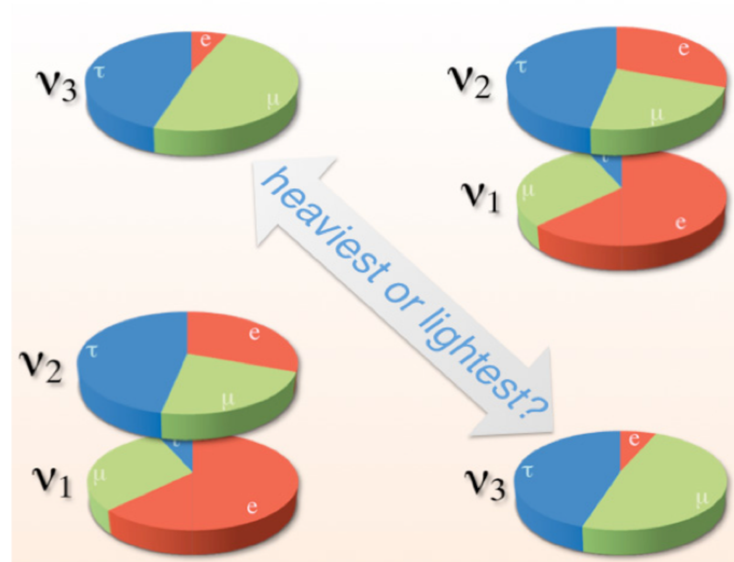
Report on the NOvA Experiment

Peter Shanahan
Fermilab PAC
19 July 2019

In partnership with:

NOvA and the Physics of Long Baseline Neutrino Oscillations

- Many of the most compelling questions related to the P5 Science Driver *Investigation of the Physics of Neutrino Mass* are accessible in long-baseline oscillation measurements
  - Neutrino Mass Hierarchy?
  - What is the Pattern of Mixings?
  - Do Neutrinos Violate CP Symmetry?
  - Is there more to the story than a 3x3 PMNS Mixing Matrix?



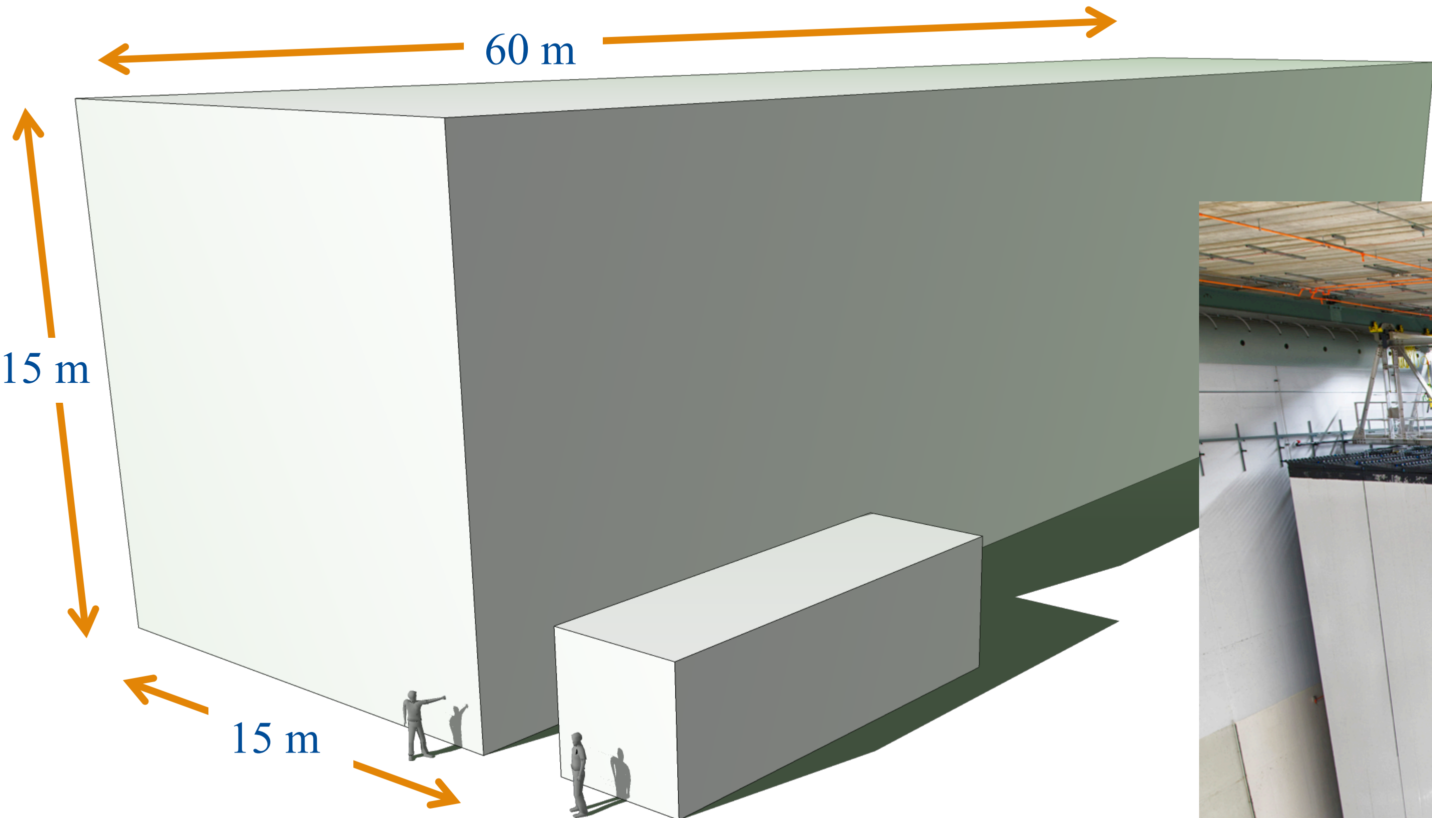
- NOvA addresses these using
  - Two detectors separated by 810 km
  - High-purity ν_μ and $\overline{\nu}_\mu$ beams
  - ν_μ disappearance, ν_e appearance, and flavor-independent (NC) disappearance
- Rich Menu of Cross-section Measurements in 1-3 GeV range for ν and $\overline{\nu}$
- Other topics
  - Exotic phenomena (monopoles), Gravitational wave multimessenger searches, Supernova neutrinos, Dark Matter, Cosmic-ray Physics

NOvA Collaboration

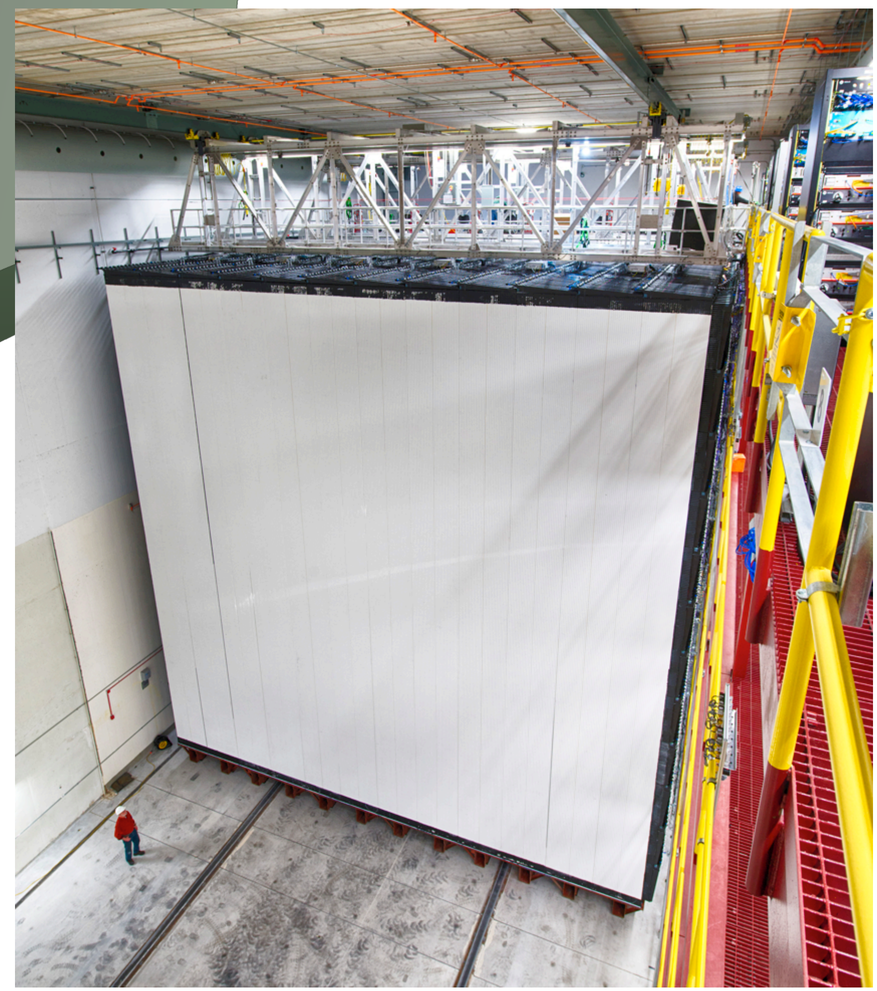
- 200 Collaborators from 48 institutions in 7 countries.
- 24 Remote Operations Centers worldwide.

NOvA Detectors

- Far Detector
  - 14 kT
  - 895 planes



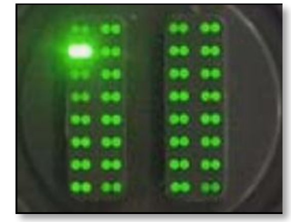
- Near Detector
  - 293 tons, including muon catcher
  - used to measure neutrino beam flavor and energy spectrum before oscillations

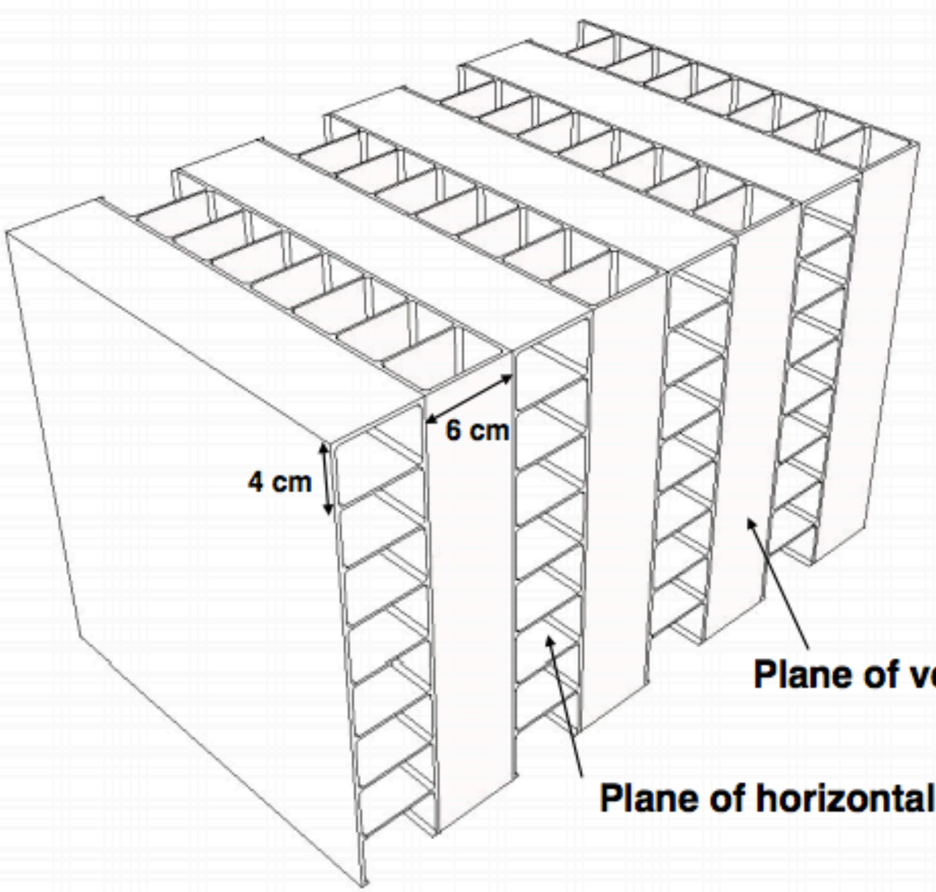


NOvA Detector Technology

- Low-Z Tracking Calorimeters
  - PVC Cell Structure
  - Filled with Mineral Oil + 5% pseudocumene

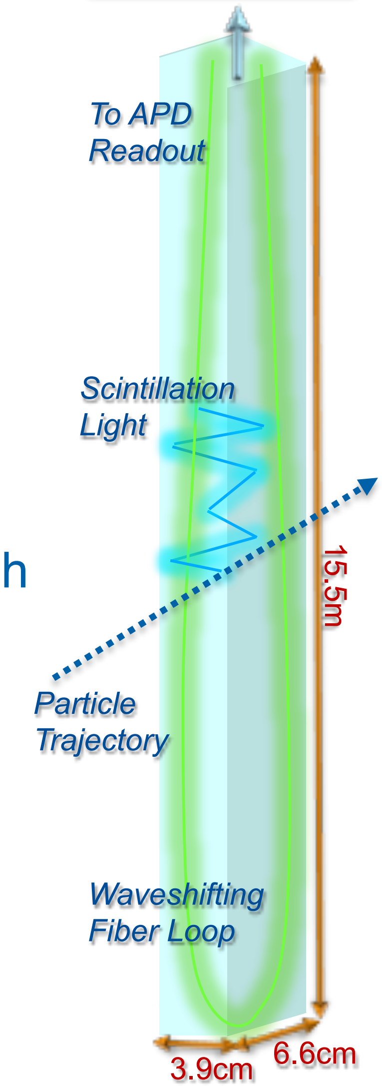
32 cells read out into 1 Avalanche PhotoDiode





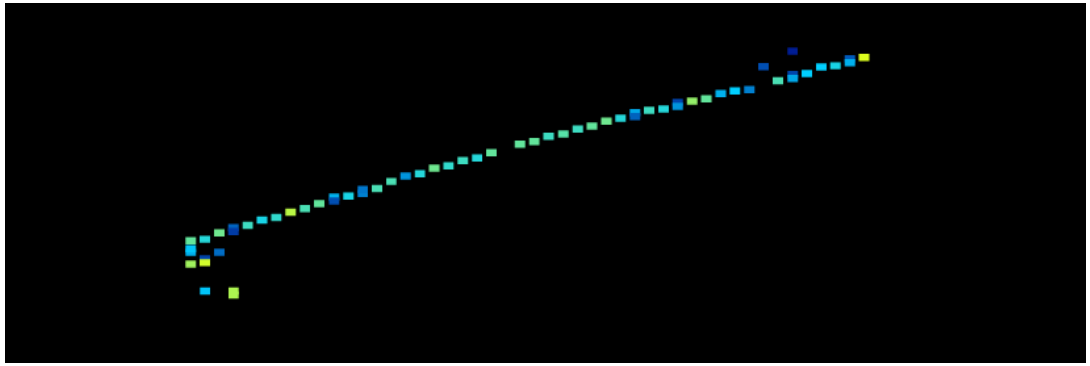
Excellent electromagnetic shower characterization with 6 samples per radiation length

Single Cell



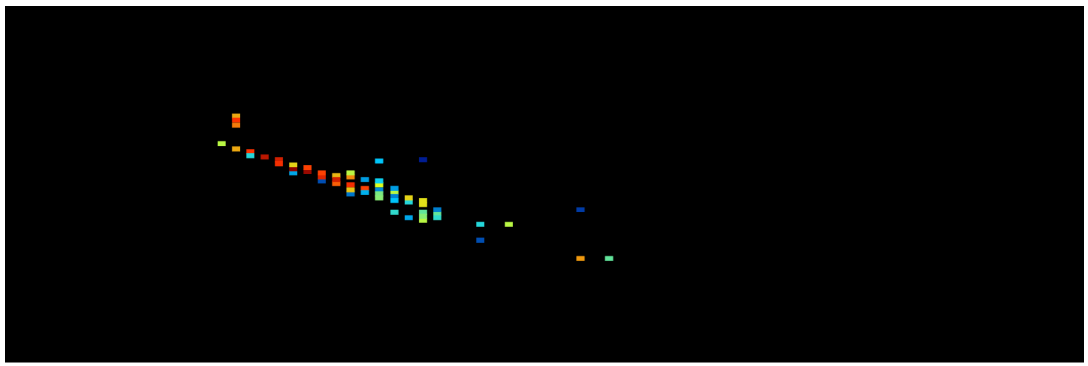
Illustrative Far Detector Neutrino Candidates

