NOvA: Results and Prospects

Peter Shanahan

Colloquium Prague V19

24 October 2019

In partnership with:

Neutrino Mixing

Weak interaction acts on flavor states

ν_e, ν_μ, ν_τ

which are quantum-mechanical superposition of mass states

ν_1, ν_2, ν_3

$|\nu_\alpha\rangle = U_{PMNS}|\nu_i\rangle$, $\alpha = e,\mu,\tau$; $i=1,2,3$

where U_{PMNS} is a unitary 3x3 matrix

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 1 & 1 \end{pmatrix}$$

parameterized by **3 mixing angles $\theta_{12}, \theta_{13}, \theta_{23}$** and one **complex phase angle δ**

$$\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

$c_{13}=\cos(\theta_{13})$, $s_{23}=\sin(\theta_{23})$, etc.

Progress from 2 Decades of Neutrino Oscillation Measurements

Approximate **3σ** ranges from JHEP11 (2014) 052

Neutrino Mixing Matrix

$$|U_{PMNS}| \approx \begin{pmatrix} 0.80-0.85 & 0.51-0.58 & 0.14-0.16 \\ 0.23-0.52 & 0.44-0.70 & 0.61-0.79 \\ 0.25-0.53 & 0.46-0.71 & 0.59-0.78 \end{pmatrix}$$

Mass Splittings

$$\Delta m^2_{21}=(7.4\pm0.2)\text{x}10^{-5}\ \text{eV}^2$$

$$|\Delta m^2_{3\ell}|=(2.52\pm0.03)\text{x}10^{-3}\ \text{eV}^2$$

arXiv:1811.05487

Neutrino mass is first laboratory measurement of physics beyond the Standard Model

Key related questions can be addressed by long-baseline neutrino oscillation measurements.

Structure of the Mixing

- θ_{23} is near maximal, but there remain important unknowns regarding the nature of ν_3

Is ν_3 more ν_τ than ν_μ?

θ_{23} in lower octant (<45°)

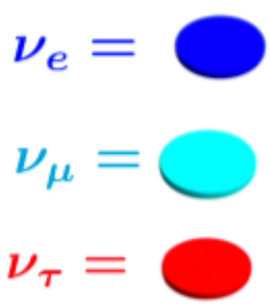
Or is ν_3 more ν_μ than ν_τ?

θ_{23} in upper octant (>45°)

Or is ν_3 equal ν_τ and ν_μ?

θ_{23} maximal (=45°)

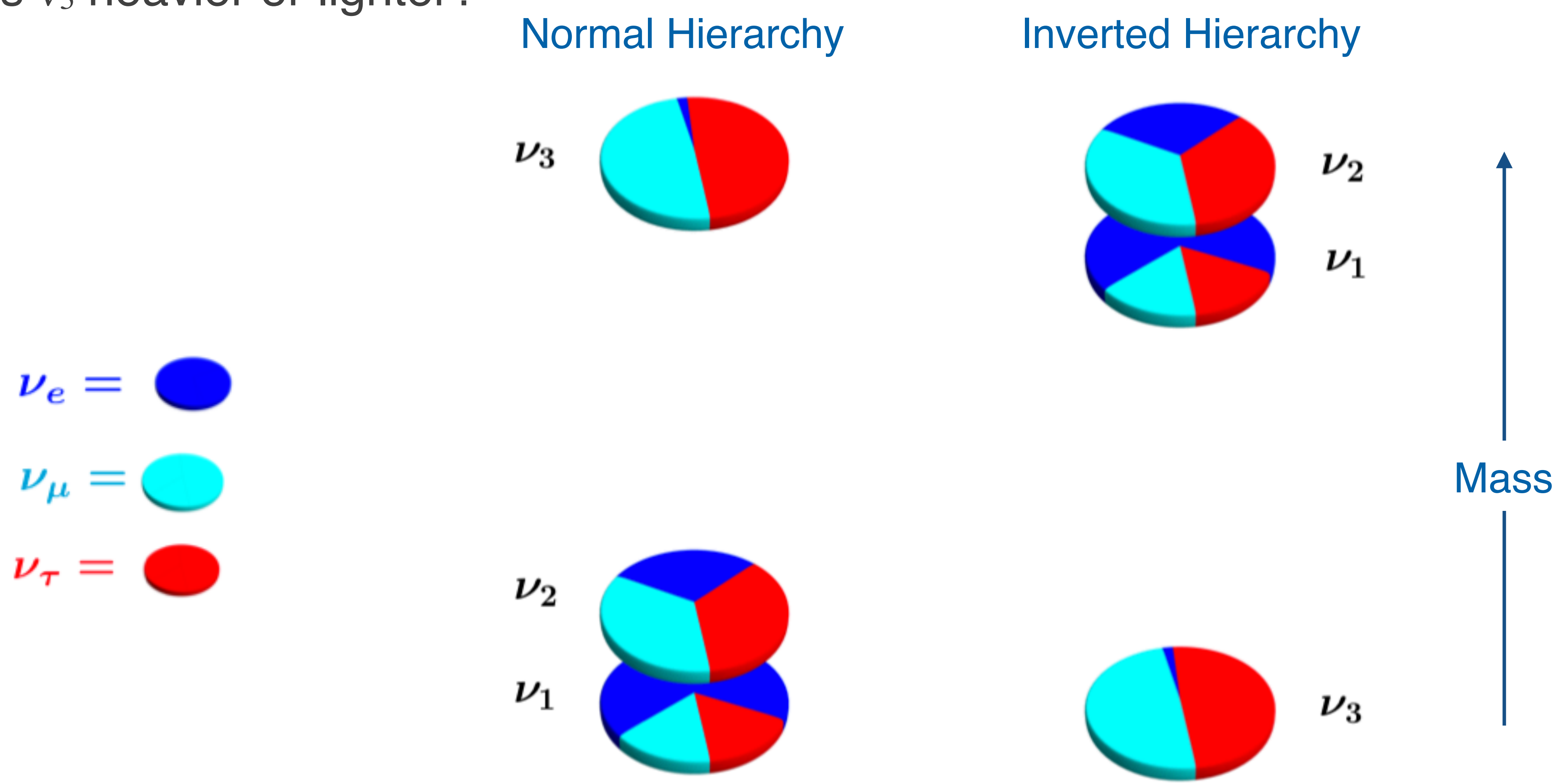
μ-τ symmetry



Graphics from S. Parke,
“Theoretical Aspects of the Quantum Neutrino circa 2025+”
https://indico.fnal.gov/event/16756/contribution/0/material/slides/0.pdf

Neutrino Mass Hierarchy (Ordering)

- Is ν_3 heavier or lighter?



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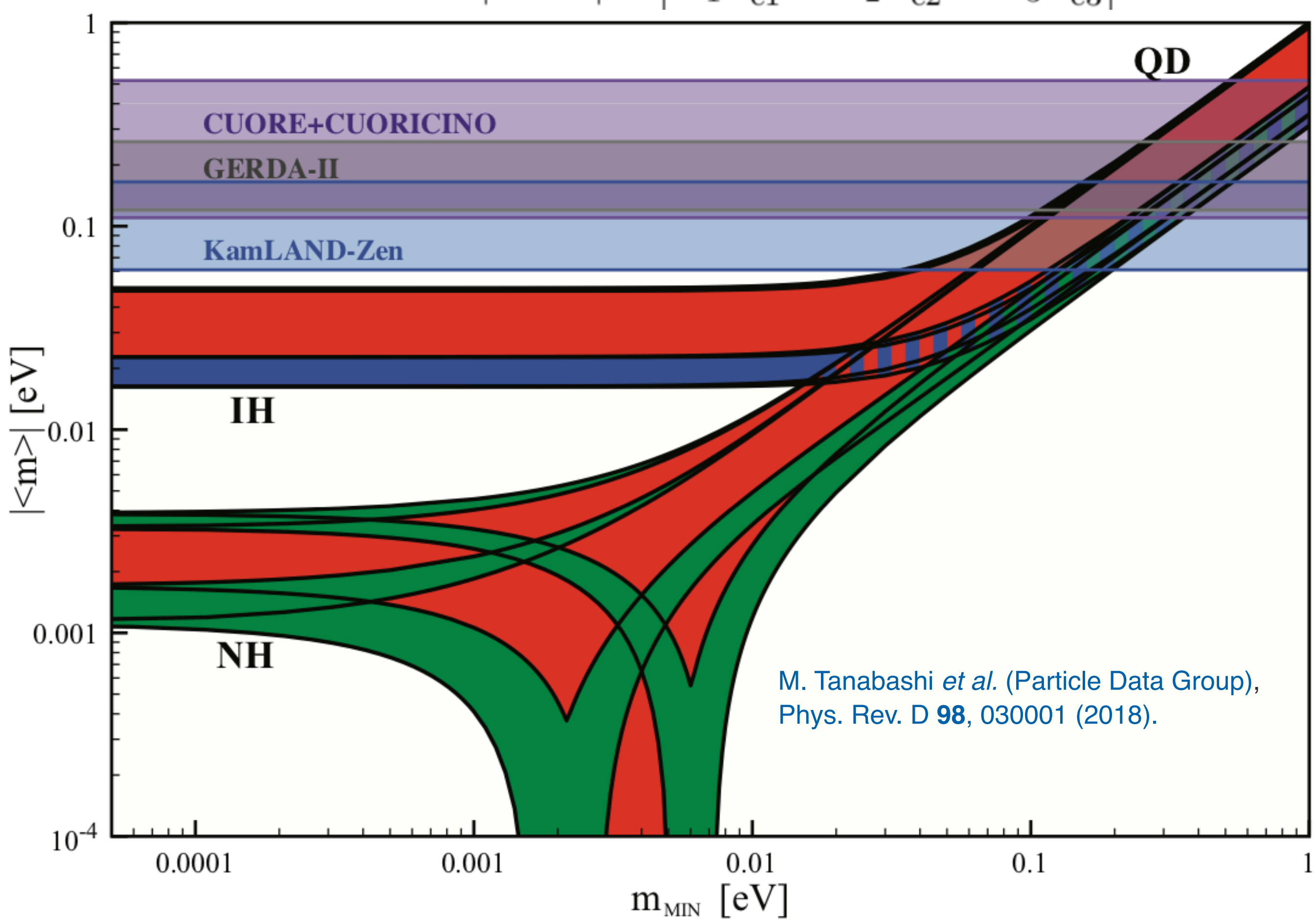
Neutrino Mass Hierarchy (Ordering)

- Discriminator of neutrino mass & mixing models

- Impacts interpretation of $0\nu\beta\beta$ searches

⇒ Dirac vs. Marojana Neutrino Mass

$$|<m>| = \left| m_1 U_{e1}^2 + m_2 U_{e2}^2 + m_3 U_{e3}^2 \right|$$



M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D **98**, 030001 (2018).

Fermilab

Charge-Parity Violation

$$U_{PMNS} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

Phase δ is CP-violating - changes sign for antineutrinos

sin(δ)≠0 ⇒ CP violation in neutrino oscillations

Leptonic CP Violation

Approximate 3σ ranges from JHEP11 (2014) 052

Mixing matrix is substantially off-diagonal

$$|U_{PMNS}| \approx \begin{pmatrix} 0.80-0.85 & 0.51-0.58 & 0.14-0.16 \\ 0.23-0.52 & 0.44-0.70 & 0.61-0.79 \\ 0.25-0.53 & 0.46-0.71 & 0.59-0.78 \end{pmatrix}$$

Mixing matrix is much more diagonal

$$|U_{CKM}| \approx \begin{pmatrix} 0.974 & 0.225 & 0.004 \\ 0.225 & 0.973 & 0.04 \\ 0.009 & 0.04 & 0.999 \end{pmatrix}$$

Jarlskog invariant:
Scale of maximum CP-violating effect from the mixing

$$J = sin(2\theta_{12})sin(2\theta_{13})sin(2\theta_{23})cos(\theta_{13})sin(\delta)/8$$

Lepton sector: 0 ≤ $|J_{PMS}|$ ≤ 0.03

Quark sector: J_{CKM} ≤ 0.00003

Is CPV in U_{PMNS} related to the Baryon Asymmetry of the Universe

Leptogenesis: CP-violating process created matter-antimatter asymmetry in leptons that was transferred to baryons in early universe

See, e.g., M. Drewes at Neutrino 2018, DOI:10.5281/zenodo.1287033
Michal Malinsky's talk later today

CP violation in neutrinos is why we're here

Colloquium Prague v19

2019

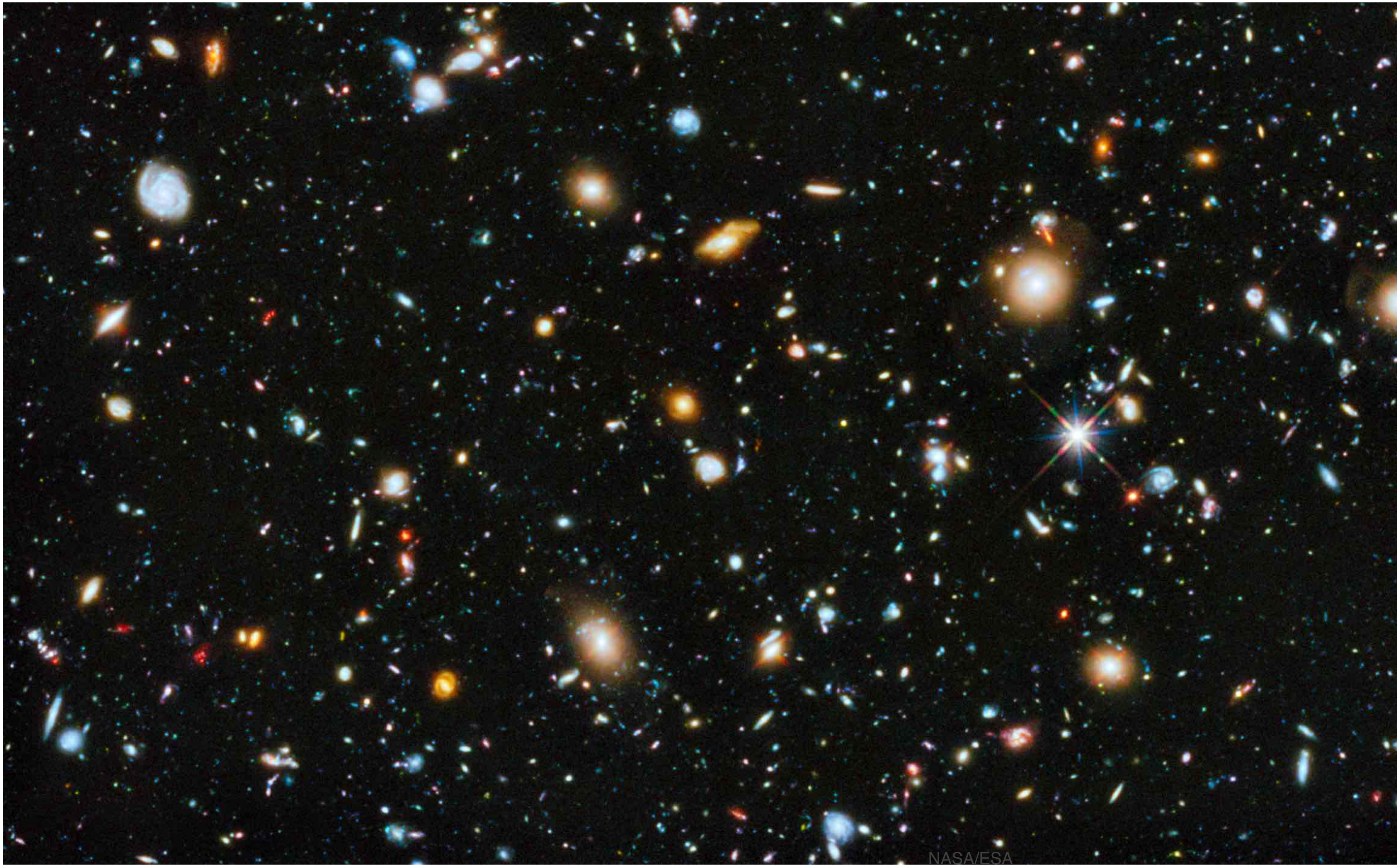
24-25 October 2019
J. Heyrovsky Institute of Physical Chemistry
Europe/Prague timezone

Colloquium Towards CP violation in neutrino Physics

The aim of the Colloquium is to present a status and plans for CP violation measurement in neutrino experiments. It plans to provide an overview of recent experimental results, theoretical predictions, experiments under construction and planned experiments to measure CP violation in lepton sector. It consists of invited talks.

Petr Novák, Wikipedia https://creativecommons.org/licenses/by-sa/2.5/deed.en

CP violation in neutrinos is why we're here?



