Inclusive ν-A CC Interactions in the NOvA Near Detector

Jonathan Paley, for the NOvA Collaboration

NuINT 2017, Toronto

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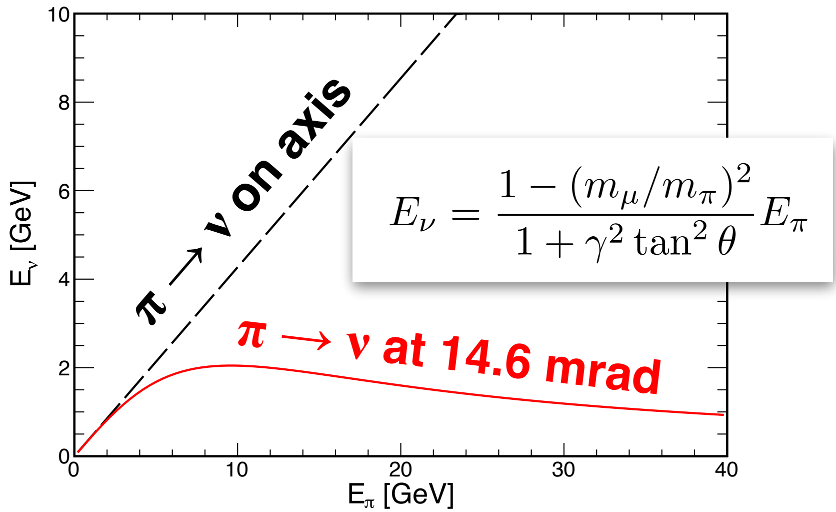
Outline

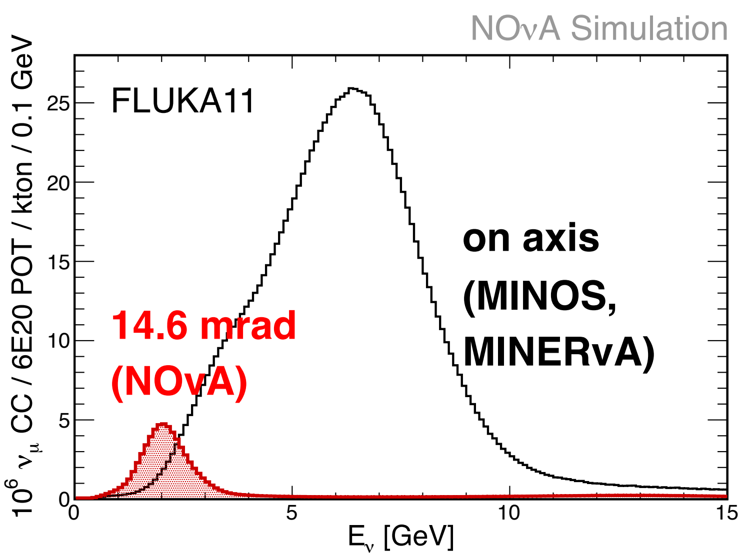
- Overview of the NOvA beam, detector and simulation
- Measurements:
  - ν_μ CC inclusive
  - ν_e CC inclusive

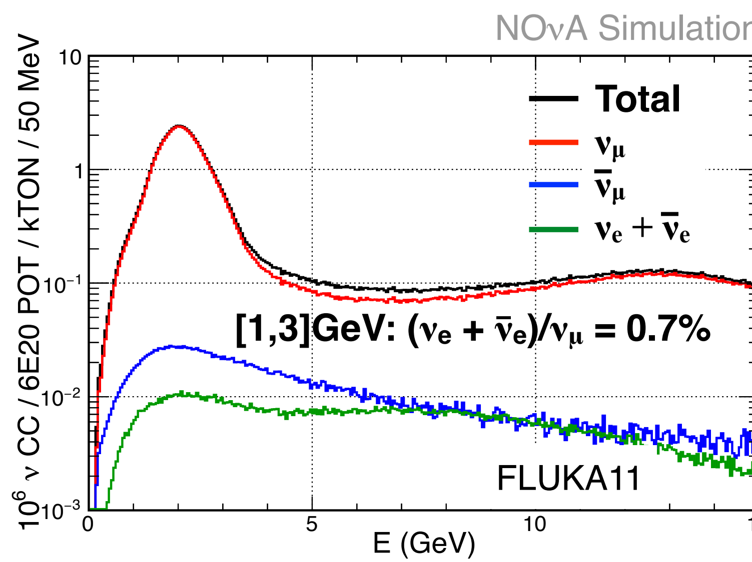
  } phase space, event selection, efficiency, purity and preliminary systematics
- Summary and outlook

A Reminder of the Beam at NOvA



- Off-axis position w.r.t. NuMI beam results in:
  - narrow-band beam centered around 2 GeV
  - small flux shape uncertainties. Hadron production uncertainties are mostly a normalization effect.
- 95% pure ν_μ beam





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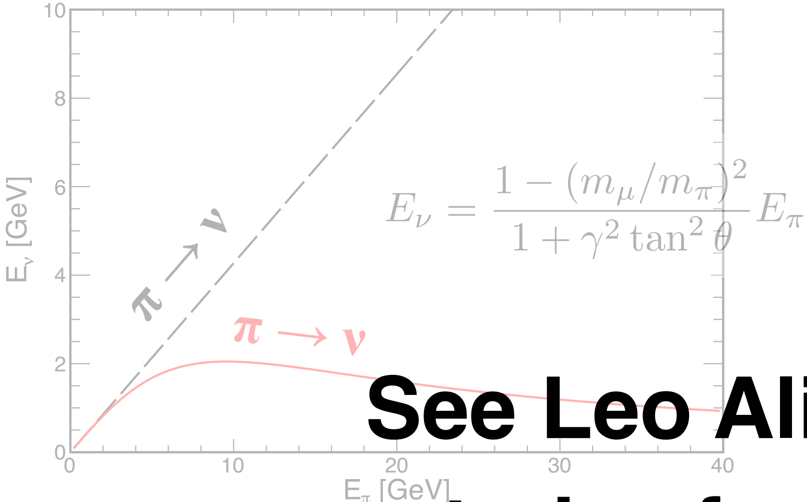

$$E_\nu = \frac{1-(m_\mu/m_\pi)^2}{1+\gamma^2\tan^2\theta}E_\pi$$

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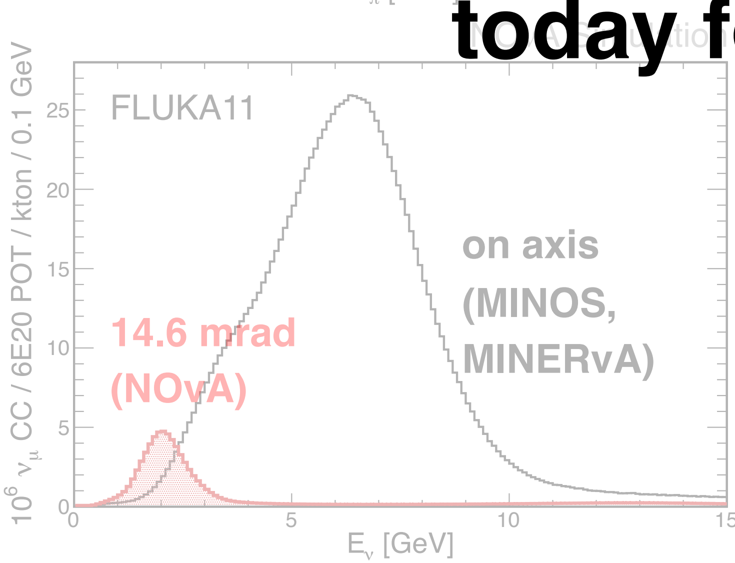
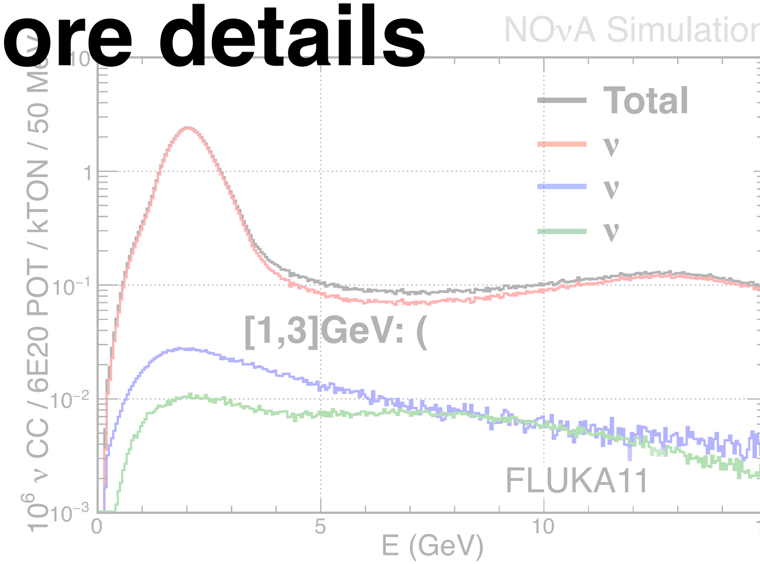
- 95% pure

See Leo Aliaga's talk later today for more details





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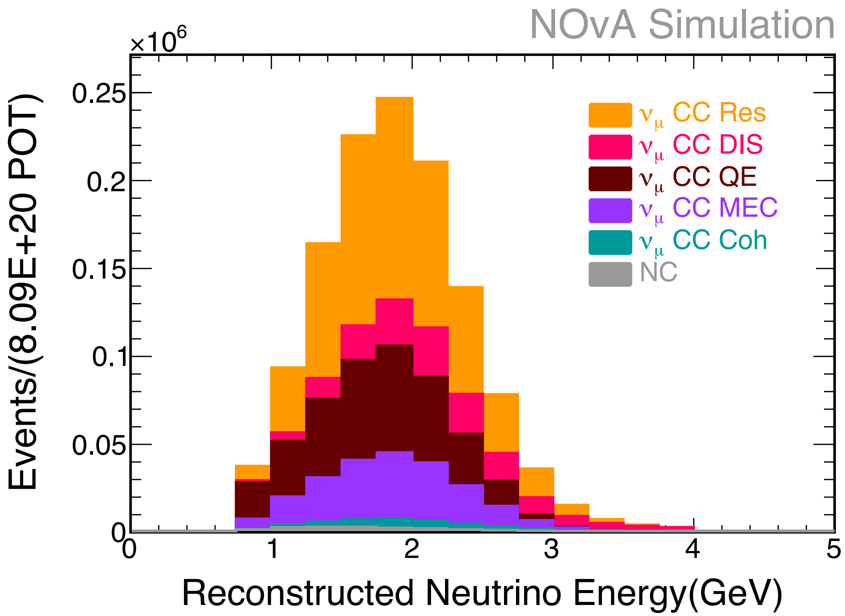

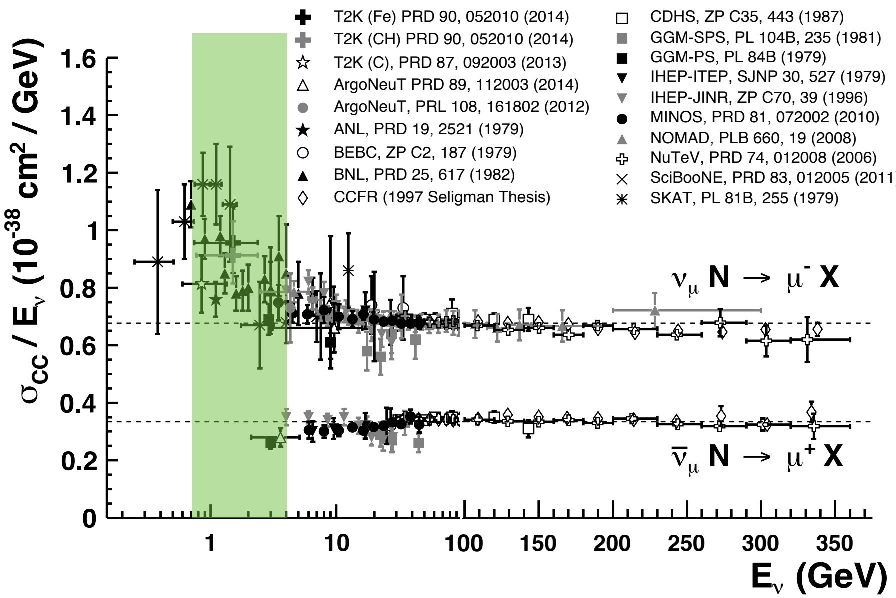

- Even with a narrow band beam, NOvA is still sensitive to many different nu+A interaction channels.
- Cross sections in NOvA's energy range are not well measured, no measurements below 3 GeV for antineutrinos.