$\bar{\nu}_\mu$ CC, 2 GeV



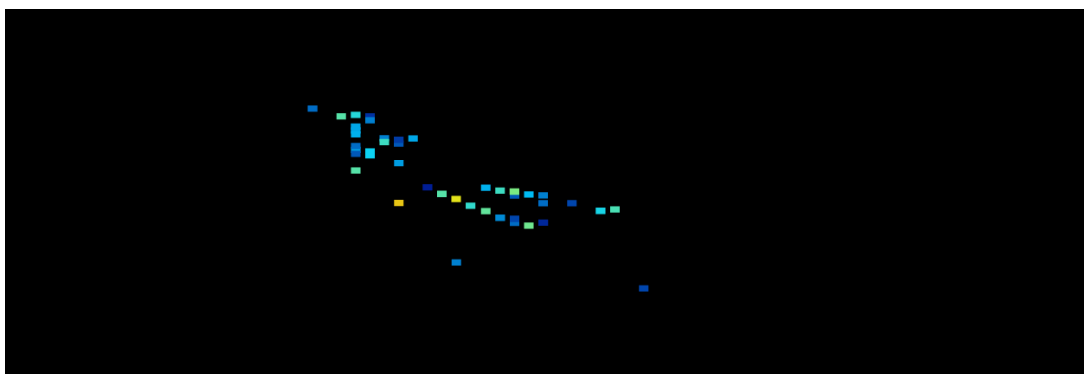
$E_\nu = E_\mu(\text{length}) + E_{had}(\text{calor.})$

ν_e CC, 2.6 GeV



$E_\nu = E_{em}(\text{calor.}) + E_{had}(\text{calor.})$

NC, 2.8 GeV visible



$E_{visible}$

← 10 m →

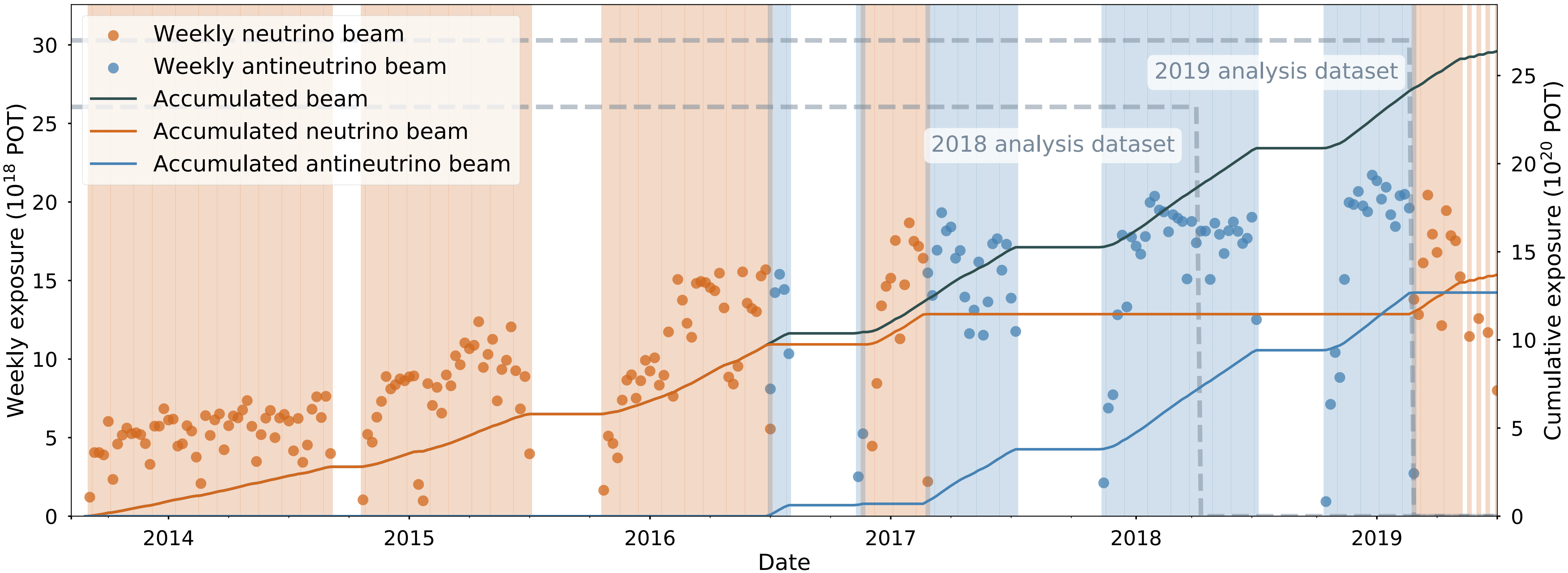
Data-Taking

Far Detector Beam Exposure To Date: Protons-on-target (POT) to NuMI

- 11.1×10^{20} (14 kt-equivalent) POT Forward Horn Current (neutrino beam)
- 12.7×10^{20} POT in Reverse Horn Current (antineutrino beam)

FY19: Far Detector recorded data for 99.1% of 5.56×10^{20} POT delivered to NuMI

756 kW hourly beam power record achieved



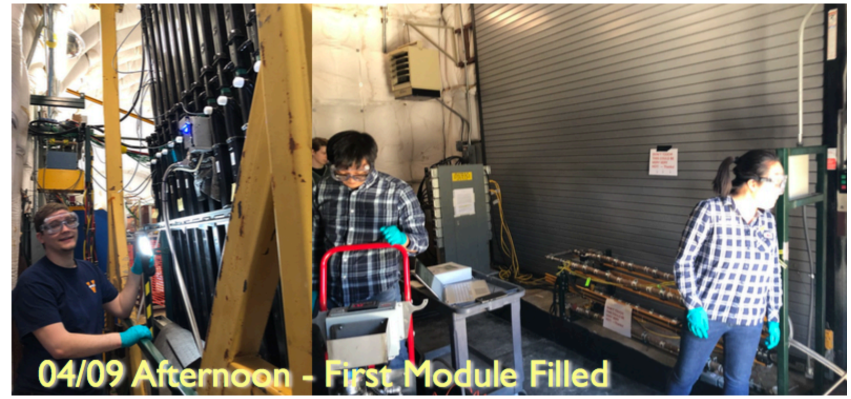
NOvA Publications and Theses

- 7 Peer-reviewed publications to-date.
  - 3-flavor oscillations with neutrinos
    - PRL 116 (2016), 151806
    - PRD 93 (2016), 051104
    - PRL 118 (2017), 151802
    - PRL 118 (2017), 231801
    - PRD 98 (2018) 032012
  - NC disappearance, 2017
    - PRD 96 (2017), 072006
  - Seasonal variation of multi-muon cosmic ray events in the Near Detector, 2019
    - PRD 99 (2019), 122004
- Two in journal Review.
  - NC Coherent π^0 production
    - arXiv:1902.00558
  - NOvA's 1st 3-flavor results with ν and $\bar{\nu}$
    - arXiv:1906.04907

- Total of 31 Ph.D. Theses Defended.
- In the past year
  - Shaokai Yang, Long-baseline NC Disappearance, Cincinnati
  - Rijeesh Keloth, Short-baseline sterile search with ν_τ appearance, Cochin University of Science & Technology
  - Barnali Chowdhury, Cross-section ratio, South Carolina
  - Kuldeep Kaur Maan, Empirical Neutrino Flux Constraints, Panjab University
  - Tristan Blackburn, Muon (anti)neutrino disappearance, Sussex
  - Erika Cataño-Mur, Oscillation Parameter Fits in 3-flavor analysis, Iowa State
  - Andrew Vold, ν_e ID with long short-term memory, Minnesota
  - Biswaranjan Behera, ν_μ CC inclusive cross-section, IIT Hyderabad
  - José Andrés Sepulveda Quiroz, Constraining NuMI kaon production using uncontained ν_μ CC in the Far Detector, Iowa State
  - Siva Prasad Kasetti, Short-baseline sterile search with ν_e appearance and ν_μ disappearance, Hyderabad
  - Vladimir Bychkov, ν_μ disappearance with uncontained events, Minnesota
  - Nitin Yadav, Electromagnetic showers in cosmic rays, IIT Guwahati

Test Beam

- Start of Filling Detector with Scintillator Started in April
- Following successful filling of 1st of 2 blocks, scintillator was contaminated with water during transfer from storage tank to tanker.



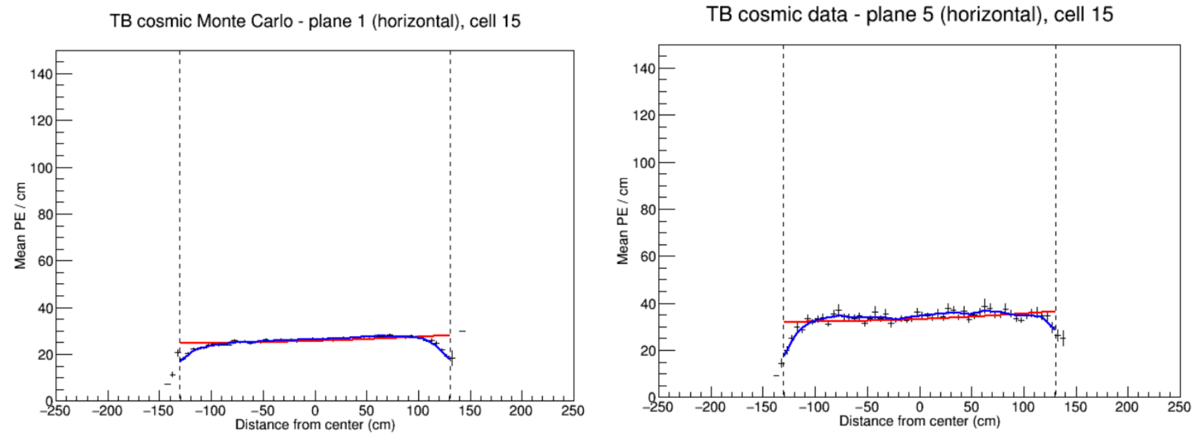
- We decided to
  - proceed on outfitting and commissioning 1st block with remaining available beam,
  - address filling of second block during shutdown.

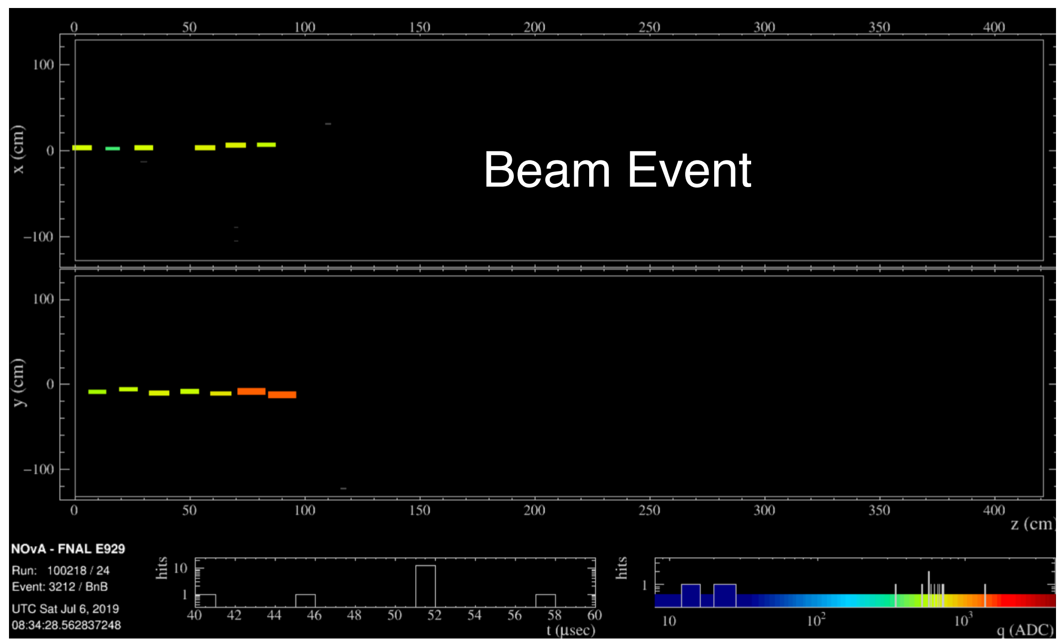
- Remaining block will be filled this summer with excess NOvA oil at Ash River and UT/Texas A&M

Test Beam Commissioning

- Examining rates, basic reconstruction, detector calibration
- Tuning up triggers, chambers, particle ID
- Beam scans to reduce halo-to-beam ratio
- Scans of primary beam intensity and secondary beam energy to find optimal operation configurations.
- Analysis will continue throughout the summer

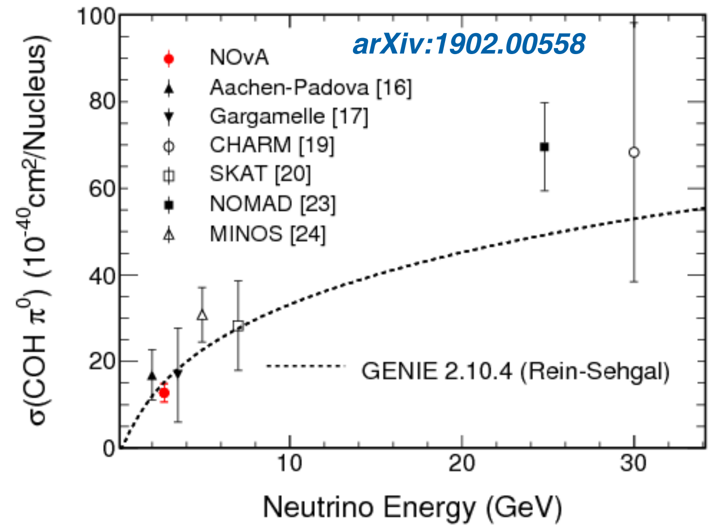
Cell Attenuation Calibration with Cosmic-ray muons





Recent Progress on Cross-Section Measurements

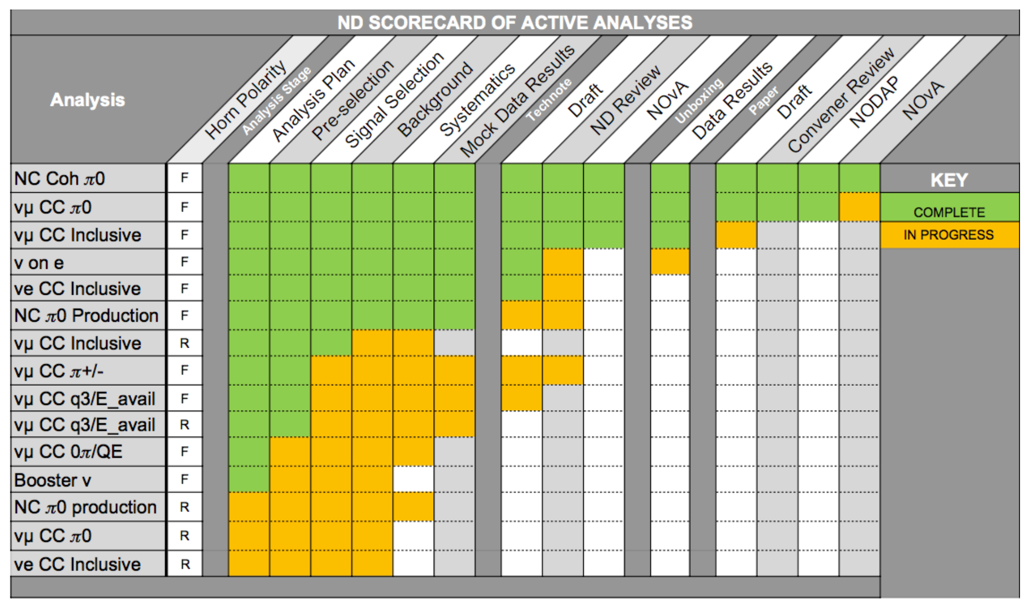
- Paper on Neutral Current Coherent π^0 production submitted to PRD
  - In second round of referee comments



- Charged Current π^0 production cross-section in internal review

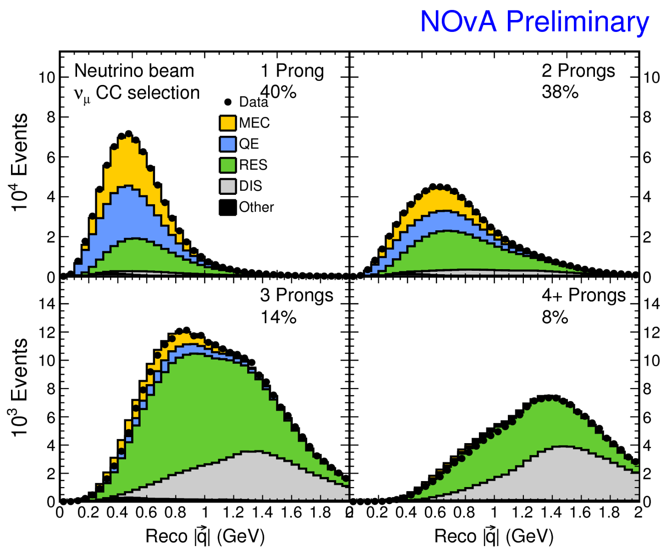
- ν_μ Charged Current Inclusive cross-section
  - An important measurement, and challenging in an an energy range with a poorly-constrained mix of channels.
  - We have revisited choice of kinematic variables and are re-working the unfolding scheme.