Long-baseline ν_μ Disappearance

- Survival probability is well approximated by 2-flavor case, dominated by $\nu_\mu \to \nu_\tau$

Baseline: km

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2(2\theta_{23})\sin^2(1.27\Delta m^2_{32}\frac{L}{E})$$

Energy: GeV

- Size of effect dominated by ***$\sin^2(2\theta_{23})$***
  - measure of the degree of μ-τ mixing in ν_3 - a large effect
- Frequency depends on ***$|\Delta m^2| \cdot L/E$***
  - $|\Delta m^2| \sim 2.5 \times 10^{-3}$ eV^2 — Oscillation Maximum ~1.6 GeV at 810 km
- Note the degeneracies
  - θ_{23} <—> 45^o - θ_{23} — no sensitivity to the Octant of θ_{23}
  - Δm^2 <—> $-\Delta m^2$ — no sensitivity to Mass Hierarchy
  - No $\sin(\delta)$ dependence due to CPT symmetry — no sensitivity to CP Violation

Long-baseline ν_e Appearance

- $P(\nu_\mu \rightarrow \nu_e) \cong |\sqrt{P_{Atm}} + \sqrt{P_{Sol}}|^2$

Leading term $P_{Atm} = \sin^2\theta_{23} \sin^2 2\theta_{13} \frac{\sin^2[(A-1)\Delta]}{(A-1)^2}$

$\Delta = \Delta m^2_{31} L/4E$

$\sin^2(\theta_{23}) \sim 0.5$, $\sin^2(2\theta_{13}) = 0.086$, so $\nu_\mu \rightarrow \nu_e$ **is subdominant: $P_{Max} \sim 0.05$**

$\sin^2(\theta_{23})$ breaks the $\theta \rightarrow 45^o - \theta$ degeneracy of $\nu_\mu \rightarrow \nu_\mu$
Sensitivity to the Octant of θ_{23}

$A = \pm\sqrt{2} G_F N_e 2E/\Delta m^2_{31}$ is Matter Effect: potential shift for ν_e flavor from electrons in matter. + for neutrinos, - for antineutrinos. **Proportional to Δm^2_{31}**
Sensitivity to Mass Hierarchy

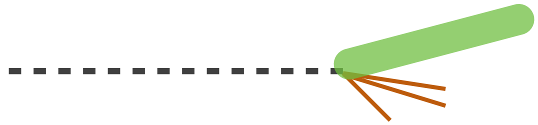
Interference term $\sqrt{P_{Atm}}^* \sqrt{P_{Sol}} + \sqrt{P_{Atm}} \sqrt{P_{Sol}}^*$ depends on $J \sim \sin(\delta)$
Sensitivity to CP Violation

Neutrino Signatures at the GeV Scale

Charged Current

Outgoing charged lepton tags neutrino flavor

ν_e



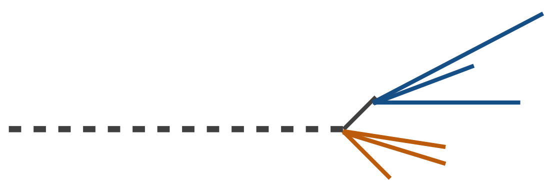
Electromagnetic cascade

Muon Track

ν_μ E>0.11 GeV

τ travels ~mm before decay

ν_τ E>3.5 GeV

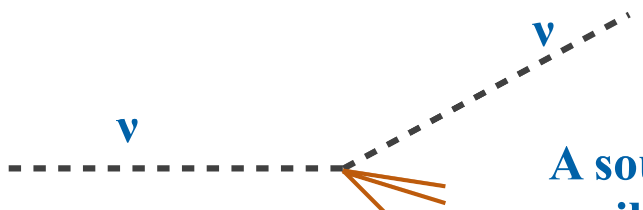


High threshold and difficult signature means ν_τ are effectively absent from Charged Current channel.

Neutral Current

No flavor information

Outgoing neutrino carries unknown energy



A source of backgrounds to standard oscillation measurements

NOvA

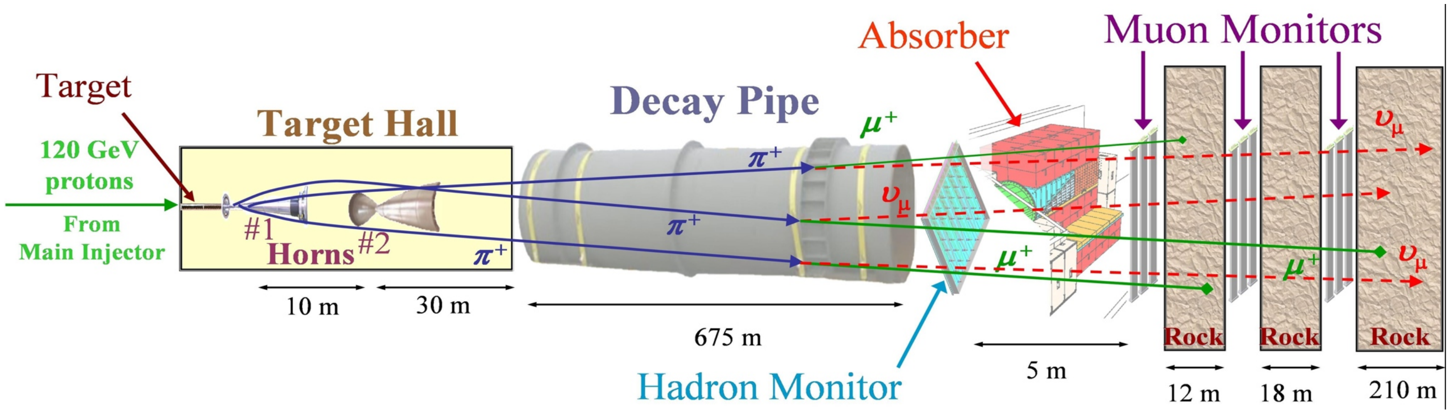
- Measure $\nu_\mu \rightarrow \nu_\mu$, $\nu_\mu \rightarrow \nu_e$, $\nu \rightarrow \nu$, for neutrinos and antineutrinos
  - Mass Hierarchy, Octant/Maximal Mixing, CP Violation
  - Search for phenomena outside 3-flavor mixing framework
    - Sterile Neutrinos
- Measure for sub-dominant (P~0.05) $\nu_\mu \rightarrow \nu_e, \bar{\nu}_\mu \rightarrow \bar{\nu}_e$
  with sensitivity to Matter Effect (±19%)
  and CP violation (-22%…+22%)
  - Powerful neutrino and antineutrino beam
  - Large Detector, location optimized for Mass Hierarchy and background suppression
  - Detector Technology Optimized for ν_e Detection
- Non-oscillation topics
  - Neutrino cross-sections
  - Non-beam-neutrino studies
    - Supernova neutrinos, Exotic phenomena: Dark Matter, Magnetic Monopoles

NOvA Collaboration

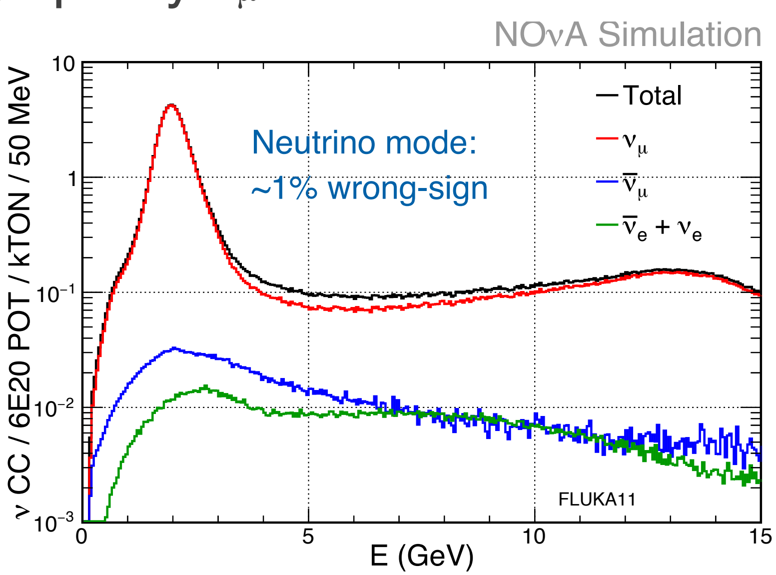
- 200 Collaborators from 48 institutions in 7 countries.
- 24 Remote Operations Centers worldwide.

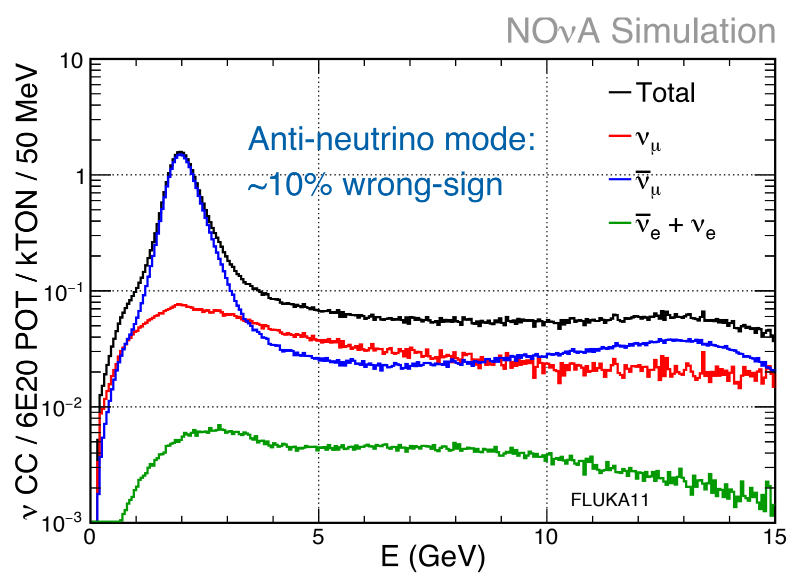
NuMI Beam

- 700 kW design power: O(10^6) ν delivered to Far Detector every 1.33 seconds



- ν and $\bar{\nu}$ beam modes selected by polarity of focusing horn current
- High purity ν_μ content

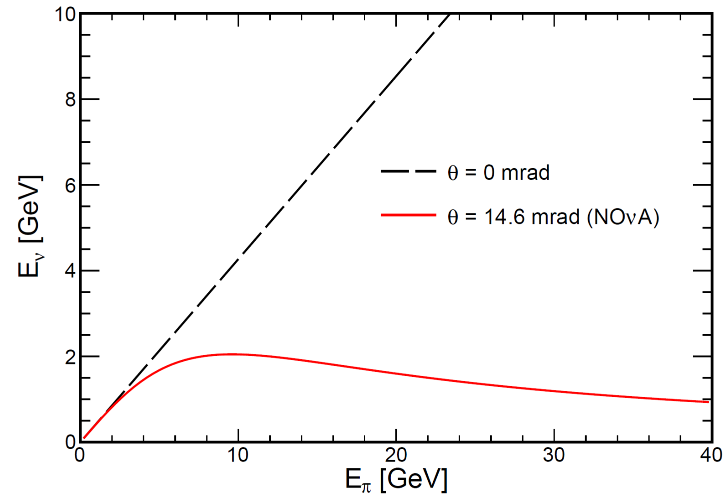




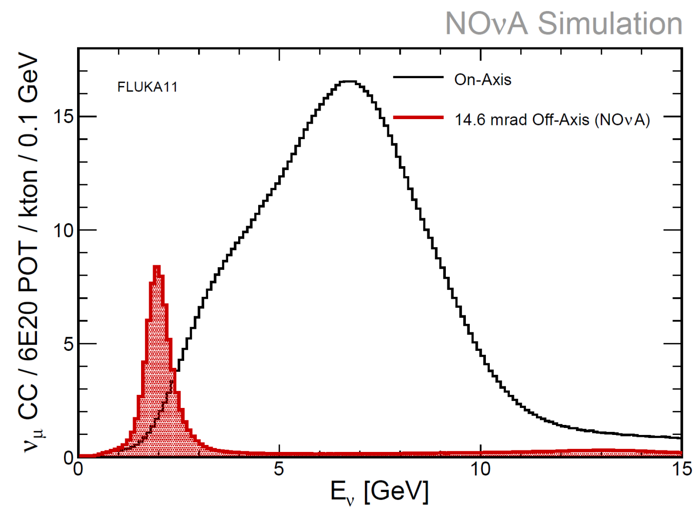
Detector Location

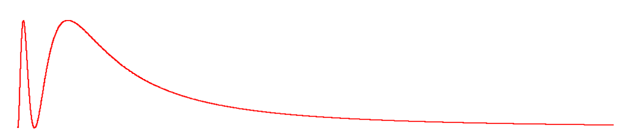
- 14 mrad (11km) off the NuMI beam axis
  - pion 2-body decay kinematics

$$E_\nu = \frac{0.43 E_\pi}{1 + \gamma^2 \theta^2}$$



  - Neutrino spectrum peaks near 1st oscillation maximum
  - High energy tail is suppressed:
    reduced Neutral Current π^0 backgrounds



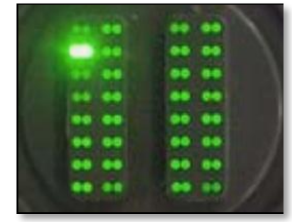


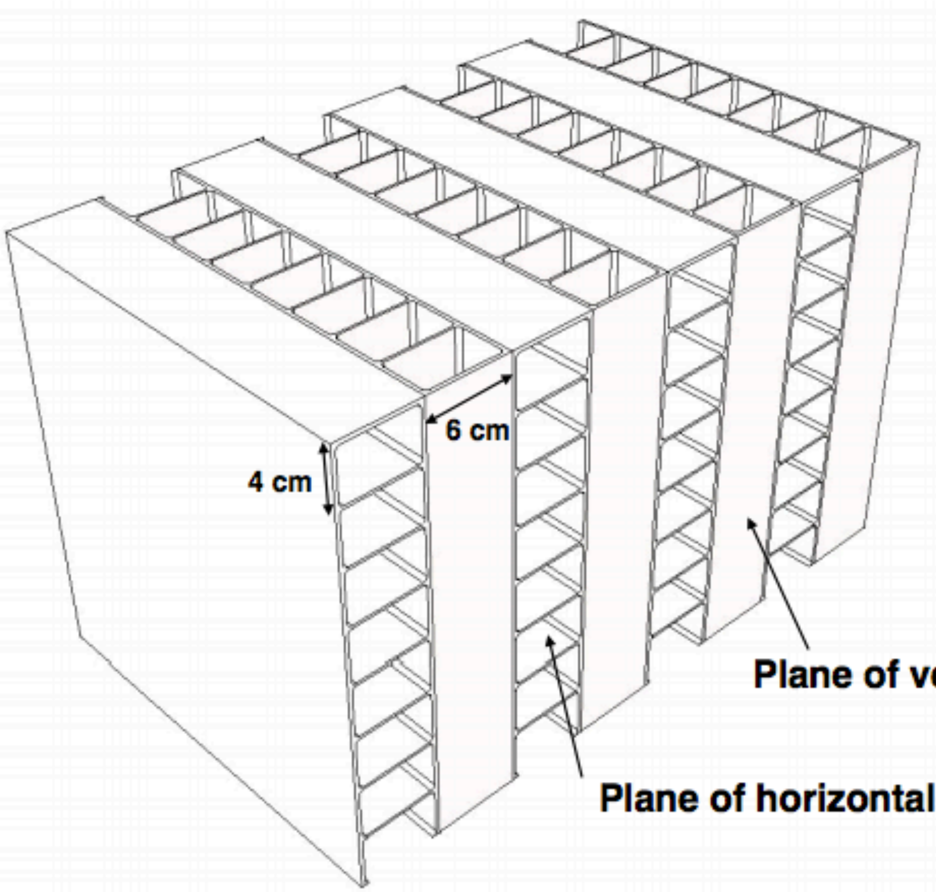
- As far as possible from Fermilab for maximum matter effect ⇒ Sensitivity to Mass Hierarchy

NOvA Detector Technology

- Low-Z Tracking Calorimeters for ν_e sensitivity
  - PVC Cell Structure Filled with Liquid Scintillator
    - Mineral Oil + 5% pseudocumene

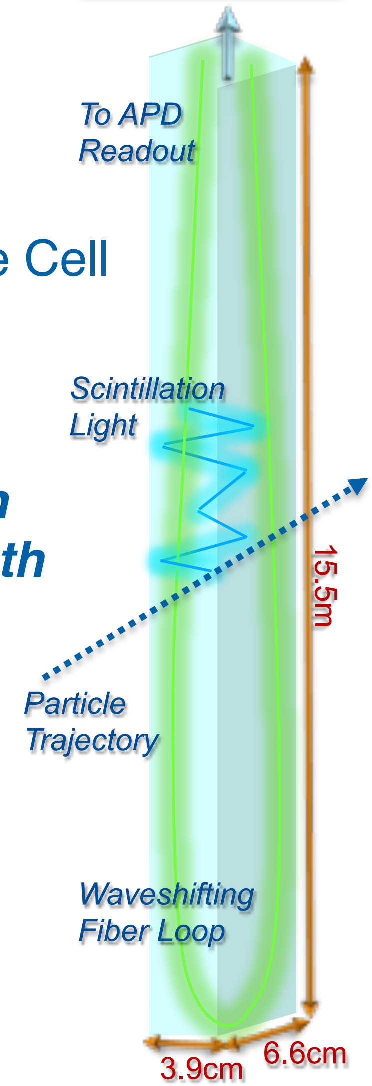
32 cells read out into 1 Avalanche PhotoDiode



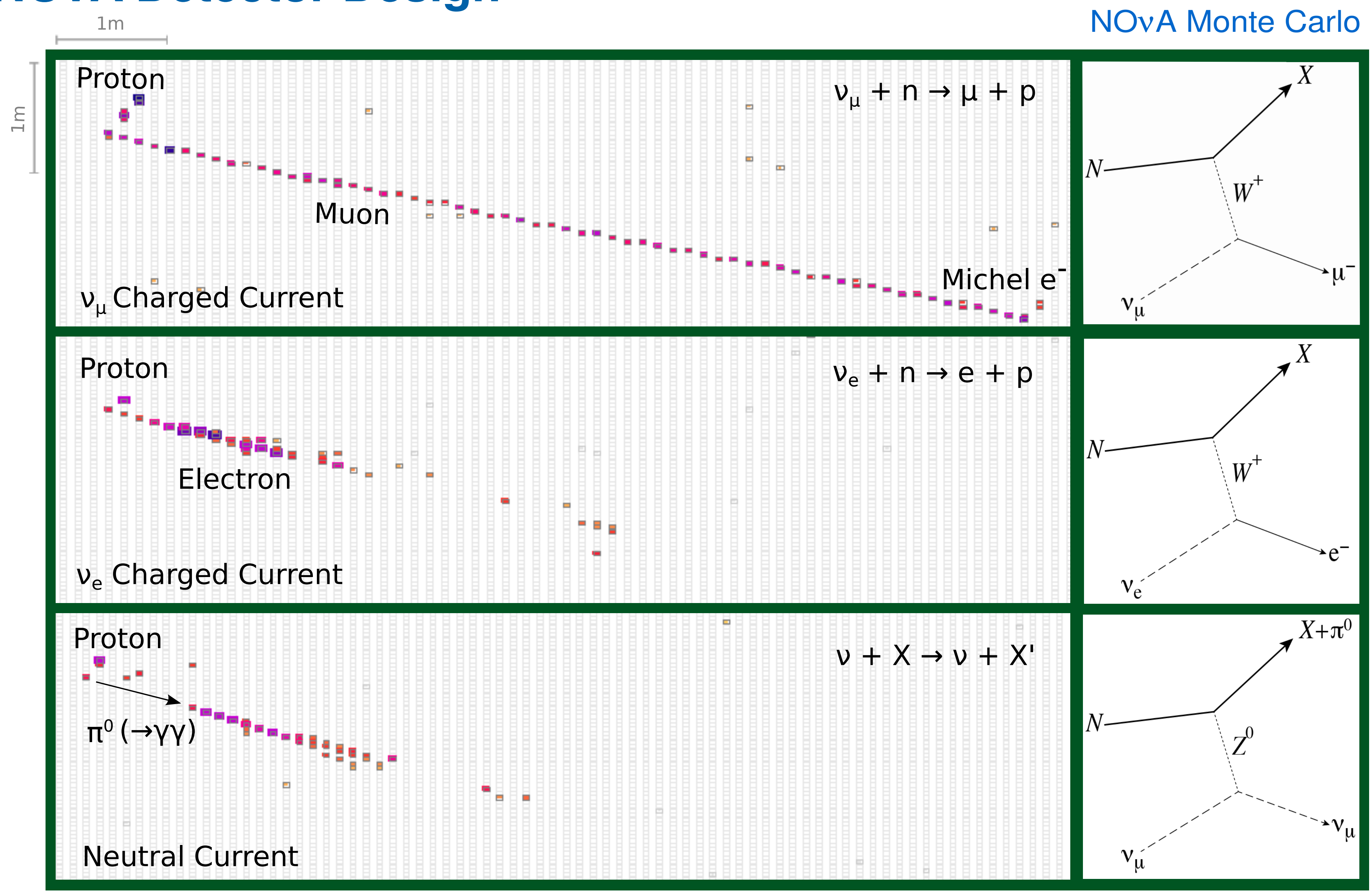


Excellent electromagnetic shower characterization with 6 samples per radiation length