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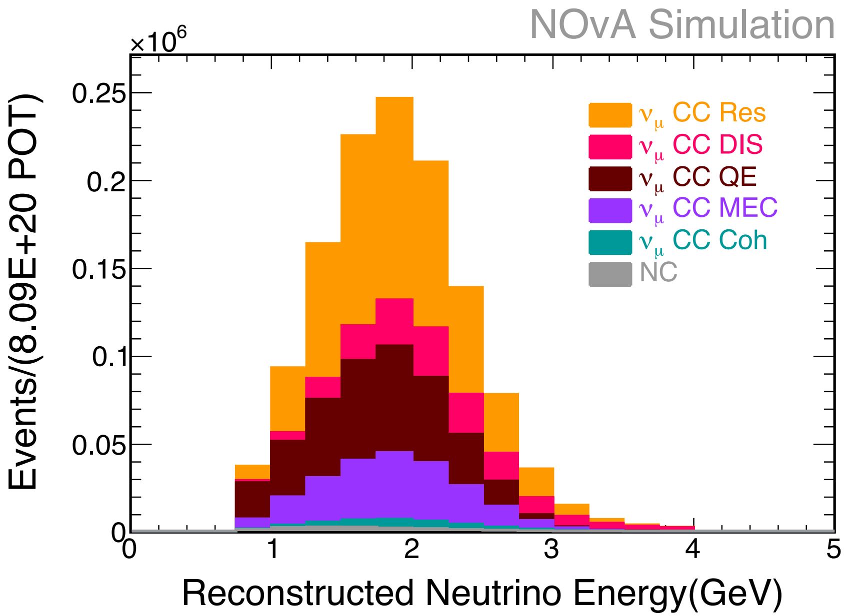
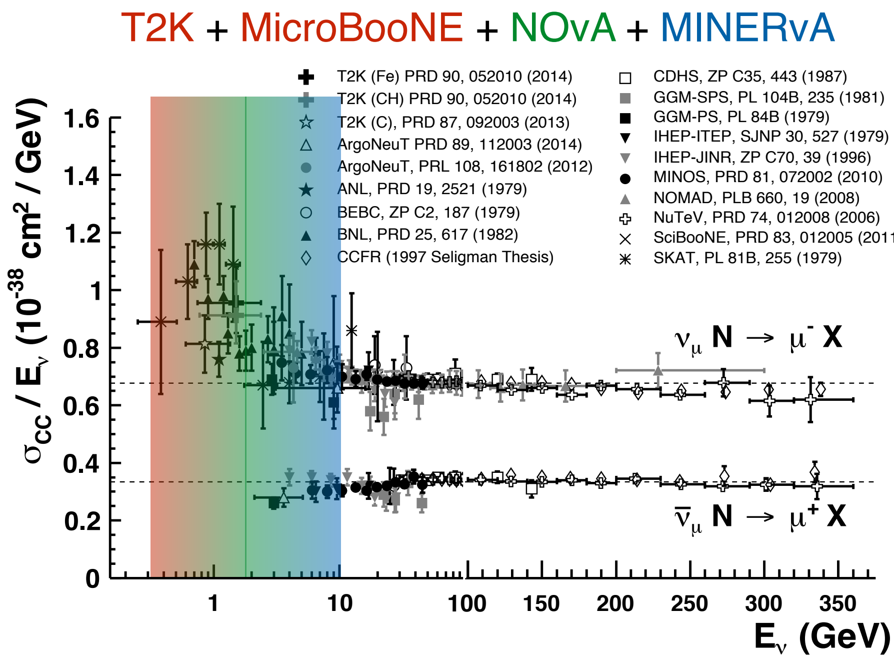
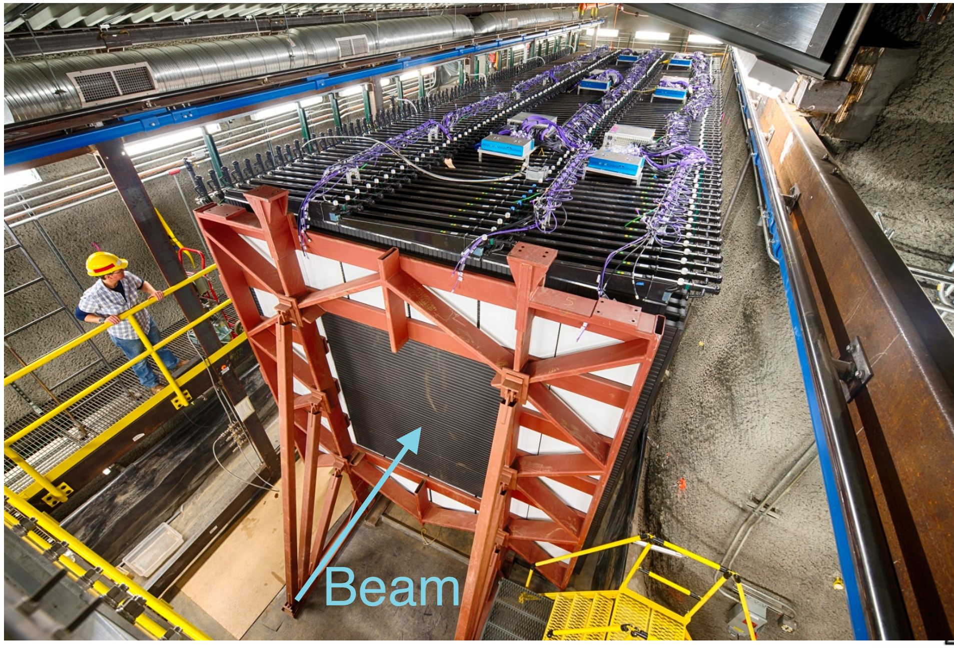
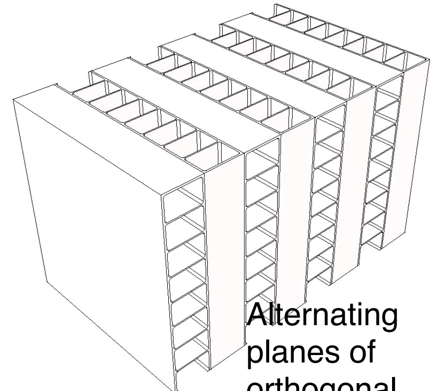




- Even with a narrow band beam, NOvA is still sensitive to many different nu+A interaction channels.
- Cross sections in NOvA's energy range are not well measured, no measurements below 3 GeV for antineutrinos.
- Nice overlap with other currently running experiments.

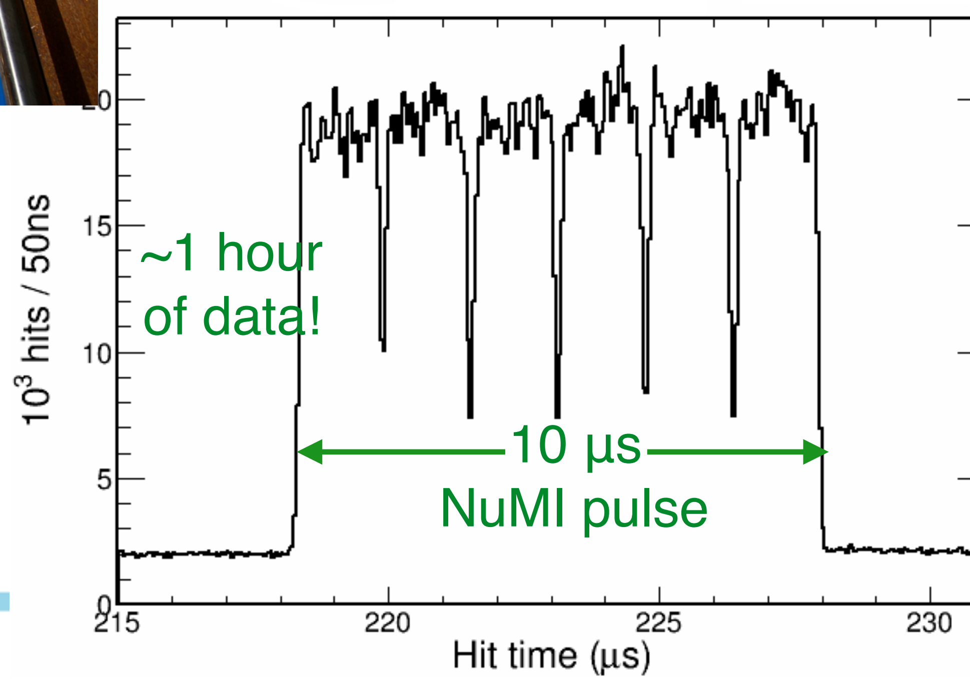
The NOvA Near Detector





Wavelength-shifting fibers routed to a single cell on an Avalanche Photodiode (APD).

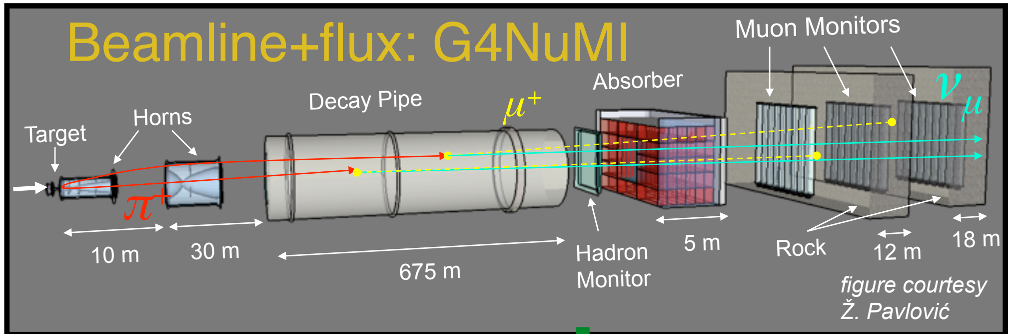
NOvA ND Data

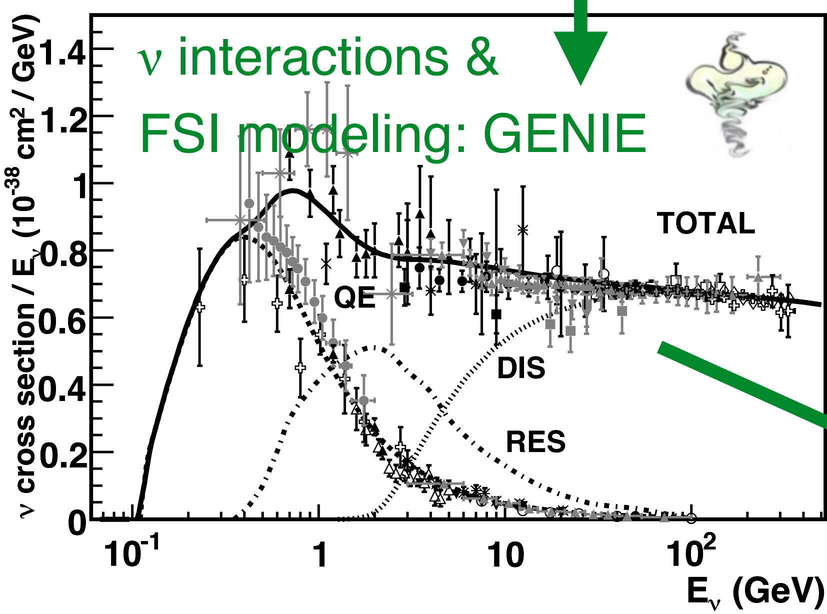


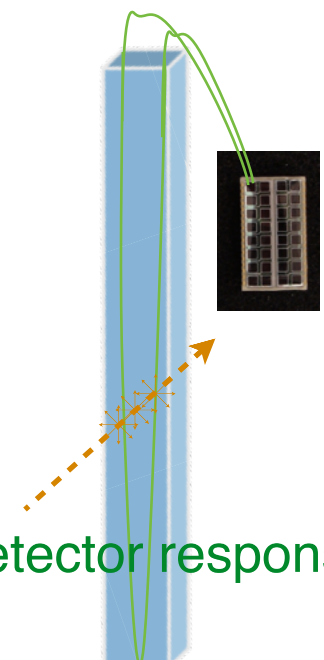
Tracking calorimeter:

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

Simulation







Readout electronics & DAQ: Custom simulation routines

Detector response: GEANT4

- **We make use of the GENIE reweighting scheme to assess xsec and FSI systematics. Described in Jeremy Wolcott's presentation yesterday.**
- We will soon have NEUT, GiBUU and others integrated into our simulation framework.
- Systematics associated with every step in the chain.

