Sandbox Studio, Chicago

Cross-section measurements at the NOvA near detector

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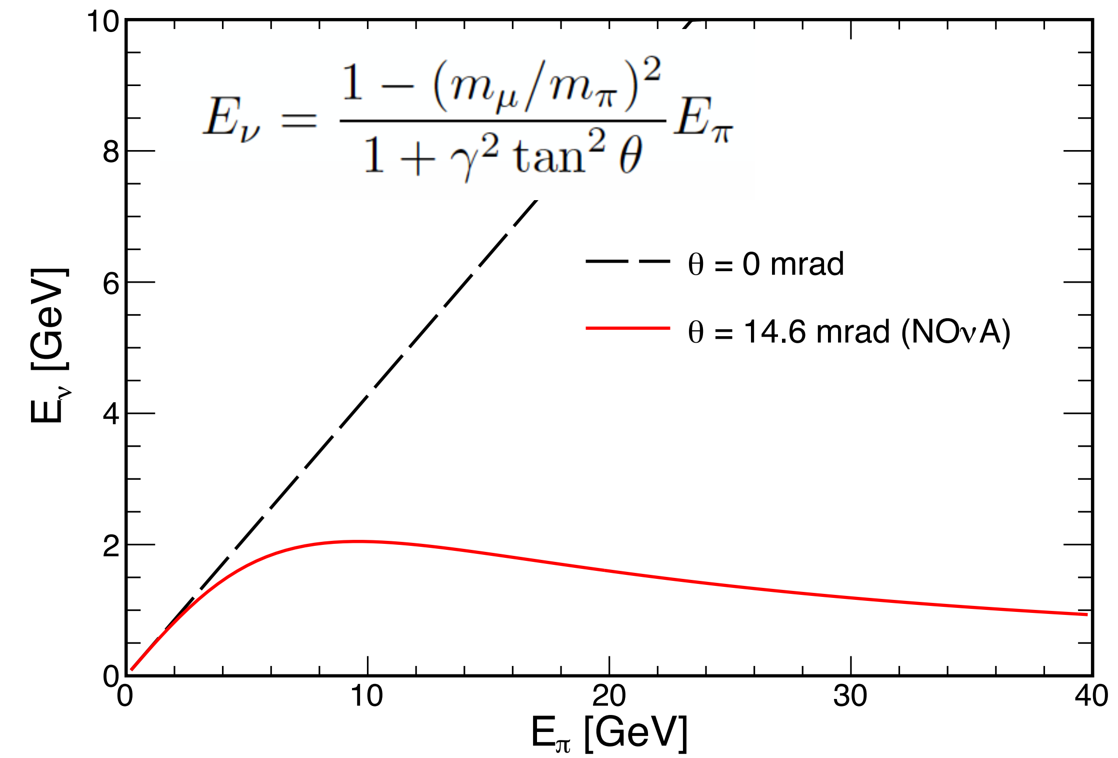
for the NOvA Collaboration

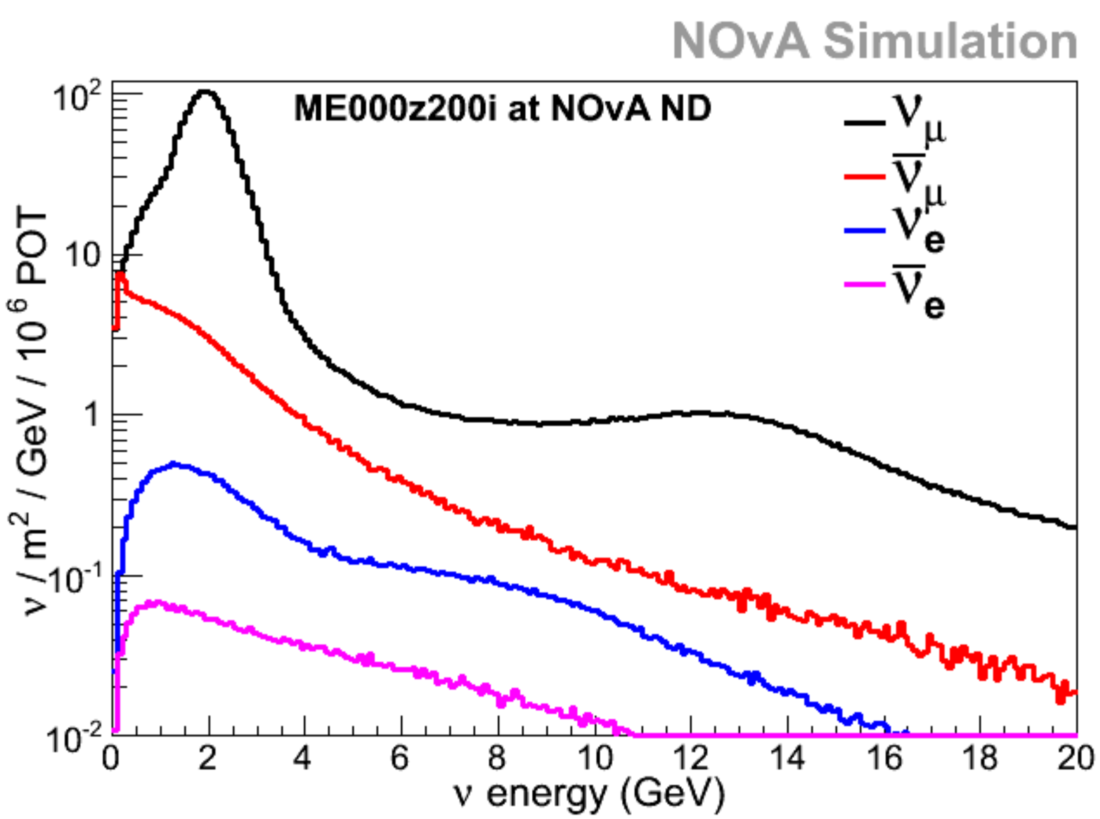
Outline

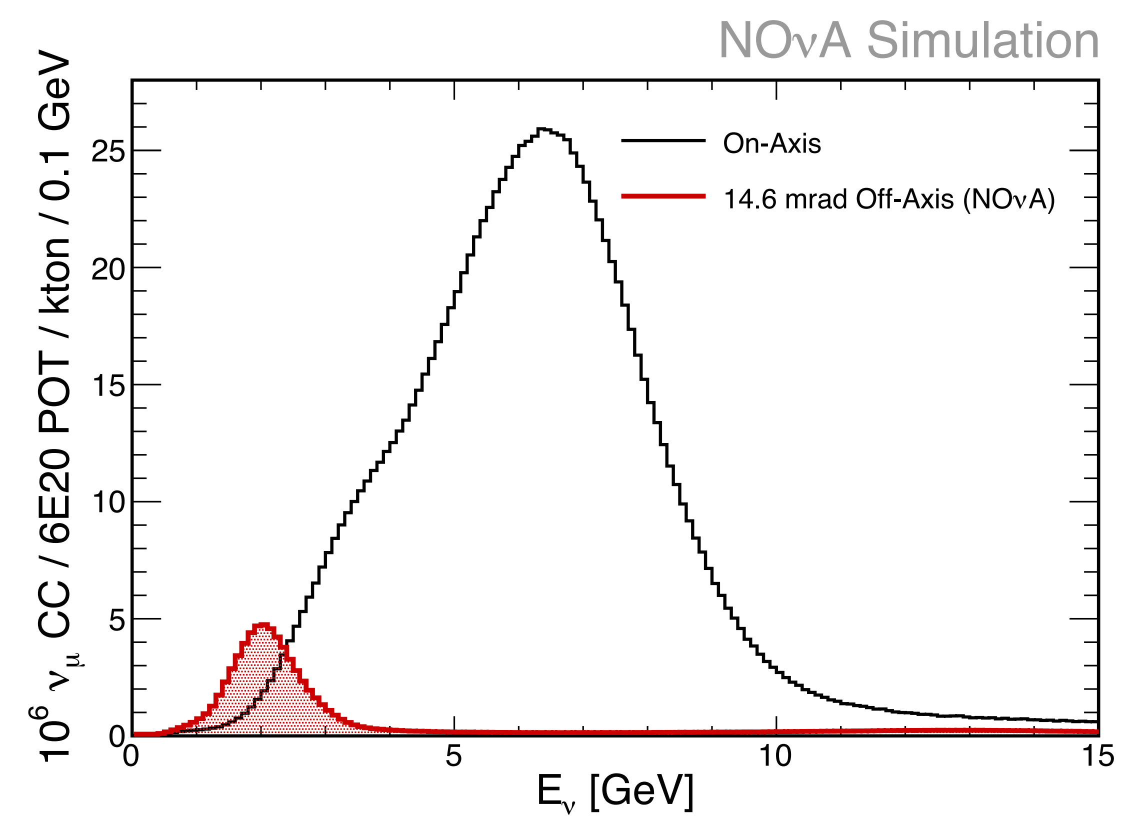
- Overview of the NOvA beam, detector and simulation
- Inclusive measurements
- Pion production measurements
- NC coherent π^0 results
- Summary and outlook

Beam at NOvA

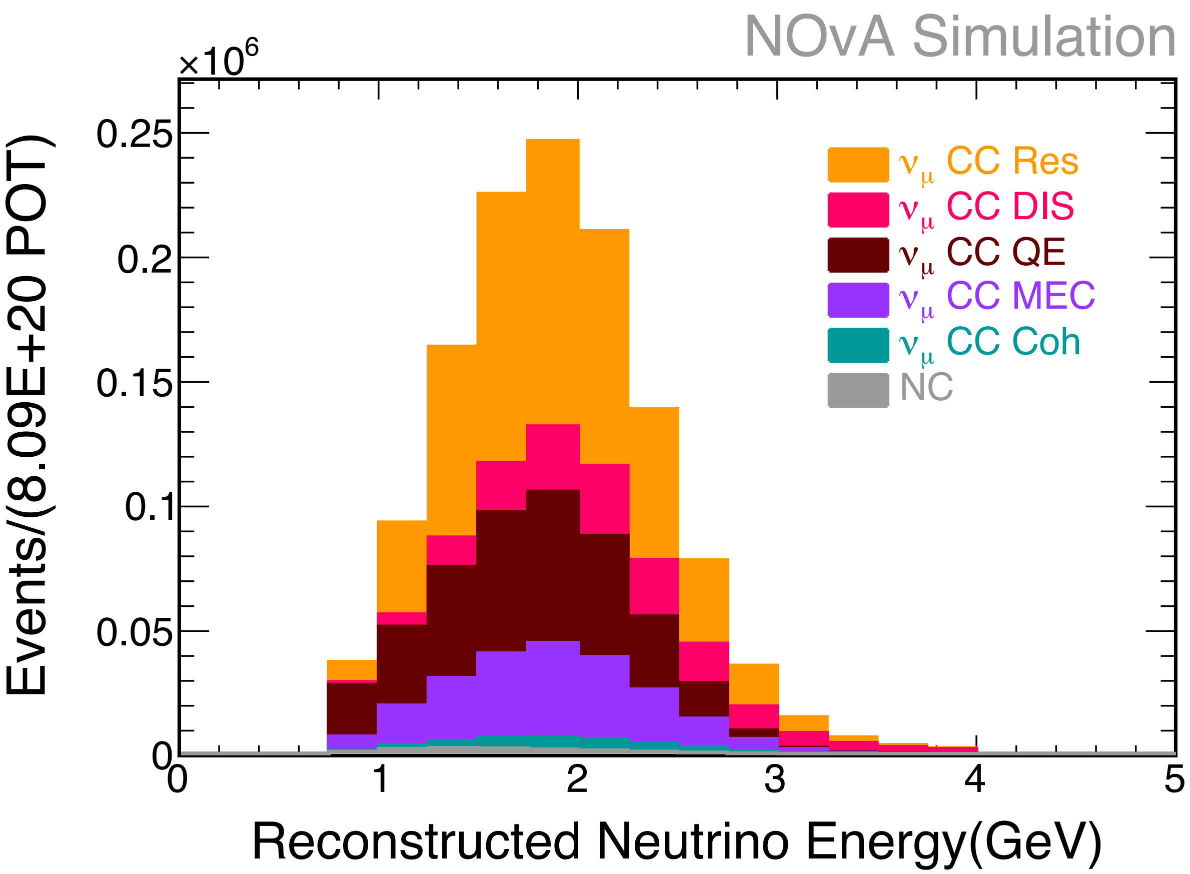
- NOvA detectors are 14 mrad off the NuMI beam axis.
  - narrow 2-GeV spectrum
  - small flux shape uncertainties (hadron production uncertainties are mostly normalisation effect)
- 95% pure ν_μ beam

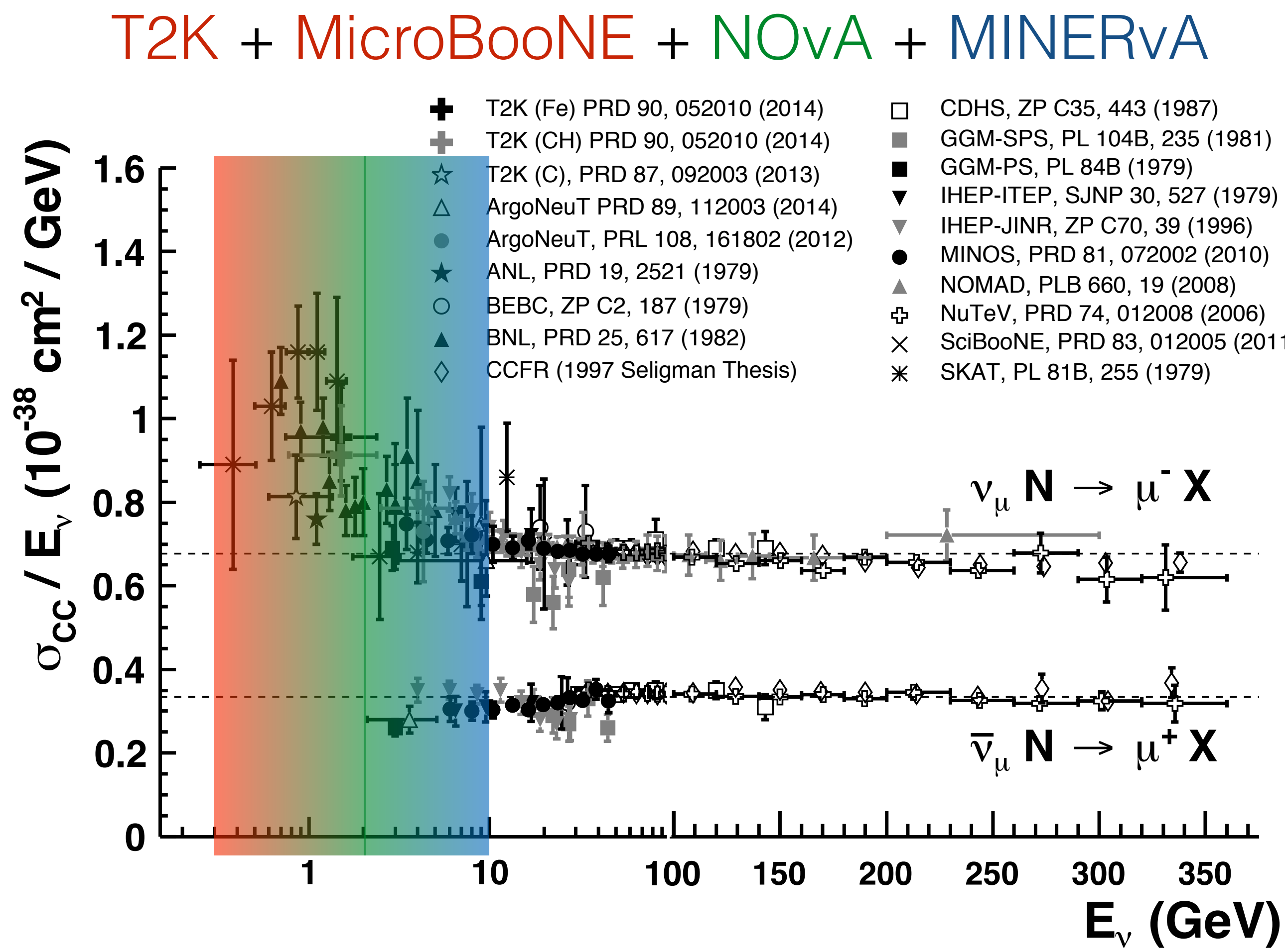






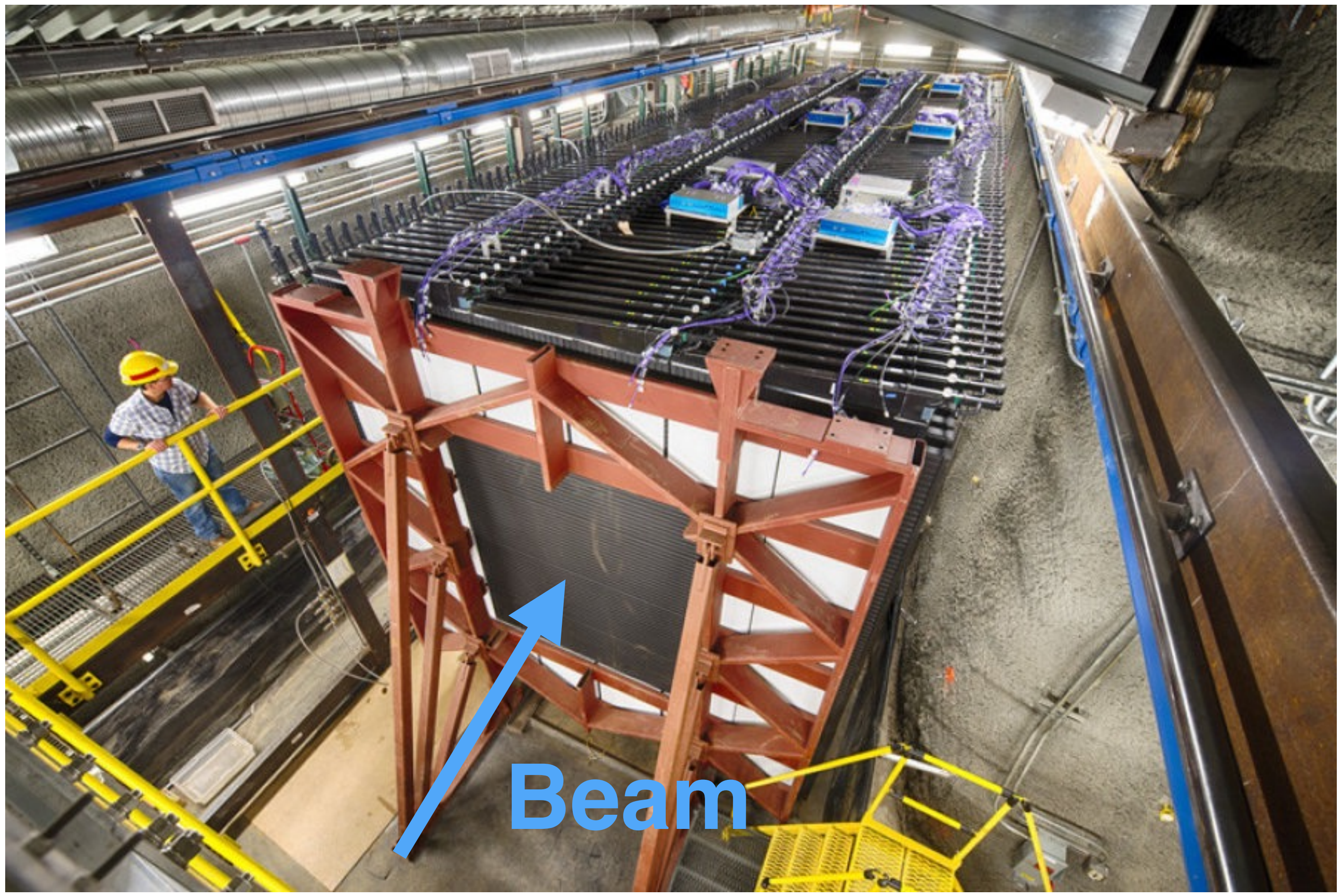
Beam at NOvA

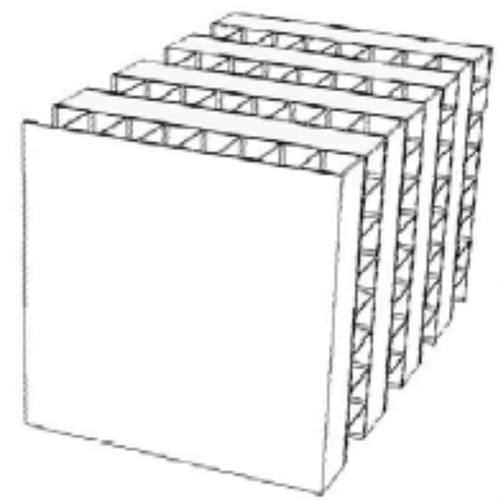




- NOvA is sensitive to many different nu+A interaction channels.
- Cross sections in NOvA's energy range suffer from high uncertainties in neutrinos and no measurements below 3 GeV for antineutrinos.
- Nice overlap with currently running experiments, as well as future experiments in the US.