Single Cell

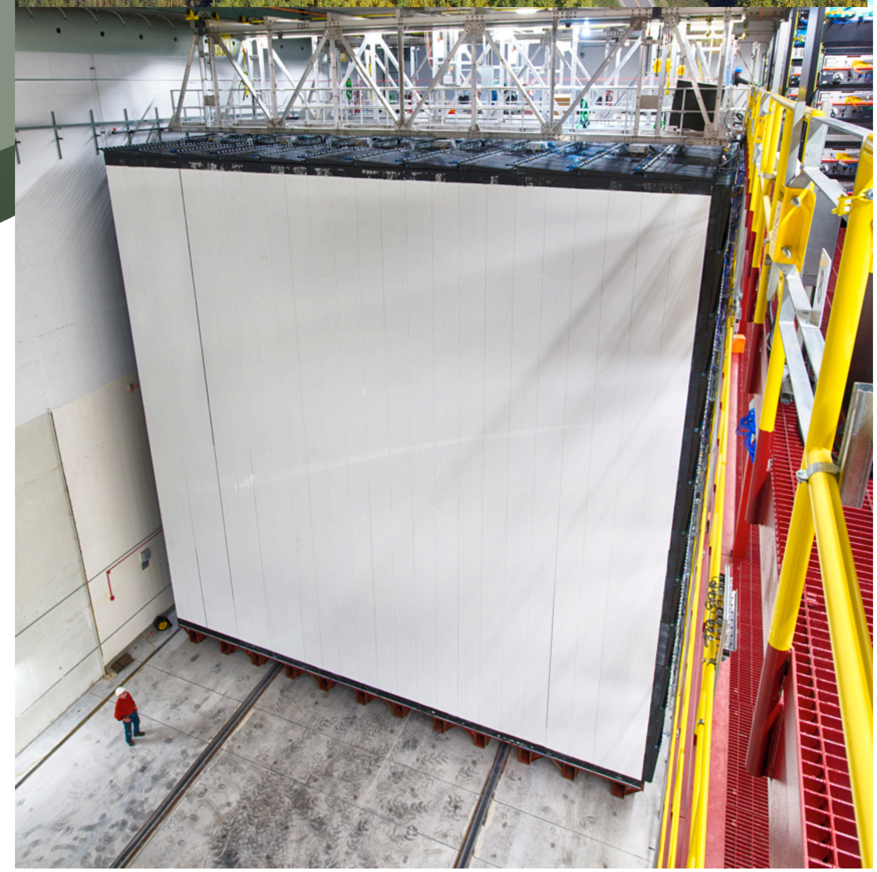


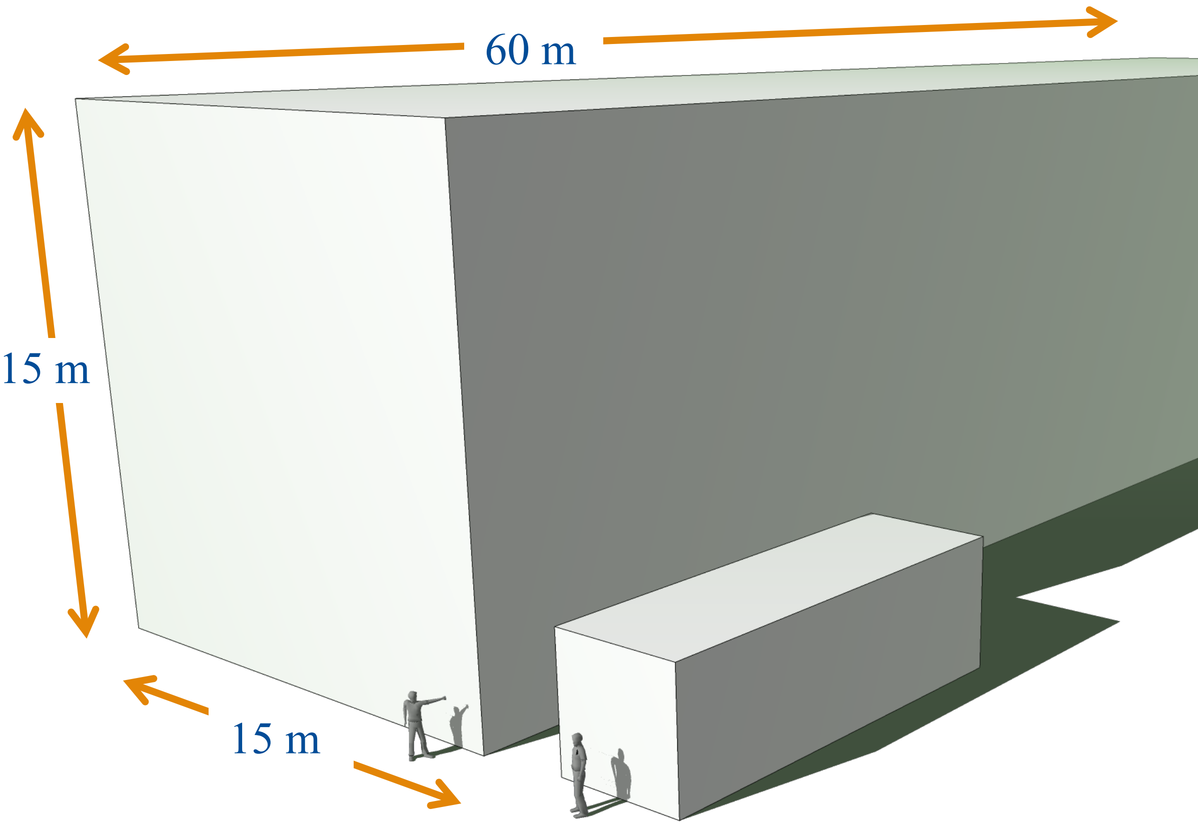
NOvA Detector Design



NOvA Detectors

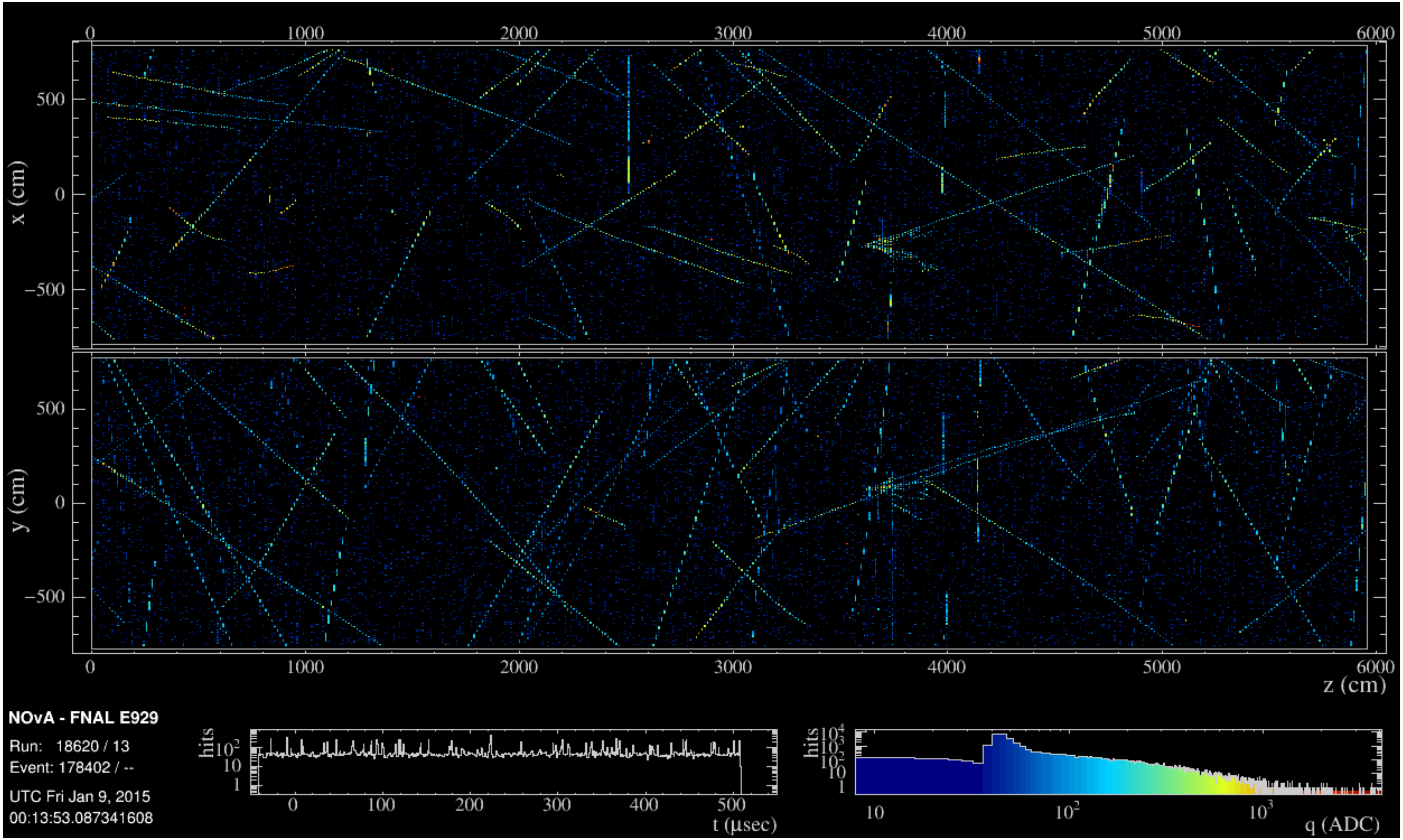
- Far Detector
  - 14 kt, 896 planes



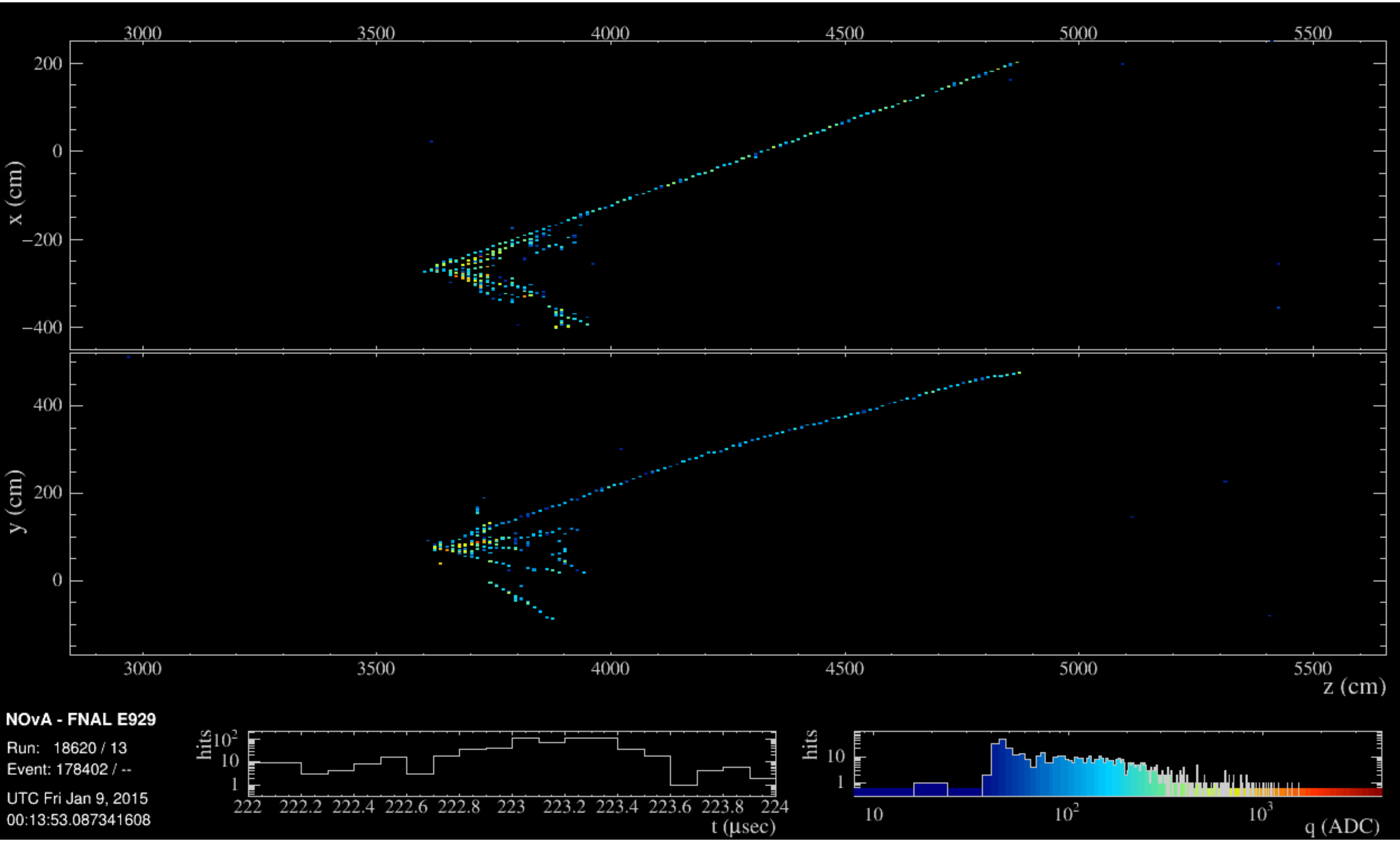


- Near Detector at Fermilab
  - 293 tons, including muon catcher
  - used to measure neutrino beam flavor and energy spectrum before oscillations

Far Detector - 550 μs NuMI Beam Spill Window



Zoom-in: ν_μ candidate event



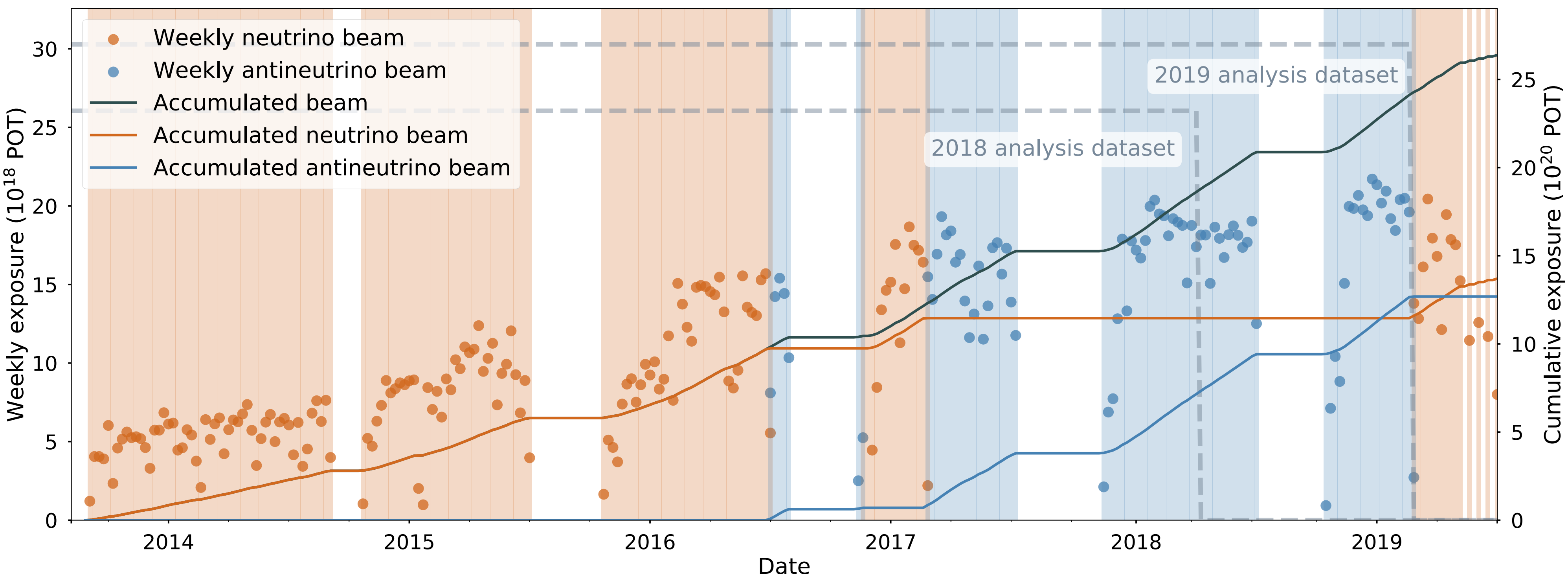
Data-Taking since 2014

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)
  - *8.85×10^{20} POT Forward Horn Current used in most recent analysis*
- 12.7×10^{20} POT in Reverse Horn Current (antineutrino beam)
  - *All 12.7×10^{20} POT Reverse Horn Current used in most recent analysis*