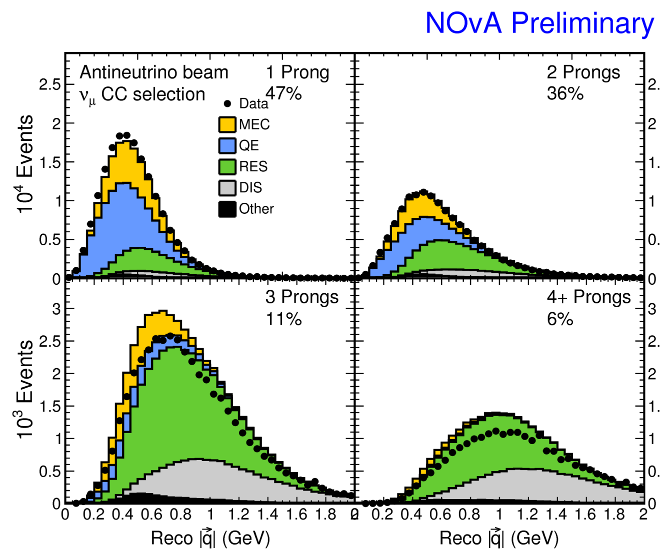
- A variety of other measurements are in progress



Progress on Cross-Section Tuning

- Held 1-day joint workshop with MINERvA in September
  - Comparison of methods and results of the MINERvA and NOvA tunes
    - NOvA tune shared with MINERvA expert in advance.
  - E.g., NOvA use of RPA suppression for Resonance Production
    - Long-range nuclear correlation not consistent with higher Q^2 in resonance production: indications our application of the effect is remediating other nuclear effects.
  - E.g., both experiments see excess of data at lowest hadronic energies, in antineutrino tune.
  - Suggestions for NOvA, including finer sub-division of final states.



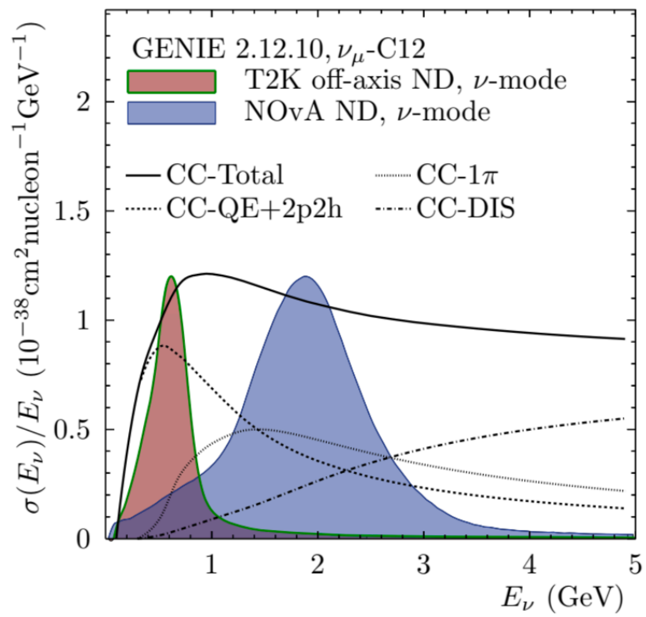


Reconstructed 3-momentum transfer by prong multiplicity

- Cross-section tuning paper drafted, in internal committee review
  - Software package to be released at same time has been tested in MINERvA and T2K.

Joint effort with T2K

- Third formal joint workshop held at Fermilab in February.
  - Detailed meeting between experts, working group conveners, and leadership.
- Leadership session
  - Discussed inter-collaboration agreement for sharing of information.
    - Agreed in April.
  - Agreed to revisit timeline and scope of first joint fits in light of 2020 results
    - Default target of 2021.
  - Next joint Workshops in October, March.
- Comparisons of NOvA and T2K cross-section models, analysis methods, simulations.
- Identification of areas for further investigation for possible sources of correlated uncertainties
  - Multi-nucleon effects (2p2h)
  - Single pion production
  - Final state interactions
  - Modeling ν_μ vs ν_e, ν vs $\bar{\nu}$

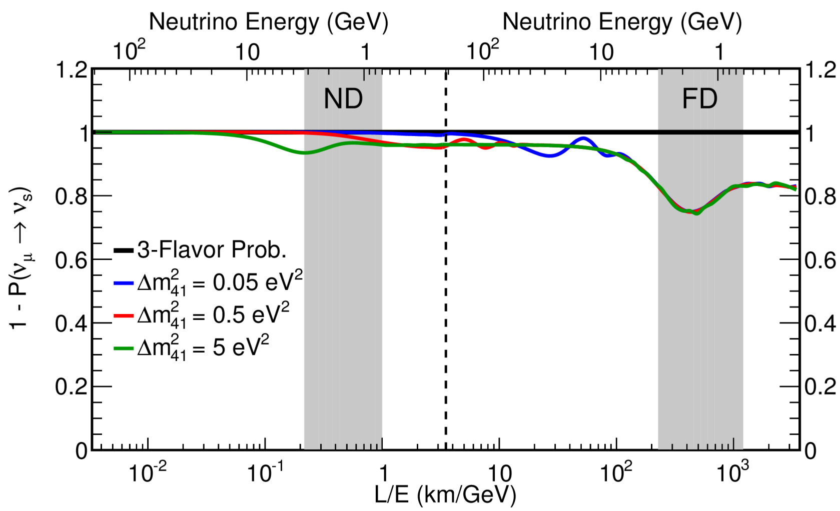


L. Pickering (T2K)

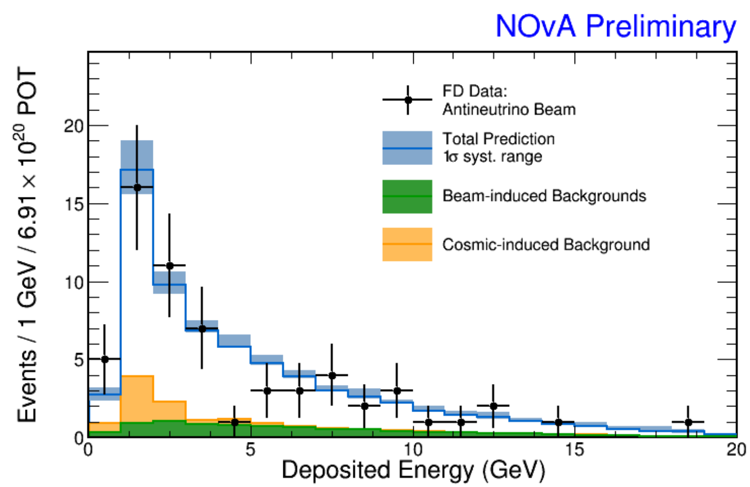
Sterile Neutrino Search via Neutral Current Disappearance

- Update to first long-baseline sterile neutrino search with antineutrinos

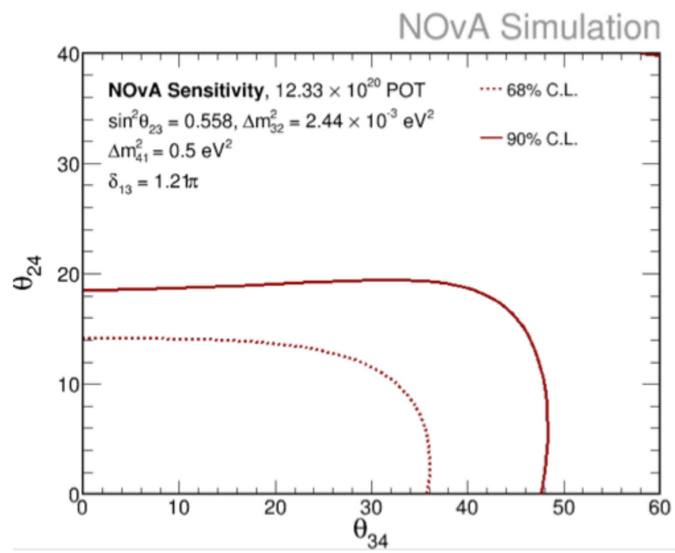
Far Detector-Only Fit: restrict to Δm^2 where there is no effect at Near Detector



2018 Far Detector NC Spectrum:
No significant suppression relative to 3-flavor prediction



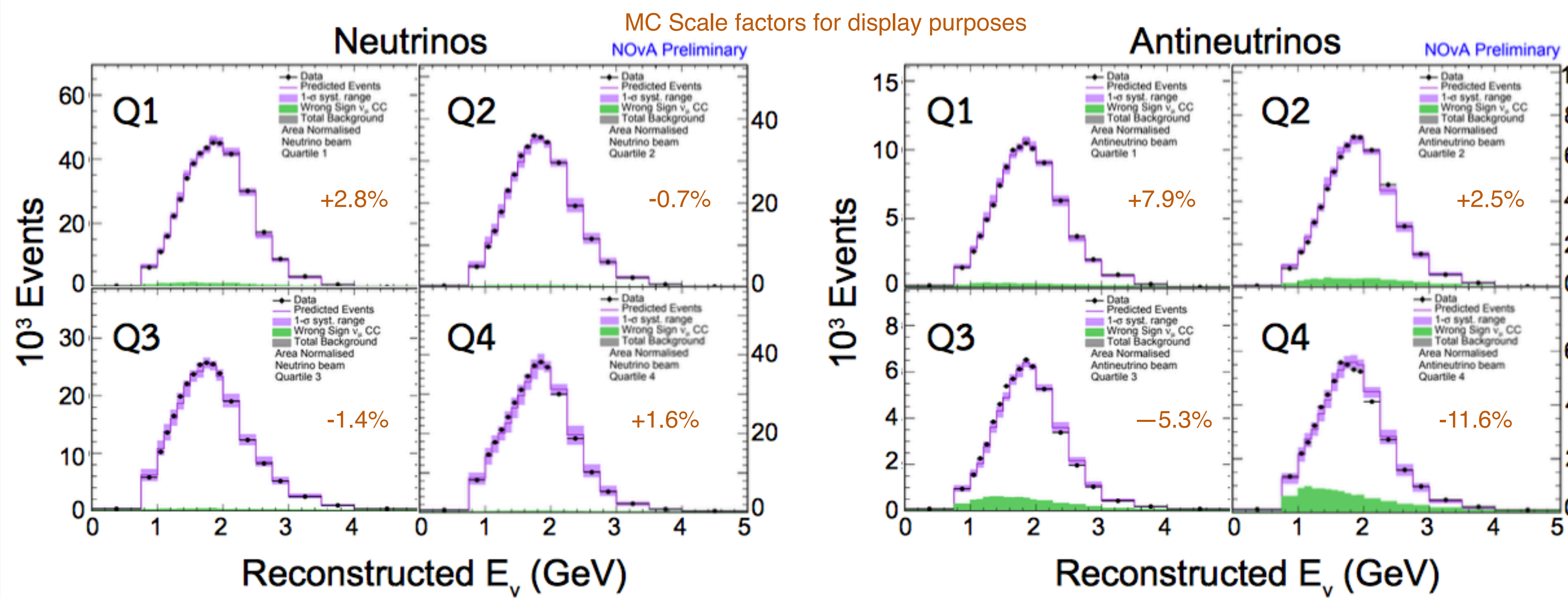
- Top-up with 78% more antineutrino exposure coming in a few weeks.
  - Targeted for DPF.
- Improvements to treatment of several systematic uncertainties.



Projected a priori sensitivity for 2019

3-flavor Oscillation "Top-Up" Results

- 78% more antineutrino mode exposure than 2018 result
  - 8.85x10^{20} POT FHC, 12.33x10^{20} POT RHC
- Same analysis techniques, selections, input systematic uncertainties.

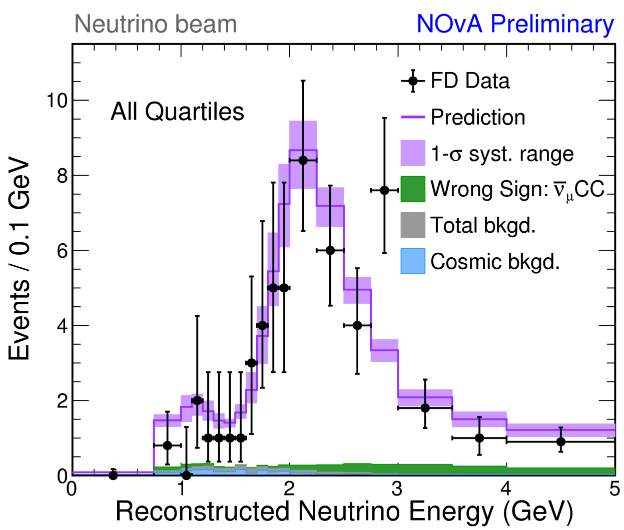


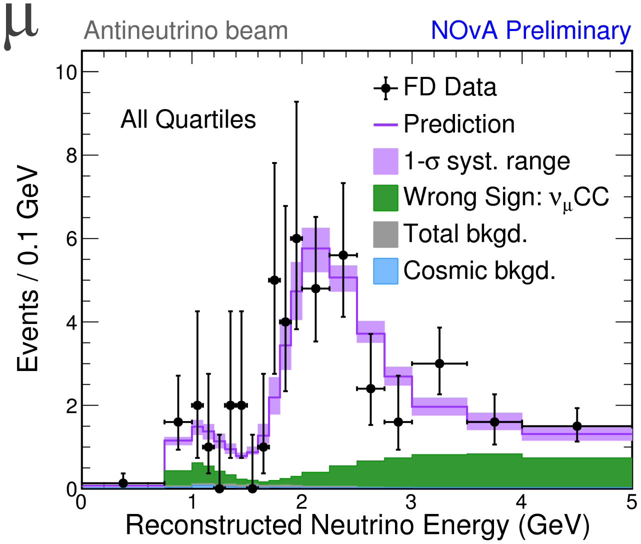
Near Detector $\overset{(-)}{\nu}_\mu$ Spectra in Quantiles of Hadronic Energy Fraction

Used to improve prediction of ν_μ disappearance and ν_e appearance signal predictions at Far Detector

Far Detector Data and Oscillation Fit

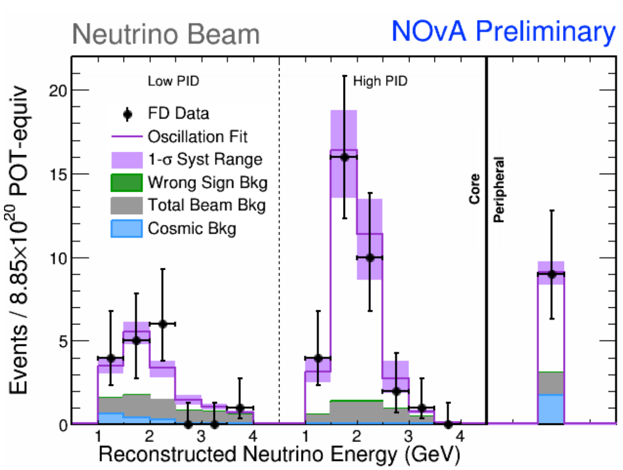
ν_μ

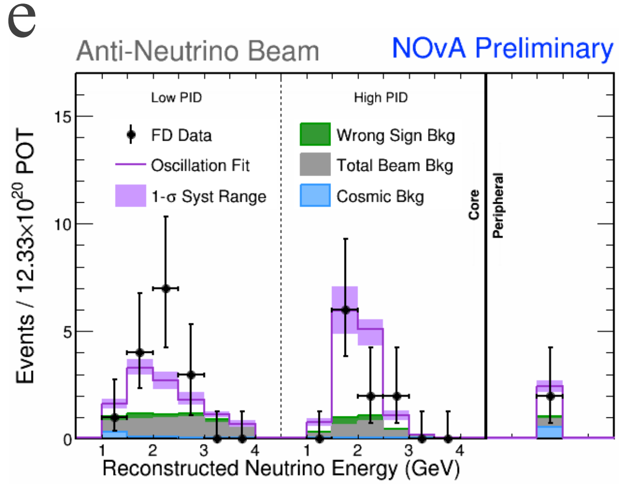




	ν	$\bar{\nu}$
Observed	*113*	*102*
Best Fit	*124*	*96*
Signal	*120(11)*	*93.9 (8)*
Background	*4.2(0.5)*	*2.2(0.4)*
No Oscillation	*730*	*476*

