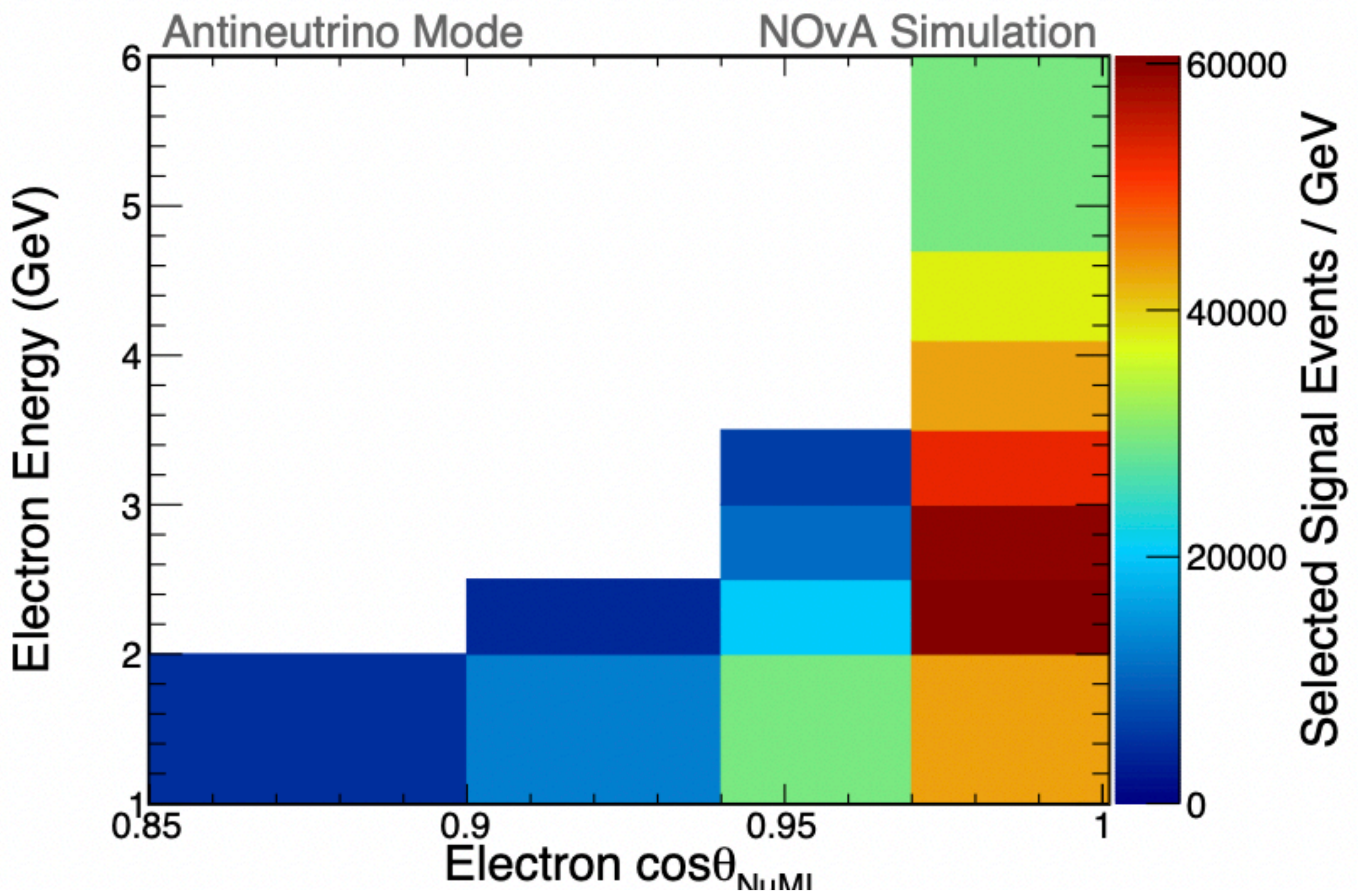
$$\left(\frac{d^2\sigma}{dE_e d\cos\theta_e}\right)_i = \frac{\sum_j U_{ij}(E_e\cos\theta_e)\hat{N}_j(E_{e,j},\cos\theta_{e,j})}{N_t\Phi\epsilon(E_e,\cos\theta_e)_i\Delta(E_e)_i\Delta(\cos\theta_e)_i}$$

Bin Width

Number of nuclei within fiducial volume of the detector — **Electron antineutrino flux at the Nova near detector**

i, j : True and measured bin index, respectively

Selected Electron kinematic Region



$0.85 \leq \cos\theta \leq 0.90 \quad \cap \quad 1.0 \leq E_e(GeV) < 2.0$

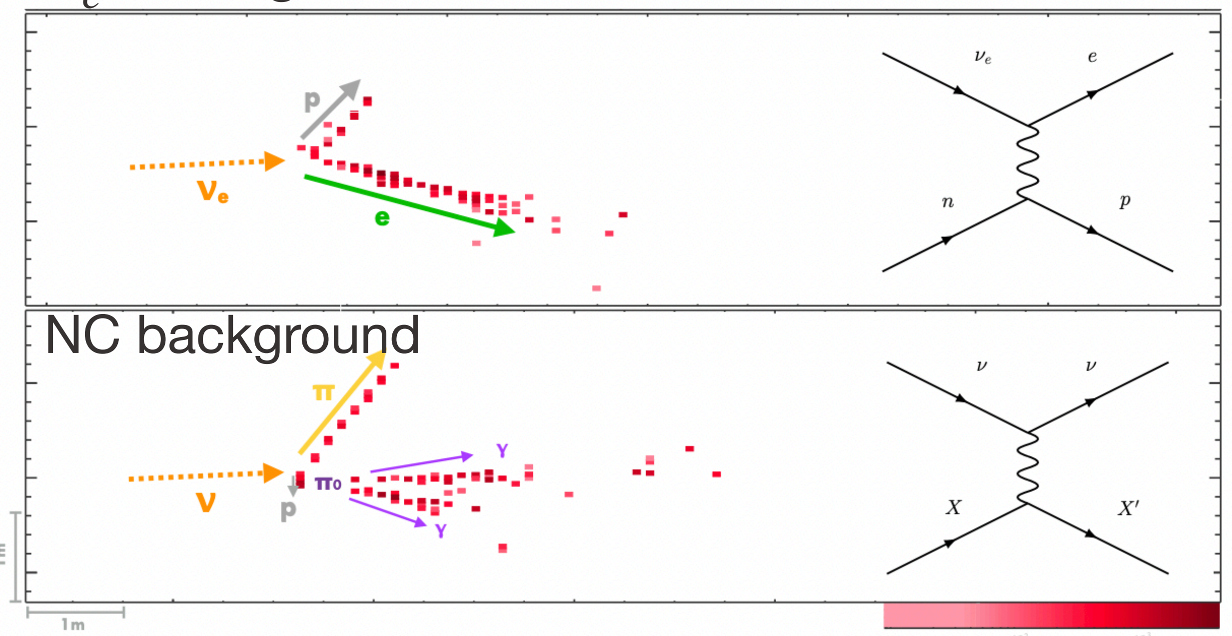
$0.90 \leq \cos\theta \leq 0.94 \quad \cap \quad 1.0 \leq E_e(GeV) < 2.5$

$0.94 \leq \cos\theta \leq 0.97 \quad \cap \quad 1.0 \leq E_e(GeV) < 3.5$

$0.97 \leq \cos\theta \leq 1.00 \quad \cap \quad 1.0 \leq E_e(GeV) < 6.0$

Challenges

$\bar{\nu}_e CC$ **Signal**



- Large Neutrol Current (NC) background.
- $NC \quad \pi^0 \rightarrow \gamma\gamma$ can mimic the $\bar{\nu}_e CC$ Signal.
- Relativity small $\bar{\nu}_e$ flux component.
- Large irreducible ν_e background.
- Detector not sensitive to the electron vs positron.

