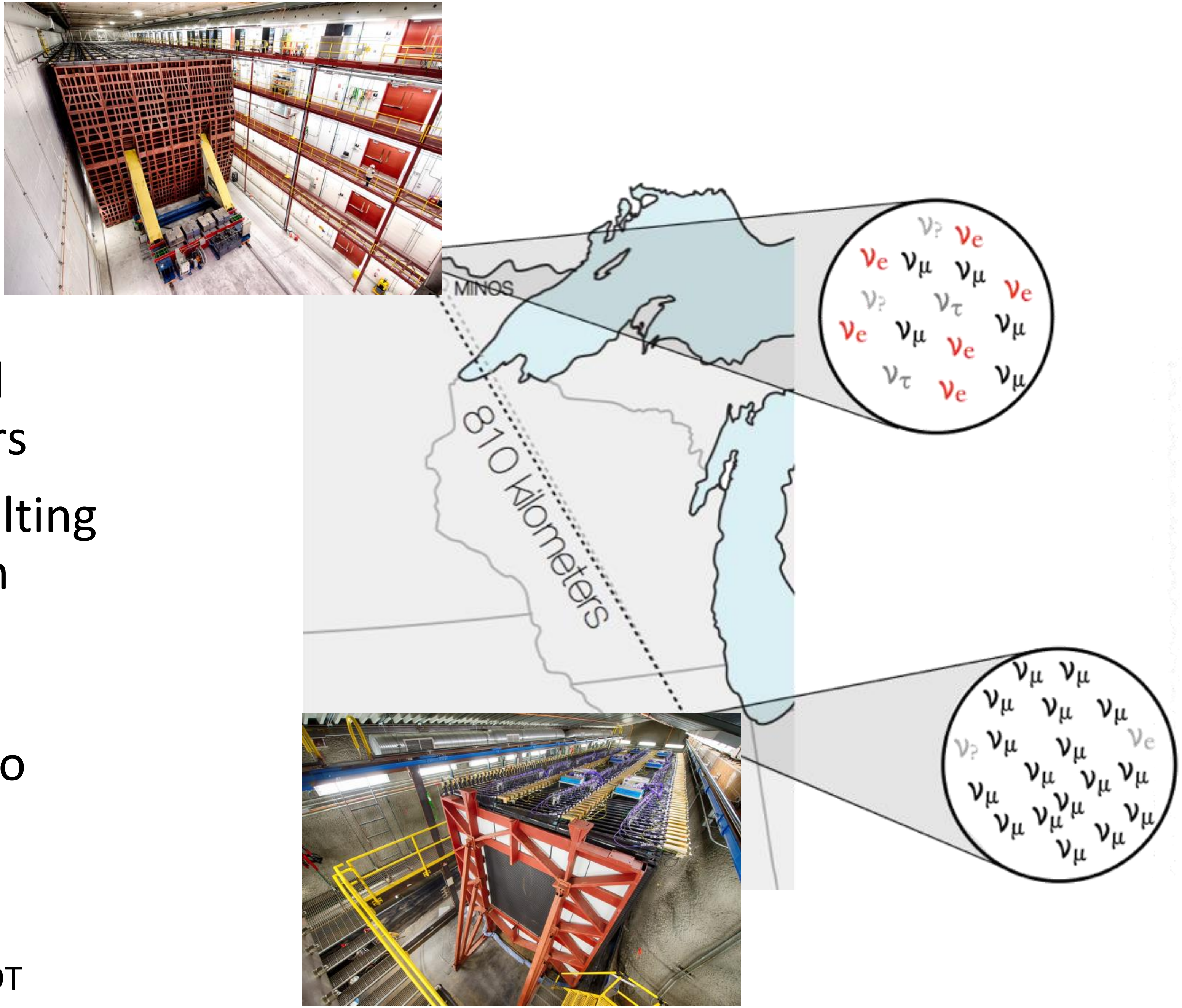
Details of the NOvA Oscillation Analyses

Erica Smith
on behalf of the NOvA collaboration
Indiana University
August 16, 2018

NOvA



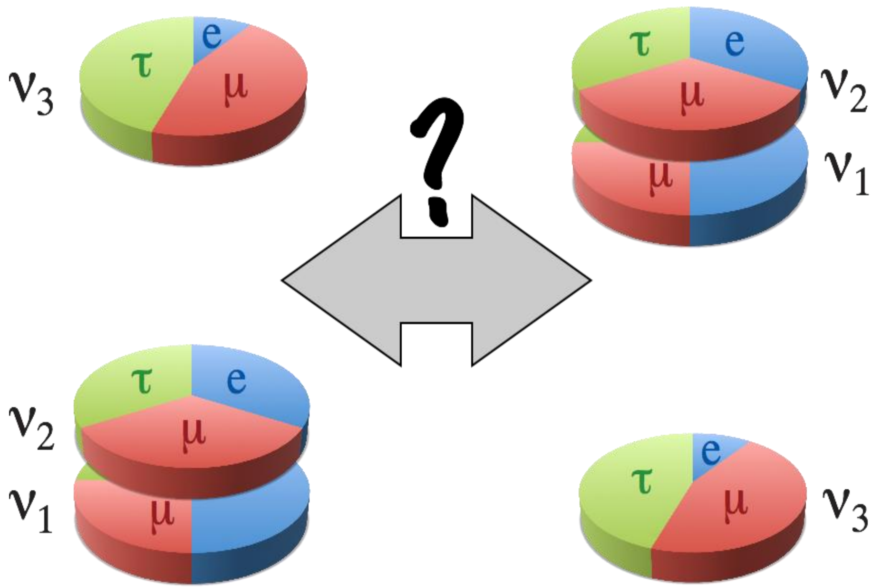
- Functionally identical near and far detectors
- 14mrad off-axis, resulting in narrow band beam peaked at 2 GeV
- Planes of cells are layered, alternating to provide 3D tracking

Neutrino mode: 8.85 x 10^{20} POT
Anti-neutrino mode: 6.9 x 10^{20} POT

Physics Program

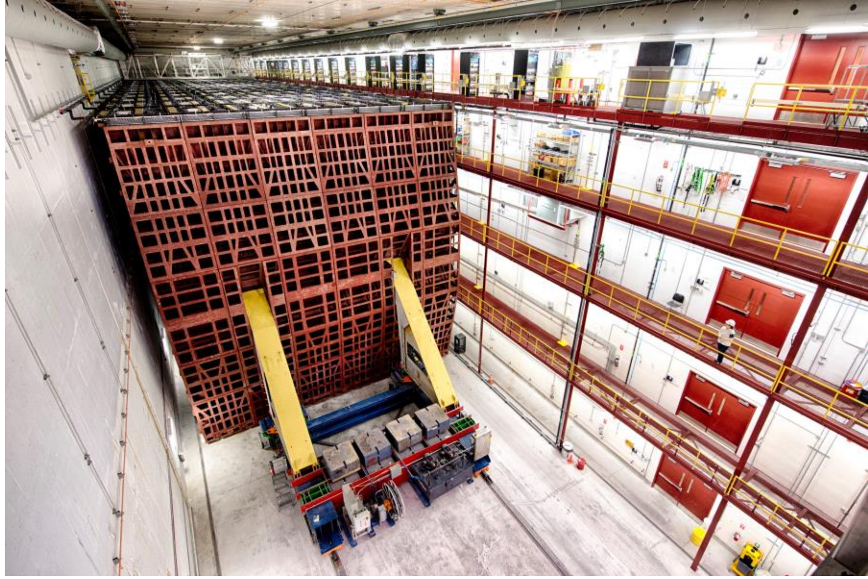
- ν_μ disappearance
  - $\sin^2(\theta_{23})$
  - Δm_{23}^2

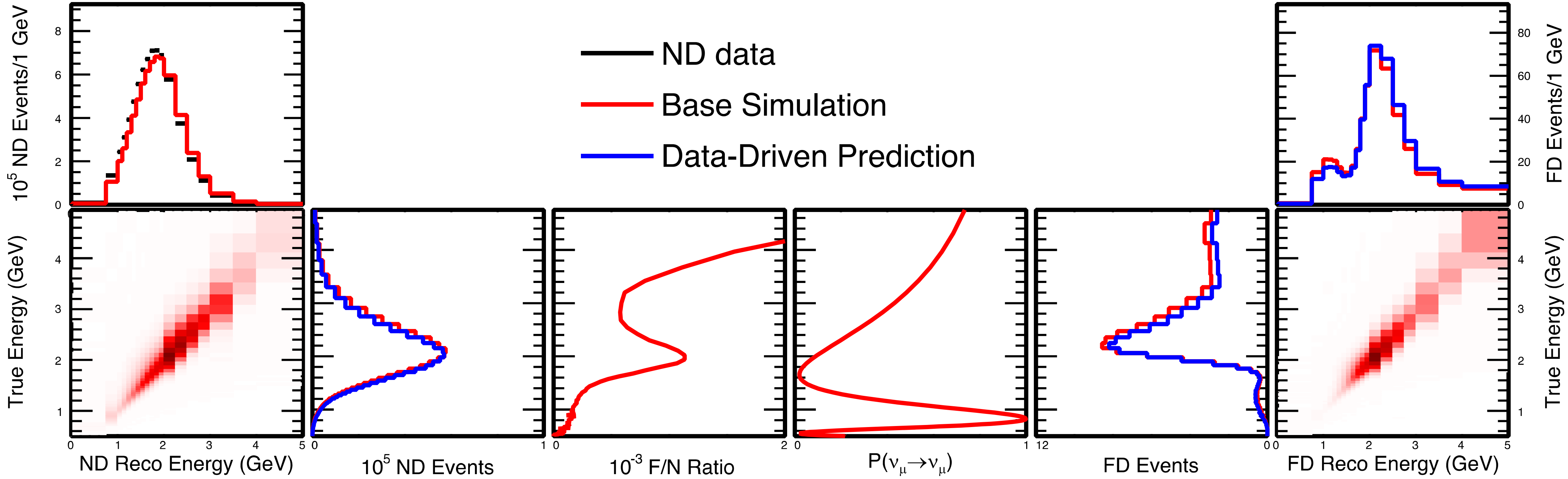
- ν_e appearance
  - Mass hierarchy
  - θ_{23} octant
  - CPV phase



- NC disappearance
  - Limits on Δm_{41}^2, θ_{34}, θ_{24}

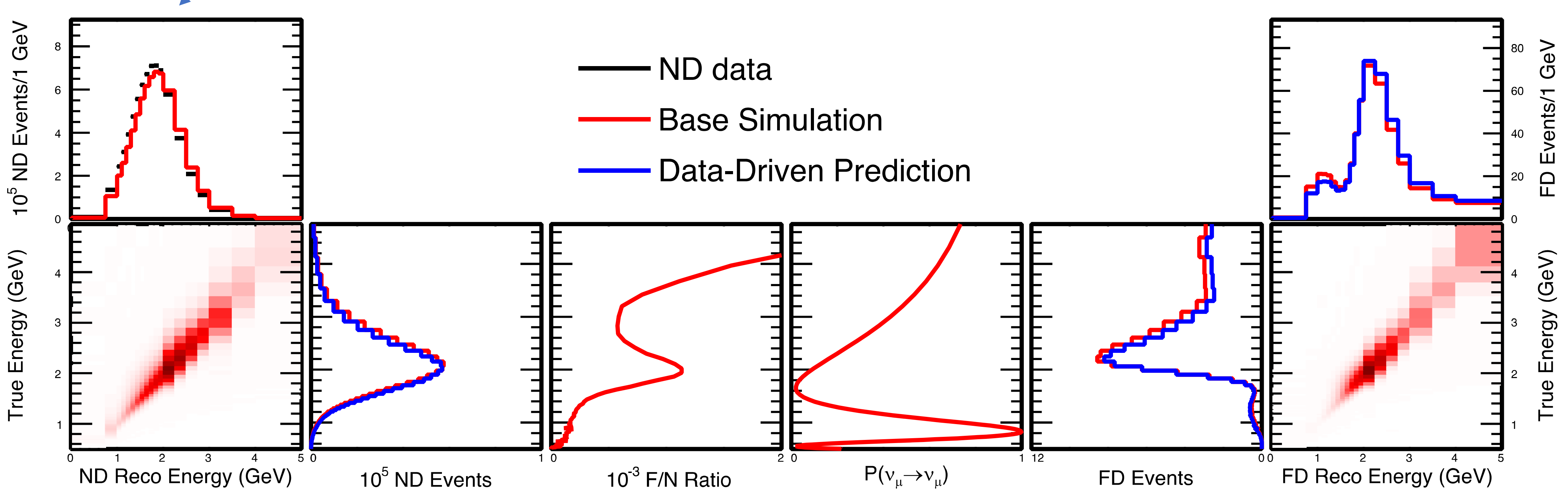
- Cross sections with Near Detector
- Supernova
- Other exotic phenomena





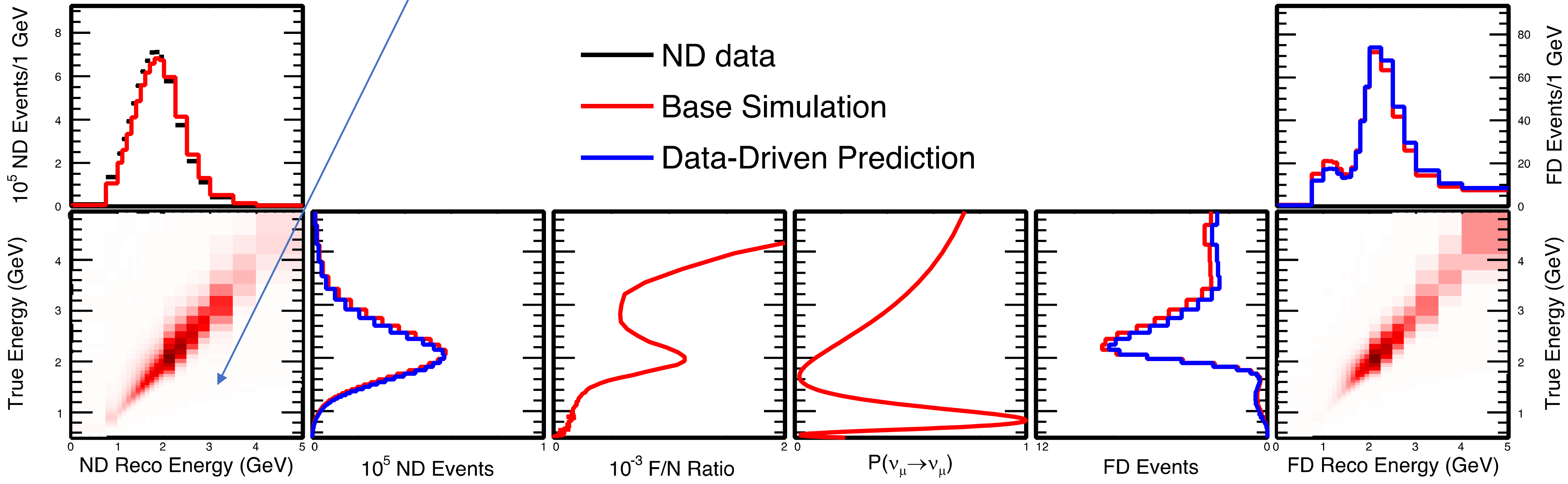
ND data
Base Simulation
Data-Driven Prediction
10^5 ND Events/1 GeV
FD Events/1 GeV
True Energy (GeV)
ND Reco Energy (GeV)
10^5 ND Events
10^{-3} F/N Ratio
$P(\nu_\mu \rightarrow \nu_\mu)$
FD Events
FD Reco Energy (GeV)

how do we select what goes into this spectrum?



how do we select what goes into this spectrum?

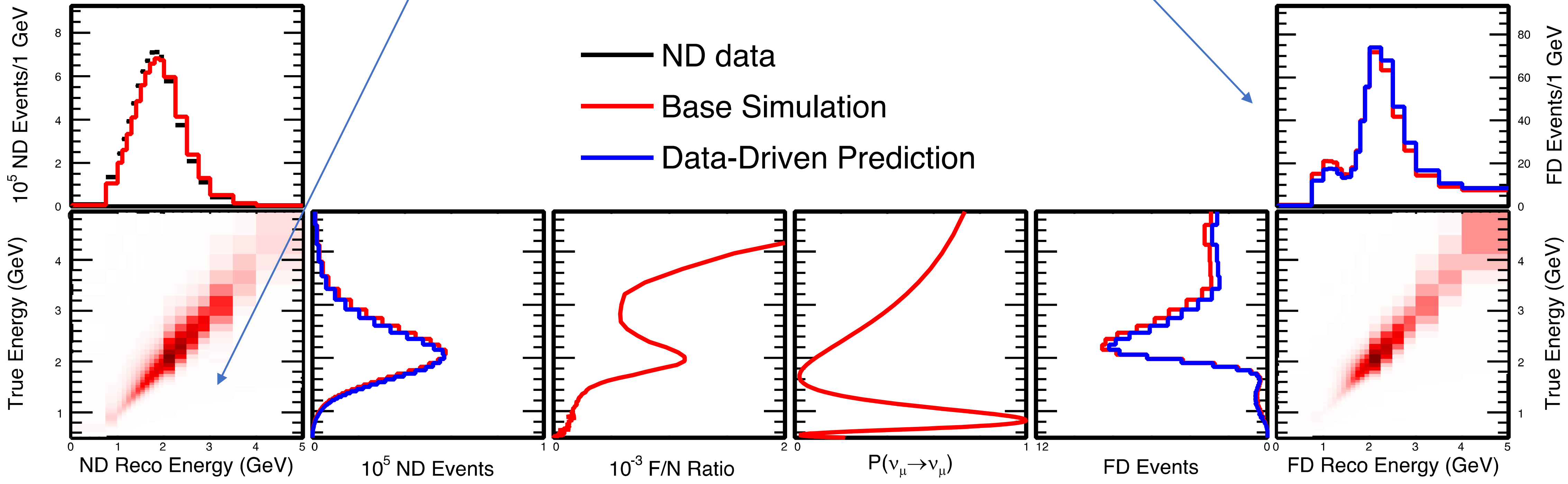
how do we calculate this reco energy?



how do we select what goes into this spectrum?

how do we calculate this reco energy?

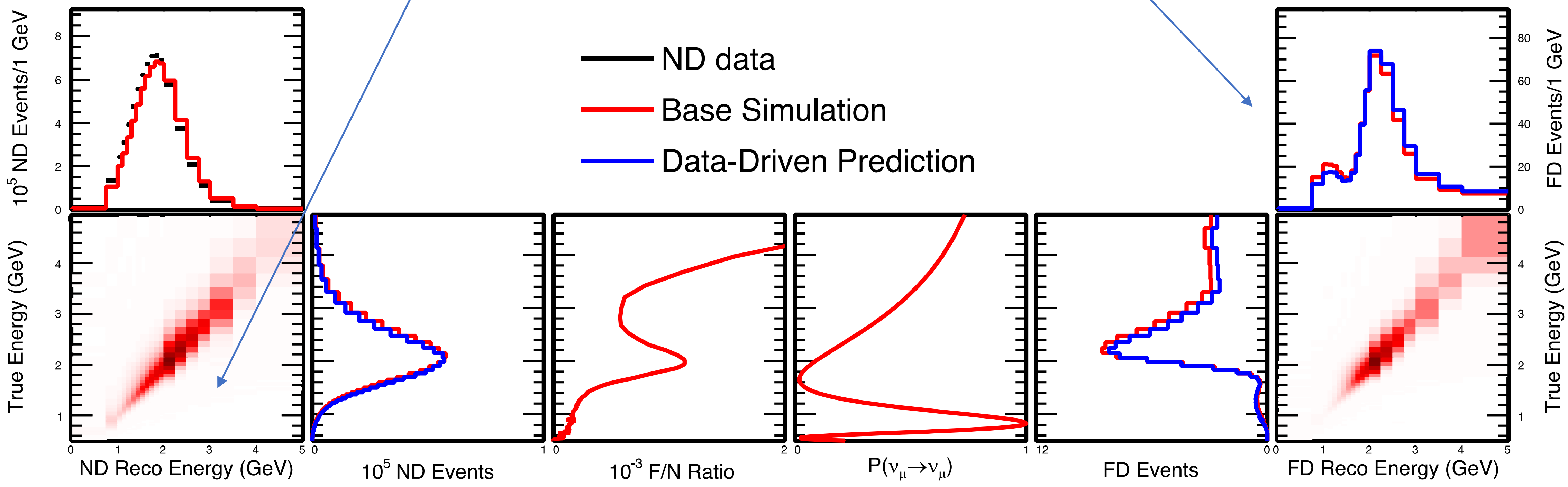
how do we estimate backgrounds?



how do we select what goes into this spectrum?

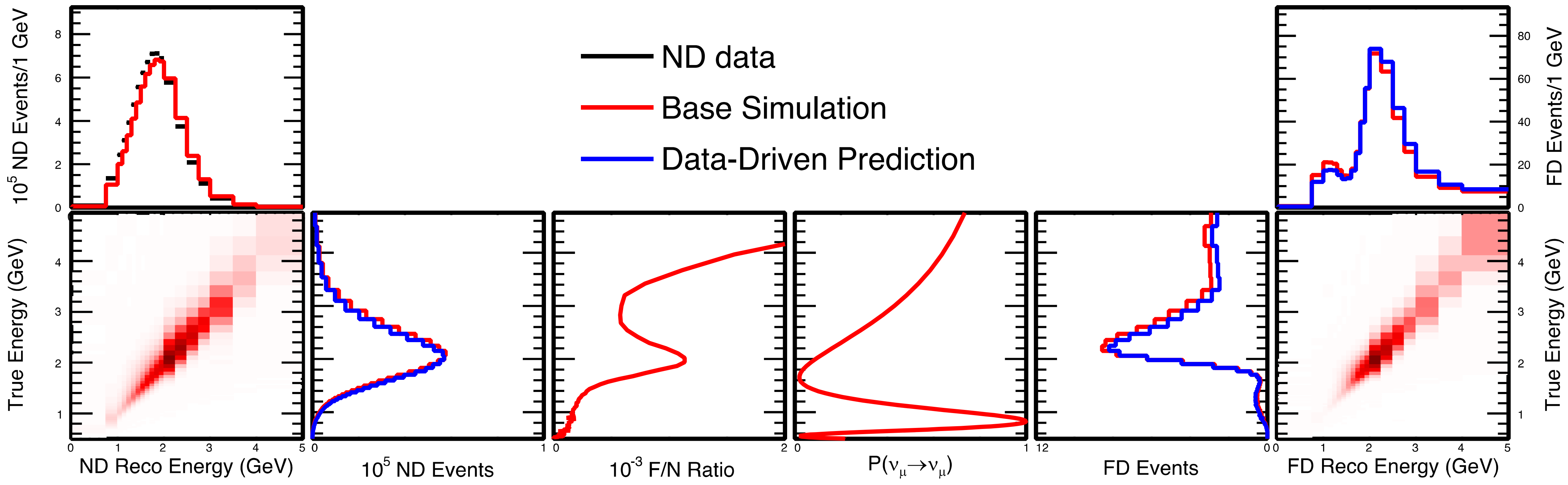
how do we calculate this reco energy?

how do we estimate backgrounds?

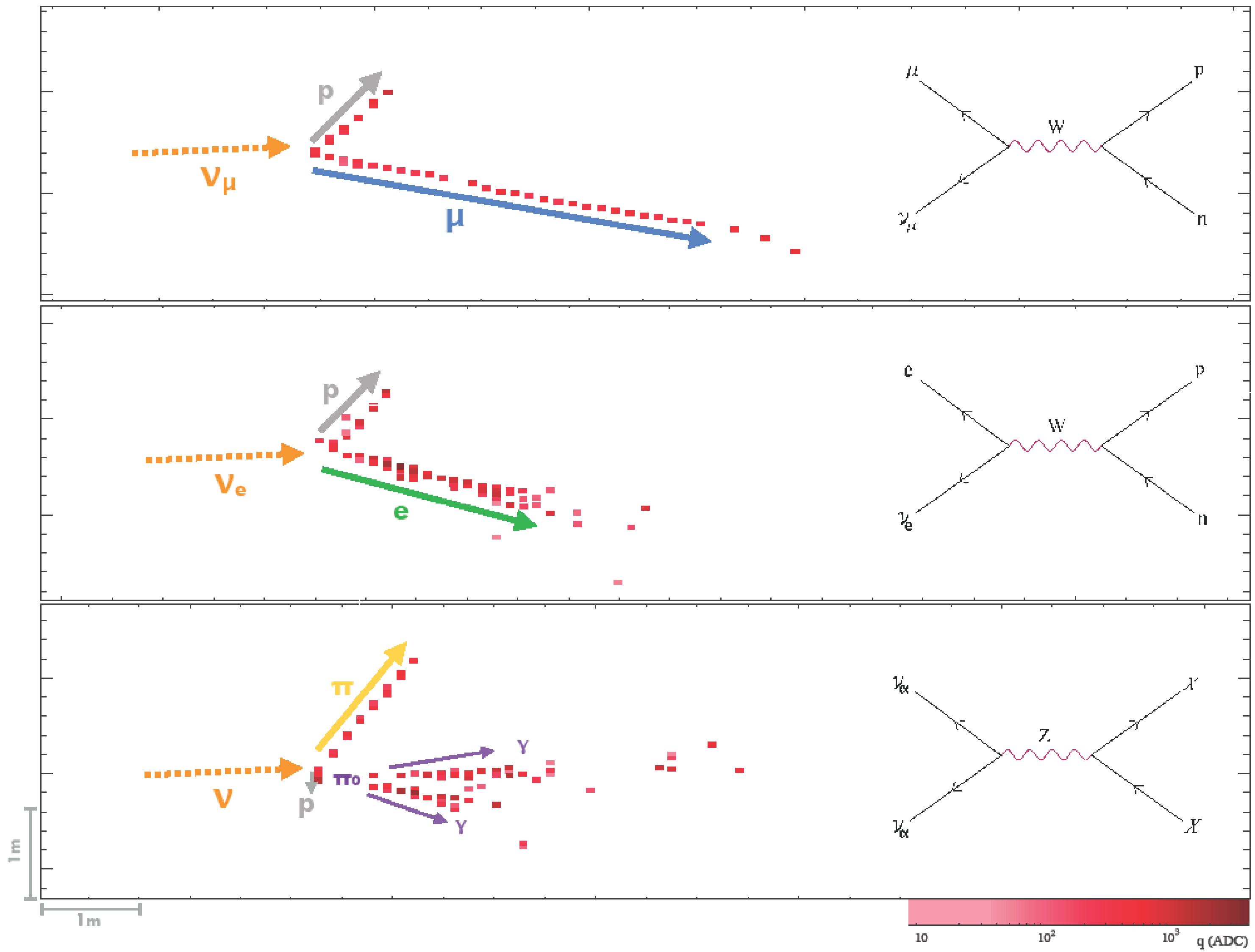


Event Selection

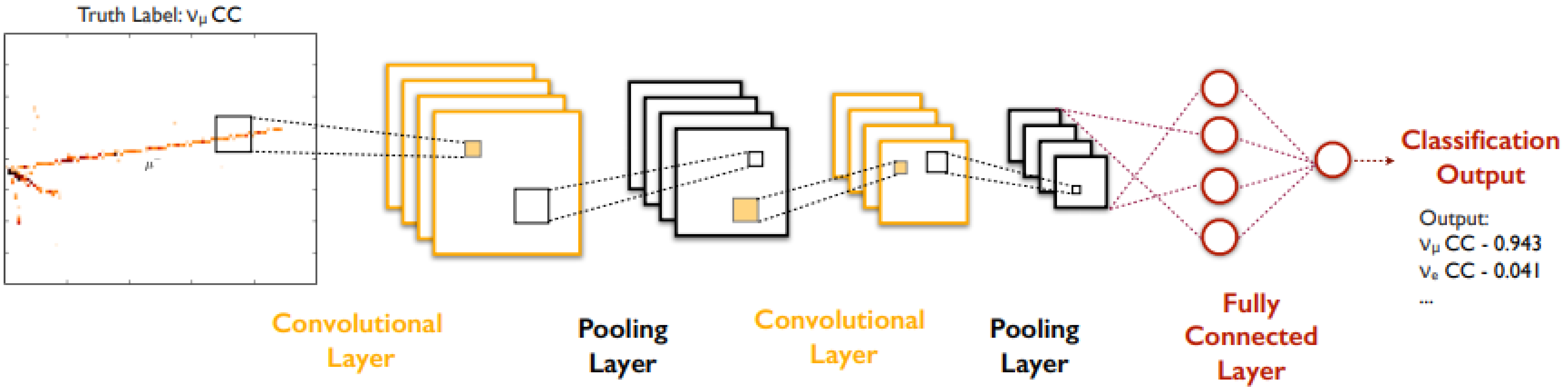
how do we select what goes into this spectrum?