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ν_μ CC inclusive

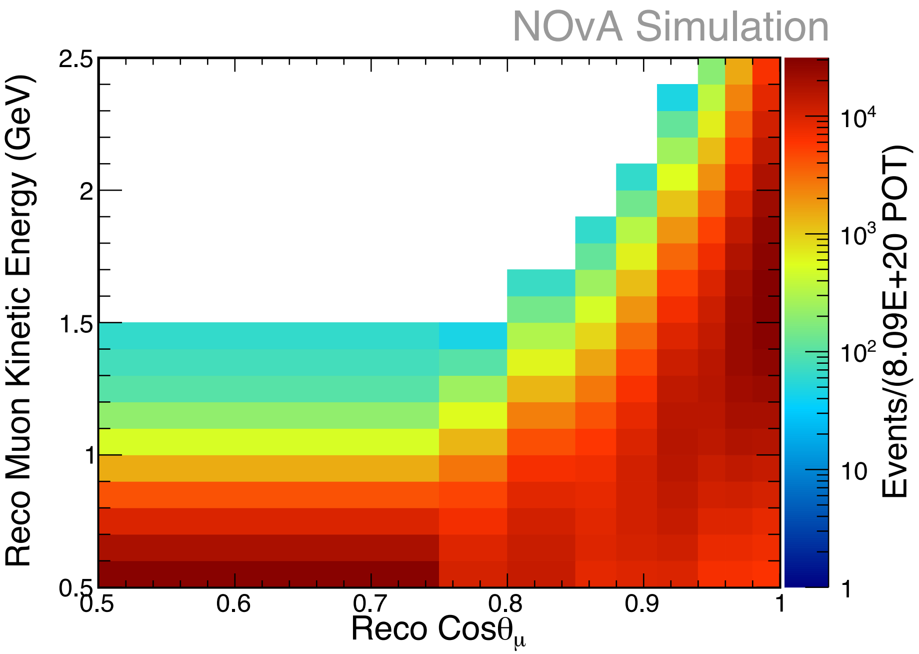
ν_μ CC inclusive - Overview

- $\sigma(E)$ and flux-averaged $d^2\sigma/dT_\mu d\cos\theta_\mu$

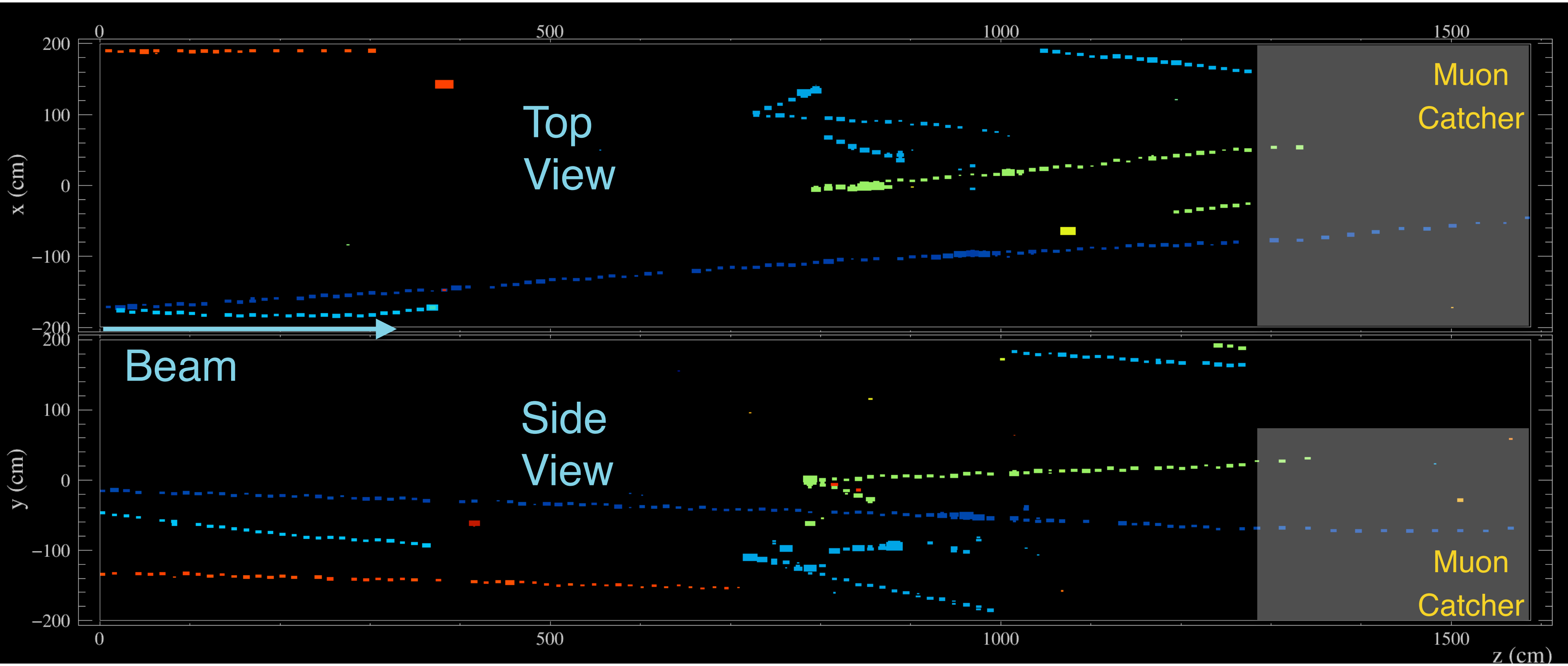
$$\sigma(E_i) = \frac{\sum_j U_{ij}\left(N^{\mathrm{sel}}(E_j) - N^{\mathrm{bkg}}(E_j)\right)}{\epsilon(E_i) N_{\mathrm{target}} \phi(E_i)}$$

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

- Measurements are kinematically restricted to the filled phase space to the right due to limited statistics and low efficiency.
- Neutrino energies also restricted to be between 0.7 and 4 GeV.

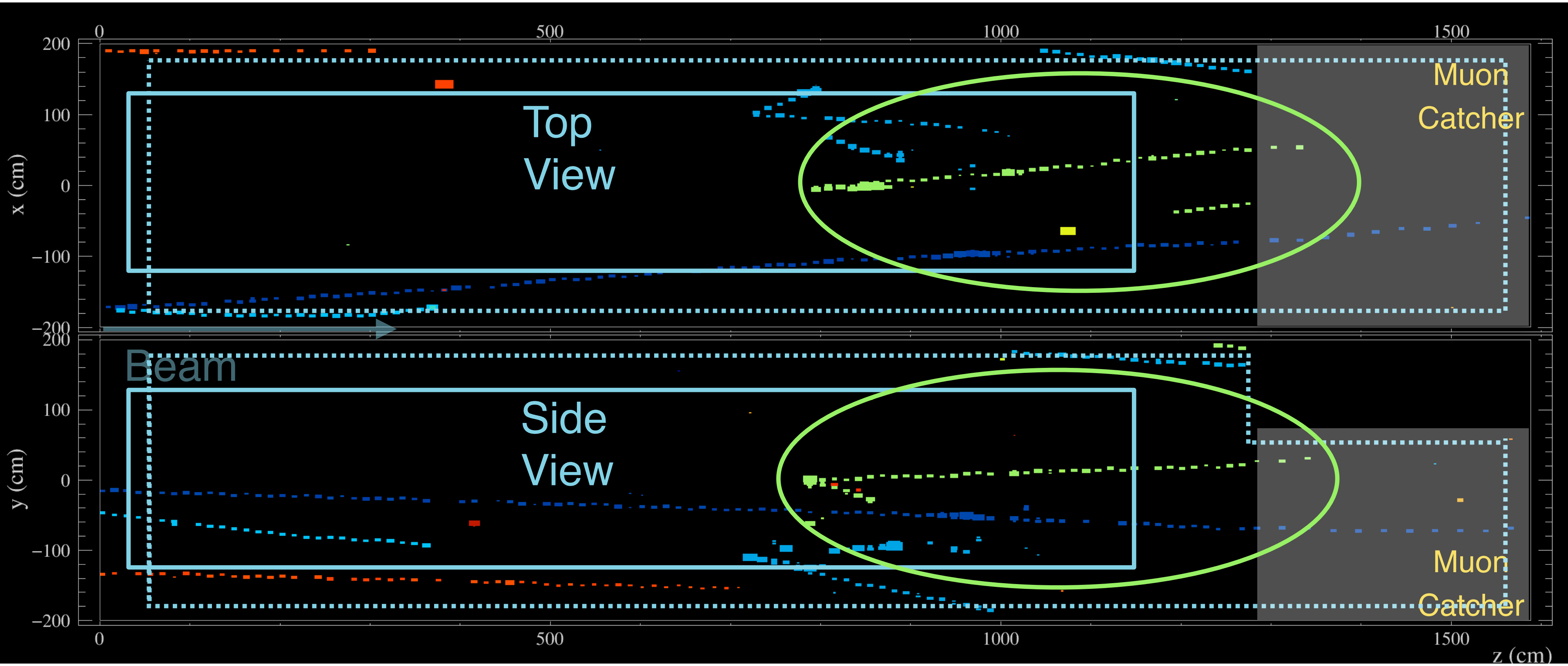


ν_μ CC inclusive - Reco + Selection



- Hits associated in time and space are used to form a candidate interaction. Tracks and showers are reconstructed from these hits.
- Vertices are also reconstructed; in this analysis, the start of the reconstructed muon track is defined as the vertex.

