NOvA's approach to cross-section analyses and publishing results

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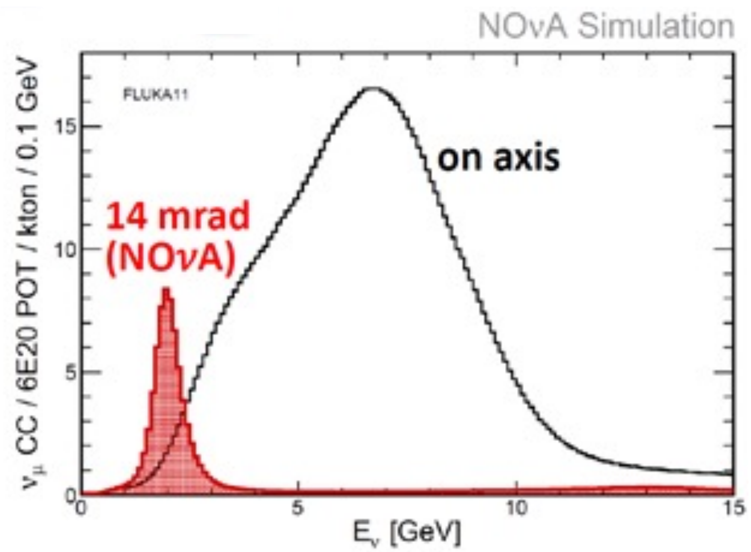
What is NOvA

Accelerator neutrino experiment

NuMI beam at Fermilab

E ≈ 1.9 GeV (off-axis narrow band beam)