Selected Events from Near Detector Data



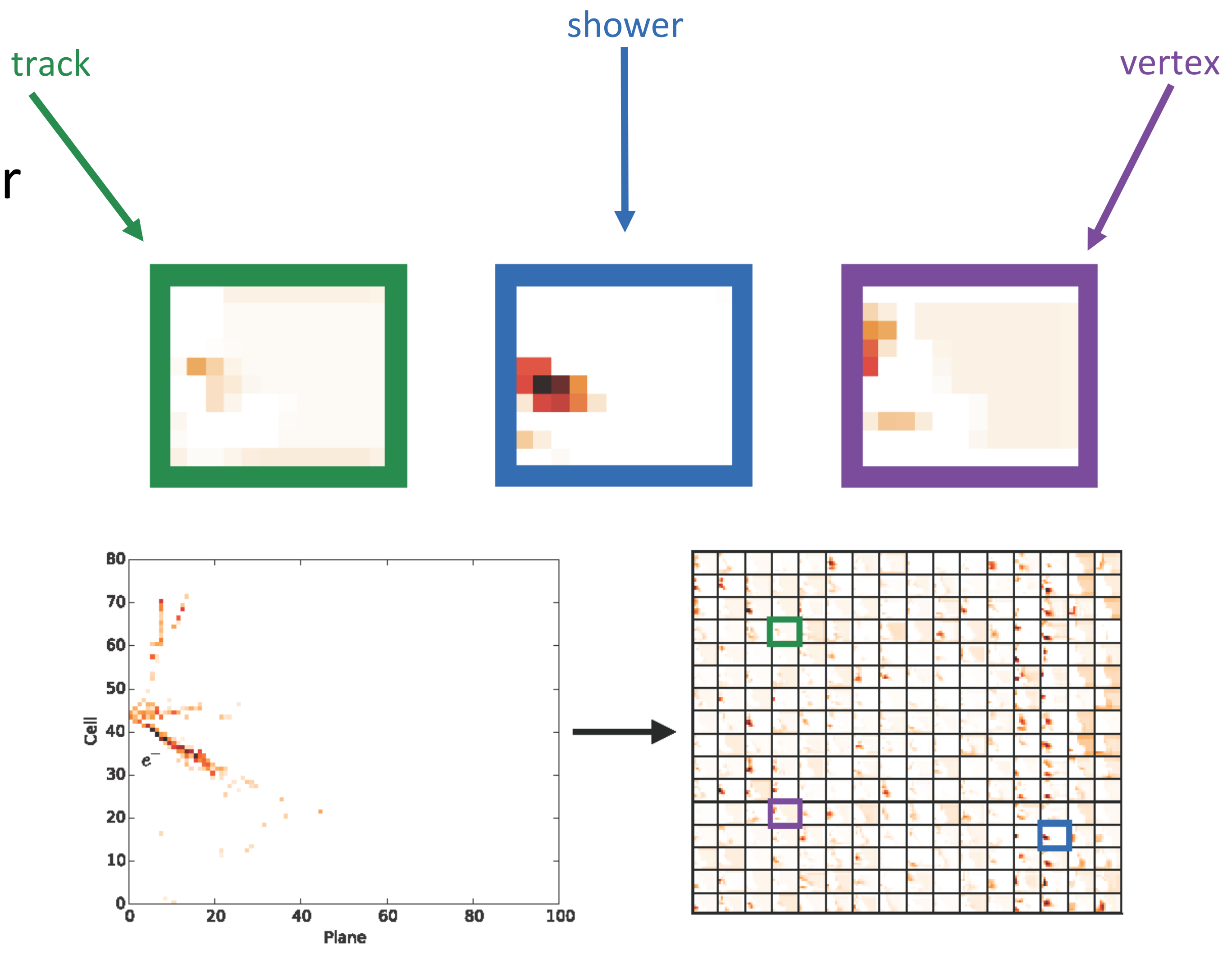
Convolutional Neural Networks



- Convolutional layers – kernels are used to extract features and create feature maps
- Pooling layers – feature maps are downsampled
- Fully connected layer – correlates feature maps to labels

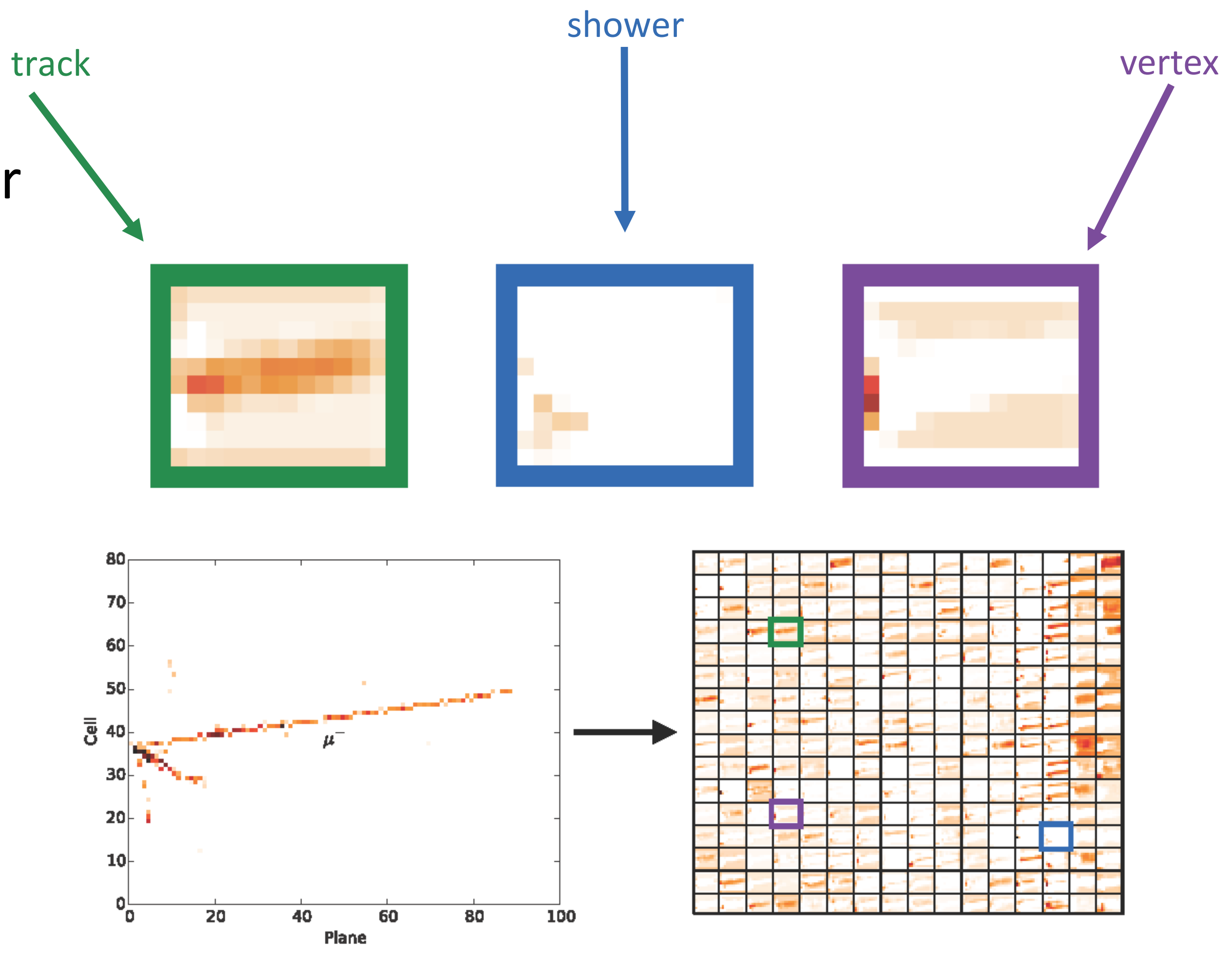
Signal Identification

- Signal identification done by our CVN (convolutional visual network)
    - Trained on 2D views of the event's calibrated hits
    - Information of each view is combined in the final layers of the network
    - An effective increase of 30% exposure from previous traditional reconstruction methods

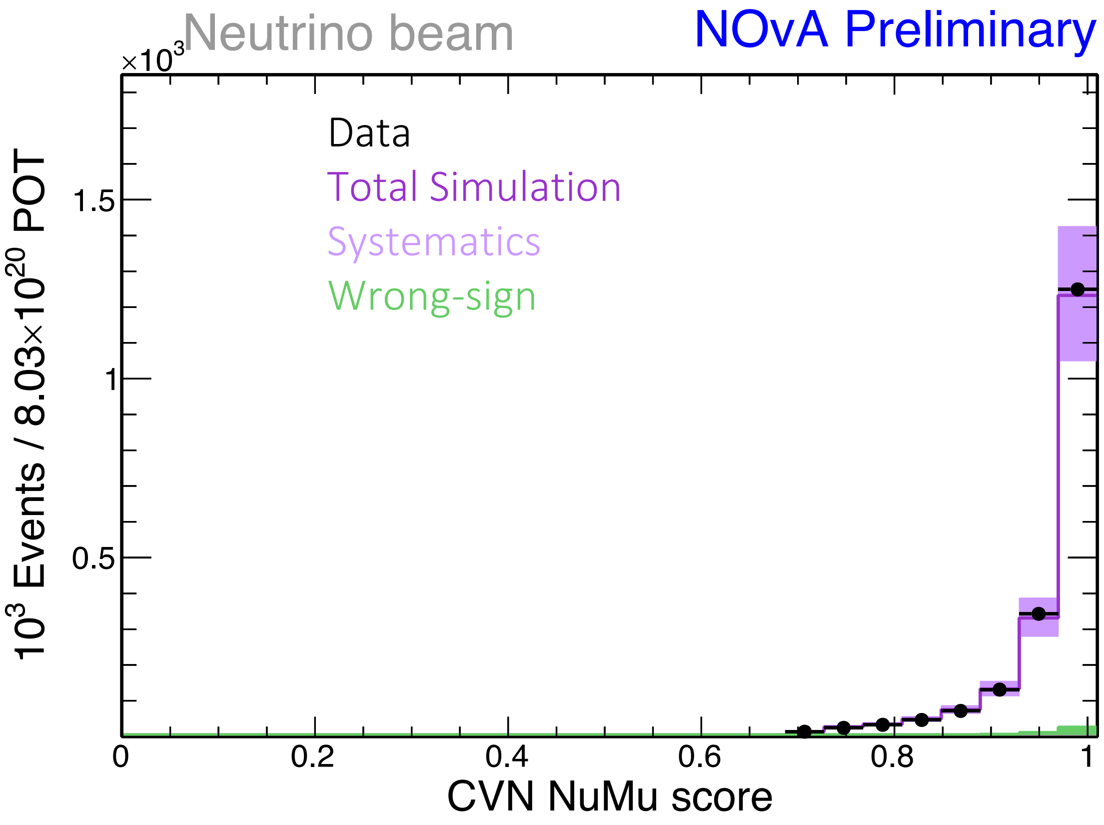


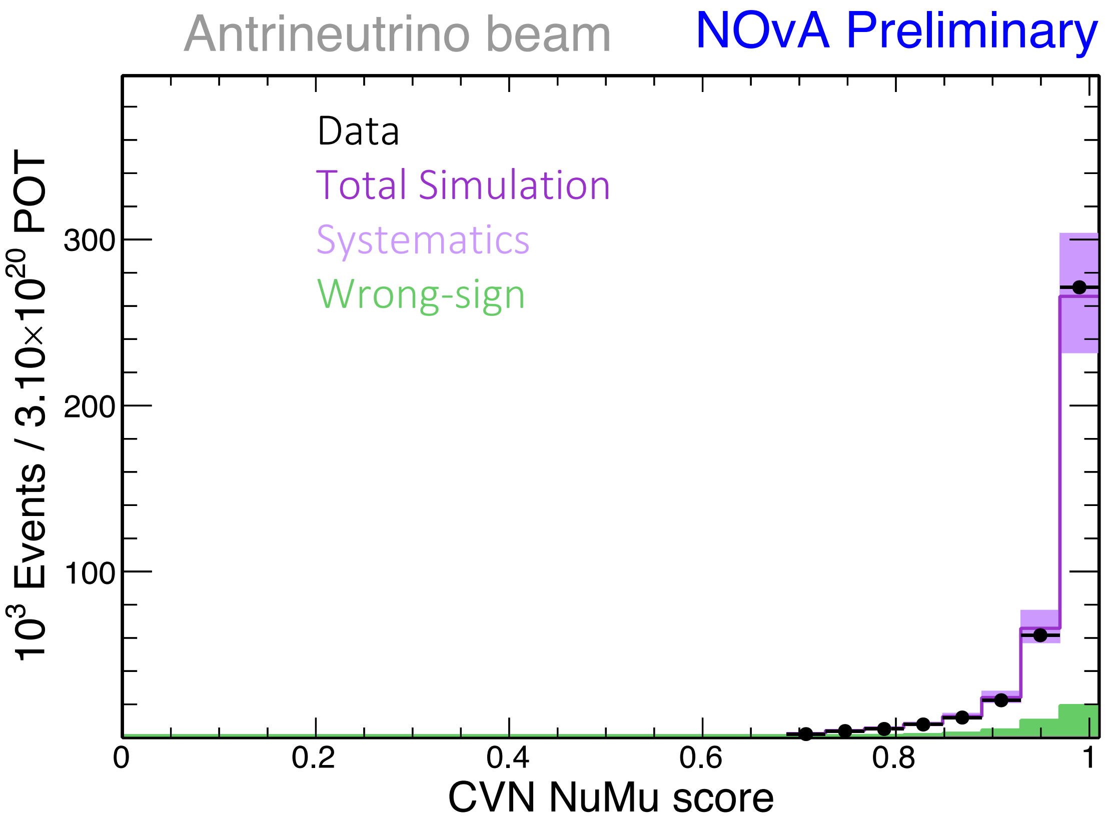
Signal Identification

- Signal identification done by our CVN (convolutional visual network)
  - Trained on 2D views of the event's calibrated hits
  - Information of each view is combined in the final layers of the network
  - An effective increase of 30% exposure from previous traditional reconstruction methods



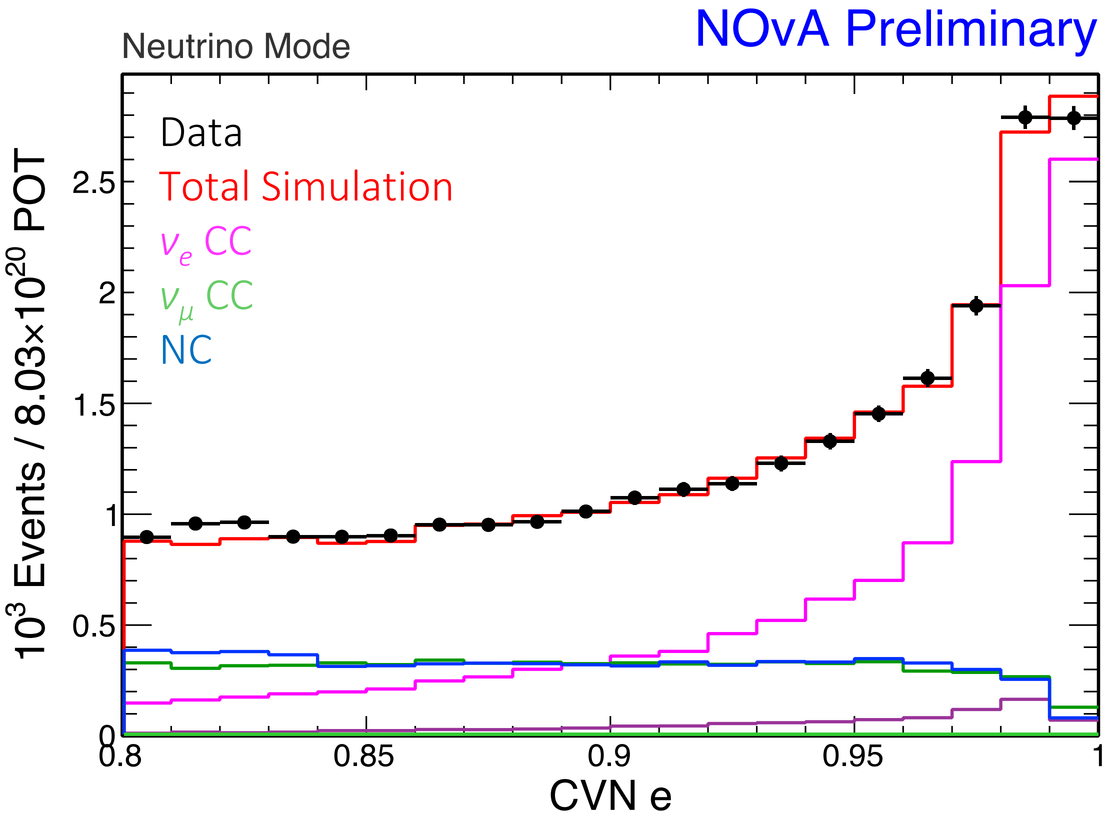
CVN Performance – Data/MC

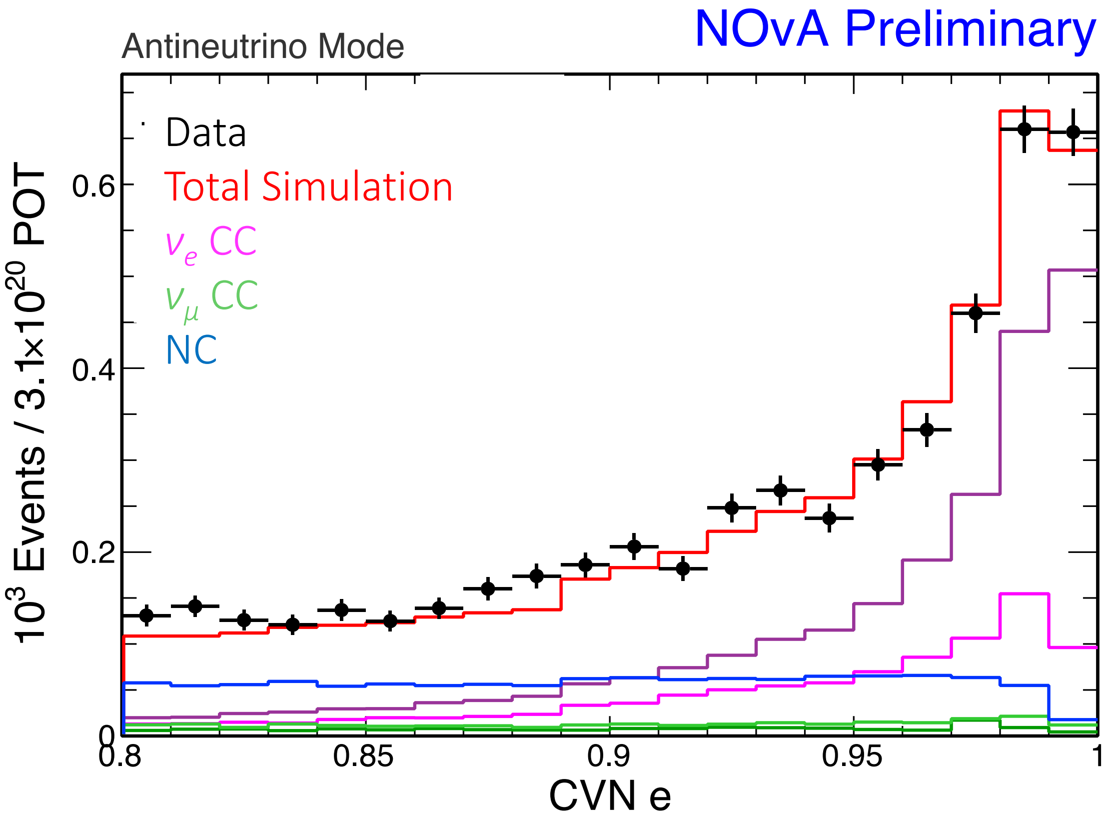




- Separate training for neutrino and anti-neutrino beams to capture differences in kinematics, topologies
  - Wrong sign treated as signal in the training
  - Improved efficiency with a dedicated anti-neutrino network

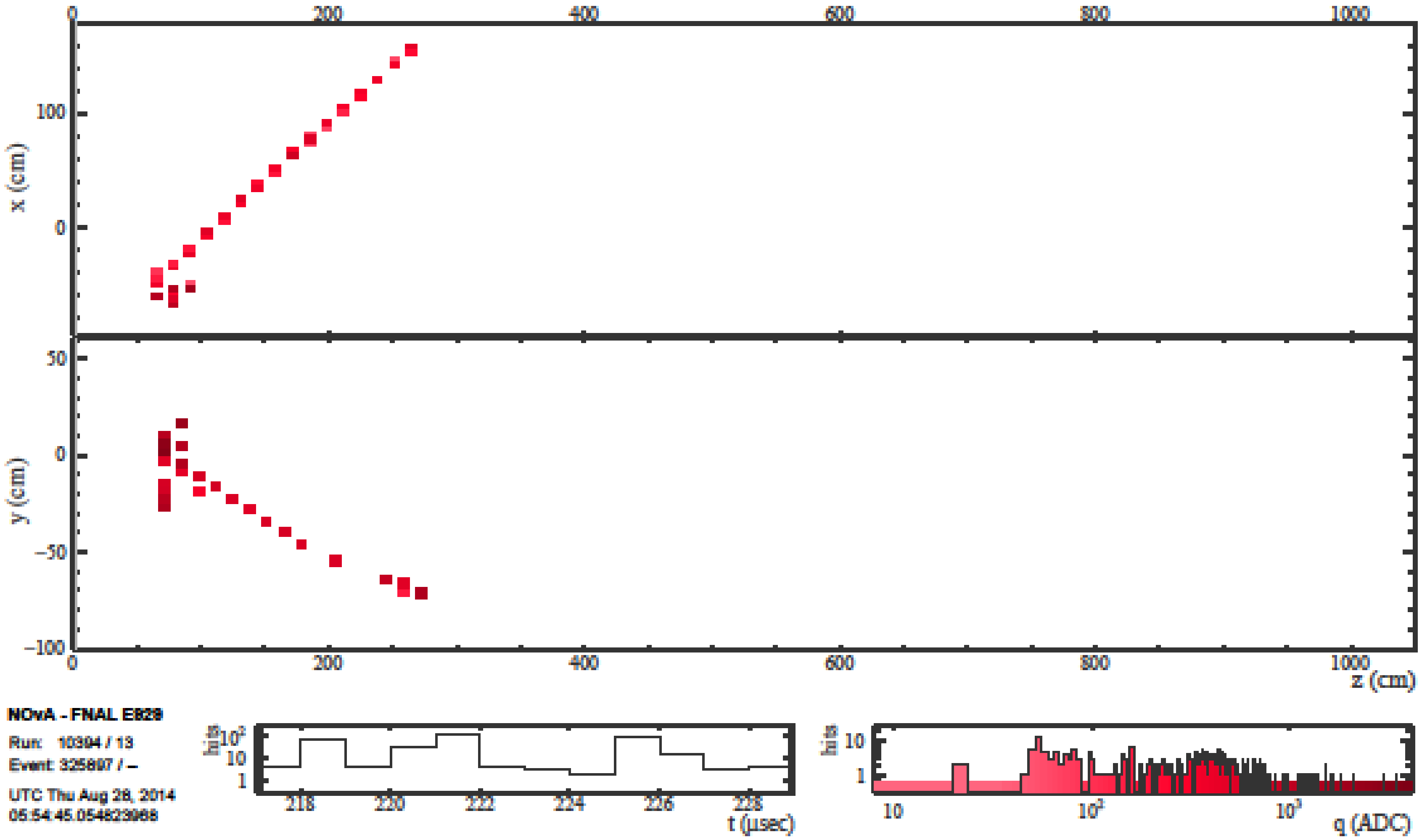
CVN Performance – Data/MC



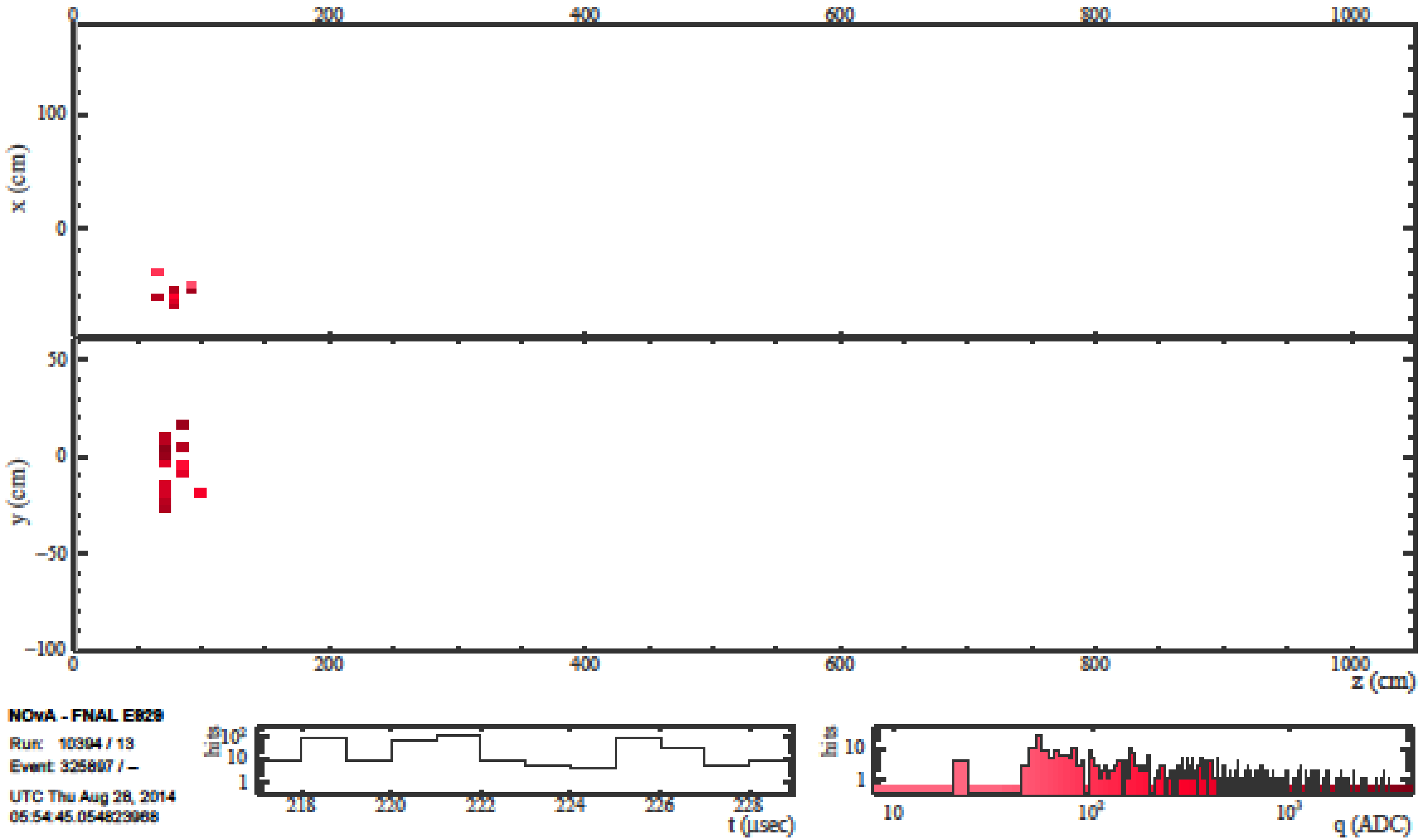


- Separate training for neutrino and anti-neutrino beams to capture differences in kinematics, topologies
    - Wrong sign treated as signal in the training
    - Improved efficiency with a dedicated anti-neutrino network