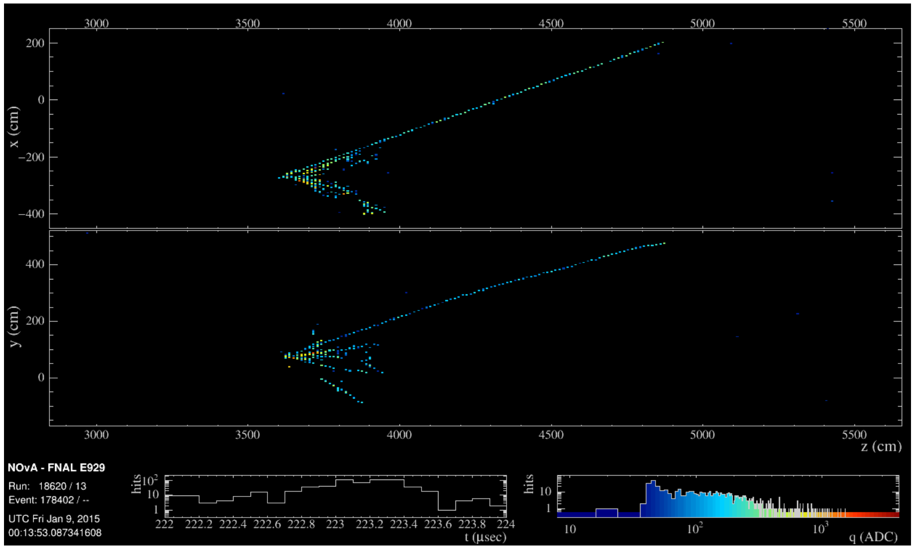
FY19: Far Detector recorded data for 99.1% of 5.56×10^{20} POT delivered to NuMI

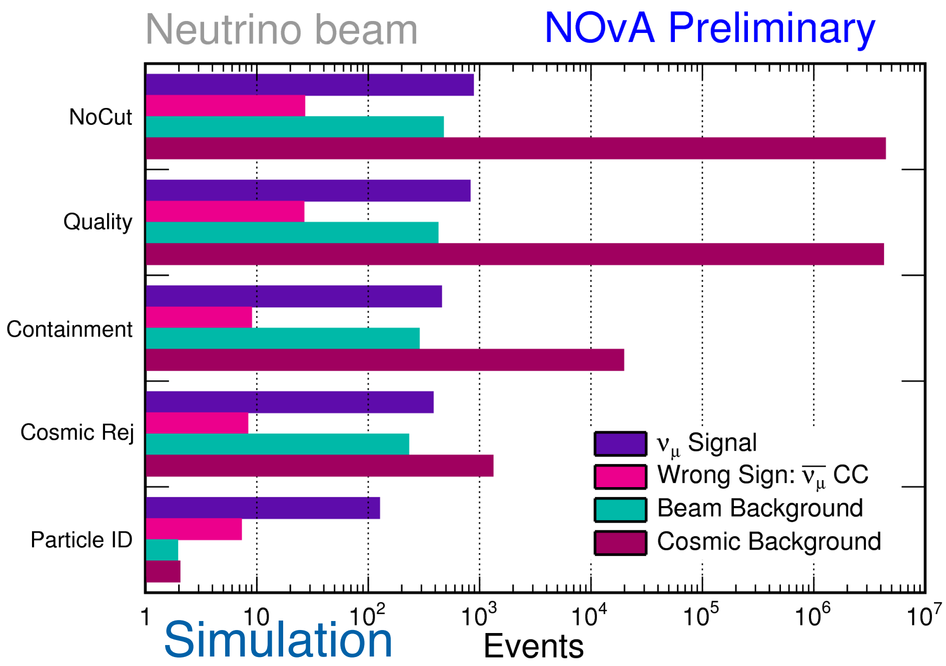
756 kW hourly beam power record achieved



Event Reconstruction and Selection Overview

- Basic quality & containment cuts
  - activity away from edges
- Identify Lepton, Hadronic Recoil
- Energy $E_\nu = E(E_l, E_{Had})$
- Deep Learning-based identification of ν_e, ν_μ CC signals, NC and Cosmic-Ray backgrounds
- Further cosmic-ray background rejection
  - Lepton characteristics, location, direction



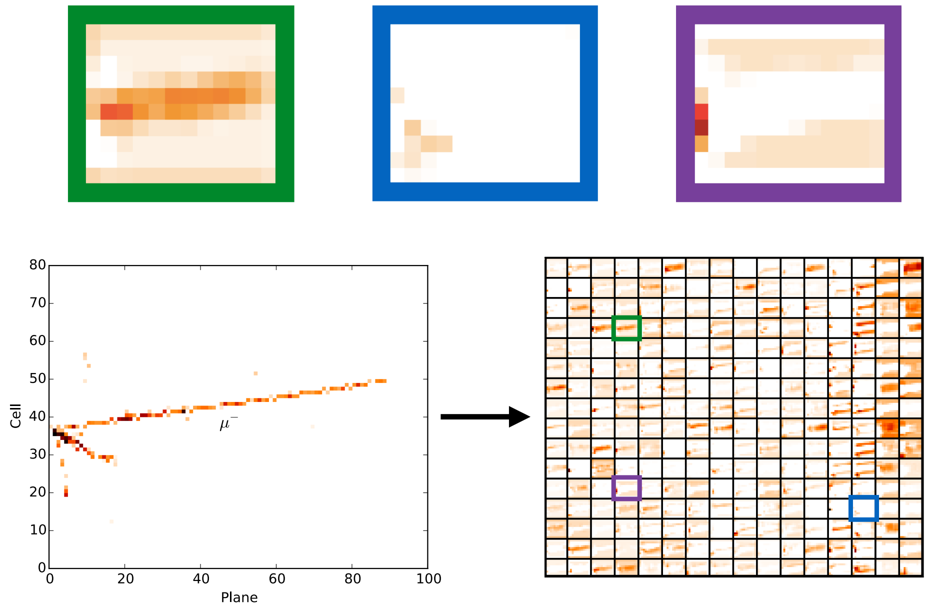


6 orders of magnitude reduction is cosmic ray background

One Step in the Analysis: Event Selection

- Computer vision-based deep learning algorithm for identification of neutrino events by flavor.
  - Convolutional Neural Net - CNN

Input hit map



Feature Maps at an early convolutional layer

- NOvA version - CVN
  - Based on GoogLeNet
  - Uses calibrated event hit maps as input.
  - Development of “Feature Maps” is part of the training
  - Led to improvement for NOvA 2016 analysis equivalent to 30% increase in exposure

Pioneering use of CNNs in Particle Physics

“A Convolutional Neural Network Neutrino Event Clas

2016 JINST 11 P09001

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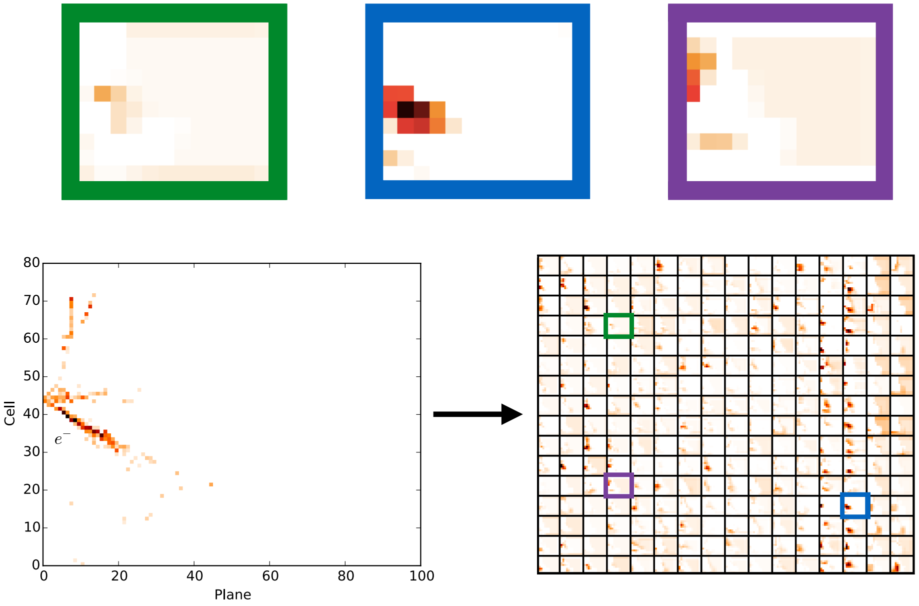

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Feature Maps at an early convolutional layer

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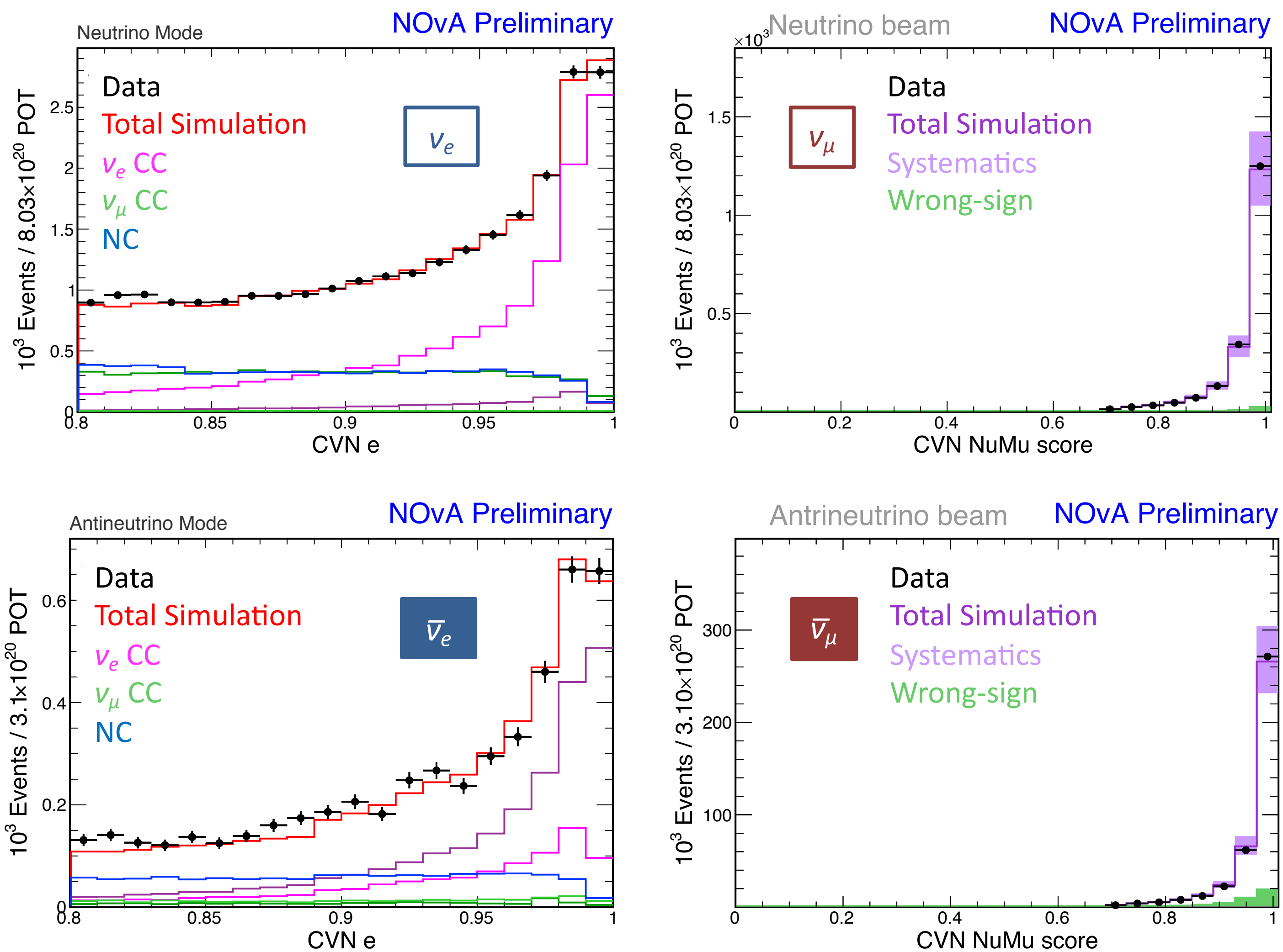
CVN Neutrino Flavor ID - Data and Simulation in Near Detector

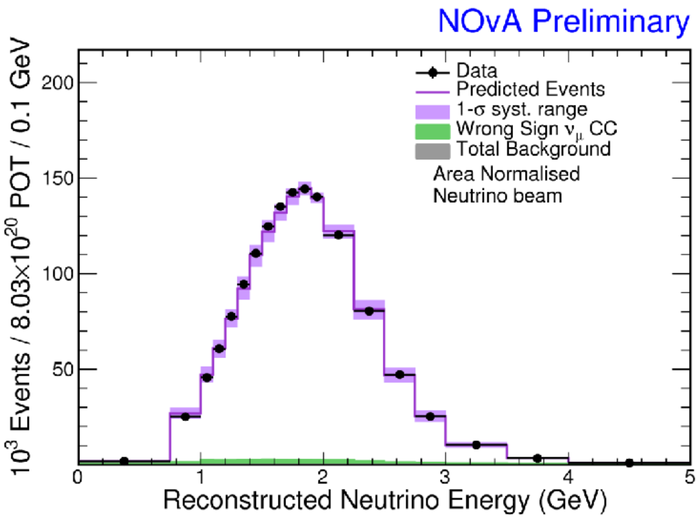
Neutrino

Anti-Neutrino

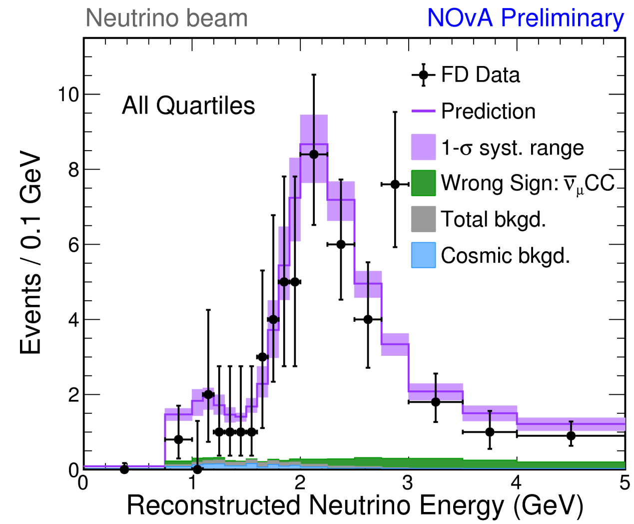


Use of the Near Detector Data

Near Detector



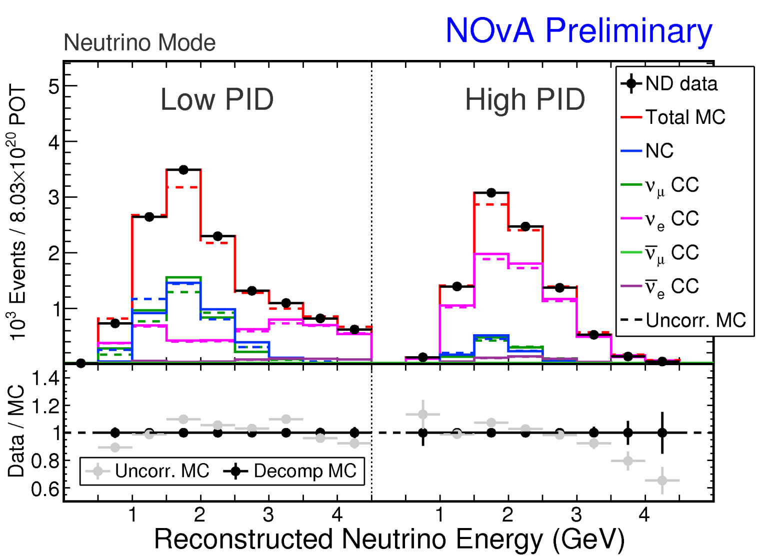
Far Detector



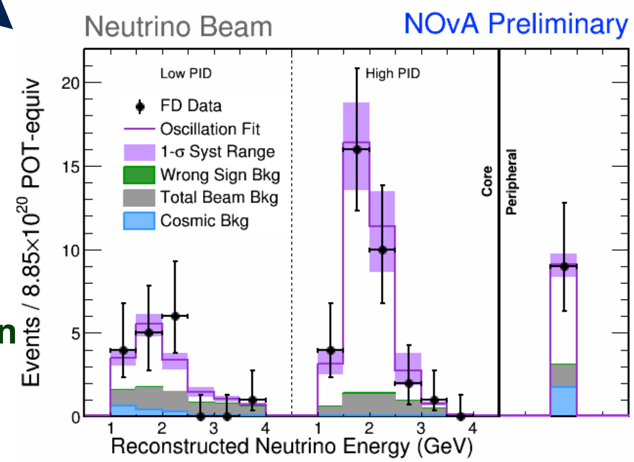
ND ν_μ Observation improves FD ν_μ Signal Prediction

Adjusted in 4 quantiles of hadronic energy

ND ν_μ Observation improves FD $\nu_\mu \rightarrow \nu_e$ Signal Prediction



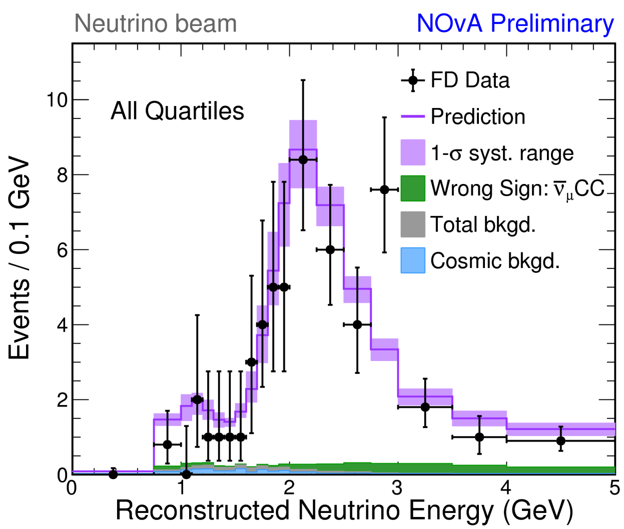
ND “ν_e” Observation improves FD ν_e Background Prediction