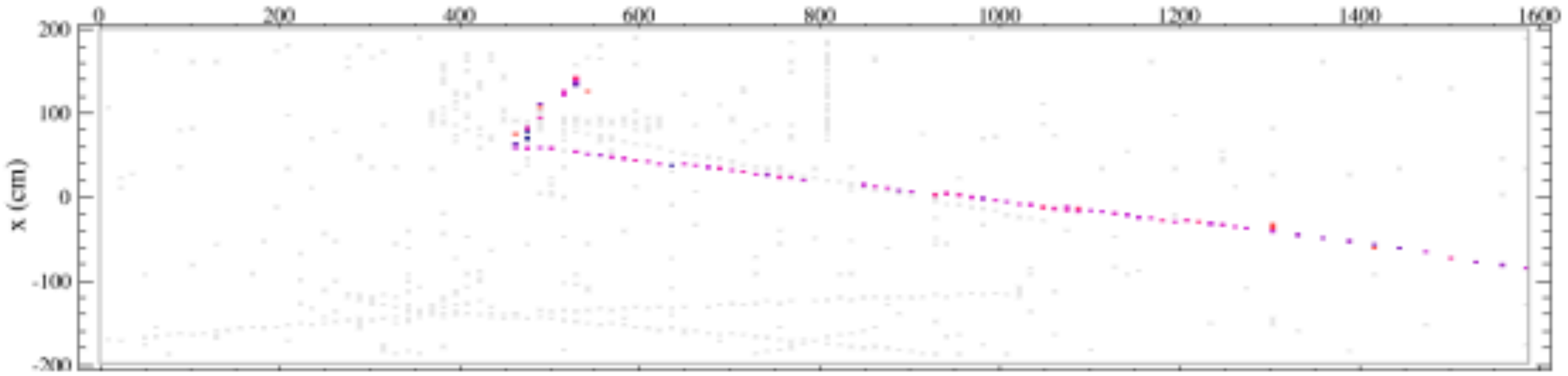
Muon Removed Electron (MRE) Added Events

- **The MRE events are constructed by removing the muon tracks from the ν_μ Charged Current (CC) interactions and replaced by the simulated electron with same kinematics (origin, direction, and energy).**

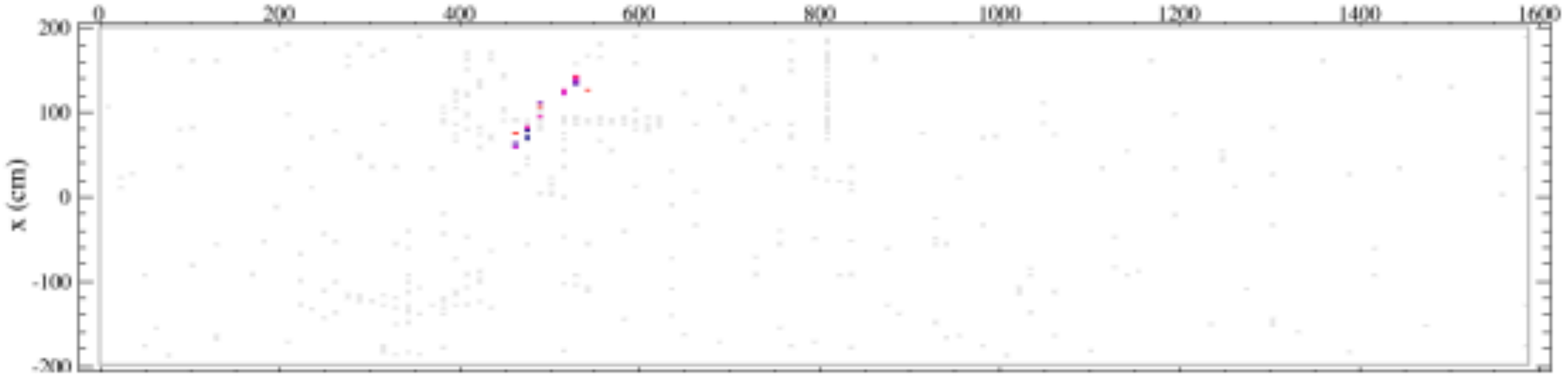
- **The aim for MRE is provide a high statistic sample for $\nu_e CC$ interactions.**

- **This procedure can be performed on both, Data and MC simulation.**

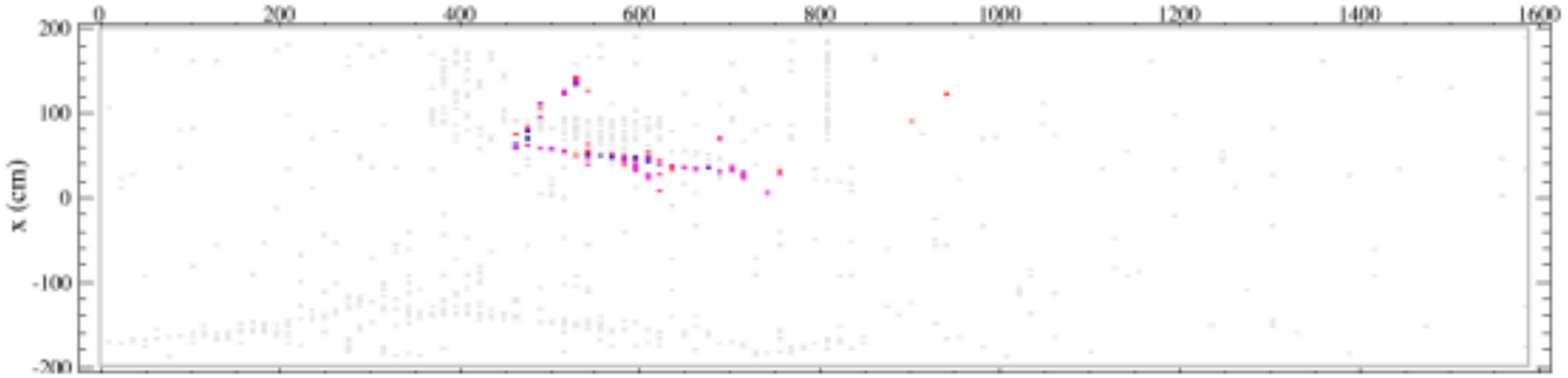
- **Why we use MRE sample is to constrain effects due to mis-modeling of hadronic activity.**



(a) A candidate ν_μ CC interaction in ND data



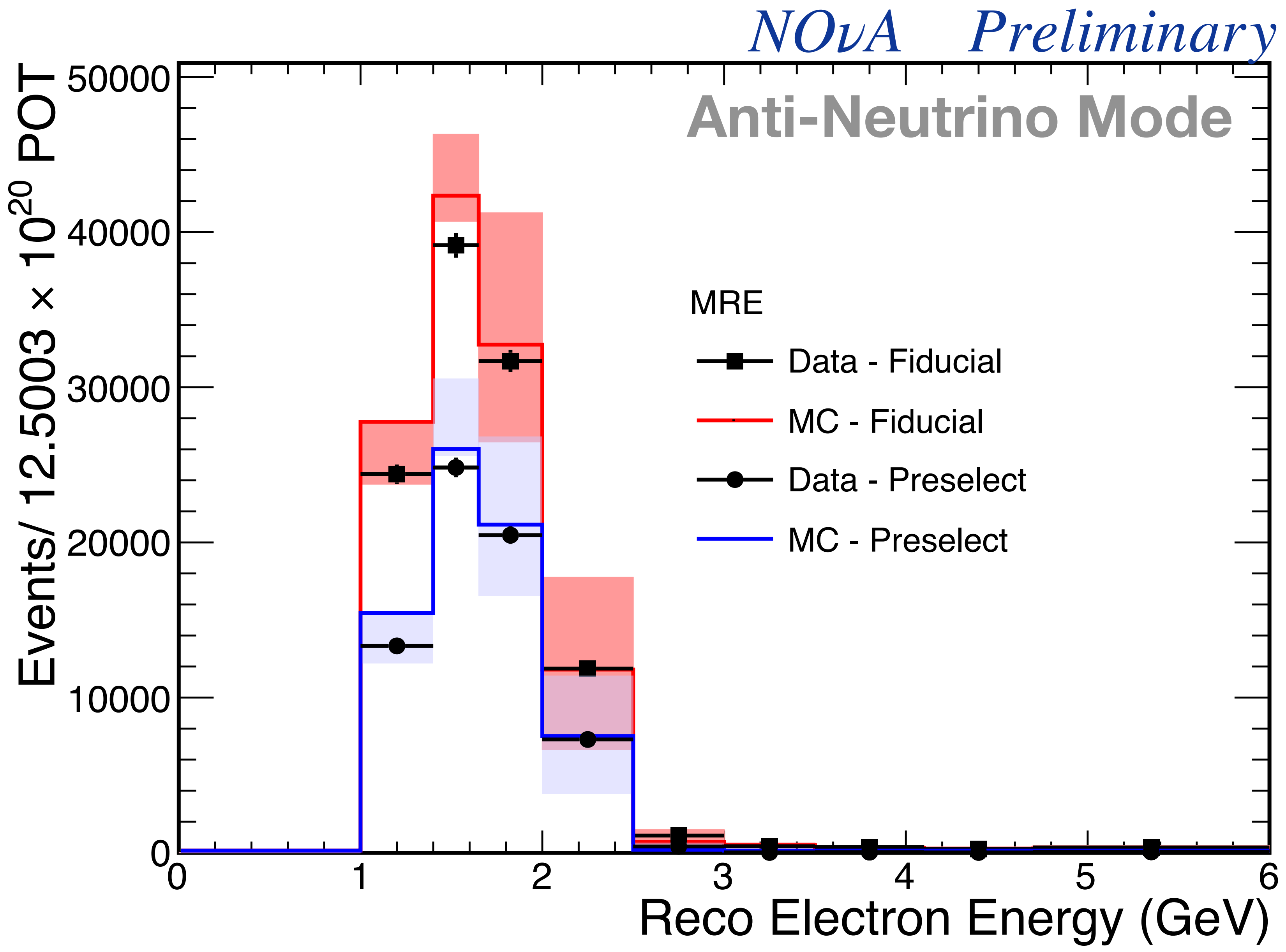
(b) The muon removed or MRCC version of the event

