Systematic Uncertainties in the NOvA ν_μ Disappearance Analysis

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Overlay Simulation and Data

to pinpoint differences in selection efficiency due to mis-modeling and pileup:

Beam Intensity | Rock Muons | Detector Geometry

Pileup | Noise

Signal Normalization

- ✦ MC in Data spill provides **effective selection efficiency** *sensitive to detector mis-modeling*
- ✦ Data/MC **efficiency difference of overlaid** ν after each cut *vs. simulated kinematics and positions*

Single-Neutrino MC Event

Overlay Software

Data Spill | MC Spill

Preselection
True *overlaid* signal.
ν_μ-CC which is truly fiducial.

Identical Selections

Reconstructed
Hits clustered in time and space.

Contained
Cluster and Tracks are far enough from the edge.

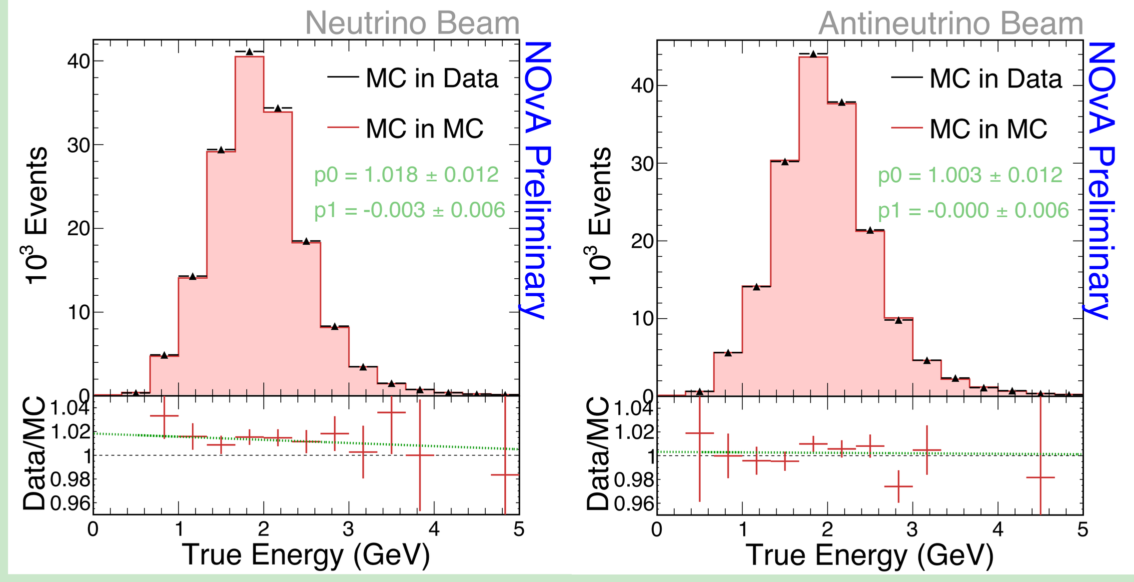
Quality
Enough hits, planes, track.

ν_μ-CC Selected
Neural Net and PID cuts.

ν-Beam	MC-MC		Data-MC		
Stage	Events (10^3)	Efficiency (%)	Events (10^3)	Efficiency (%)	Difference (%)
Overlaid	1450.3	100.000	965.3	100.000	0.000
Reconstructed	1417.4	97.733	961.9	99.652	1.963
Containment	328.5	22.651	221.0	22.895	1.075
Quality	323.2	22.284	217.4	22.523	1.069
Selected	233.9	16.133	157.9	16.357	**1.385** ★