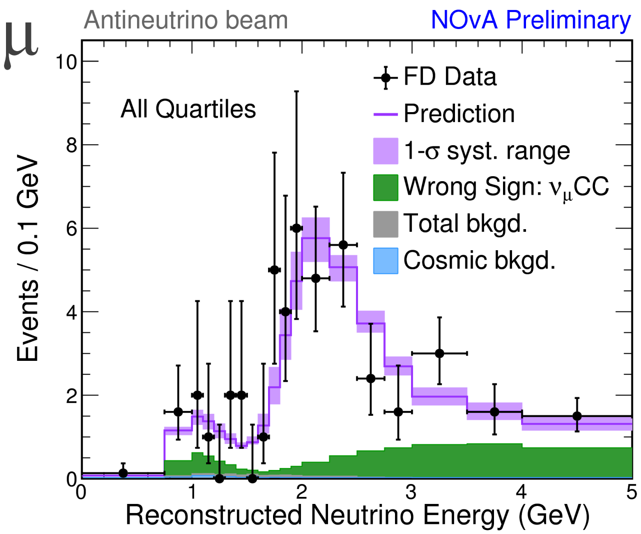


Example of neutrino mode - similar for antineutrinos

Far Detector Data and Oscillation Fit

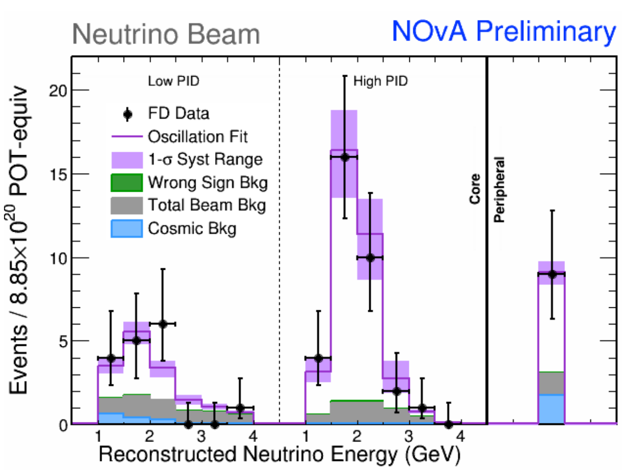
ν_μ

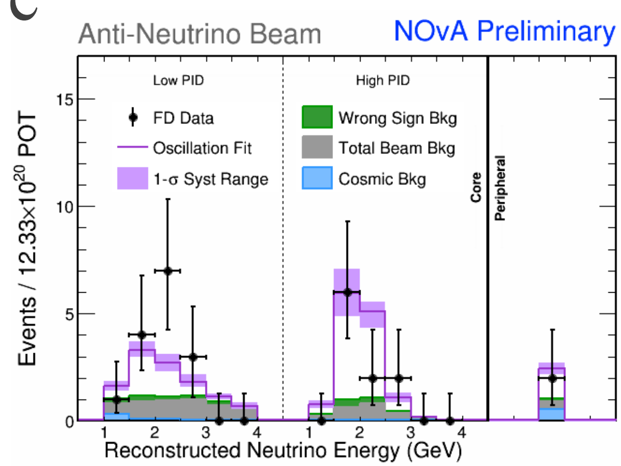




	ν	$\bar{\nu}$
Observed	*113*	*102*
Best Fit	*124*	*96*
Signal	*120(11)*	*93.9 (8)*
Background	*4.2(0.5)*	*2.2(0.4)*
No Oscillation	*730*	*476*

ν_e





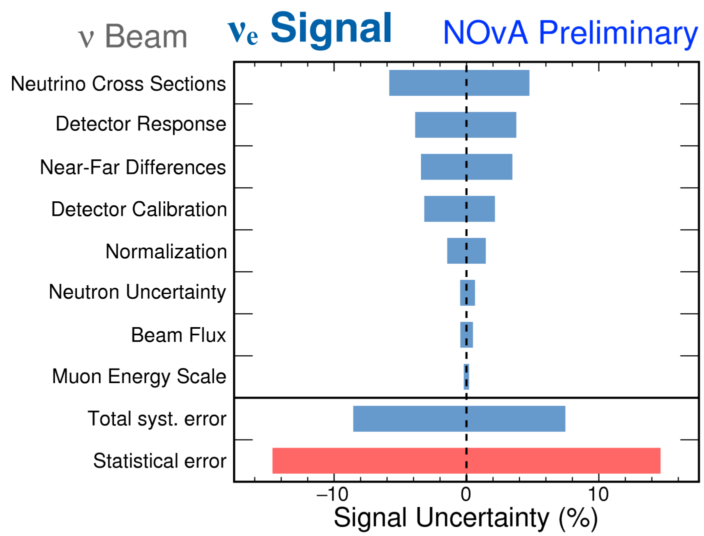
	ν	$\bar{\nu}$
Observed	*58*	*27*
Best Fit	*59.3*	*26.8*
Signal	*44.3(3.8)*	*16.6(1)*
Background	*15.0(0.9)*	*10.3(0.6)*
(Wrong Sign)	*0.6*	*2.2*

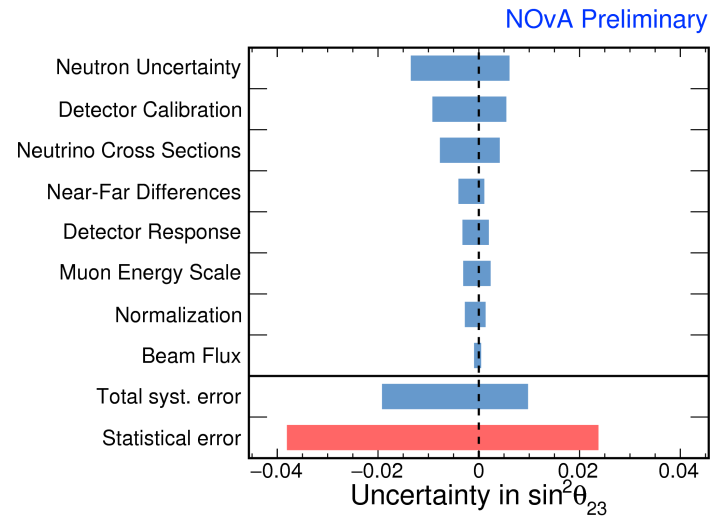
Note: uncertainties () are approximate
see arXiv:1906.04907 for full table

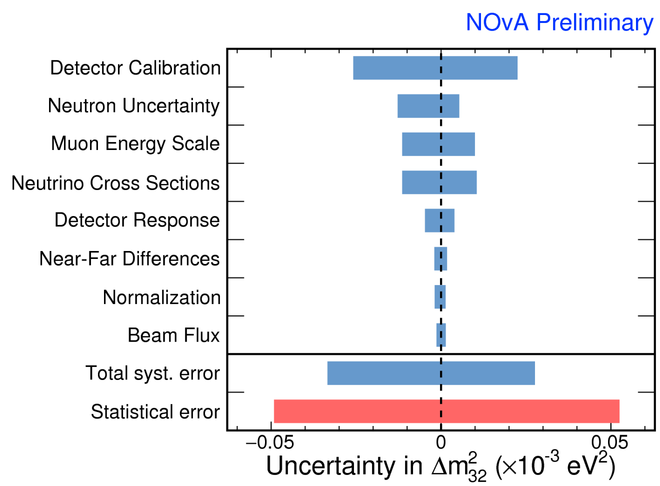
Systematic Uncertainties

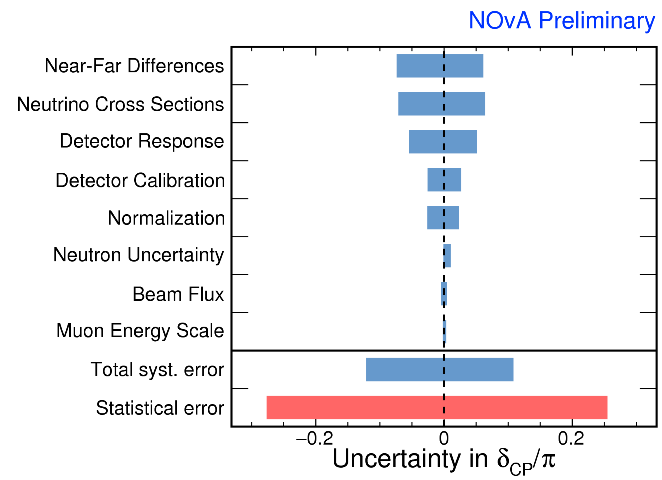
Systematic uncertainties are evaluated by modifying simulation throughout analysis chain.

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







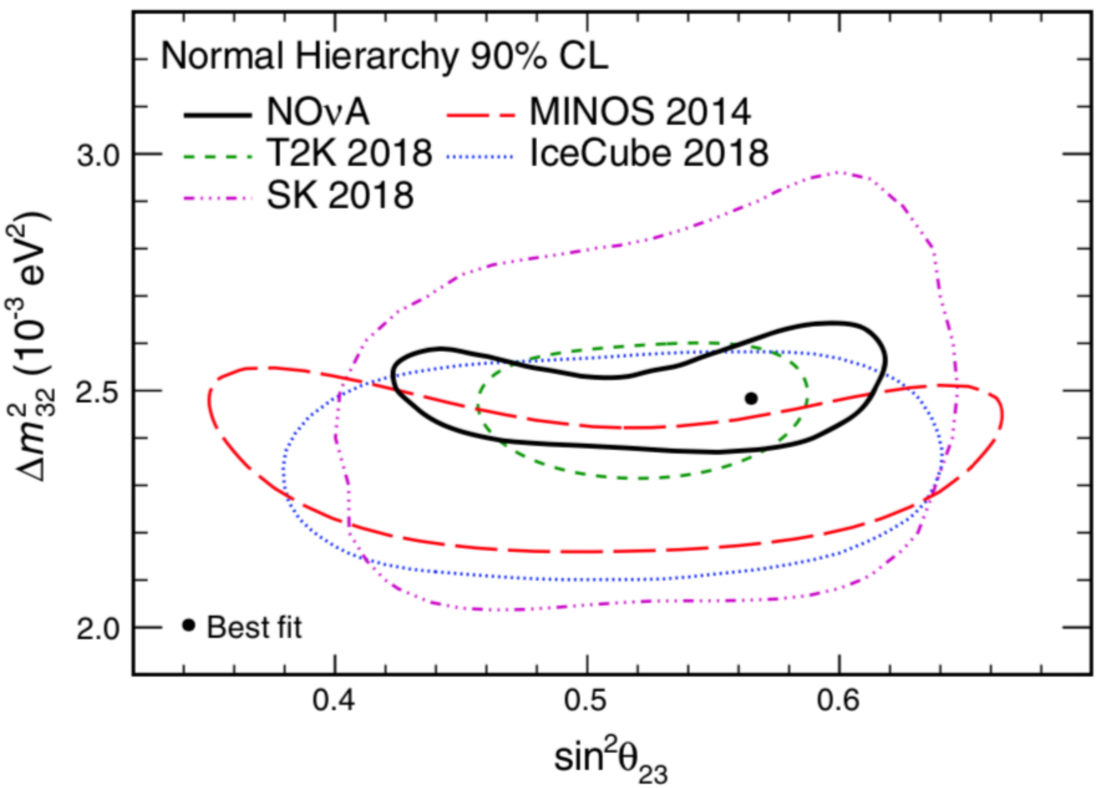


Oscillation Parameters from Joint fit to data

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

- $\Delta m^2_{32}=(+2.48^{+0.11}_{-0.06}\ \times 10^{-3})\ eV^2$
- $\sin^2(\theta_{23})=0.56^{+0.04}_{-0.03}$ (upper octant)
- Previous slight tension (p=0.04) between disappearance fit in neutrino and antineutrino beams has resolved with more statistics

Feldman-Cousins Contours



Oscillation Parameters from Joint fit to data

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

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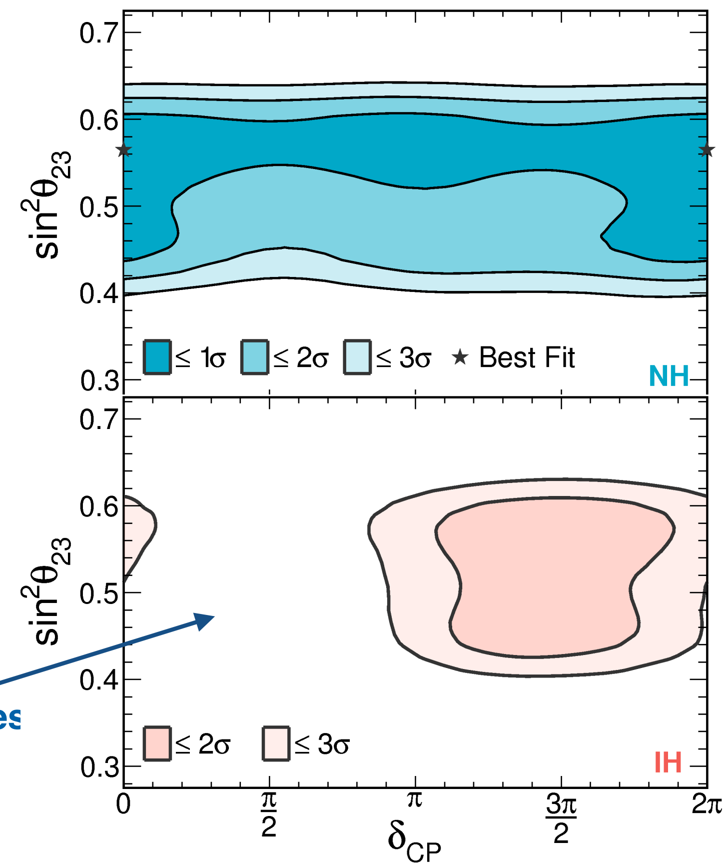
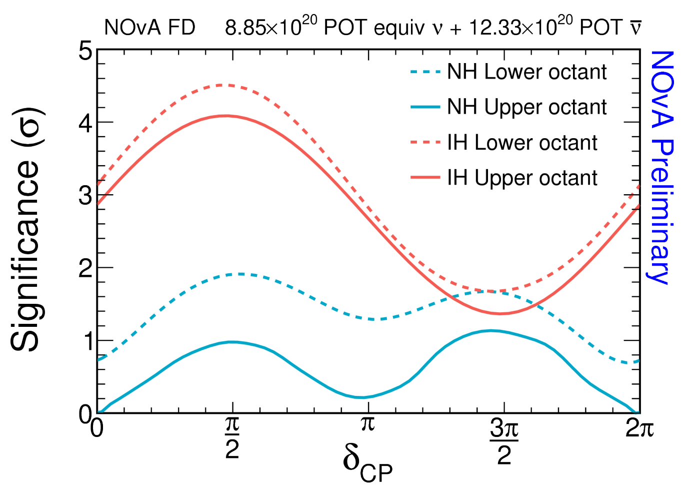
- **Previous slight tension (p=0.04) between disappearance fit in neutrino and antineutrino beams has resolved with more statistics**



- **Normal Hierarchy**
- **$\delta_{CP}/\pi=0.0^{+1.3}_{-0.4}$**

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

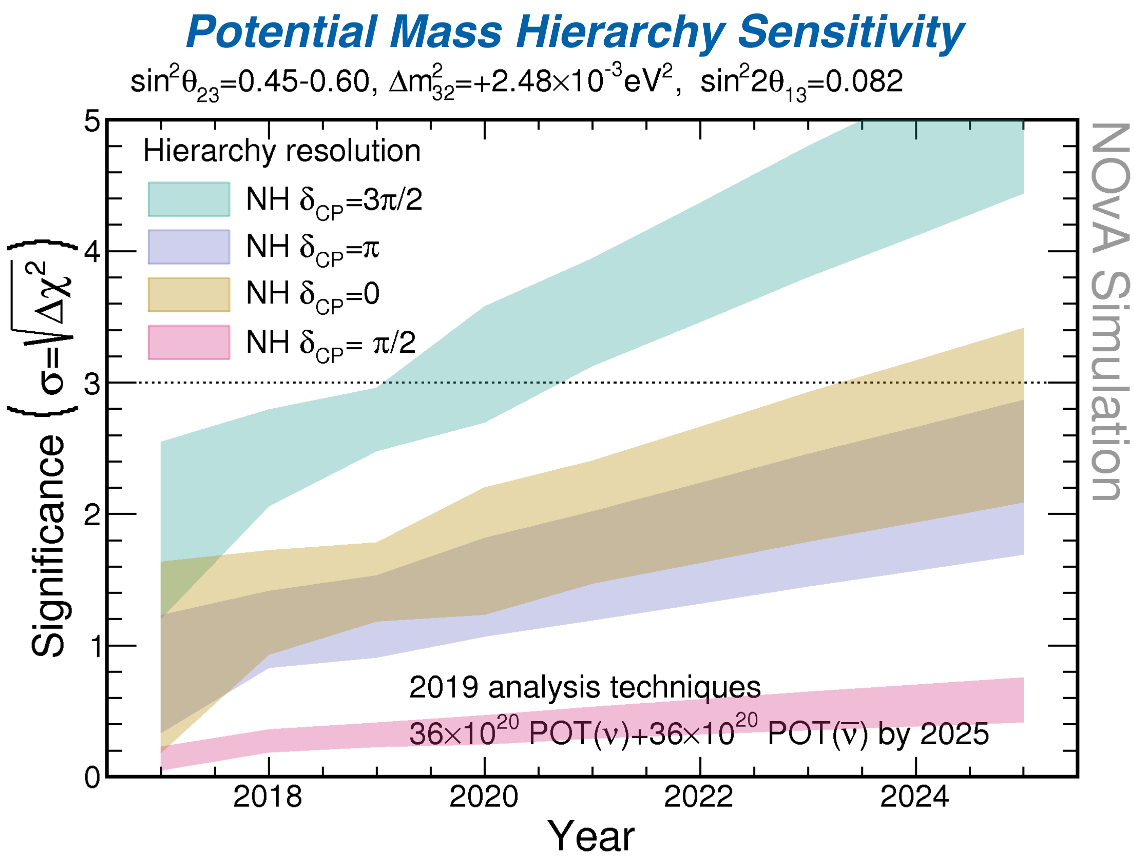


Profiling over all other parameters

- **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

A Look Ahead

- NOvA will run until 2025
- Projections assuming 72×10^{20} protons-on-target
- Beam Improvements
  - 1 MW-capable target recently installed will allow up to 770 kW this year