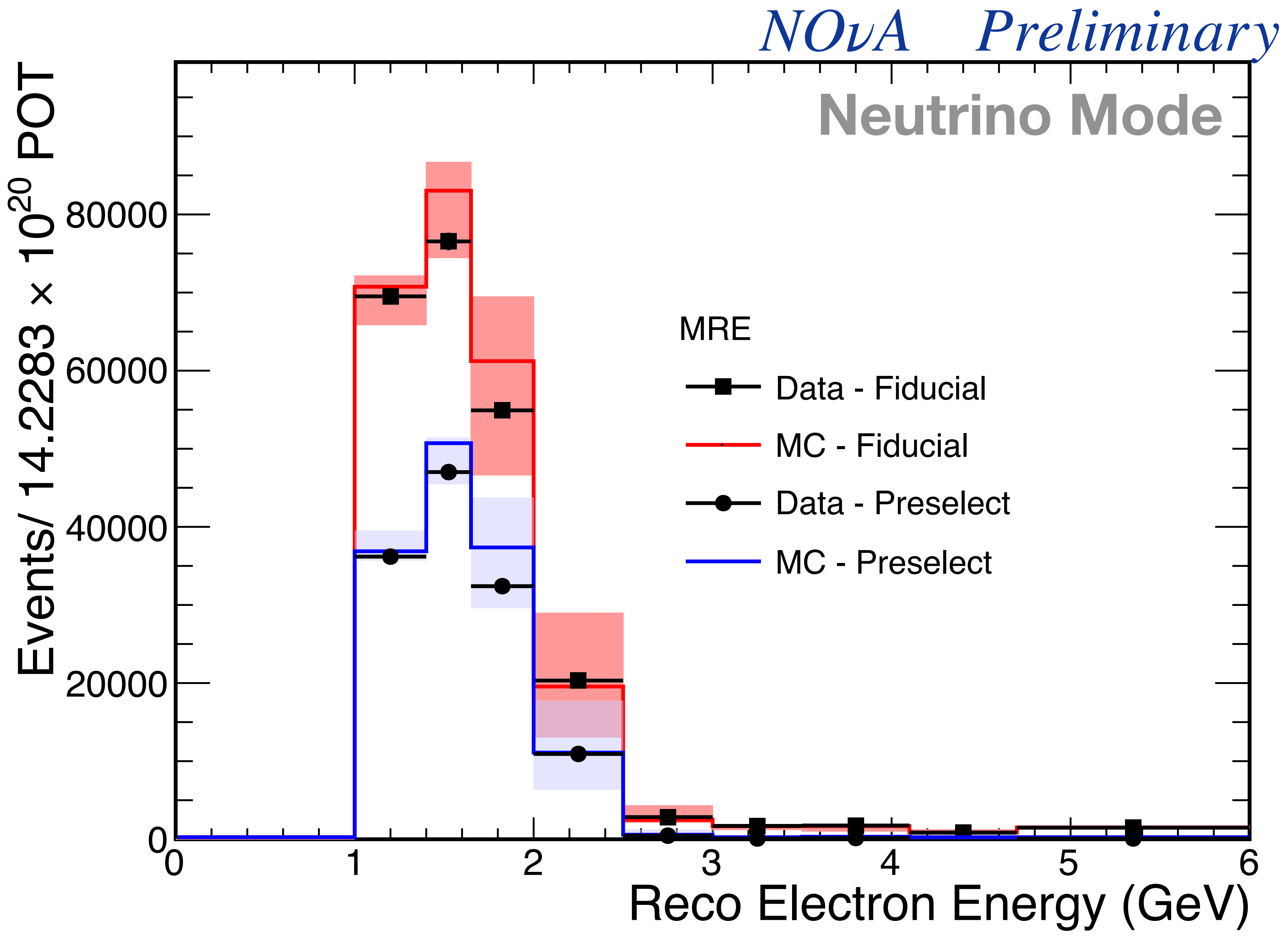


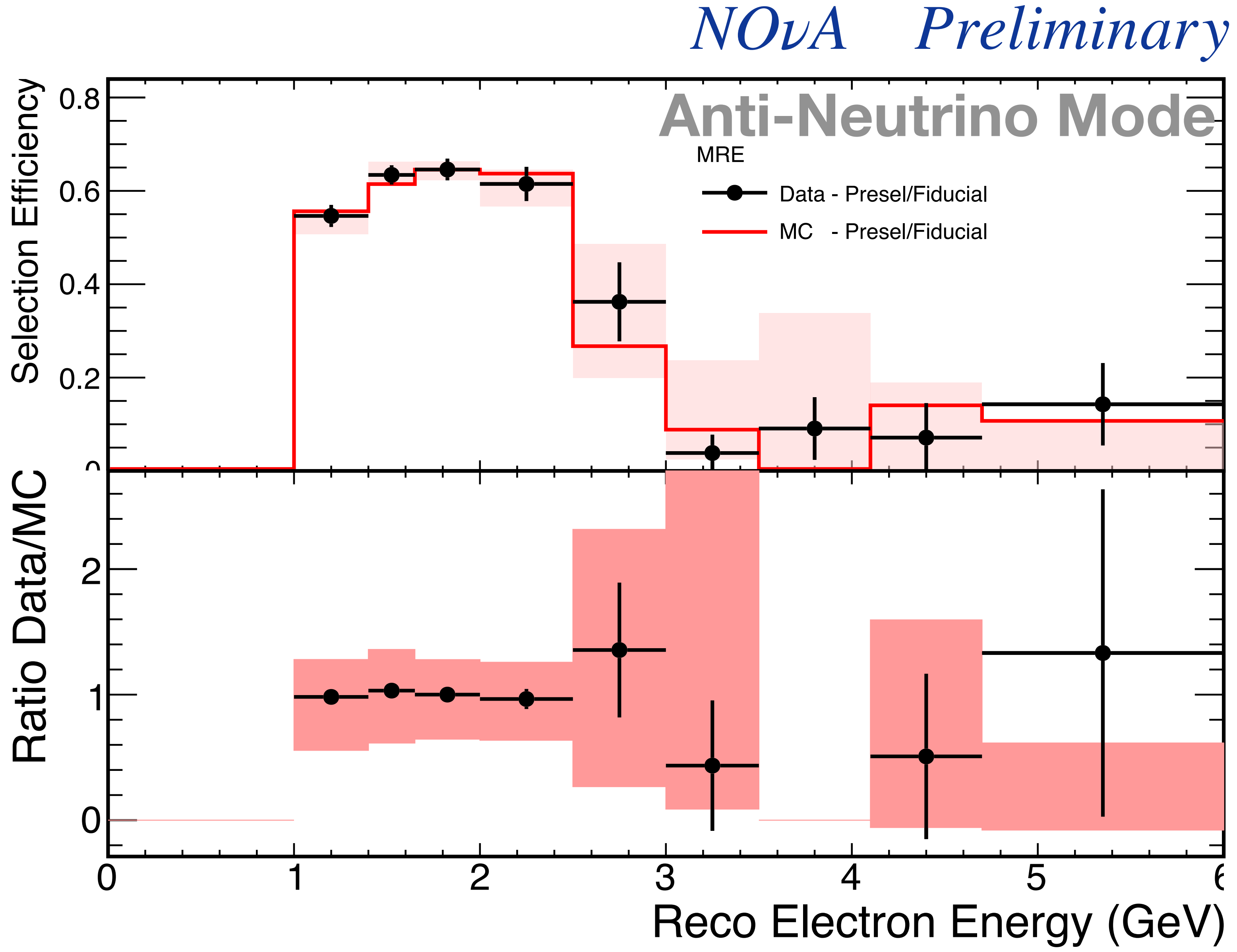
(c) A simulated electron is inserted in place of the muon to make an MRE event.