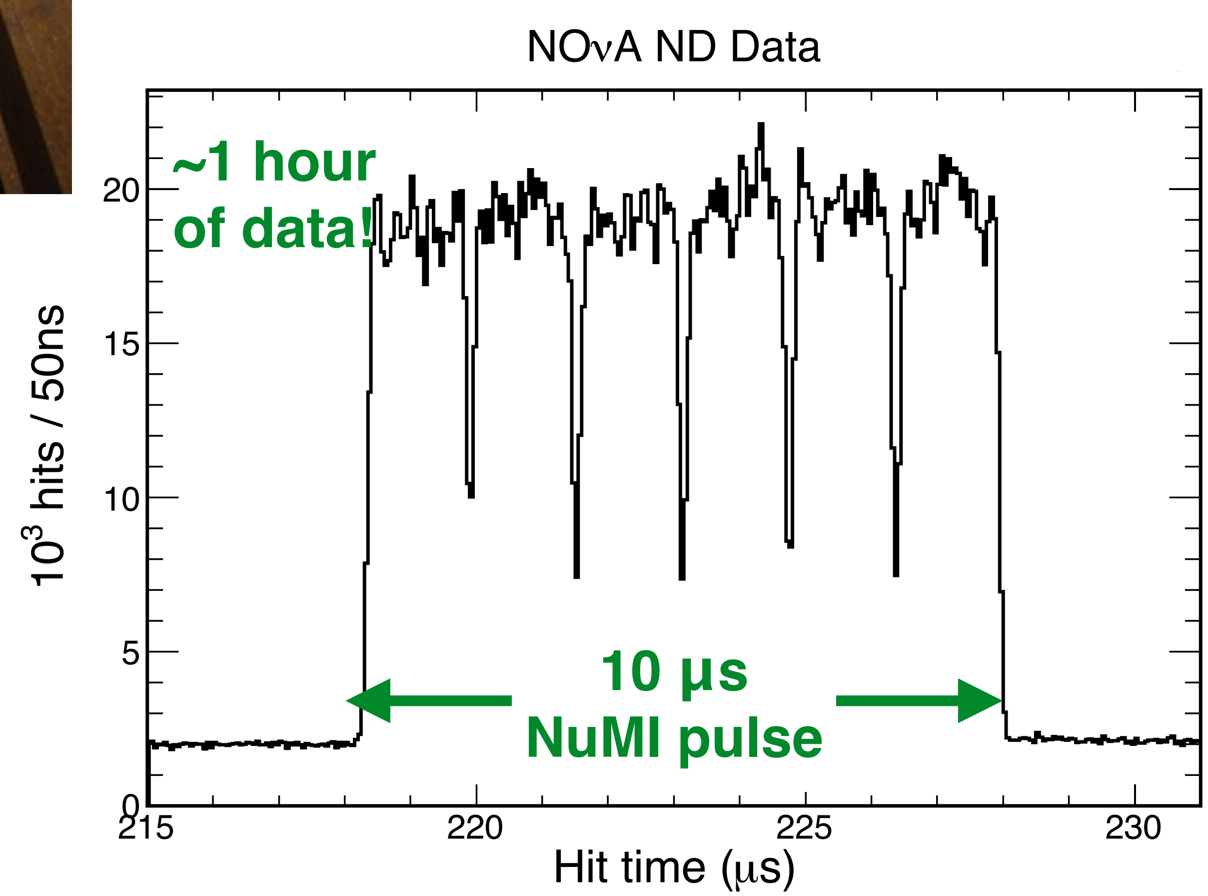
The NOvA Near Detector



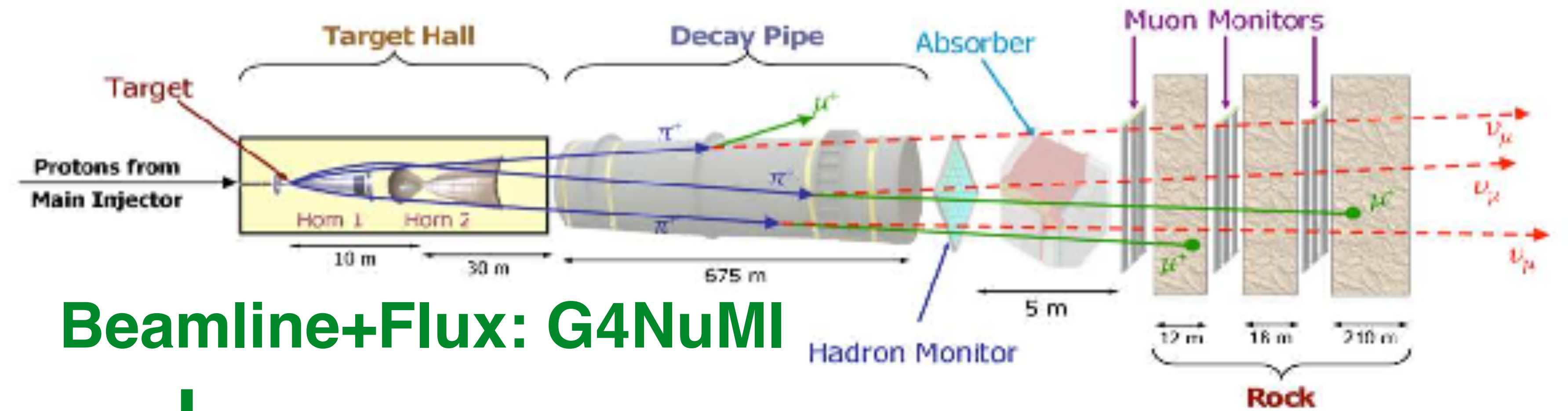


Wavelength-shifting fibres routed to a single cell on an Avalanche Photodiode

- Tracking calorimeter
- 77% hydrocarbon by mass, 16% chlorine, 6% TiO_2
- Muon catcher (steel + NOvA cells) at downstream end to range out ~2GeV muons.
- O(10) ns single hit timing resolution.

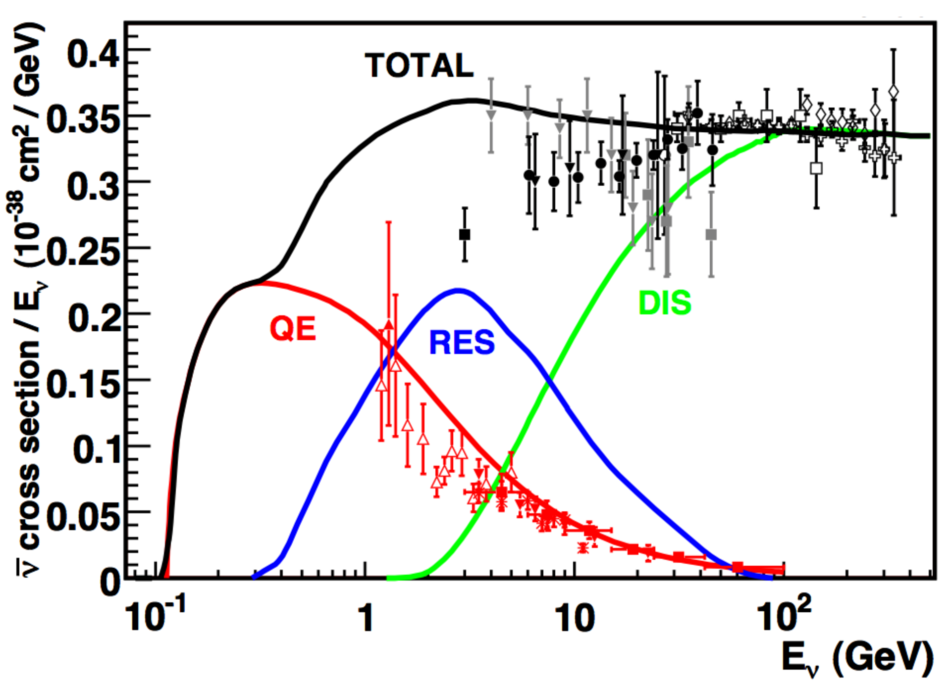


Simulation

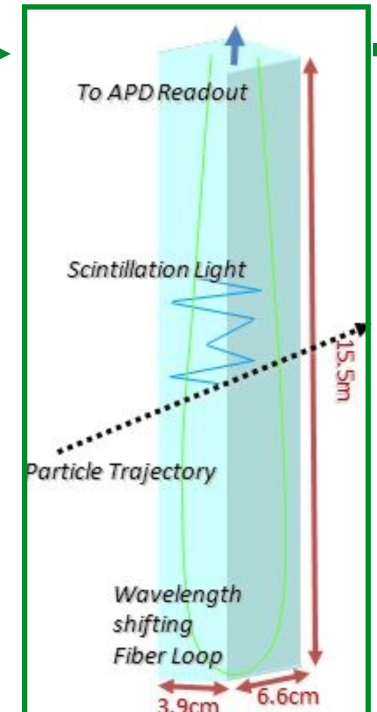


Beamline+Flux: G4NuMI

nu interactions & FSI modelling: GENIE



Detector response: GEANT4



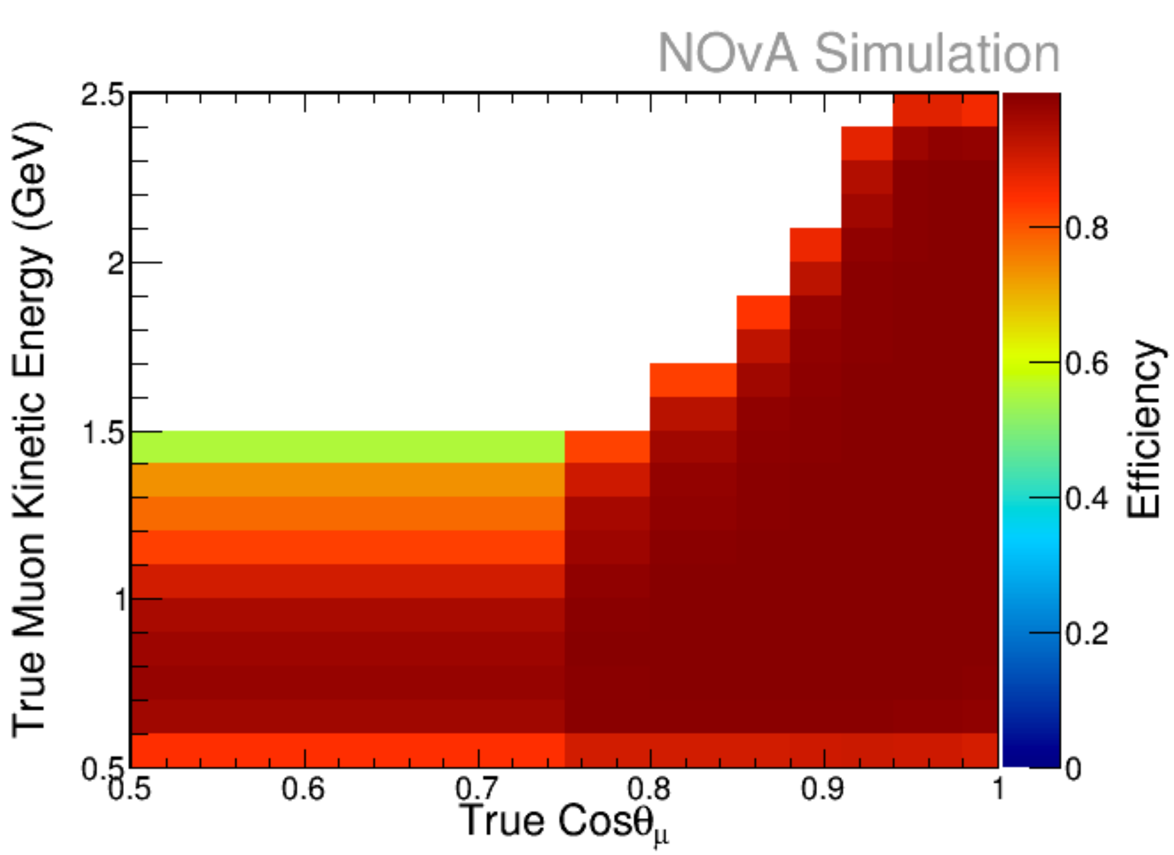
Readout electronics & DAQ: Custom simulation routines

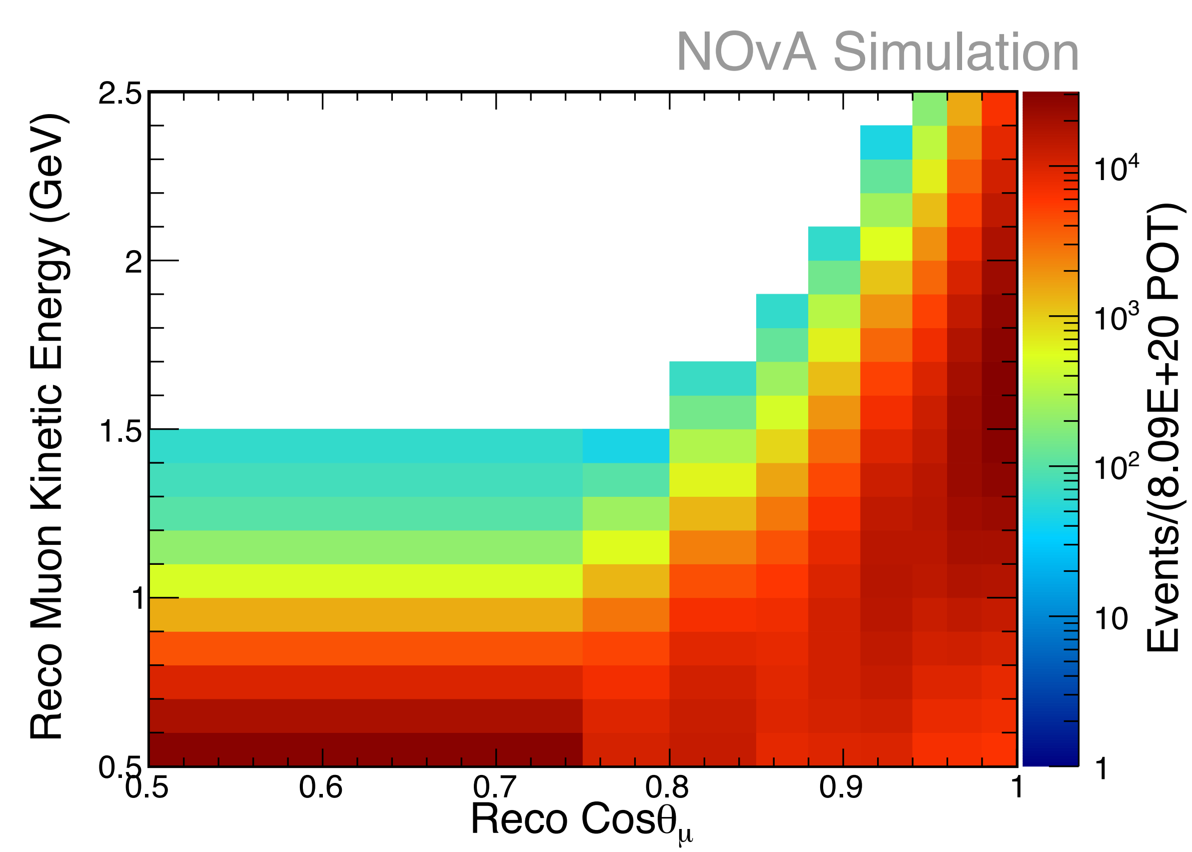
ν_μ CC inclusive

- σ(E) and flux-averaged double differential cross section in muon kinematics variables

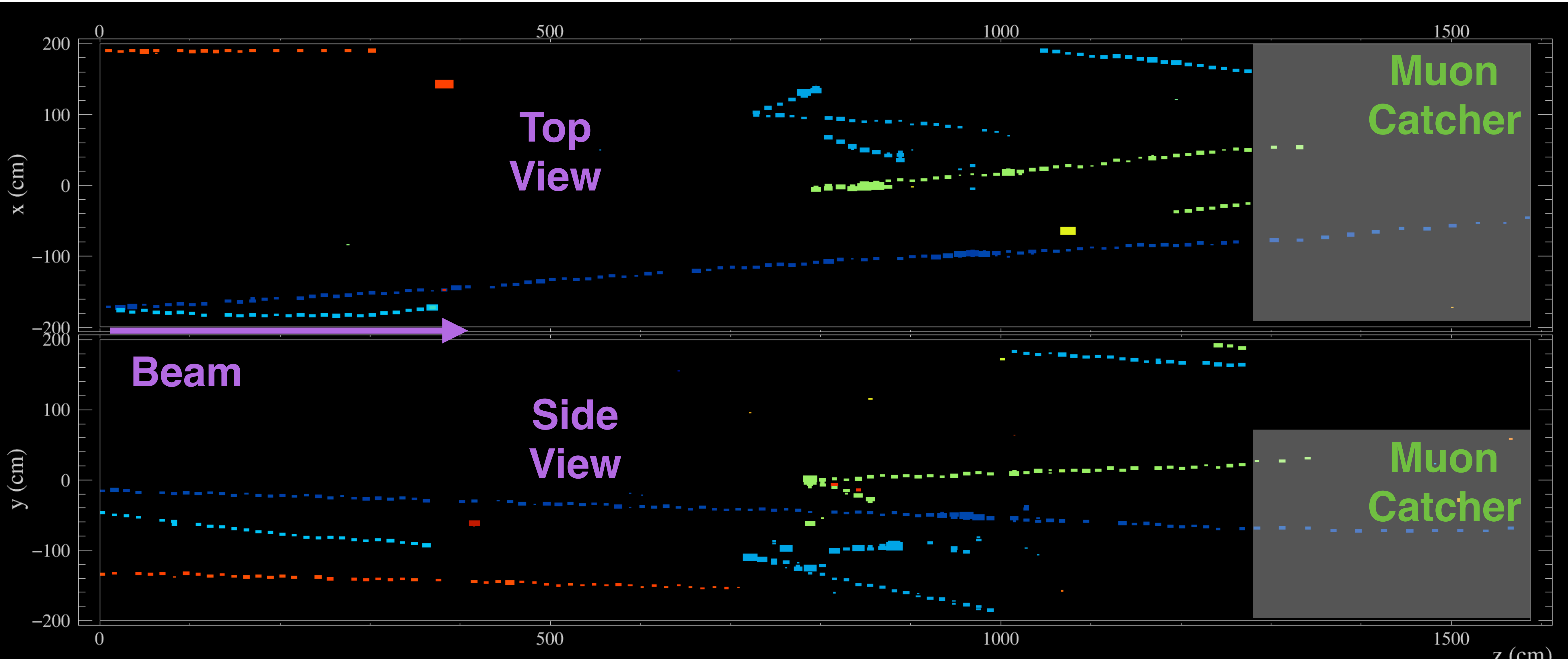
$$\left(\frac{d^2\sigma}{d\cos\theta_\mu dT_\mu}\right)_i = \frac{\sum_j U_{ij}(N^{\text{sel}}(\cos\theta_\mu, T_\mu)_j - N^{\text{bkg}}(\cos\theta_\mu, T_\mu)_j)}{\epsilon(\cos\theta_\mu, T_\mu)_i(\Delta\cos\theta_\mu)_i(\Delta T_\mu)_i N_{\text{target}}\phi}$$

- σ(E) measurements are kinematically restricted this phase space due to limited statistics and low efficiency



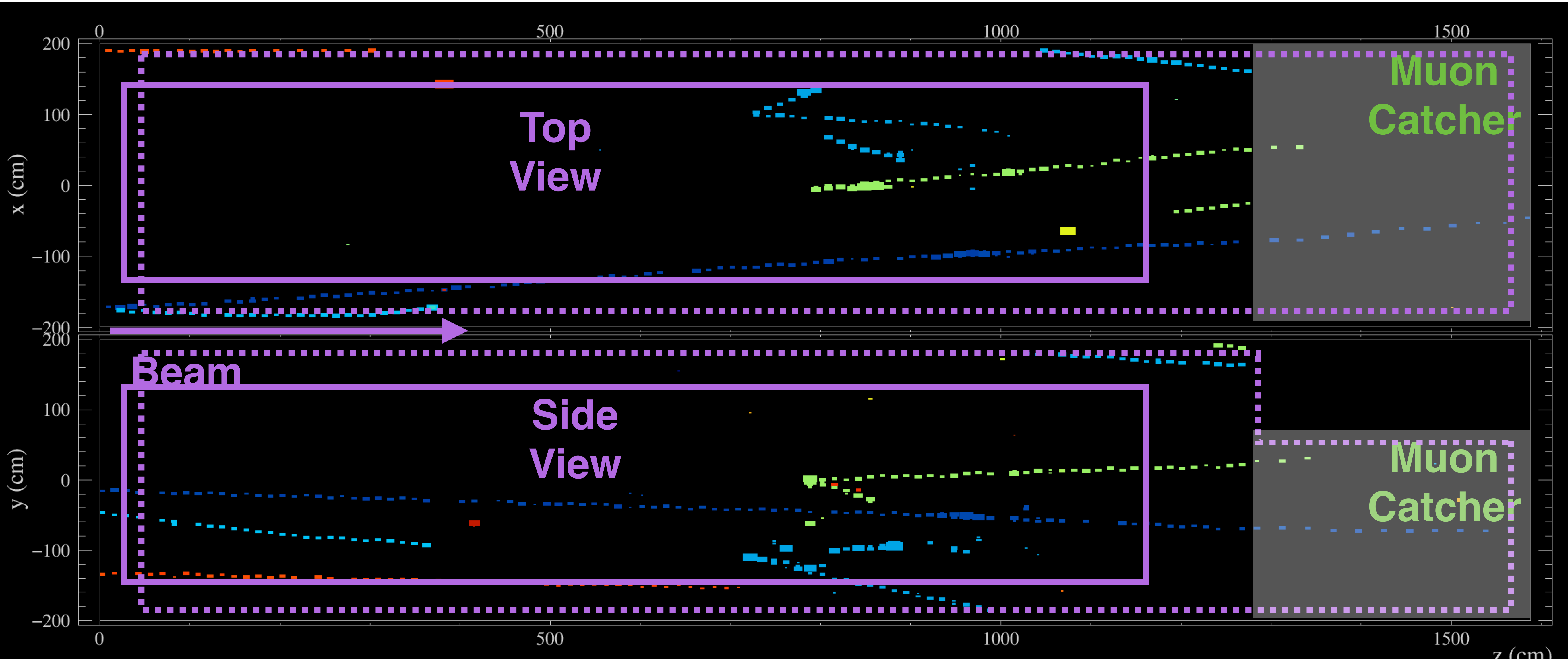


ν_μ CC inclusive: Reco + Selection



- Hits associated in time and space are used to form a candidate interaction.
- Vertices, tracks and showers are reconstructed from these hits.