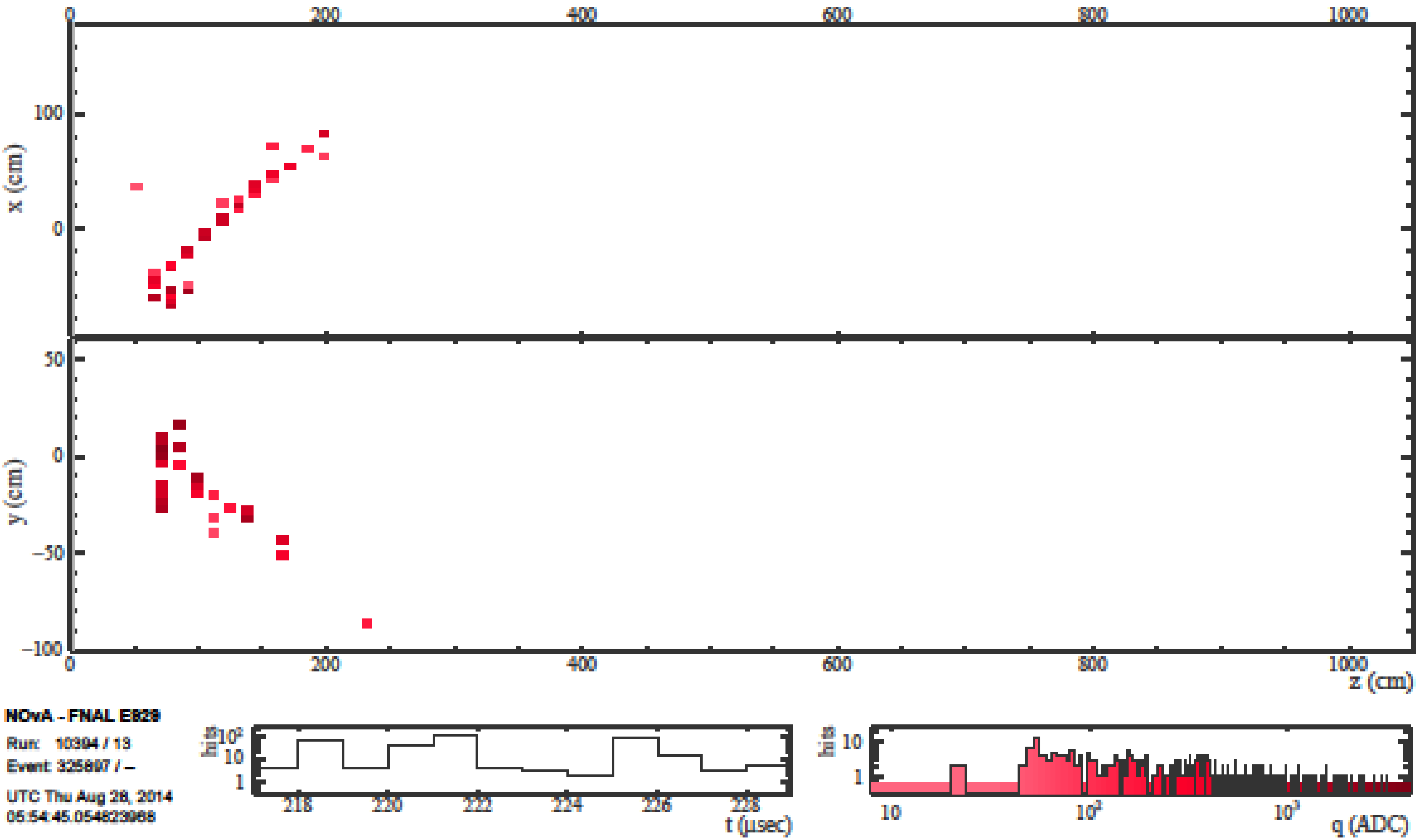
Muon Removed Events



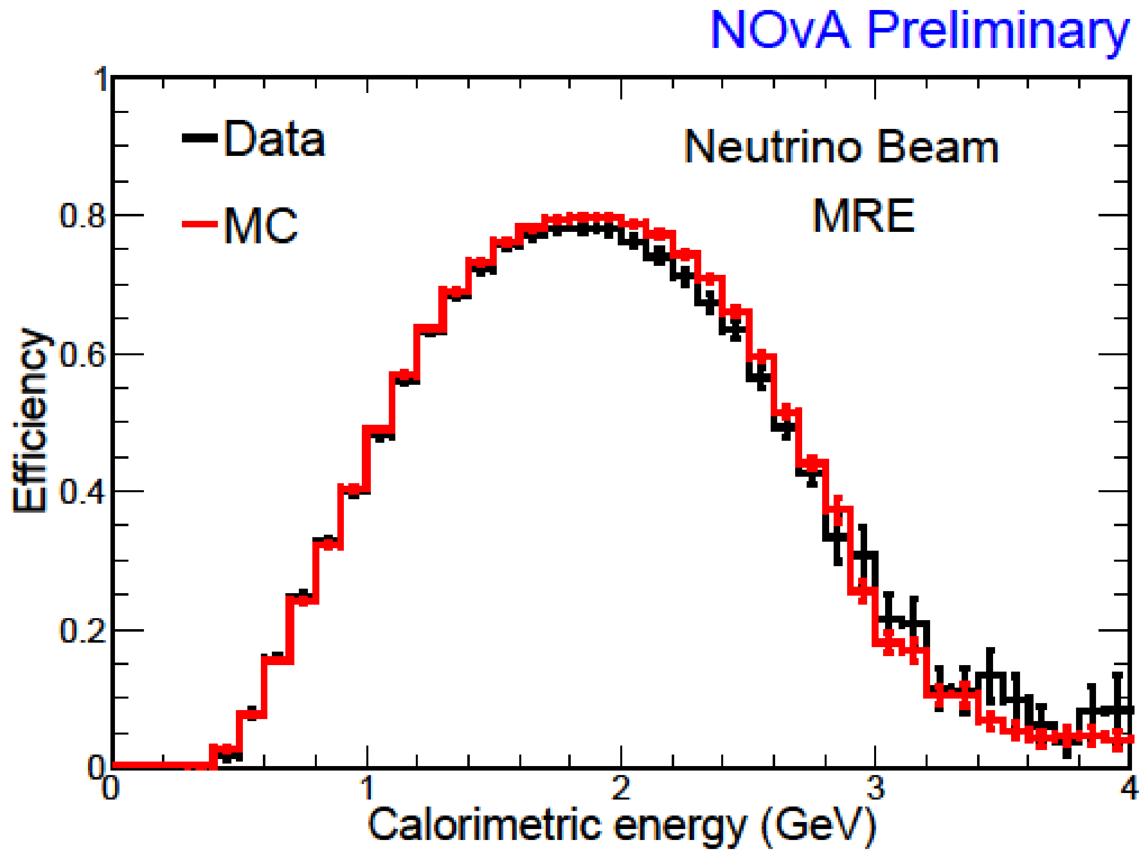
Muon Removed Events

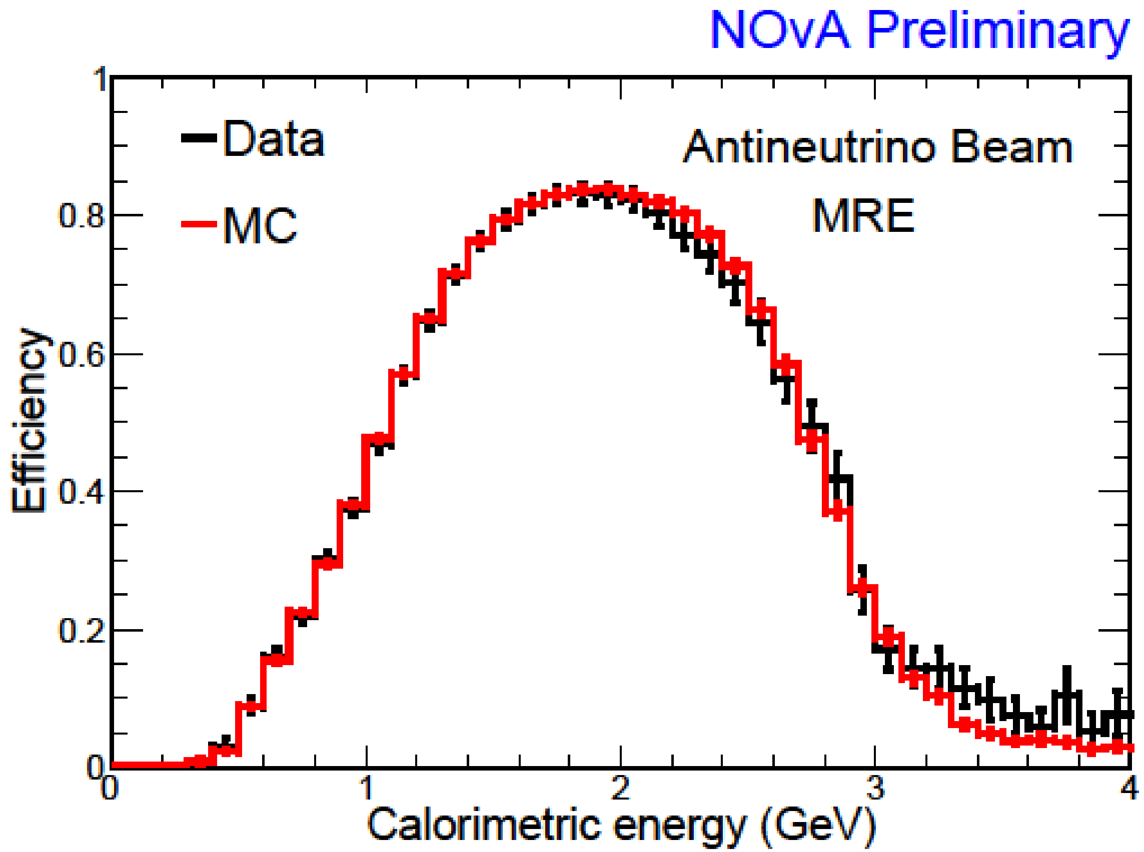


Muon Removed Events



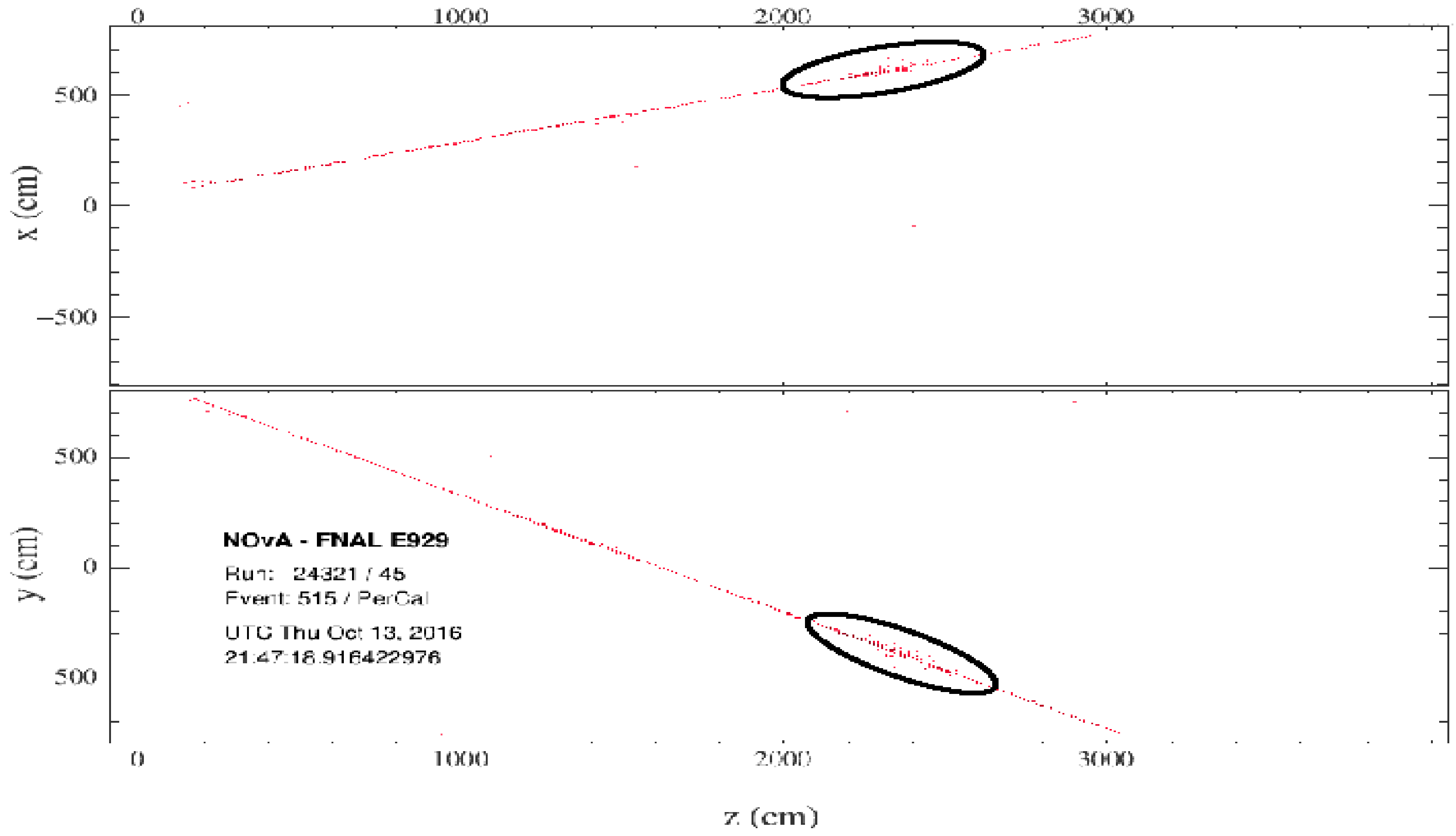
Muon Removed Events





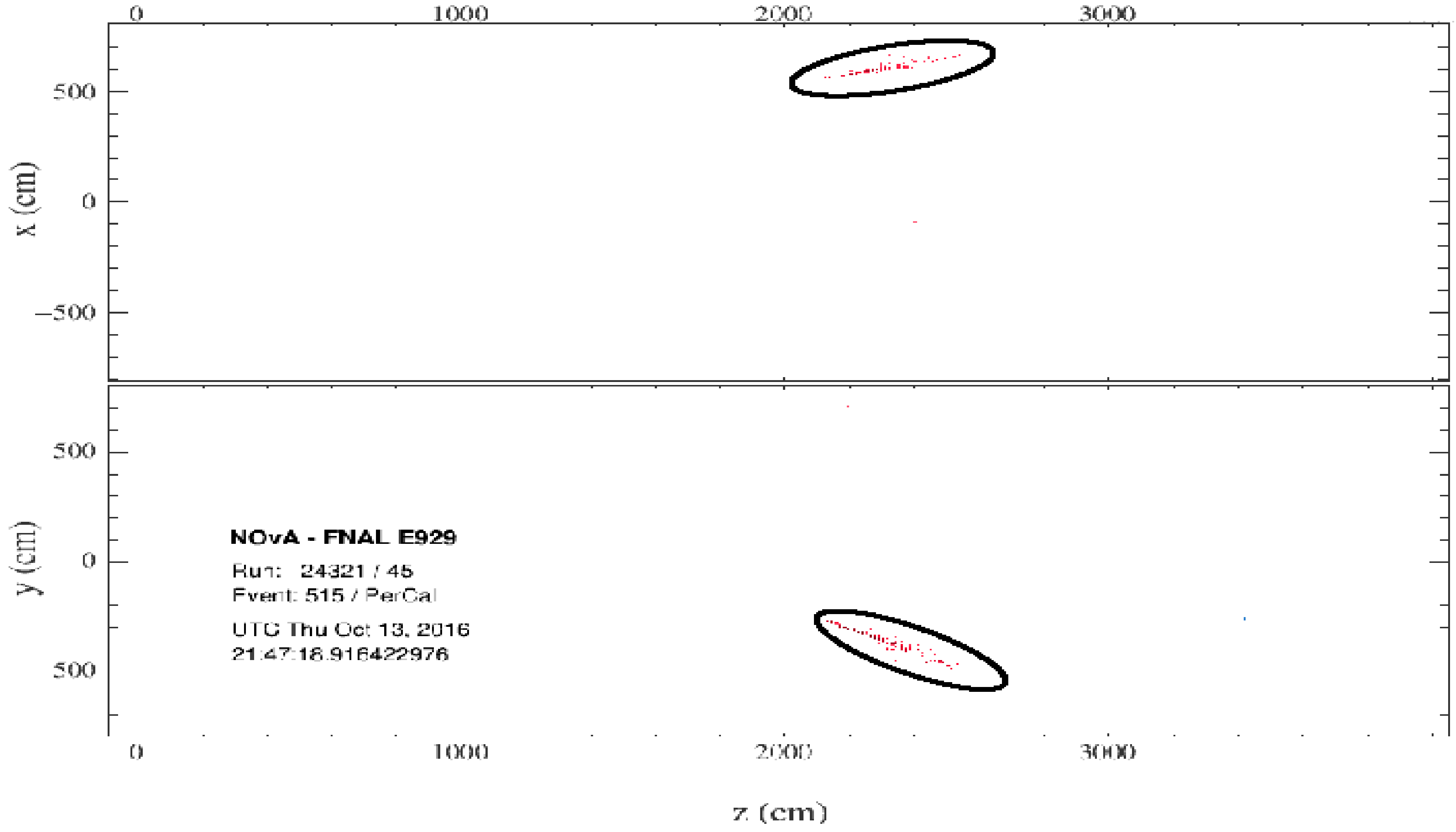
- Works at the Near Detector where there is a large statistics ν_μ sample
- Allows us to focus on the effect of the hadronic shower on efficiency
- Data/MC agreement is within 3% for neutrino mode, 2% for anti-neutrino mode – covered by systematics

MRBrem



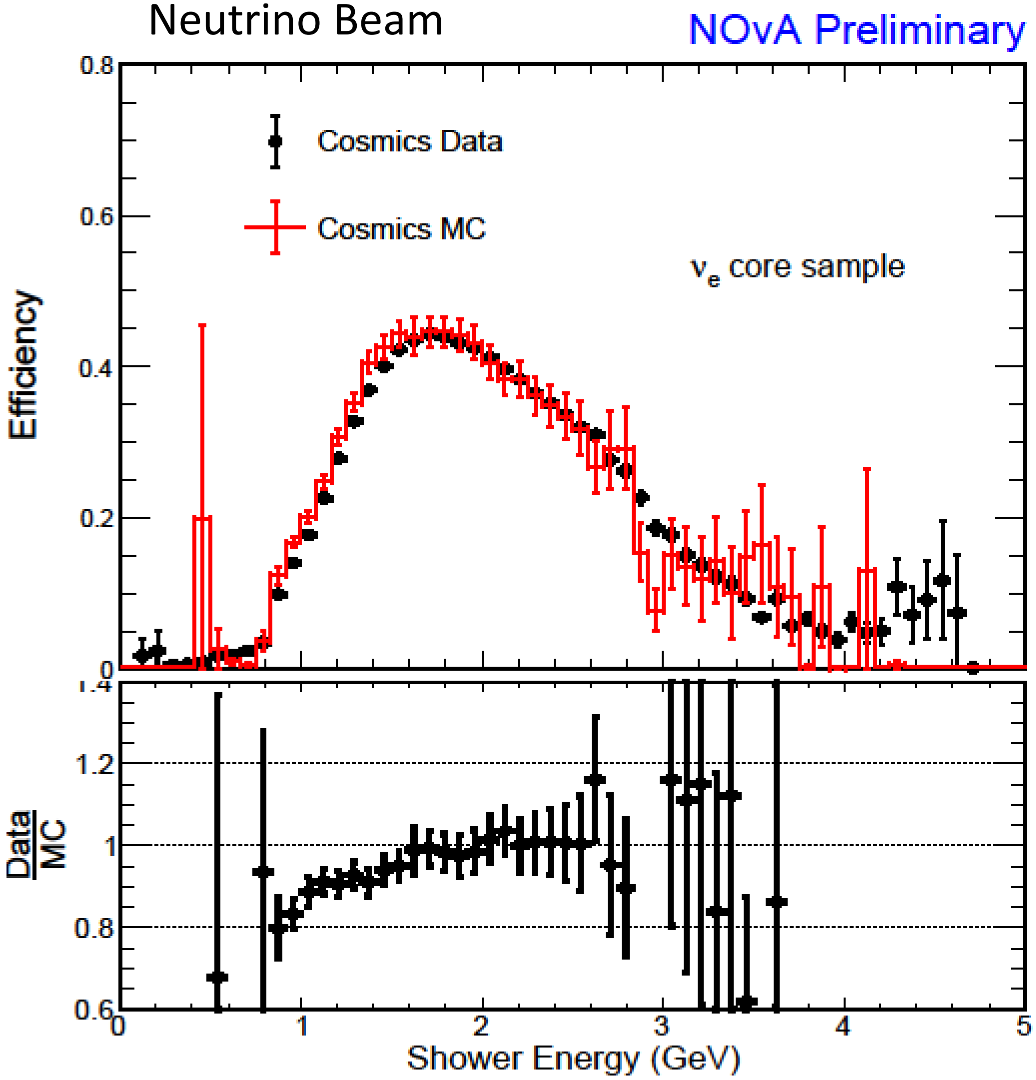
0
1000
2000
3000
500
0
−500
x (cm)
y (cm)
NOvA - FNAL E929
Run: 24321 / 45
Event: 515 / PerCal
UTC Thu Oct 13, 2016
21:47:16.916422976
z (cm)

MRBrem

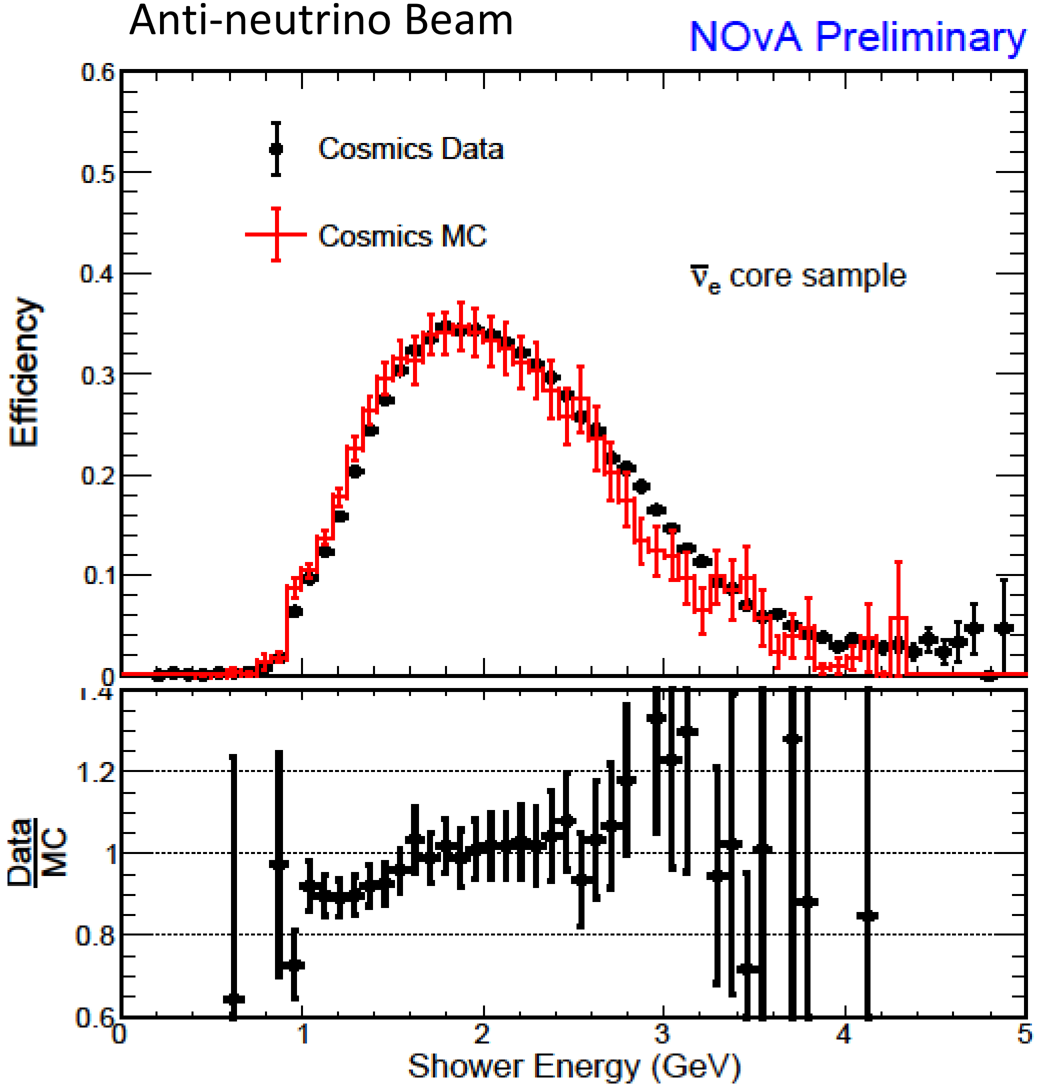

NOvA - FNAL E929
Run: 24321 / 45
Event: 515 / PerCal
UTC Thu Oct 13, 2016
21:47:16.916422976
x (cm)
y (cm)
z (cm)

MRBrem

Neutrino Beam

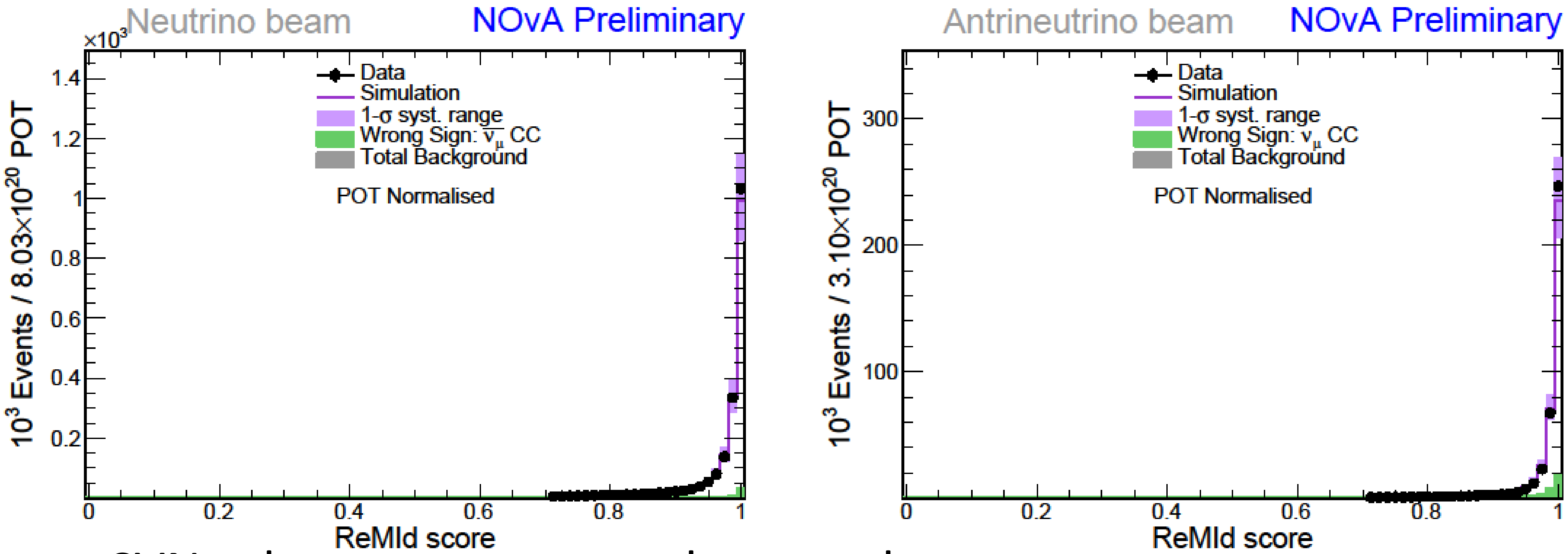


Anti-neutrino Beam



Selection efficiency is within 2% for both modes; covered by systematics.

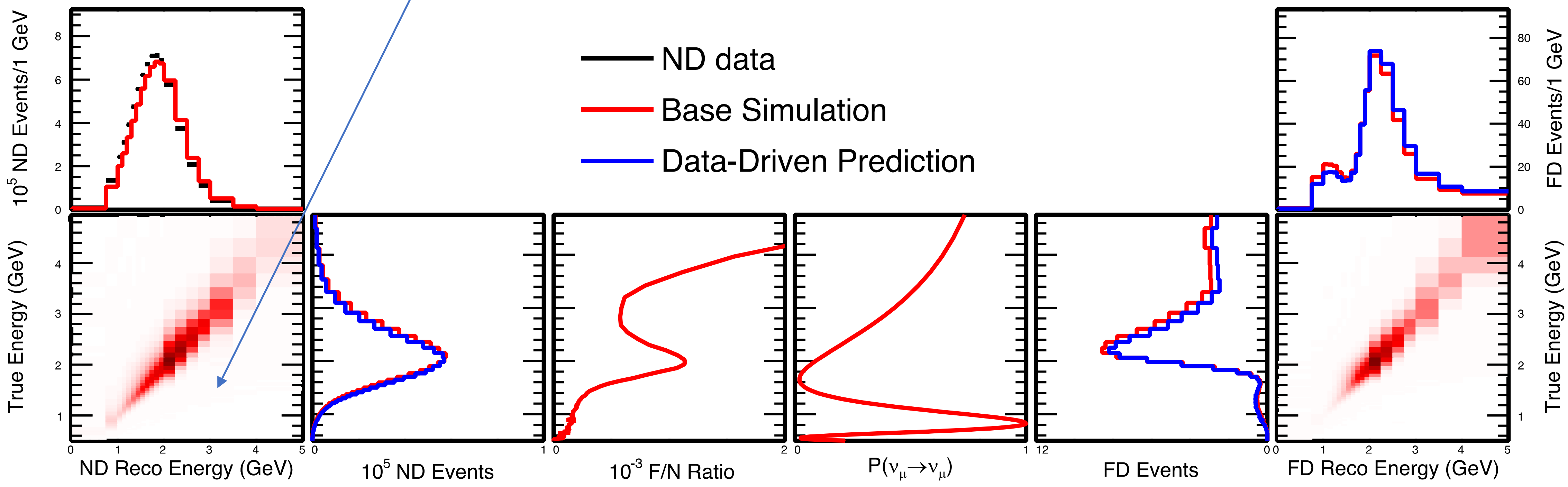
Additional Selection - ν_μ



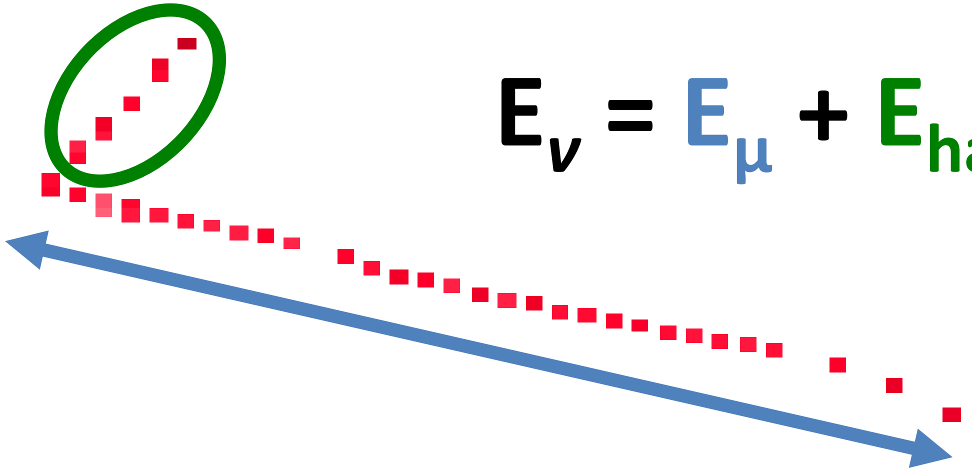
- CVN selects muon events but not the muon
- Identify muon tracks with a traditional kNN: track length, dE/dx along track, scattering along track, track-only plane fraction

Energy Reconstruction

how do we calculate this reco energy?