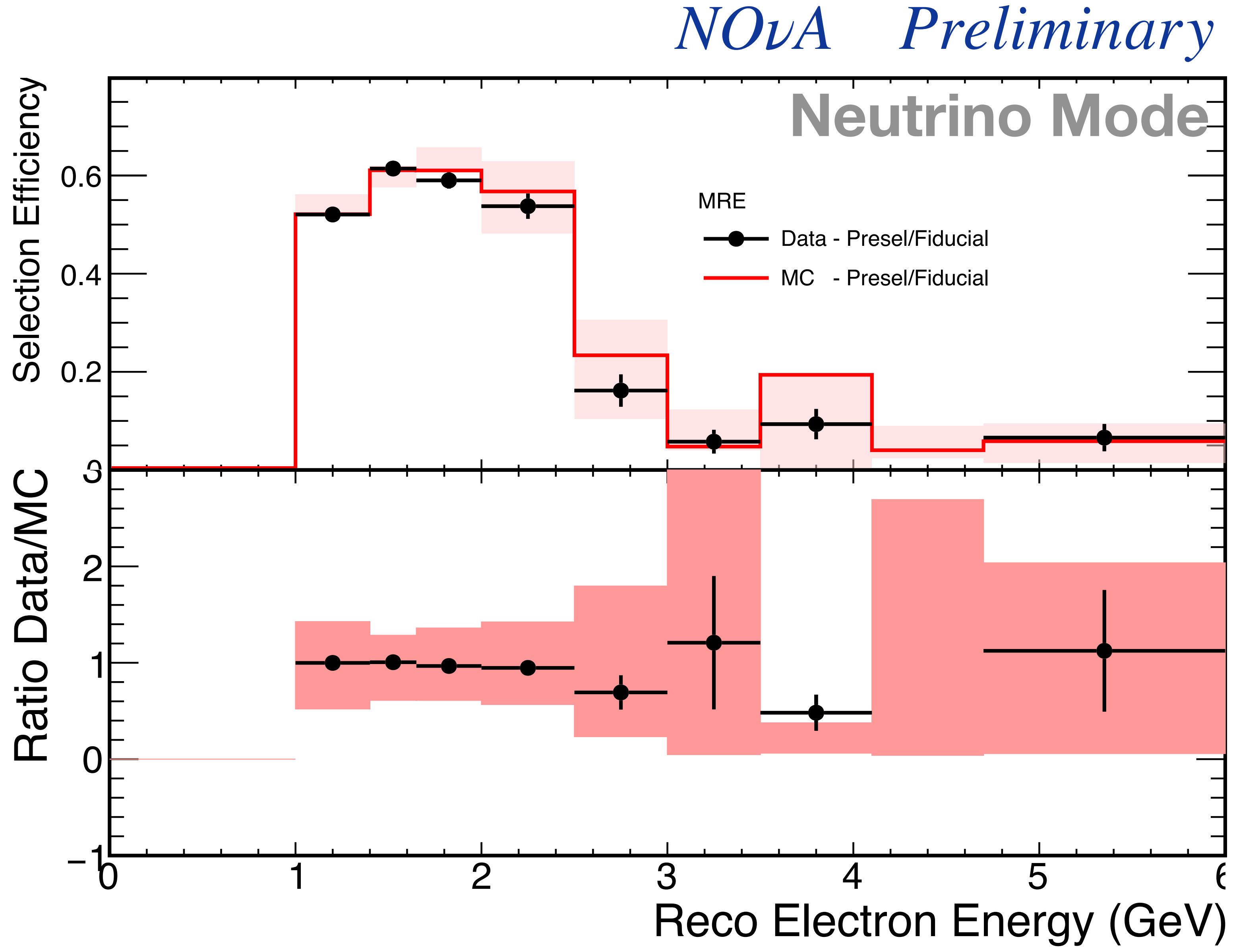
Kanika Sachdev, Ph.D. Thesis

Reco Electron Energy

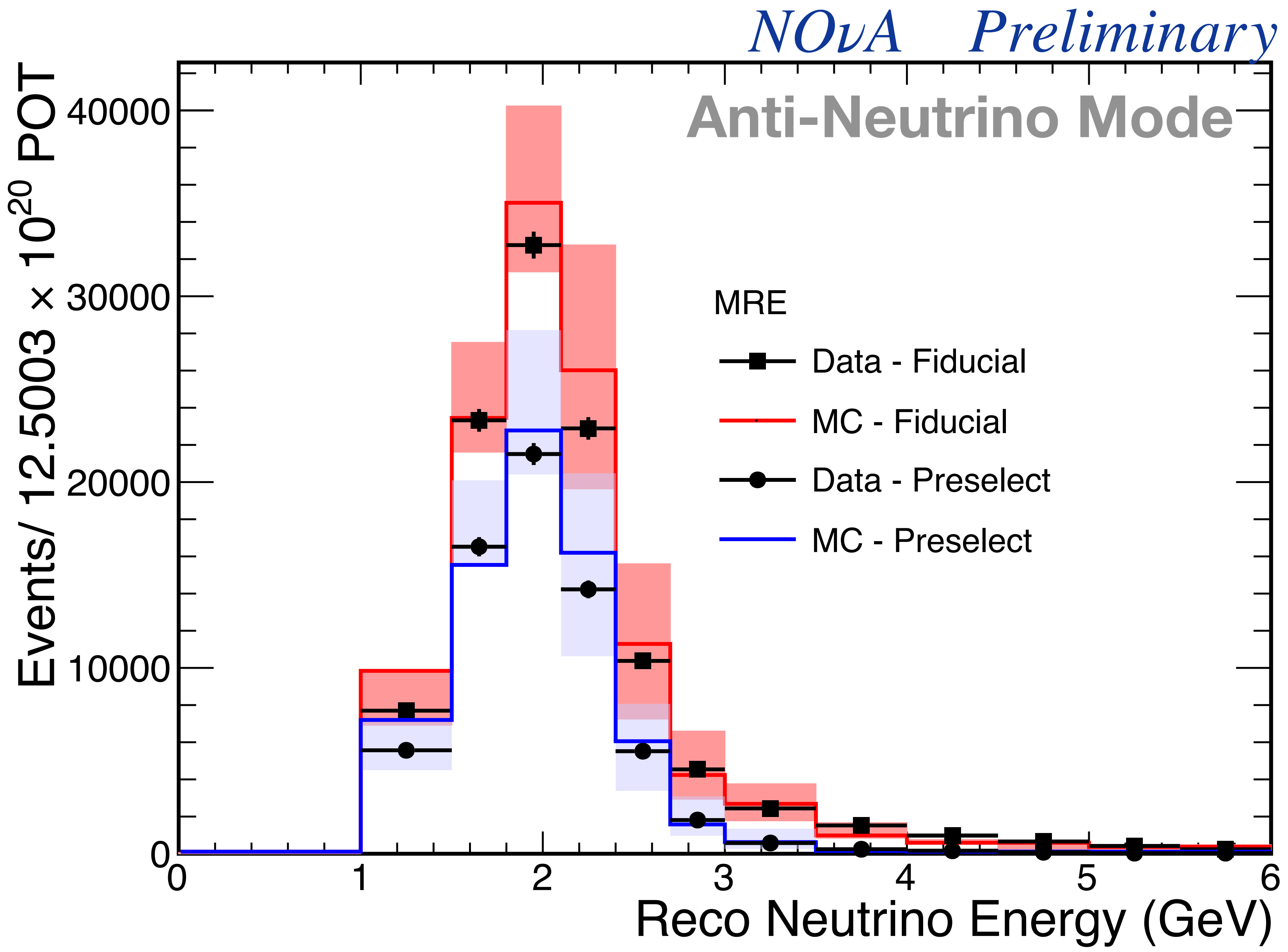