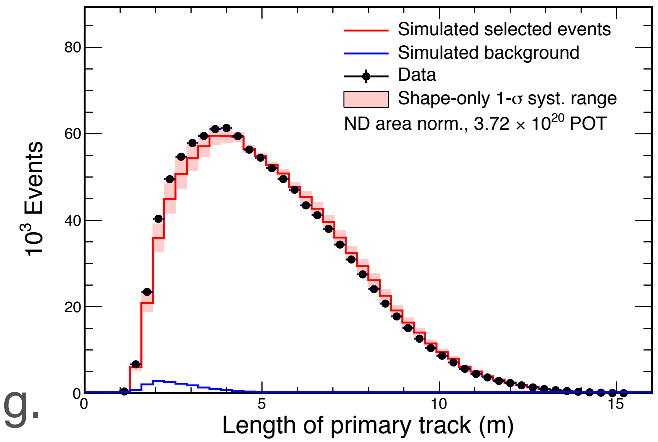
ν_μ CC inclusive - Reco + Selection

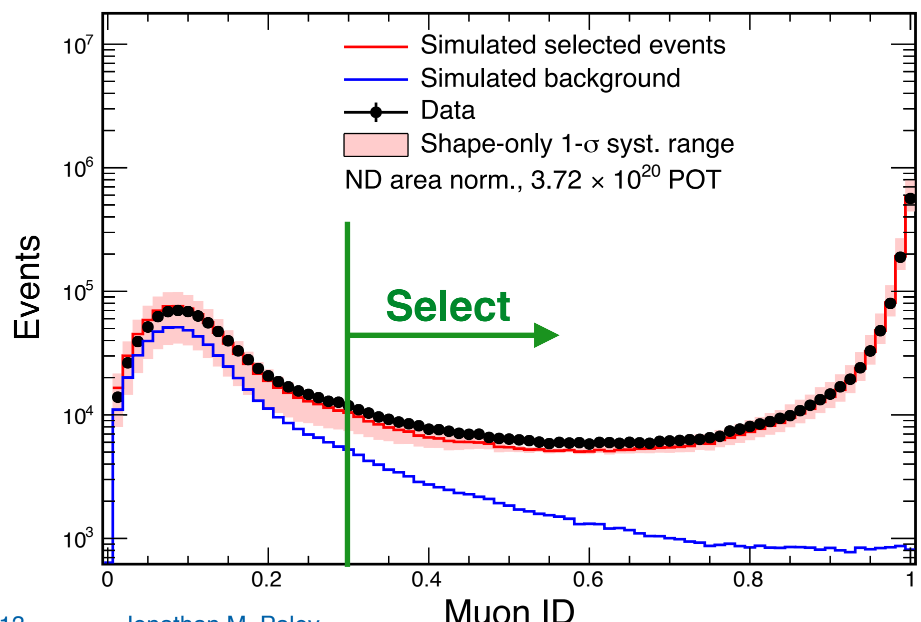


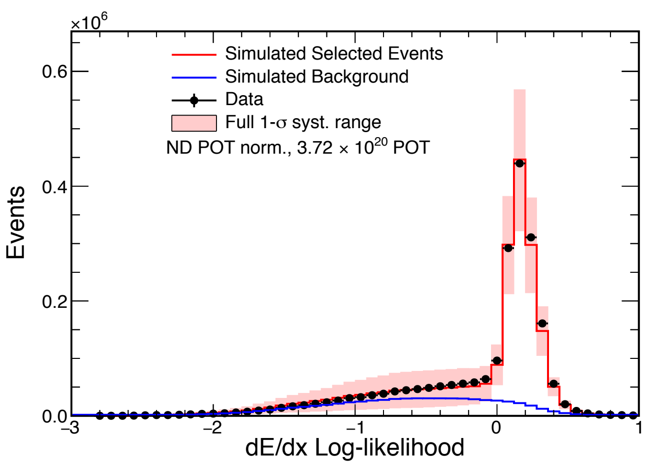
- Fiducial volume is well defined (blue solid box), we exclude the muon catcher.
- Containment uses nearest projected distance to an edge, the dashed box above is a rough approximation of the volume. Note, events with hadronic activity in or near the muon catcher are excluded.

ν_μ CC inclusive - PID

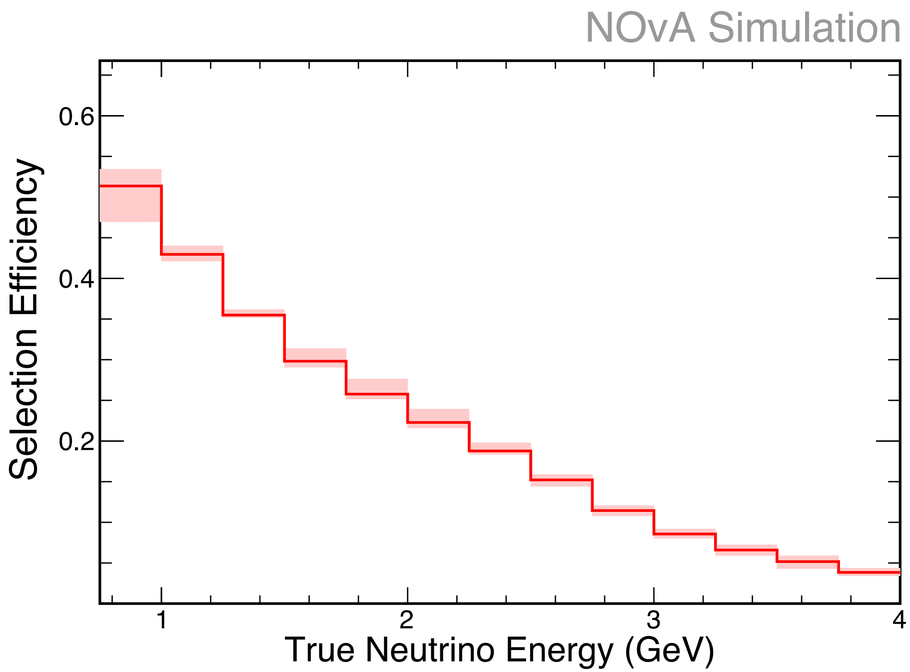
- Select events that have a muon-like track. Use a *kNN* to separate signal and background tracks based on 4 variables:
  - track length
  - dE/dx along track
  - scattering along track
  - fraction of track planes w/ single particle dE/dx
- Distributions below are from 2016 oscillation analysis. This analysis will use new MC and tuning.

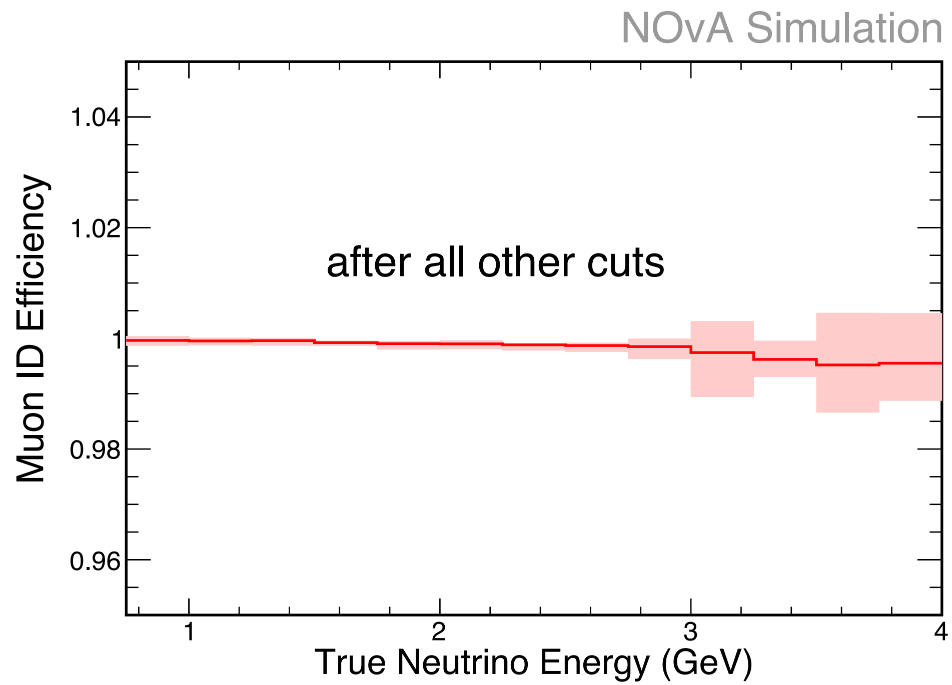






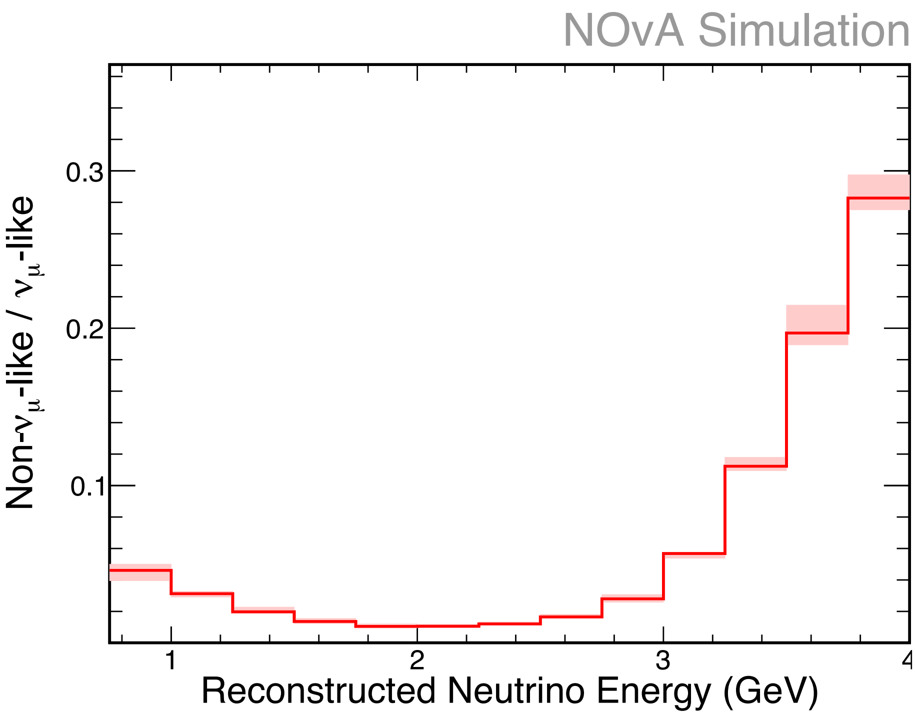
ν_μ CC inclusive - Selection Efficiency (w/ Uncertainties)

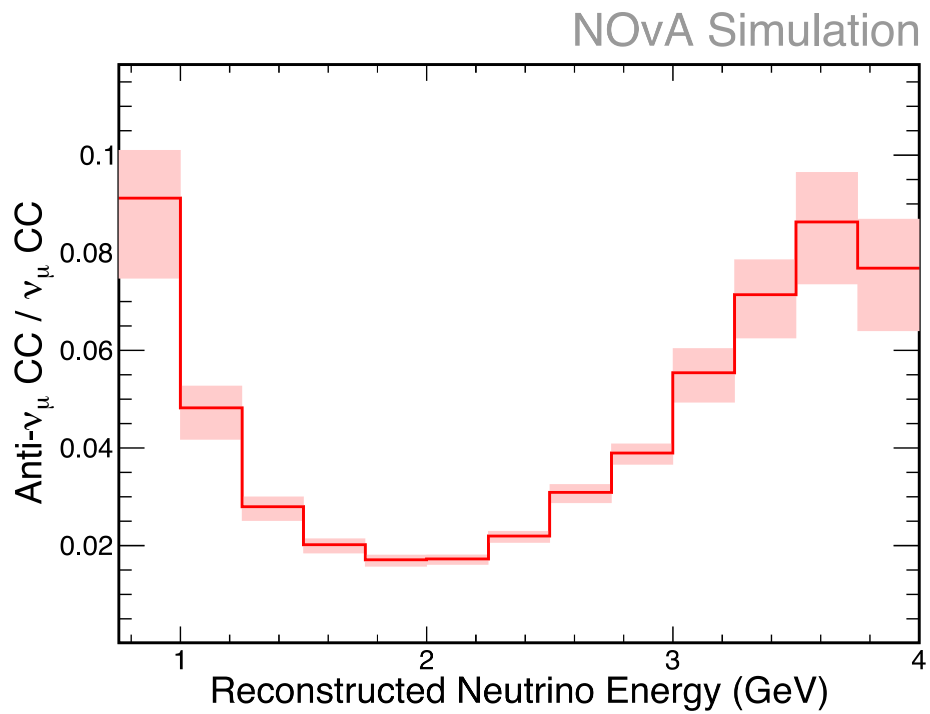




- Error bands include nearly all systematics.
- Muon ID efficiency after all other cuts is very flat vs. energy. Selection efficiency is dominated by containment.
- Uncertainties are <~ 10%.