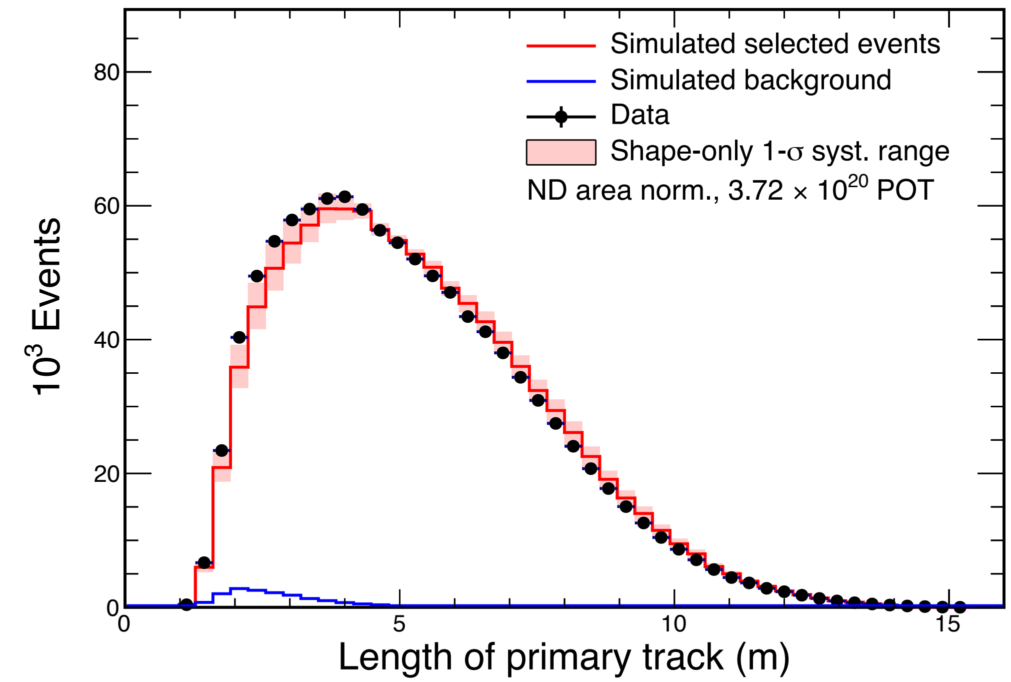
ν_μ CC inclusive: Reco + Selection

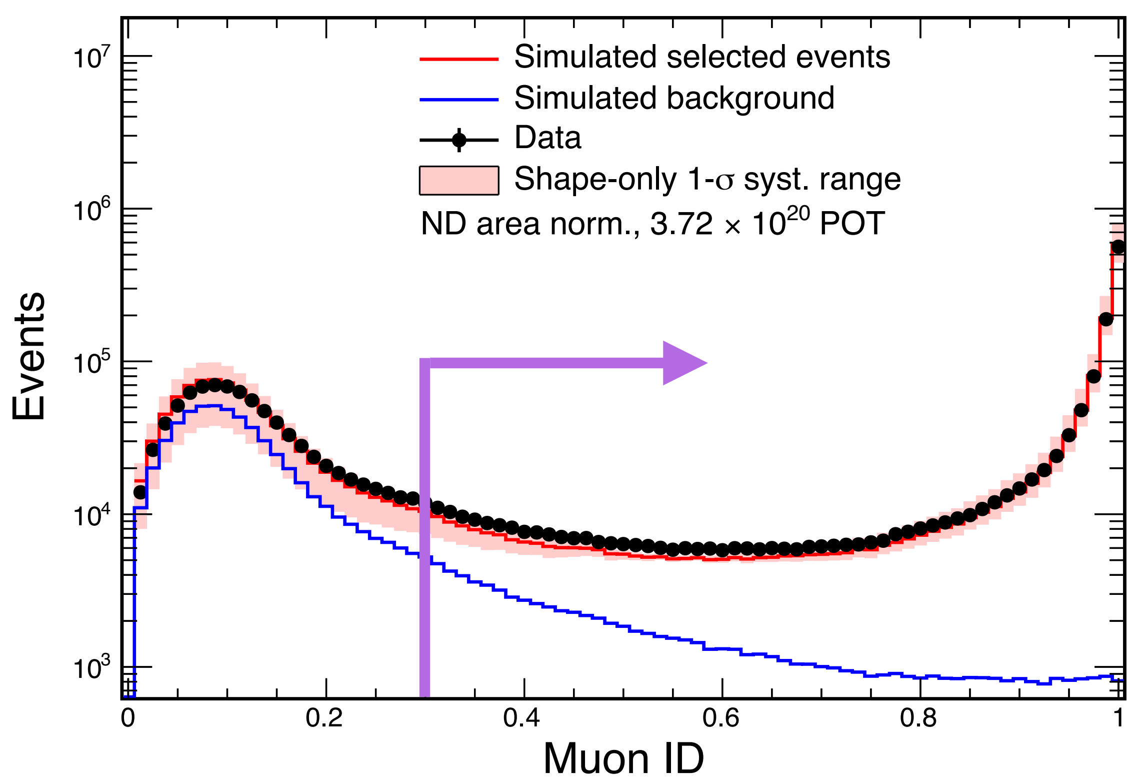


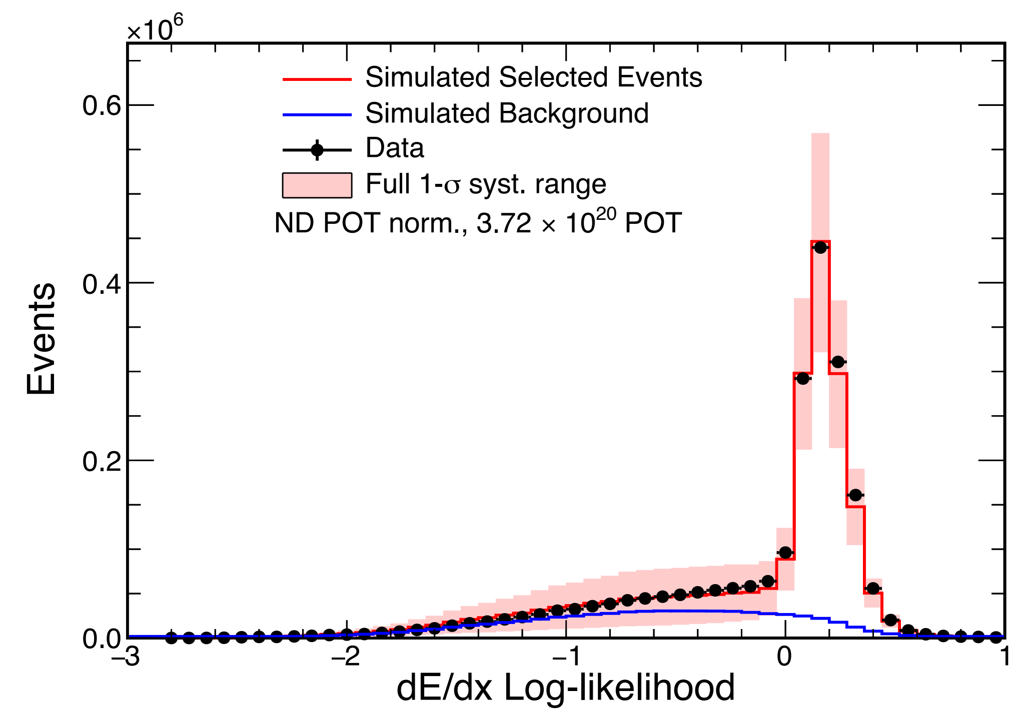
- Solid box is Fiducial Volume
- Containment uses nearest projected distance to an edge (dashed box is rough approximation).
- Events with hadronic activity in or near the muon catcher are excluded

ν_μ CC inclusive: PID

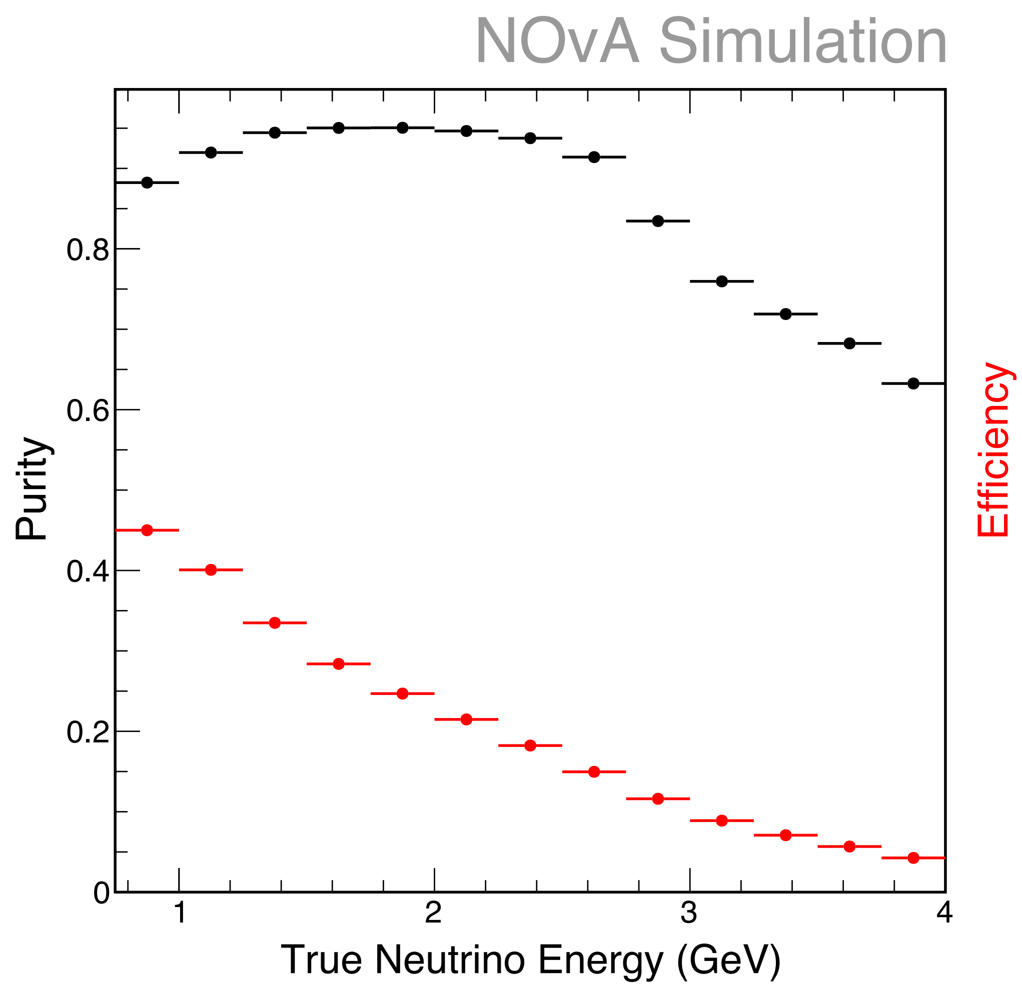
- Use a *kNN* to separate signal and background tracks based on 4 variables:
    - track length
    - dE/dx along track
    - scattering along track
    - fraction of track planes w/ single particle dE/dx

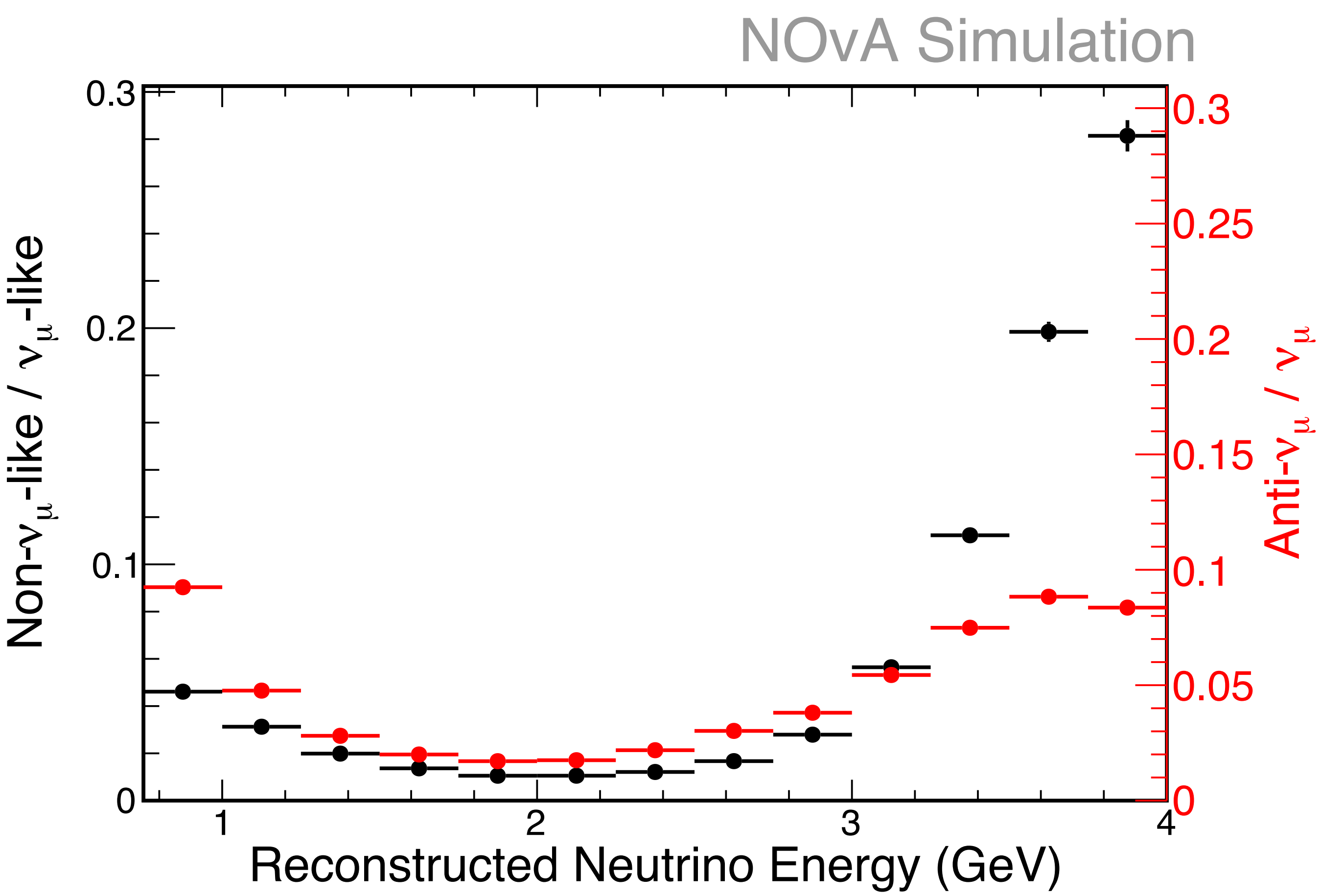






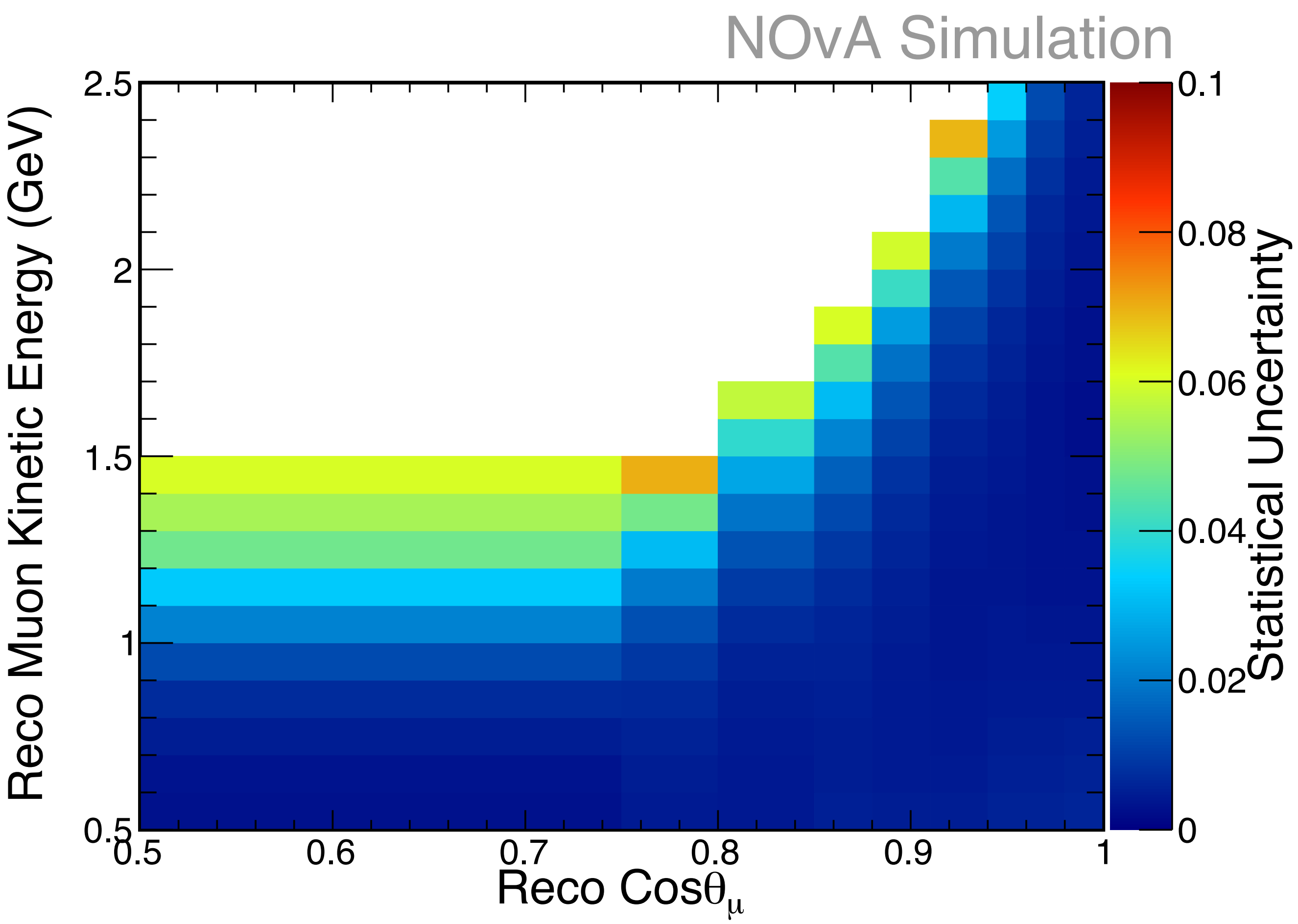
ν_μ CC inc: efficiency and background

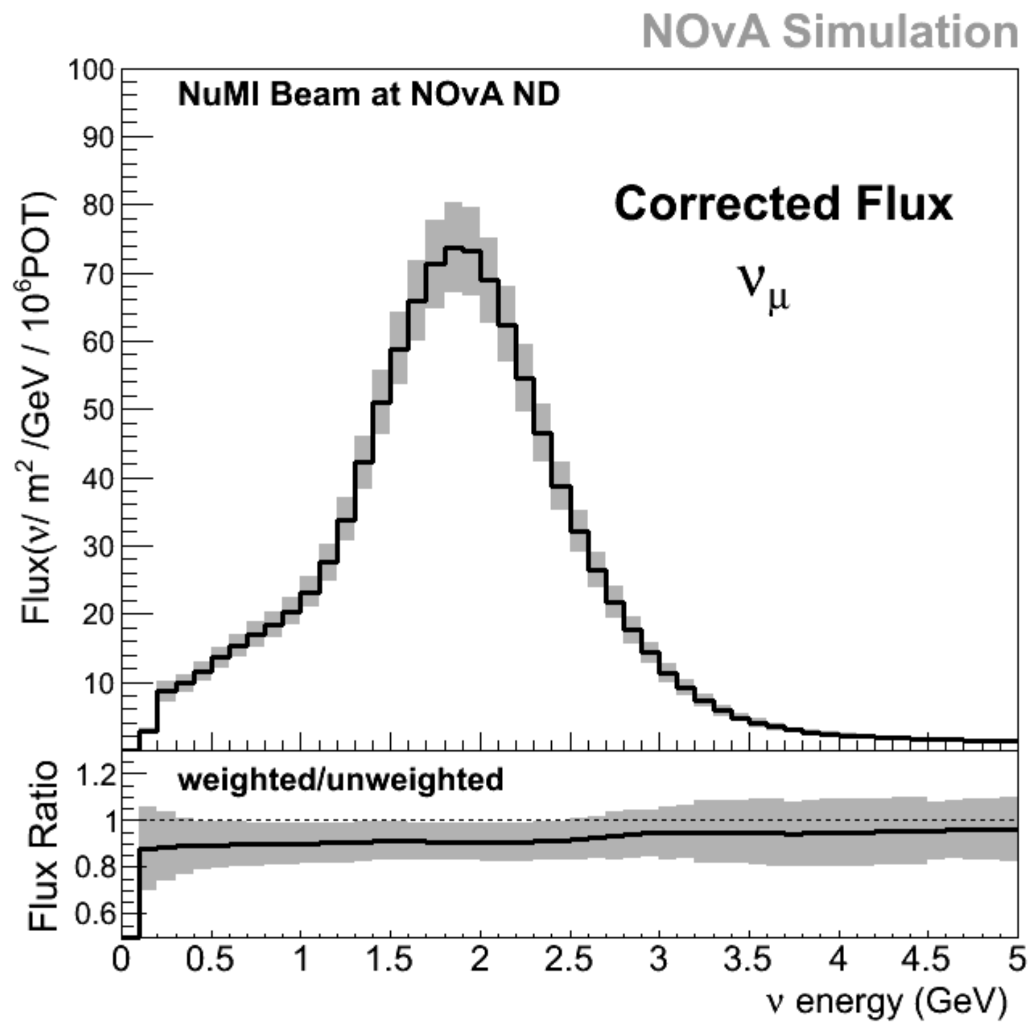




- Selection efficiency is dominated by containment cut.
- Backgrounds are small near the 2 GeV peak, larger in the tails of the spectrum.
- Uncertainties are at the level of a few %.

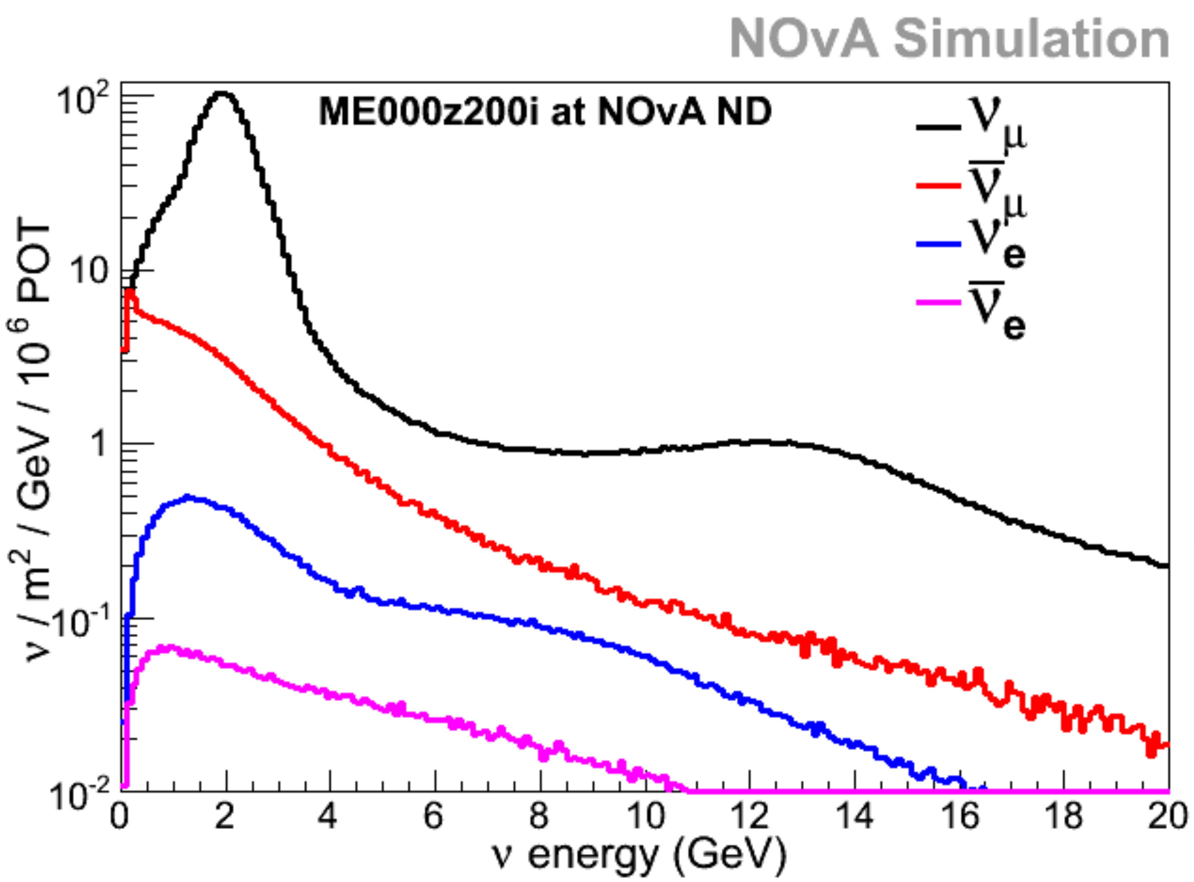
ν_μ CC inc: Summary of Uncertainties





- Statistical uncertainties are typically <2%.
- Systematics are still being assessed, but we expect for the differential measurement ~10% highly correlated (normalisation) flux uncertainties, and all the other systematics combined to be 5-8%
- σ(E) measurement systematics will be similar, although systematics from energy scale uncertainties will be larger on the rising and falling edges of the spectrum.