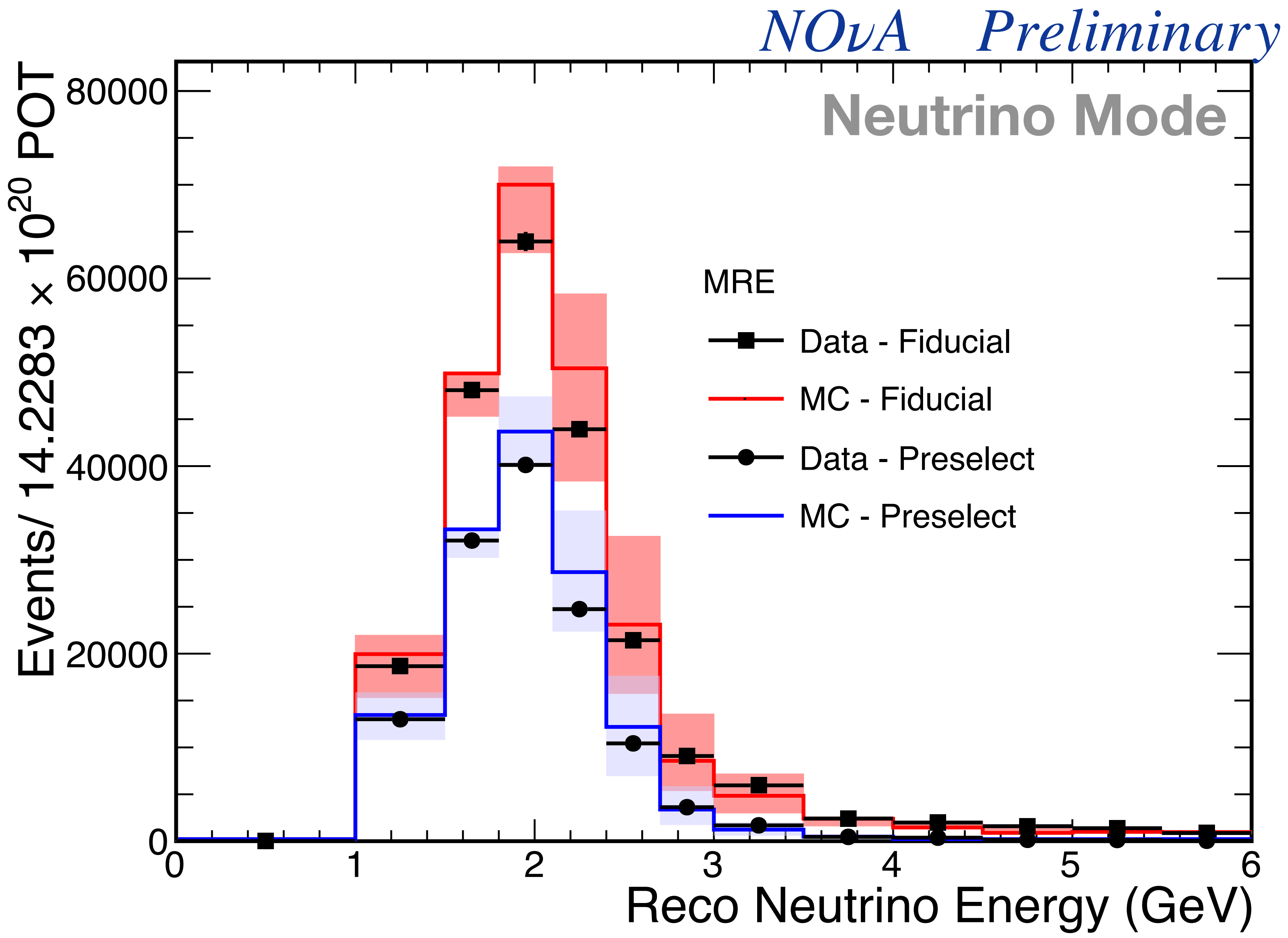


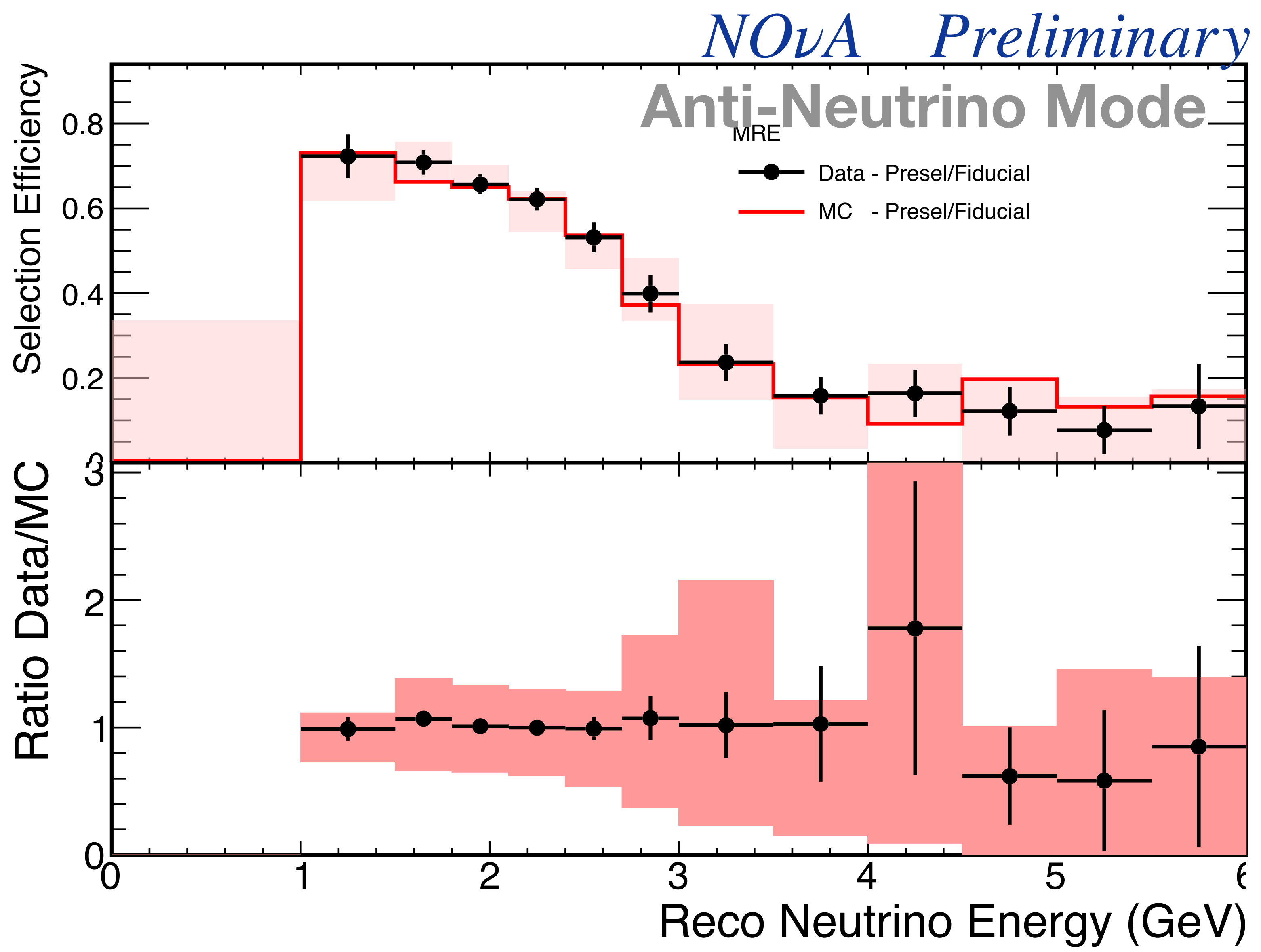


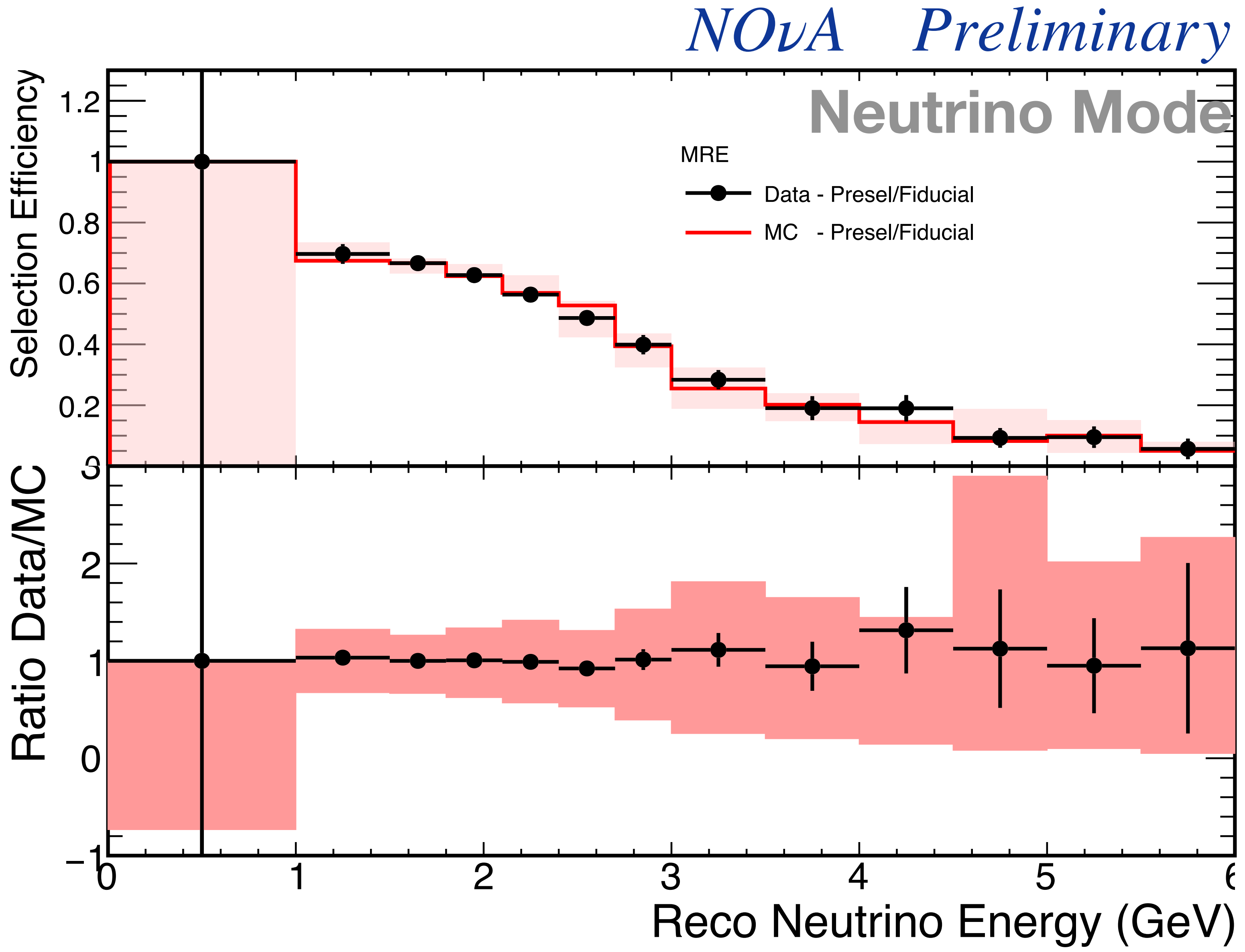


Reco Neutrino Energy