ν_μ and $\bar{\nu}_\mu$ beam modes



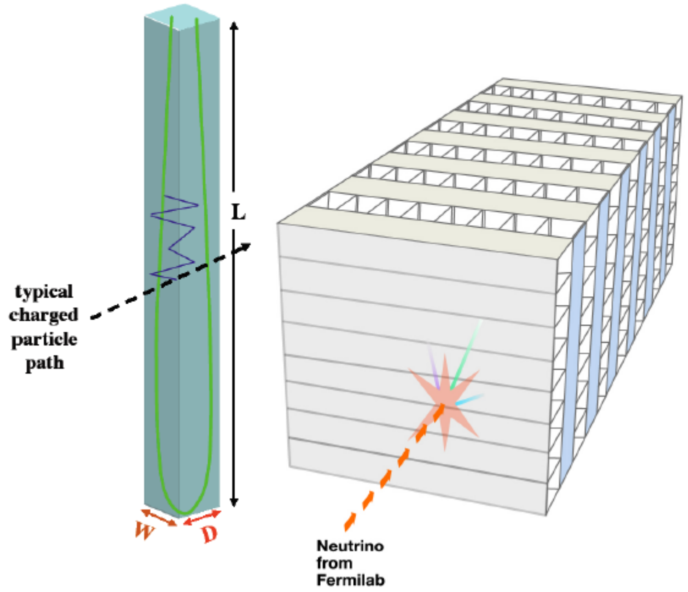
Near Detector

~1km from production target at Fermilab

Active liquid scintillator hydrocarbon target

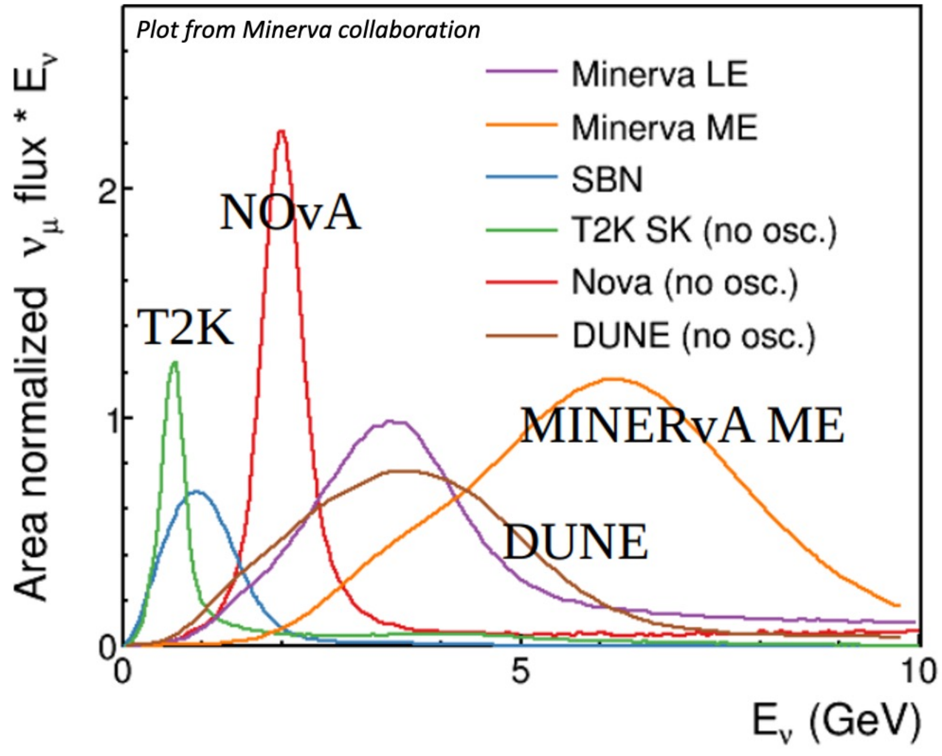
67% C, 11% H with 16% Cl, 3% Ti, 3% O

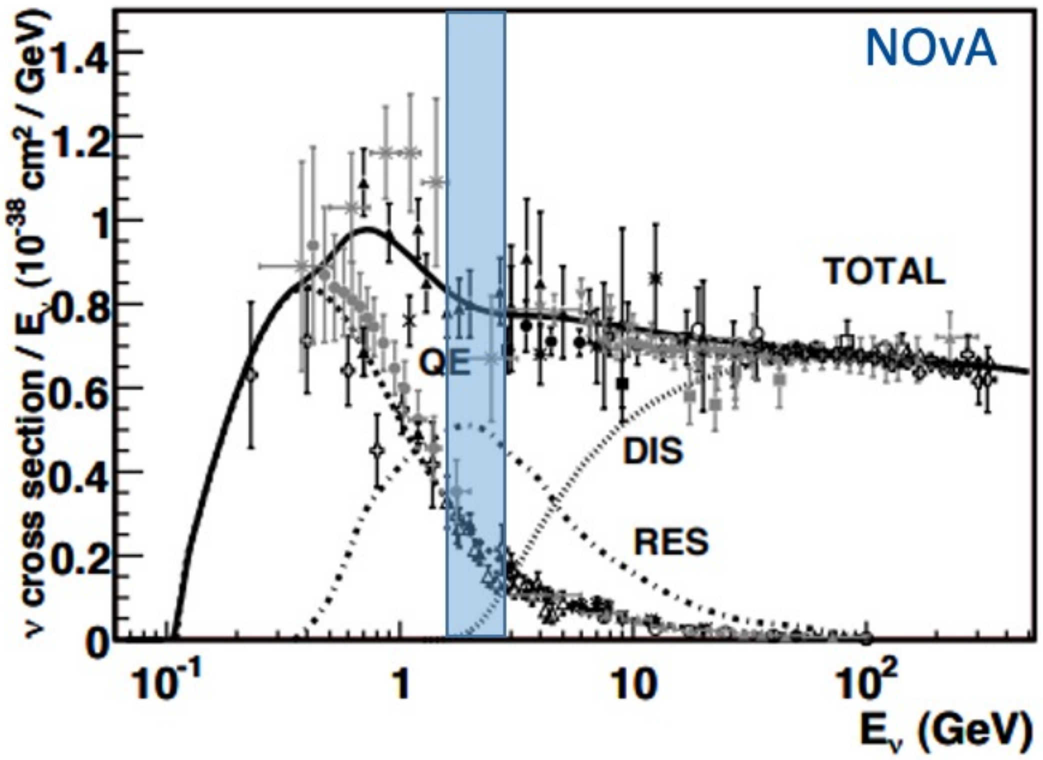
Tracking calorimeter



NOvA's role in cross-section measurements