ν_e CC inclusive: Overview



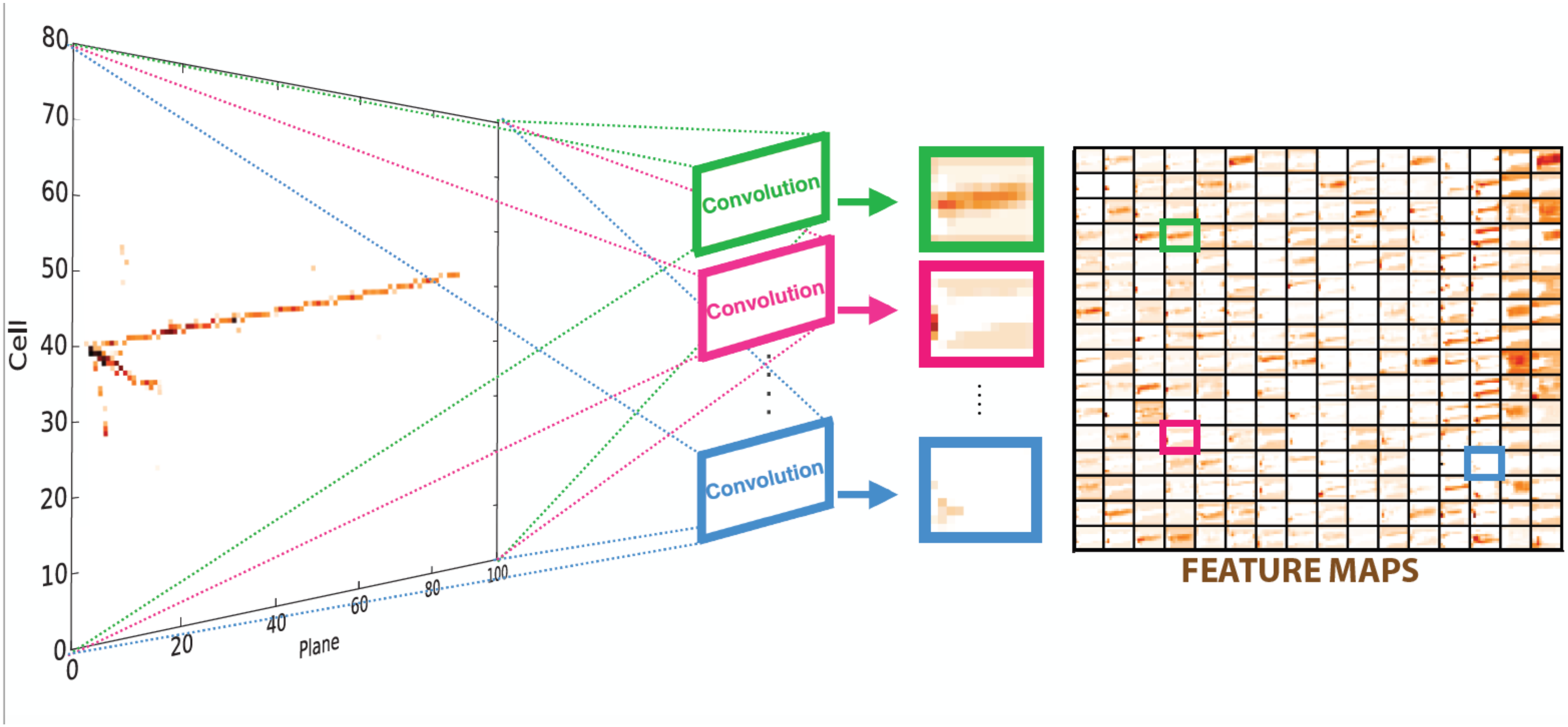
- σ(E) and flux-averaged single differential cross-section as a function of the electron kinematics for energies between 1 and 3 GeV.

$$\frac{d\sigma}{dX_i} = \frac{\Sigma_j U_{ij}(N^{\mathrm{sel}}(X_j) - N^{\mathrm{bkg}}(X_j))}{\epsilon(X_i)\Delta X_i N_{\mathrm{target}}\phi}$$

- Challenging because (by design) there are ~1% of ν_e.
- We have shown preliminary results on this channel in the past. That analysis is now superseded with a different event identification developed in the oscillation analysis.

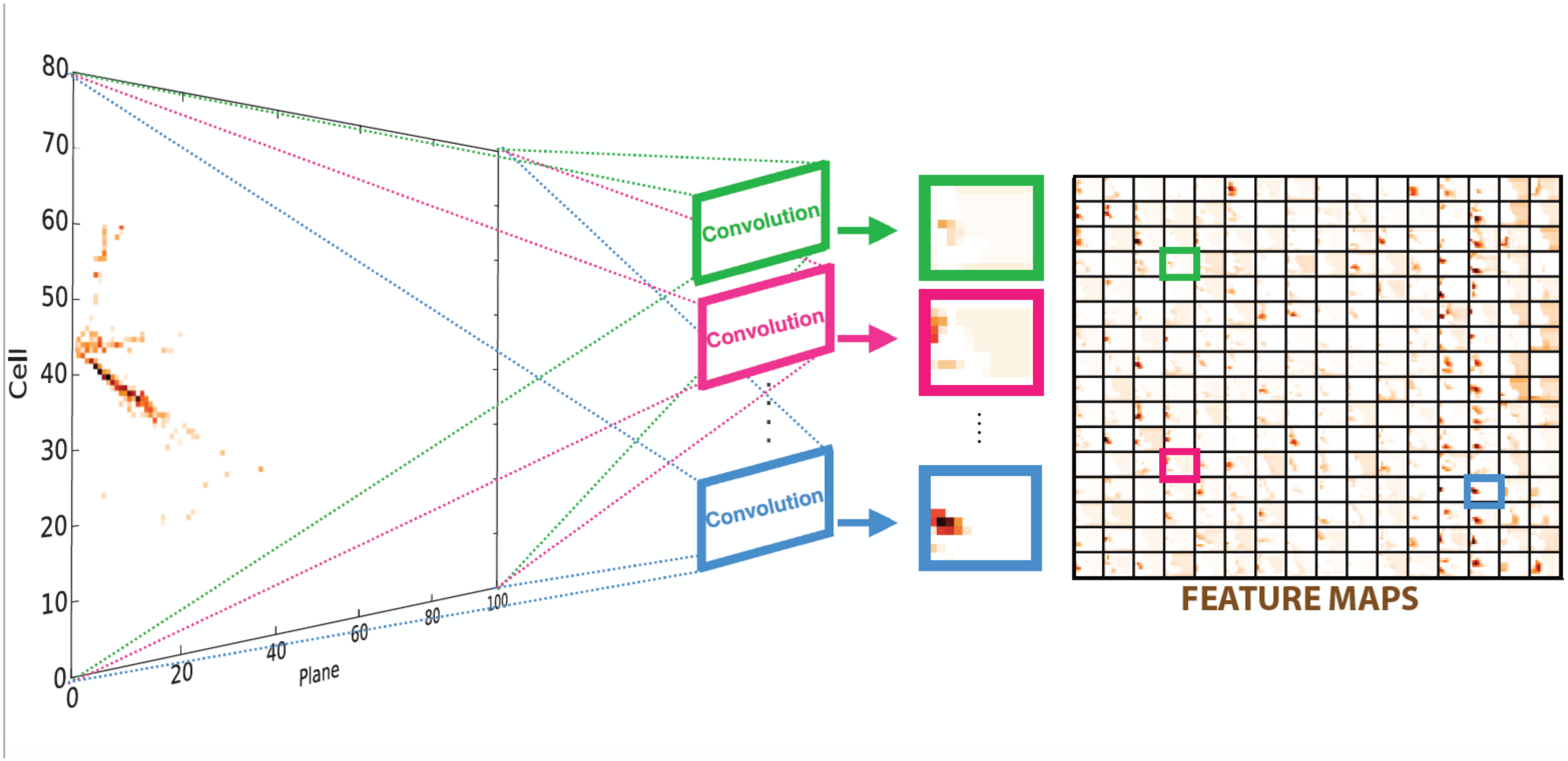
ν_e CC inclusive: CVN

- NOvA uses a Convolutional Neural Network (CNN) where a series of image filters are applied to hit map images to extract features associated with an interaction
- Not limited to features chosen a priori
- CNNs extract features of varying complexity and learn correlations

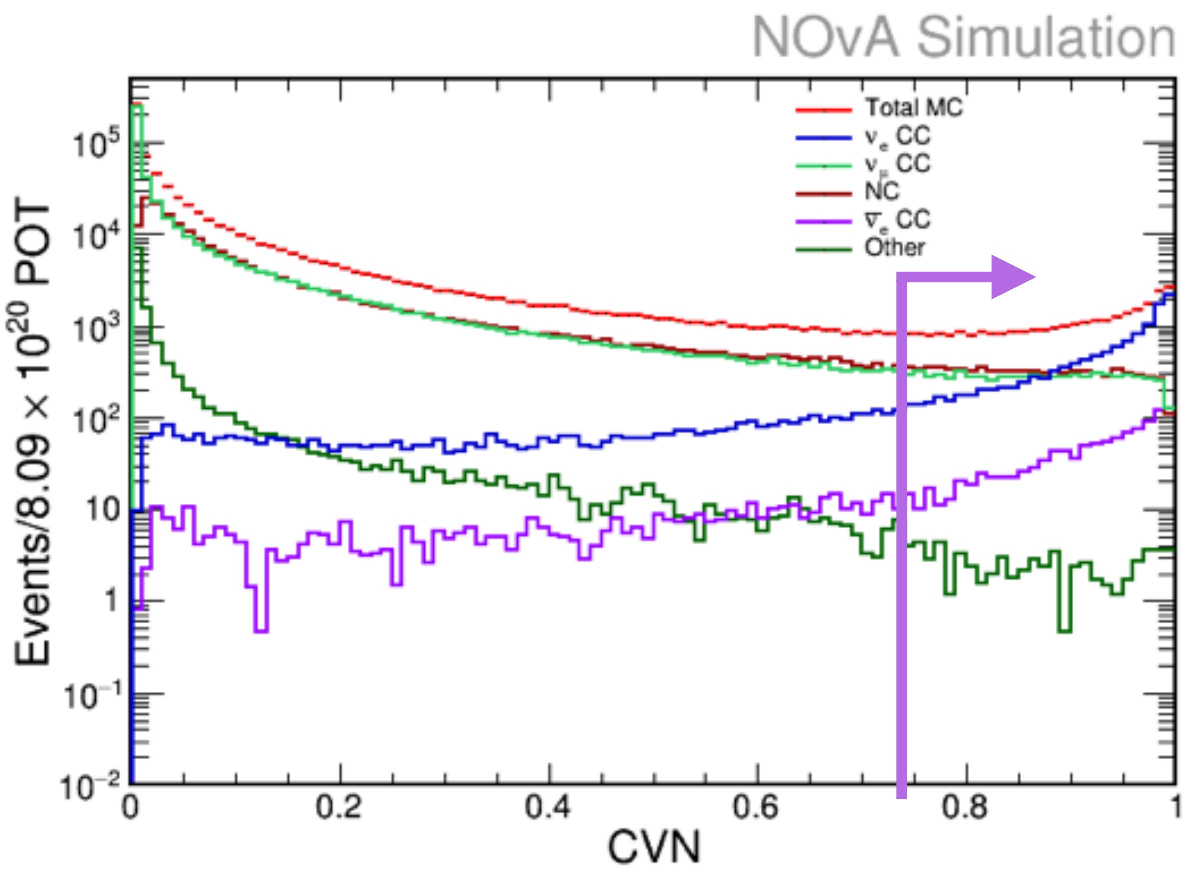


ν_e CC inclusive: CVN

- A convolutional visual network (CVN) is then trained on these filters.
- 30% effective increase in exposure in the Far Detector for the oscillation analysis



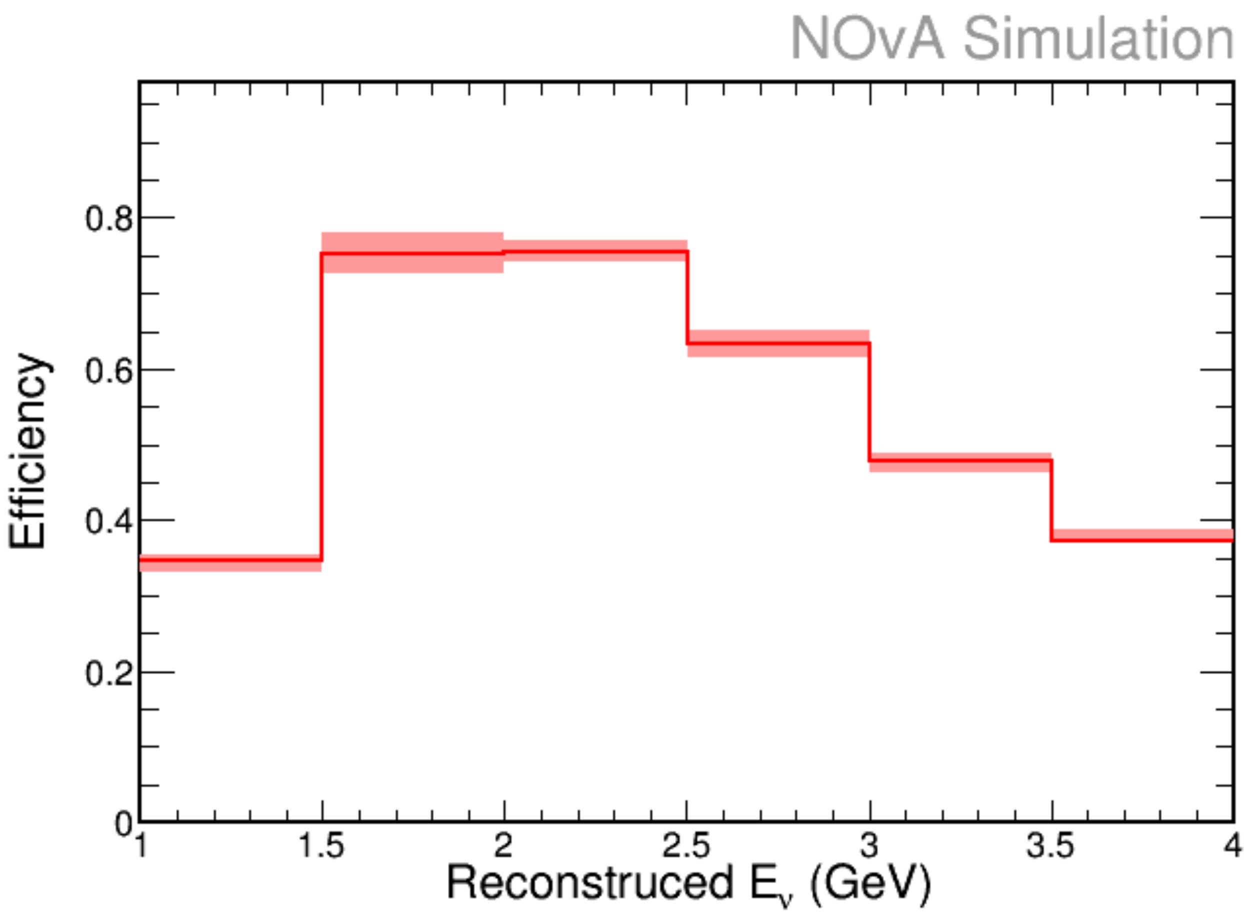
ν_e CC incl: PID

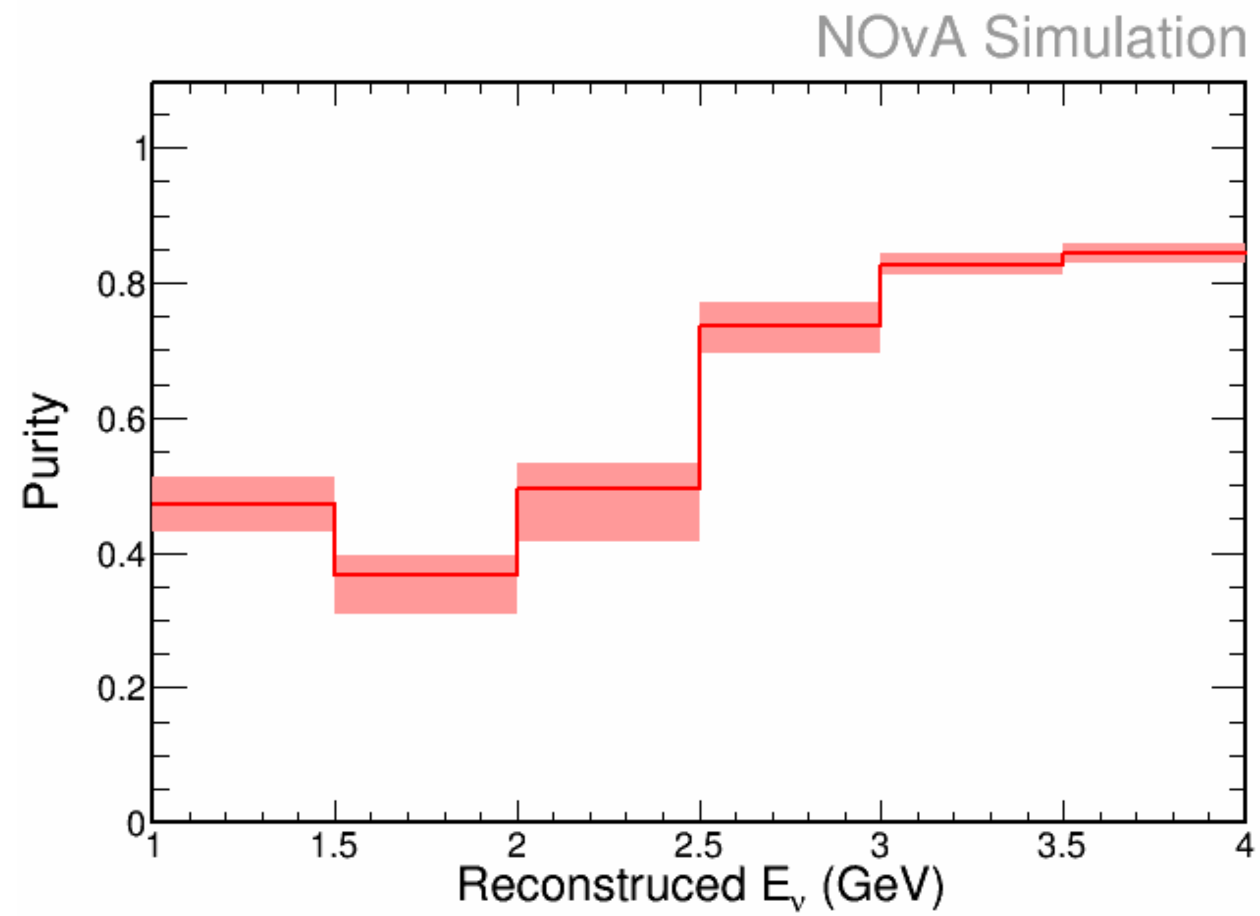


$Interaction$	$Fraction(\%)$
$\nu_e CC$	51.2
$\bar{\nu}_e CC$	4.4
$\nu_\mu CC$	21.1
NC	23.0
$Other$	0.18

- Currently using a cut (CVN > 0.85) that optimises the FoM of $S/\sqrt{(S+B)}$
- Backgrounds are significant, and we are investigating potential driven data constraints.

ν_e CC incl: Efficiency and Purity

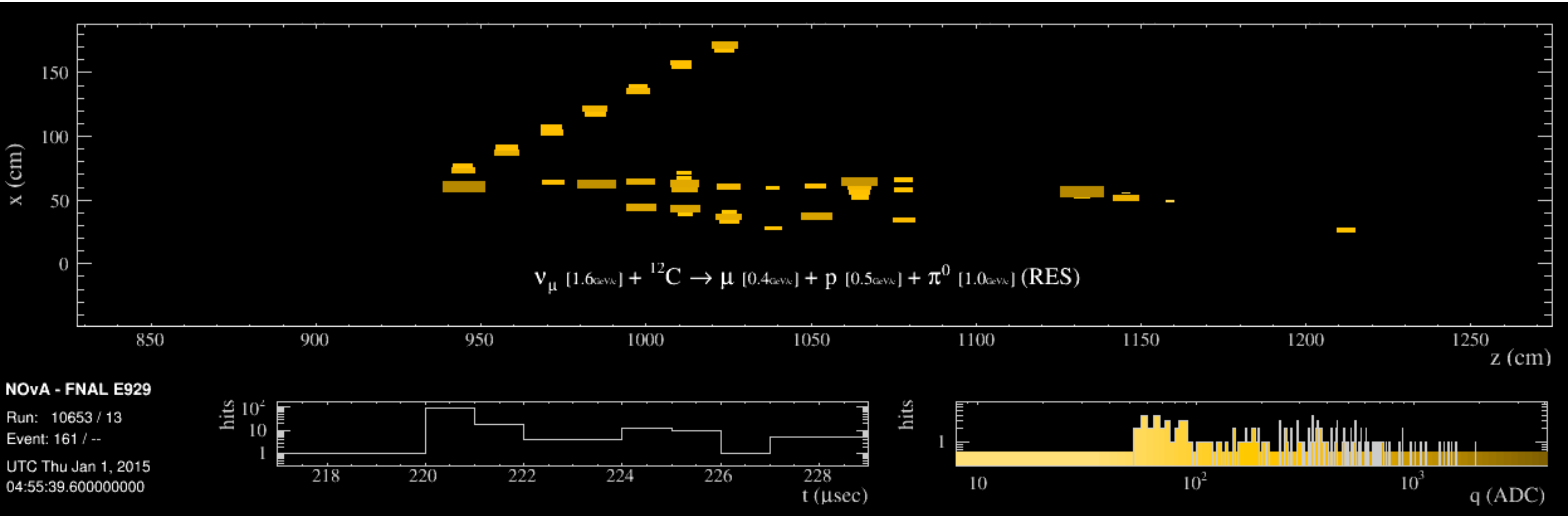




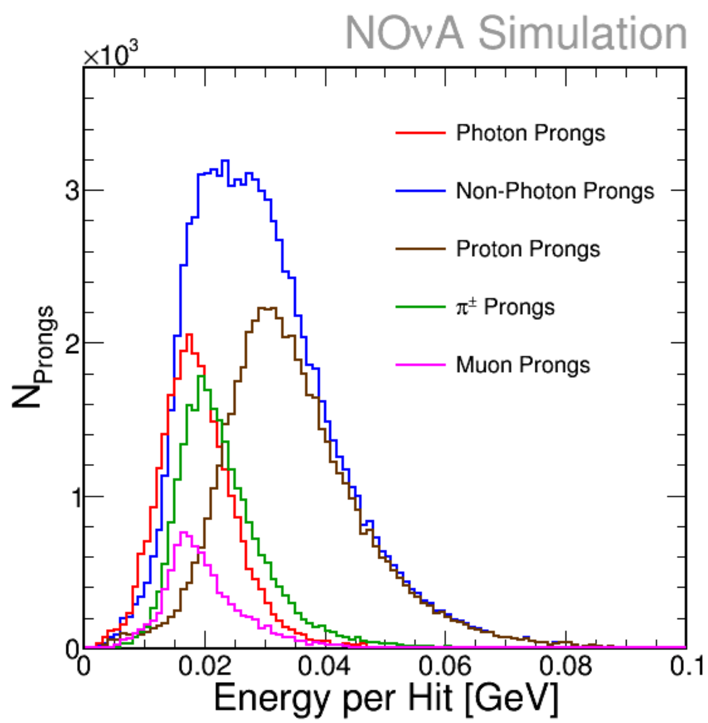
- Xsec, FSI and calibration systematics included in error bands.
- Uncertainties on efficiency and backgrounds is between 5-10%.
- Data-driven constraints on the efficiency and backgrounds are being explored.