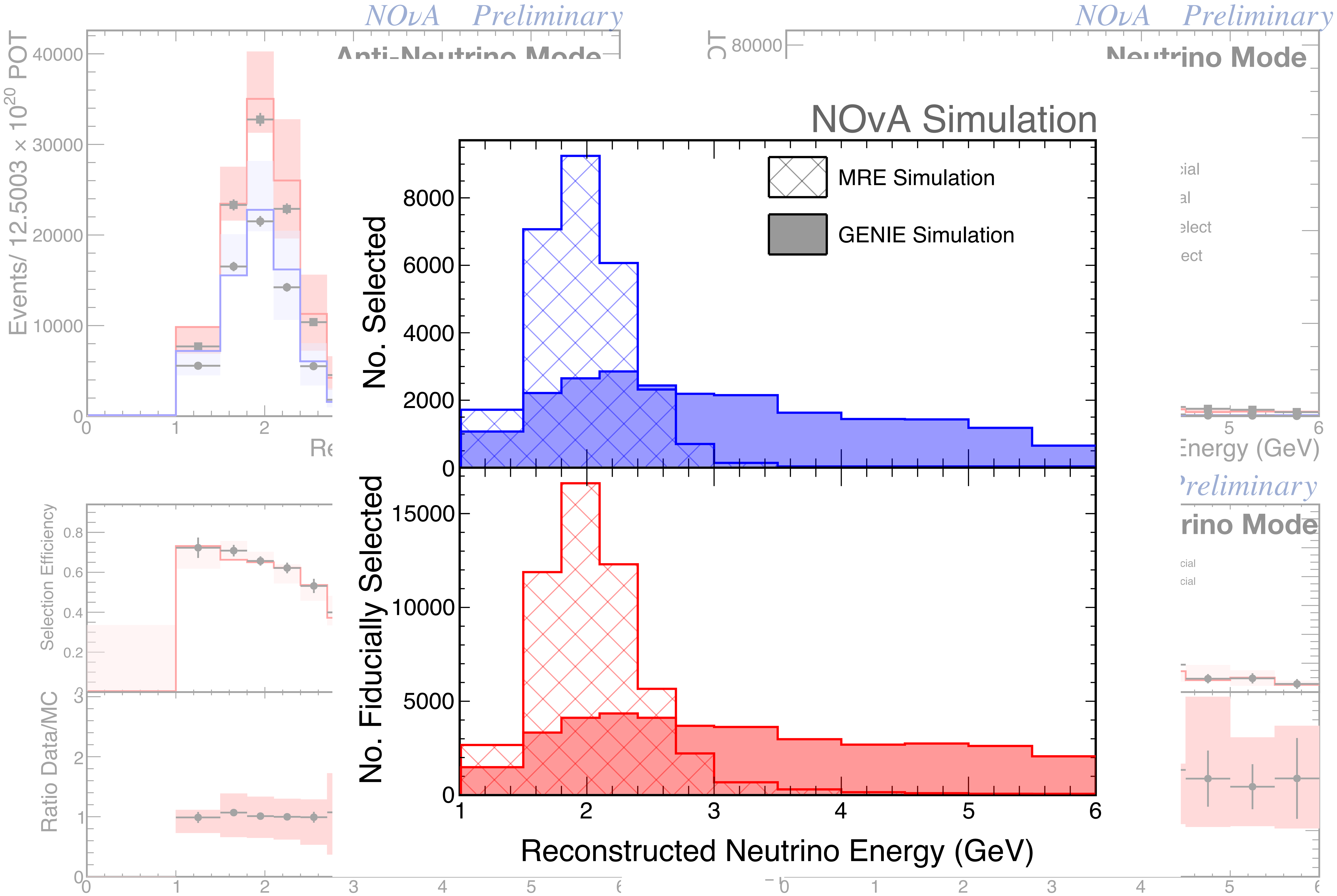






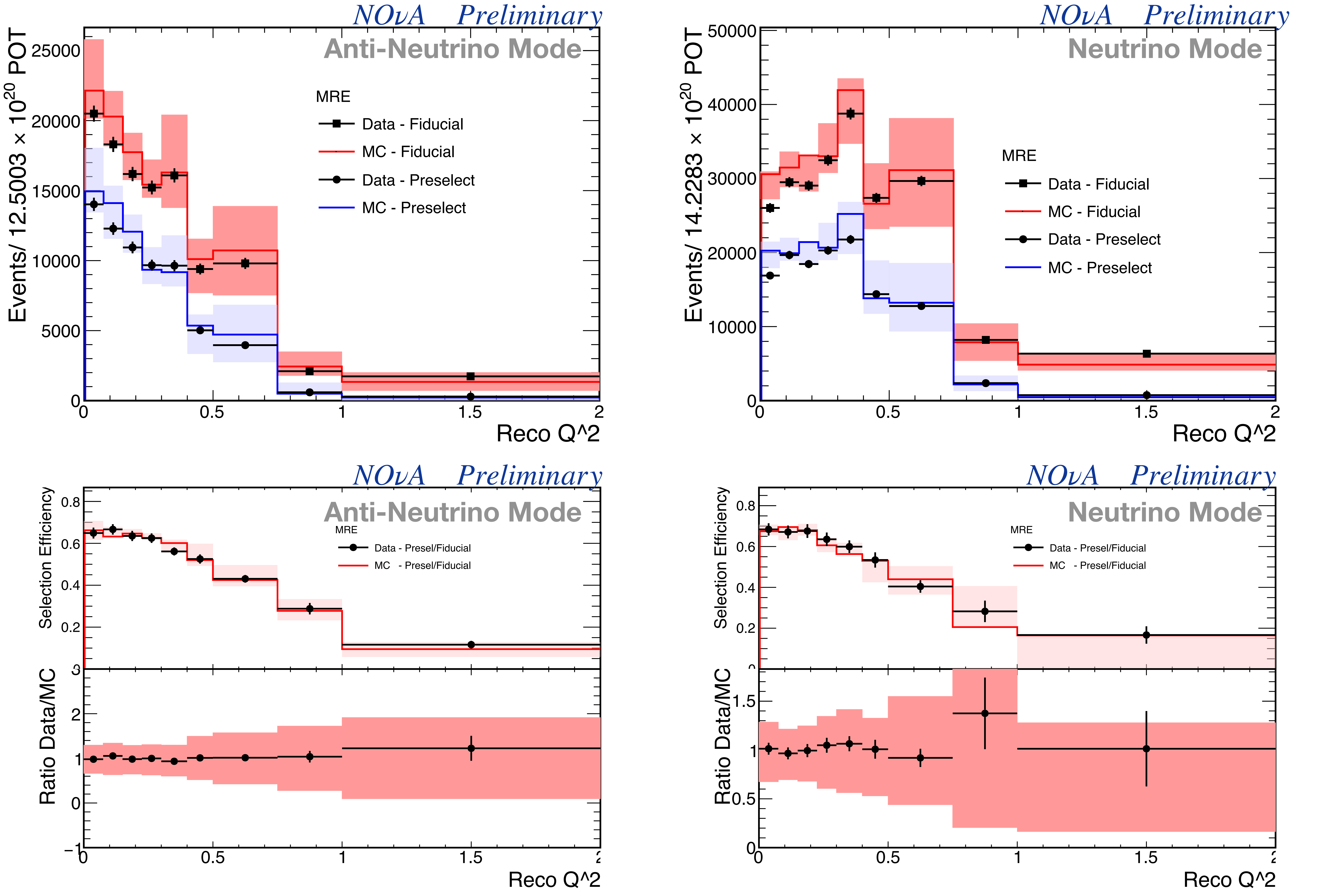


Reco Neutrino Energy

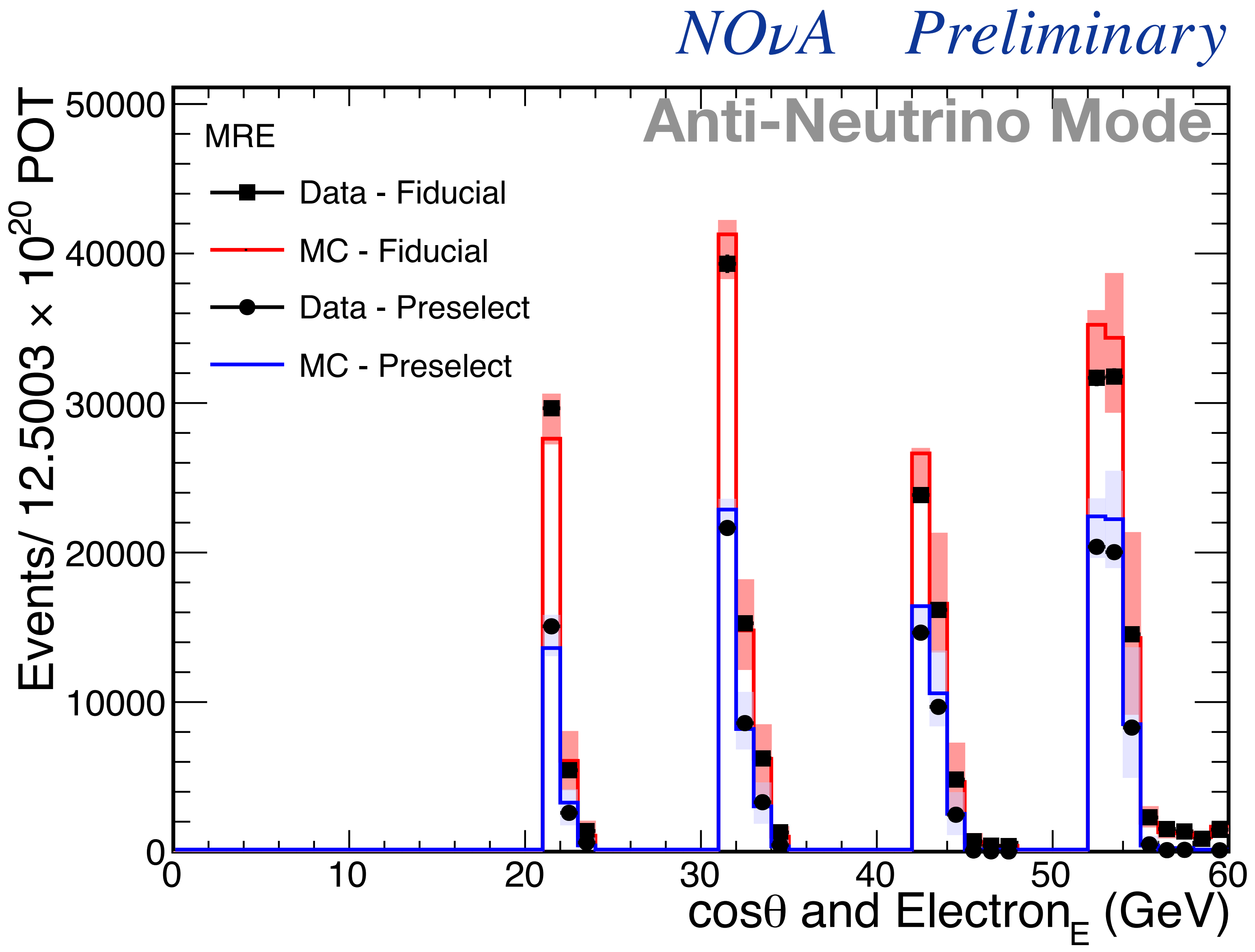