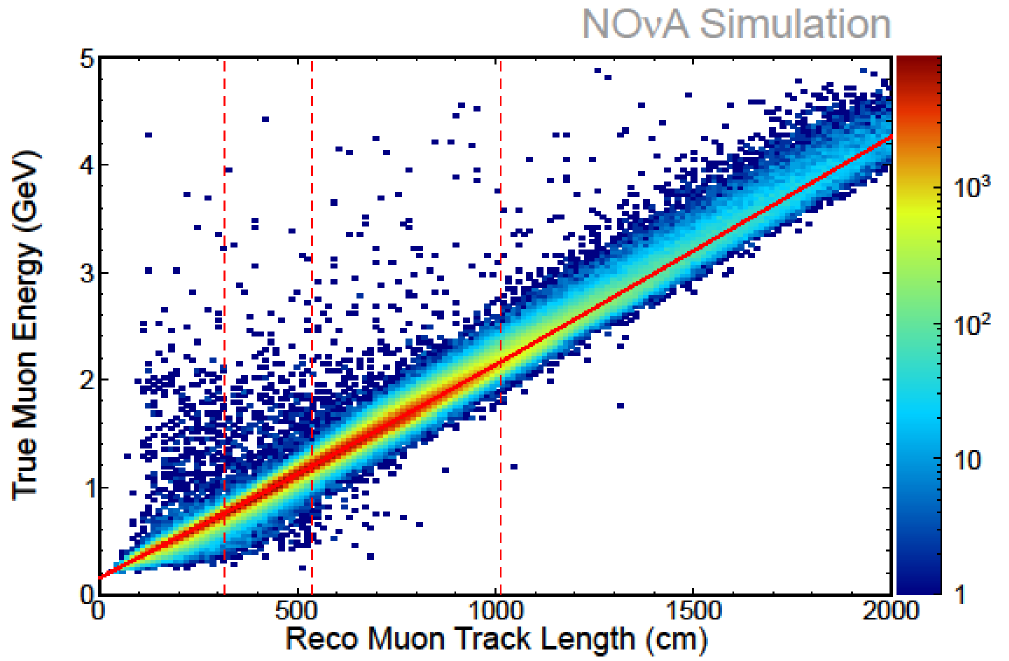


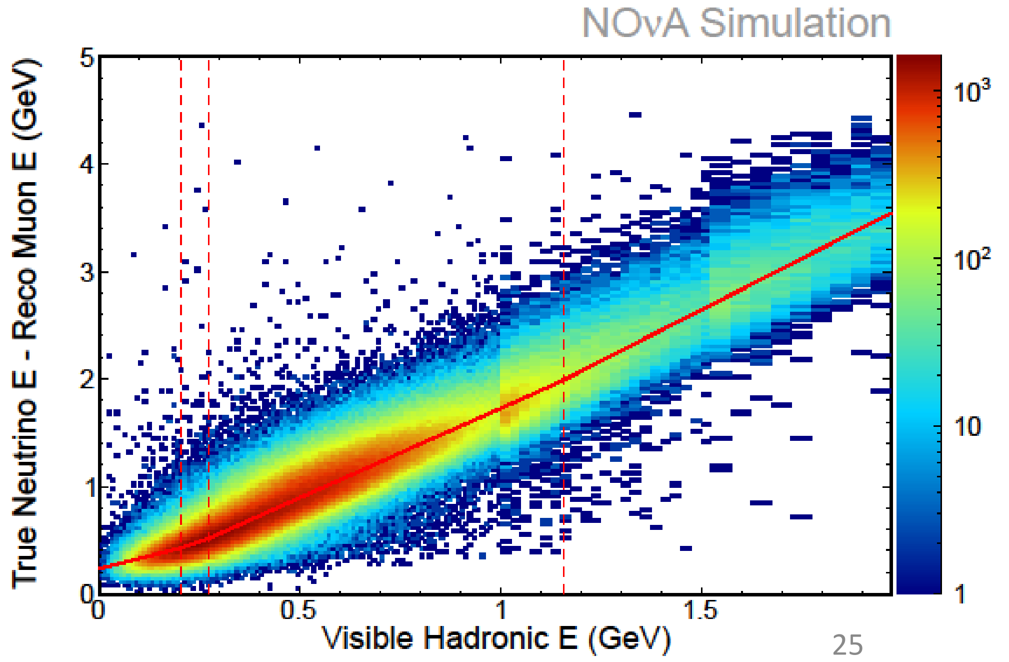
Energy Estimation - ν_μ



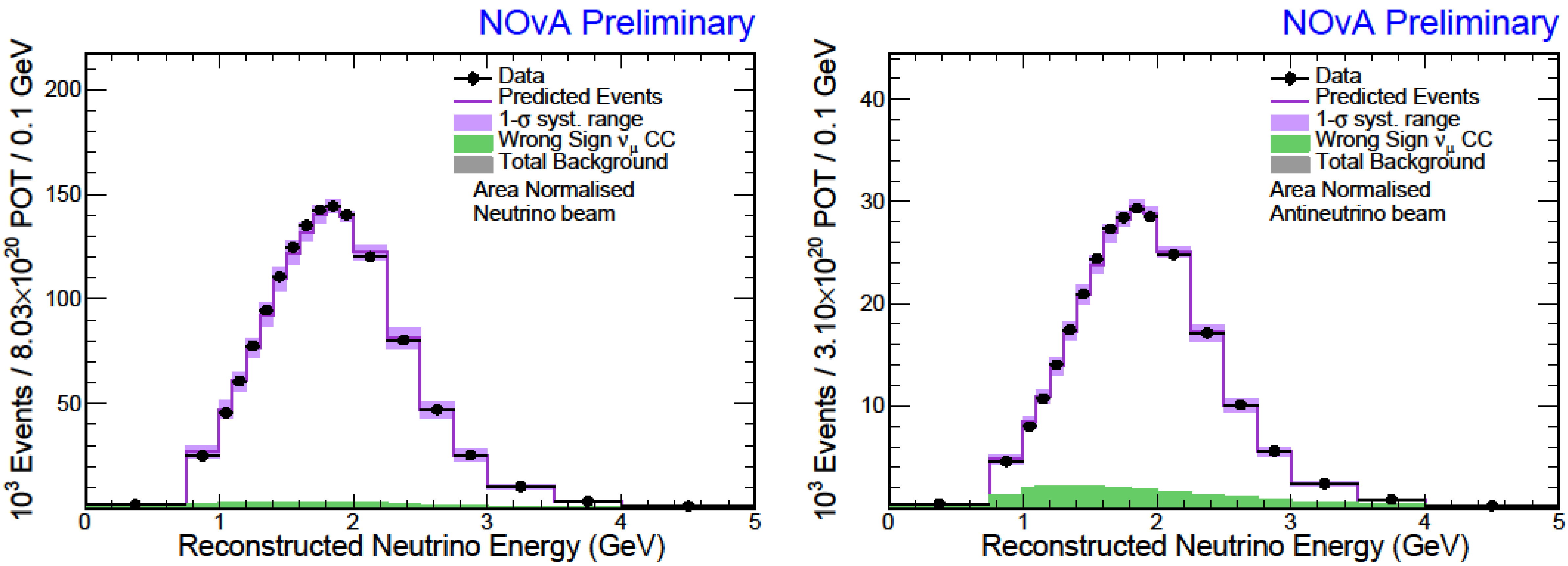
$$E_\nu = E_\mu + E_{had}$$

- Muon energy is calculated with a conversion from track length.
- Hadronic energy is the summed calorimetric energy of the non-muon hits, converted to true energy.
- Muon energy resolution (3%) is much better than hadronic energy resolution (30%).



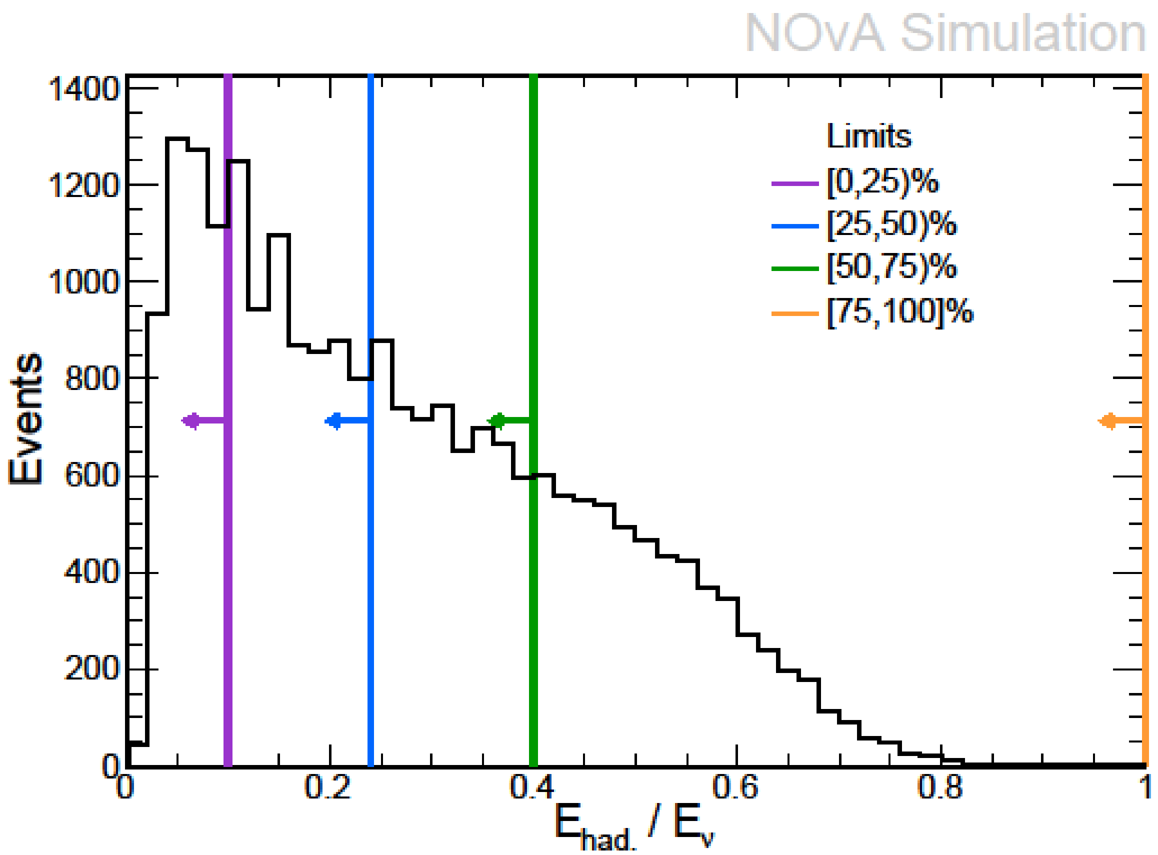


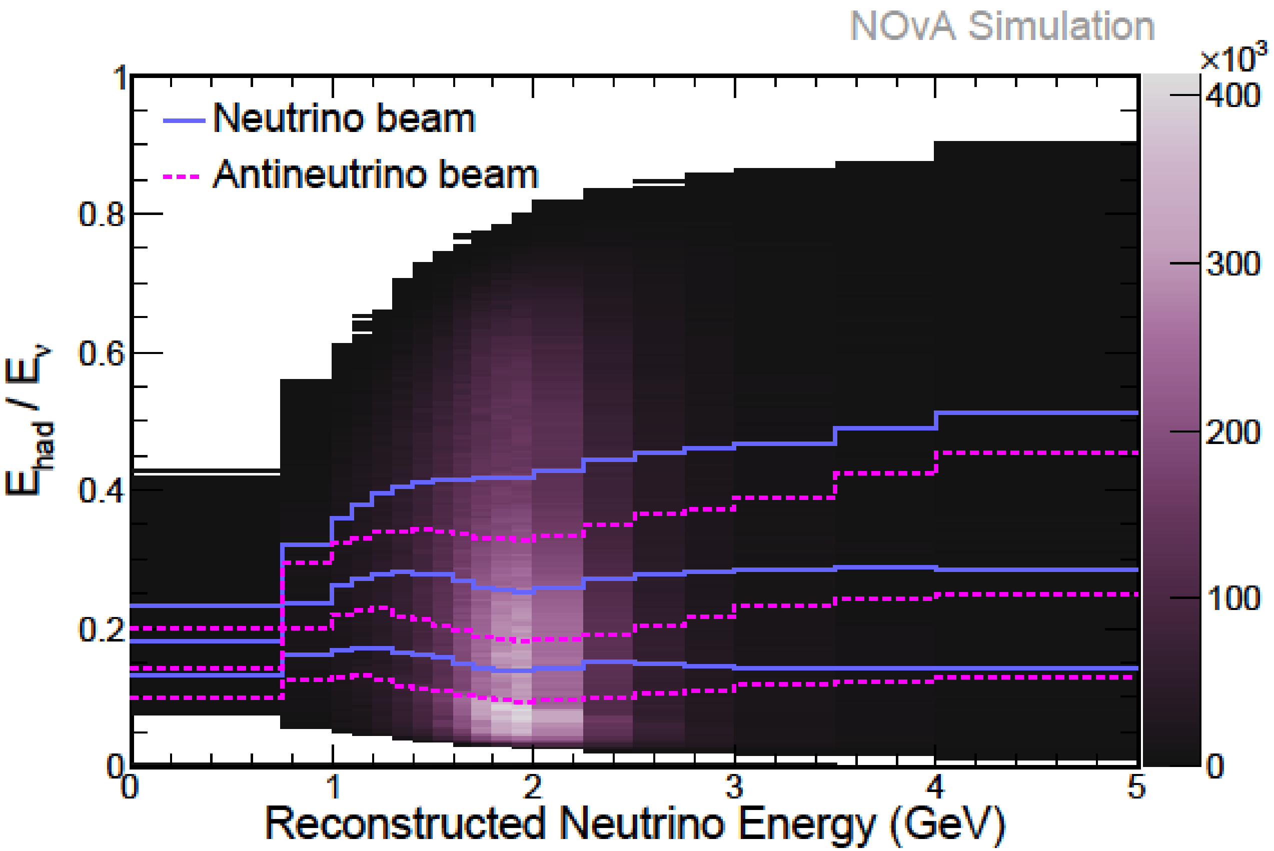
ν_μ Energy



MC normalized: scaled +1.3% in neutrino mode, -0.5% in anti-neutrino mode

Improving Energy Resolution





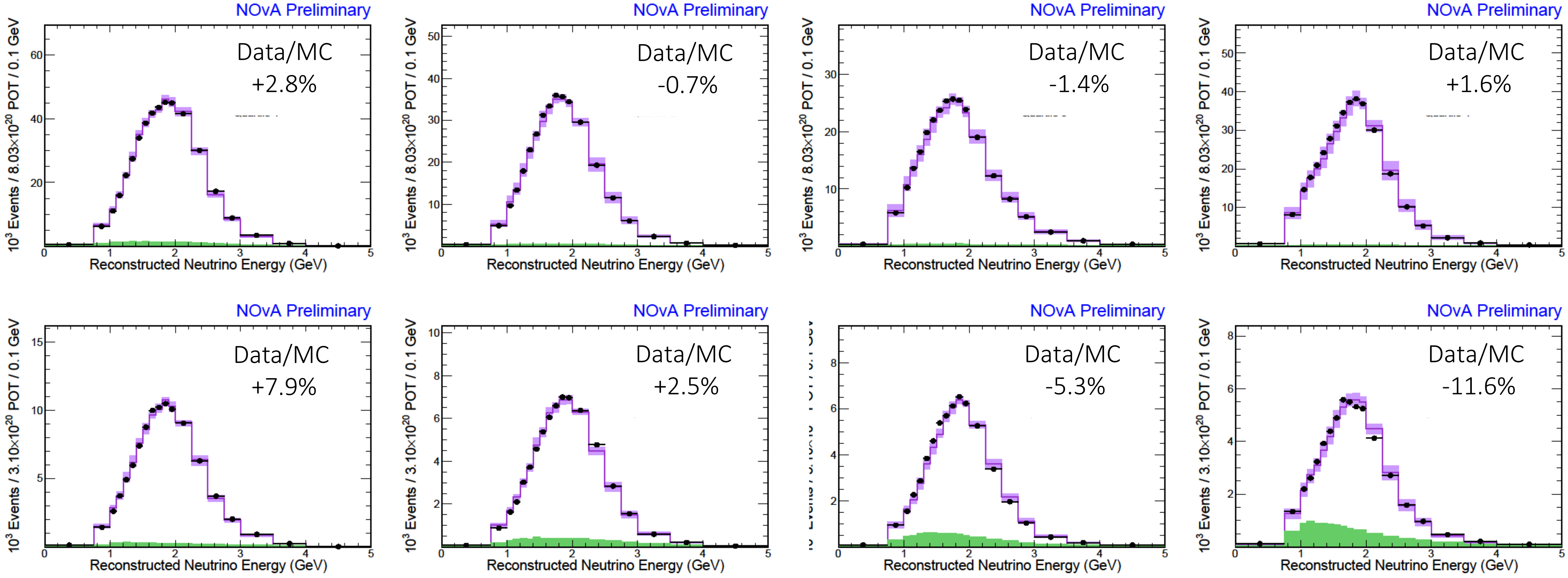
- Oscillation sensitivity depends on spectrum shape
- Improve sensitivity by separating high and low resolution events
- Split energy spectrum into quartiles by hadronic energy fraction
  - Also puts the majority of the backgrounds in quartile 4 (improves NC systematic by a factor of 2-4)
  - Better extrapolation of cross sections

Improving Energy Resolution

Data
Area-normalized MC
Shape-only systematics
Wrong-sign

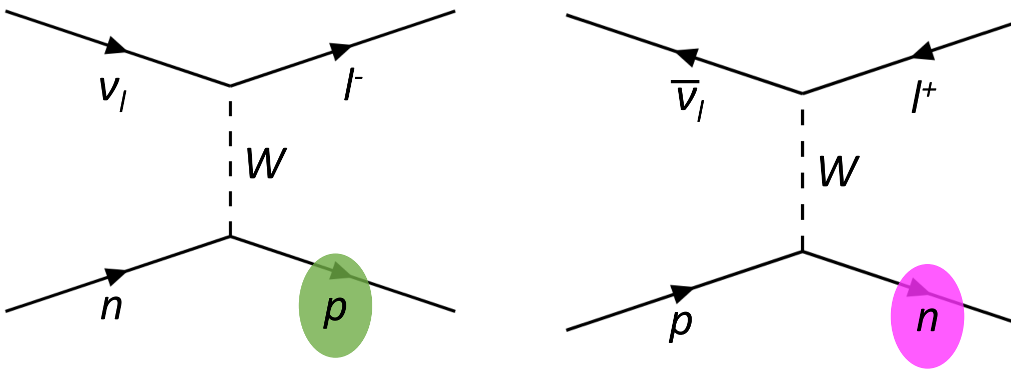
Quartile 1
Best Resolution ~6%

Quartile 4
Worst Resolution ~12%

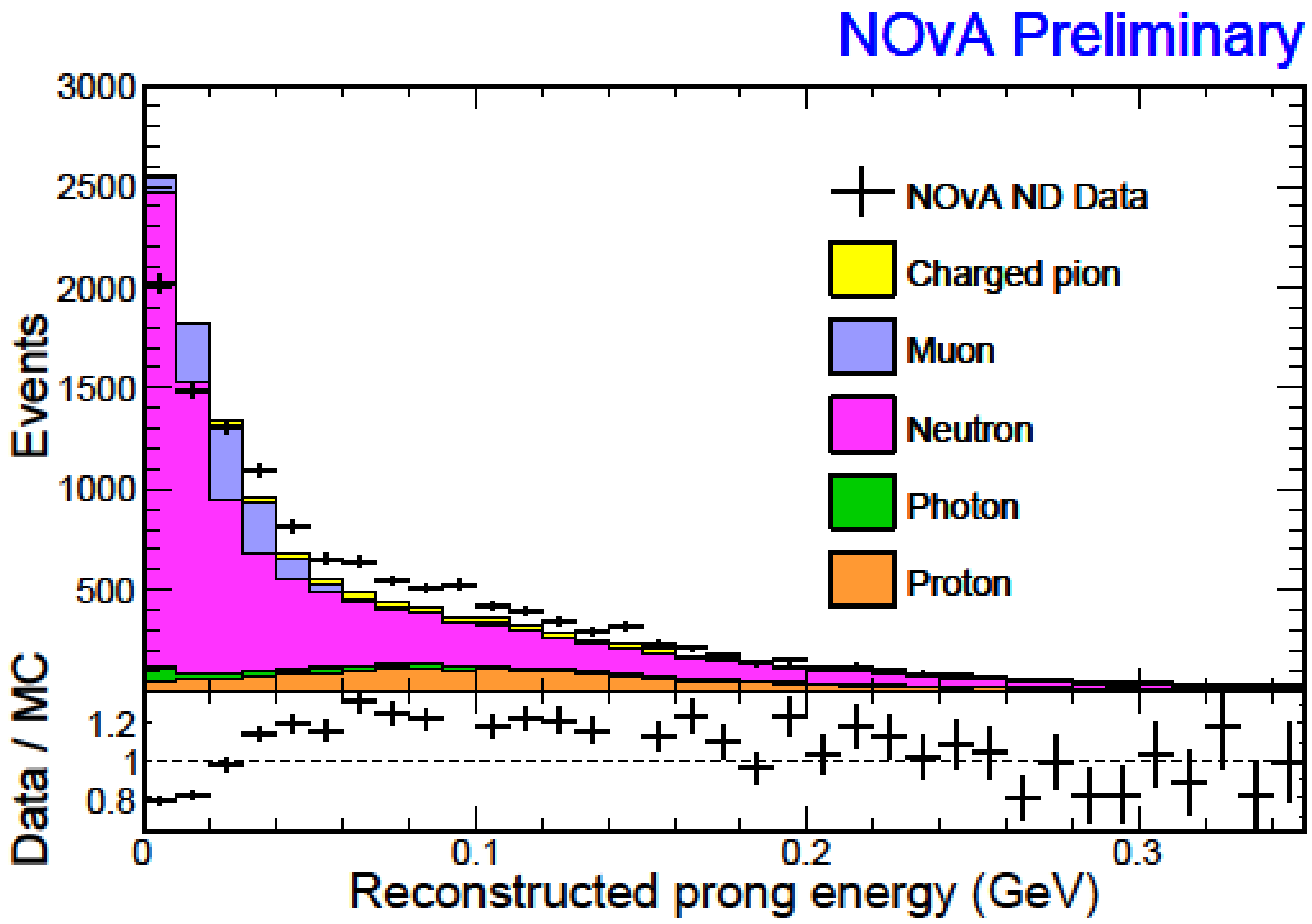


Data/MC shape agrees well per quantile

Neutron Response

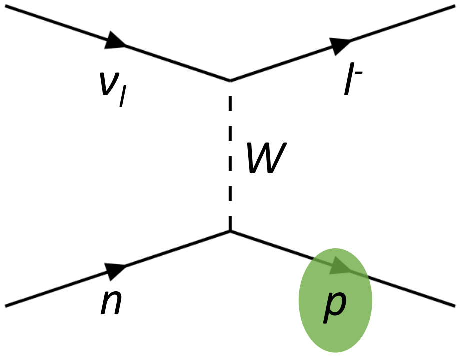


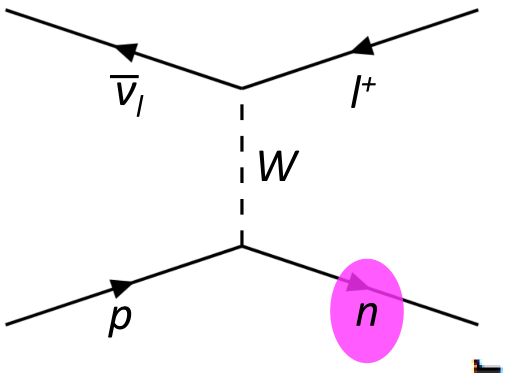
- Anti-neutrino data has increased importance of understanding neutron response
- In selected samples, neutrons show softer spectrum than simulated

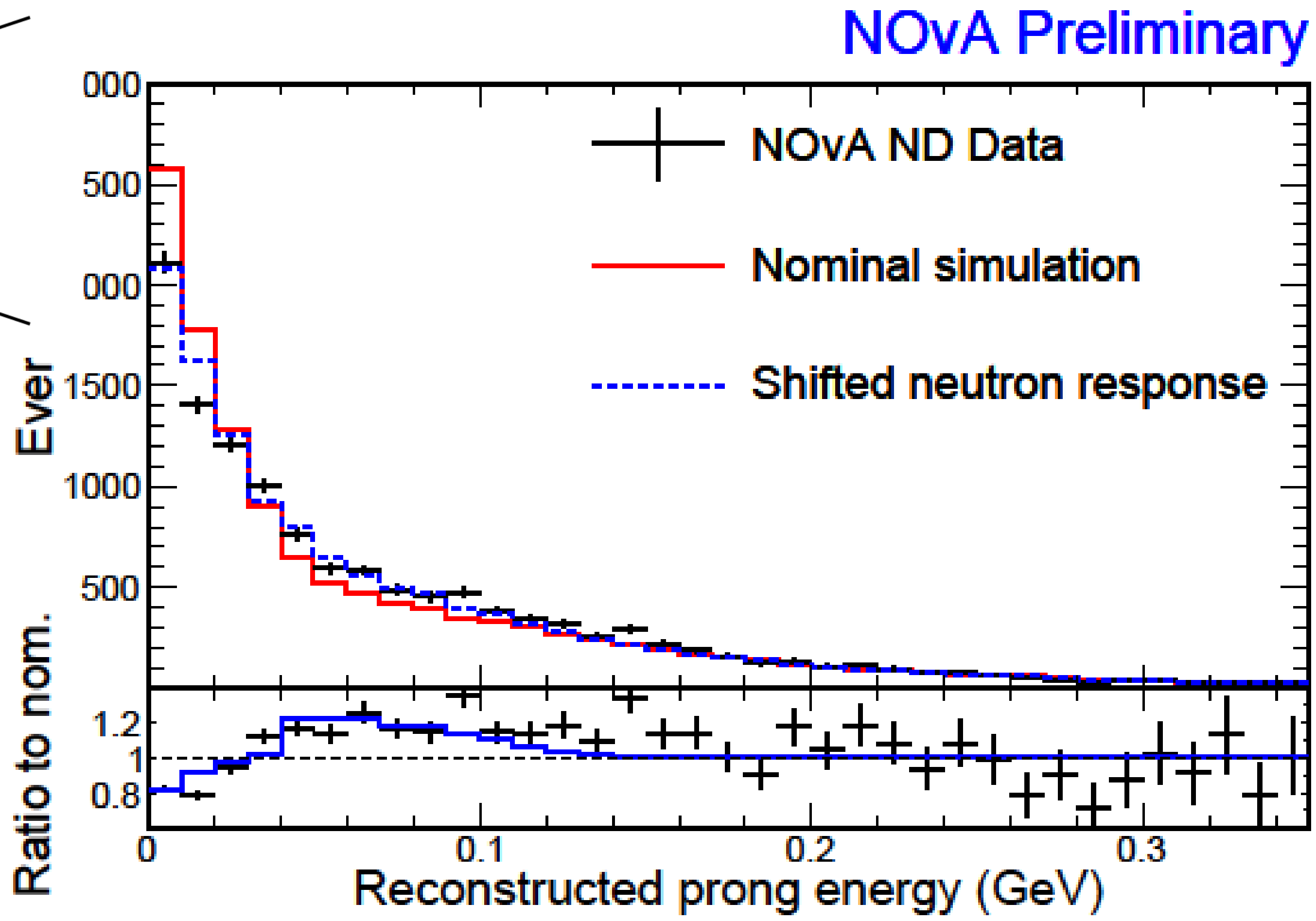


New systematic introduced: scales the amount of deposited energy up for some neutrons