ν_μ CC π^0

- Signal: ν_μ-CC events with at least one primary π^0 in the final state.
- π^0 production vital for ν_e appearance searches
- Flux-averaged differential cross sections in final state kinematics



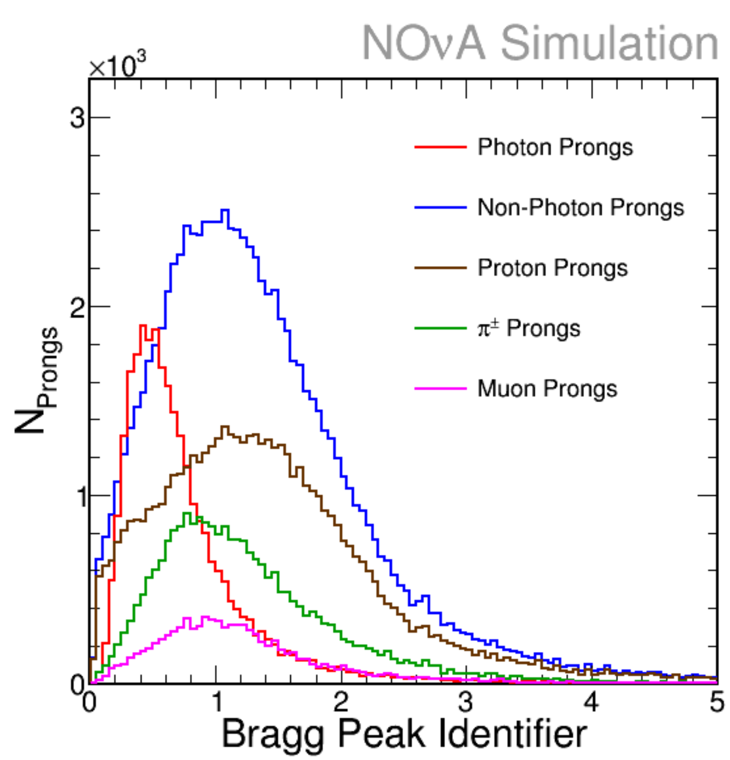
ν_μ CC π^0: PID

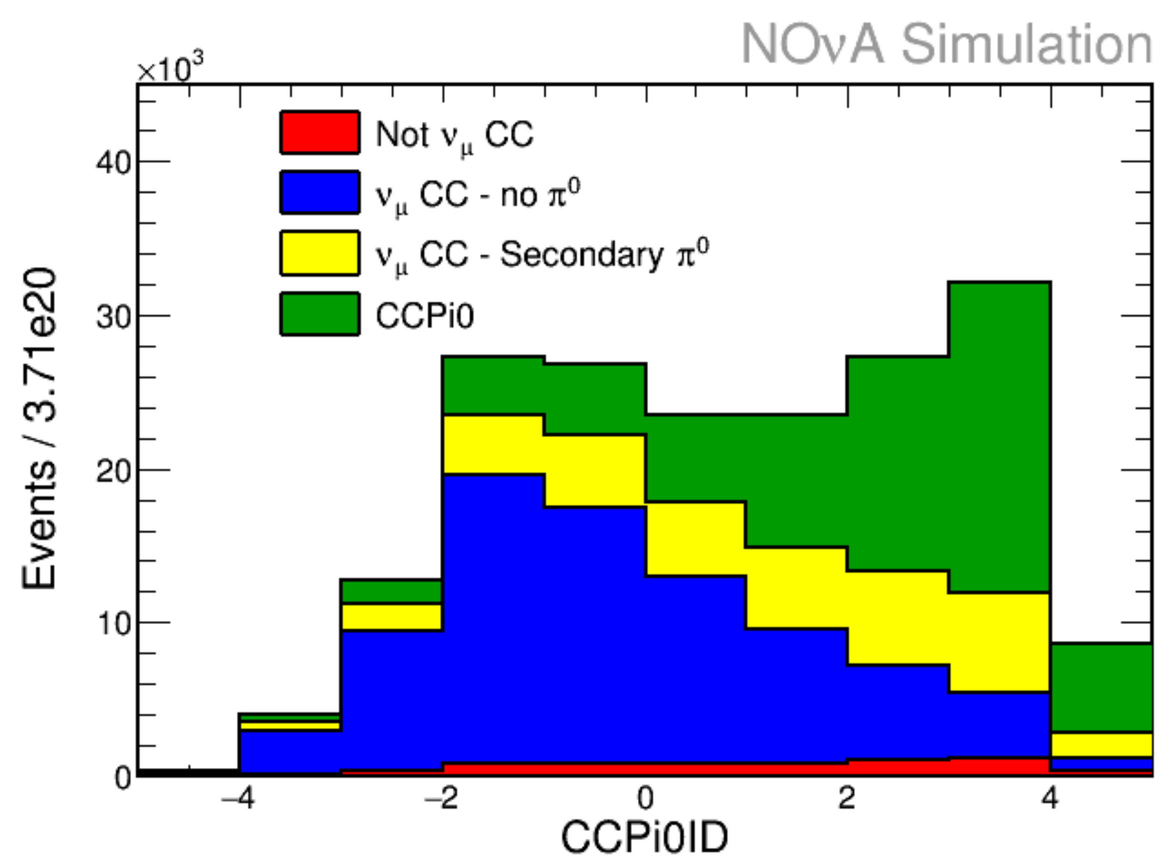


Use non-muon shower variables to form a π^0 identifier:

- Bragg peak identifier.
- Energy per hit.
- Photon gap from vertex.
- Number of missing planes.

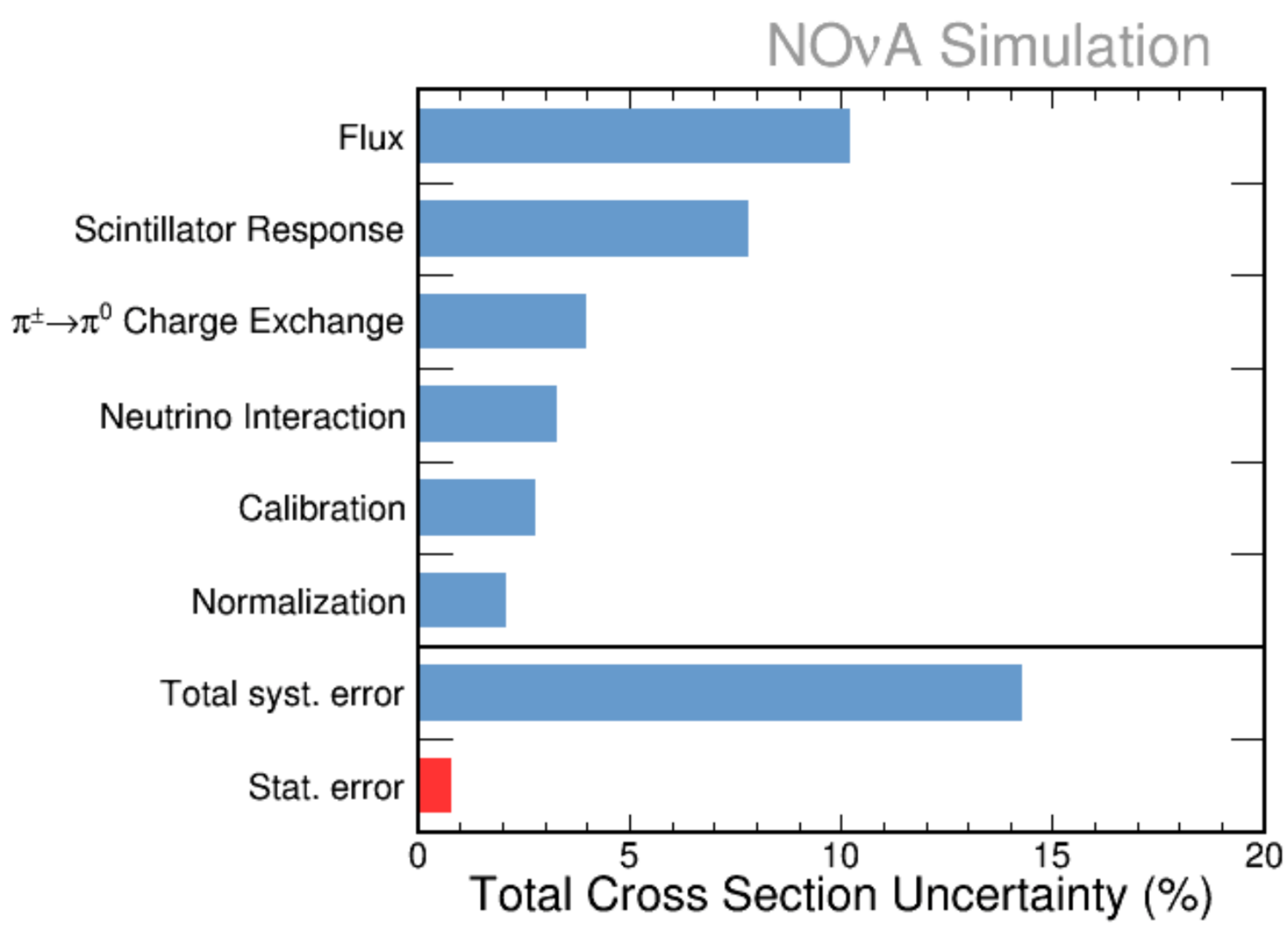
Fit signal and background MC to data in each kinematic bin.

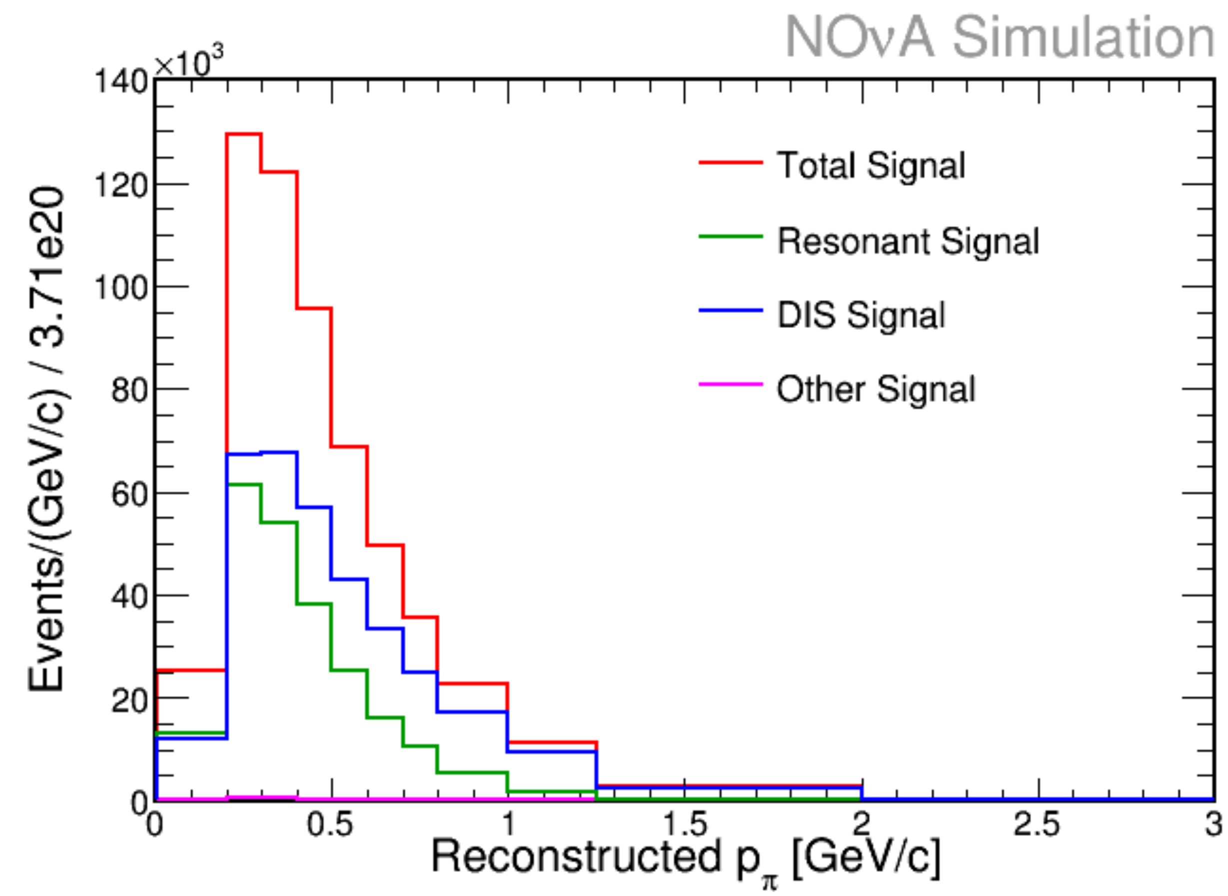




ν_μ CC π^0

- Signal is dominantly RES (38.3%) and DIS (61.3%).
- Uncertainty (~15%) is systematic dominant.

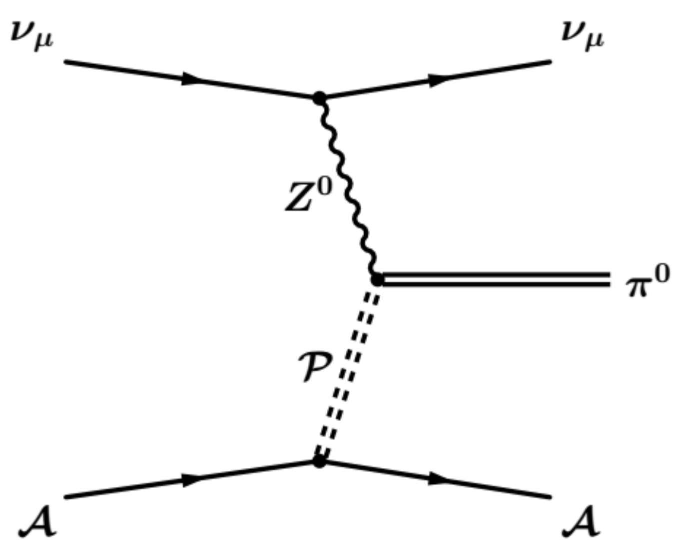




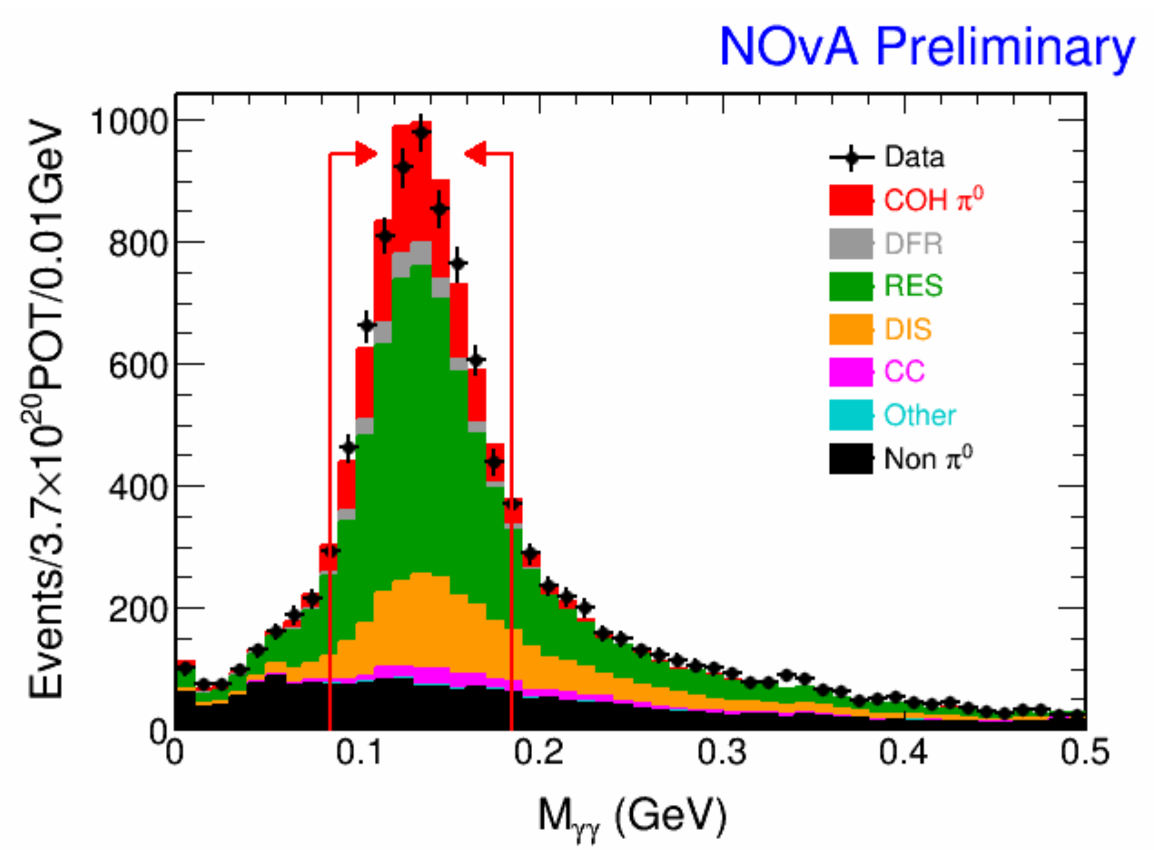
- Plan to report flux-averaged differential cross section in final state muon and pion kinematics.
- At final stage of internal review.

Results soon!

NC Coherent π^0



- Neutrino coherent scattering = small momentum transfer.
- Single forward-going pion, without other pions or nucleons.



To identify the NC π^0 sample:

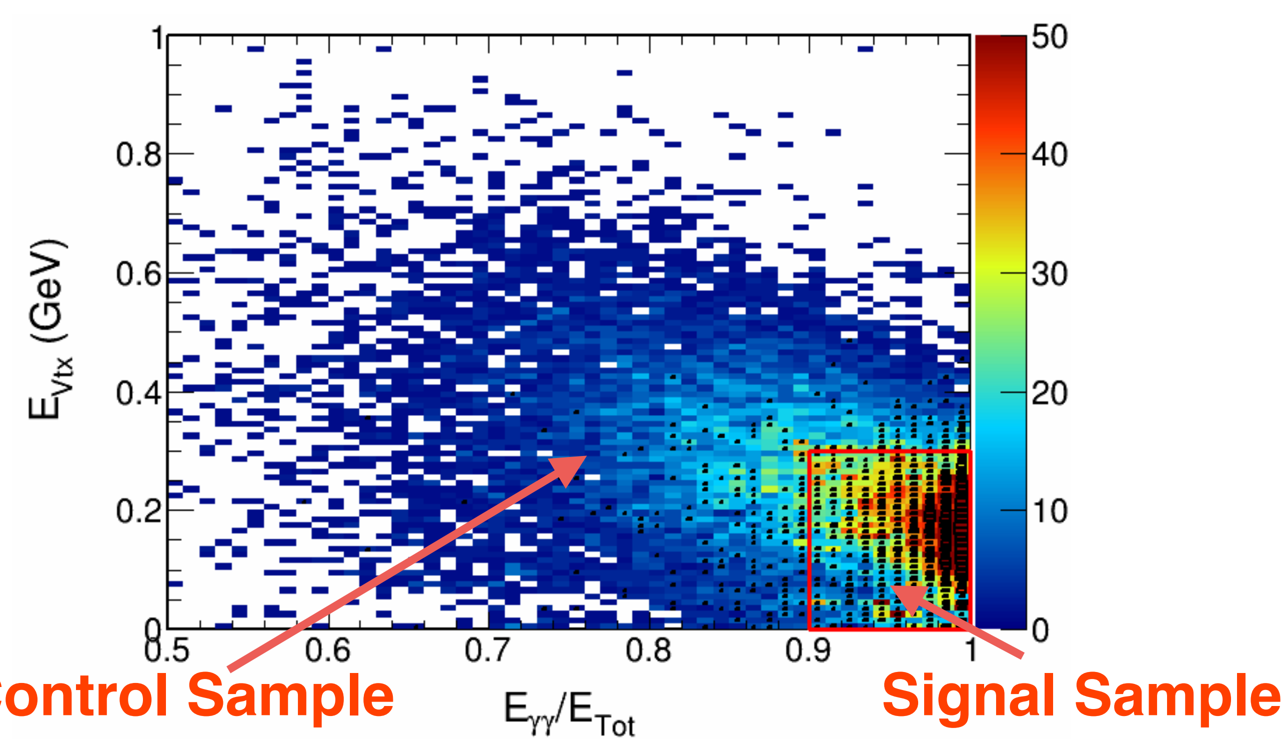
- Absence of muon.
- Two showers identified as photons by dE/dx-based likelihoods.
- Cut on invariant mass to select π^0s

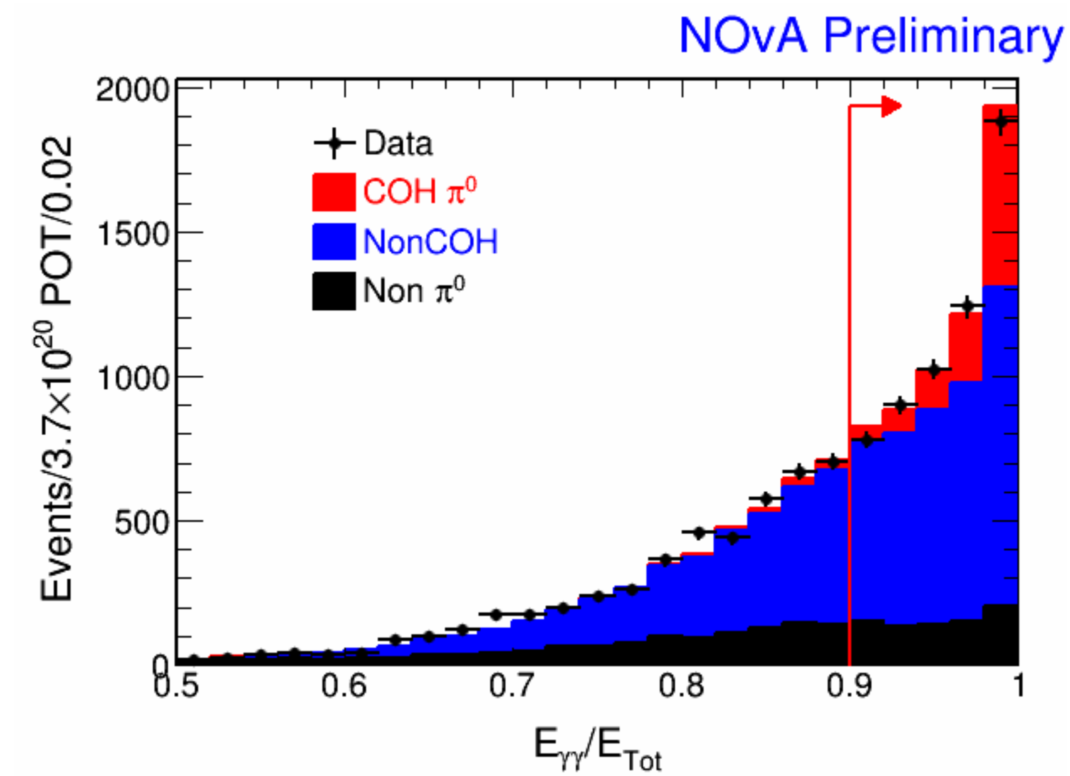
Main background is RES and DIS π0s.