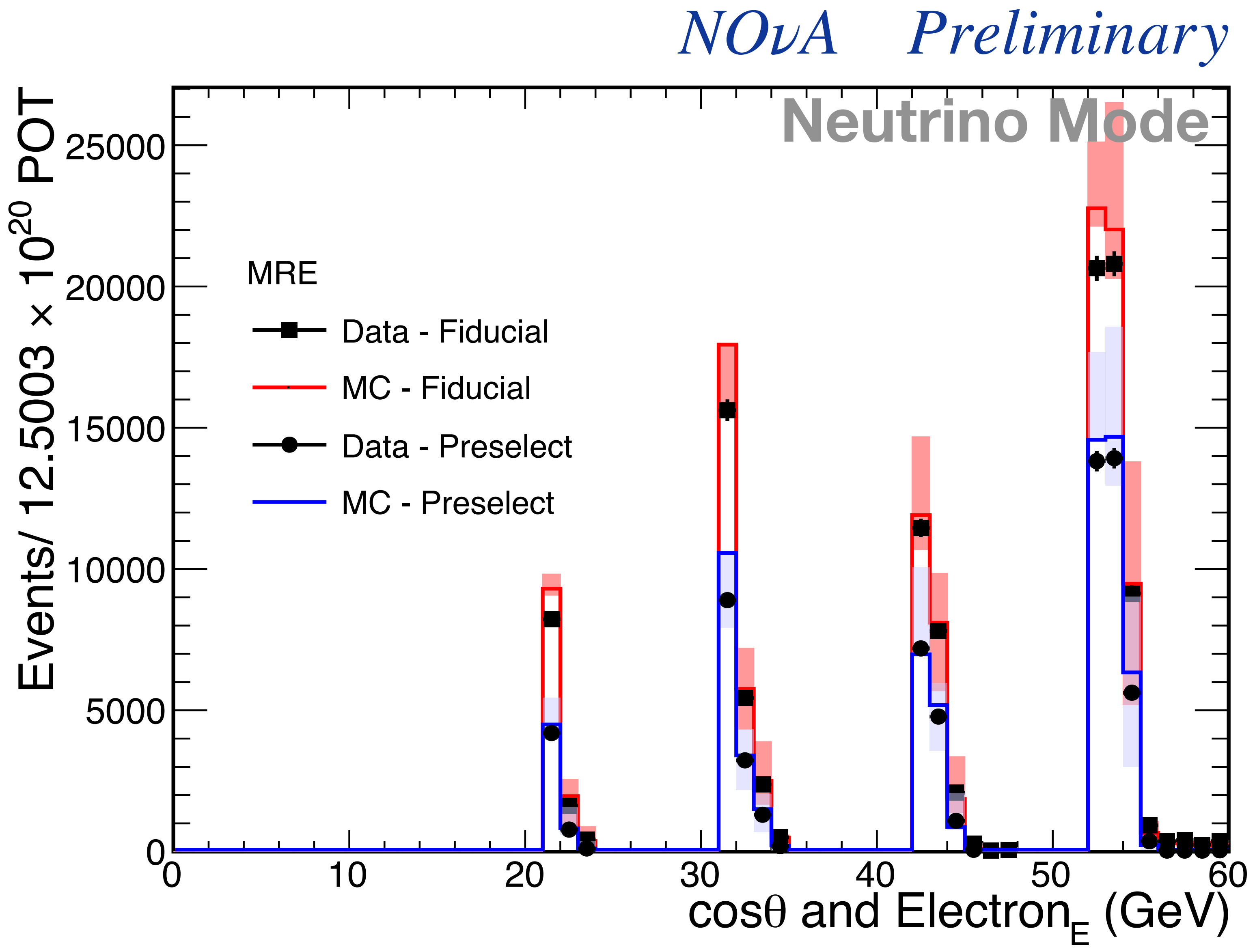
The corrections can be apply up to the 3 GeV because of limited ν_μ flux and lepton kinematic..