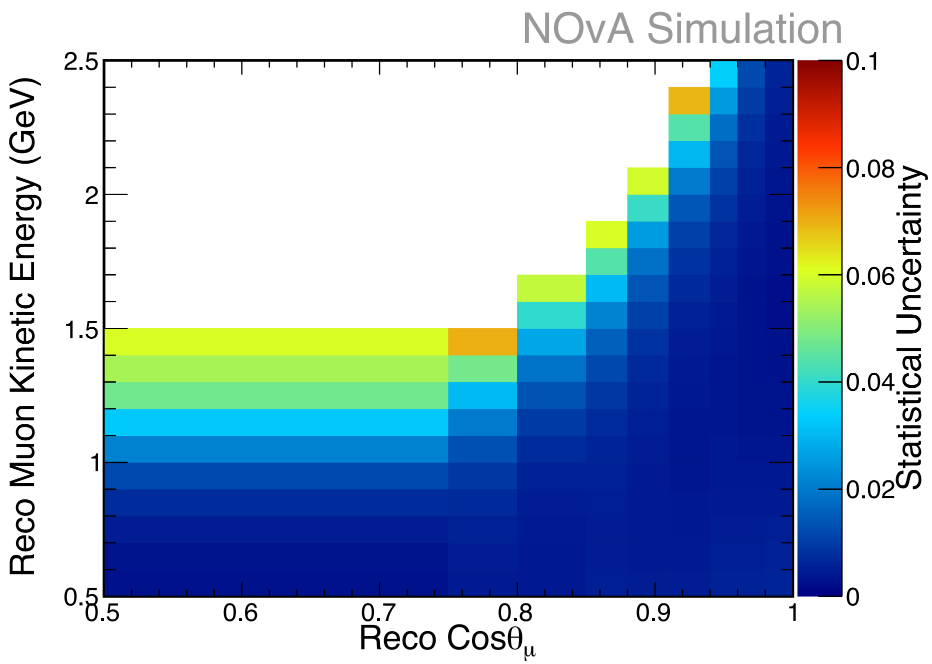
ν_μ CC inclusive - Backgrounds (w/ Uncertainties)

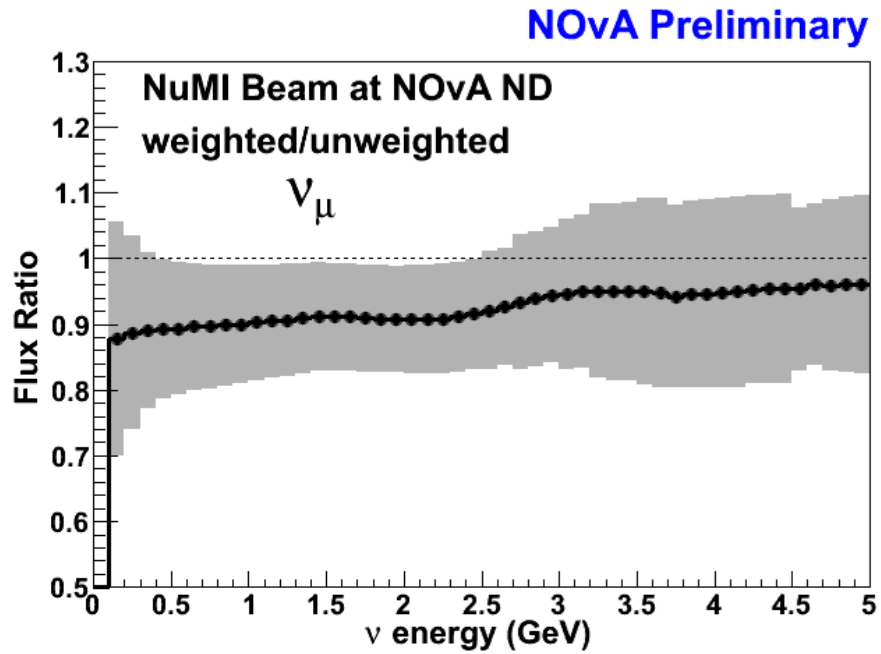




- Dominant xsec and FSI systematics only shown in plot on left. Dominant flux systematics only shown in plot on right.
- Backgrounds are small near the 2 GeV peak, larger in the tails of the spectrum.
- Uncertainties are at the level of a few %.

ν_μ CC inclusive - Summary of Uncertainties

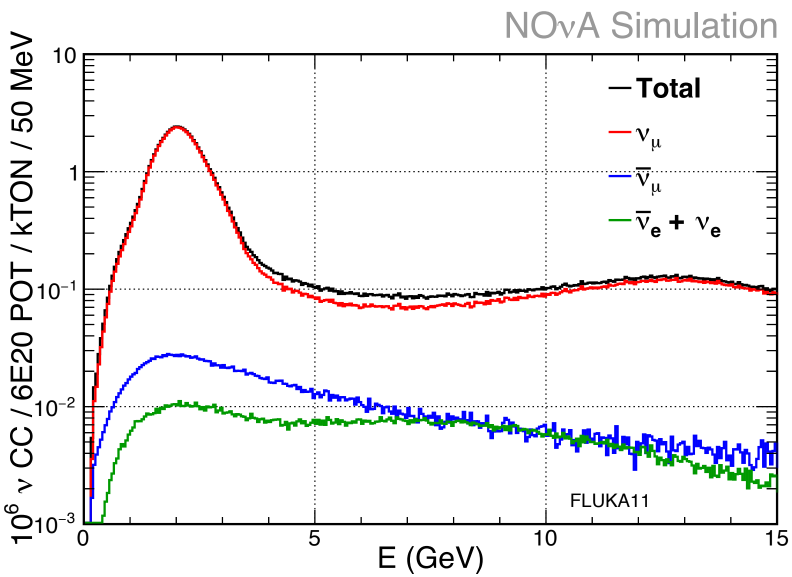




- Statistical uncertainties are typically < 2%
- Systematics are still being assessed, but we expect for the differential measurement ~10% highly correlated (normalization) flux uncertainties, and all others systematics combined to be 5-8%.
- $\sigma(E)$ measurement systematics will be similar, although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

ν_e CC inclusive

ν_e CC inclusive - Overview



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

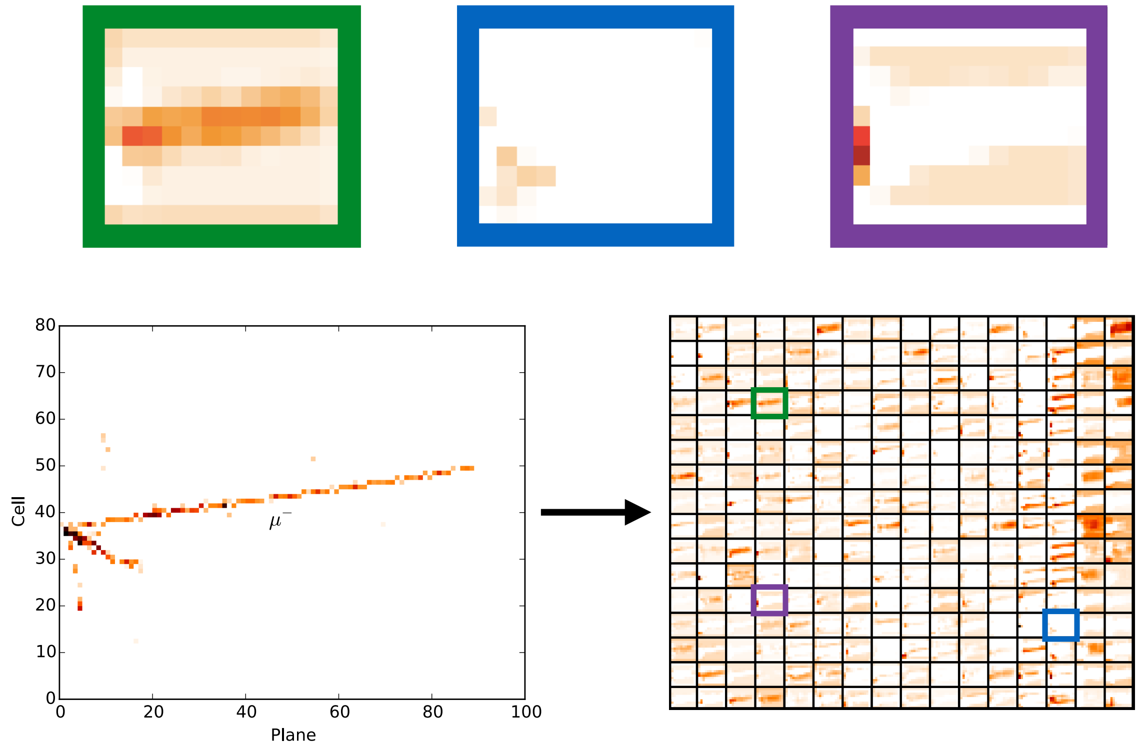
- σ vs. E and flux-averaged $d\sigma/dT_e$, $d\sigma/d\cos\theta_e$ for energies between 1 and 3 GeV.
- Challenging because (by design) there are ~1% of ν_e
- We have shown preliminary results on this channel in the past. That analysis is now superseded with a different approach using the event identification algorithm that the ν_e appearance oscillation analysis developed.

ν_e CC inclusive - PID and Selection

- Use progress in image recognition technology via a convolutional neural network (CNN), where a series of *learned* image filters are applied to hit map images to extract features associated with an interaction in our detector.

- Different filters highlight the topological features of the different types of neutrino interactions.

- A convolutional visual network (CVN) is then trained on these filters.



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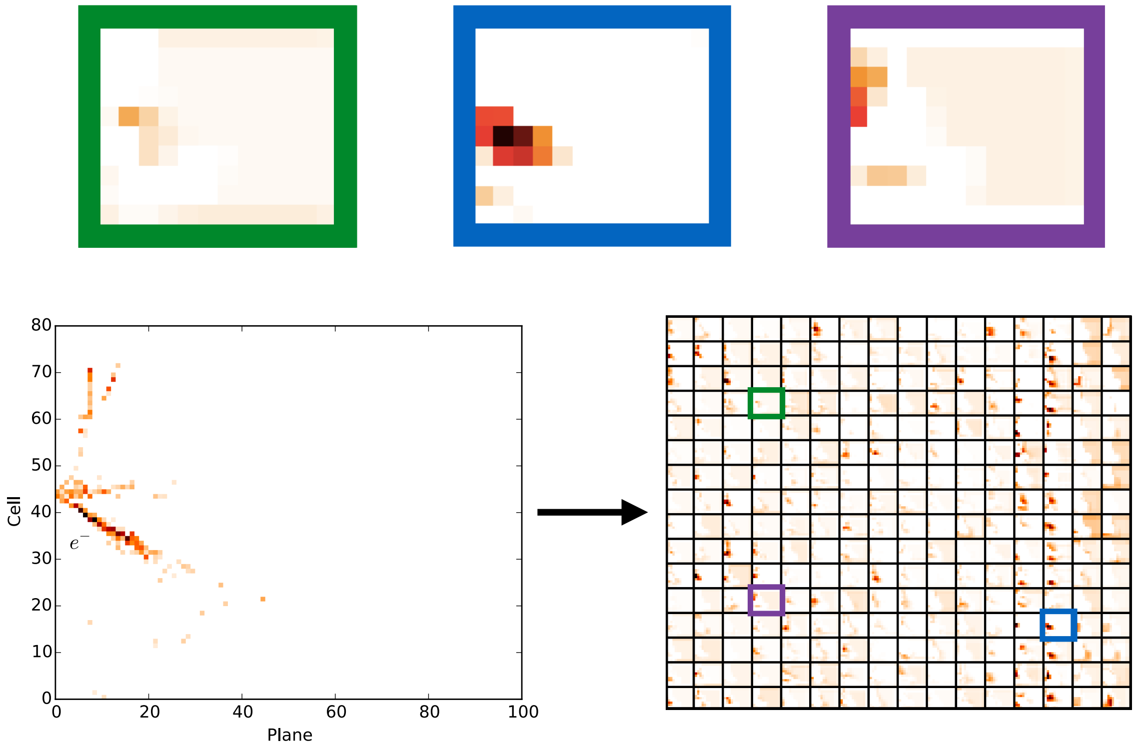