NOvA probes a unique energy range with high statistics



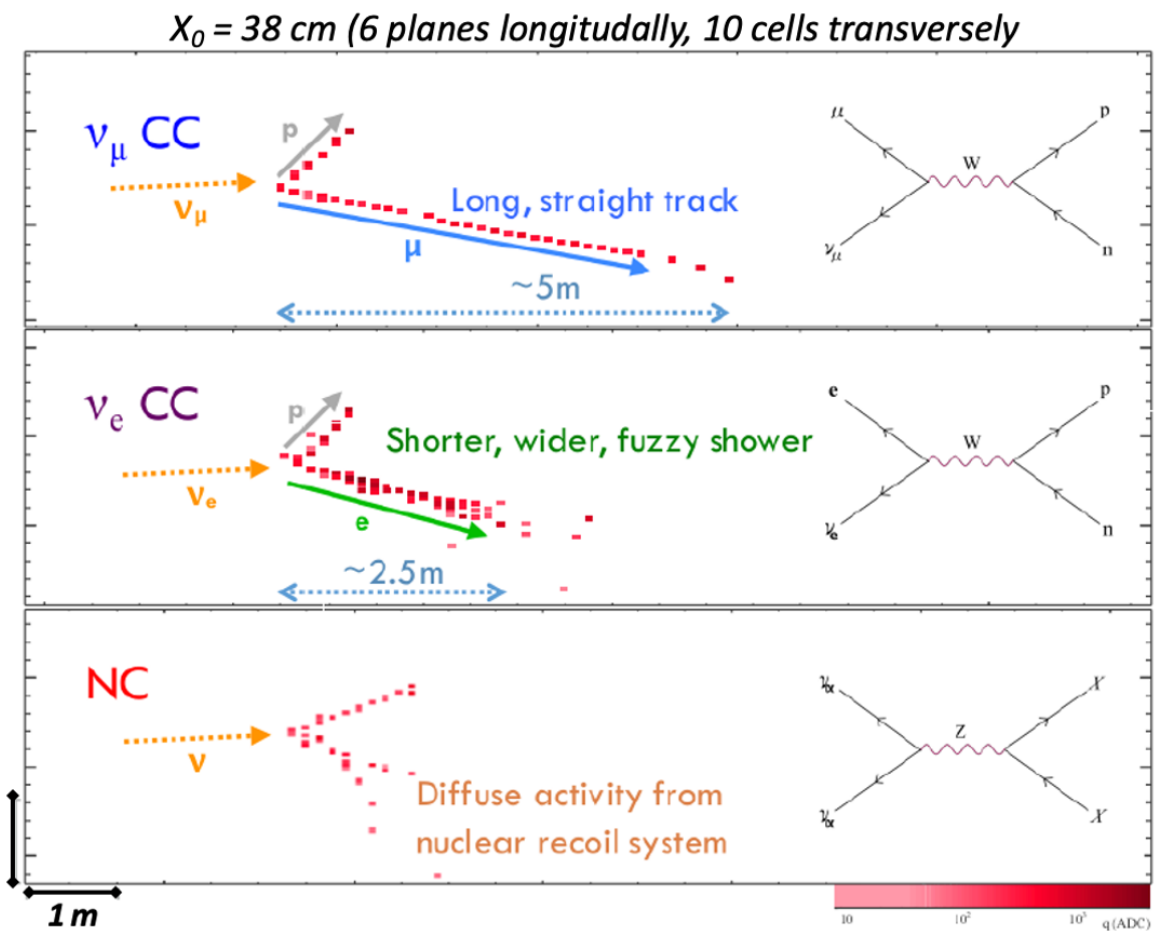


Energy is where resonant interactions are dominant

The mix of QE, 2p2h, RES, and DIS is important

Observe individual particles

Tracking calorimeter detects individual particles



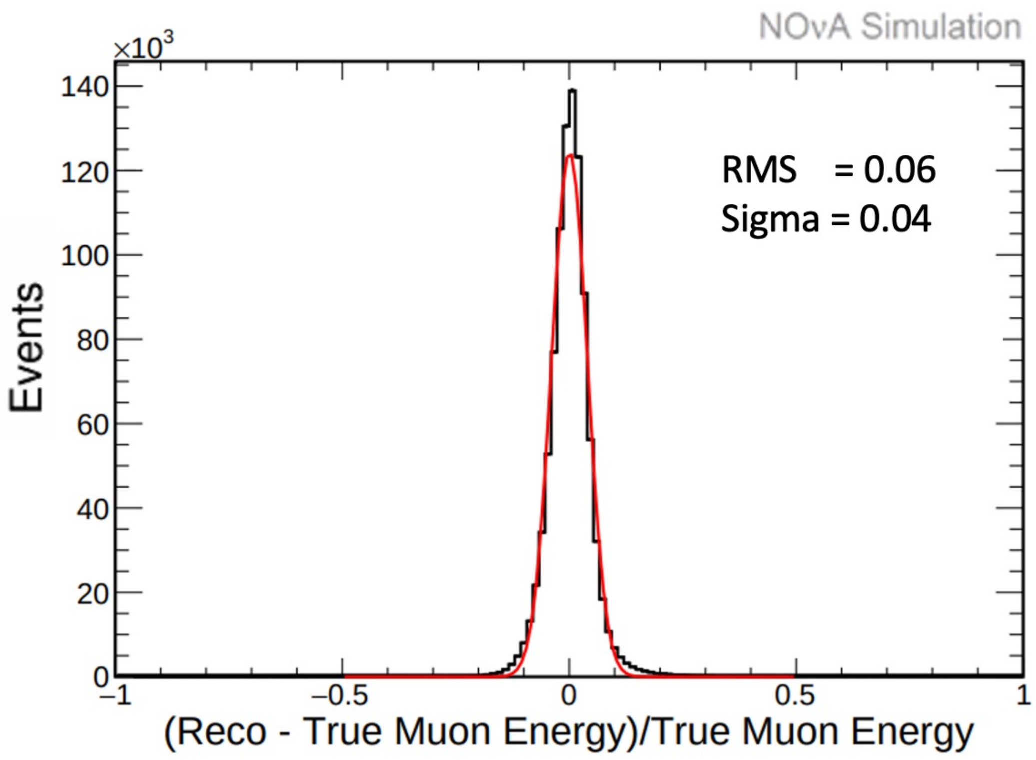
Can measure individual particle kinematics
(leptonic and hadronic particles)