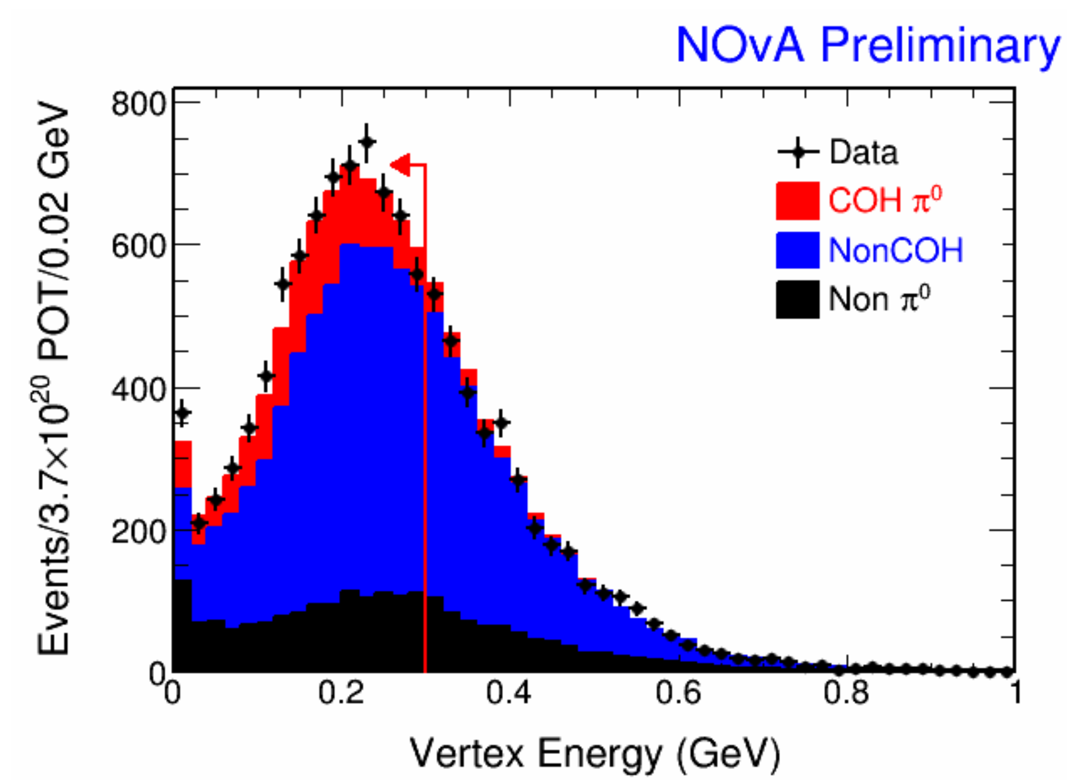
NC Coherent π^0

Divide the NC π^0 into two sub-samples:

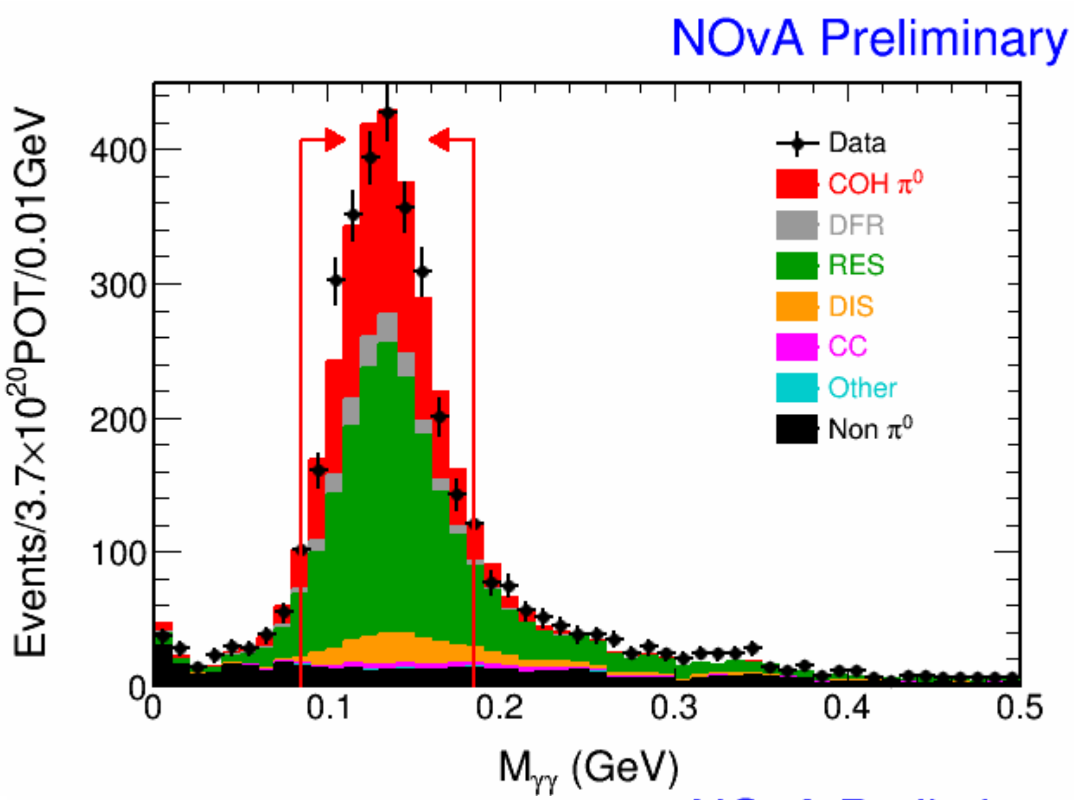
- **Signal sample:** events with most of their energy in the 2 photon showers and low vertex energy: it has >90% of the signal.
- **Control sample:** the events with extra energy other than the photons or in the vertex region, dominated by non-coherent π^0 s (RES and DIS).



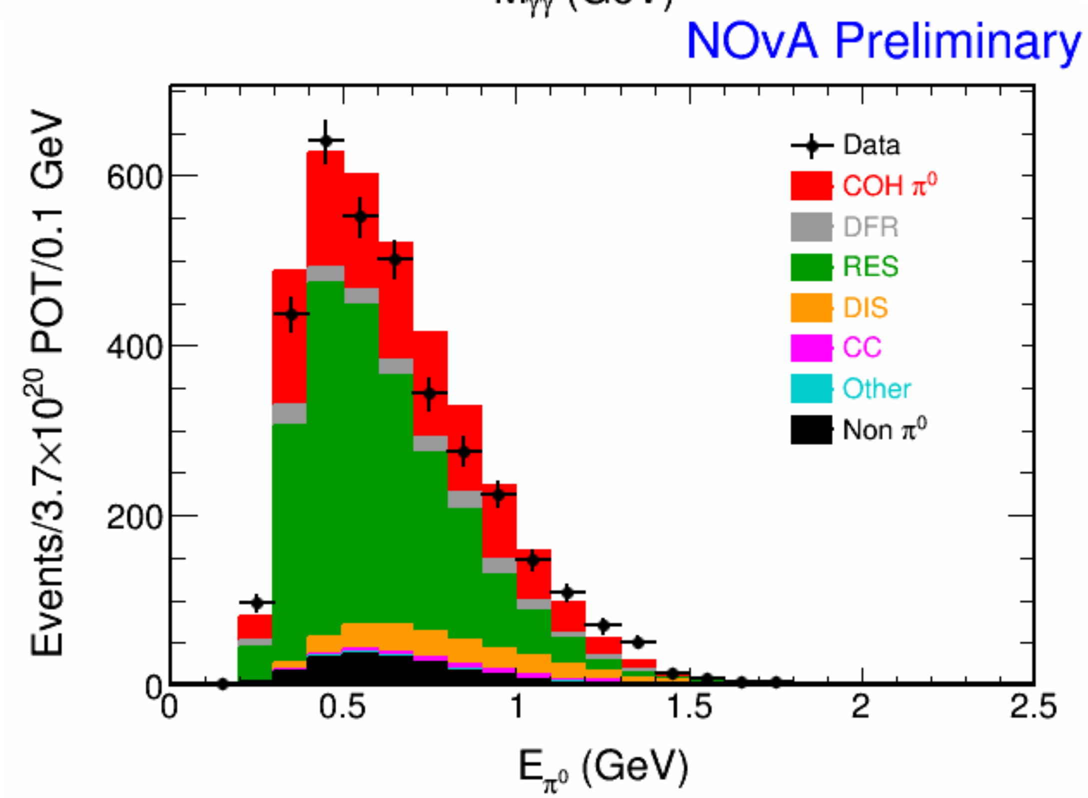


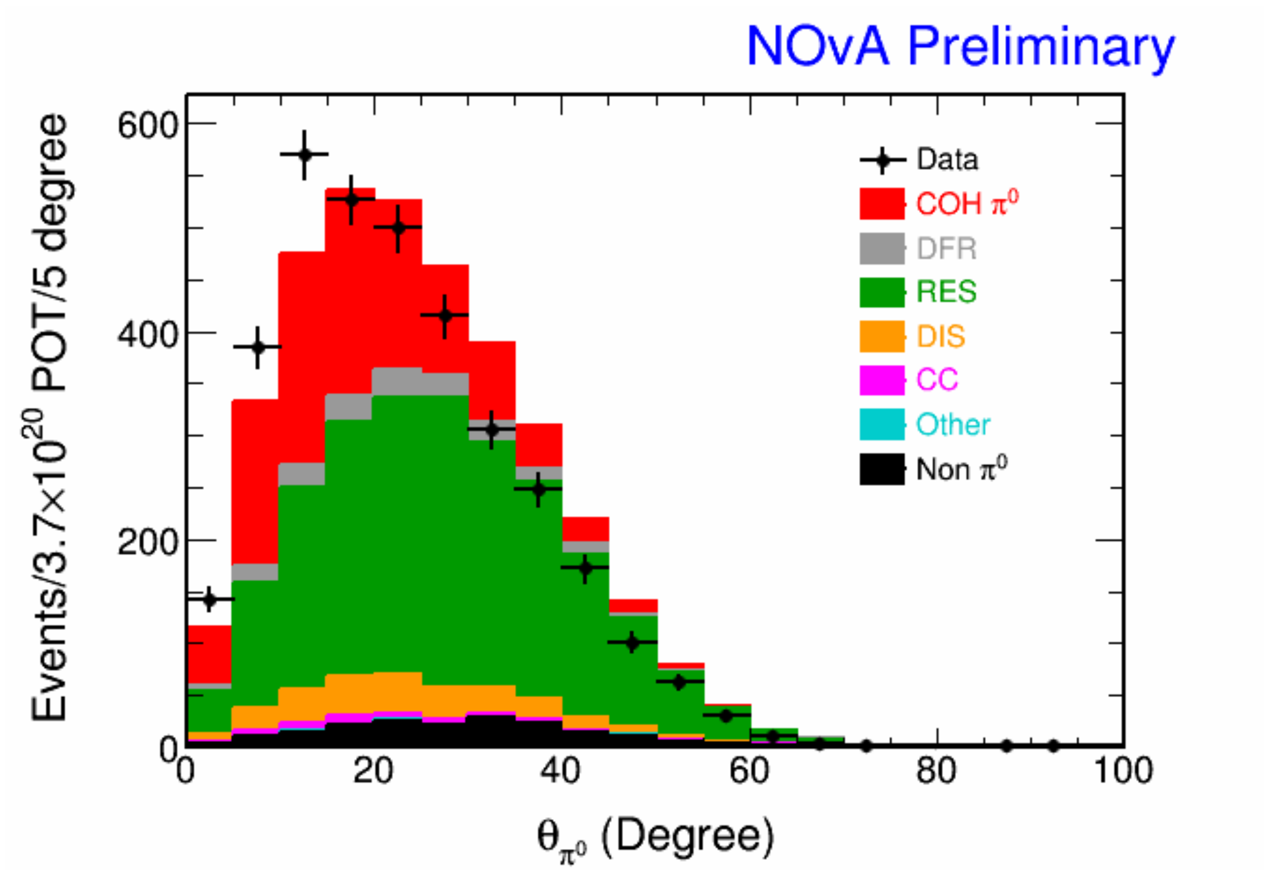


NC Coherent π^0

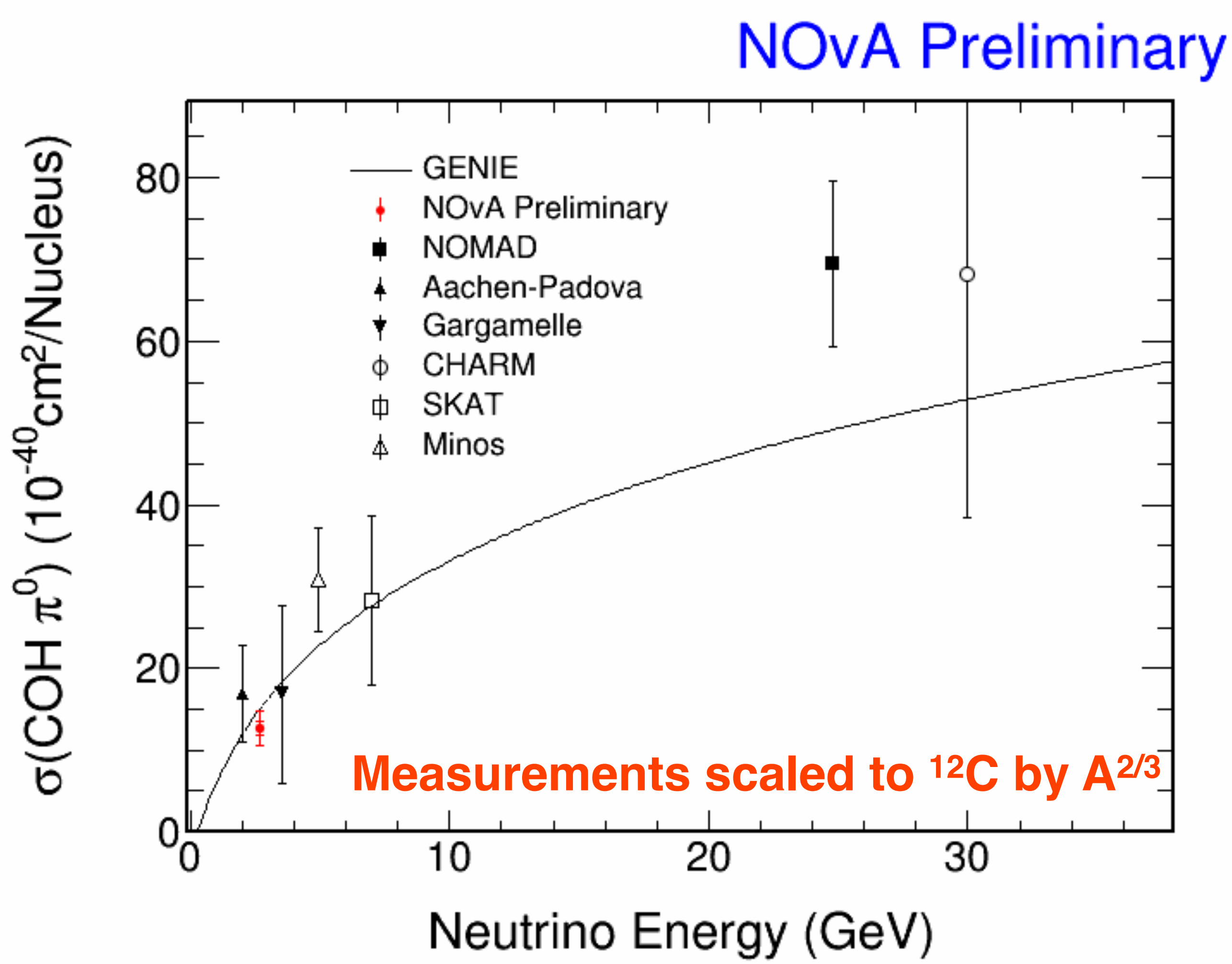


- Fit the backgrounds to control sample data in $\pi 0$ energy vs angle 2D space.
- Background fit result are applied to the backgrounds in the signal sample.





NC Coherent π^0



Source	$\delta(\%)$
Calorimetric Energy Scale	3.4
Background Modeling	10.0
Control Sample Selection	2.9
EM Shower Modeling	1.1
Coherent Modeling	3.7
Rock Event	2.4
Alignment	2.0
Flux	9.4
Total Systematics	15.3
Signal Sample Statistics	5.3
Control Sample Statistics	4.1
Total Uncertainty	16.7

- Renormalised background using energy and angle 2D space.
- Measured flux-averaged cross-section using background subtraction:

$\sigma = 14.0 \pm 0.9(\text{stat.}) \pm 2.1(\text{syst.}) \times 10^{-40} \text{cm}^2/\text{nucleus}$

- Total uncertainty 16.7%, systematic dominant

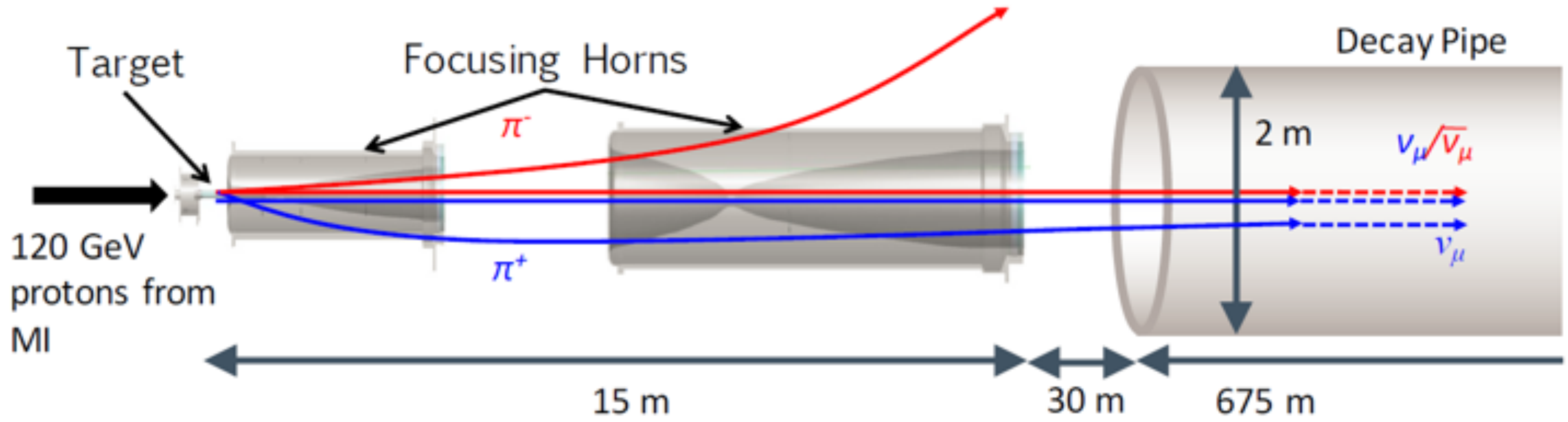
Summary and future plans

- The NOvA experiment has excellent opportunities to make high precision measurements of neutrino-nucleon/nucleus interactions
- 8×10^{20} POT neutrino ND dataset:
  - systematics-limited inclusive and CC neutral pion production measurement to be released this year
  - CC charged pion production and NC neutral pion production measurements are in progress
- 3×10^{20} POT antineutrino ND dataset —> inclusive measurement are high priority for NOvA
- Stay tuned for results soon!