ν_e





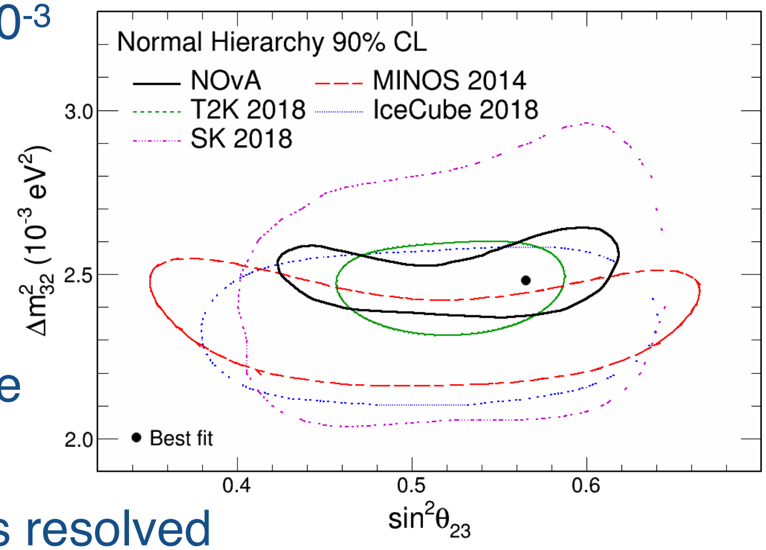
	ν	$\bar{\nu}$
Observed	*58*	*27*
Best Fit	*59.3*	*26.8*
Signal	*44.3(3.8)*	*16.6(1)*
Background	*15.0(0.9)*	*10.3(0.6)*
(Wrong Sign)	*0.6*	*2.2*

Note: uncertainties () are approximate
see arXiv:1906.04907 for full table

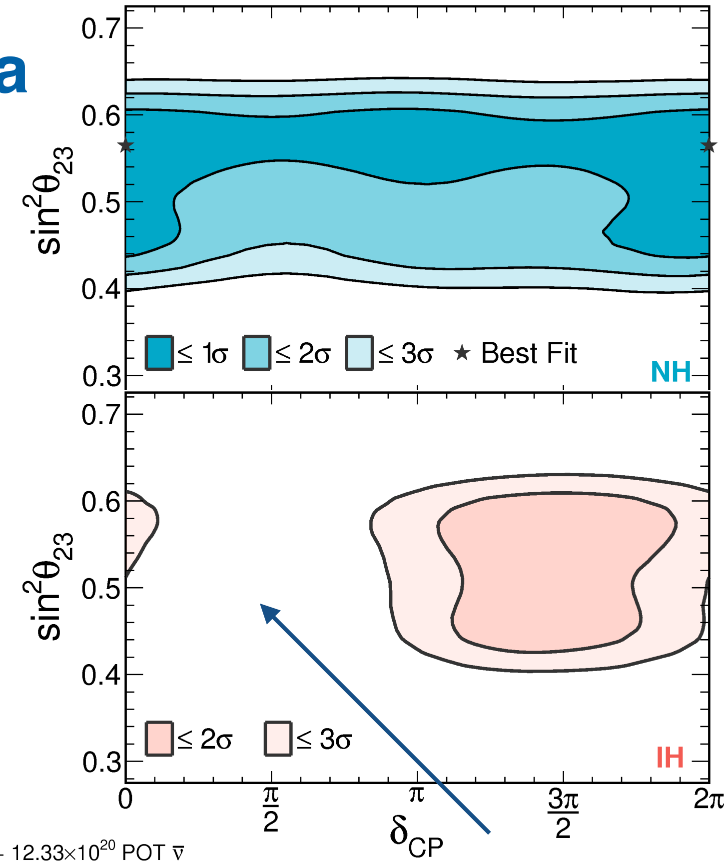
Oscillation Parameters from Joint fit to ν_μ, ν_e, neutrino, antineutrino data

Best fit (with reactor θ_{13} constraint):

- $\Delta m^2_{32}/eV^2 = +2.48^{+0.11}_{-0.06} \times 10^{-3}$
- Normal Hierarchy
- $\sin^2(\theta_{23}) = 0.56^{+0.04}_{-0.03}$
- $\delta_{CP}/\pi = 0.0^{+1.3}_{-0.4}$
- Tension (p=0.04) between disappearance fit in neutrino and antineutrino beams has resolved



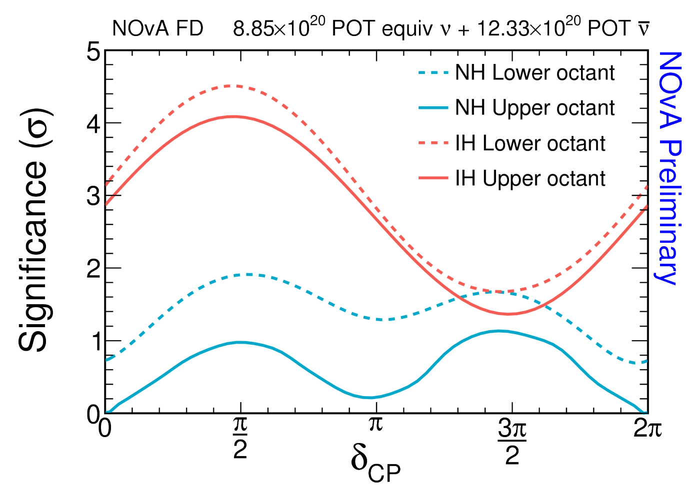
NOvA Preliminary



Large slice of δ_{CP} values disfavored at > 3σ for all θ_{23} values in IH

Profiling over all other parameters

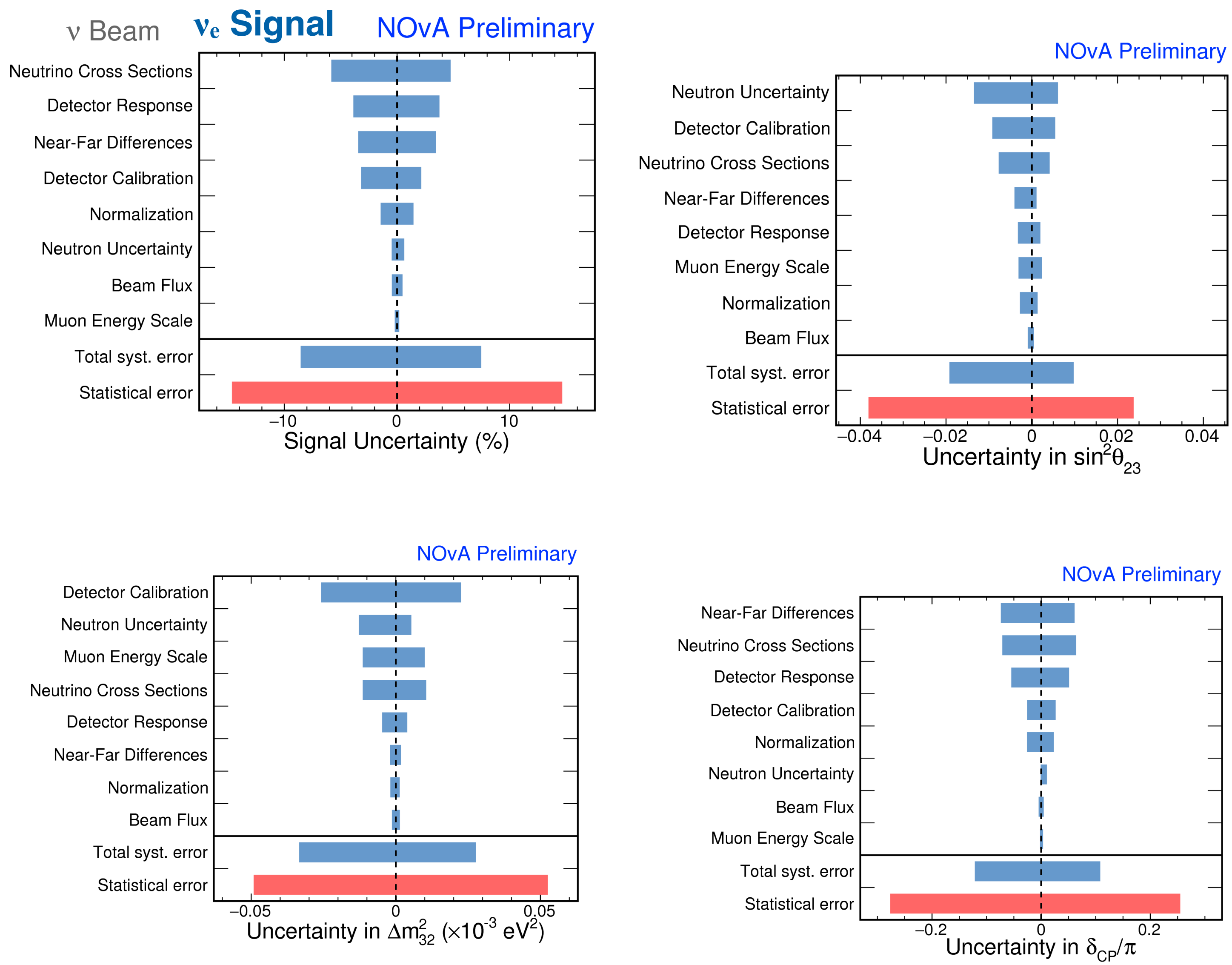
- **Normal Hierarchy preferred at 1.9σ**
- **Upper θ_{23} Octant preferred at 1.6σ**
- Within Normal MH, Upper Octant, all values of δ_{CP} compatible at 1.1σ



Systematic Uncertainties on ν_e signal and background prediction

Systematic uncertainties are evaluated by modifying simulation throughout analysis chain.

Most significant uncertainties compared to the statistical uncertainty are Cross-sections, calibration, detector response, acceptance effects.

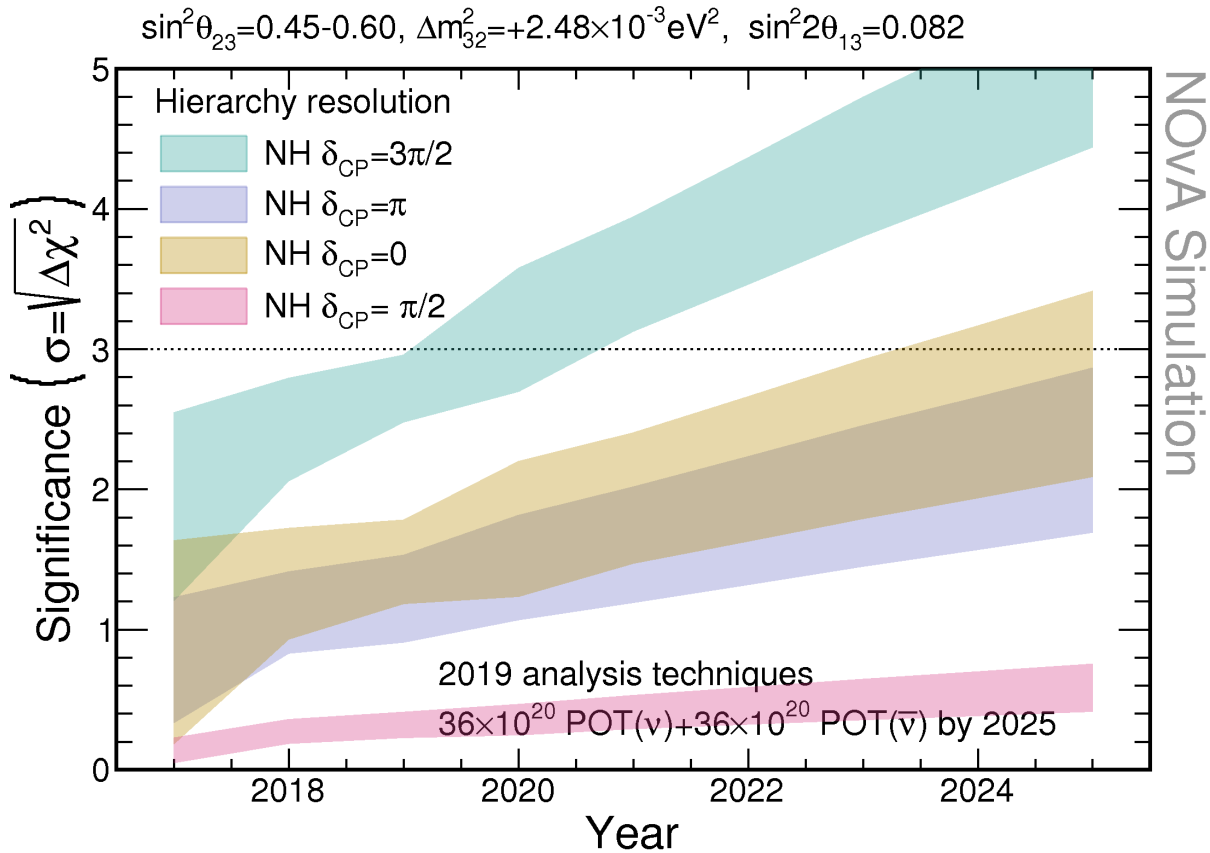


3-flavor Neutrino Oscillation Results for Neutrino 2020

- Current projection: Additional 75% neutrino-mode data.
  - 15.5x10^{20} POT neutrino mode, 12.33x10^{20} POT antineutrino mode.
- A variety of analysis improvements are targeted or *under investigation*
  - Neutrino interactions
    - Moving from GENIE 2.12 to GENIE 3.
  - Detector simulation
    - Cell brightness variations in Near Detector, Geometry improvements, light level tuning using protons
  - Calibration
    - Updated self-shielding and threshold corrections for cosmic muons, *finer time bins*
  - Reconstruction and Selection
    - New "slicer", retraining of CVN, *exploring new CVN architectures, new LSTM energy estimator, early cosmic rejection for faster processing*.
  - Potentially new Systematic Uncertainties on each of the above.
  - *New Extrapolation and Oscillation Parameter Fitting Strategies*
- Targeting new production campaign September-January

Long Term Sensitivity Projections

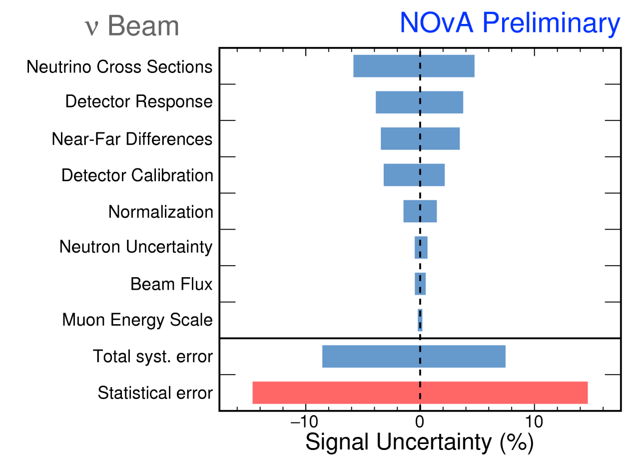
- Assuming 2019 Analysis Techniques
- No systematic uncertainties
- Assumed beam delivery
  - In FY20-25:
    - 750 kW, 800 kW, 800 kW, 900 kW, 900 kW, 1000 kW
  - 40 week runs starting FY21
  - Scaled from 2019 beam delivery as “700 kW @ 34 weeks”

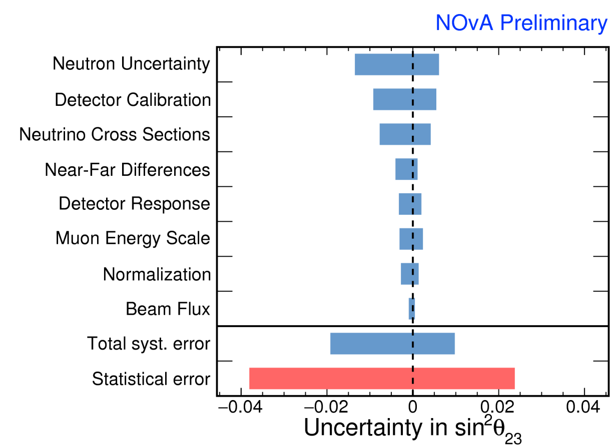


- Beam Progress
  - 1 MW-capable target scheduled to be installed during current summer shutdown.
  - Complex capable for 1.2s rep rate (down from 1.33s) after current shutdown.
    - 1.4s whenever Muon program is taking beam.
  - Booster improvements for PIP-II scheduled for completion by 2023 will allow 900 kW.
- End of NuMI Running: start of Long LBNF shutdown in 2025.