Can reconstruct total hadronic energy

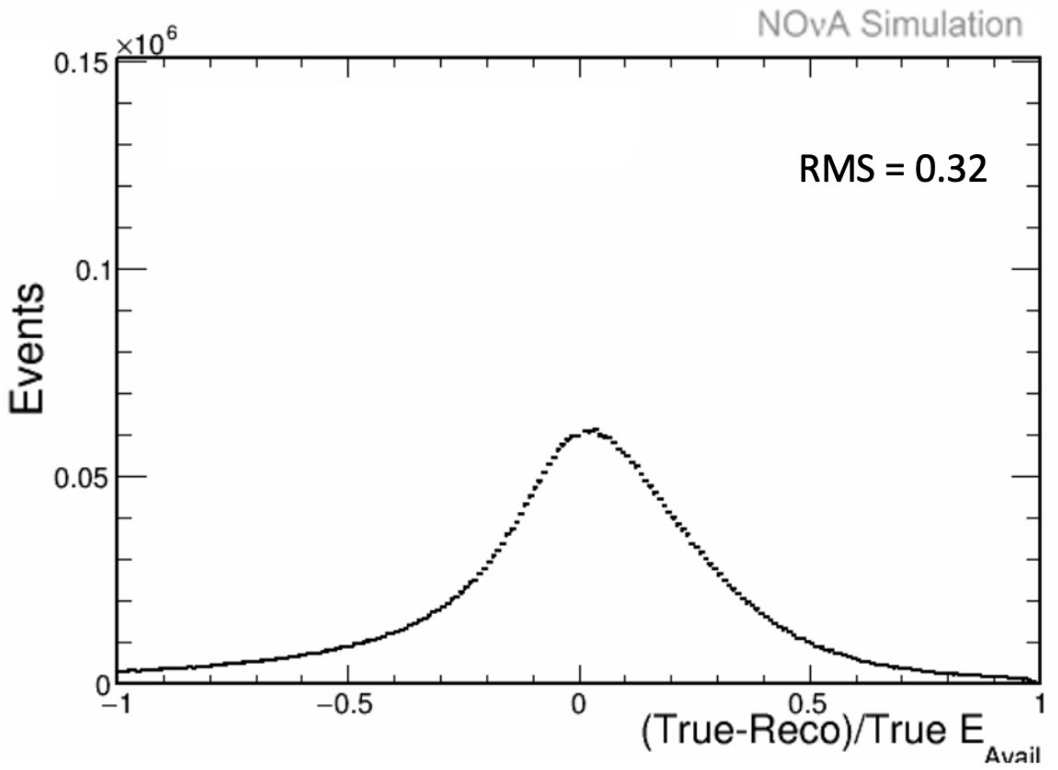
Can do differential cross-section measurements in leptonic and hadronic observables

Example Energy Resolutions

Muon Energy Resolution



Available Energy Resolution



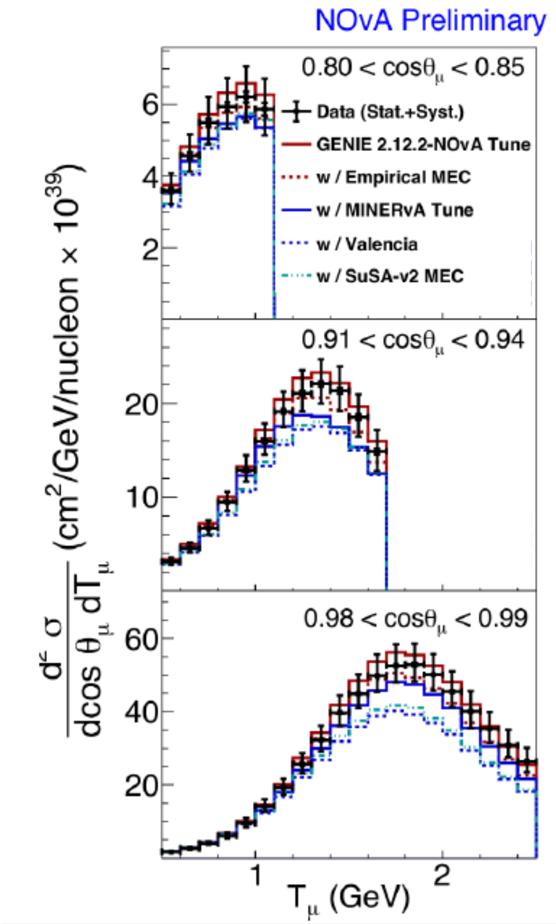
Available energy follows Minerva prescription
P.A. Rodrigues et al, Phys Rev Lett 116, 071802 (2016)