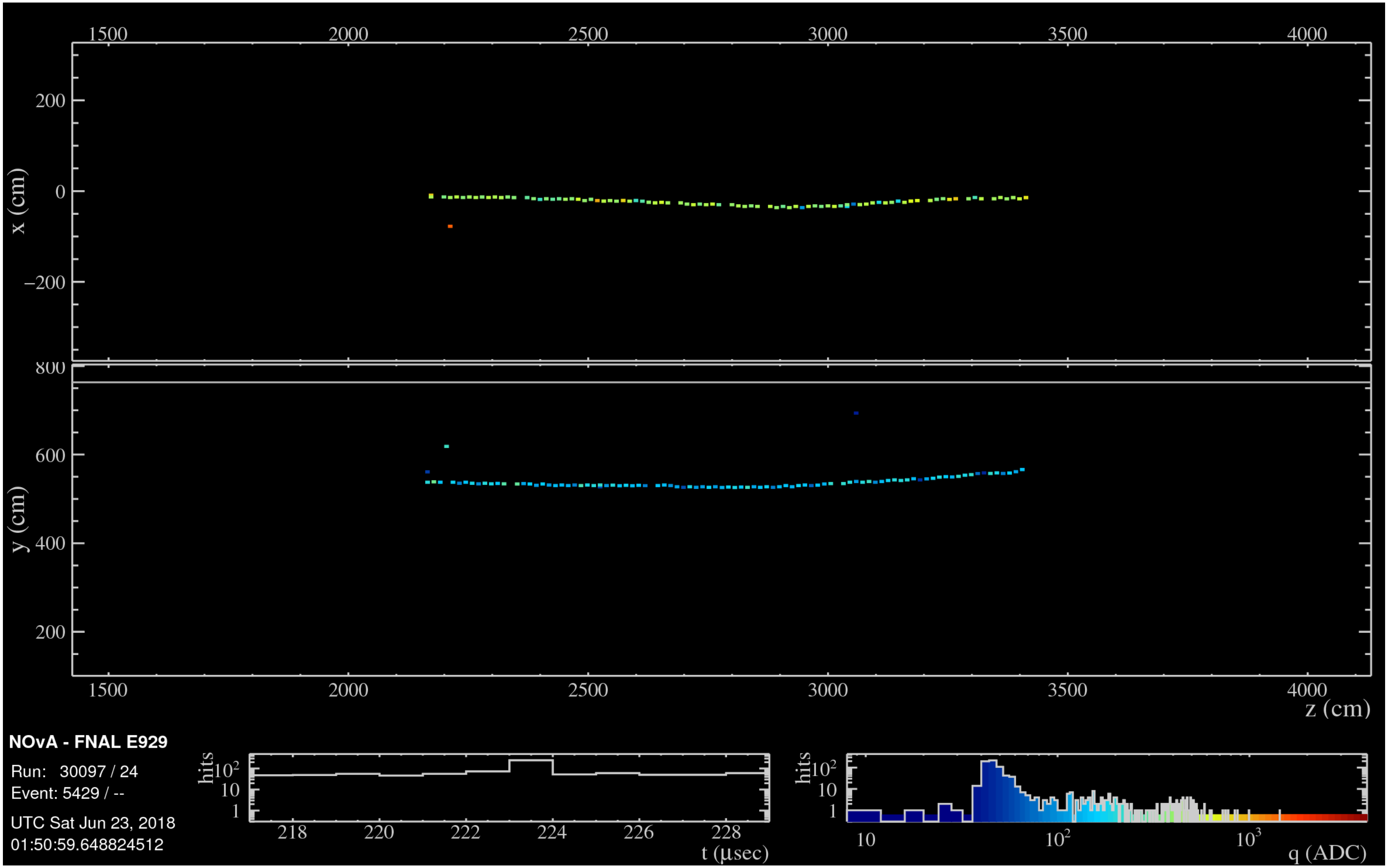


  - Further improvements to target system expected next year will allow beyond 800 kW.
  - Planned reduction of losses in 8 GeV Booster may enable beyond 900 kW by 2022/3.
- Ongoing Joint Analysis Effort with T2K
  - Maximize the benefit of the experiments' complementarities.

Thank You

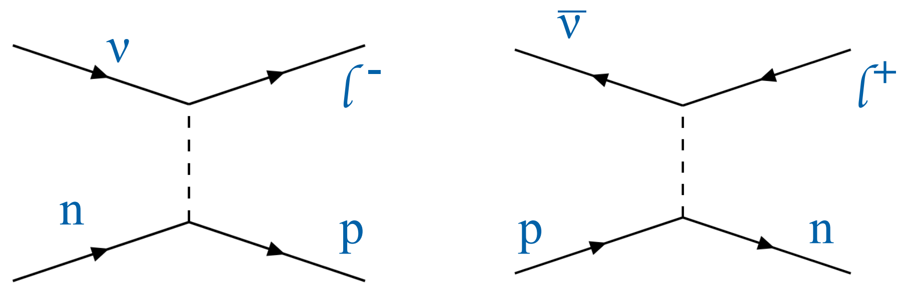
More details

Candidate antineutrino interaction with neutron

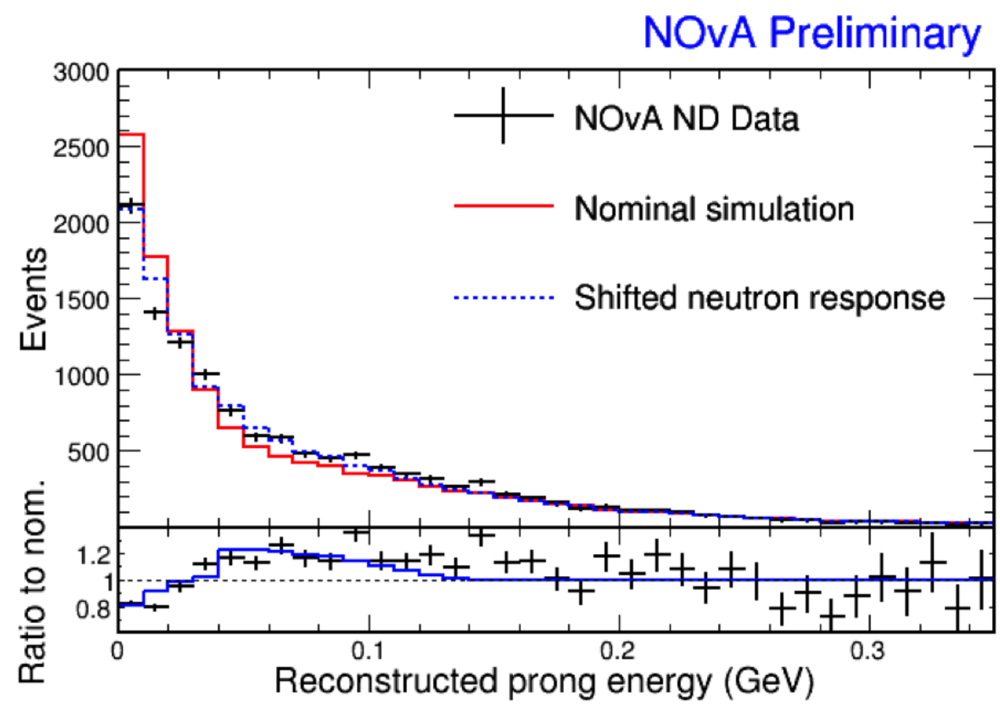


Neutron Systematic

- 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

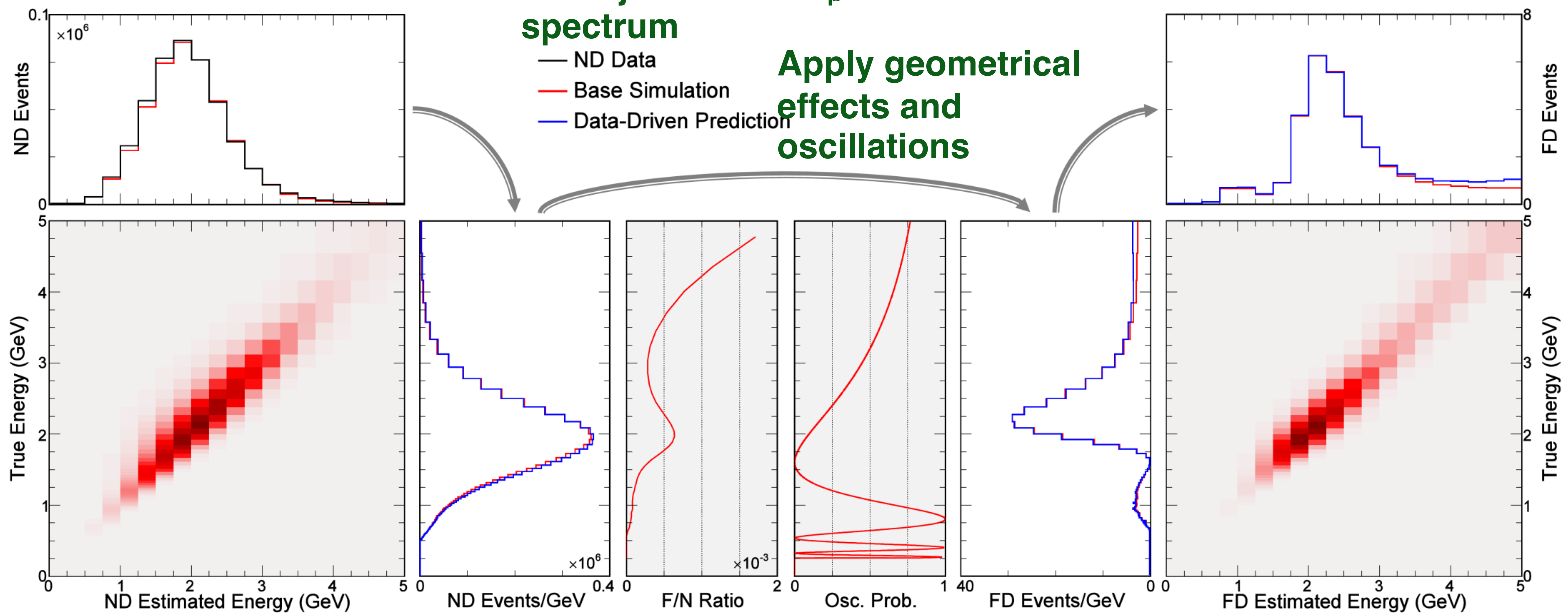
Signal

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



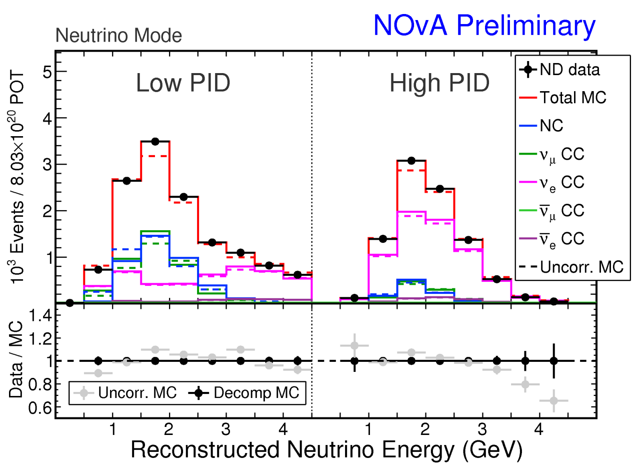
Blind Analysis: examine Far Detector Data only after all systematic studies are complete

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 $\bar{\nu}_e$

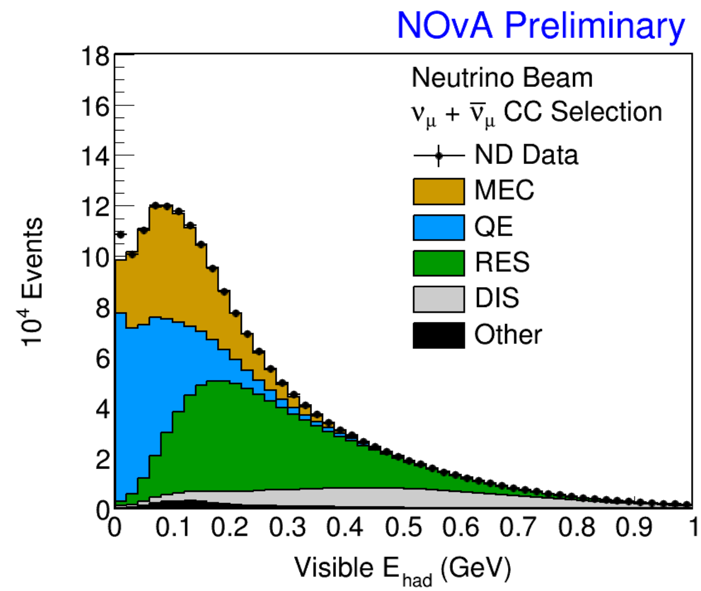


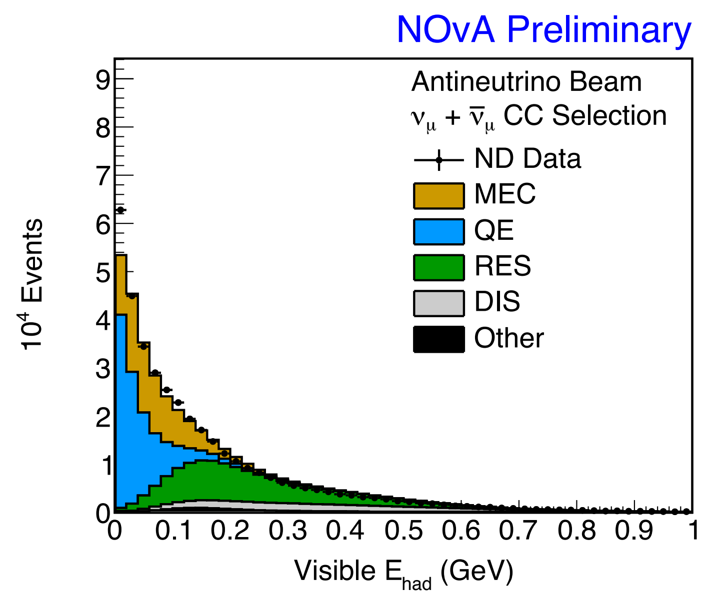
Cosmic Rays

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

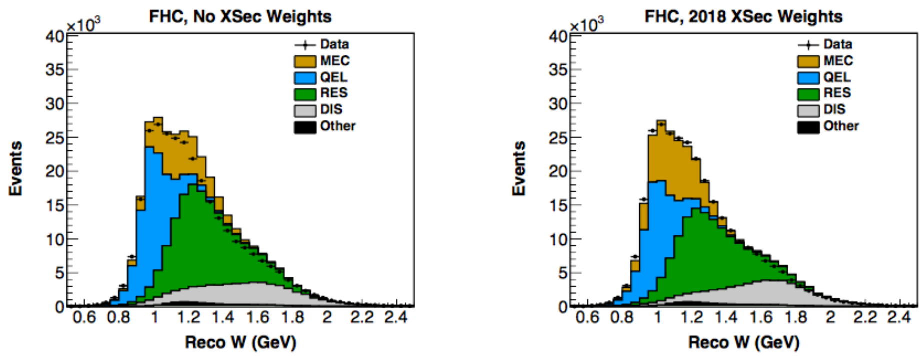
Cross-section Tuning to Near Detector Data

- 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.



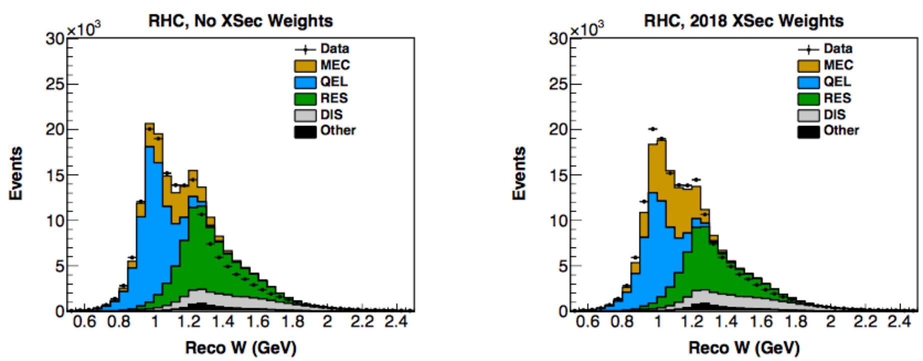


Cross-section tune in W and Q²



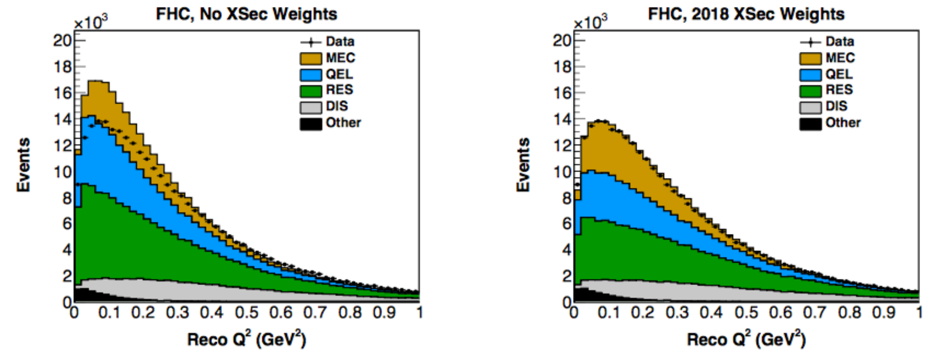
(a) No cross-section weights applied (b) 2018 cross-section weights applied

Figure 29: Reconstructed W, FHC



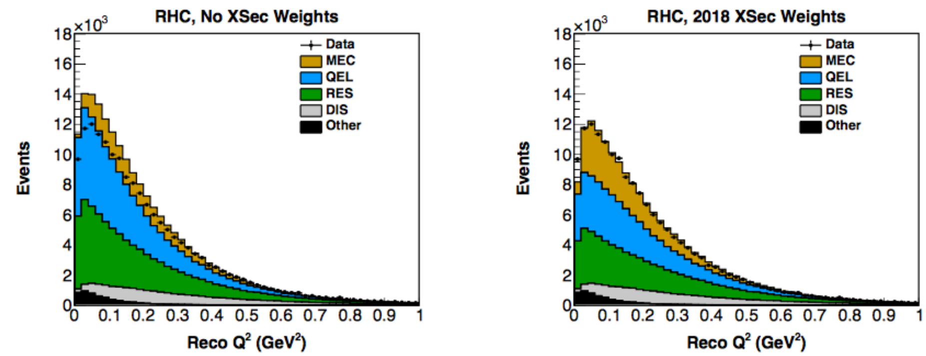
(a) No cross-section weights applied (b) 2018 cross-section weights applied