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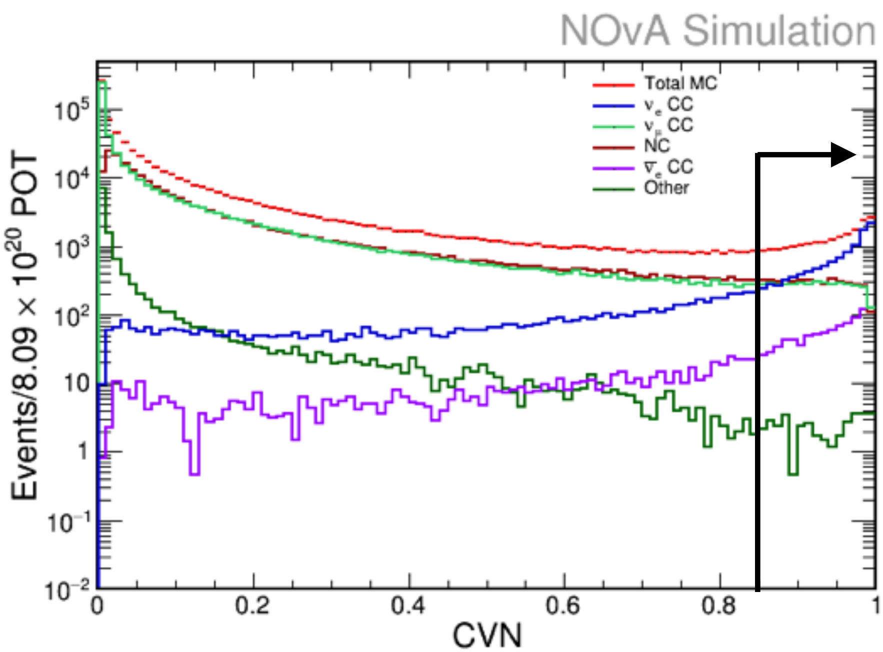
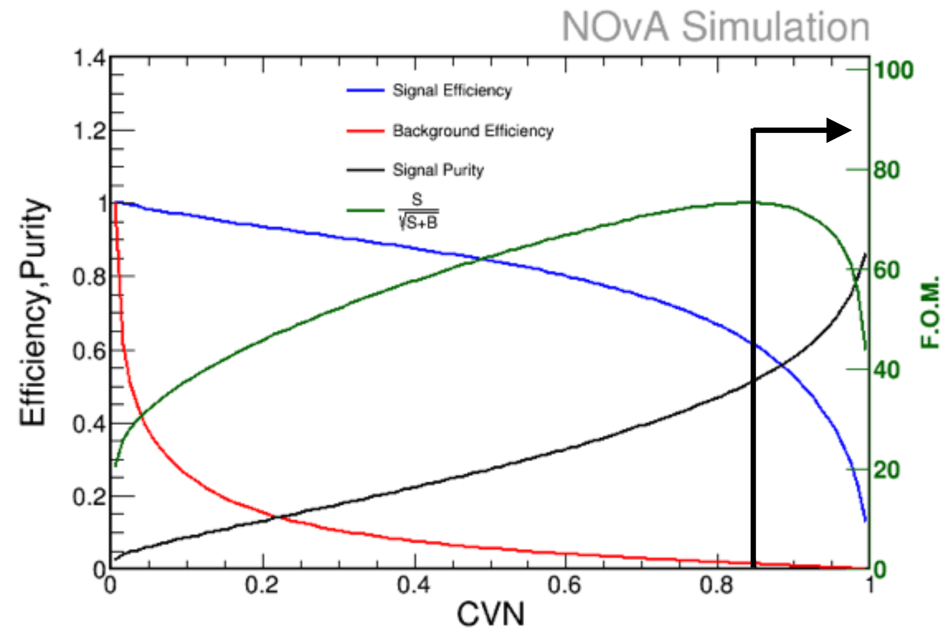
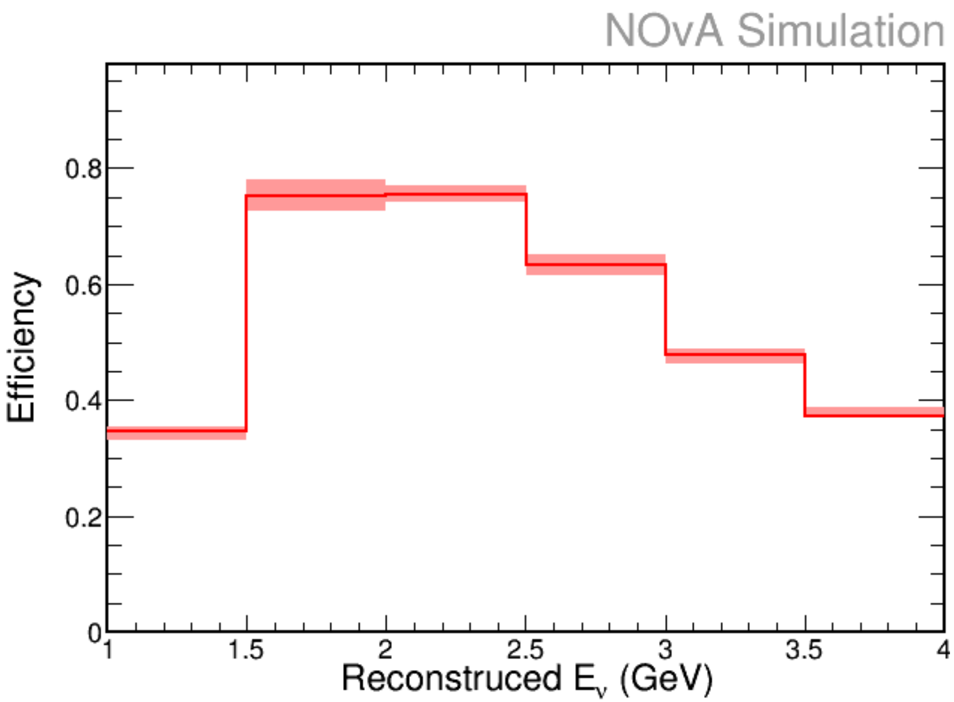


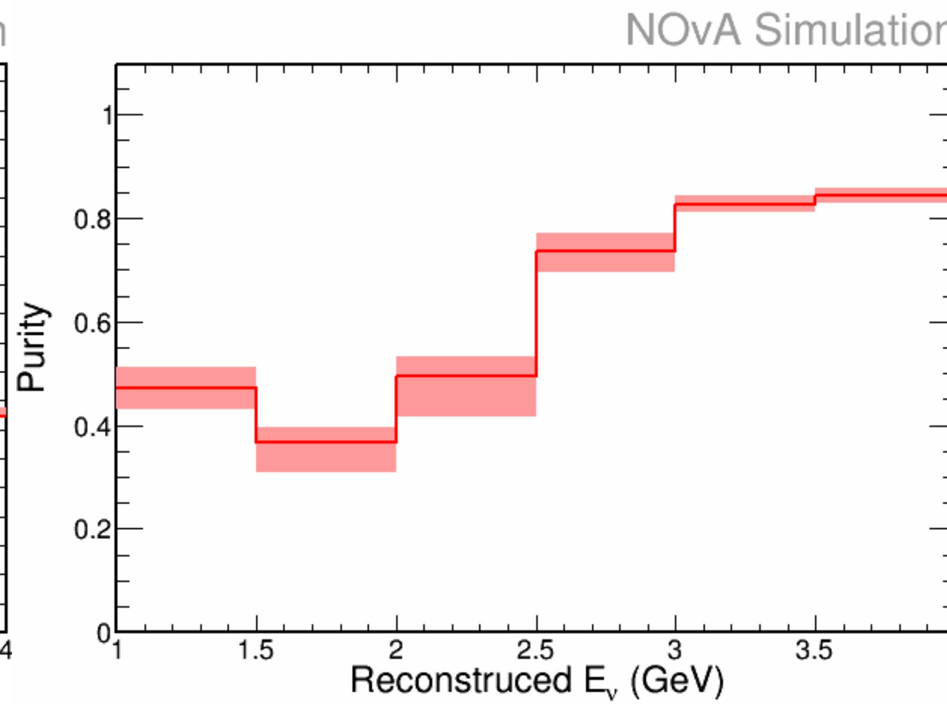


- Currently using a cut (CVN > 0.85) that optimizes the FoM of S/√(S+B).
- Backgrounds are significant, and we are investigating potential data-driven constraints.

Interaction	Fraction (%)
ν_e CC	51.2
Anti-ν_e CC	4.4
ν_μ CC	21.1
NC	23.0
Other	0.18

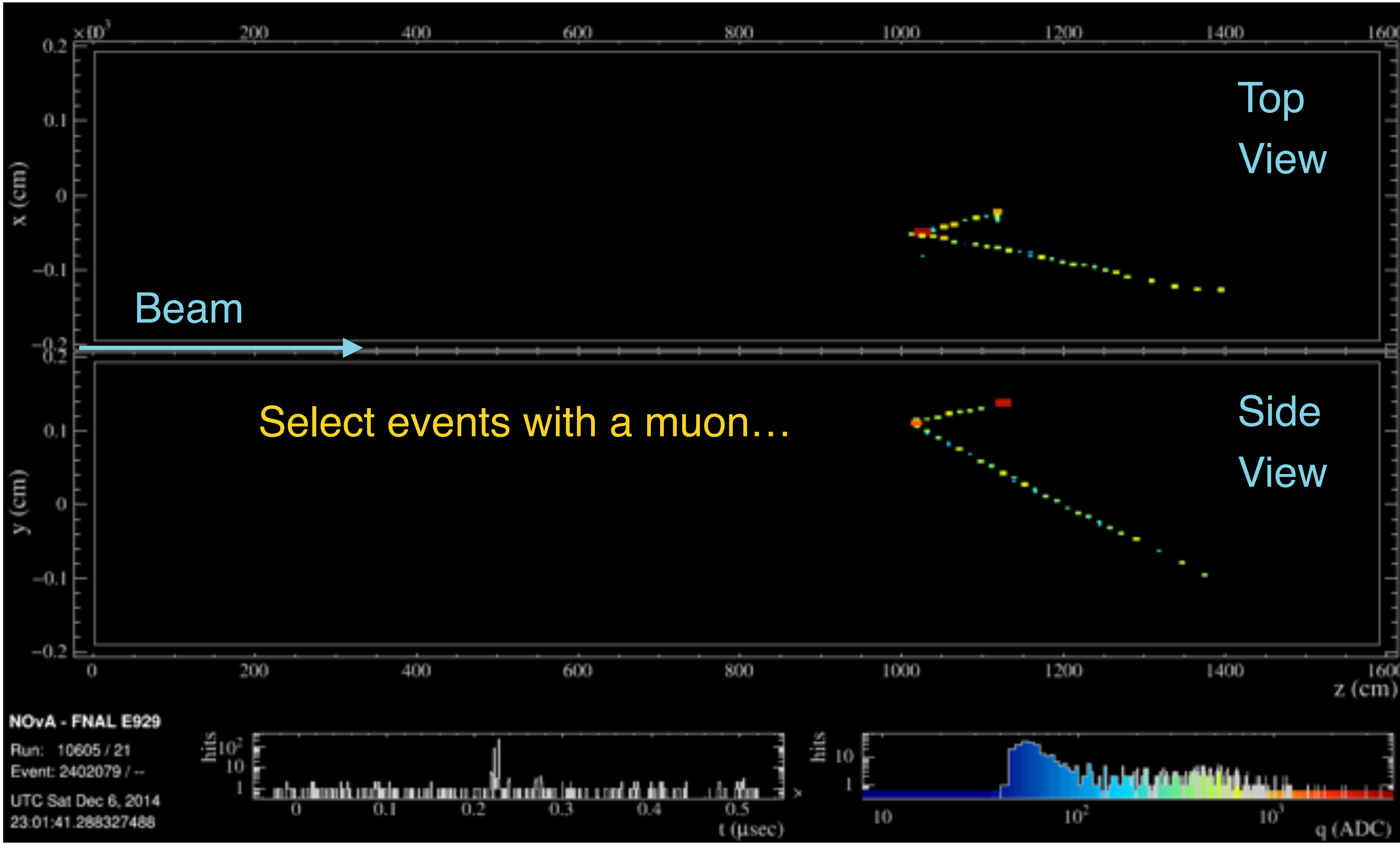
ν_e CC inclusive - Efficiency and Purity