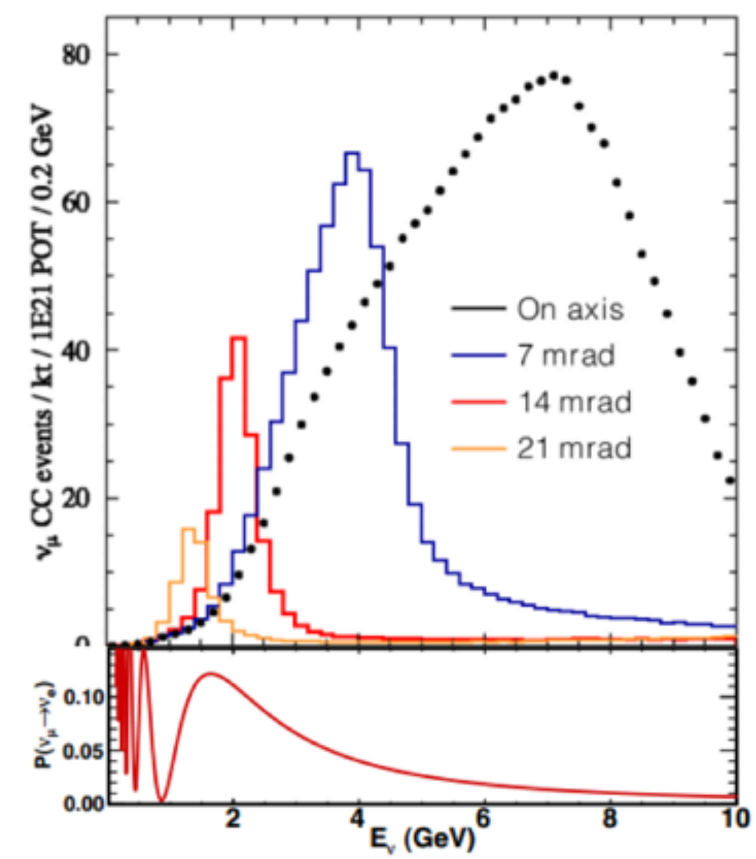

Thank you!
NOvA
Fermilab

Neutrino beam

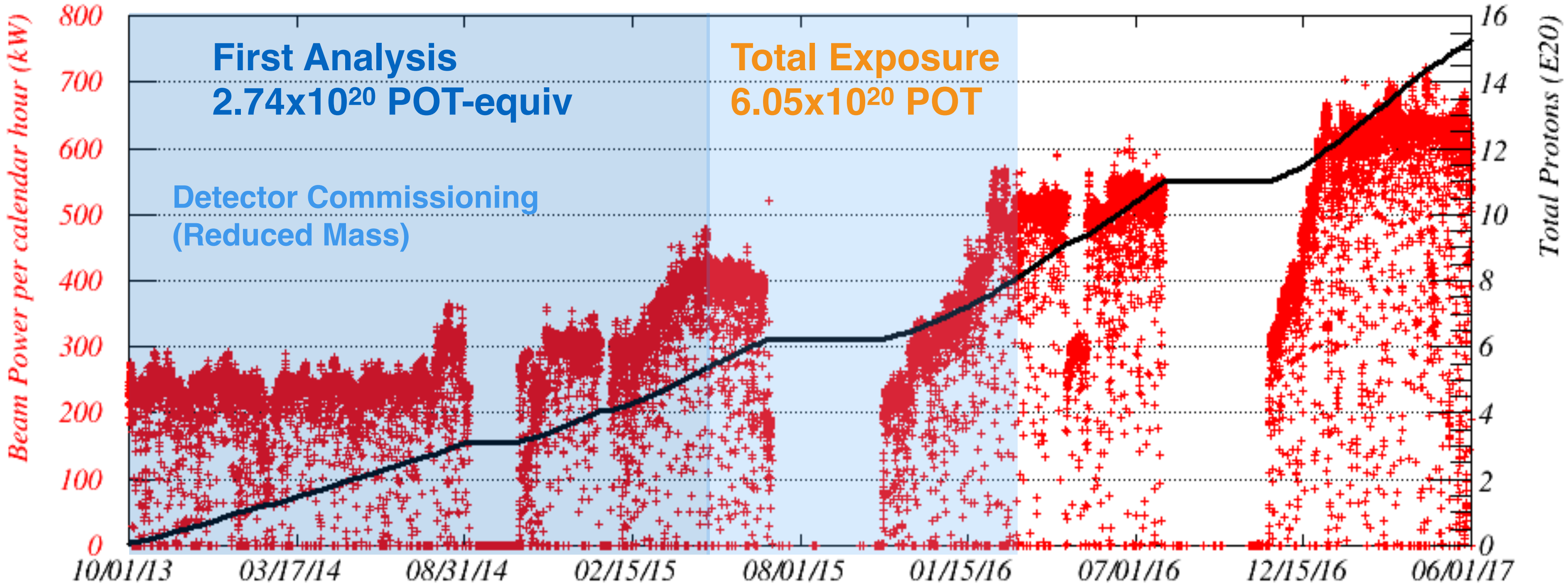
NuMI Beam



- 120 GeV protons extracted from the Main Injector at Fermilab in 10 μs spills
- Focus secondary pions using magnetic horns
  - Positive hadrons for neutrino beam
  - Negative hadrons for antineutrino beam
- Decay kinematics mean a detector at 14.6 mrad sees a narrowly peaked energy spectrum
- Beam 97.5% ν_μ with 0.7% ν_e and 1.8% wrong-sign



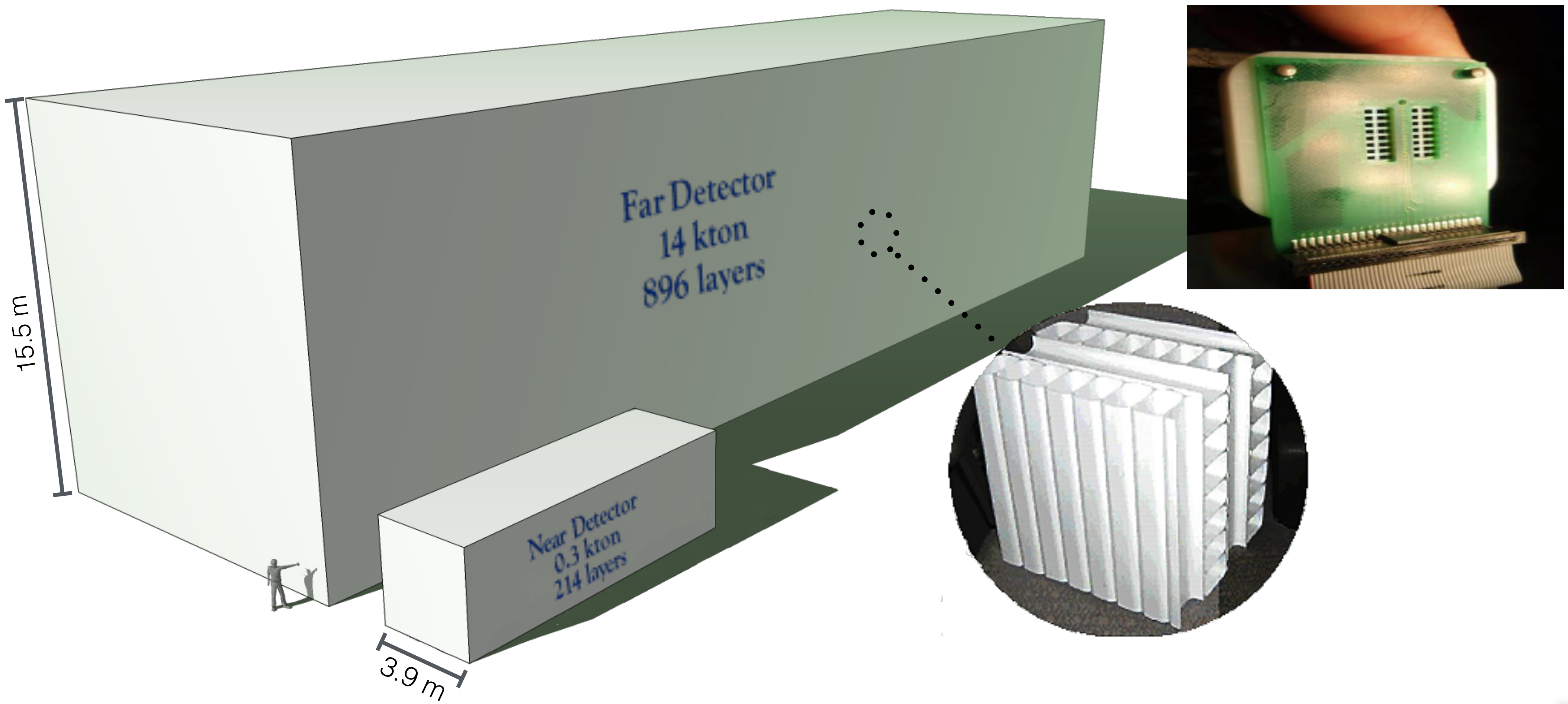
NuMI beam performance

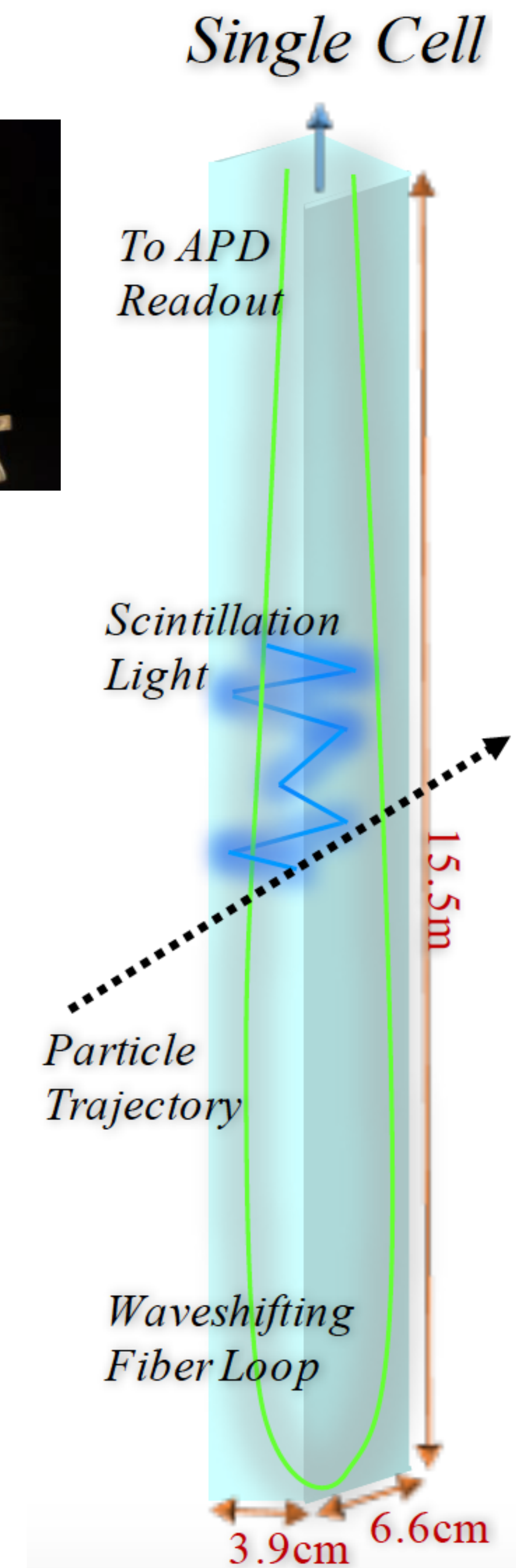


Switched to antineutrinos on Feb 20th 2017

- Present results data collected between February 6, 2014 and May 2, 2016
- Equivalent to $6.05\text{x}10^{20}$ protons-on-target in a full 14 kT detector
- Beam had been running at 560 kW
- **Achieved 700 kW design goal, most powerful neutrino beam in the world**

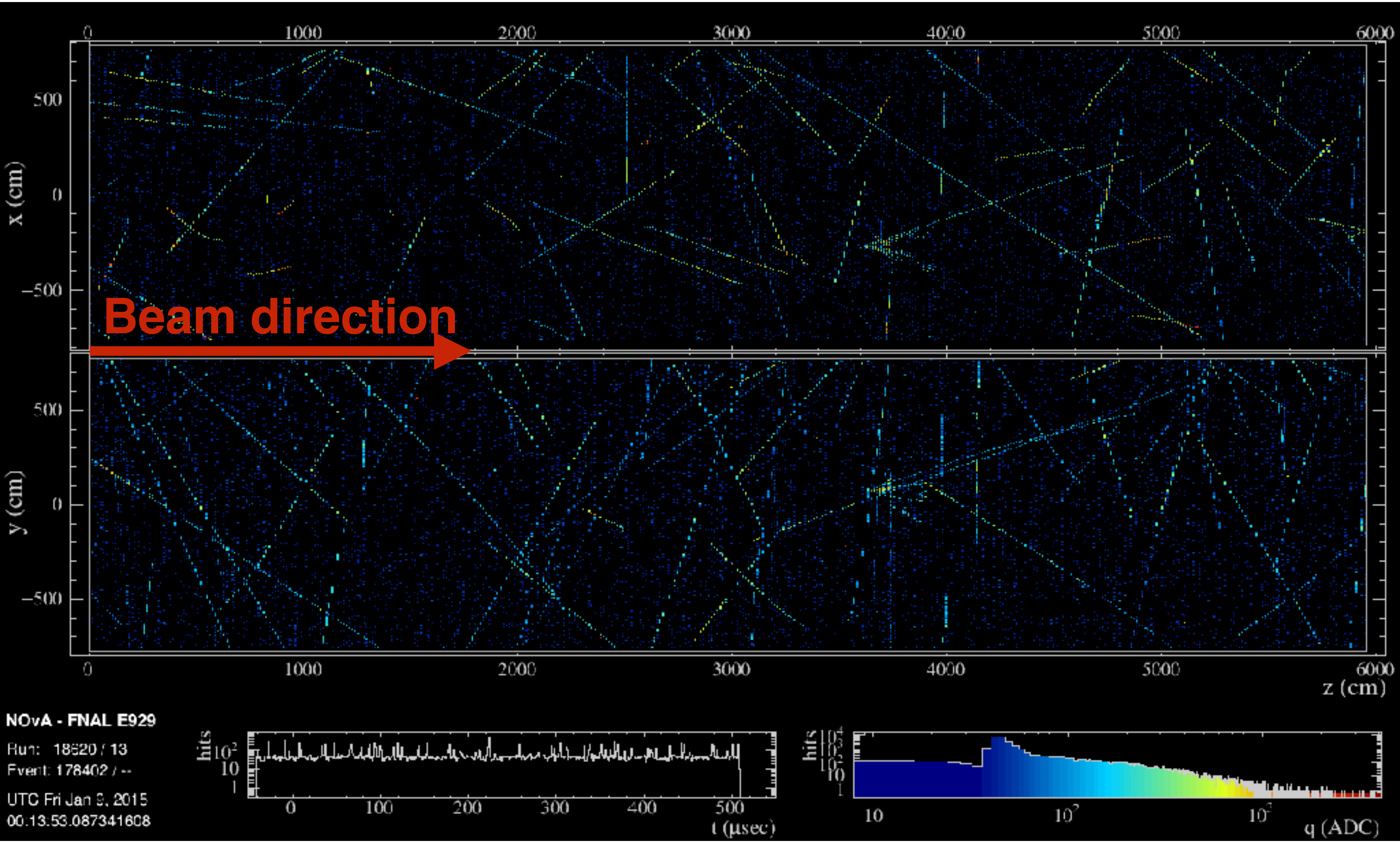
NOvA detectors





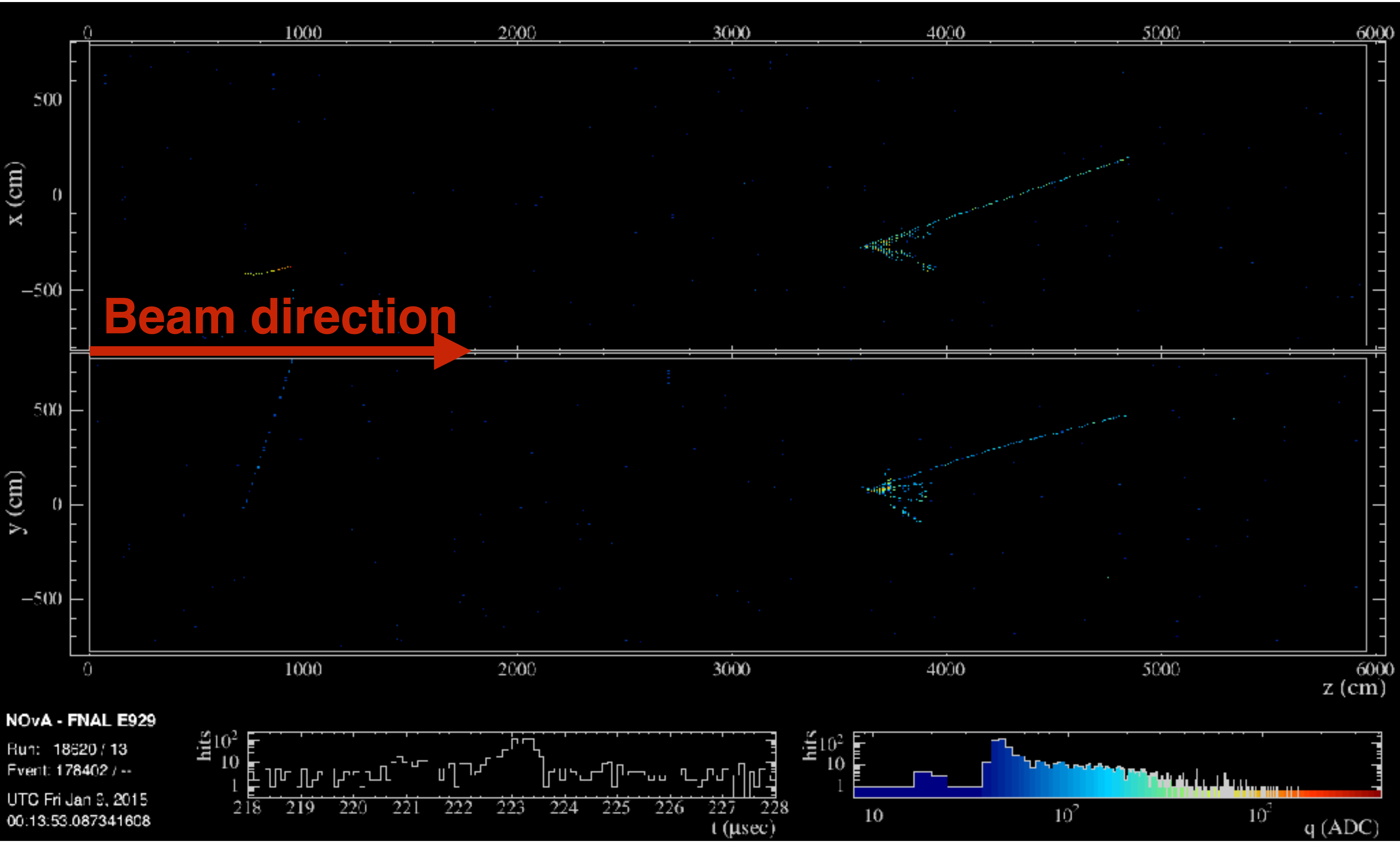
- Two functionally identical detectors
- Extruded plastic cells alternating vertical and horizontal orientation filled with liquid scintillator
- Charged particles passing through cells produce light which is collected.

Far Detector 550 µs Readout Window



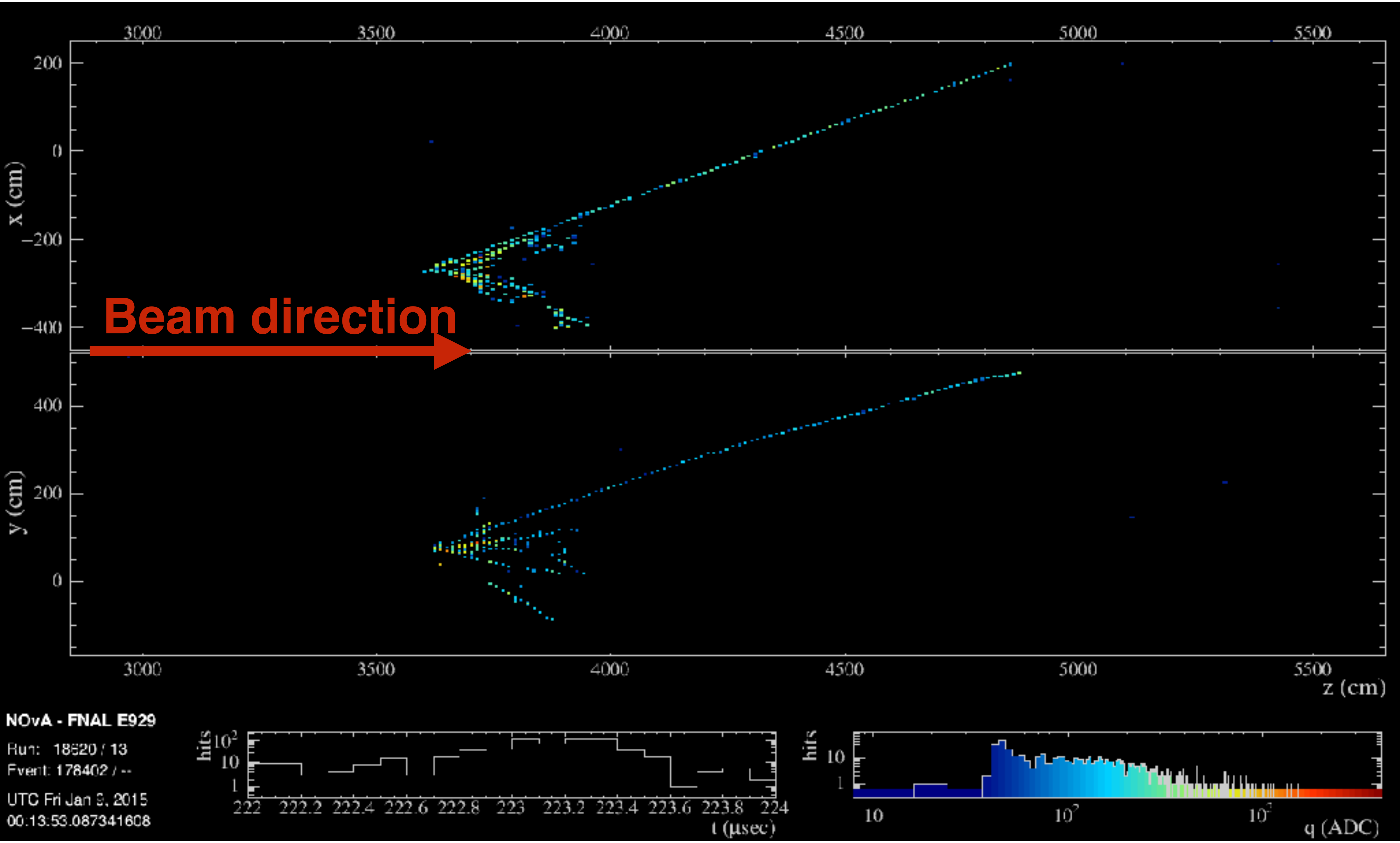
Cell hits coloured by recorded charge (~photoelectrons)

Far Detector 10 μs NuMI Beam Window



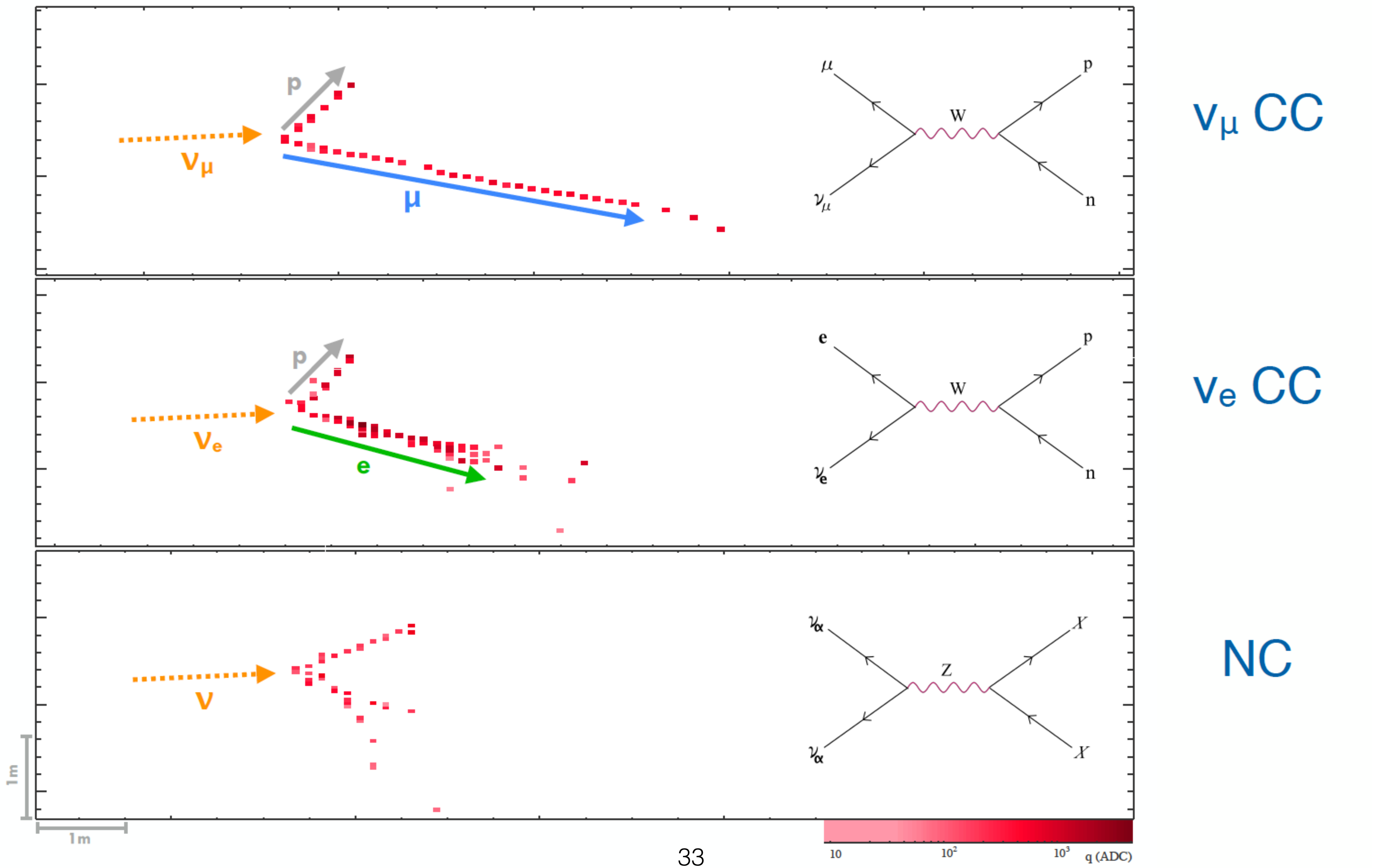
Cell hits coloured by recorded charge (~photoelectrons)