Figure 30: Reconstructed W, RHC



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

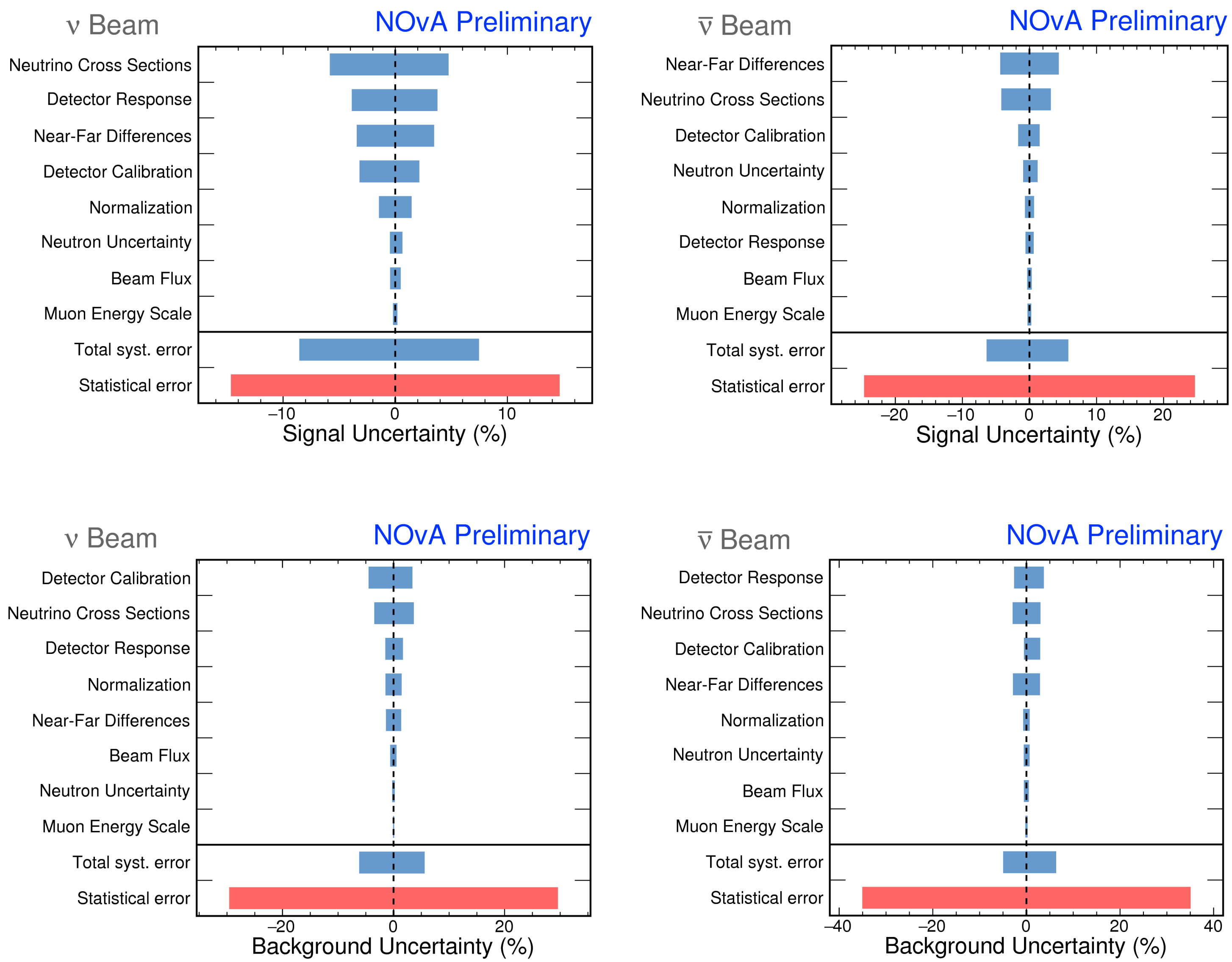
Figure 31: Reconstructed Q^2, FHC



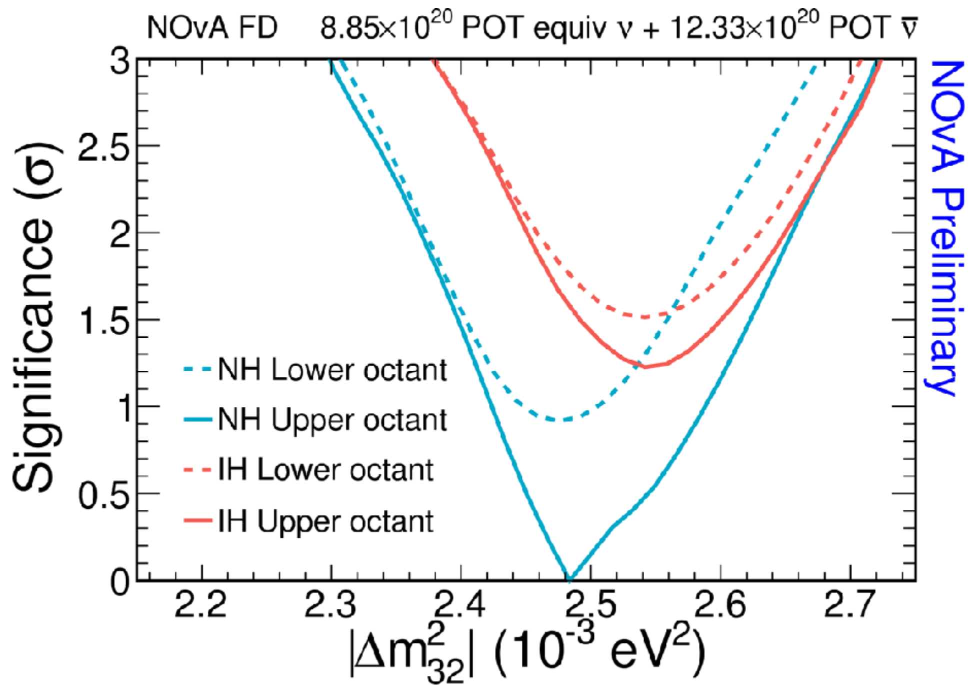
(a) No cross-section weights applied (b) 2018 cross-section weights applied

Figure 32: Reconstructed Q^2, RHC

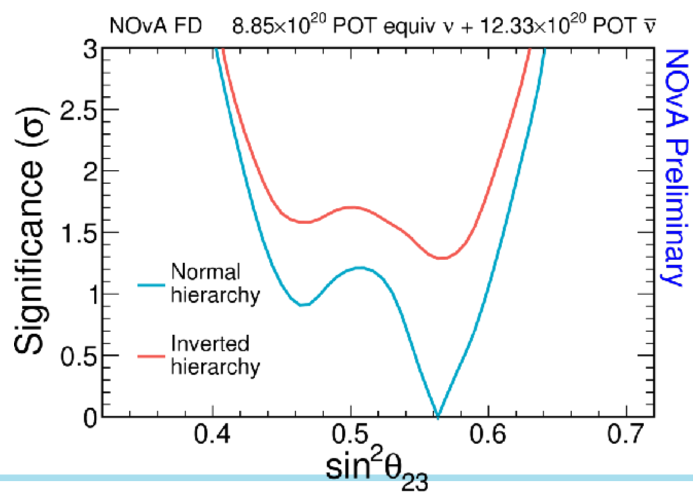
Impact of Systematic Uncertainties on ν_e Signal and Background



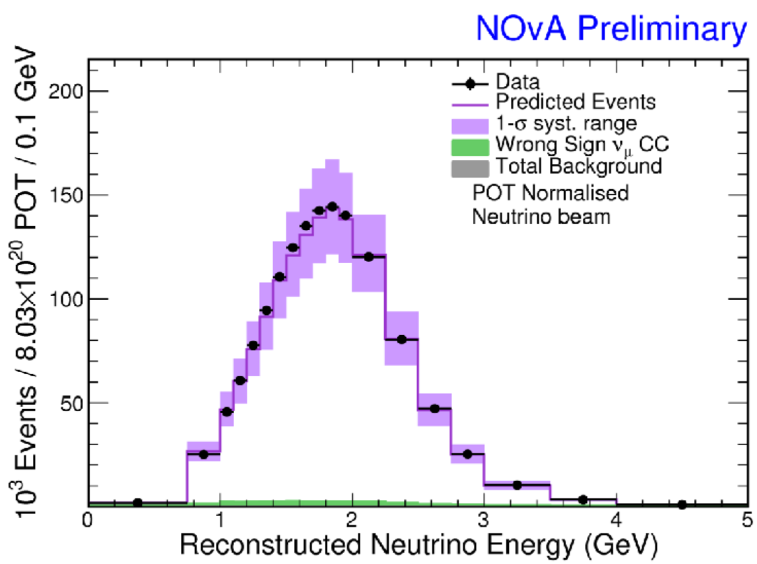
Other slices

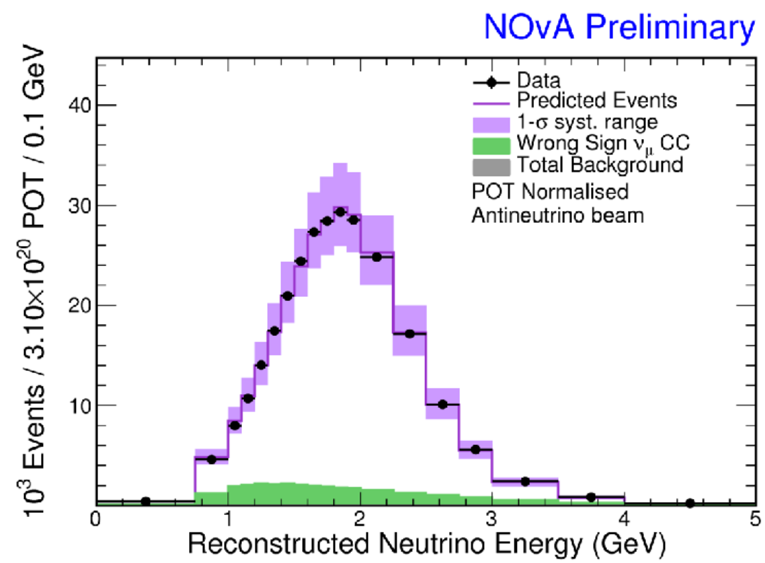


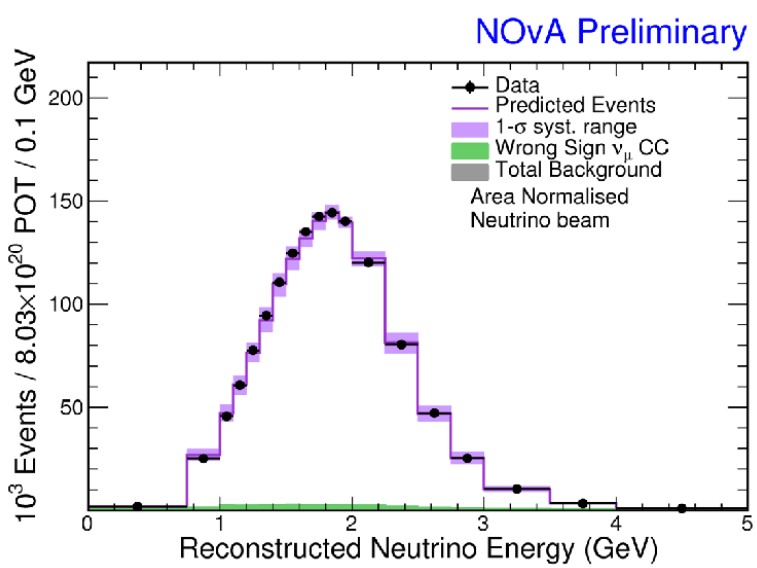
	σ data (gaussian)	FC p-value	FC σ
IH	1.65	0.057	1.89
LO	1.16	0.112	1.59
NHLO	1.16	0.121	1.55
IHUO	1.65	0.080	1.75
IHLO	1.93	0.051	1.95