Neutron Response



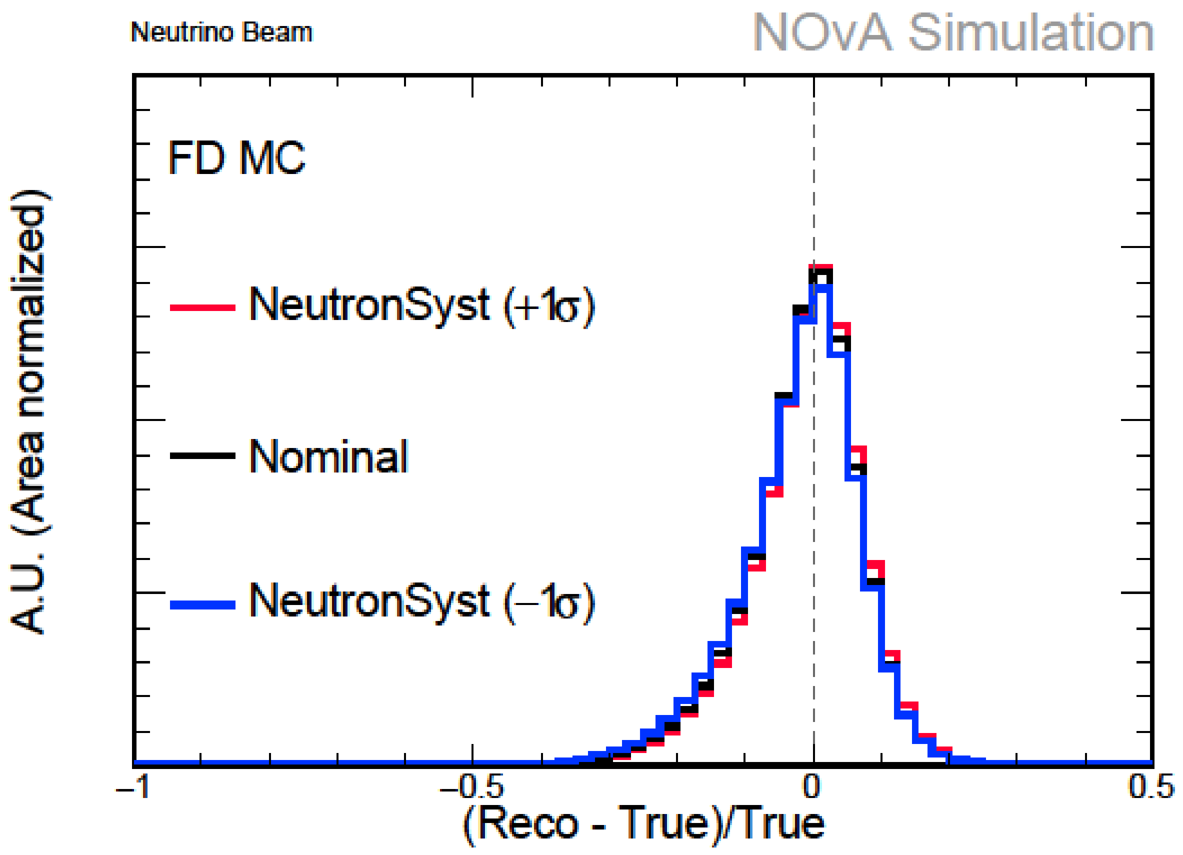


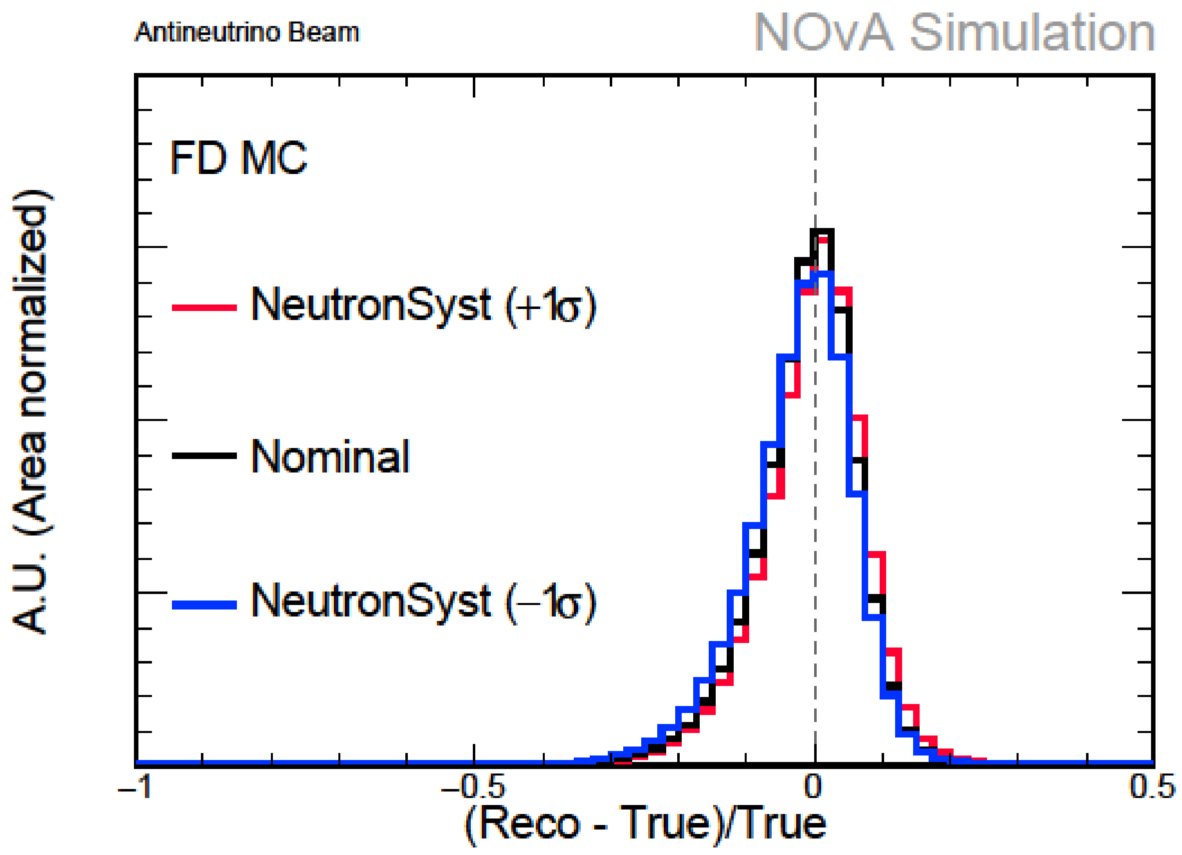


- Anti-neutrino data has increased importance of understanding neutron response
- In selected samples, neutrons show softer spectrum than simulated

New systematic introduced: scales the amount of deposited energy up for some neutrons

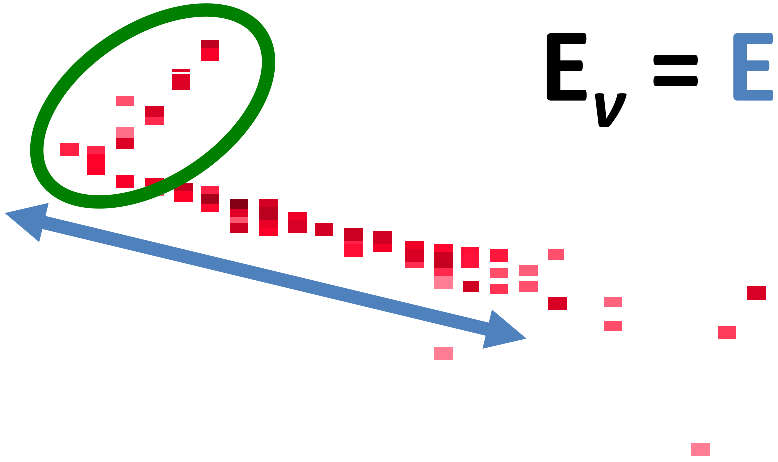
Impact of Neutron Response





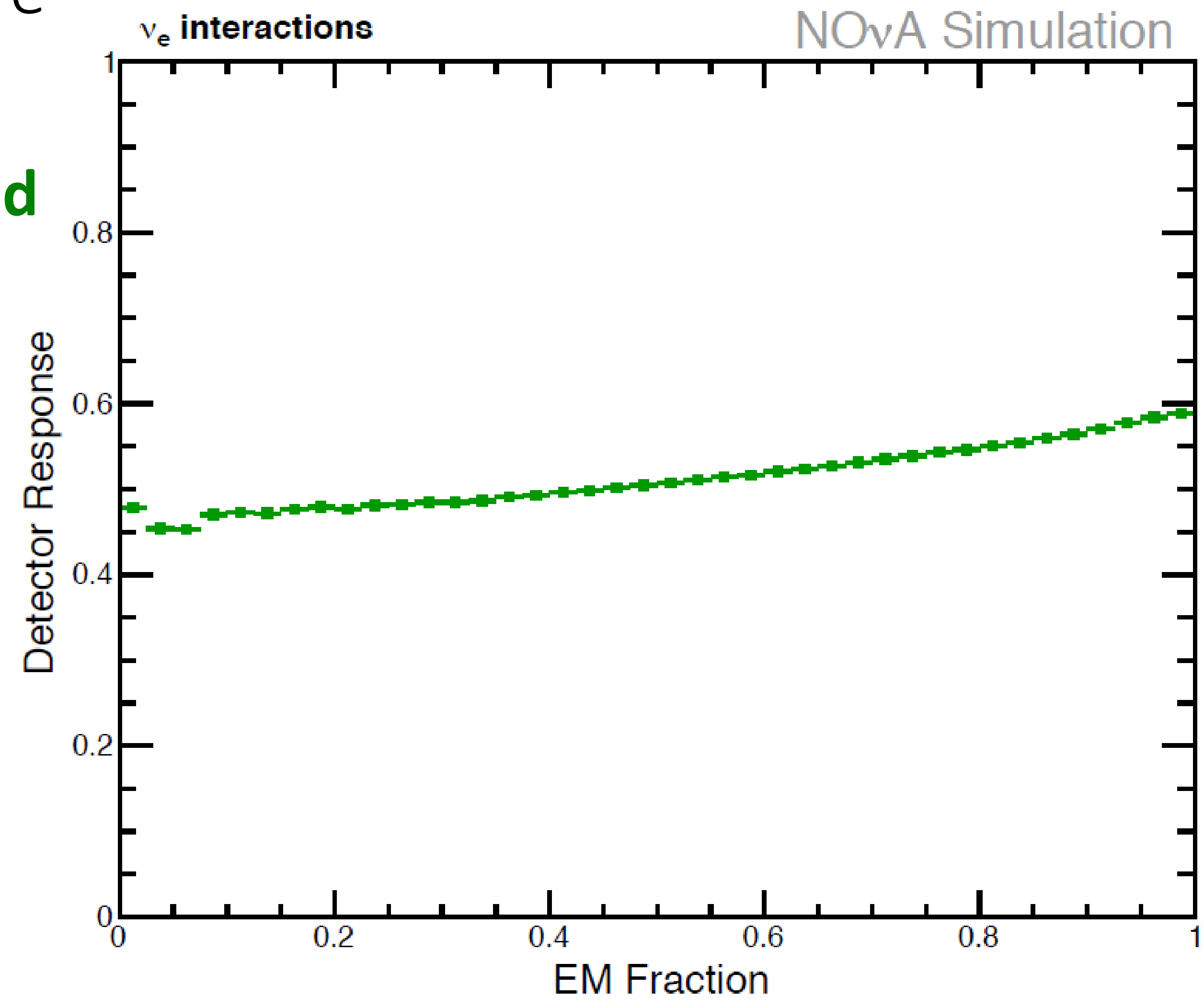
Shifts mean energy by 1% in anti-neutrino mode, 0.5% in neutrino mode
Negligible impact on selection efficiency

Energy Estimation - ν_e

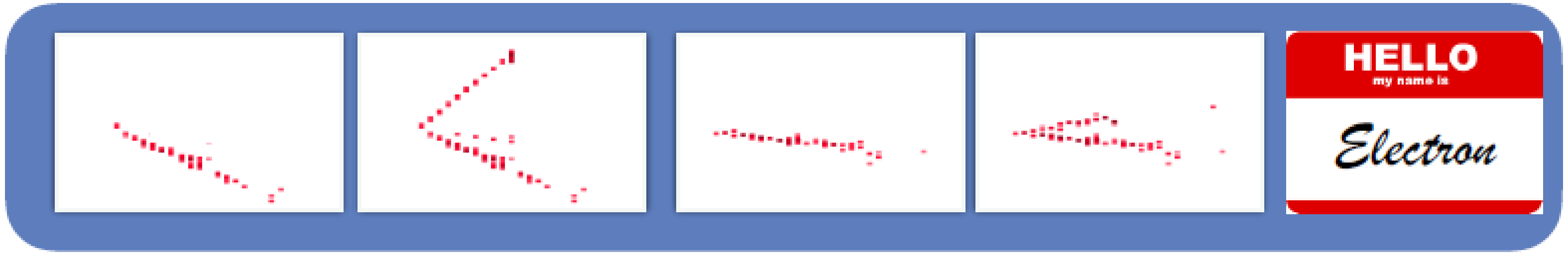


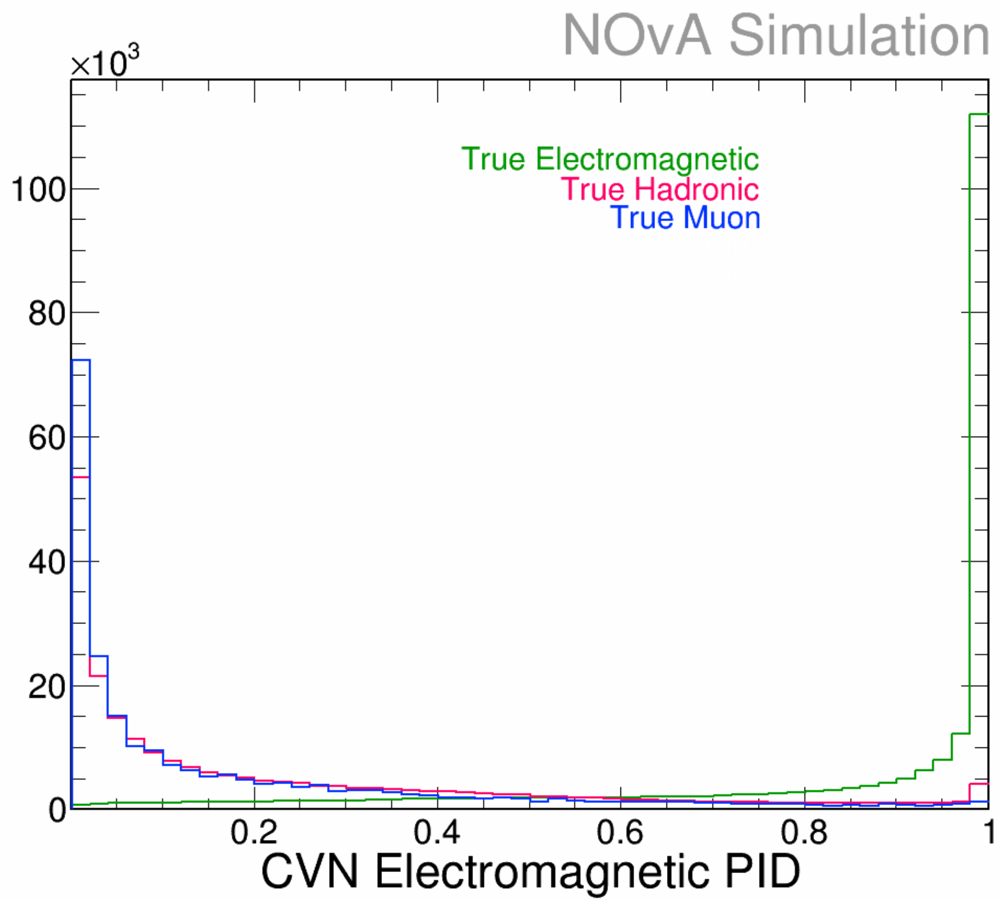
$$E_\nu = E_{EM} + E_{had}$$

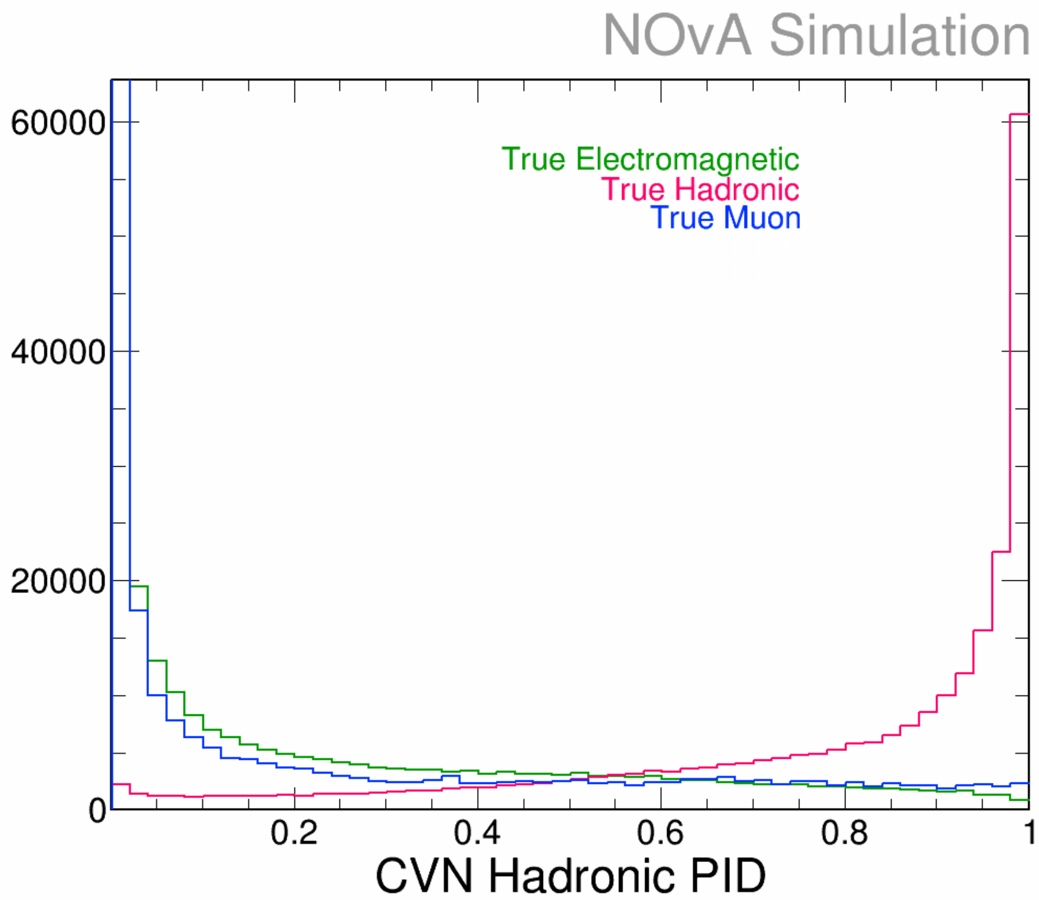
- Detector response is different for EM energy and hadronic energy
- To take this into account we separate the EM and hadronic depositions



Particle Identification



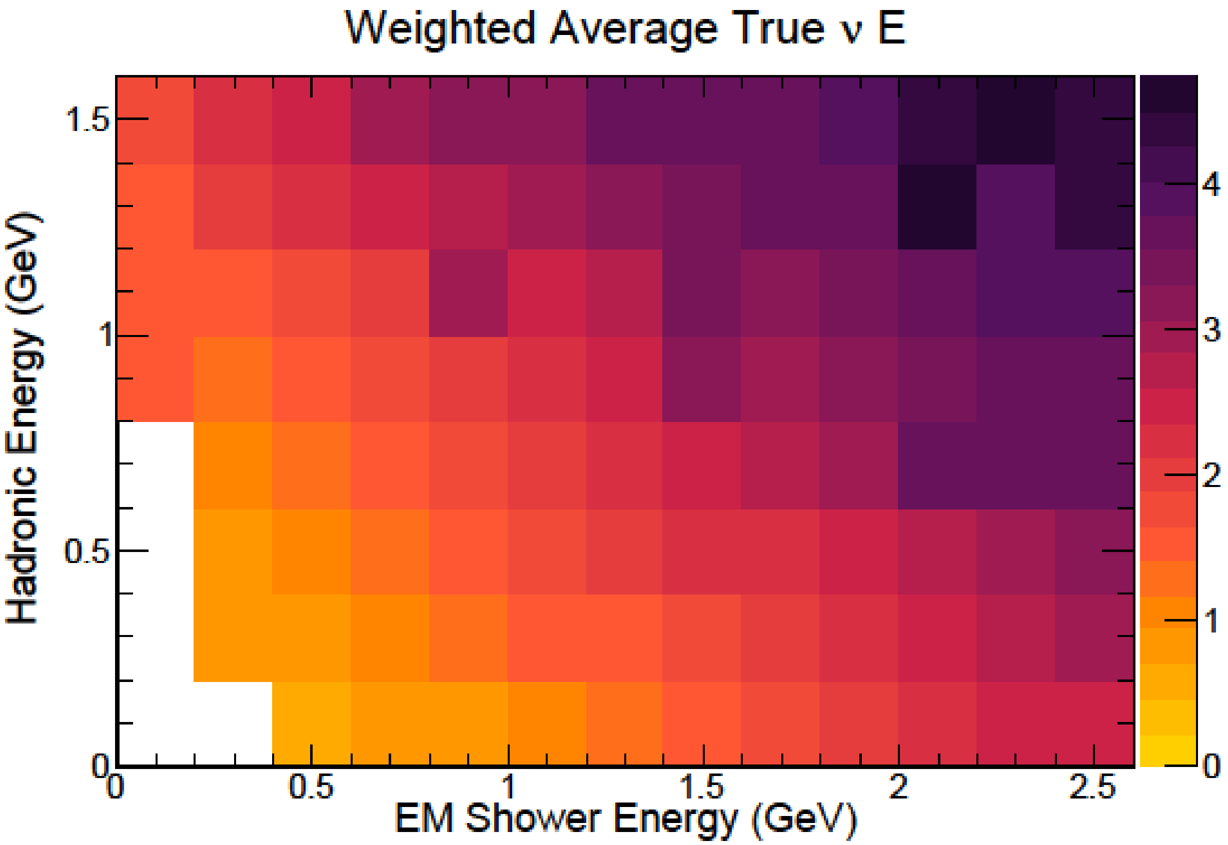




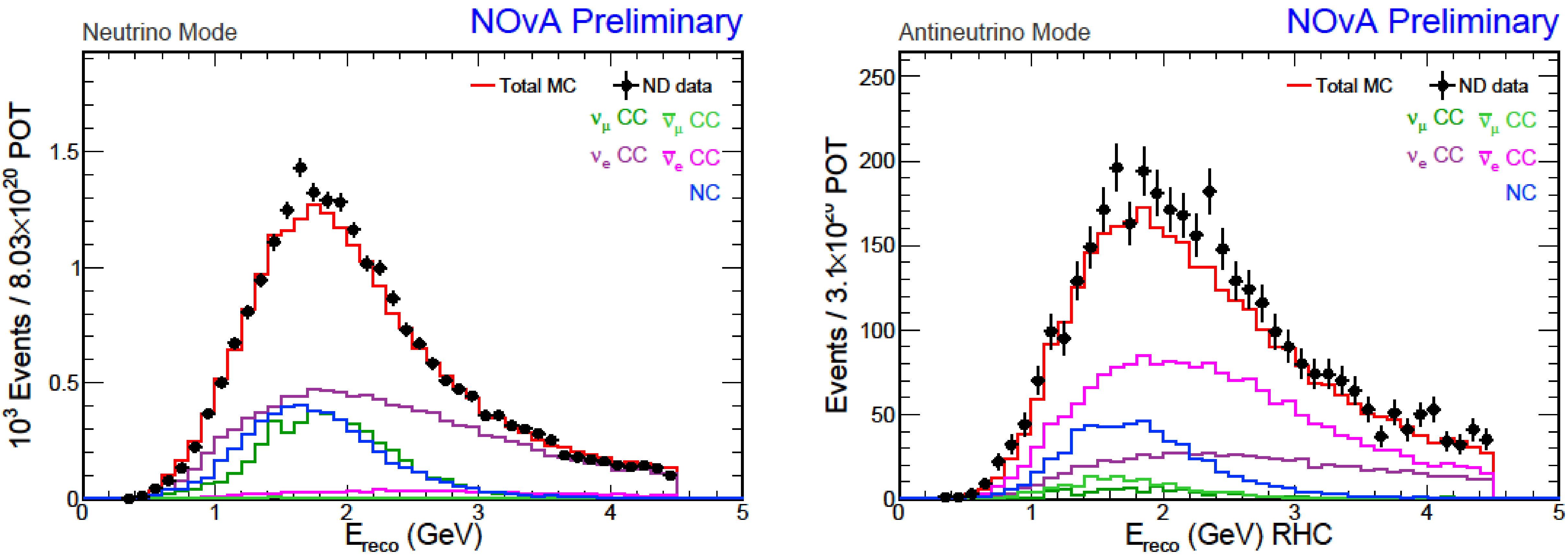
Energy Estimation - ν_e

- Electromagnetic energy is the summed calorimetric energy for CVN-selected showers.
- Hadronic energy is the total calorimetric energy minus EM shower energy.
- Neutrino energy is calculated as the following:

$$E_{\nu e} = A*E_{EM} + B*E_{HAD} + C*E_{EM}^2 + D*E_{HAD}^2$$

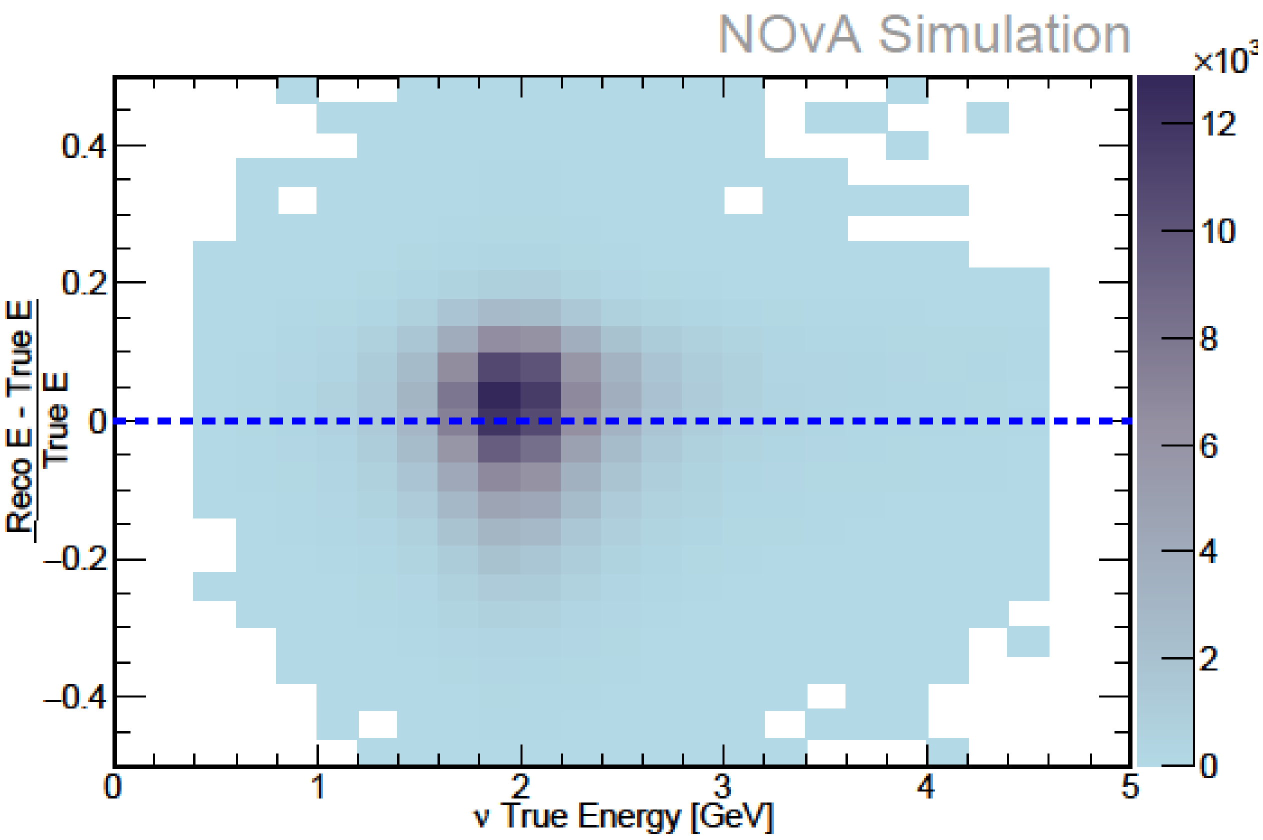


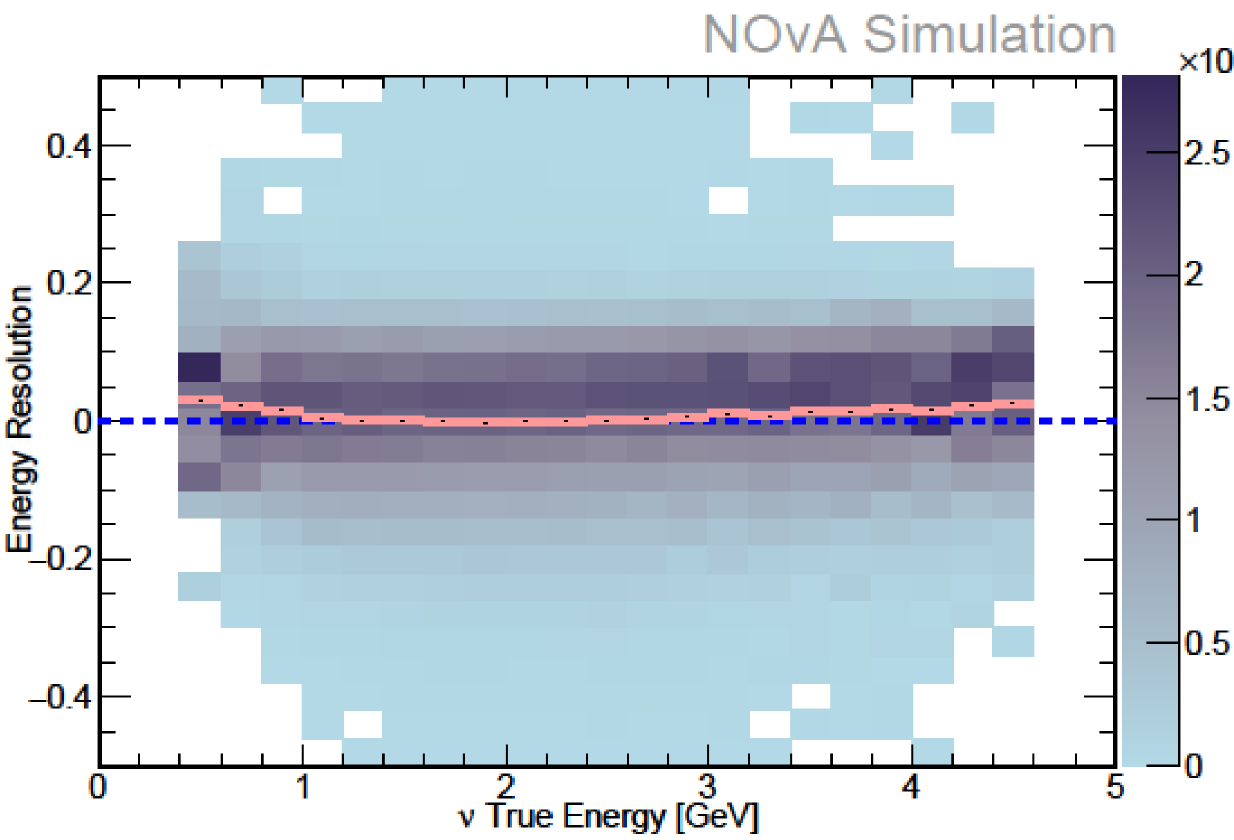
Near Detector ν_e



All beam ν_e – nothing from appearance

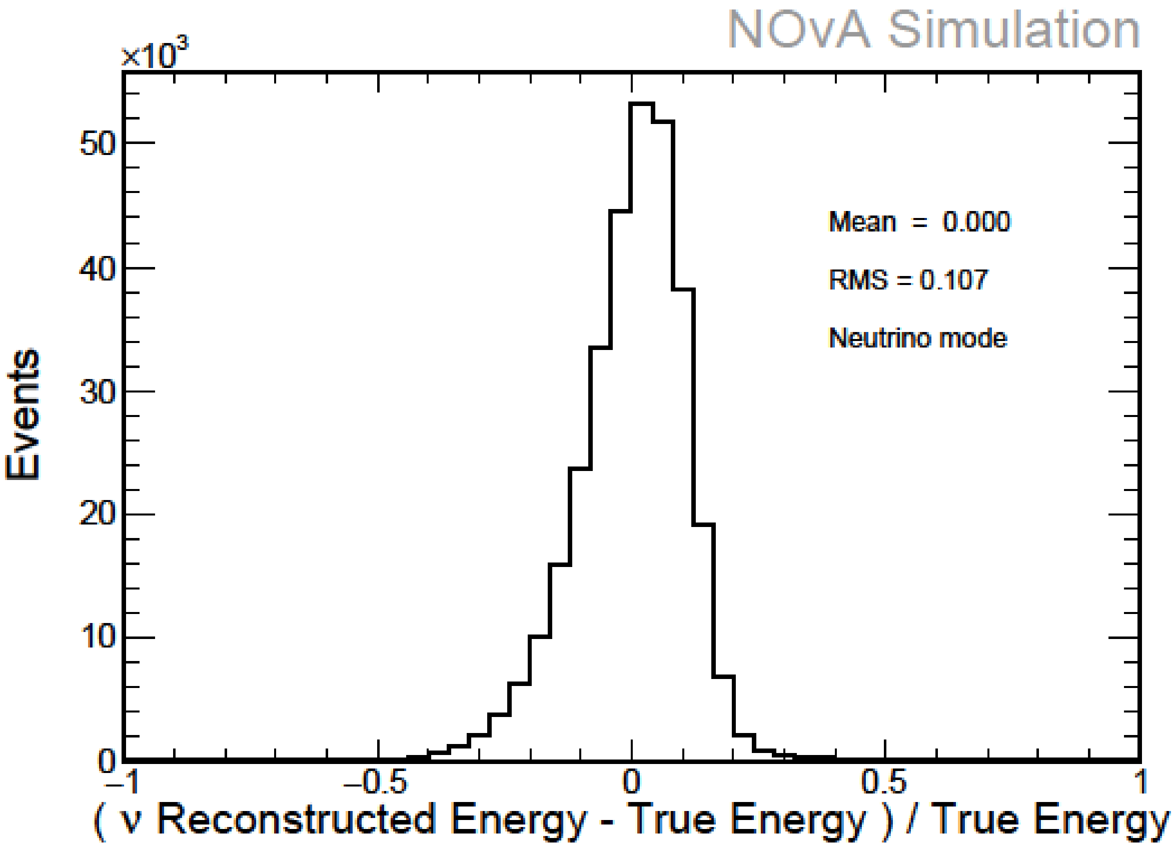
Energy Resolution - ν_e

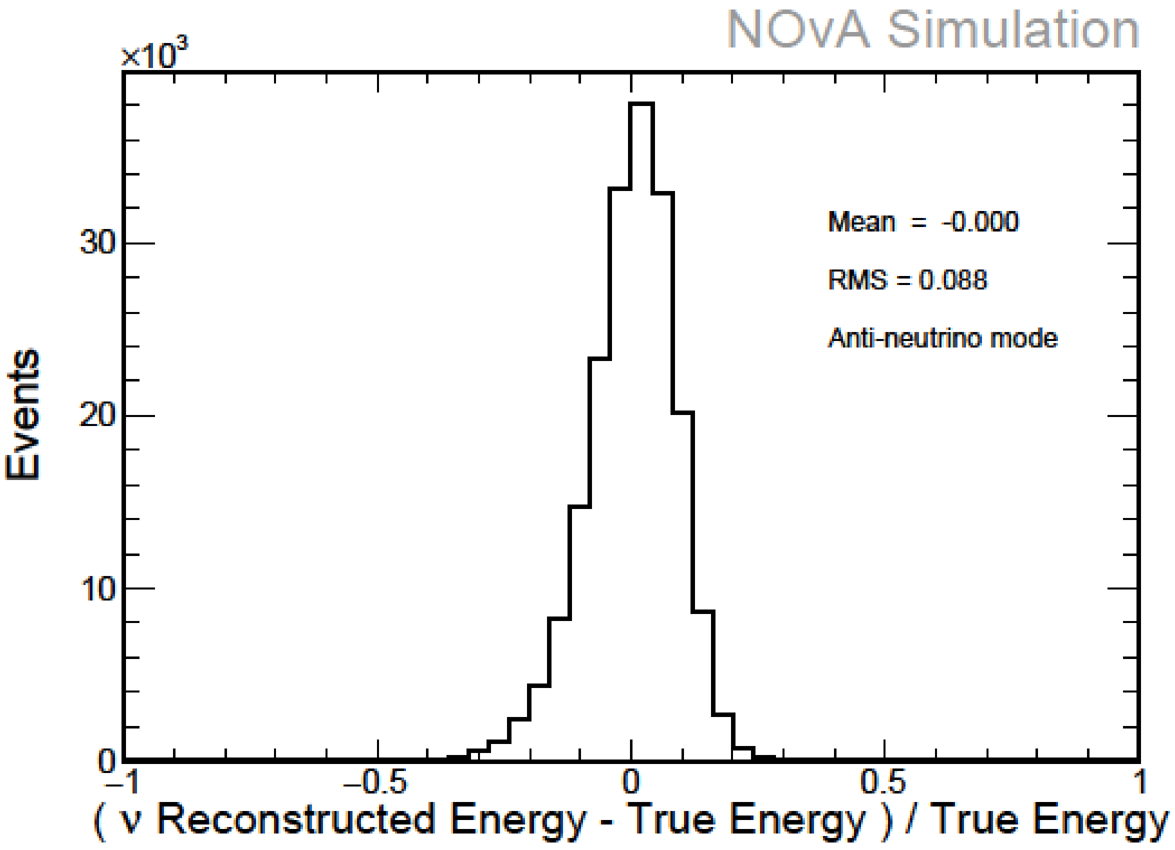




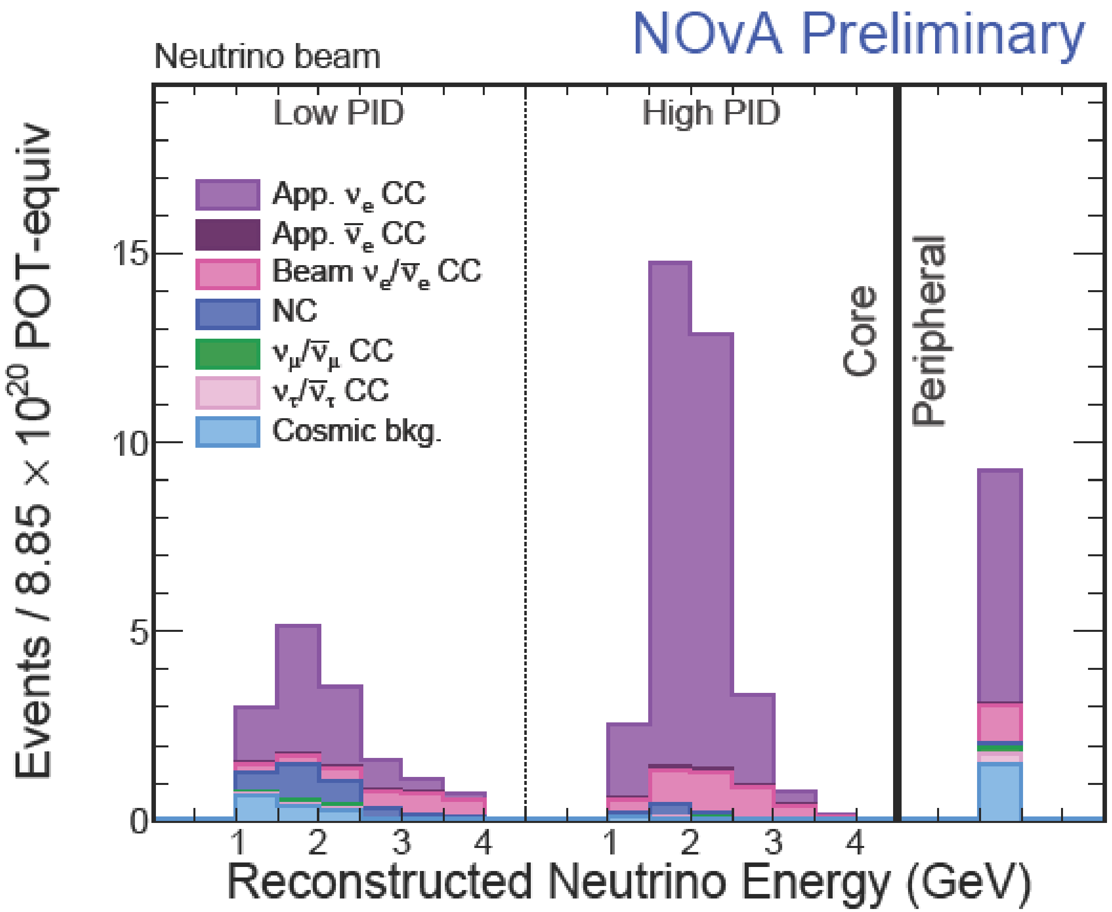
- events are weighted by a function that flattens the true energy spectrum implicit in the simulation
- this minimizes bias between 1-4 GeV

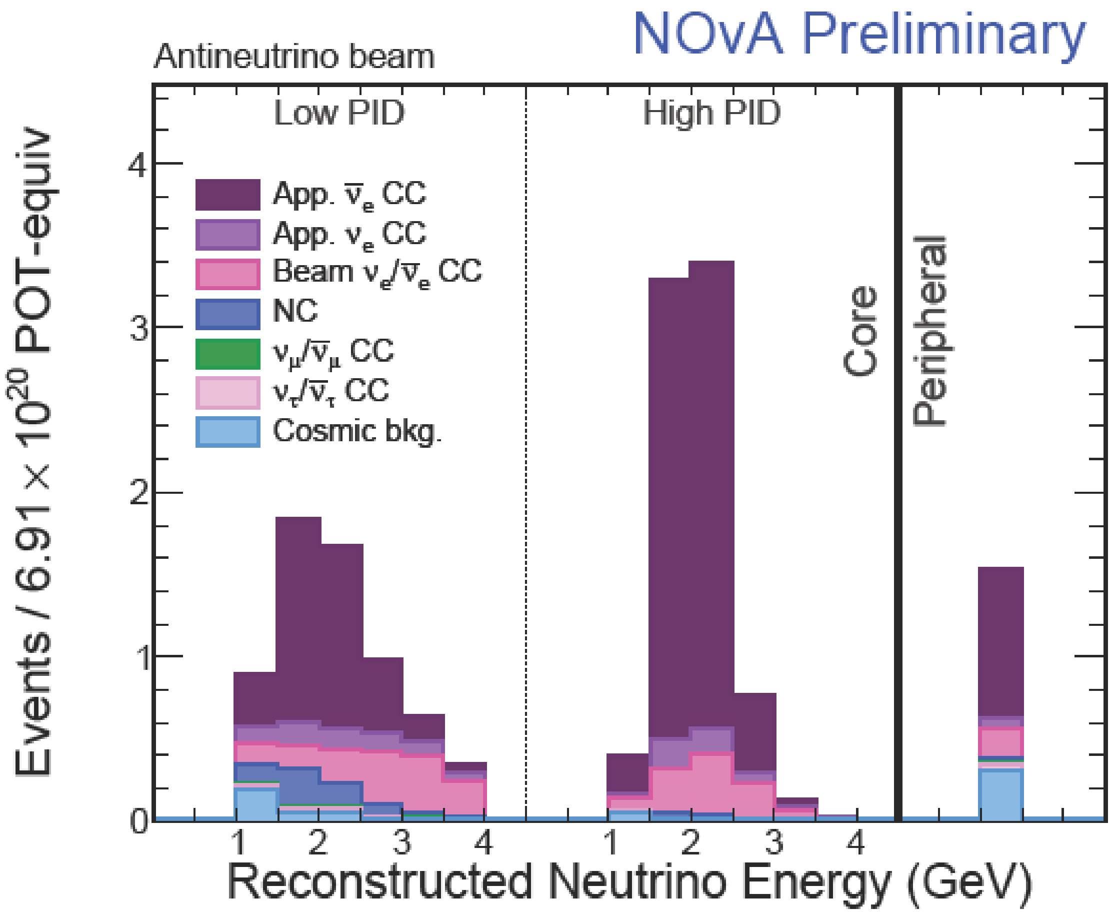
Energy Resolution - ν_e





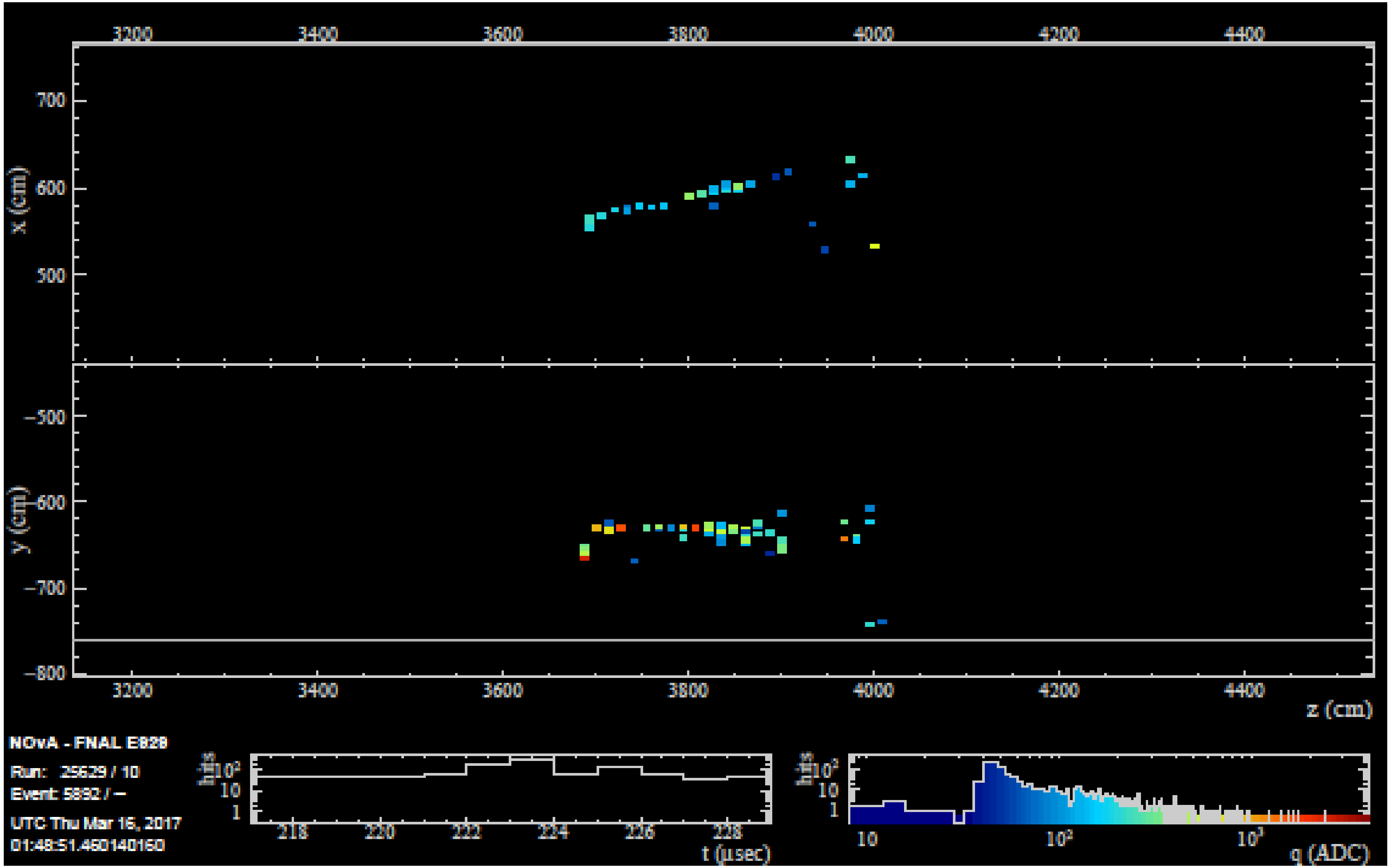
Optimizing Binning



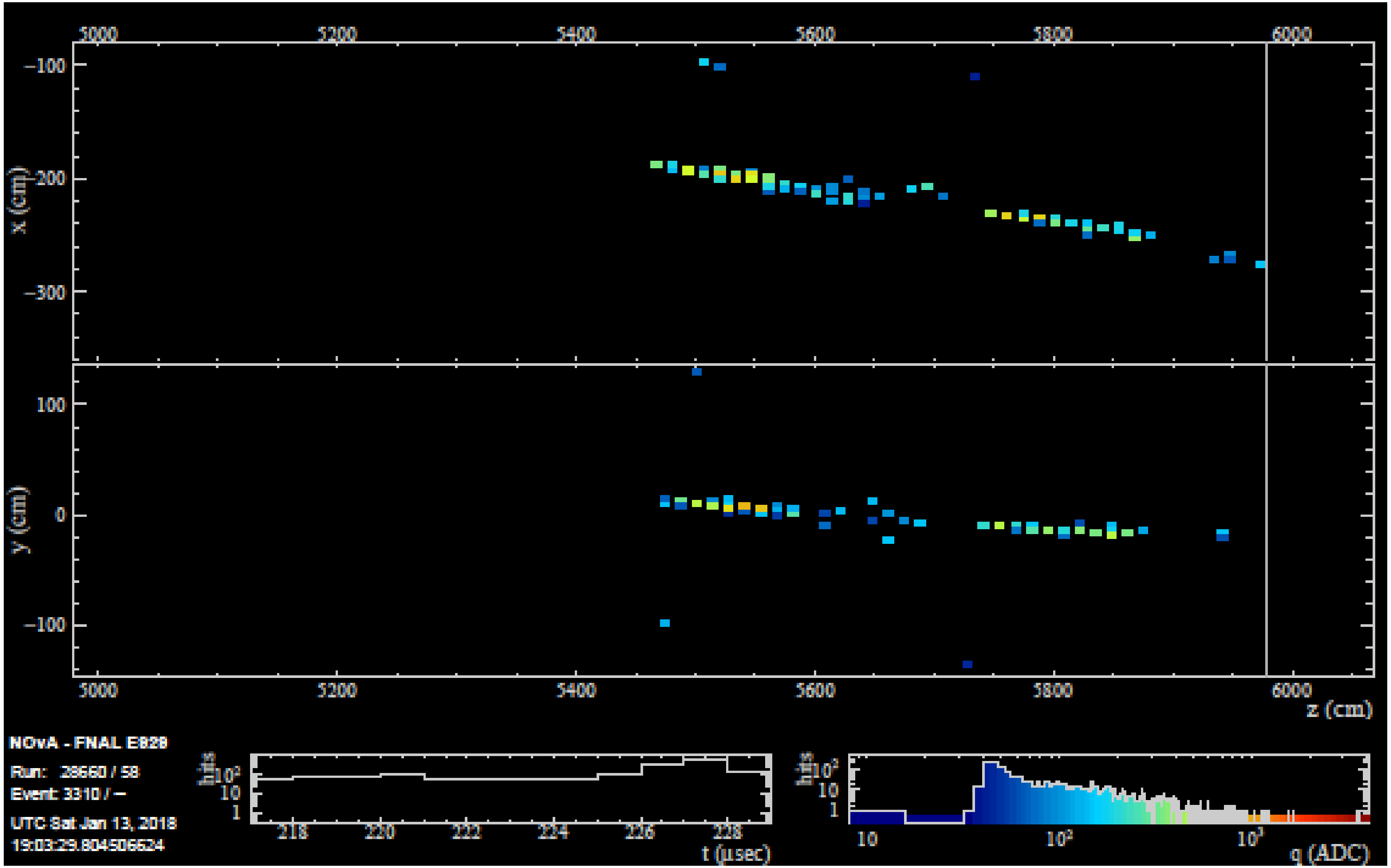


- Oscillation sensitivity depends on separating ν_e signal from background
- PID binning separates sample by purity
- Energy binning separates appeared ν_e from beam ν_e

Core Event – High CVN bin

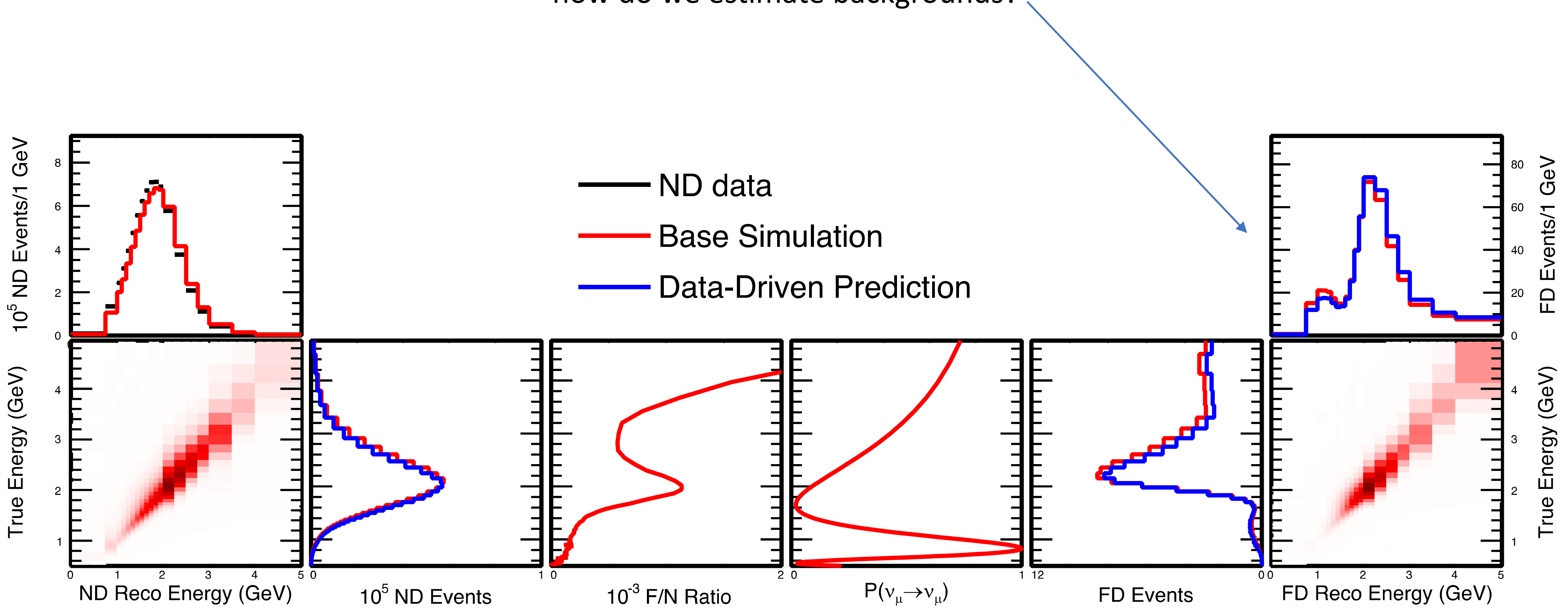


Peripheral Event

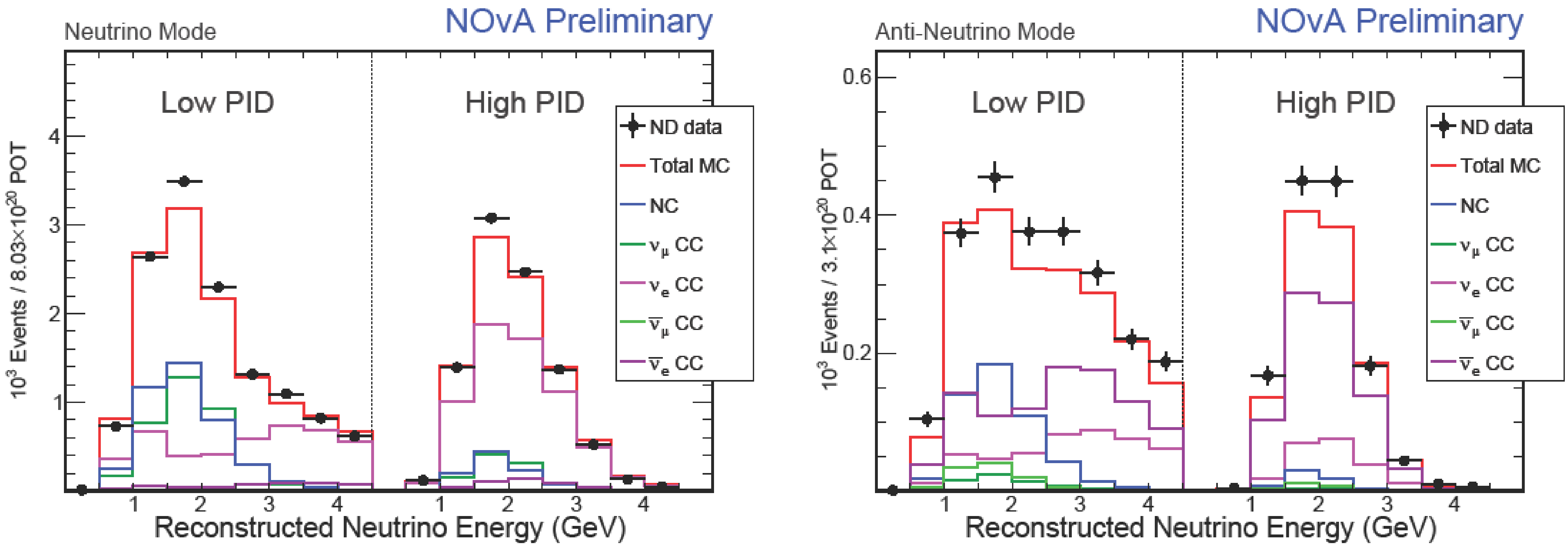


Near Detector Decomposition

how do we estimate backgrounds?