Far Detector Neutrino Interaction



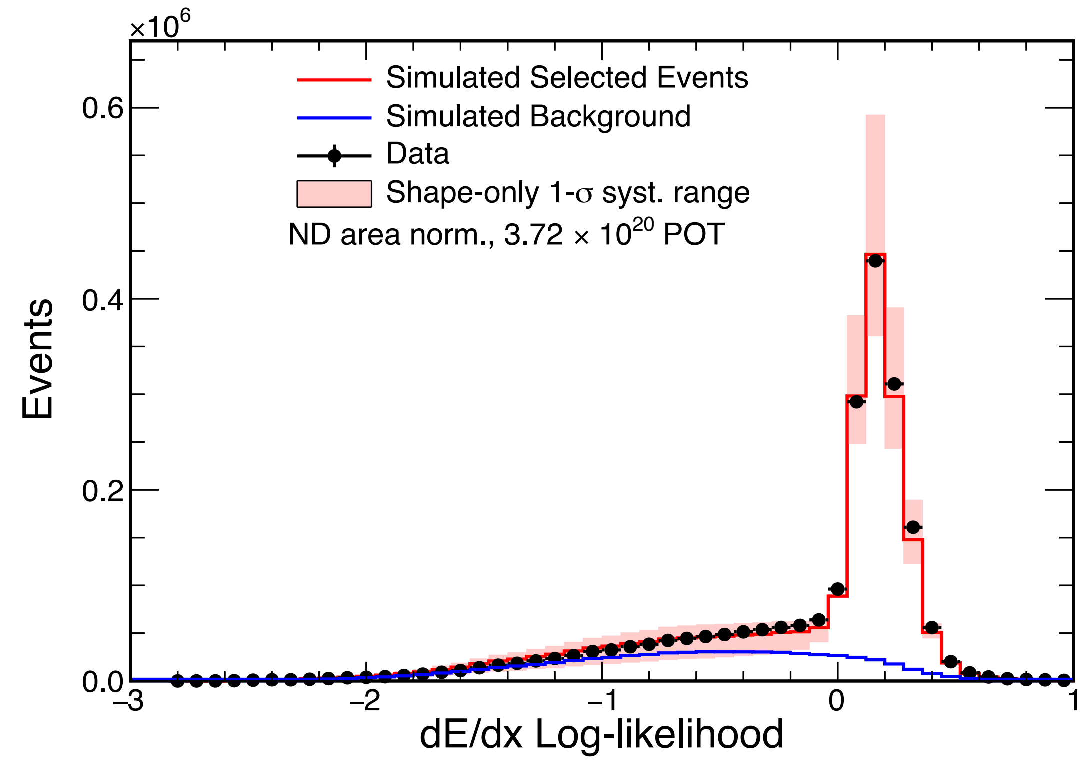
Cell hits coloured by recorded charge (~photoelectrons)

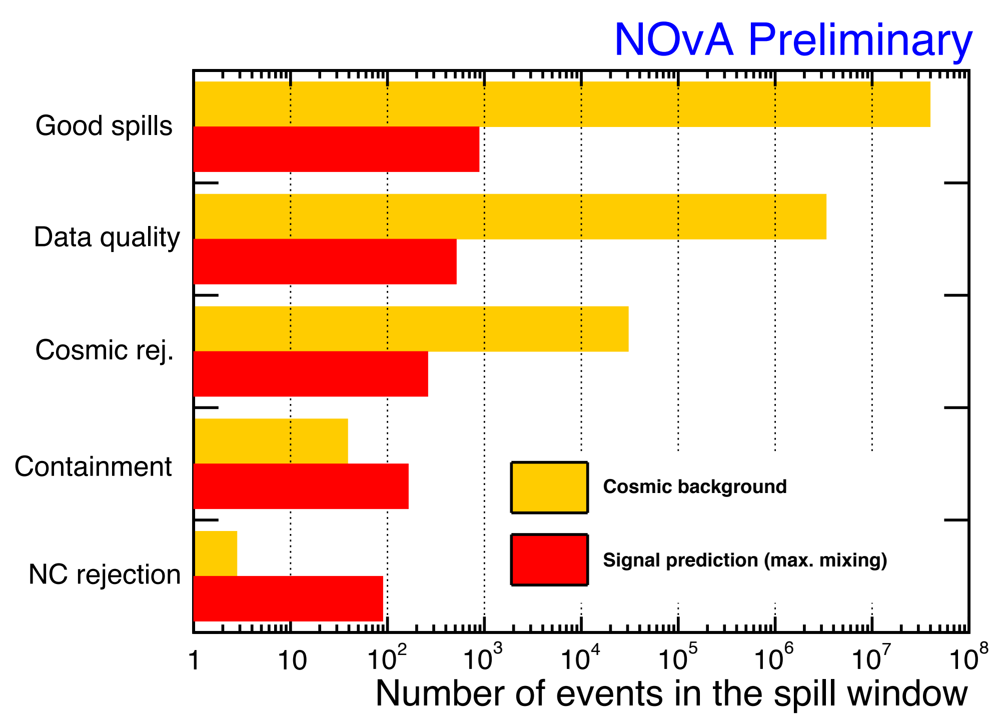
Event topologies

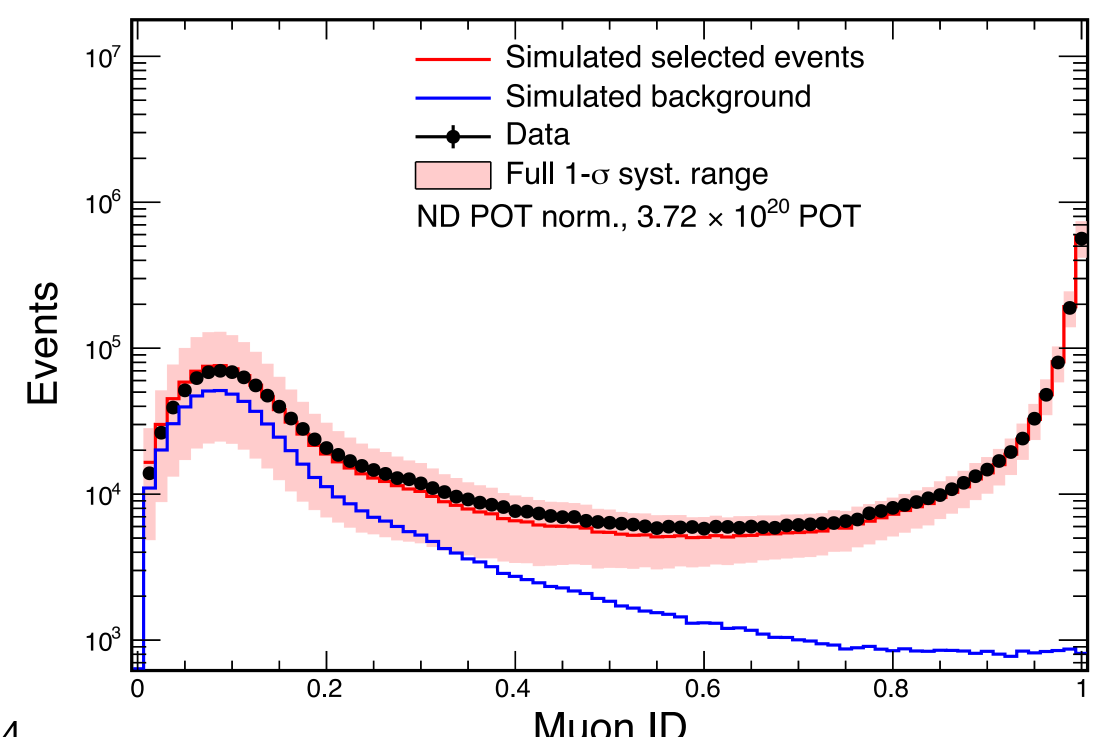


Muon neutrino selection

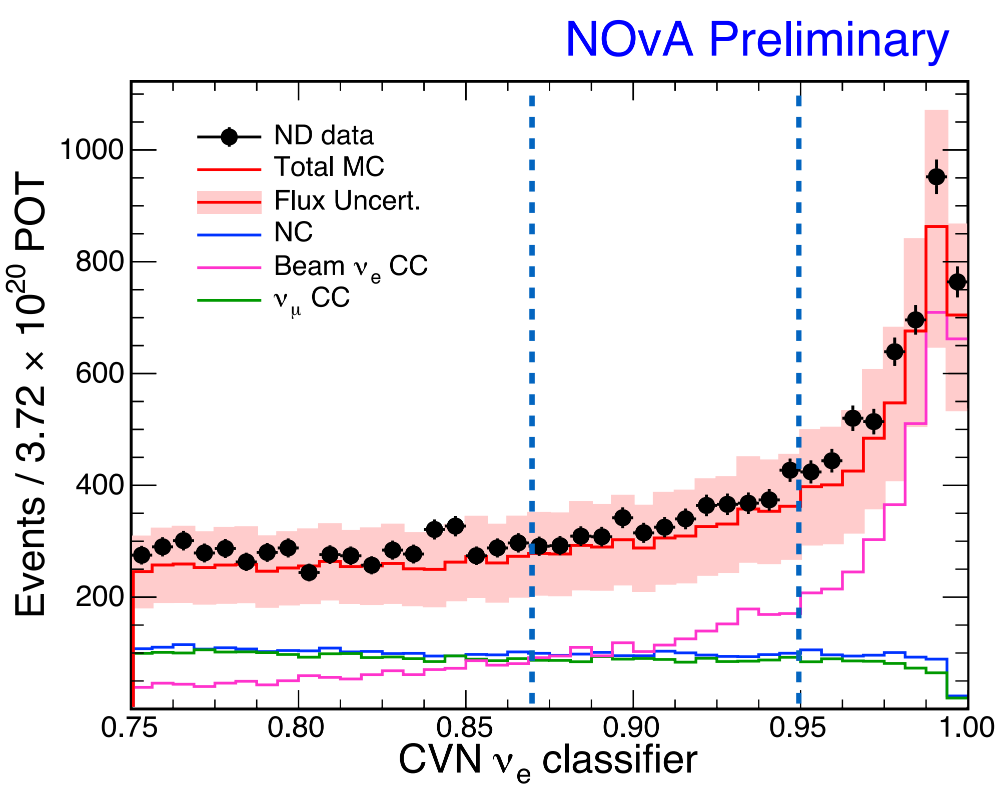
- Separate νμ CC interactions from NC and cosmic-ray backgrounds
- Use 4 variable k-Nearest Neighbour to select μ
- Selection is 81% efficient and 91% pure
- Containment cuts remove activity near walls
- Additional Cosmic rejection from event topology and Boosted Decision Tree

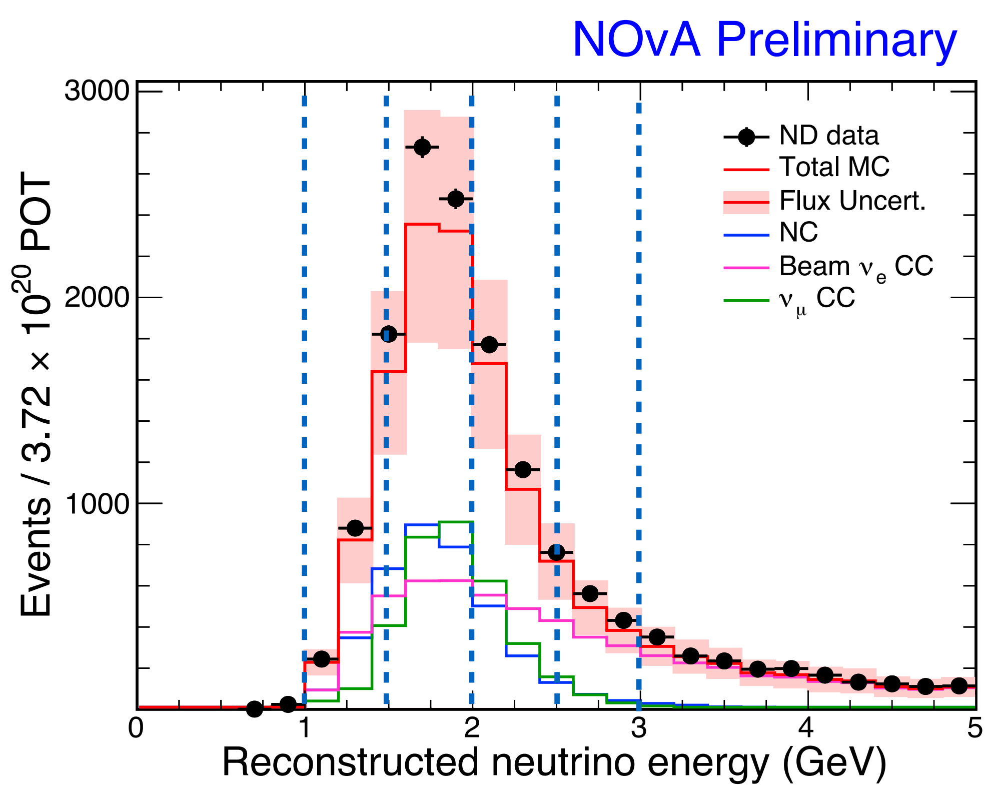






Electron neutrino selection



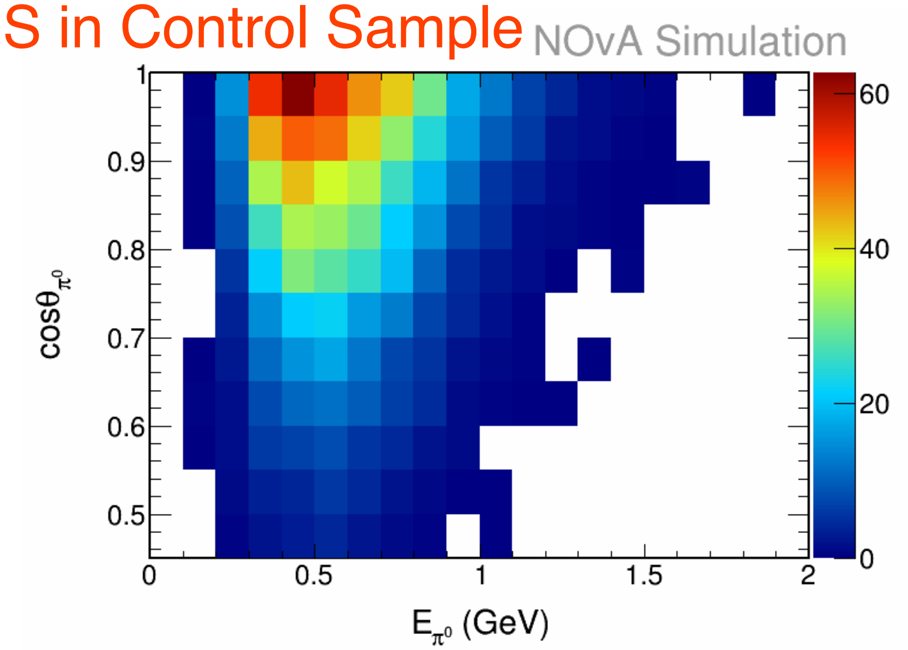


- 73% ve CC selection efficiency, 76% purity with CVN classifier
- Good ND Data/MC agreement
- CVN provides better cosmic rejection and similar systematics to 2015 classifiers
- Bin analysis in 3 bins of CVN and 4 bins of energy

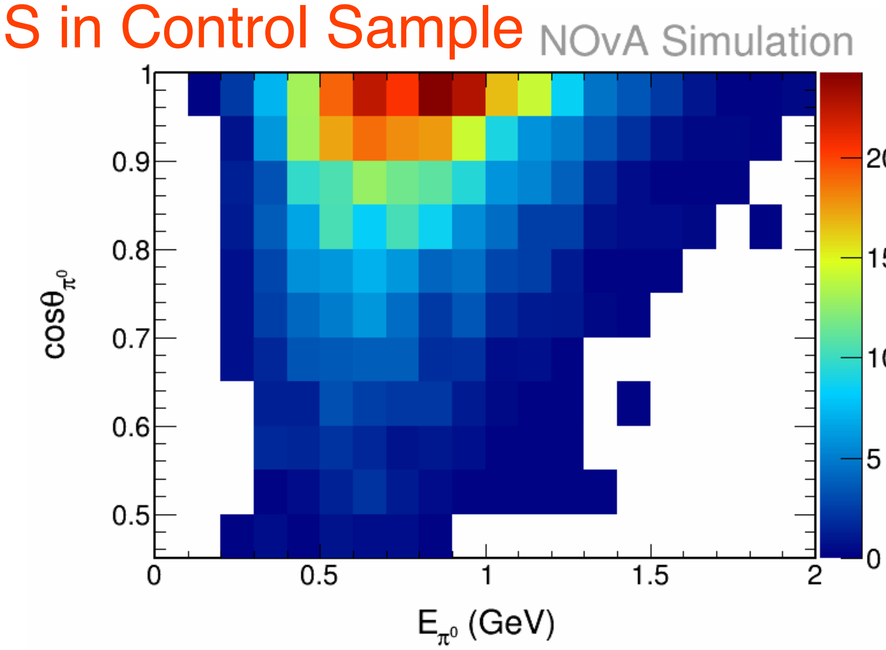
NC Coherent pi0

Fit the backgrounds to control sample data in π_0 energy vs angle 2D space.

RES in Control Sample

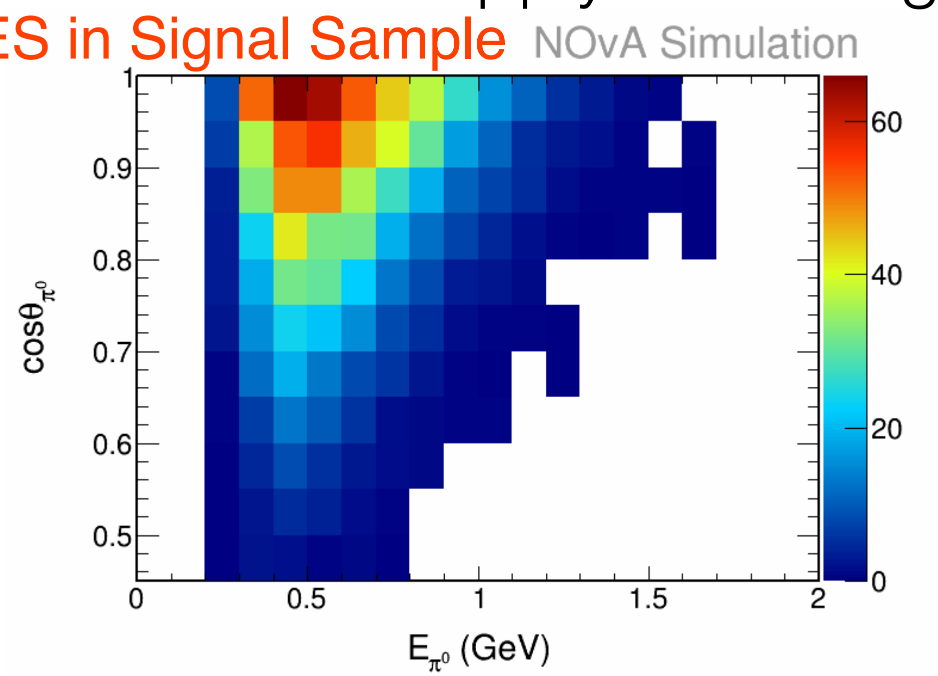


DIS in Control Sample

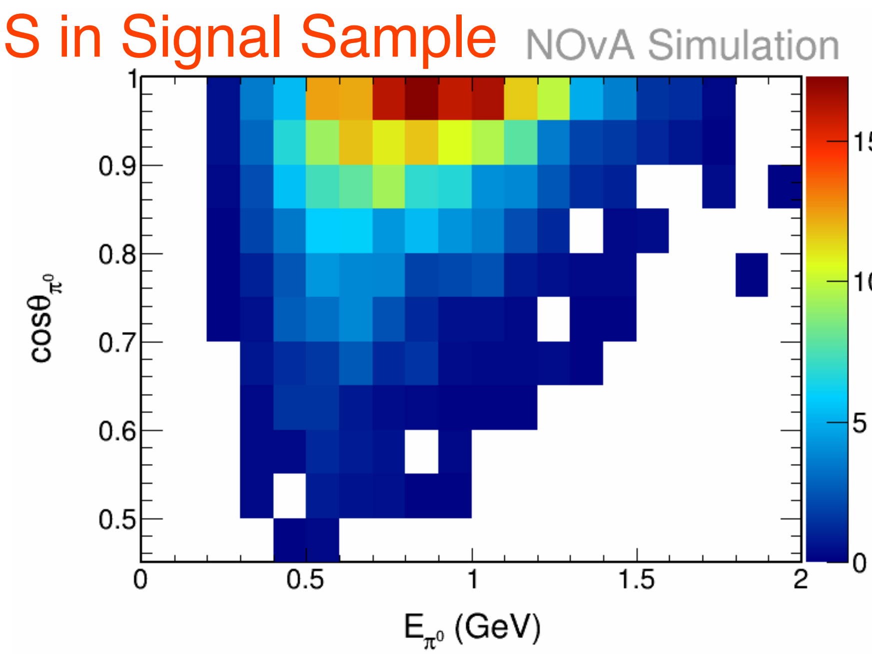


Apply the background tuning to the signal sample.

RES in Signal Sample



DIS in Signal Sample



Bragg Peak Identifier

- The Bragg Peak Identifier (BPI) is a measure of the increase in dE/dx towards the end of a prong.
- The BPI value is defined for prongs with Nhit ≥ 4 as the ratio of average energy deposit in the furthest min(6, Nhit/2) hits from the prong start point to the average energy deposit in the rest of the prong.
- Here, Nhit/2 is always rounded down.