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

ν_e CC inclusive - Data-Driven Efficiency Cross Check



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ν_e CC inclusive - Selection Efficiency

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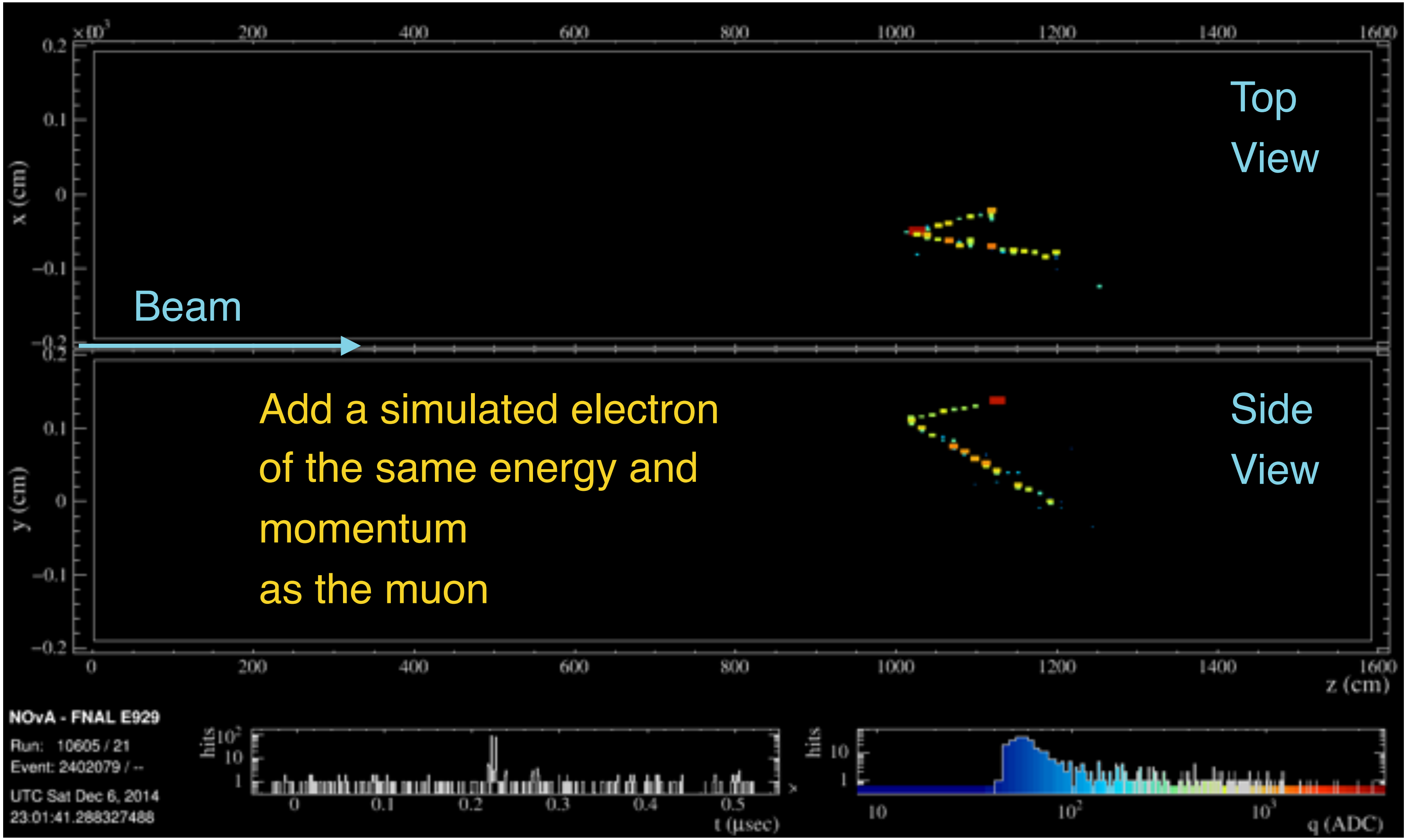
ν_e CC inclusive - Selection Efficiency



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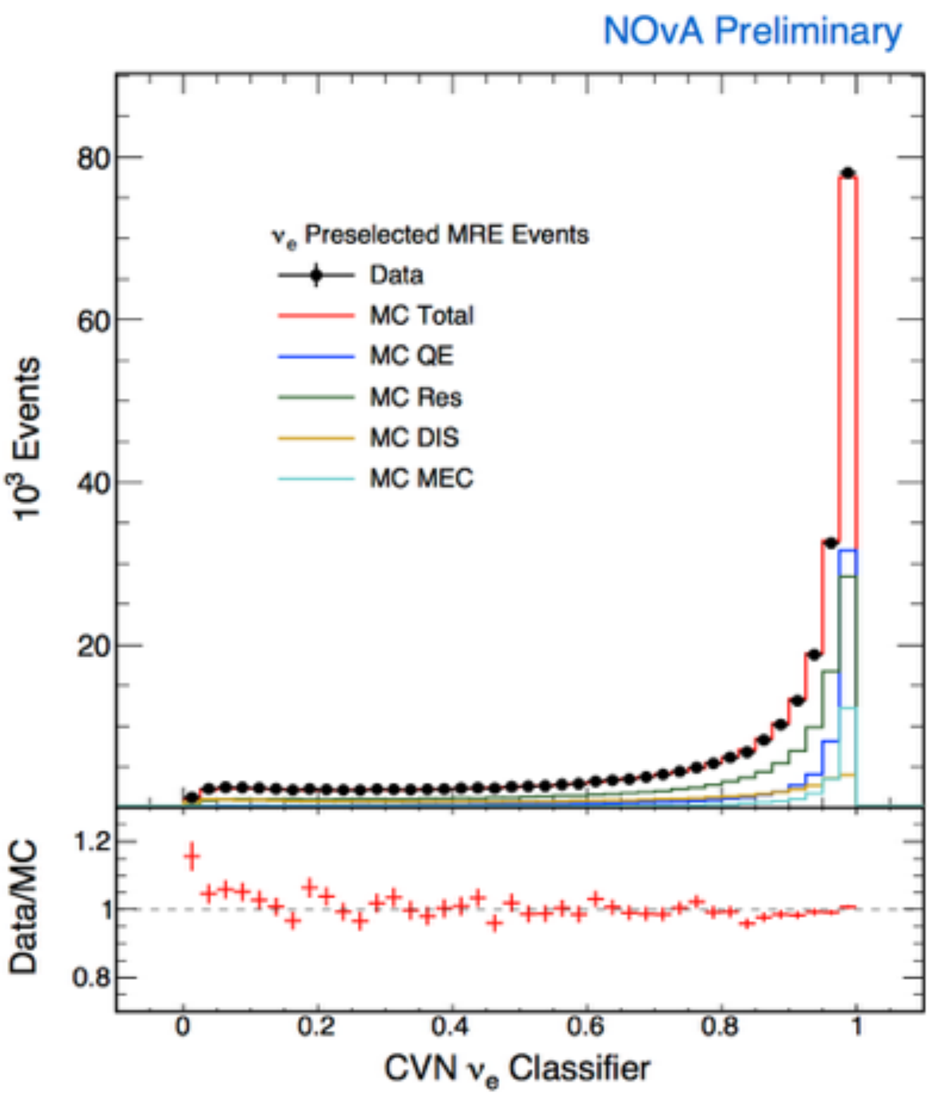

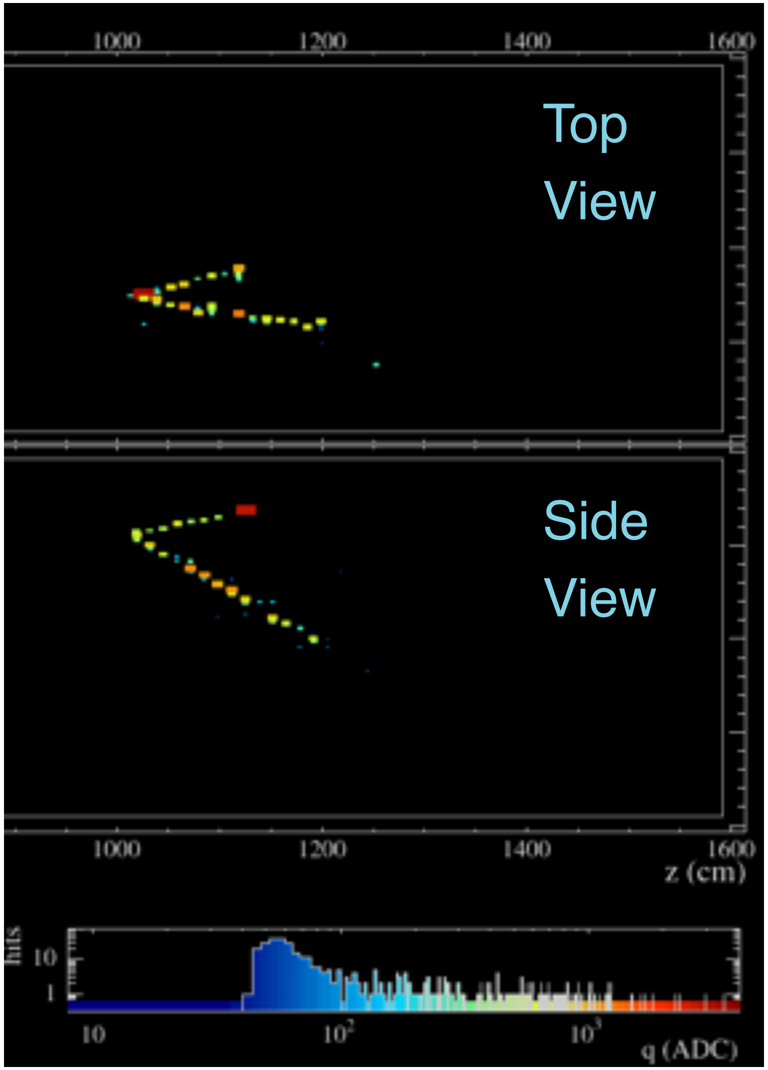

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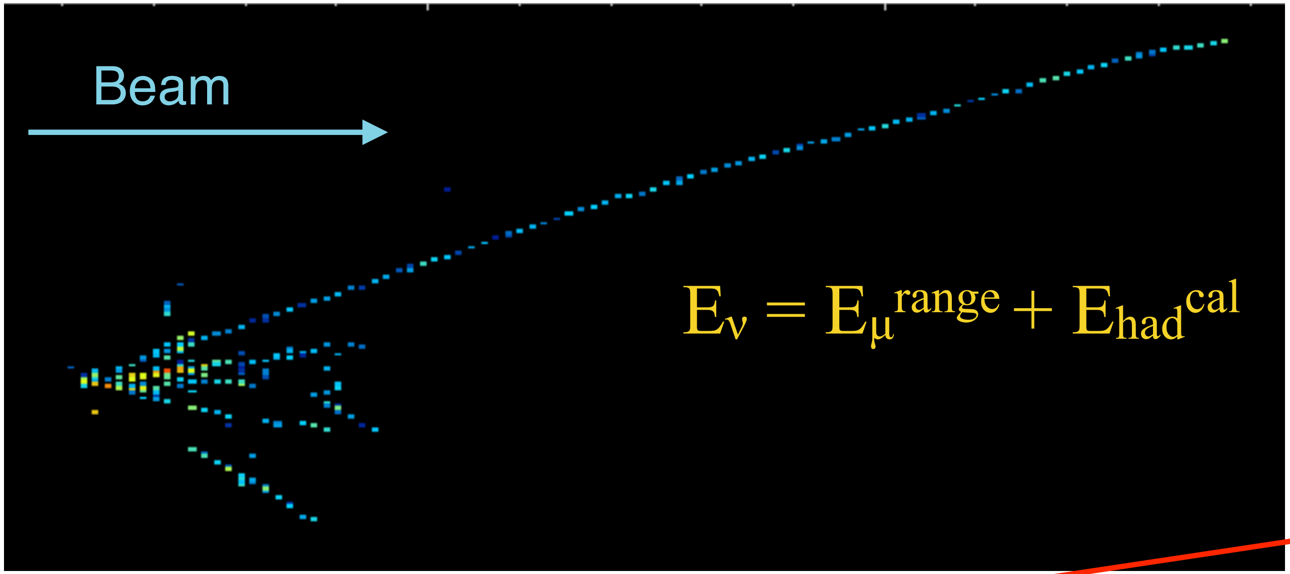
Looking Forward and Summary