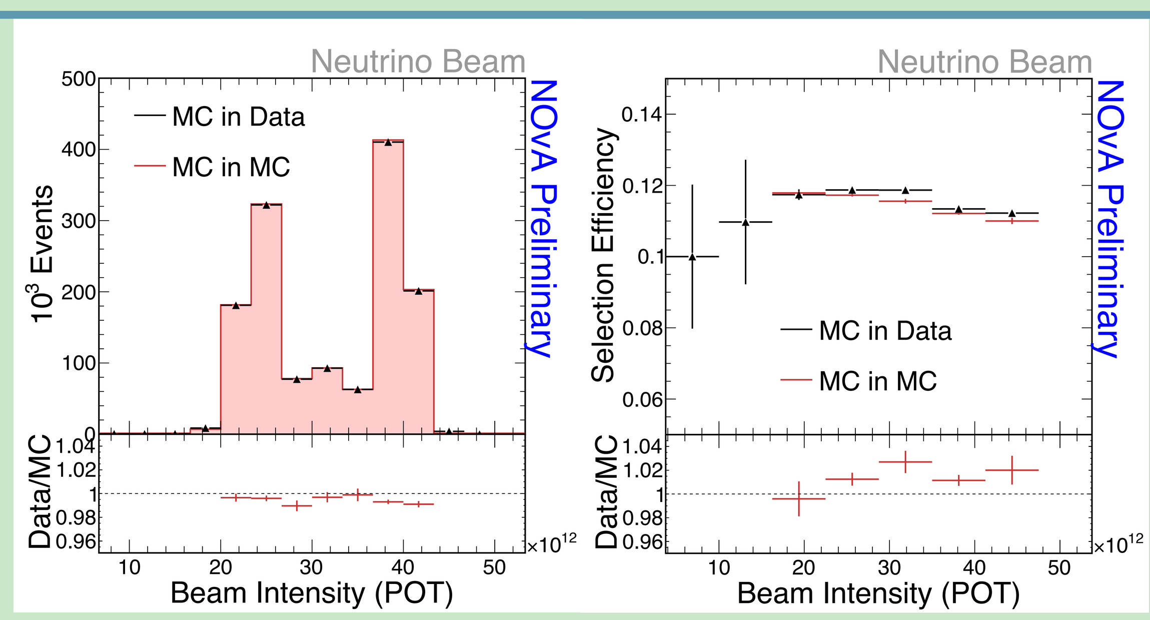
$\bar{\nu}$-Beam	MC-MC		Data-MC		
Stage	Events (10^3)	Efficiency (%)	Events (10^3)	Efficiency (%)	Difference (%)
Overlaid	895.8	100.000	1159.5	100.000	0.000
Reconstructed	878.6	98.078	1155.2	99.639	1.589
Containment	214.5	23.948	278.6	24.025	0.323
Quality	211.6	23.620	274.5	23.674	0.228
Selected	177.9	19.861	230.8	19.903	**0.213** ★

Cut-flow Tables: Beginning with all preselected, overlaid MC neutrinos, observe the fraction of events which pass each cut.

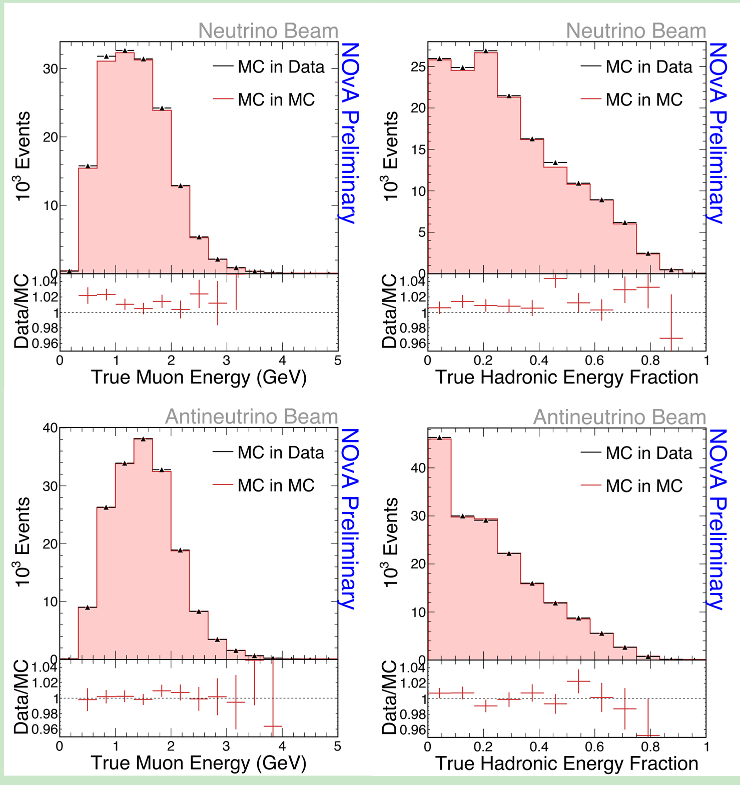


True Energy of Selected MC Overlaid into Data and MC
Data/MC ratio is consistent with being flat (p1 ~ 0), so a normalization rather than a shape effect has been isolated

Overlay Probes Many Effects



Search for Beam Intensity Effects
Left: Check that the MC spills match the intensities in Data spills.
Right: Fraction of preselected, overlaid νs passing full selection.