Evolution of Systematic Uncertainties

- Paths to reduce uncertainties for which current value would be significant in final data set, which will have 4x current ν and 3x current $\bar{\nu}$ statistics.
  - Neutrino cross-section model
    - Continued benefit from T2K and MINERvA experience.
  - Neutron response
    - Recent studies indicate smaller discrepancy than seen in 2018 study
    - Investigating possible overlap with cross-section uncertainties.
  - Detector response
    - Test Beam
  - Acceptance
    - Investigating possibly overlap with cross-section uncertainties
    - Test beam



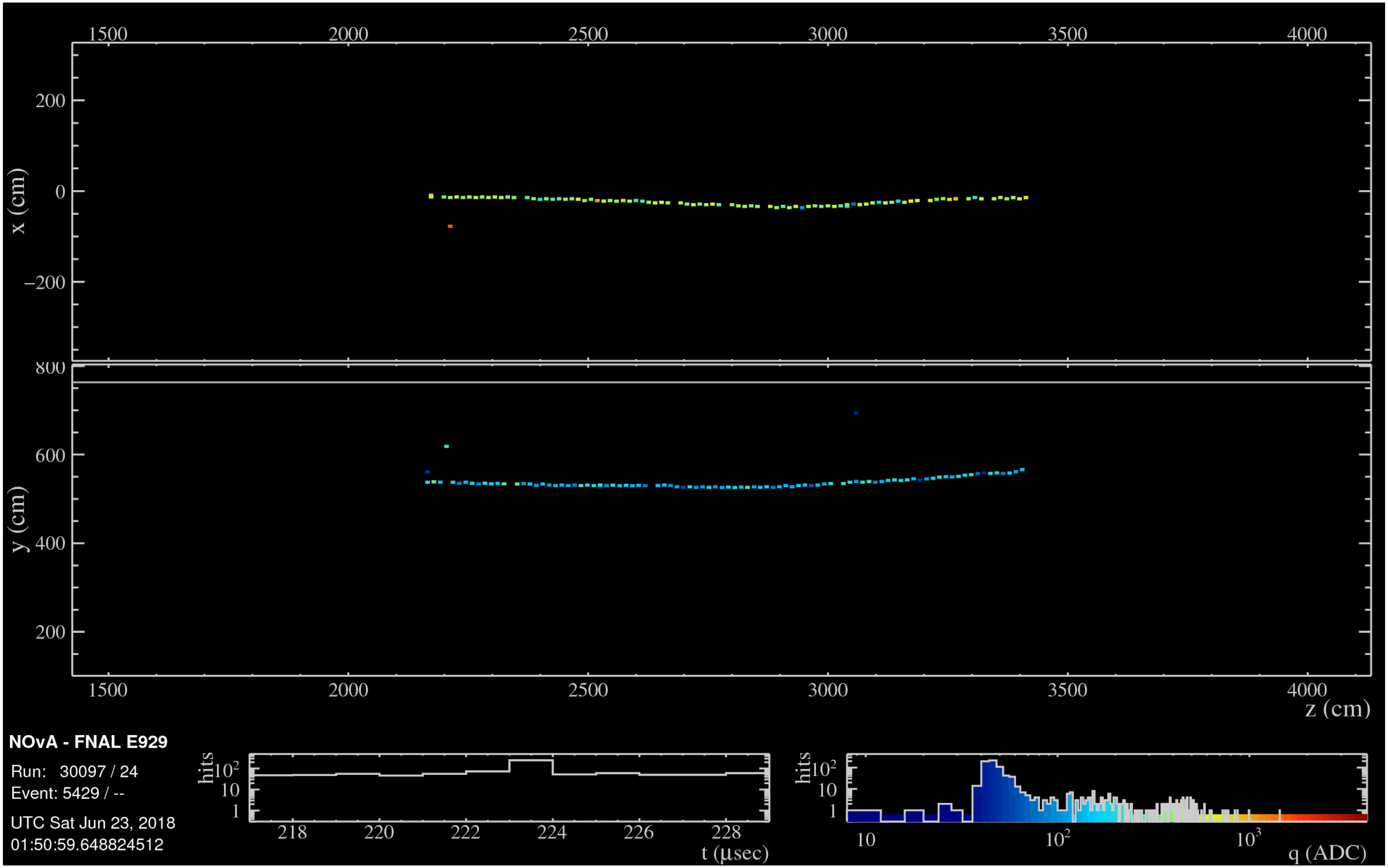


Summary

- NOvA has accumulated a combined 23.8×10^{20} POT over 5 years of running.
- We are looking forward to increasing beam power over the coming years.
  - New high-power target being installed this summer.
- Publications in peer review
  - Updated 3-flavor oscillation result with neutrinos and antineutrinos.
  - First cross-section result - NC Coherent π^0.
- Future plans
  - Updated NC Disappearance sterile search with antineutrinos shortly.
  - New 3-flavor results with updated analysis for Neutrino 2020.
  - More cross-section results coming.
  - More sterile searches
  - Various exotics searches
- Combined fit with T2K.
- Mass Hierarchy reach of 3-5 sigma for favorable scenarios.

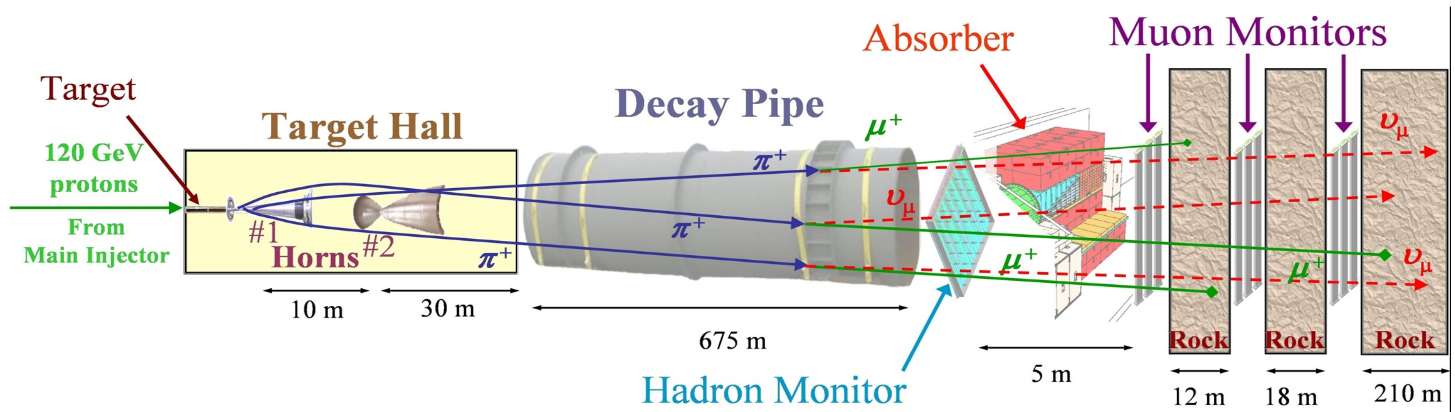
Extras

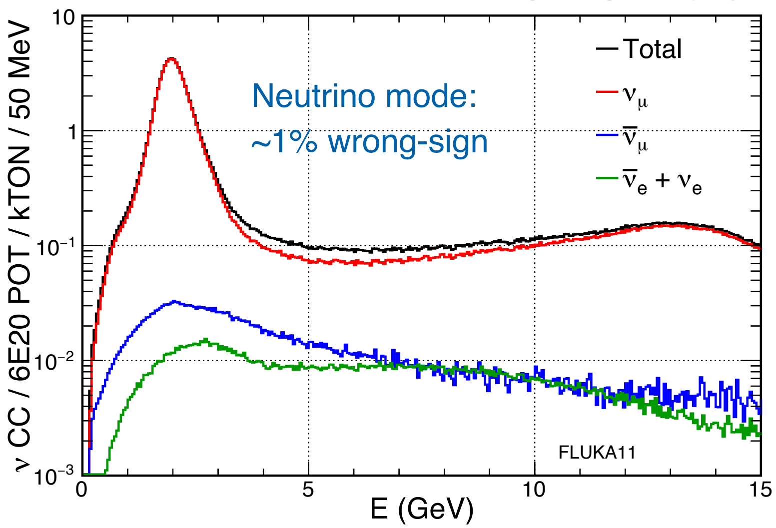
Candidate antineutrino interaction with neutron

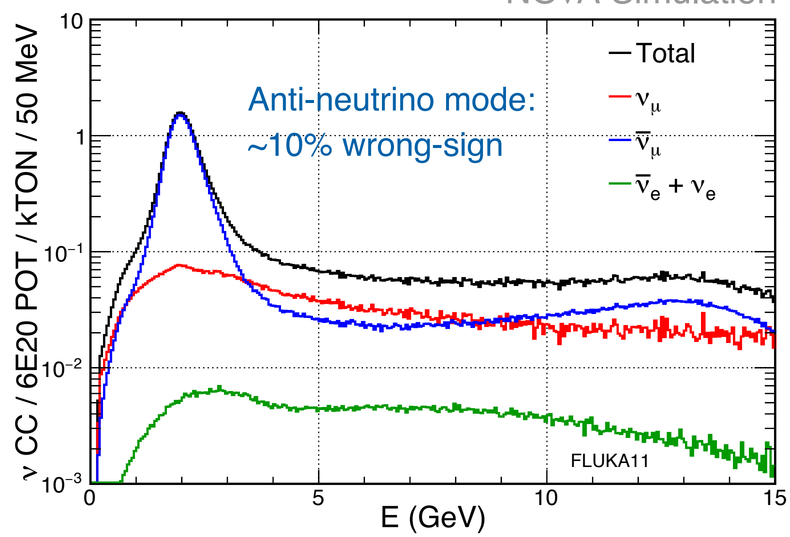


NuMI Beam

- 700 kW design power
- Hourly power record of 756 kW achieved this year.
- ν and $\bar{\nu}$ beam modes selected by polarity of focusing horn current

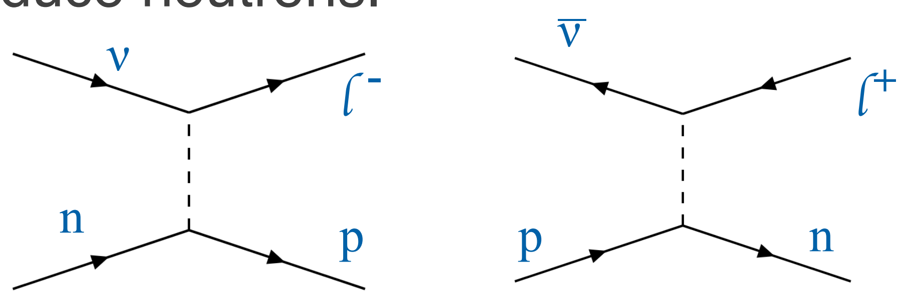




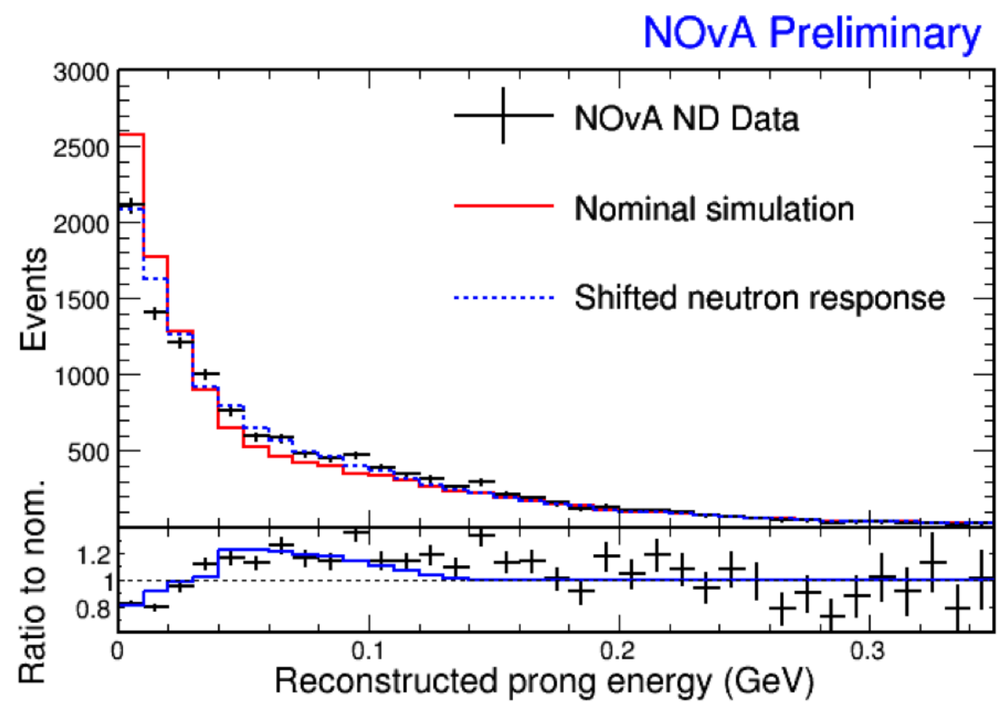


Neutron Systematic

- Antineutrino interactions produce neutrons.



- Energy distribution of neutron candidates predicted in quasi-elastic ν_μ events
- Current evaluation of uncertainty
  - Scale lower energy neutron-induced energy depositions to improve data-simulation match.
  - Shifts average $\overset{(-)}{\nu}_\mu$ energy by 0.5% (1%)
- More recent studies with a more general neutron selection indicate a smaller uncertainty may be appropriate.
  - Investigations continue.



Predicting the Far Detector Spectra

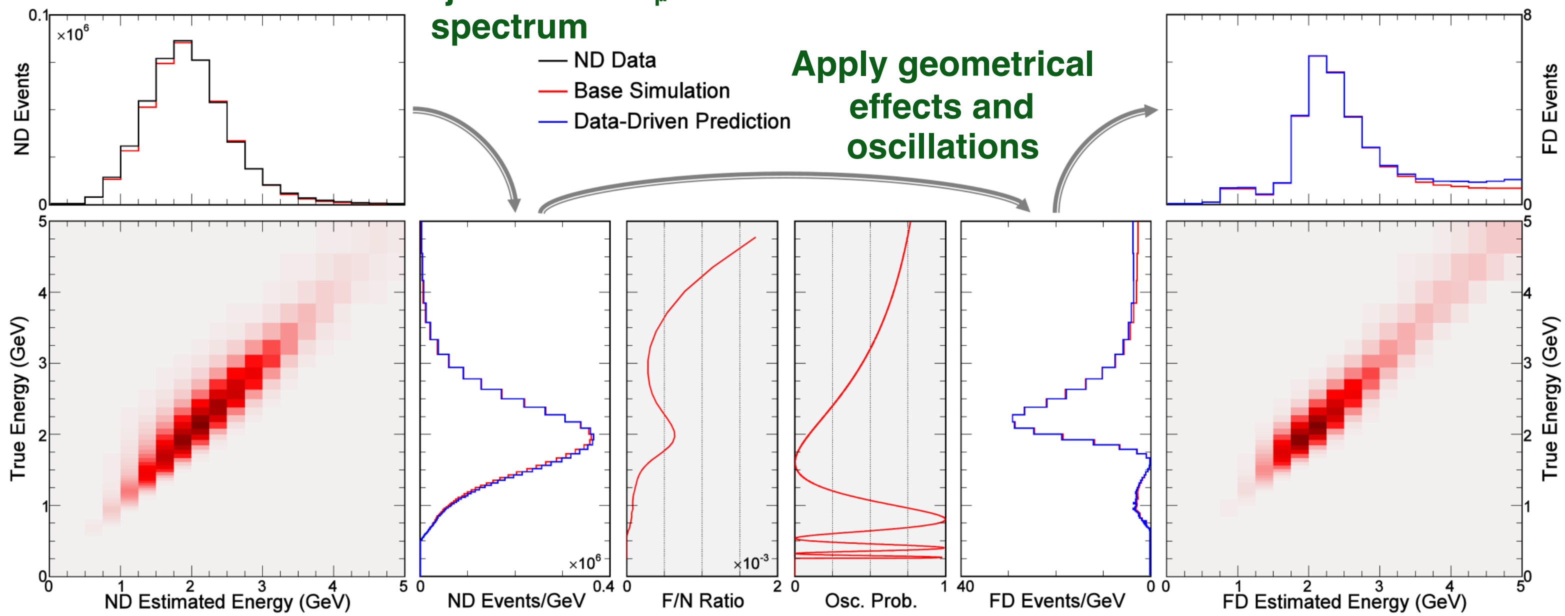
Signal

Compare observed and simulated Near Detector ν_μ Charged Current Interaction Spectrum