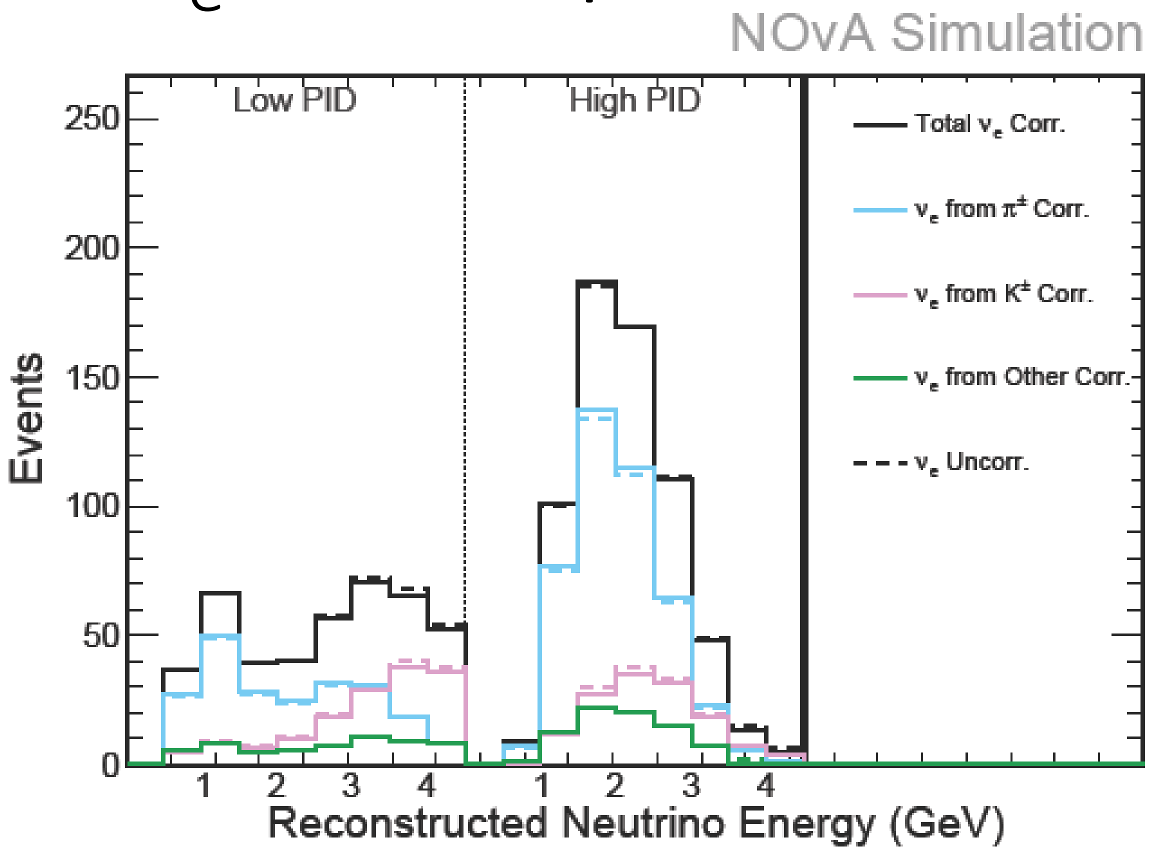


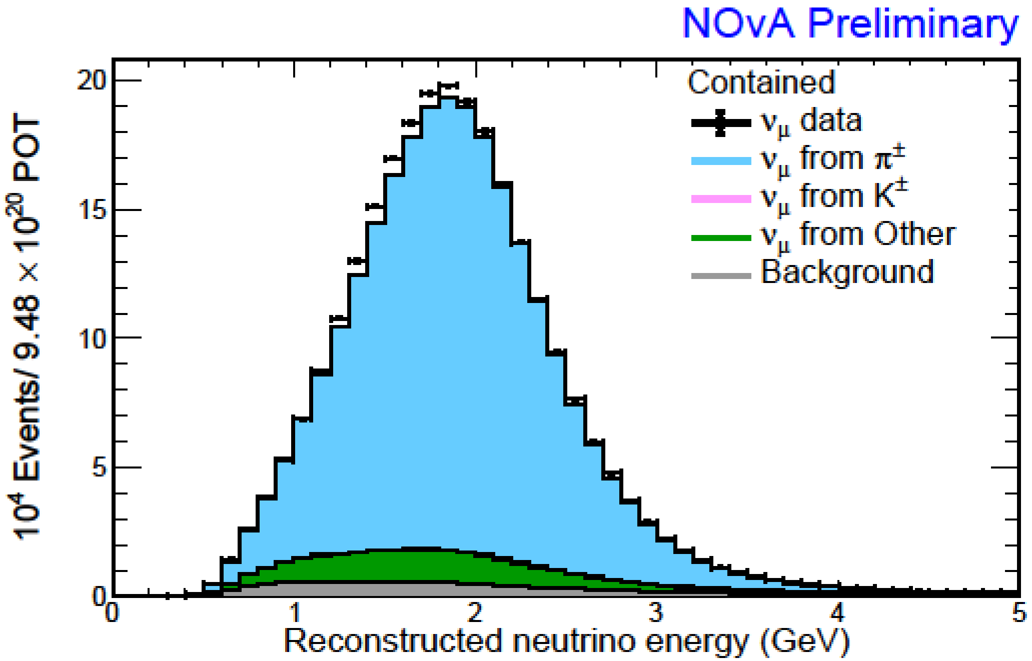
Near Detector ν_e Spectra

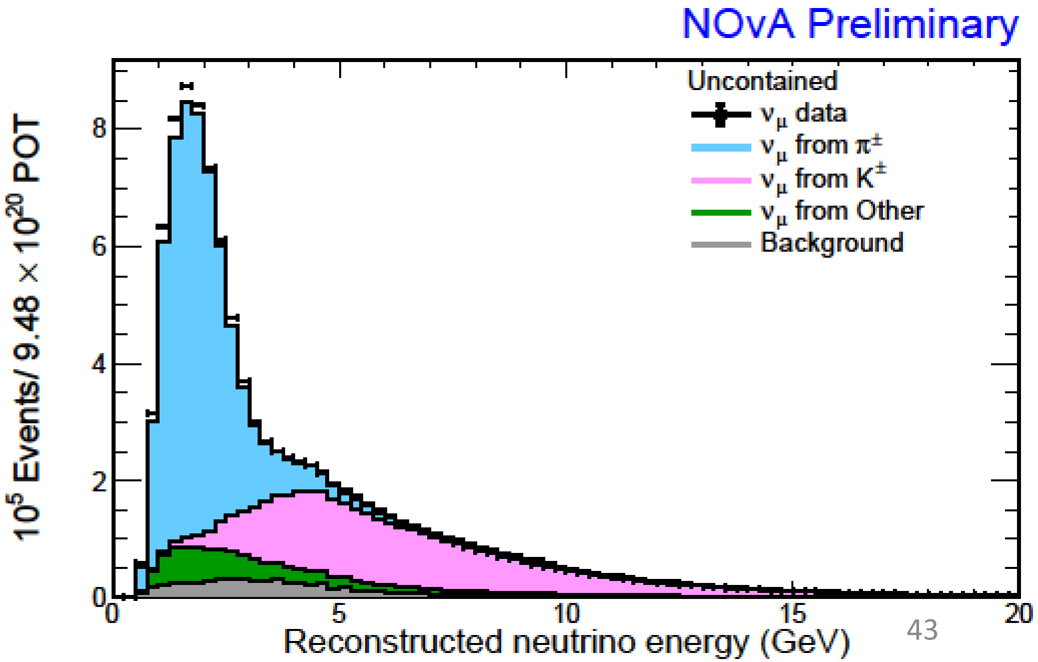


- To constrain backgrounds we use two data-driven techniques for the neutrino beam
- For the anti-neutrino beam we scale all components proportionally but plan to implement the data-driven techniques in future analyses.

ν_e Decomposition



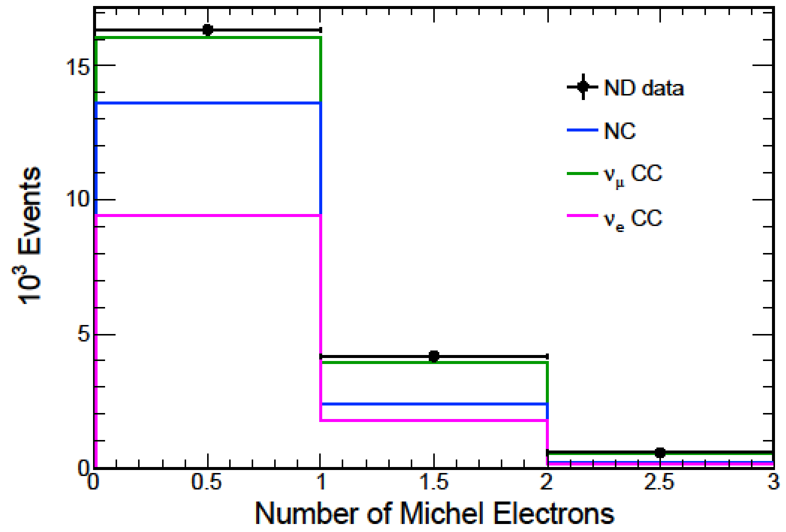


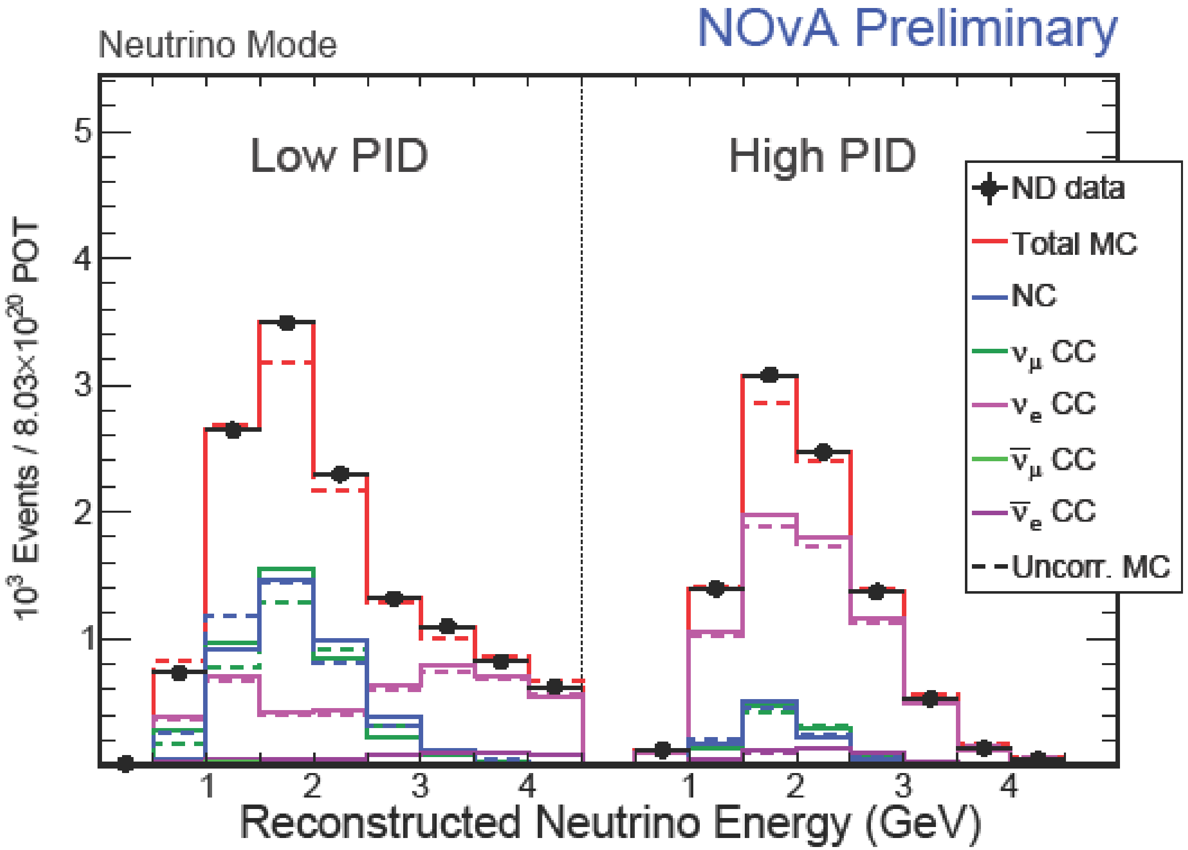


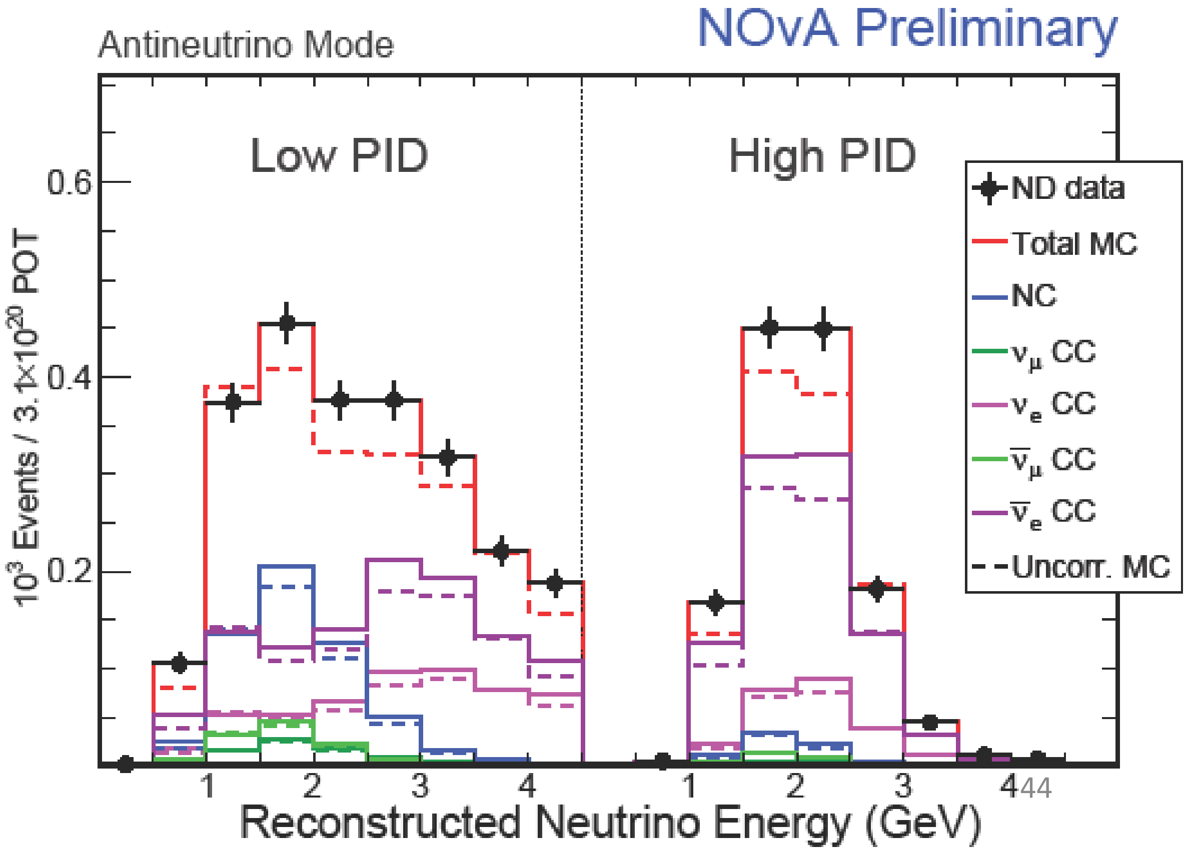
- ν_e and ν_μ have the same parents
  - Lower energy from pion decay
  - Higher energy from kaon decay
- Use contained ν_μ data to constrain pion flux
- Higher energy uncontained events constrain kaon flux

ν_e Decomposition

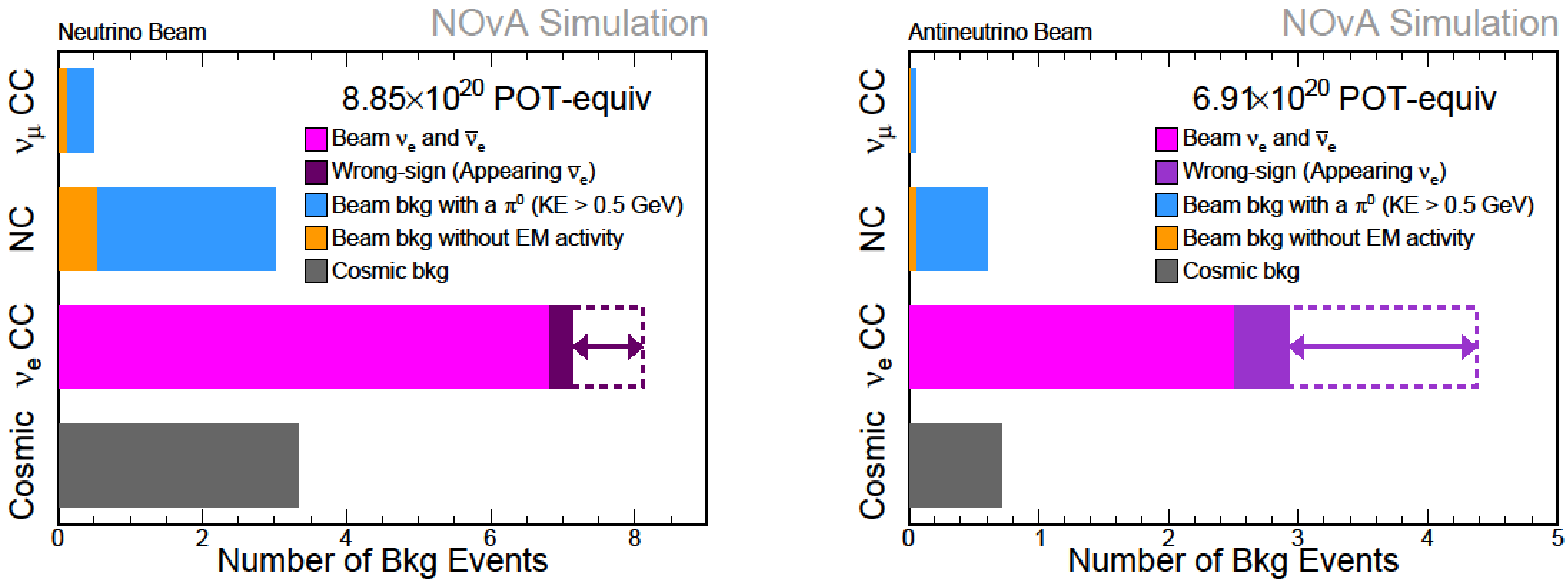
- CC/NC ratio determined by number of observed Michel electrons
  - Done separately in each bin of PID and energy







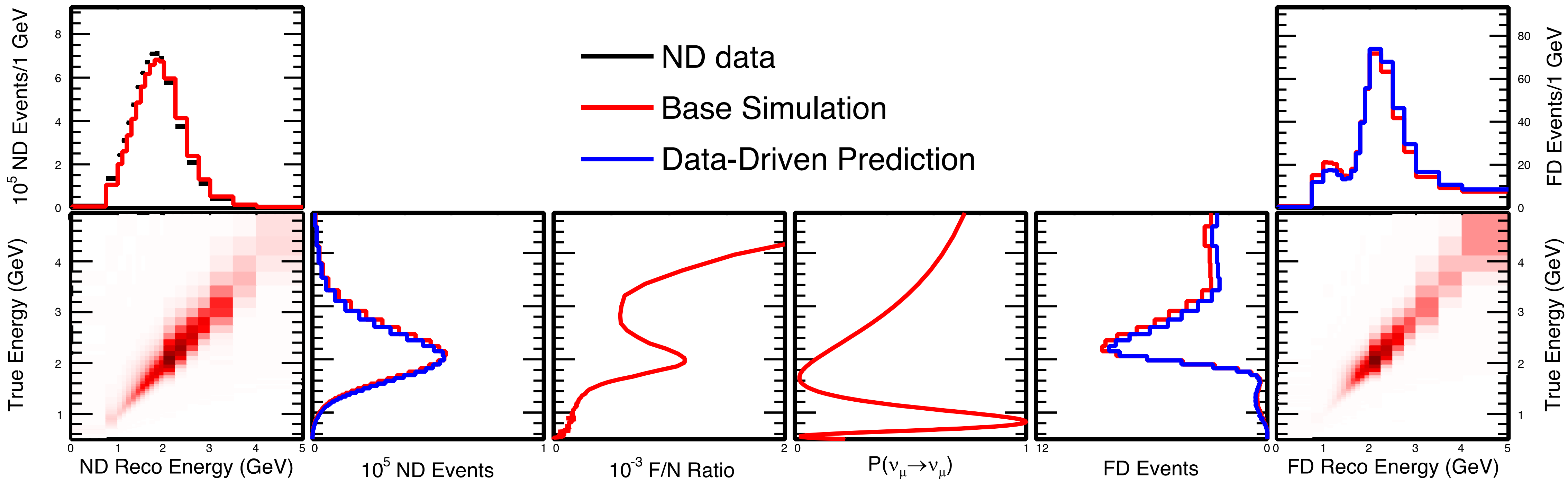
ν_e Background at the Far Detector



- 14.7 – 15.4 total ν_e background, 4.7 – 5.7 total $\bar{\nu}_e$ background
  - Wrong sign depends on oscillation parameters

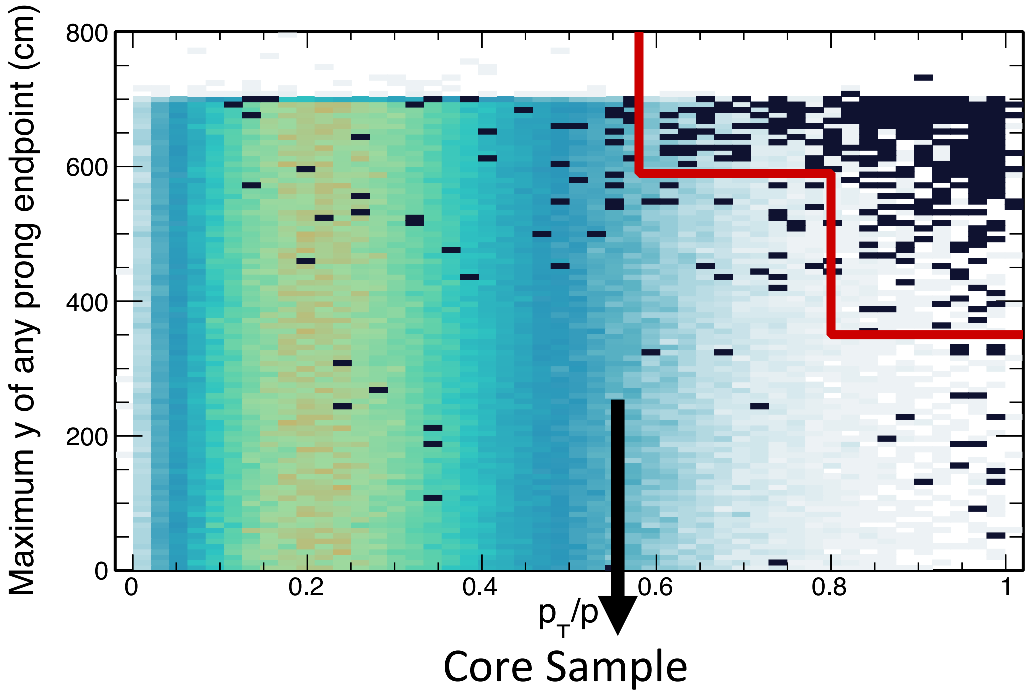
Additional Far Detector Event Selection

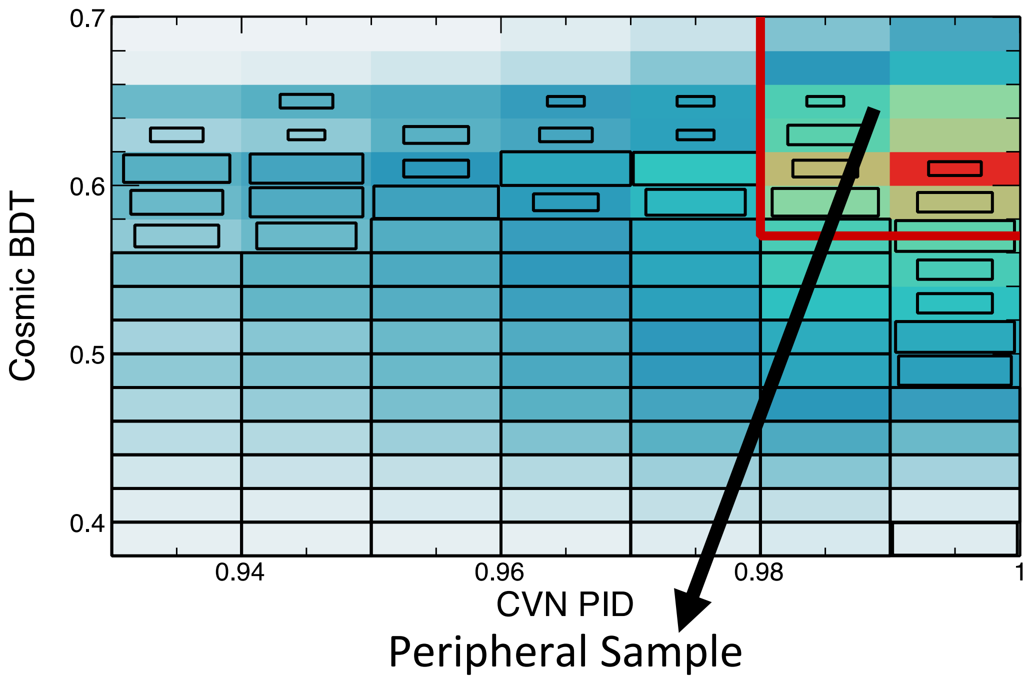
how do we select what goes into this spectrum?