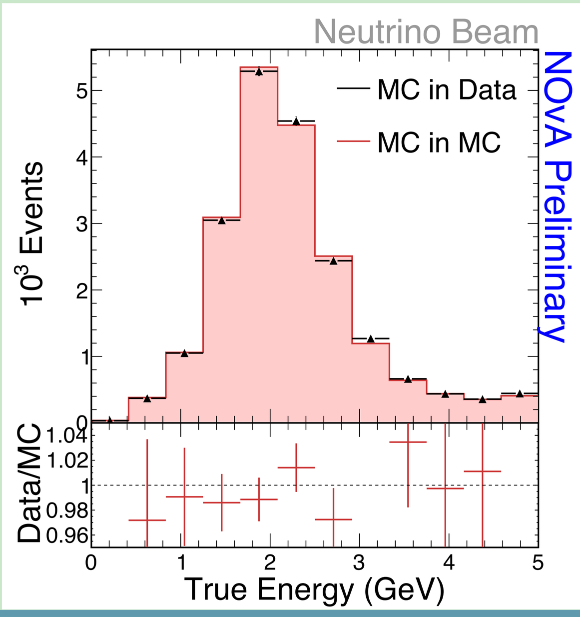
Search for Shaping in Kinematic Variables

Probe Rock Muon Effects

Muons from upstream ν

Energy of MC neutrino with rock muon clustered in

Rock muon modeling is fine does not shape energy spectrum

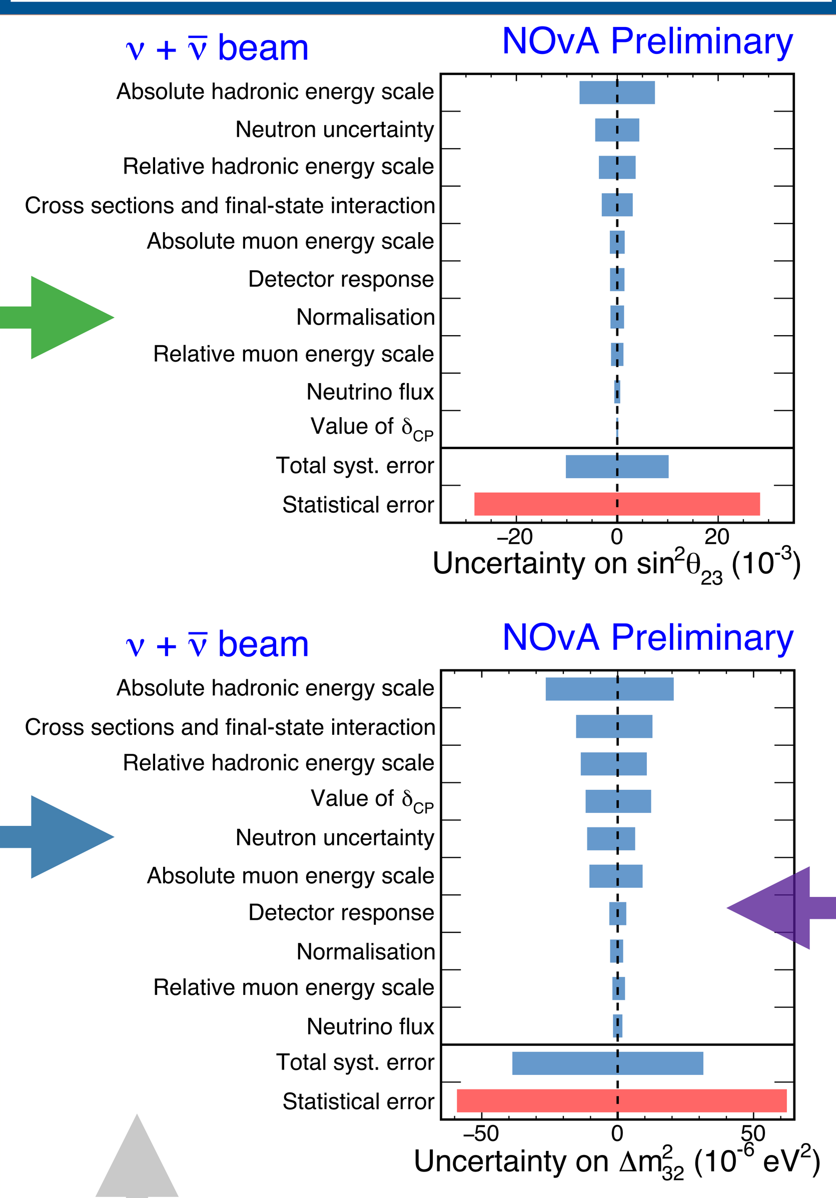


Normalization Systematic

0.5% POT Uncertainty ⊕ 0.26% Mass Uncertainty ⊕ Difference in Selection Efficiency (Nu 1.3%, AntiNu 0.3%)