Example Analysis: Inclusive Measurements

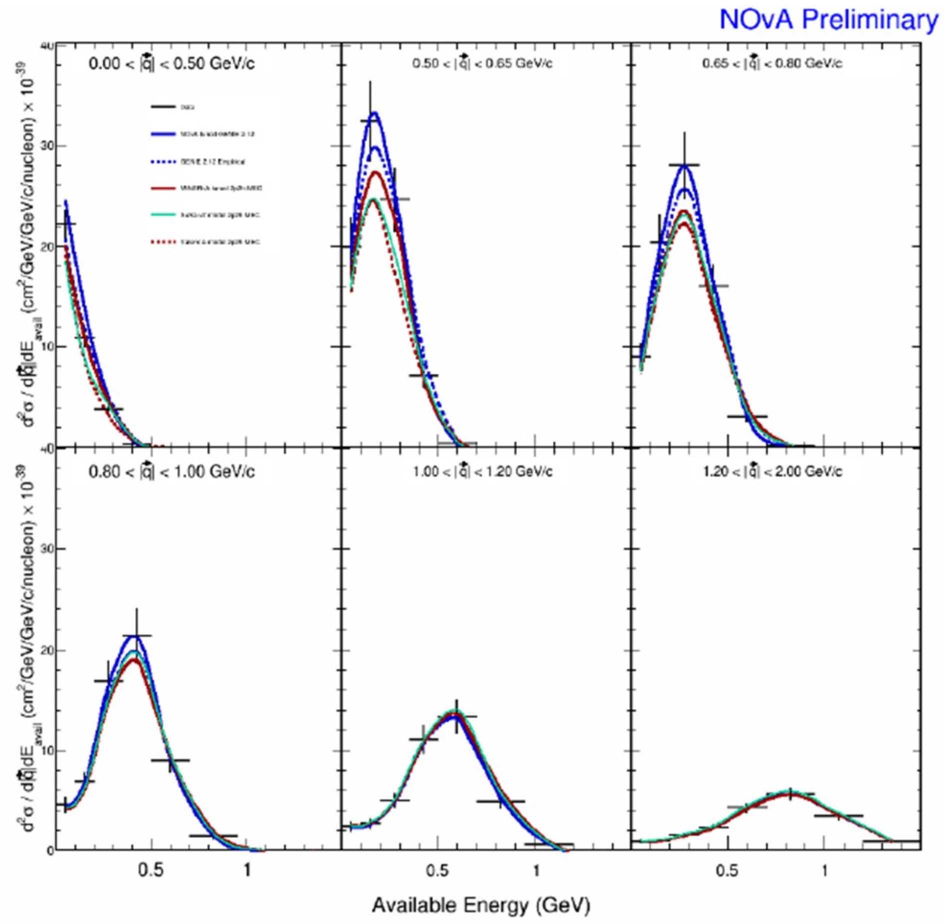
Measures the collective sum and interference of the various interaction modes, nuclear effects and FSI

Tracking calorimeter allows us to make differential measurements in leptonic and hadronic observables

Leptonic Observables



Hadronic Observables



So how do we compare measurements to theory?

Converting measurement to "truth"

We take reconstructed data and attempt to undo measurement affects

1) Compensate for background by either
   - Subtracting off background
   - Correcting for the purity
2) Un-smear observed quantities with unfolding
3) Correct for selection efficiency and flux
4) Generate covariance matrices

Example Calculations

Background Subtraction

$$\left(\frac{d\sigma^2}{d|\vec{q}|\,dE_{avail}}\right)_{ij} = \frac{\sum_{\alpha\beta} U_{ij,\alpha\beta}\left(N^{Data}_{\alpha\beta} - N^{Bkgd}_{\alpha\beta}\right)}{\epsilon_{ij}\,(\Phi_\nu T_N)\,(\Delta|\vec{q}|)_i(\Delta E_{avail})_j}$$

Purity Correction

$$\left(\frac{d^3\sigma}{d\cos\theta_\mu dT_\mu dE_{Avail}}\right)_i = \frac{\sum_j U_{ij}(N^{\text{sel}}(\cos\theta_\mu, T_\mu, E_{Avail})_j P(\cos\theta_\mu, T_\mu, E_{Avail})_j)}{\epsilon(\cos\theta_\mu, T_\mu, E_{Avail})_i(\Delta\cos\theta_\mu)_i(\Delta T_\mu)_i(\Delta E_{Avail})_i N_{\text{target}}\phi}$$