Scale simulation for adjusted true ν_μ spectrum

Apply geometrical effects and oscillations

Predict Oscillated reconstructed ν_μ and ν_e spectra at Far Detector



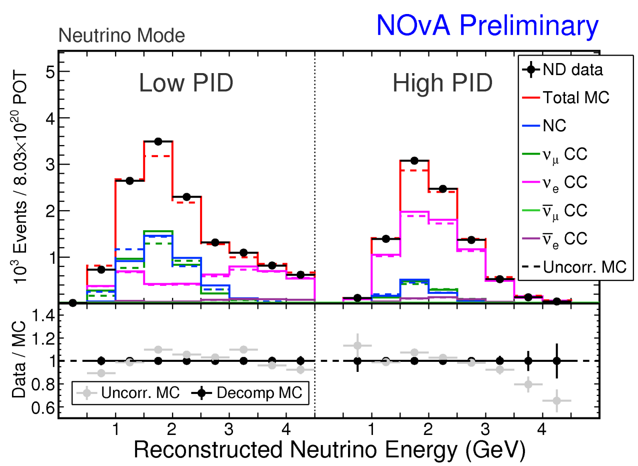
Blind Analysis: examine Far Detector Data only after all systematic studies are complete

Backgrounds

ν_e Beam Backgrounds

Tune Near Detector beam ν_e prediction using ν_μ constraints on parent π, K yields, Michel electron multiplicity distributions for NC, ν_μ

Single scale factor for $\overline{\nu}_e$

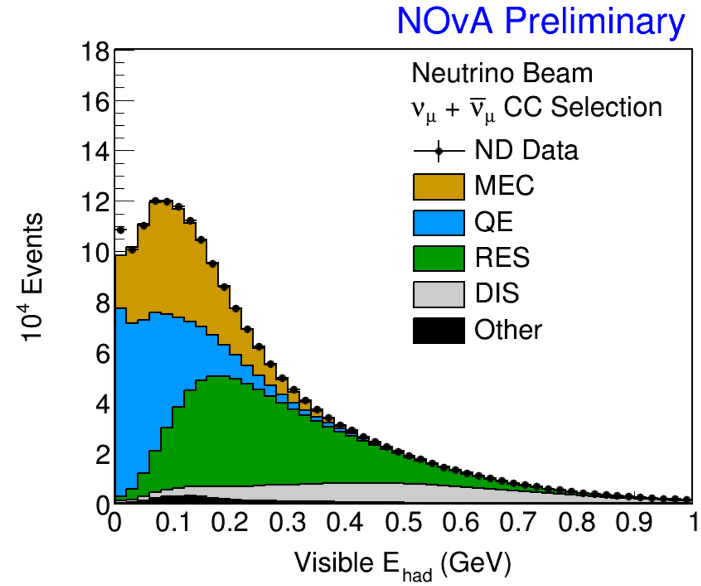


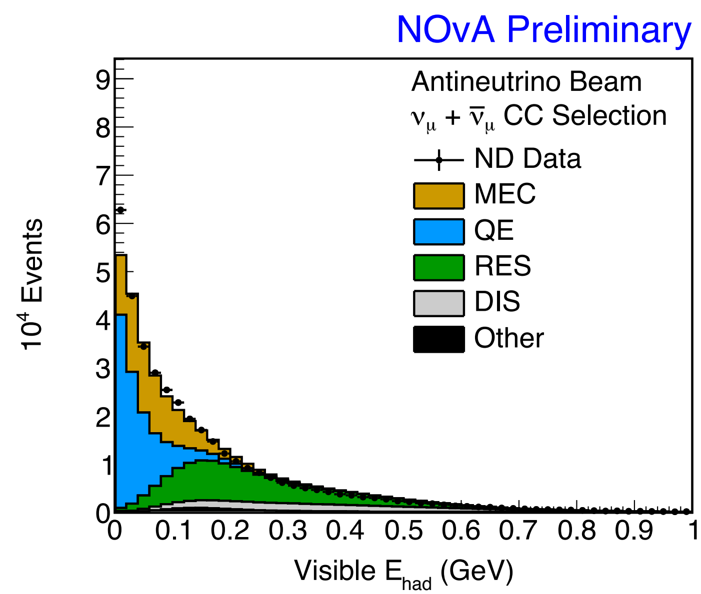
Cosmic Rays

Data-driven, using copious beam trigger time sidebands and random pulser triggers

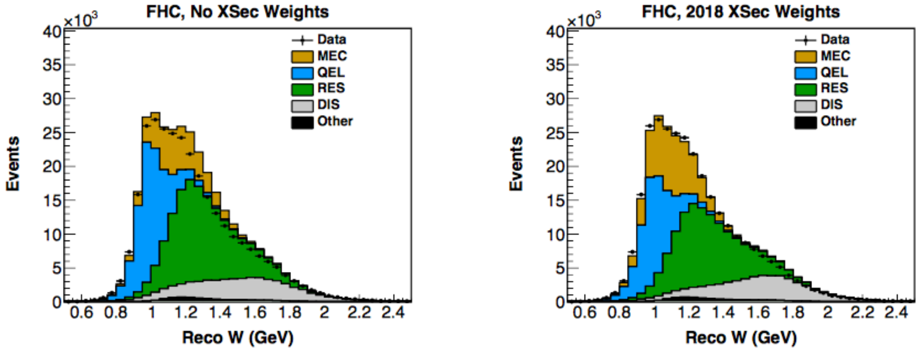
Cross-section tune

- Start with GENIE 12.2
- M_A increased by 5%
- Suppression of QE from long-range correlations (RPA), Valencia model, via MINERvA (R. Gran)
- Application of RPA suppression to resonance production, as a placeholder for suppression at low Q^2 of unknown origin. Observed in our data, earlier in MiniBooNE, MINOS, MINERvA.
- Increase DIS with W>1.7 GeV/c^2 by 10% for better agreement with our data (neutrino-only).
- Reduce non-resonant single pion production for W<1.7 GeV/c^2 (following Rodrigues, Wilkinson, McFarland)
- 2p2h: Scale GENIE empirical Meson Exchange Current model (Dytman) in bins of q_0 and $|q_3|$ to fit remaining difference from data, separately for neutrino and antineutrino. Informed by MINERvA, T. Katori.



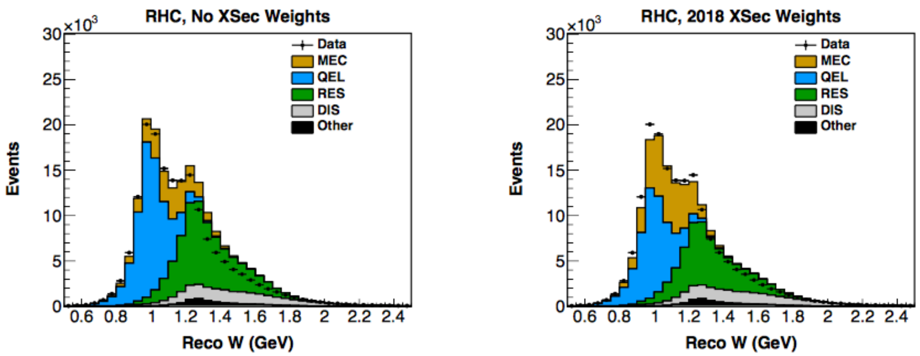


Cross-section tune in W and Q^2



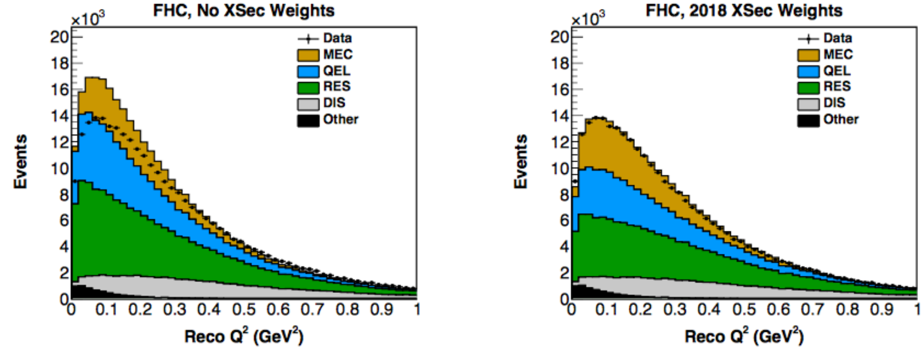
(a) No cross-section weights applied (b) 2018 cross-section weights applied

Figure 29: Reconstructed W, FHC



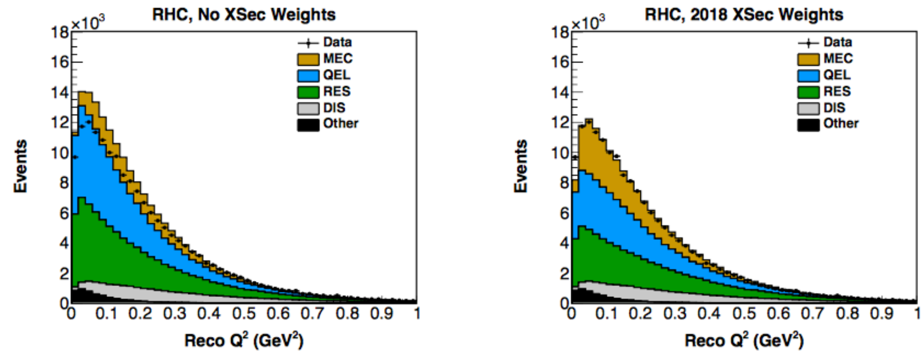
(a) No cross-section weights applied (b) 2018 cross-section weights applied

Figure 30: Reconstructed W, RHC



(a) No cross-section weights applied (b) 2018 cross-section weights applied

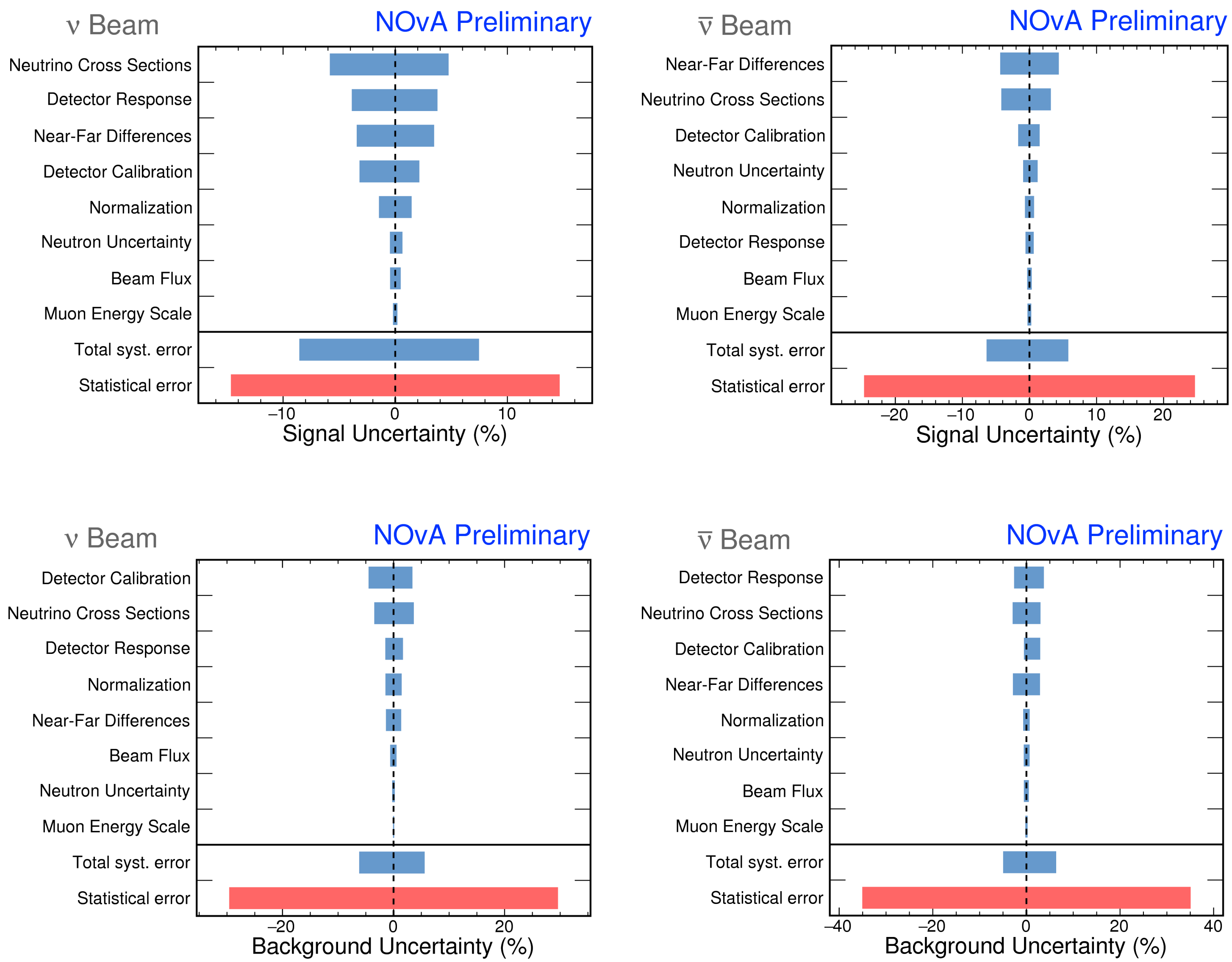
Figure 31: Reconstructed Q^2, FHC



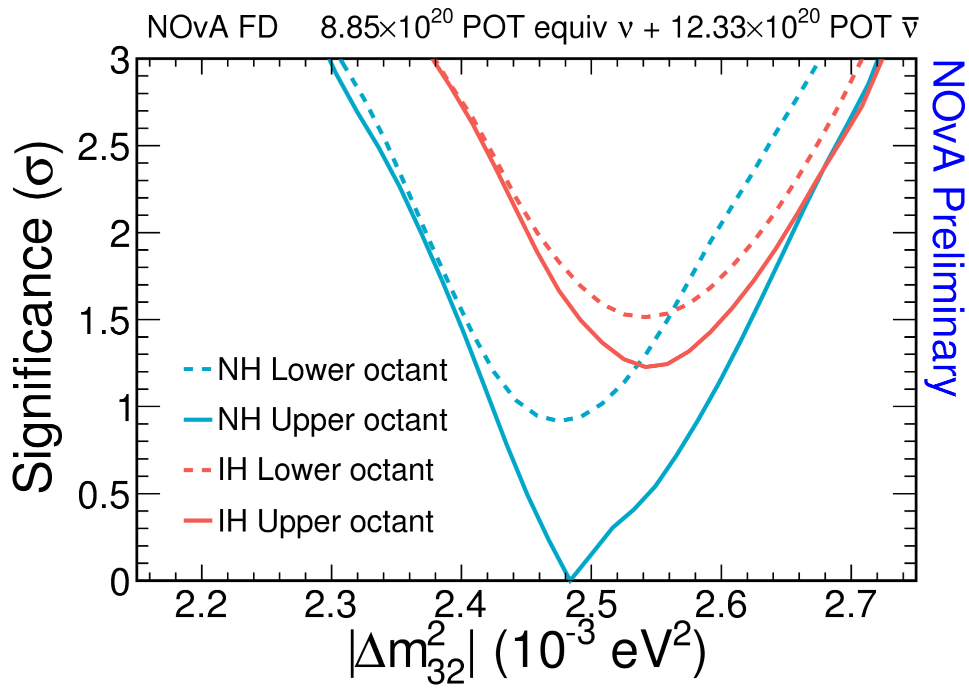
(a) No cross-section weights applied (b) 2018 cross-section weights applied