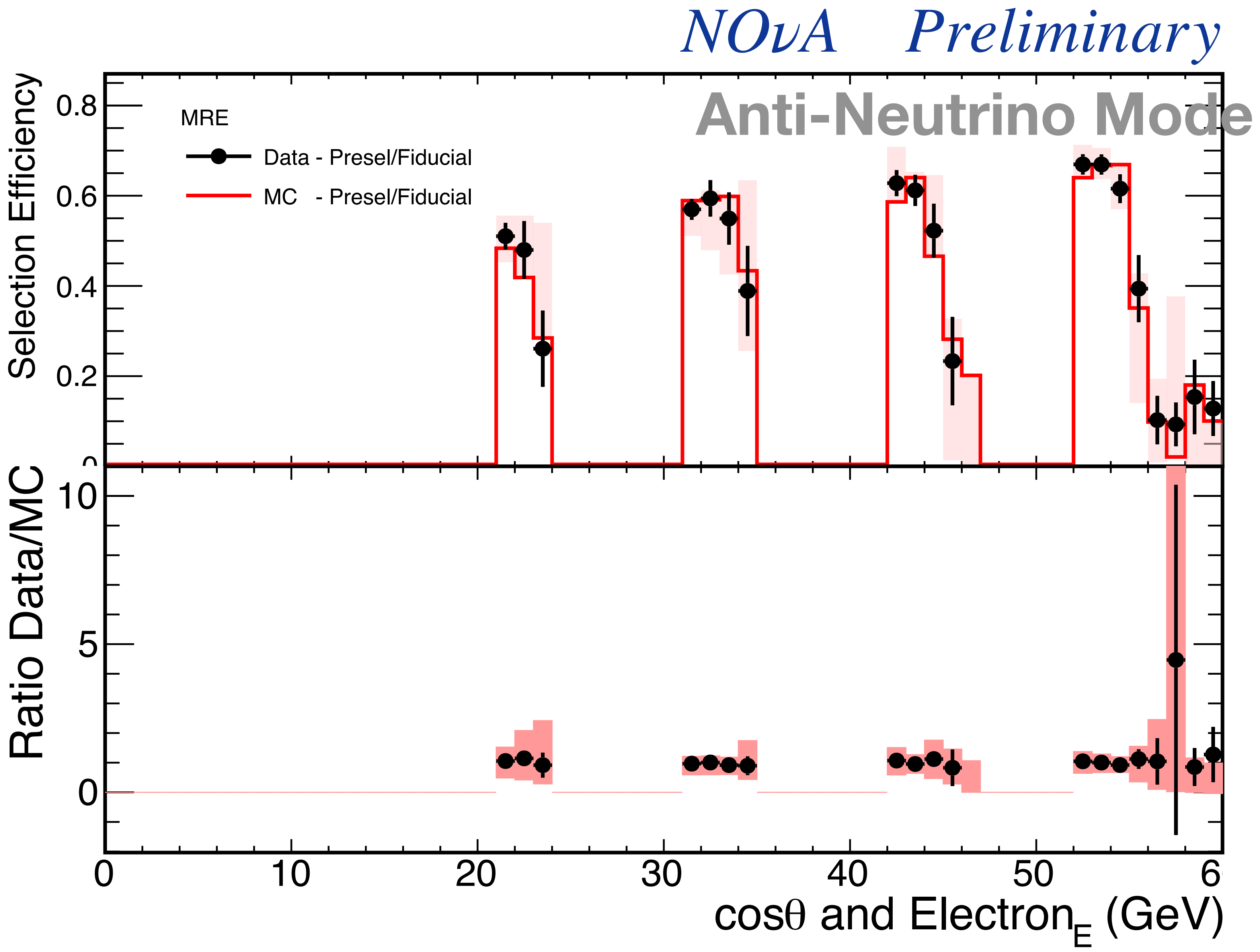
Reco Q^2

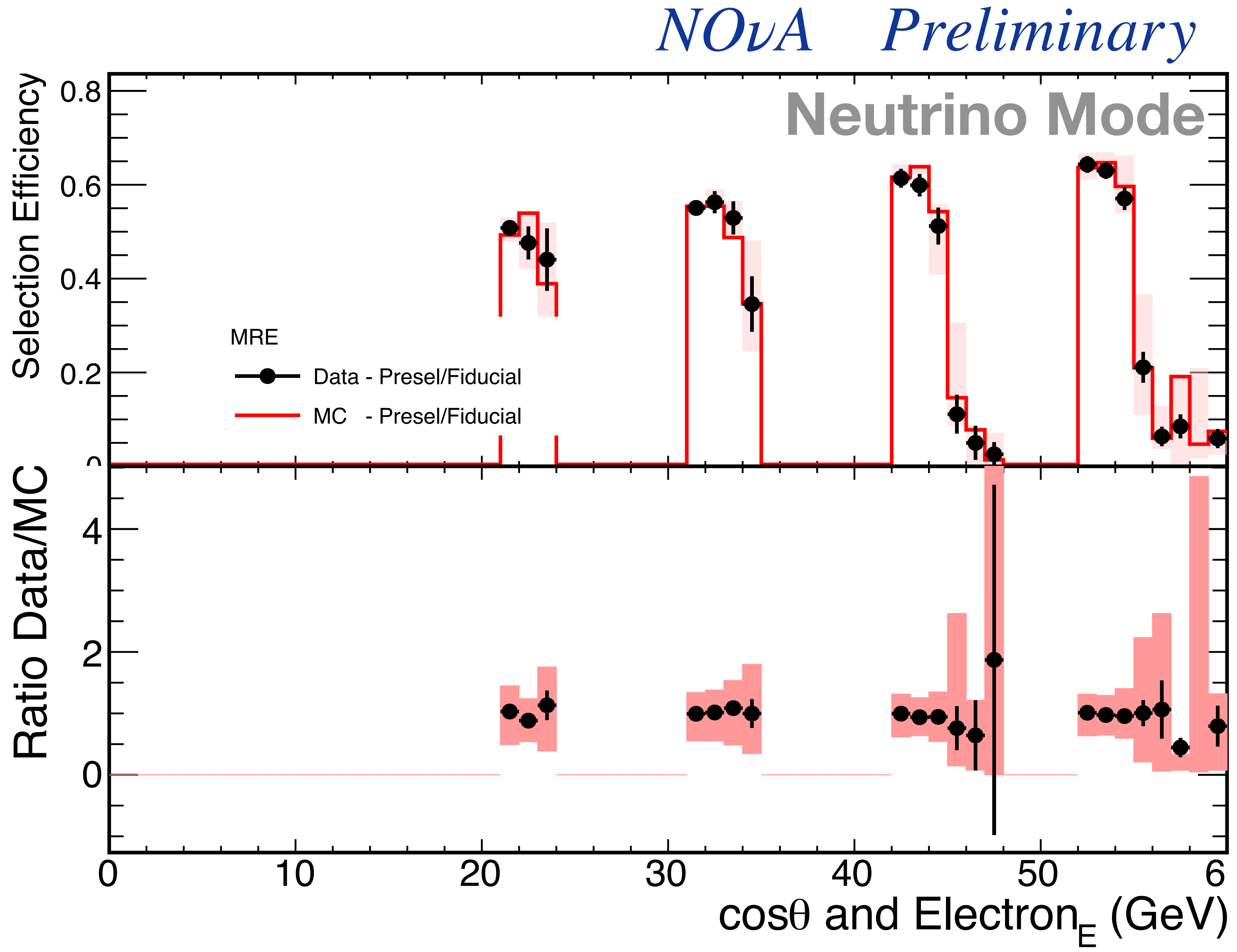

NOνA Preliminary
Anti-Neutrino Mode
MRE
Data - Fiducial
MC - Fiducial
Data - Preselect
MC - Preselect
Events/ 12.5003 × 10^20 POT
Reco Q^2
NOνA Preliminary
Neutrino Mode
Events/ 14.2283 × 10^20 POT
Data - Presel/Fiducial
MC - Presel/Fiducial
Selection Efficiency
Ratio Data/MC

Electron Phase Space









Outline

- The analysis will attempt to measure the $\bar{\nu}_e CC$ inclusive cross section and still in progress.
- Analyze the largest sample of of the $\bar{\nu}_e CC$ for first ever double differential cross-section.
- Enable future measurement the ratio of neutrino cross-section to anti-neutrino cross section.

The project was supported by Scientific Research Project (BAP) of Erciyes University, Turkey under grant contract of FDS-2021-10856.


October 2021

MRE Data and MC Sample

Fiducial: Fiducial + MRE Cuts

Preselect: Preselection + MRE Cuts

Signal: ν_μ or $\bar{\nu}_\mu$ inside the Fiducial Volume

Weight: kPPFXFluxCVWgt && kXSecCVWgt2020

- We apply the two cut selection both Data and MC
- Signal selection only applied to the MC
- All plots are POT normalized
  - RHC - POT -> kAna2020RHCPOT = 12.5003e20
  - FHC - POT-> kAna2020FHCPOT = 14.2283e20

Preselection Cut
kDQ
Fiducial
Containment
Frontplanes
Nhits
KMuonID

Fiducial Cut
DQ
FrontPlanes
Fiducial

MRE Cuts
ana::kNue2017MRParentSliceCut
kMREQualityCut:
kRecoElectronPhaseSpaceCut

No used
kMRESignalPhaseSpaceCut

- $Selection \quad Efficiency = \dfrac{Preselected \quad Events}{Fiducially \quad Selected \quad Events}$
- **Ratio Data /MC = Selection Efficient (Data)/ Selection Efficient (MC)**

Kinematics

- **Hadronic Energy**
  - *slc.calE - sr->vtx.elastic.fuzzyk.png[0].calE*
- **Reco Electron Energy** -> kElectronE
- **Reco Neutrino Energy** -> kRecoNeutrinoE
- **Reco Q^2** -> kRecoQ2
- **kMRESignalPhaseSpaceCut**

Sytemetic Up
Light level up
Calibration up
Cherenkov Up

Sytemetic Down
Light level Down
Calibration Down
Cherenkov Down