Compared measured "true" differential cross sections to various models

Background Estimation

Either:

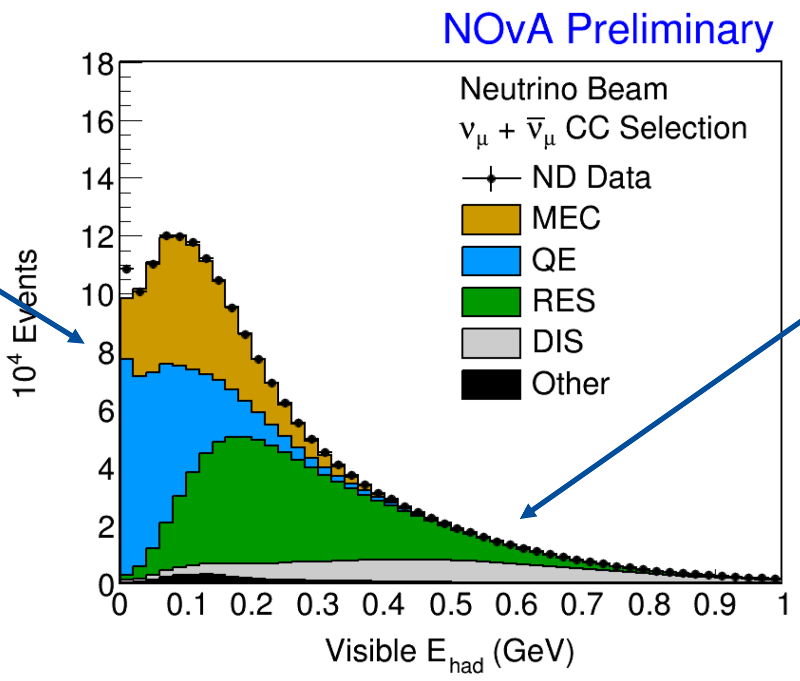
1) Take directly from simulation (larger uncertainty)
2) Fit background template in sideband region (smaller uncertainty)

Example from a MEC-enhanced analysis

QE and MEC events share similar energy and momentum transfer space

Harder to deconvolve

Don't fit QE events to template



RES and DIS events are easier to separate in energy and momentum transfer space

Do define sideband to fit RES and DIS

Background Estimation

Either:
1) Take directly from simulation (larger uncertainty)
2) Fit background template in sideband region (smaller uncertainty)

Uncertainties determined from systematic universes

- For direct estimate:	Vary central value
- For template fit:	Vary fit to data

Unfolding

Bin size chosen to not be smaller than detector resolution of quantity

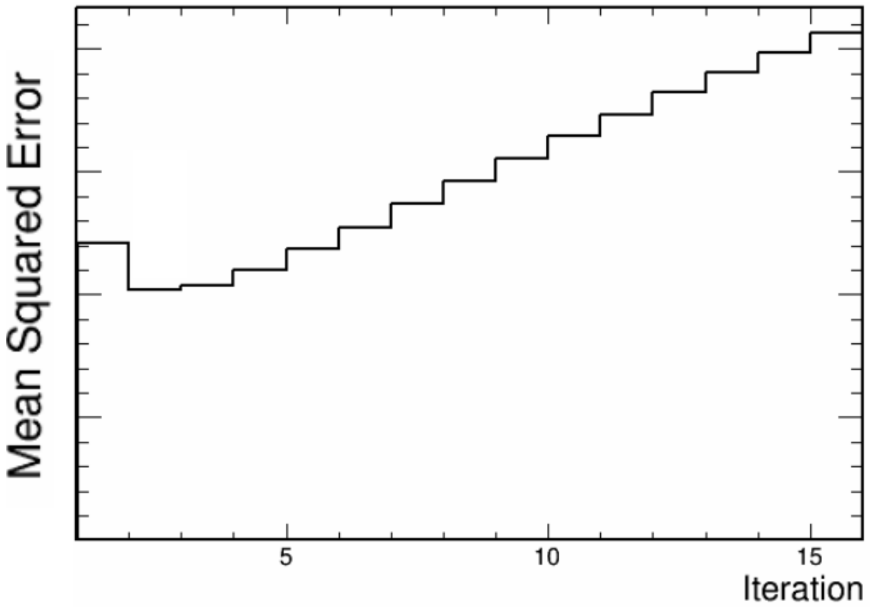
Over (under) flow bins

Use D'Agostini unfolding in RooUnfold package

Optimize number of iterations using mean squared error (MSE)