Figure 32: Reconstructed Q^2, RHC

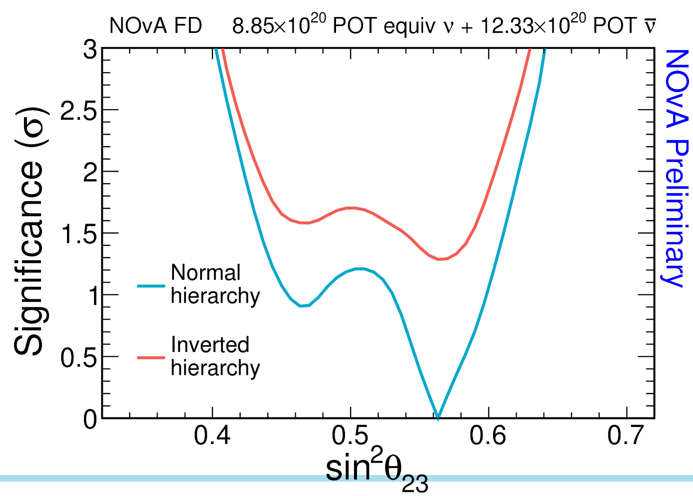
Impact of Systematic Uncertainties on ν_e Signal and Background



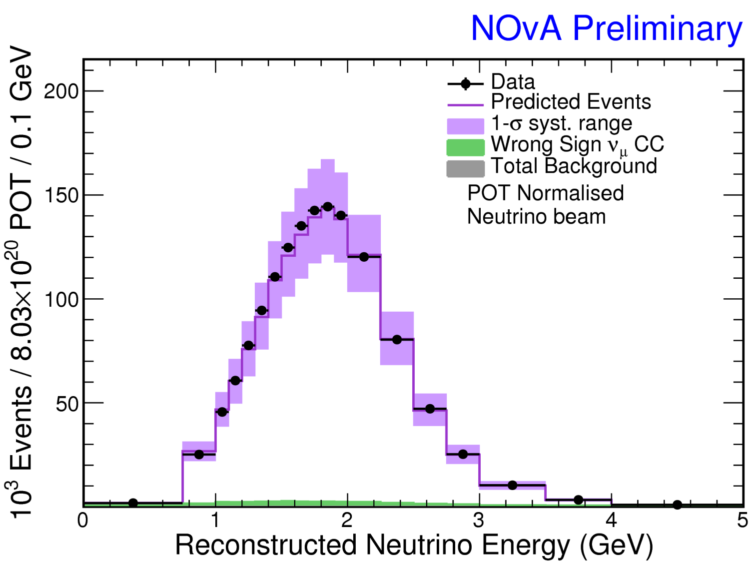
Other slices

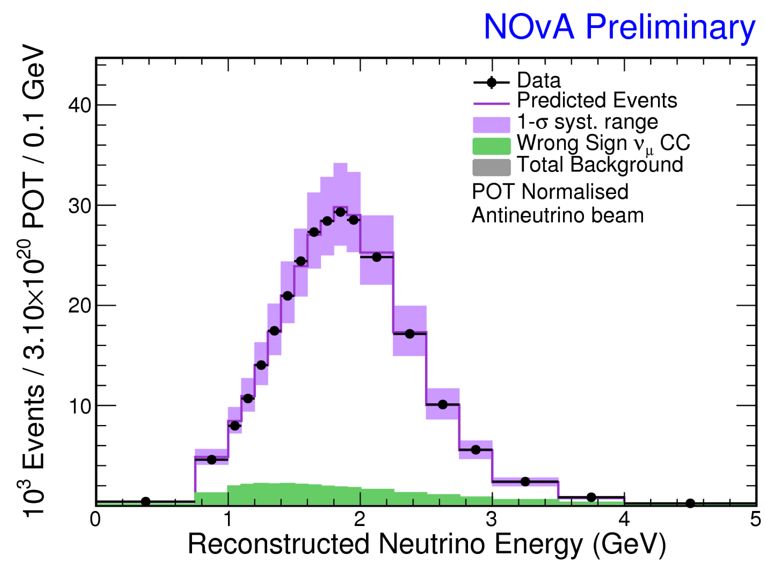


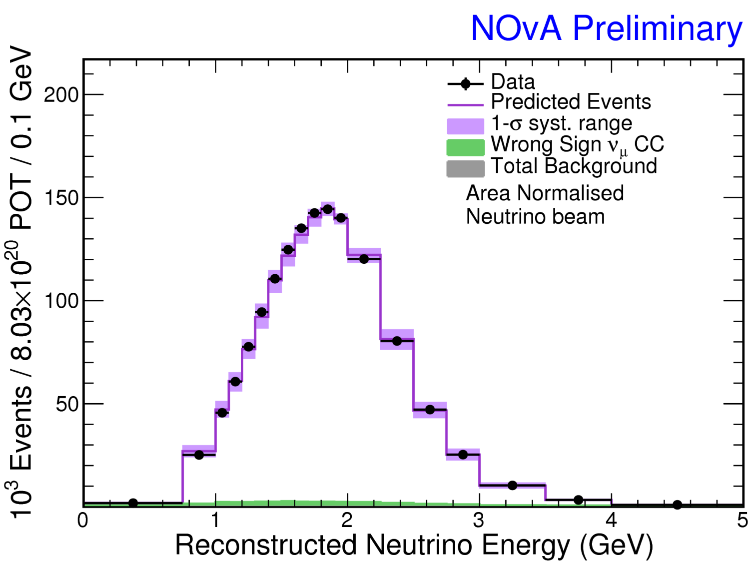
	σ data (gaussian)	FC p-value	FC σ
IH	1.65	0.057	1.89
LO	1.16	0.112	1.59
NHLO	1.16	0.121	1.55
IHUO	1.65	0.080	1.75
IHLO	1.93	0.051	1.95

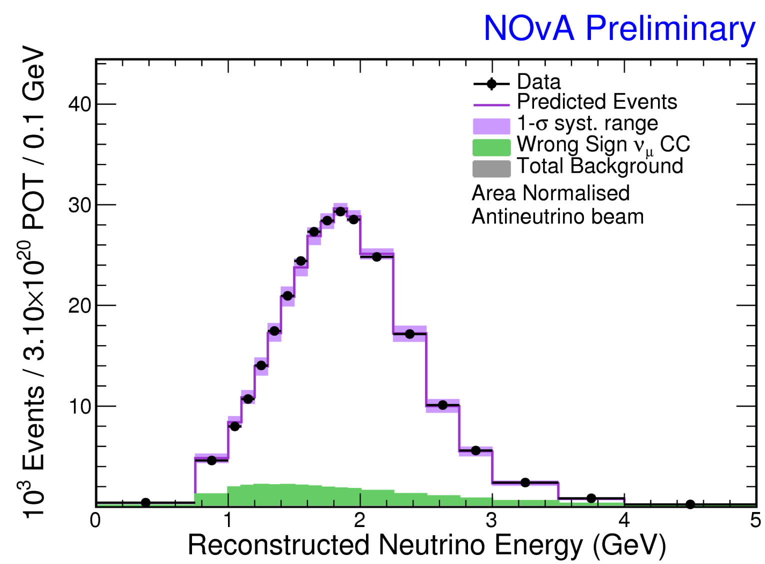


ND ν_μ Spectra with POT and Area Normalization



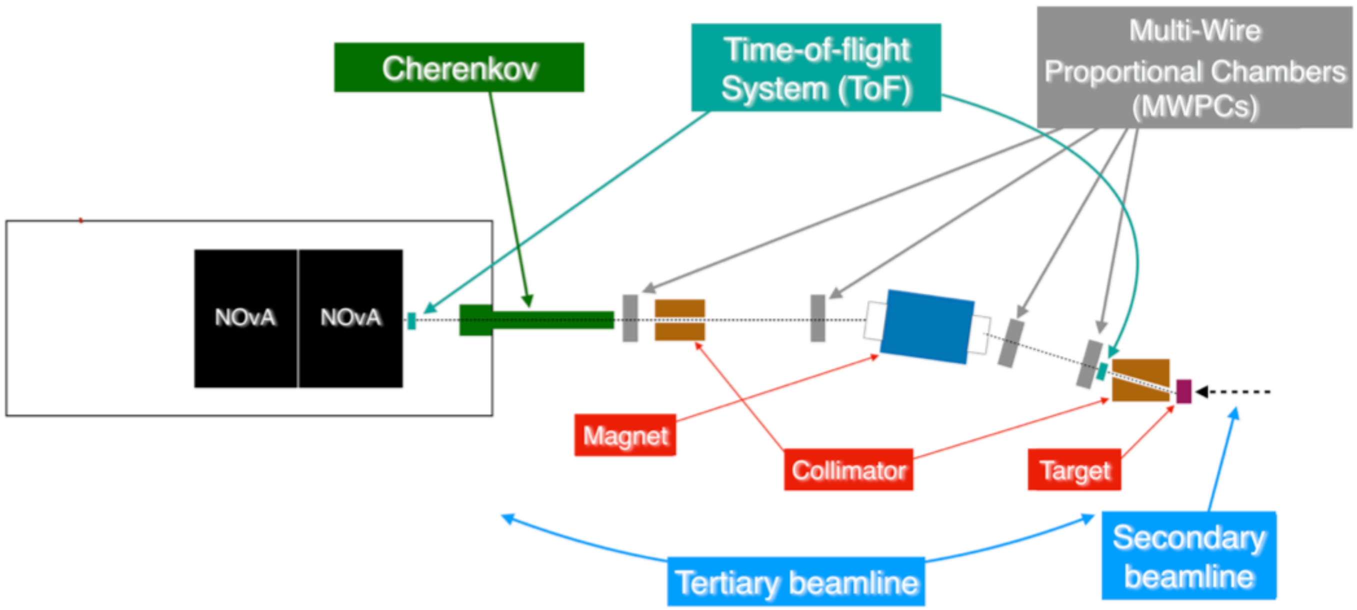




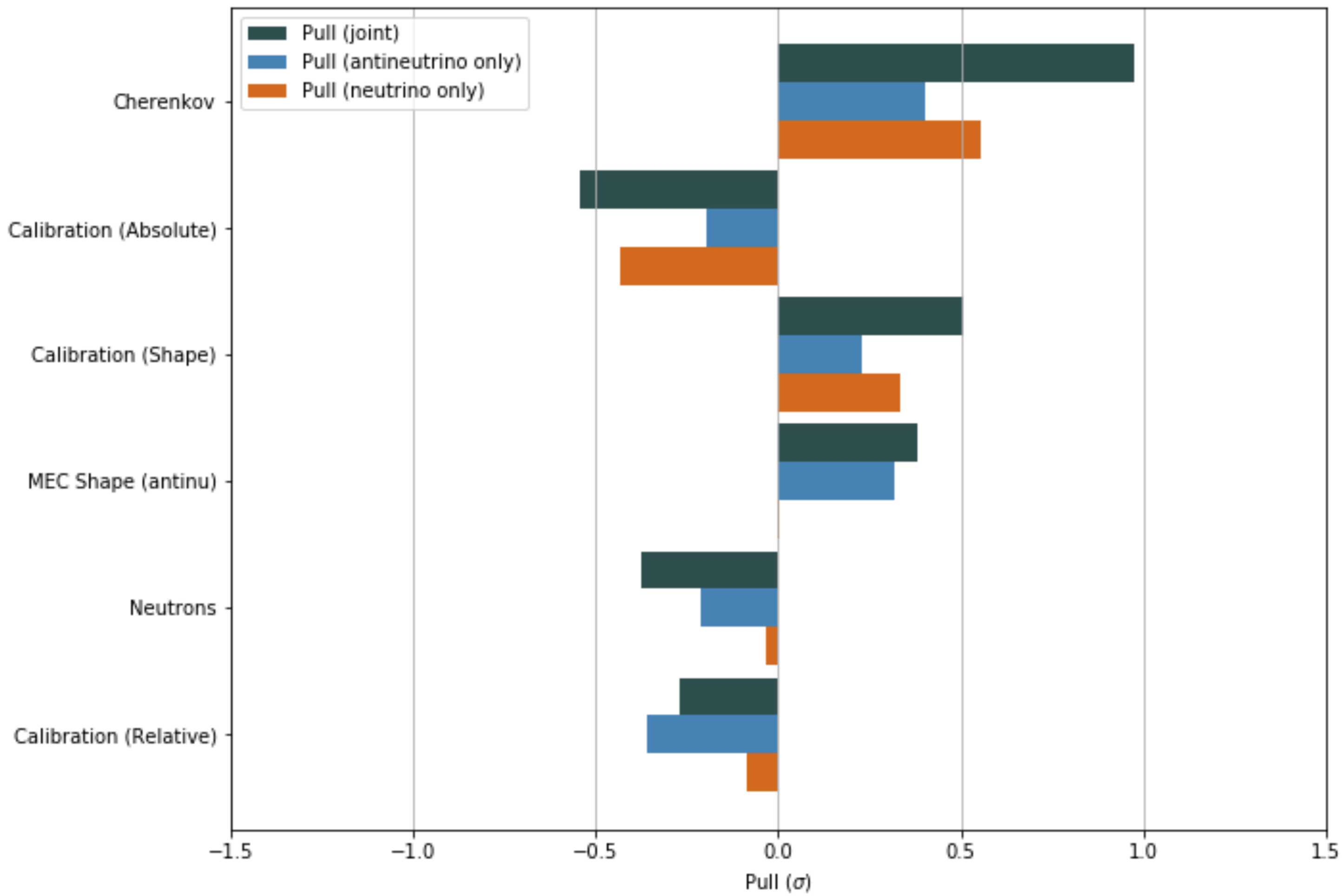


Test beam layout

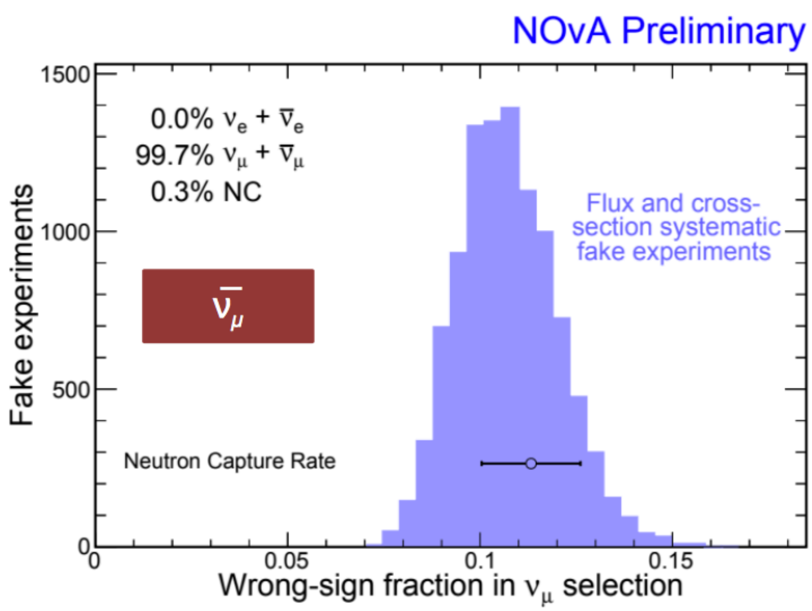
- Detector consists of two 31-plane 2x2 blocks + one horizontal plane at FTBF's MC7
- Exposed to MCenter-sourced e, μ, π, p, K, π^0 tertiary beam with known momentum from 0.2 - 2.0 Gev/c
- Provide absolute measurement of detector response and cross-check of NOvA calibration chain