***Overlay Technique** robustly reduced normalization uncertainty **by a factor of 3**.*

Uncertainties in ν_μ Analysis



Impact of Calibration

On Hadronic Energy Scale

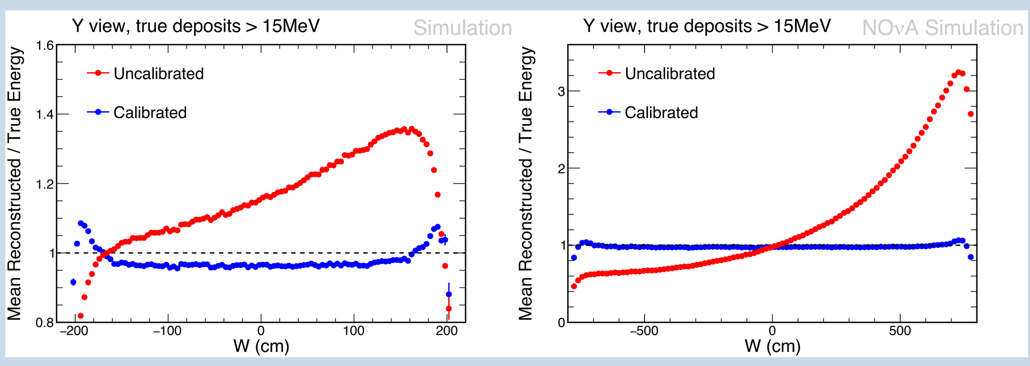
- ✦ **Calibration and scintillation light is shifted**
  - ✳ **Up/Down samples** are propagated all the way through the analysis

Beam ν Proton dE/dx Studies → Shift Absolute Energy Scale

Light Up Calib. Down | Light Down Calib. Up

Dominates Absolute & Relative

- ✦ **Absolute Hadronic Energy Scale**
  - ✳ **Fully correlated** between Near and Far Detector
- ✦ **Relative Hadronic Energy Scale**
  - ✳ **Uncorrelated** between Near and Far Detector



Impact of Detector Modeling

On Muon Energy Scale Uncertainty

Used to dominate, reduced with extremely detailed study by Matt Strait

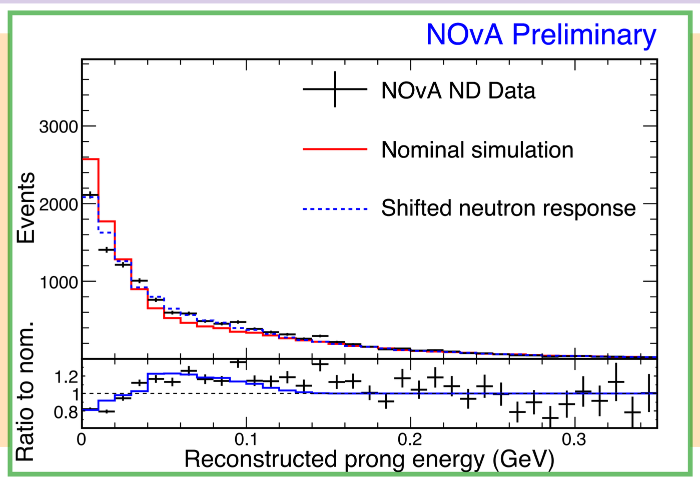
0.9% Correlated between Near and Far | **0.3%** Uncorrelated between Near and Far

- ✦ **Shifts from known mis-modeling**
  - ✳ Long **Air Bubbles** across horizontal FD cells
  - ✳ Glue and Paint in Near Detector Muon Catcher
- ✦ **Accounting for Mass**
  - ✳ Scintillator volume and density — external measurements
  - ✳ PVC mass measured by the extruder
- ✦ Elemental Composition, Bethe-Bloch Modeling, Error on Mean excitation energy of Carbon and Hydrogen

Neutron Energy Deposition

Prong
Reconstructed object with:
- Start Point
- Direction

- ✦ **Low Energy Excess of Reconstructed Prongs (Neutron Candidates)**
  - ✳ Primarily daughter Protons and Photons
  - ✳ Investigate potential Geant4 mis-modeling
- ✦ **Shift Neutron Response**
  - ✳ Increase energy response in events with neutrons of < 40 MeV true visible energy



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Neutrino 2018 Heidelberg

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http://novaexperiment.fnal.gov

Last analysis: arXiv:1806.00096