Since underlying truth is not know, we find average MSE from unfolding many systematically varied universes

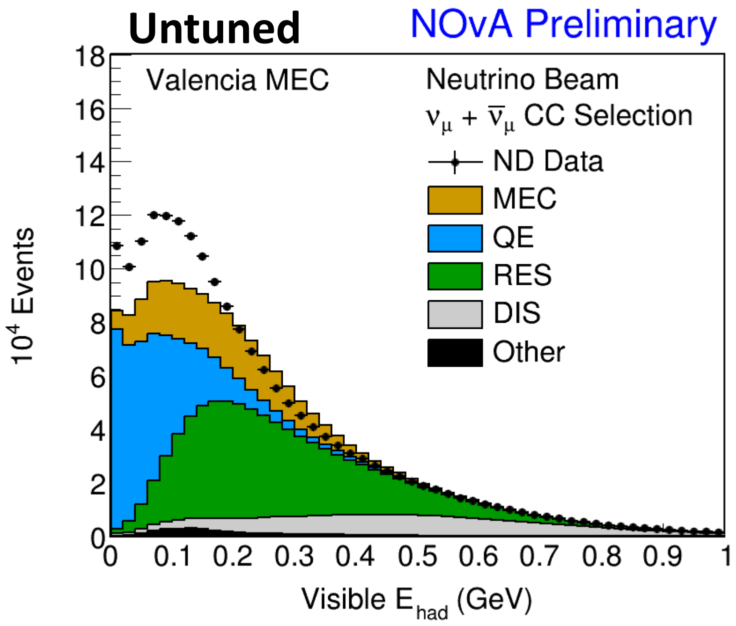
$$\overline{\mathrm{MSE}} = \frac{1}{M}\sum_{i=1}^{M}\sum_{j=1}^{Bins}\frac{(\sigma_{Unfold\,M,i,j})^2 + (Unfold_{\,M,i,j} - True_{\,M,i,j})^2}{(True_{\,M,i,j})^2}$$

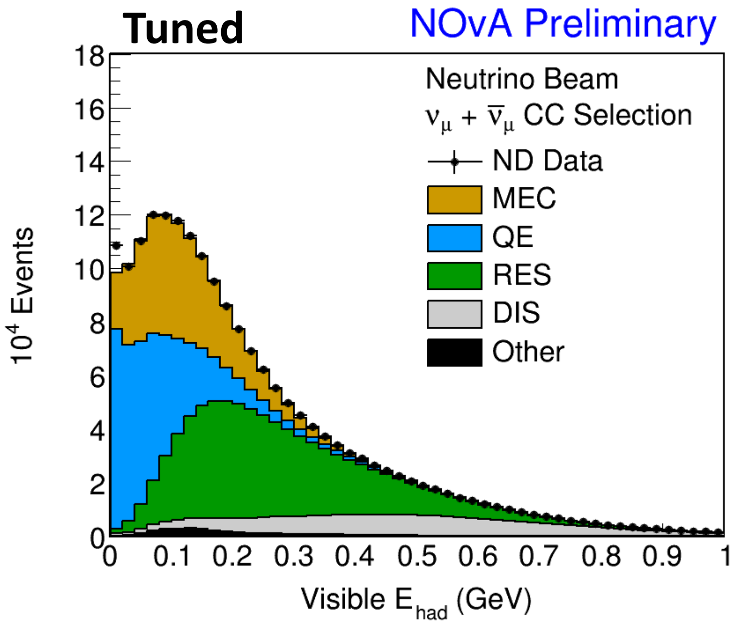


Efficiency and flux correction

Use central value simulation and propagate uncertainty on central value

We use a tuned MEC model for our central value





Choice between tuned or untuned has minimal impact on cross section extraction

e.g. For the MEC-enhanced analysis the MEC modeling uncertainty causes a 0.6% cross-section uncertainty on top of a total uncertainty of 11.5%

Covariance Matrix

There is uncertainty on our cross-section measurement

Determine covariance matrix by recalculating cross-section by introducing systematics to the background correction, unfolding, efficiency correction, and flux

For example recalculate this

$$\left(\frac{d^3\sigma}{d\cos\theta_\mu dT_\mu dE_{Avail}}\right)_i = \frac{\sum_j U_{ij}(N^{\text{sel}}(\cos\theta_\mu, T_\mu, E_{Avail})_j P(\cos\theta_\mu, T_\mu, E_{Avail})_j)}{\epsilon(\cos\theta_\mu, T_\mu, E_{Avail})_i(\Delta\cos\theta_\mu)_i(\Delta T_\mu)_i(\Delta E_{Avail})_i N_{\text{target}}\phi}$$