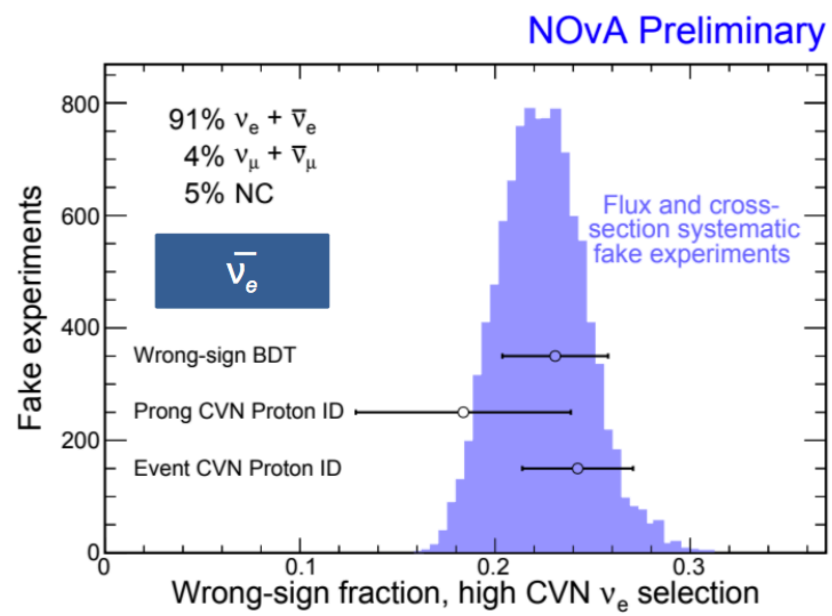


Systematic Pulls



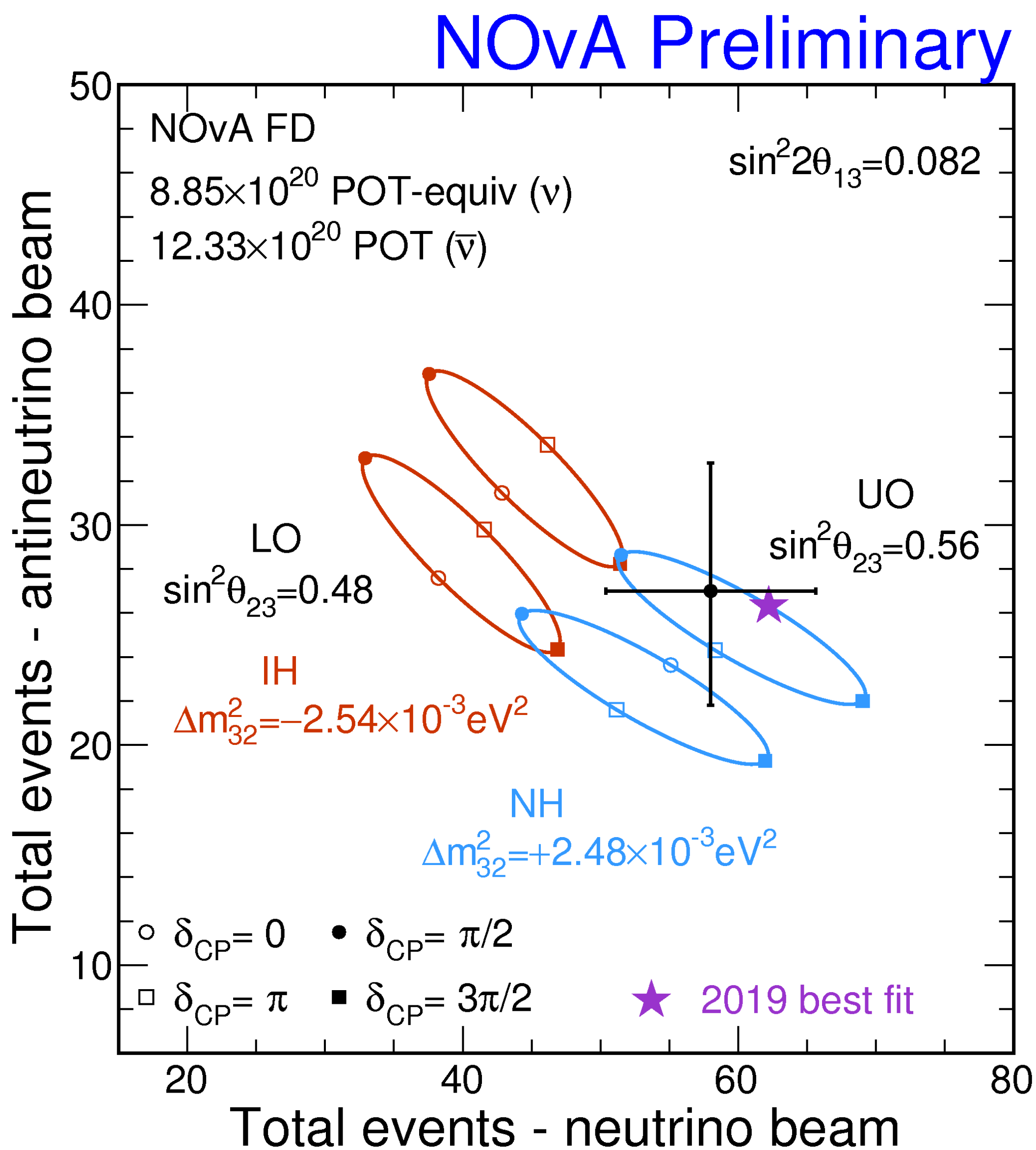
Wrong-sign contamination in antineutrino beam



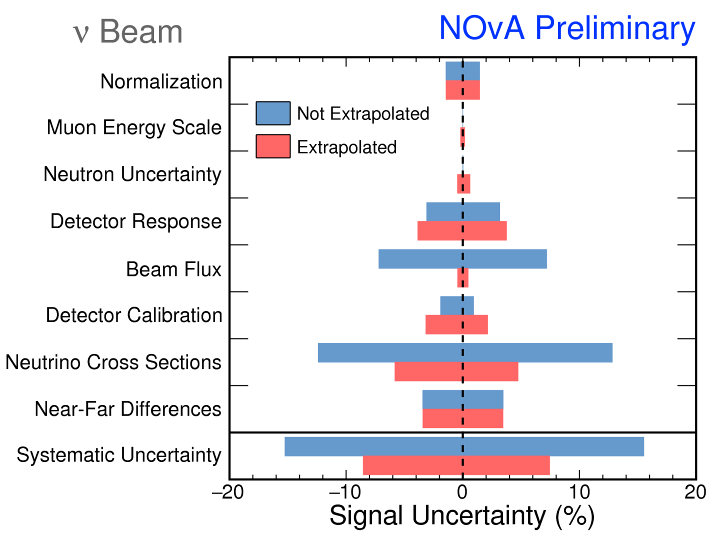


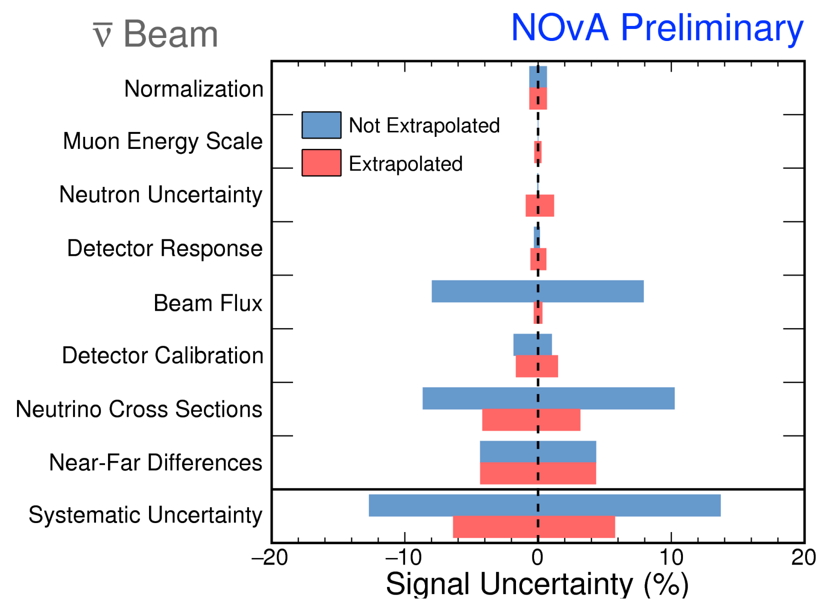
Bi-event rate plot

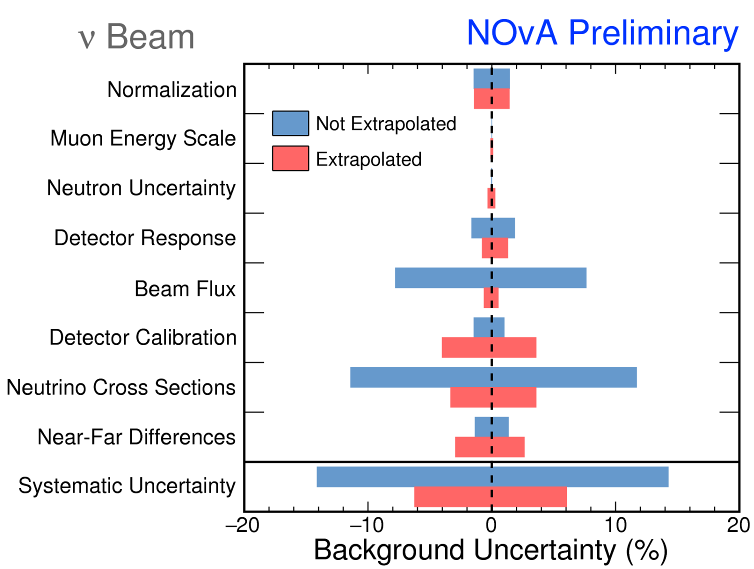
- *Caveat: this picture suppresses energy dependence and other useful variables*

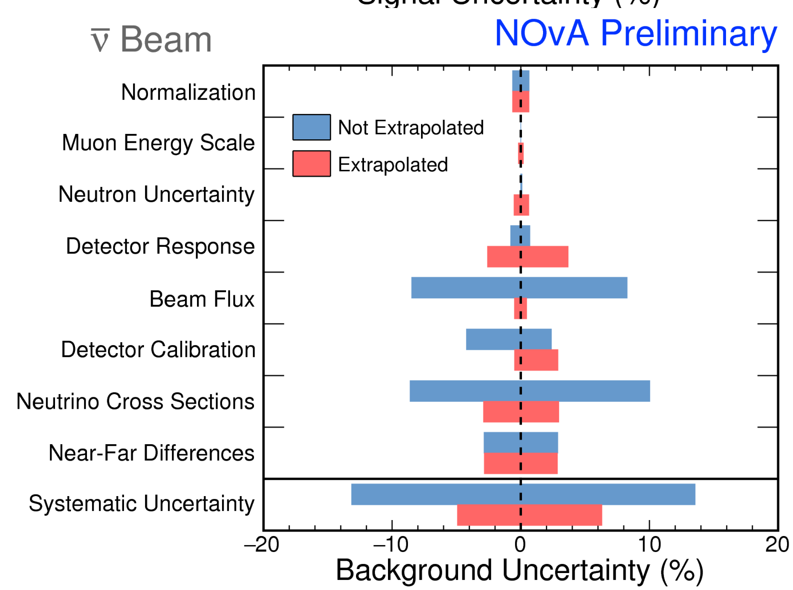


Effect of extrapolation on systematic uncertainties

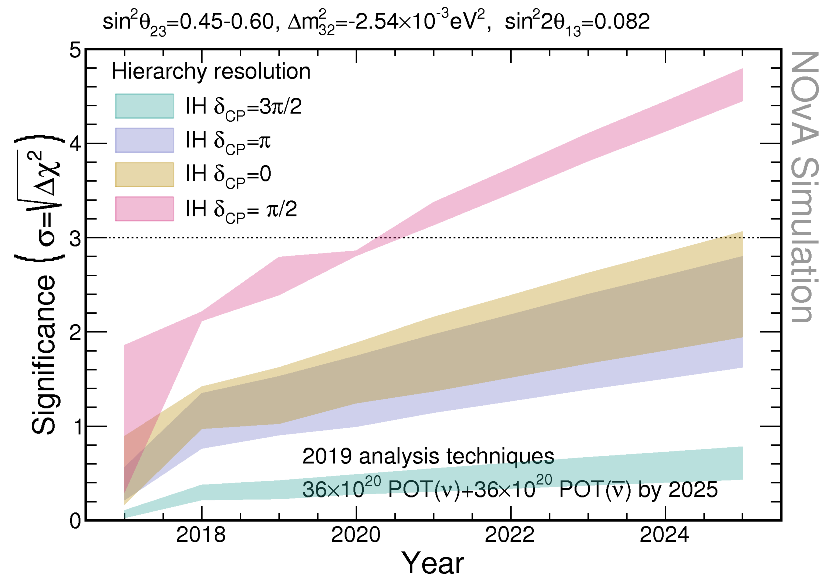


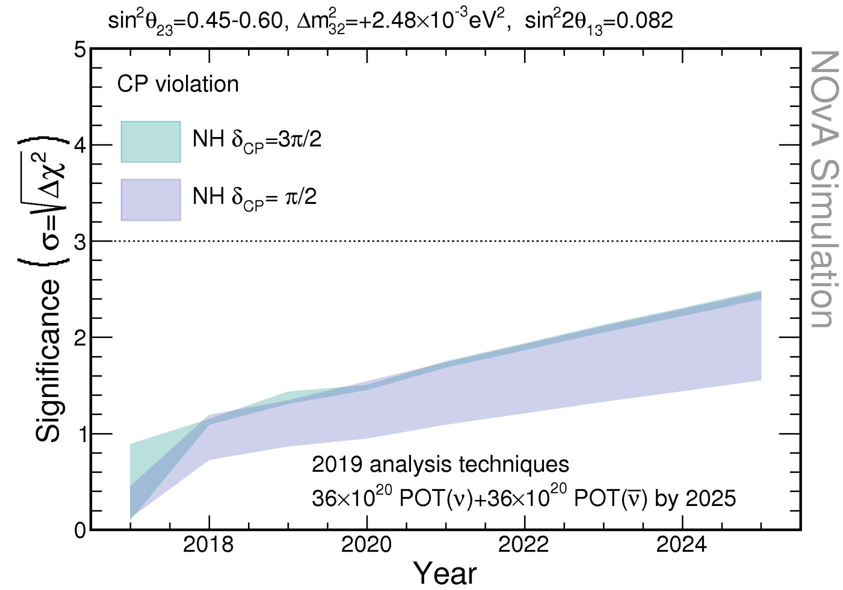


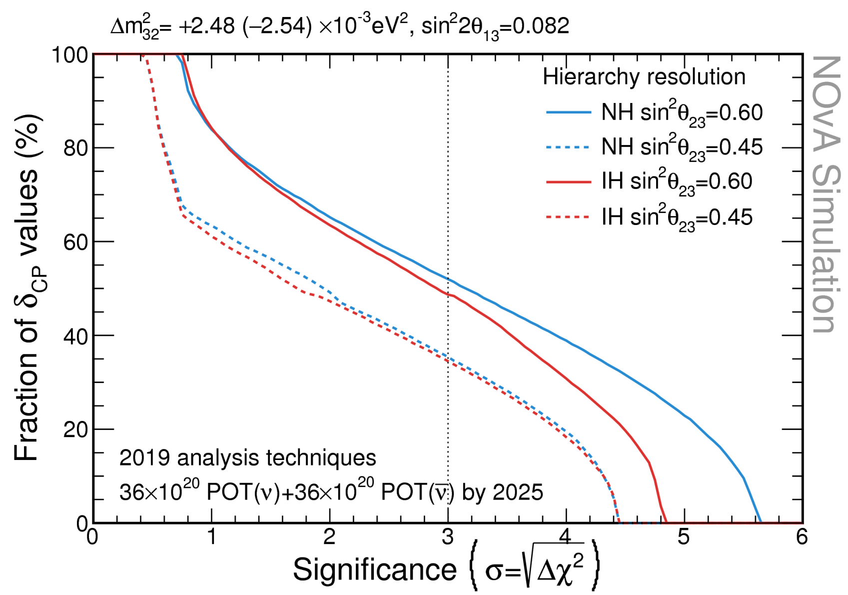


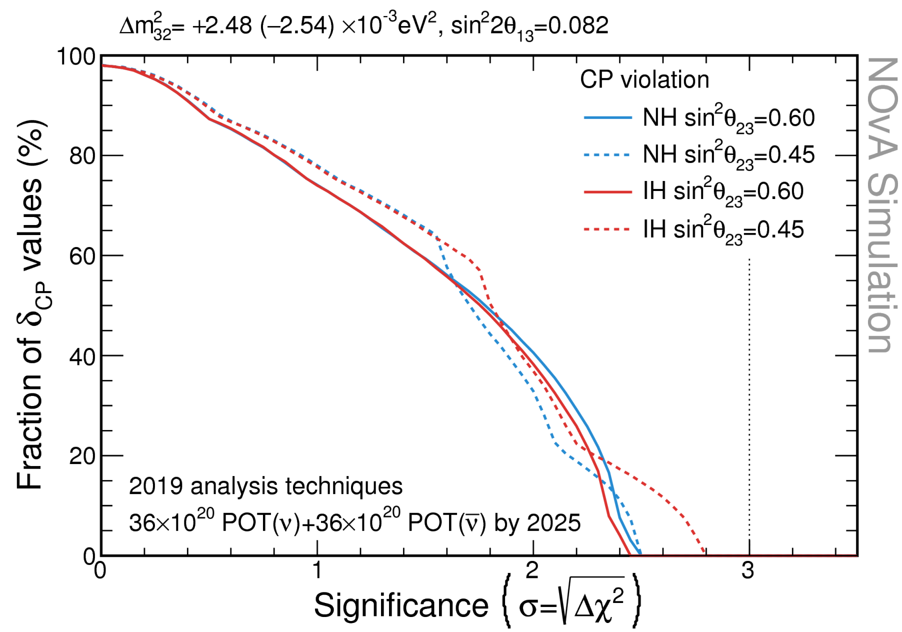


More sensitivity projections









Sensitivity Projections for Maximal Mixing Rejection and Octant