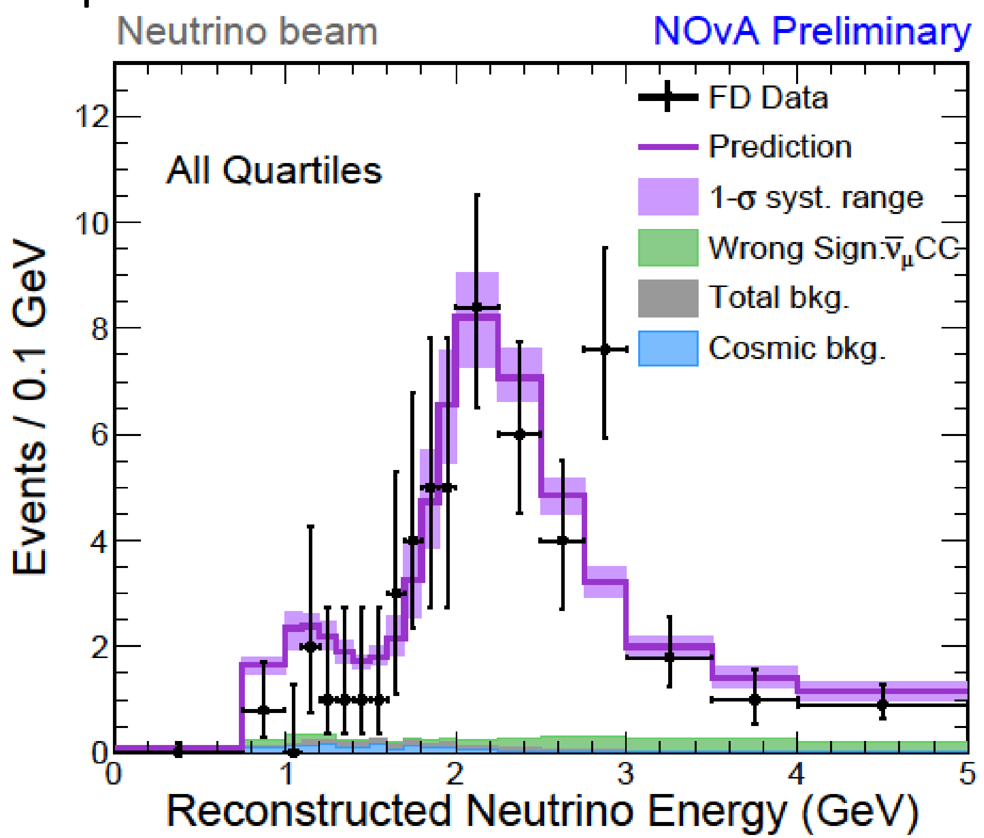
Cosmic Rejection

- Far Detector is on the surface – 11 billion cosmic rays / day
- 10^7 rejection power needed after timing cuts
- ν_μ sample uses BDT based on:
  - Track length and direction, distance from top/sides, fraction of hits in muon, CVN
- ν_e does this in two steps
  - Core sample: require contained, beam-directed events, away from the top of the detector
  - Peripheral sample: events failing core selection can pass a BDT + tight CVN cut

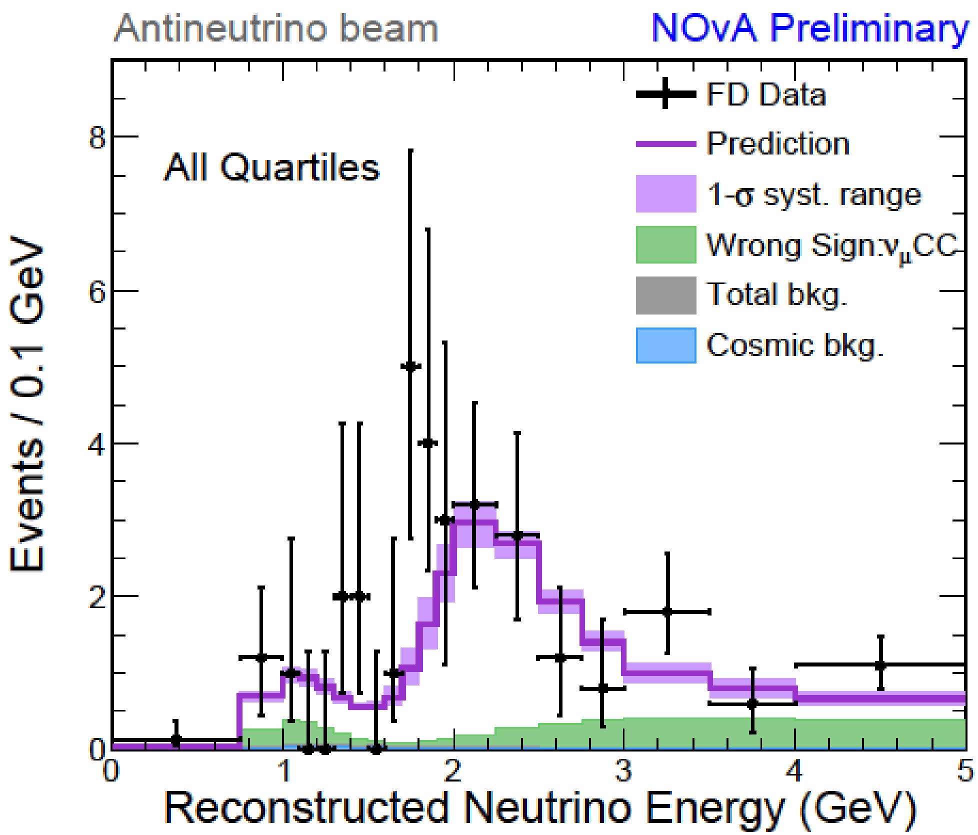




ν_μ at the Far Detector

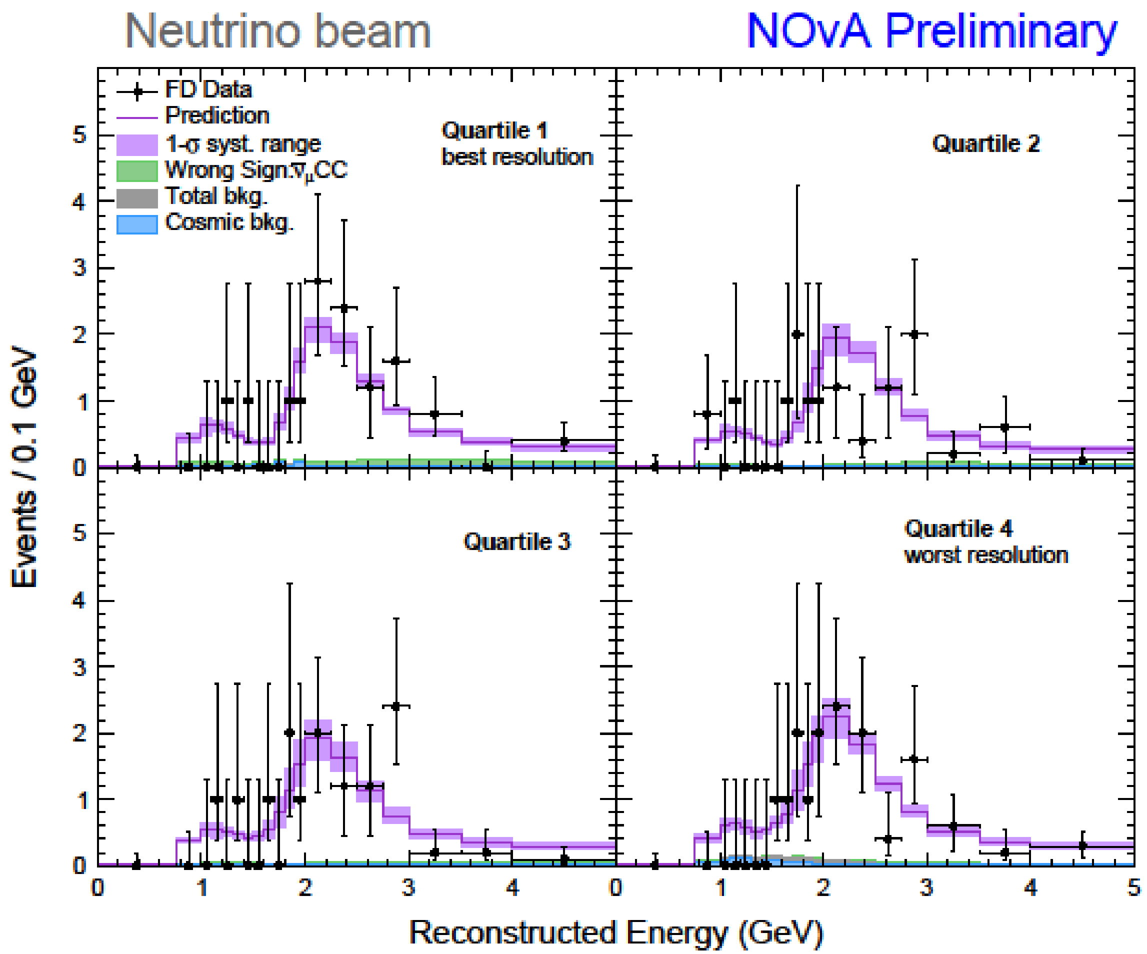


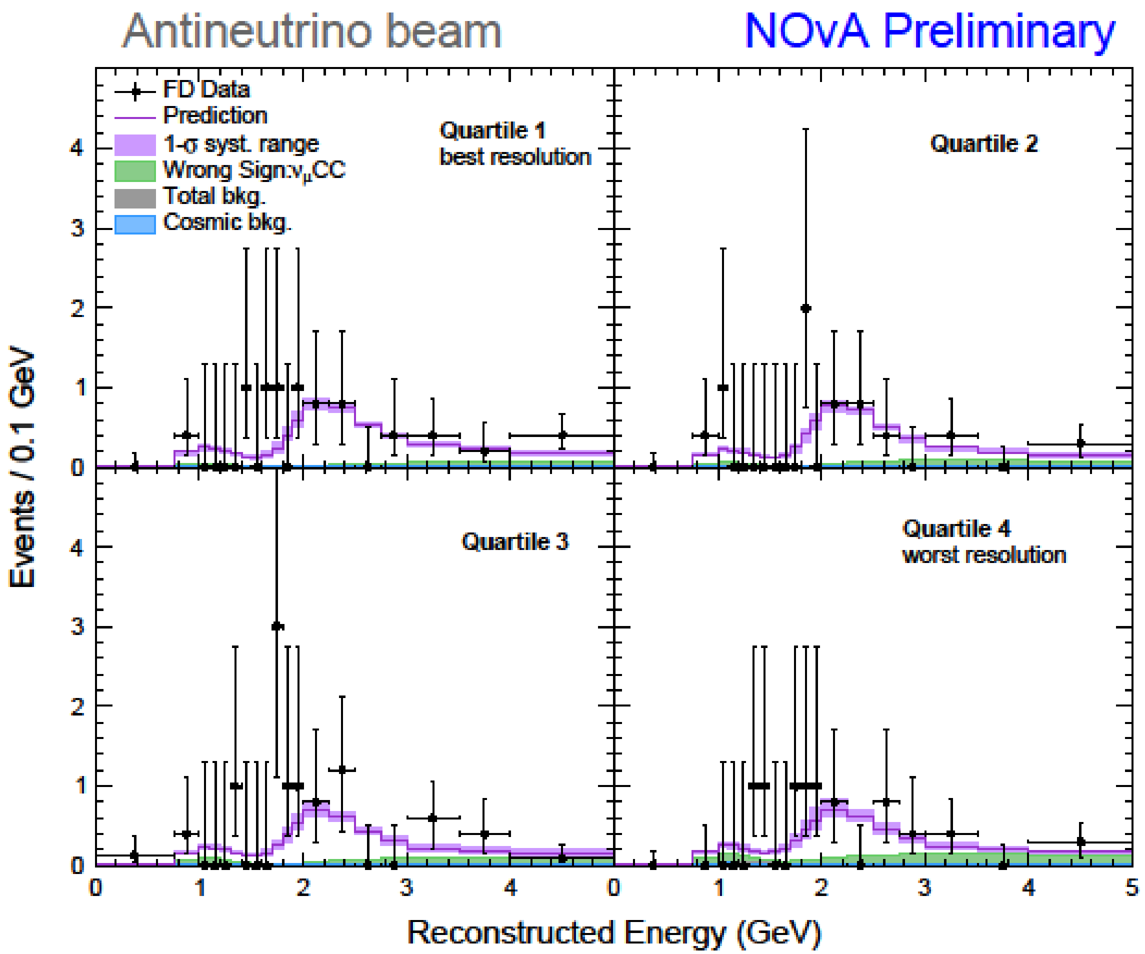
Total Observed	113
Best fit prediction	121
Cosmic Bkgd.	2.1
Beam Bkgd.	1.2
Unoscillated	730

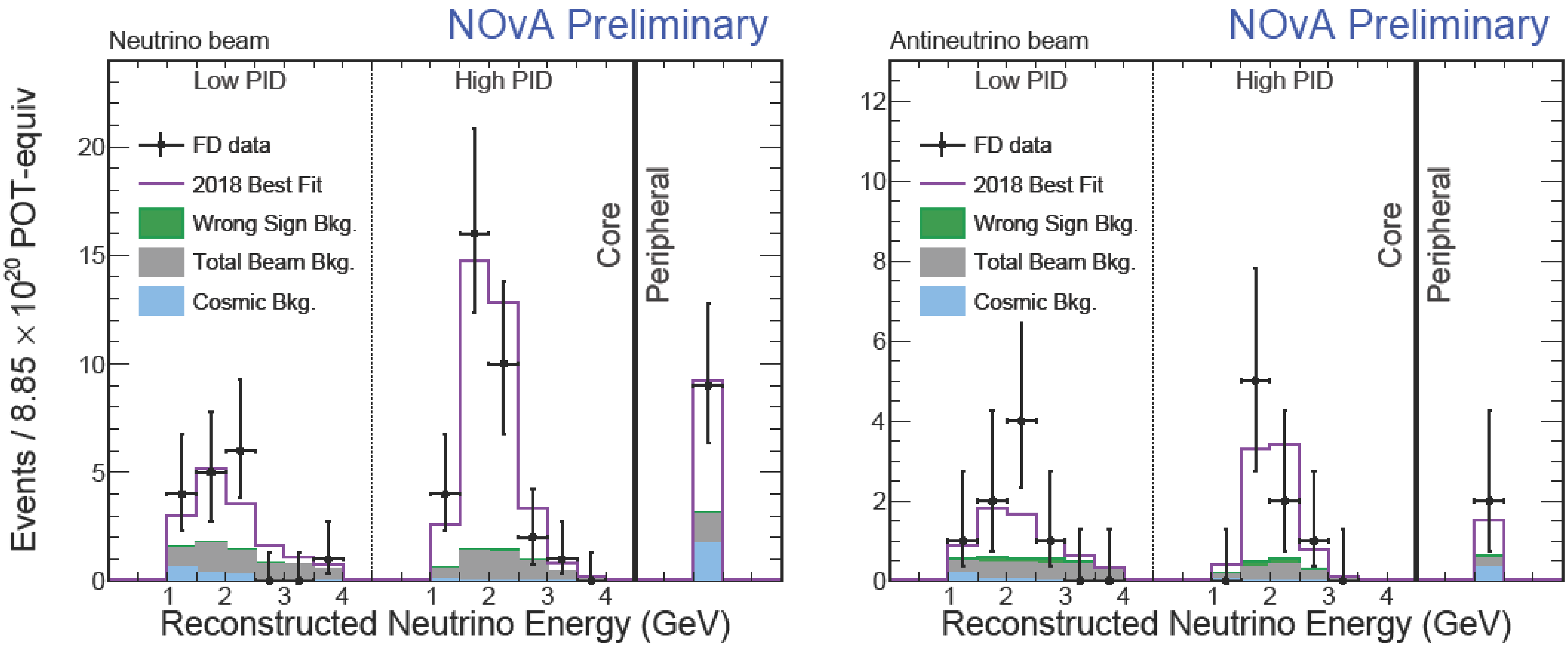


Total Observed	65
Best fit prediction	50
Cosmic Bkgd.	0.5
Beam Bkgd.	0.6
Unoscillated	266

ν_μ at the Far Detector







- Neutrino beam:
  - Observe 58 events, expect 15 background events
- Anti-neutrino beam
  - Observe 18 events, expect 5.3 background events
- > 4σ $\bar{\nu}_e$ appearance

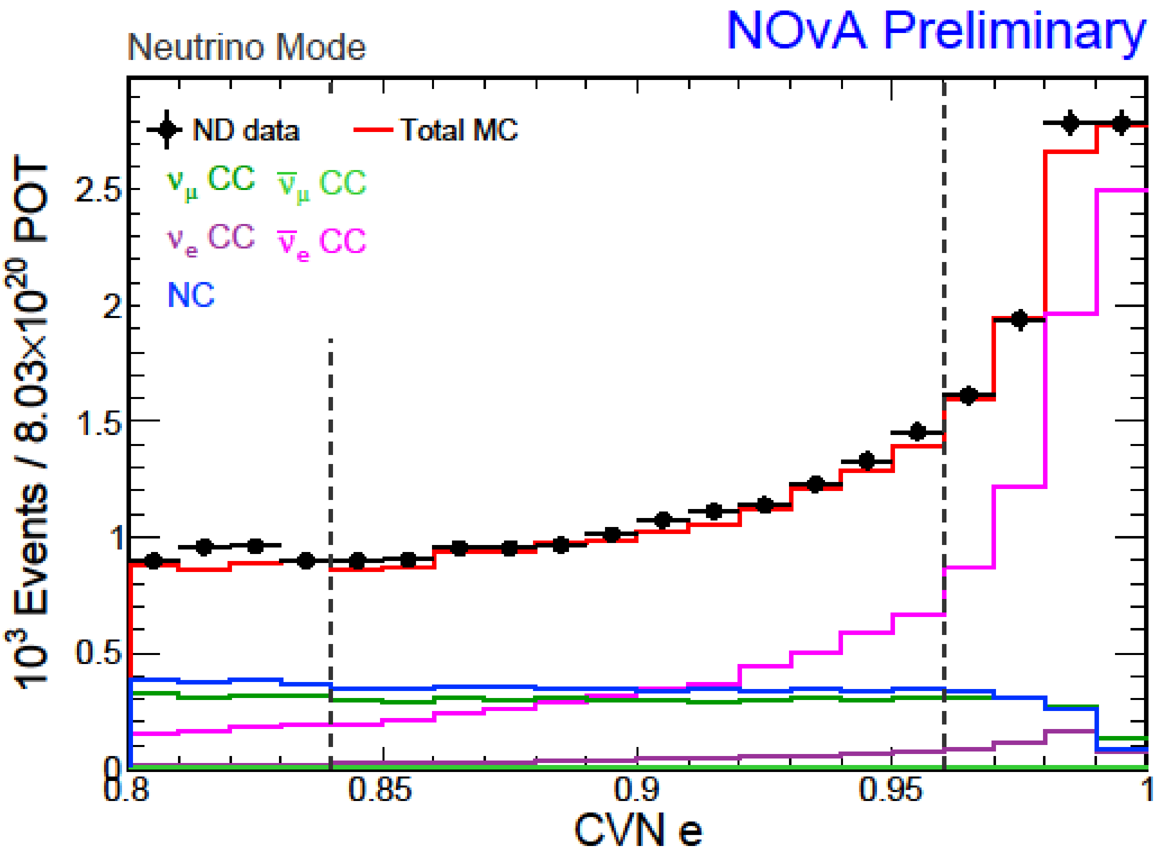
Summary

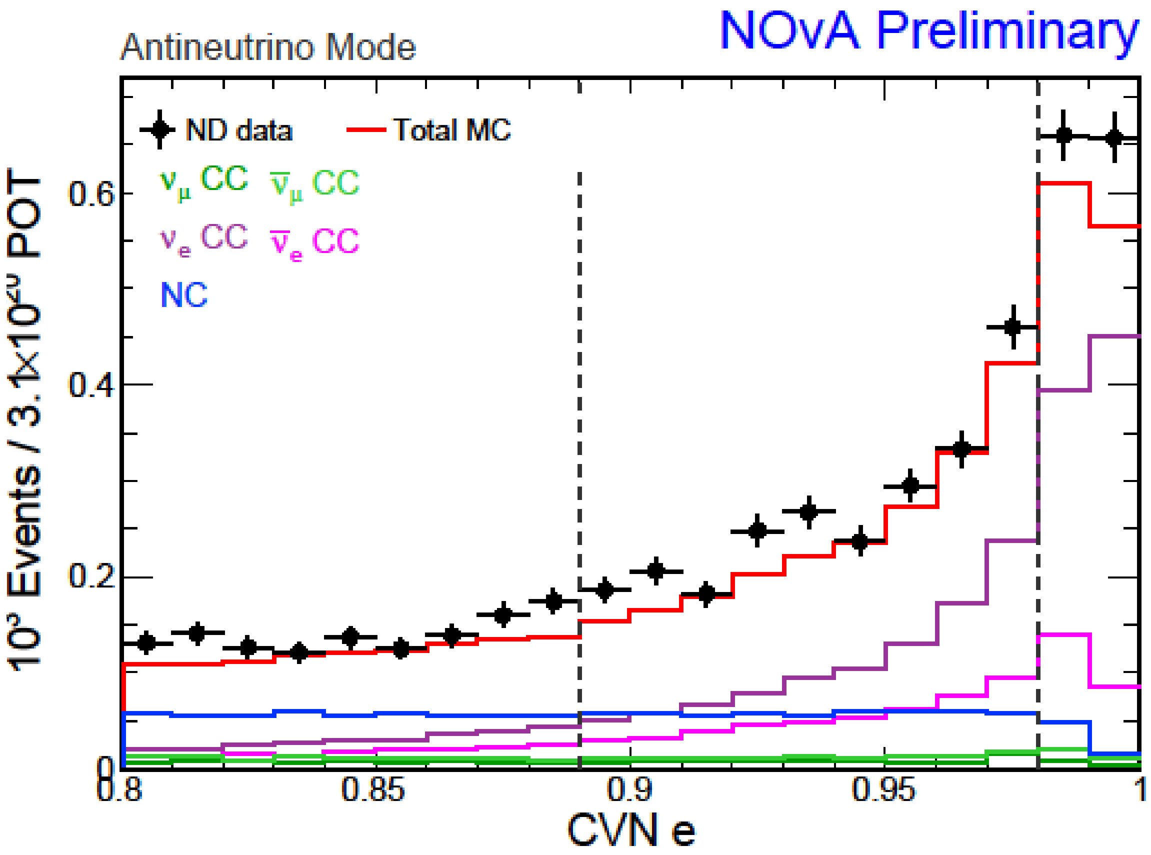
- New challenges in anti-neutrino mode!
- Can’t cover it all – see:
  - Neutrino Physics with Deep Learning on NOvA – F. Psihas, poster 206
  - The NOvA Test Beam Program – A. Sutton, poster 205
  - NOvA Cross Section Results – M. Judah, WG2 71
  - NOvA Cross Section Model / Oscillation Needs – J. Wolcott, WG2 134
  - Sterile Neutrinos search via NC dis at NOvA – M. Wallbank, WG1+5 190
  - Results and Prospects from NOvA - J. Bian, plenary III 12

Thank you for your attention!

Backups

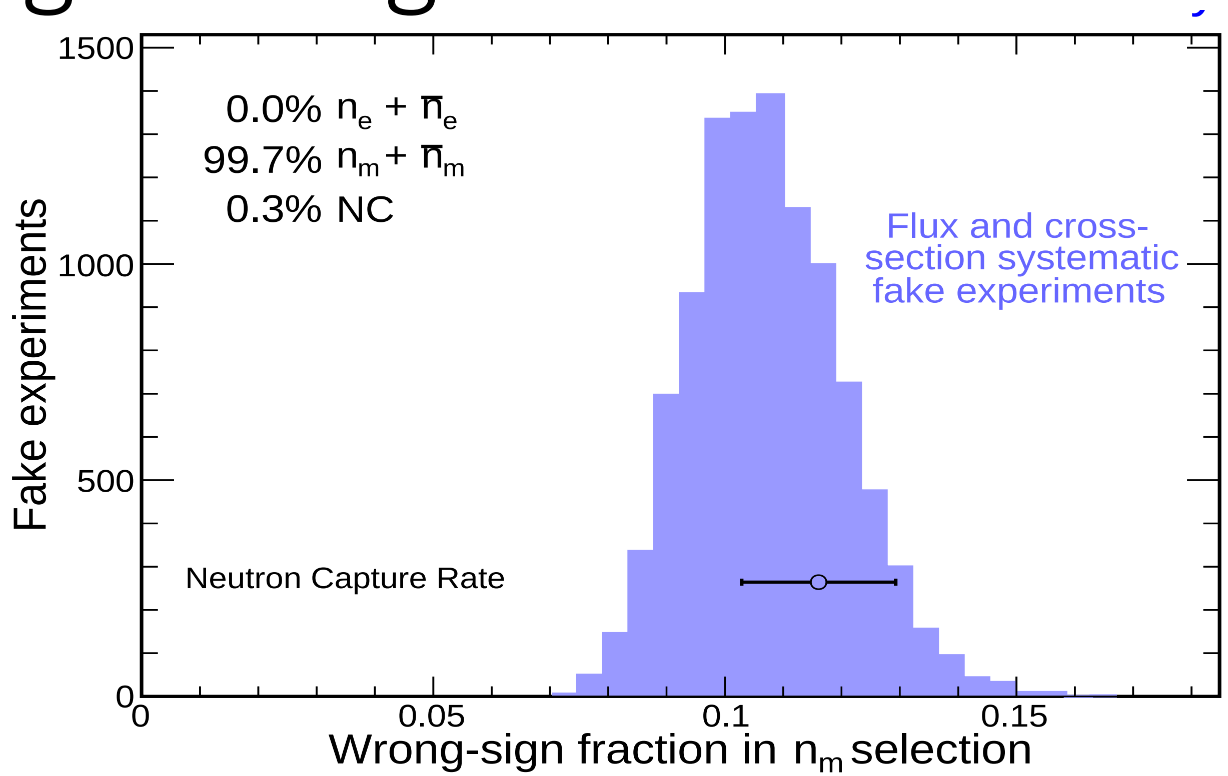
Optimizing Analysis Binning - ν_e





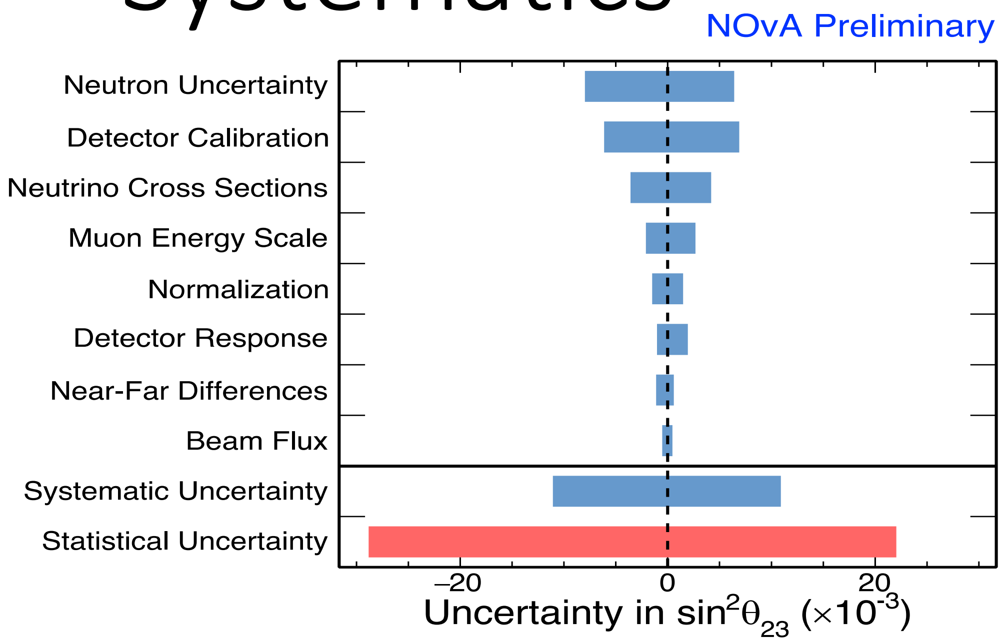
- FOM^2 = $\sum_i^{bins} \frac{s_i^2}{s_i+b_i+c_i}$ → proportional to effective exposure gain

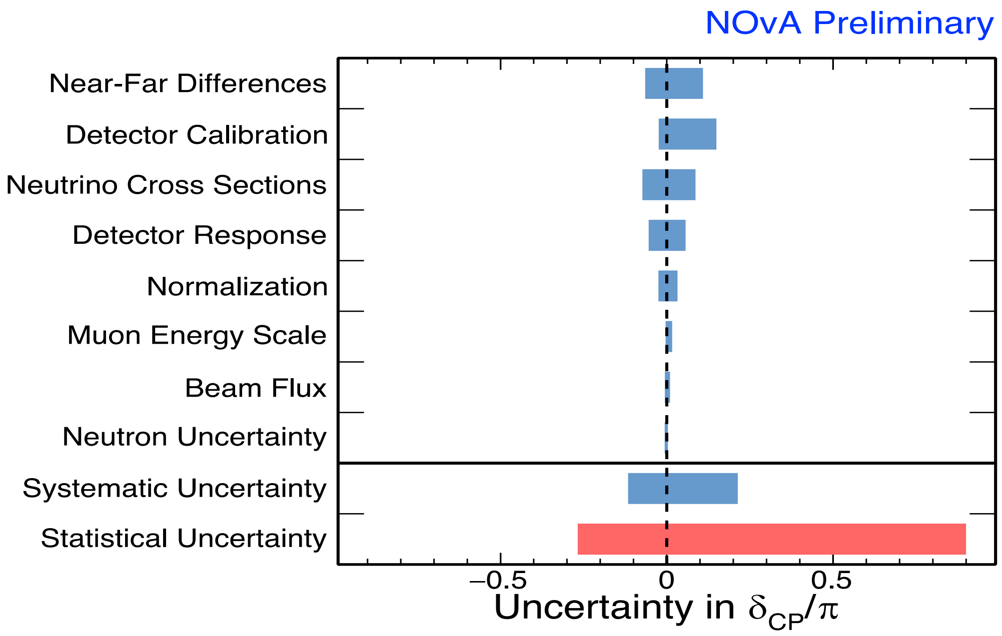
Wrong Sign Background

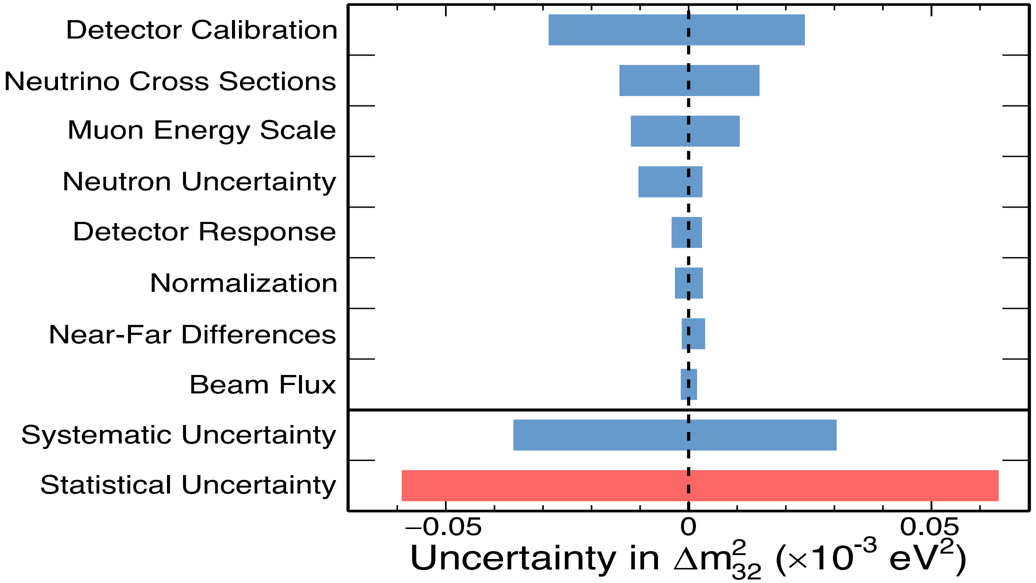


- 11% WS fraction in $\bar{\nu}_\mu$ events becomes WS background in $\bar{\nu}_e$ events
- ~10% systematic uncertainty on WS from flux and cross-section
  - Does not include uncertainties from detector effects
- Confirmed using data-driven check of WS contamination
  - 11% WS in $\bar{\nu}_\mu$ sample checked using neutron captures in neutrino and anti-neutrino beams

Systematics







- Detector calibration – will be improved by test beam program
- Neutrino cross-sections
- Muon energy scale
- Neutron uncertainty