Consider multiple systematics sources

Add covariance matrices for the various systematics sources

Detector systematics have 1σ-shifted predictions

$$V_{ij} = \sum_{k=1}^{N^{syst}} (x_i^{sy} - x_i^{cv})(x_j^{sy} - x_j^{cv})$$

GENIE, Flux, and Statistical uncertainty derived from multi-universe approach

$$V_{ij} = \frac{1}{N_{univ} - 1} \sum_{k=1}^{N_{univ}} (x_i^{sy} - x_i^{cv})\left(x_j^{sy} - x_j^{cv}\right)$$

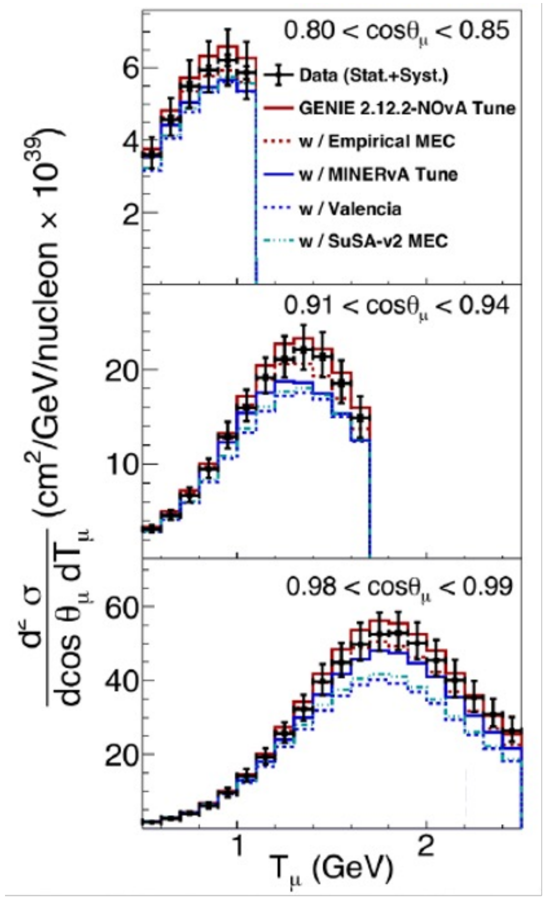
Publish covariance matrix

Comparing measurement to theory

Two options for model comparison

1) Use various generators to make the cross-section predictions for the NOvA flux and soup of elements in the detector

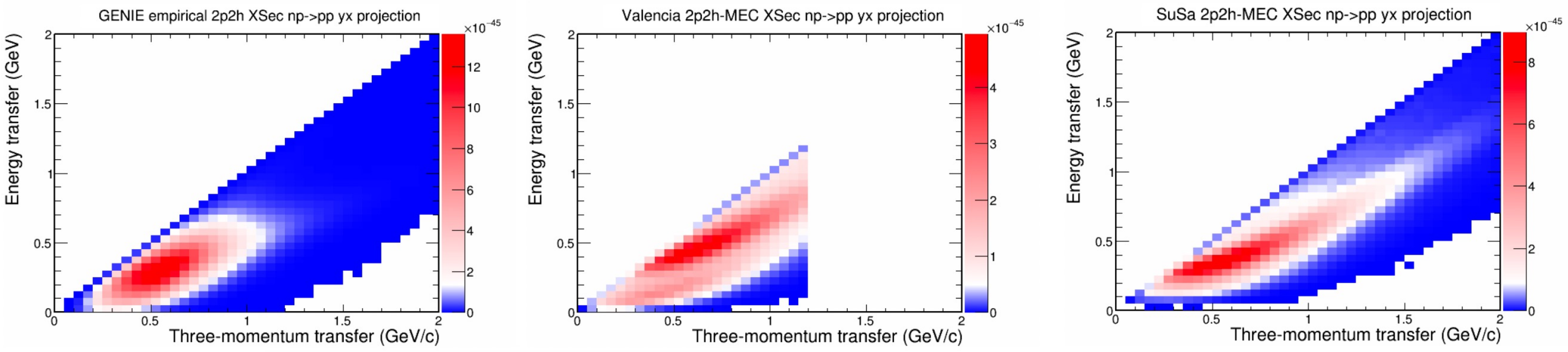
2) Reweigh fully simulated events (only done for MEC models)



Reweighing MEC models

Produce two separate sets of weights for pp and np final state

Weights done as a function of neutrino energy, energy transfer, and momentum transfer



Need to have sufficient coverage to reweight

Summary

NOvA explores a unique energy region of neutrino interactions with high statistics

- Resonant interactions dominate
- Sensitive to mix of QE, MEC, RES, D(S)IS

NOvA presents cross-section results in truth space

- Supplies covariance matrix with publication result