- NOvA's high rate of neutrino interactions in the ND, off-axis narrow-band beam, and excellent tracking capabilities provide excellent opportunities to make precision measurements of nu+A interactions.
- 8×10^{20} POT neutrino ND data set, aiming for results this year for systematics-limited (~10%) measurements:
    - ν_μ CC inclusive flux-integrated double-differential cross section.
    - ν_e CC inclusive flux-integrated single-differential cross section.
- We have also collected 3×10^{20} POT antineutrino data. Inclusive measurements of these data are a high priority for NOvA.
- Future ratios of semi-inclusive measurements w.r.t. these inclusive measurements will significantly reduce flux and other uncertainties.
- Stay tuned for results soon!

Thank you!

Backup

The Relevance of Cross Sections for NOvA

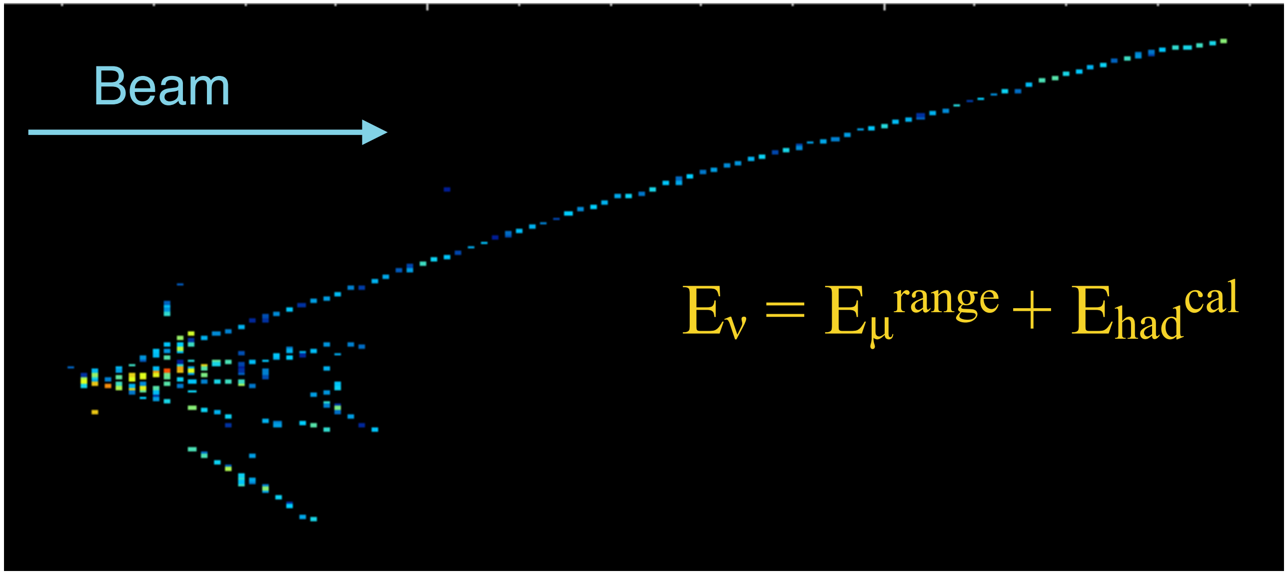


We rely on the simulation, which has models for cross sections and final state interactions (FSI), to calibrate measured visible hadronic energy to true hadronic energy.

$$N_{\rm ND}(E_{\nu_i}) = \Phi_{\rm ND}(E_{\nu_i}) \times \sigma(E_{\nu_i}, A_{\rm ND}) \times \epsilon_{\rm ND}$$

$$N_{\rm FD}(E_{\nu_j}) = \Phi_{\rm FD}(E_{\nu_j}) \times \sigma(E_{\nu_j}, A_{\rm FD}) \times \epsilon_{\rm FD} \times P_{\rm osc}(i \to j)$$

The Relevance of Cross Sections for NOvA



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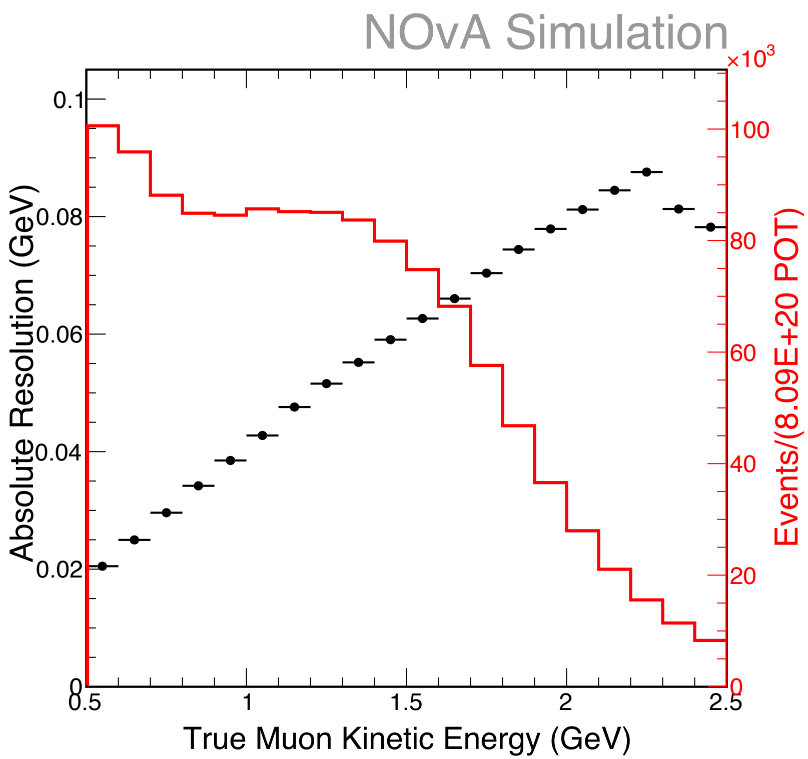
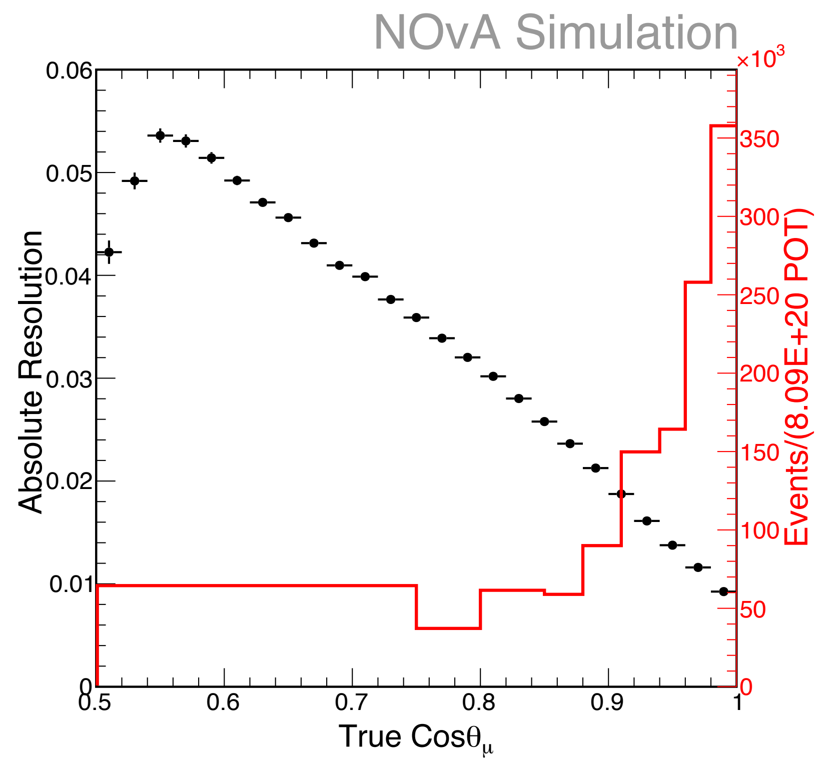
$$N_{\mathrm{ND}}(E_{\nu_i}) = \Phi_{\mathrm{ND}}(E_{\nu_i}) \times \sigma(E_{\nu_i}, A_{\mathrm{ND}}) \times \epsilon_{\mathrm{ND}}$$

$$N_{\mathrm{FD}}(E_{\nu_j}) = \Phi_{\mathrm{FD}}(E_{\nu_j}) \times \sigma(E_{\nu_j}, A_{\mathrm{FD}}) \times \epsilon_{\mathrm{FD}} \times P_{\mathrm{osc}}(i \to j)$$

Acceptance and selection efficiency depends on final state topology; modeling these right in each detector requires differential rate measurements. This is particularly important for the nue appearance measurement.

ν_μ CC inclusive - Energy Reco, Resolution and Binning





- Simulation is used to determine map between reconstructed track length and muon energy. Muon energy resolution is ~4% across all energies.
- Muon angle is w.r.t. mean direction of beam. Most muons have an angle < 200 mrad. Variable bin widths to account for resolution and statistics.

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ν_μ CC inclusive - Selection Efficiency (w/ Uncertainties)

Signal Acceptance After Each Cut

Cut	QE	Res	DIS	Coh	MEC
No Reco Cut	100	100	100	100	100
Quality	99.5809	99.8644	99.8992	99.9283	99.7744
Fiducial	97.8993	96.606	94.99	97.8522	97.8391
Muon Containment	30.132	40.1186	39.8271	65.8541	39.8536
Containment	22.4443	24.0025	16.0219	44.1746	29.7765
PID	22.4244	23.9534	15.905	44.0443	29.7601
Energy Cut	22.3757	23.9398	15.8416	43.9973	29.7323
Muon Kinematics	22.3192	23.8104	15.6596	43.6449	29.6494

Fraction of Signal After Each Cut

Cut	QE	Res	DIS	Coh	MEC
No Reco Cut	29.0132	42.7038	13.8916	1.03905	13.3524
Quality	28.9566	42.7418	13.9088	1.04064	13.3522
Fiducial	29.302	42.5591	13.6129	1.04889	13.477
Muon Containment	23.3671	45.7924	14.7881	1.82895	14.2235
Containment	27.8017	43.7615	9.50243	1.95966	16.9747
PID	27.8324	43.7589	9.45187	1.95777	16.9991
Energy	27.8111	43.7958	9.42748	1.95844	17.0072
Muon Kinematics	27.8742	43.7684	9.36401	1.95209	17.0413

ν_e CC inclusive - PID and Selection

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