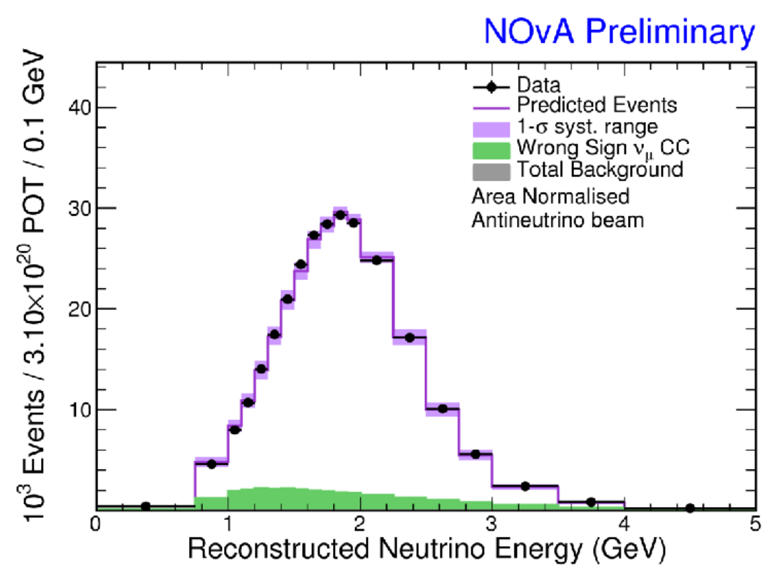


ND ν_μ Spectra with POT and Area Normalization



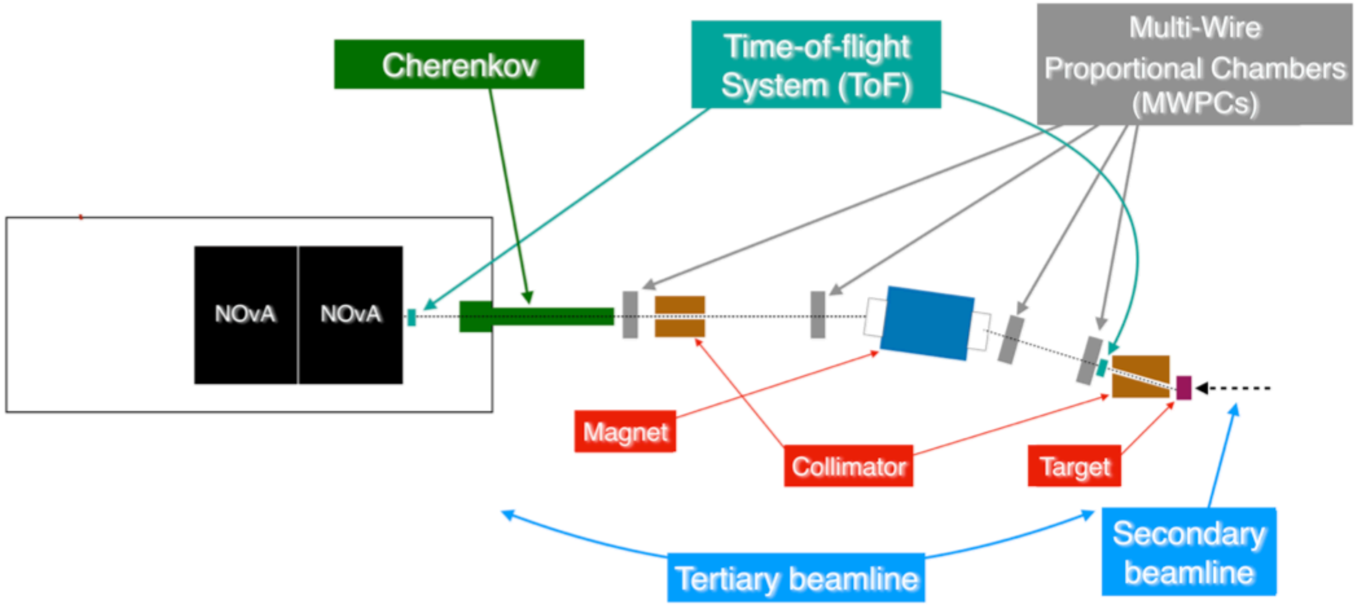




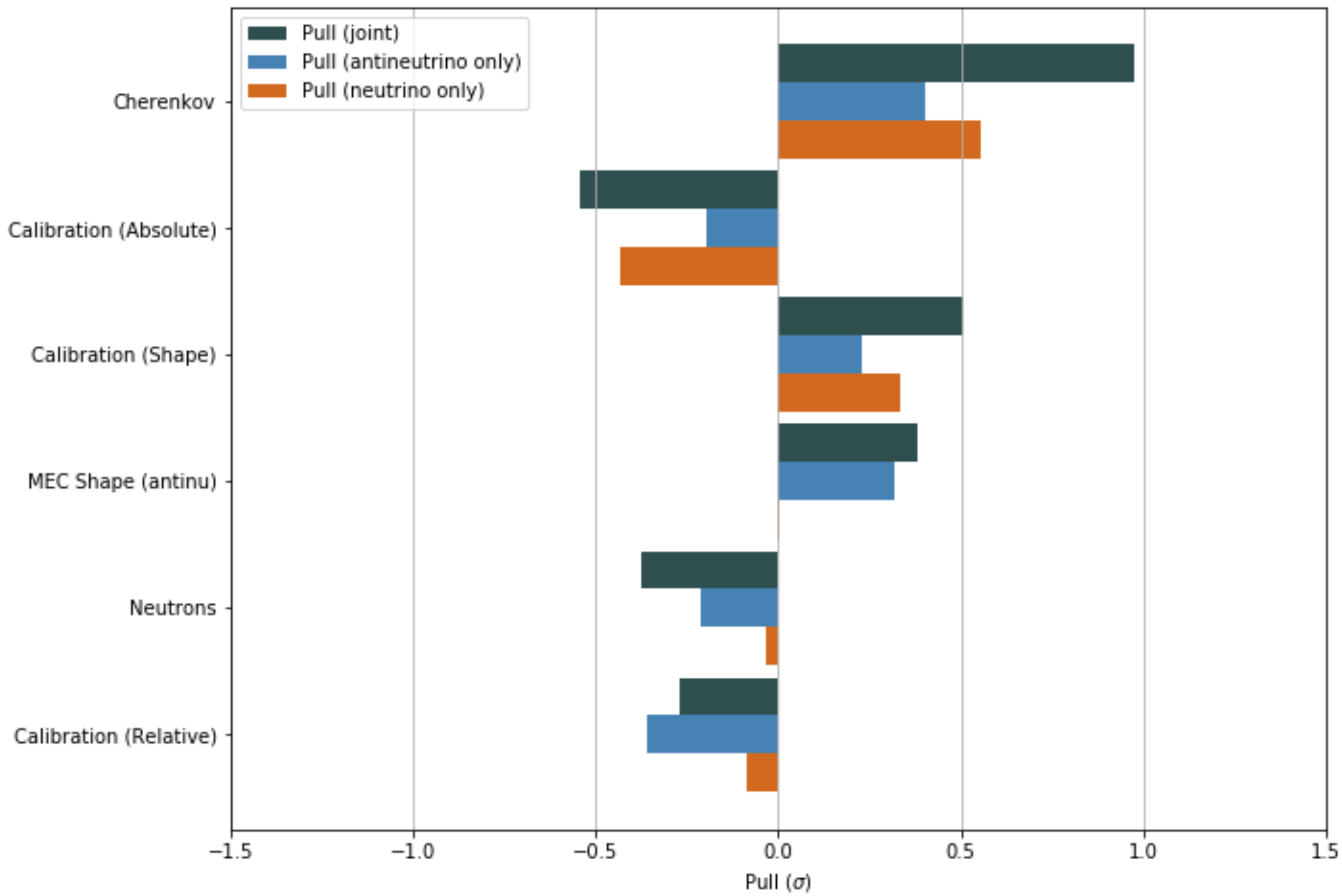


Test beam layout

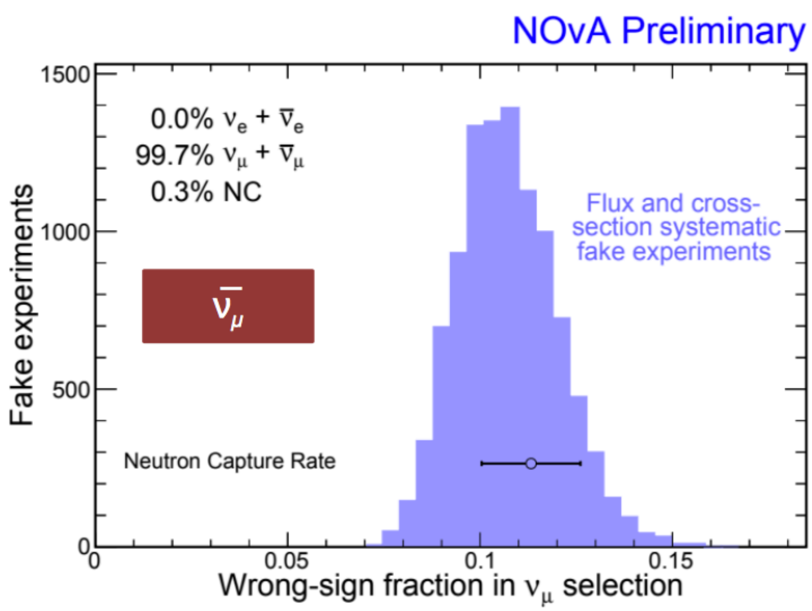
- Detector consists of two 31-plane 2x2 blocks + one horizontal plane at FTBF's MC7
- Exposed to MCenter-sourced e, μ, π, p, K, π^0 tertiary beam with known momentum from 0.2 - 2.0 Gev/c
- Provide absolute measurement of detector response and cross-check of NOvA calibration chain

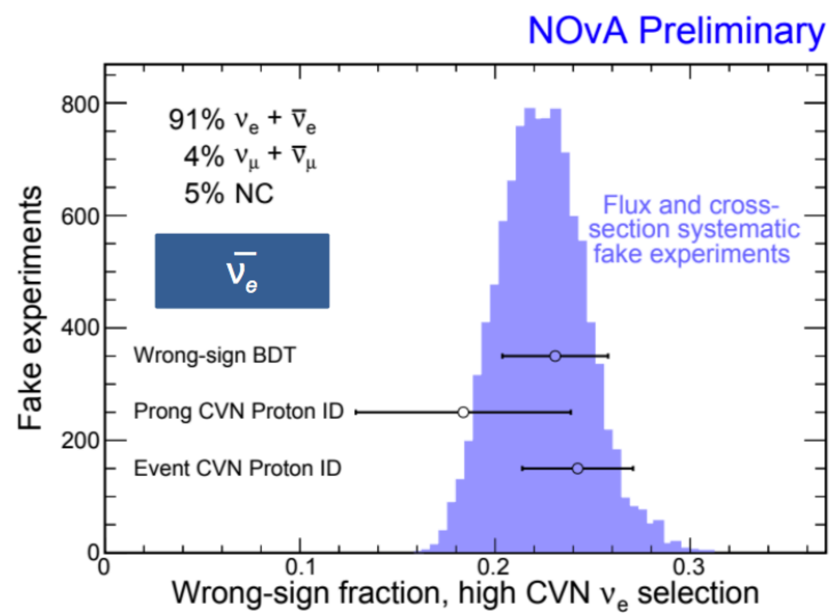


Systematic Pulls



Wrong-sign contamination in antineutrino beam





Long Baseline $\nu_\mu \rightarrow \nu_e$ Appearance Probability

- $P(\nu_\mu \rightarrow \nu_e) \cong P_{Atm} + P_{\sin\delta} + P_{\cos\delta} + P_{Sol}$

DUNE Science Report and References

$$P_{Atm} = \sin^2\theta_{23} \sin^2 2\theta_{13} \frac{\sin^2[(A-1)\Delta]}{(A-1)^2}$$

$$P_{Sol} = \alpha^2 \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(A\Delta)}{A^2}$$

$$P_{\sin\delta} = \alpha 8 J_{CP} \sin\Delta \sin(A\Delta) \frac{\sin[(1-A)\Delta]}{A(1-A)}$$

$$P_{\cos\delta} = \alpha 8 J_{CP} \cot\delta_{CP} \cos\Delta \sin(A\Delta) \frac{\sin[(1-A)\Delta]}{A(1-A)}$$

Interference Terms

δ_{CP} and A change sign for $\overline{\nu}$
A depends explicitly on (sign of) Δm^2_{31}

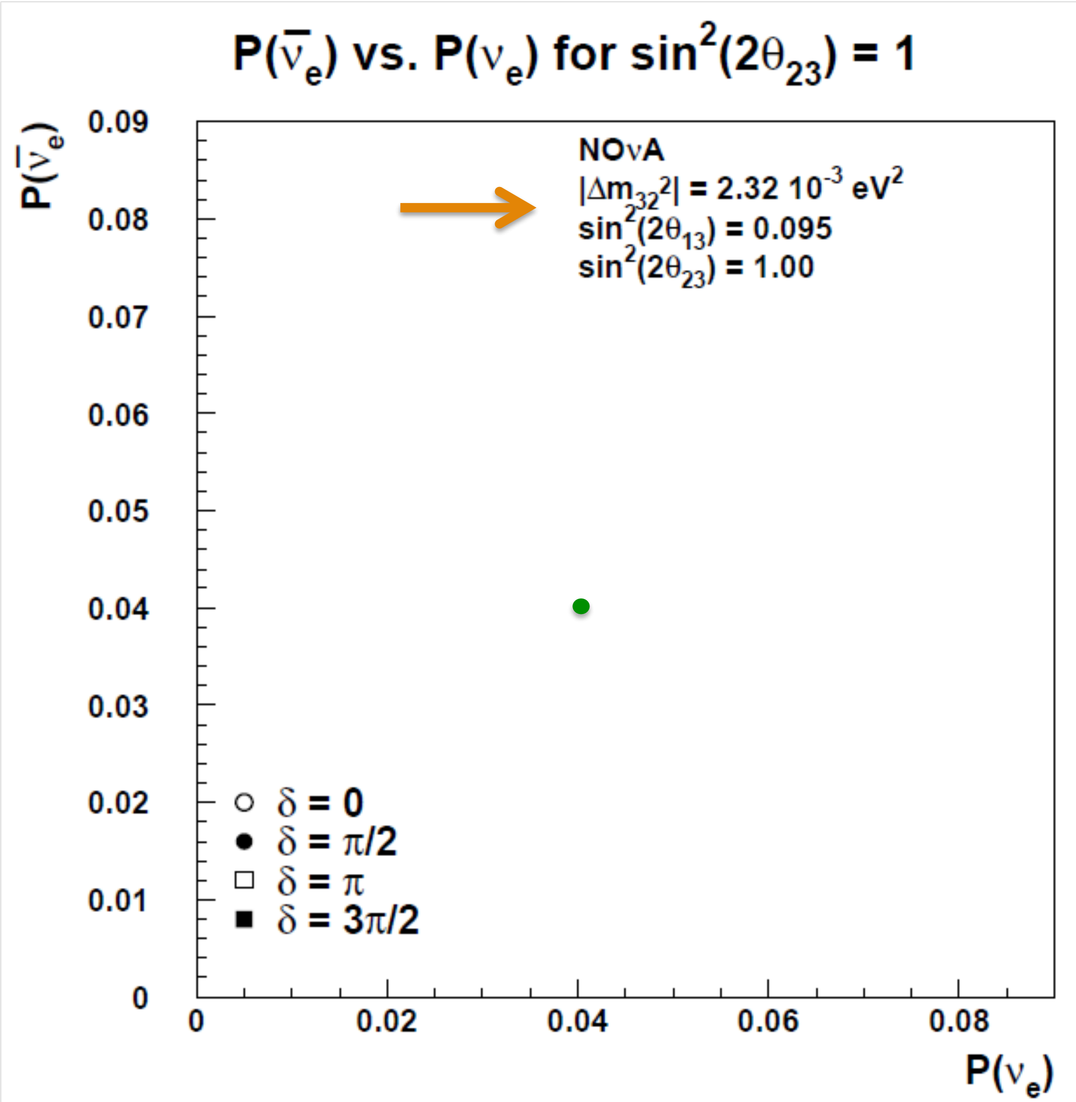
$\Delta = \Delta m^2_{31} L/4E$ $\quad$ $A = \sqrt{2} G_F N_e 2E/\Delta m^2_{31}$ $\quad$ $\alpha = |\Delta m^2_{21}|/|\Delta m^2_{31}|$

Matter Effect

Jarlskog Invariant

$J_{CP} = \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \cos\theta_{13} \sin\delta_{CP}/8 \approx 0.03 \sin(\delta_{CP})$ - up to 1000x J(CKM)

ν_e and $\bar{\nu}_e$ Appearance Probabilities

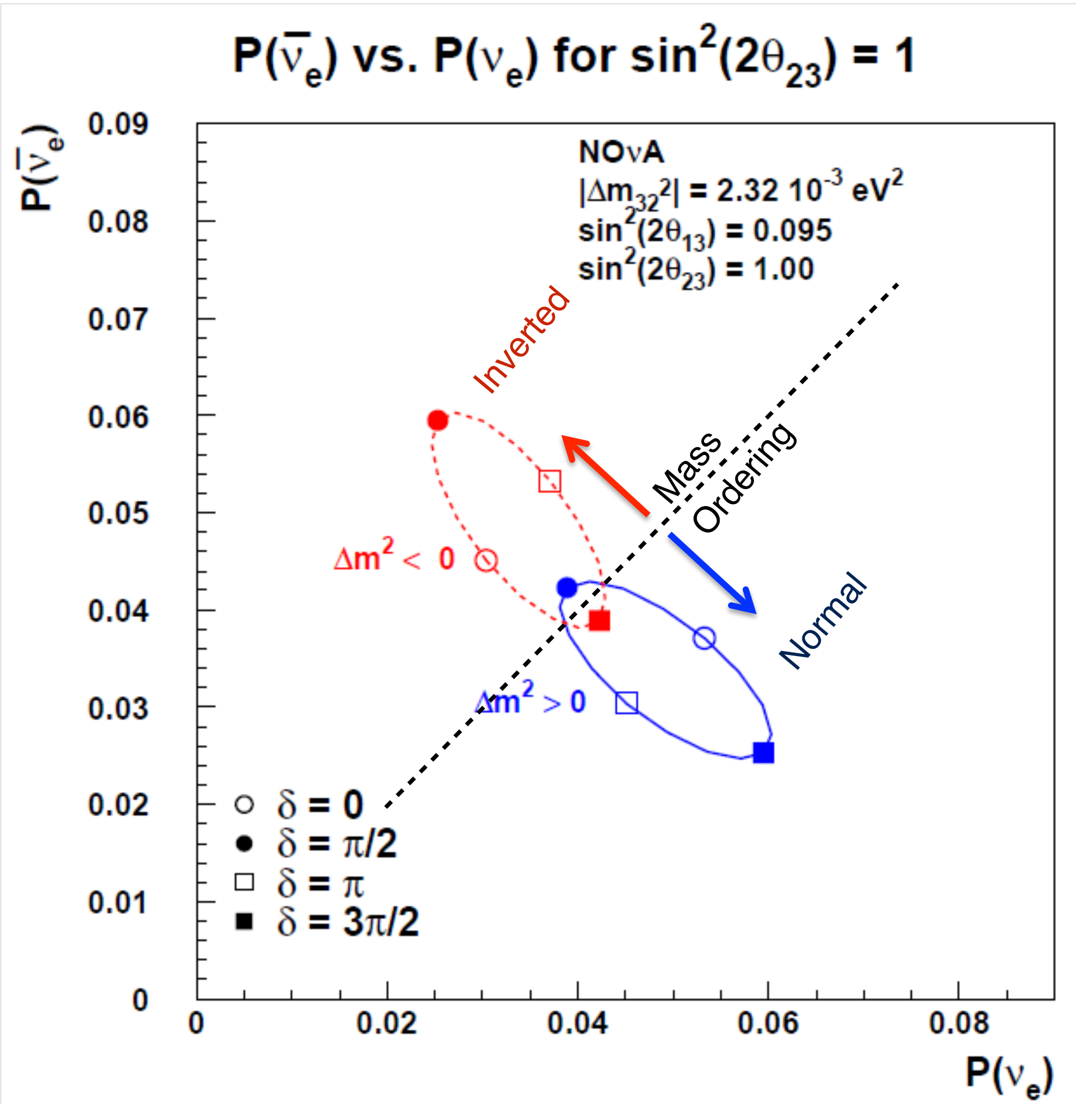


Comparison of neutrino and antineutrino appearance for a specific baseline and energy

Assuming

- No Matter Effect
- No CP Violation
- Maximal μ-τ mixing

CP Violation and Neutrino Mass Ordering



CP Violation

» *CPT theorem requires ν_μ and $\bar{\nu}_\mu$ disappearance to be equal in vacuum*

» ν_e appearance probabilities vary on an ellipse with δ_{CP}

Mass Ordering

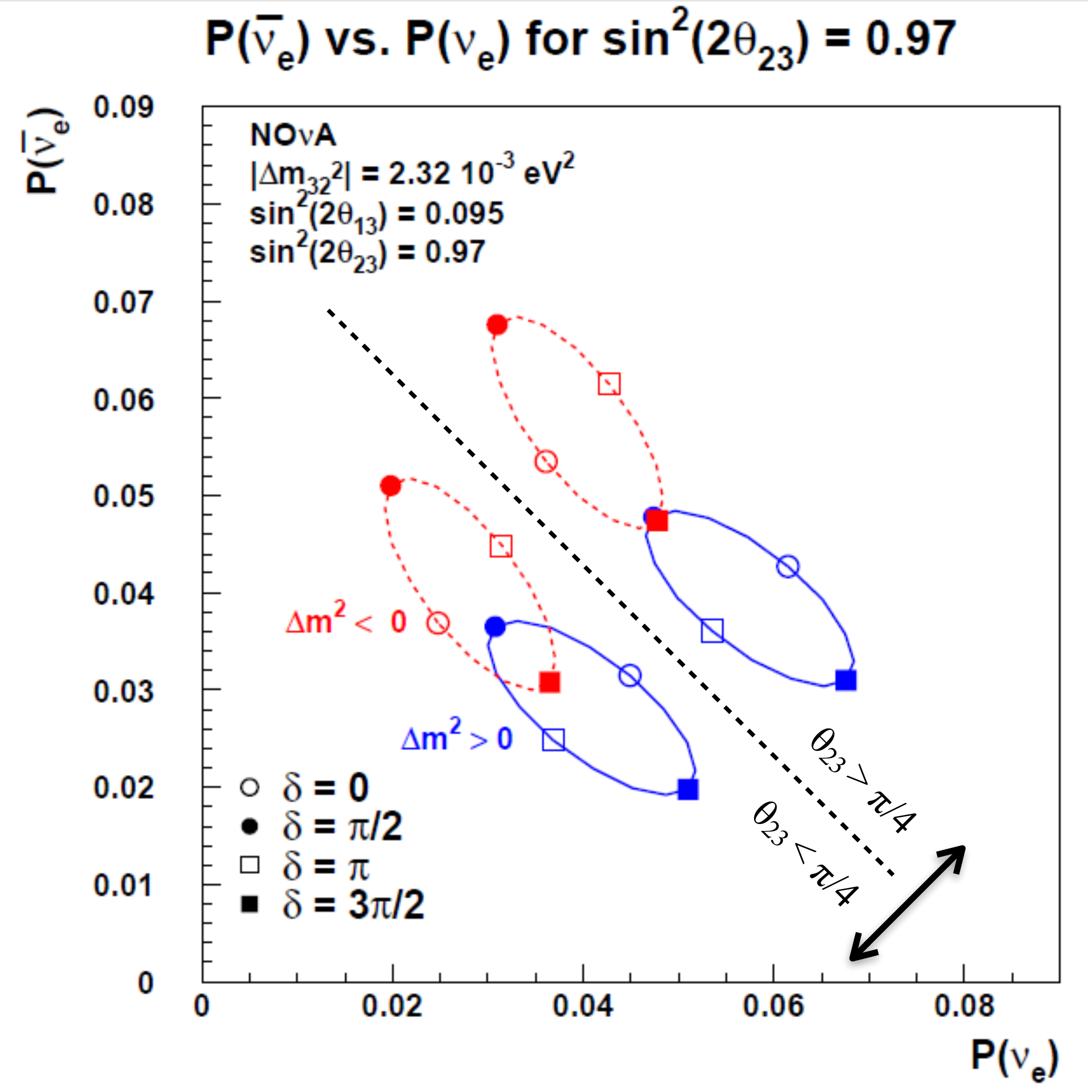
- *ν_μ disappearance largely sensitive to $|\Delta m^2|$*
- ν_e appearance is sensitive to sign(Δm^2) via matter effect
  - due to presence of electrons in matter

$\sqrt{2} G_F N_e 2E/\Delta m^2_{31}$

- ~30% effect for NOvA baseline, 11% for T2K

Shown for maximal θ_{23}

θ_{23} Octant

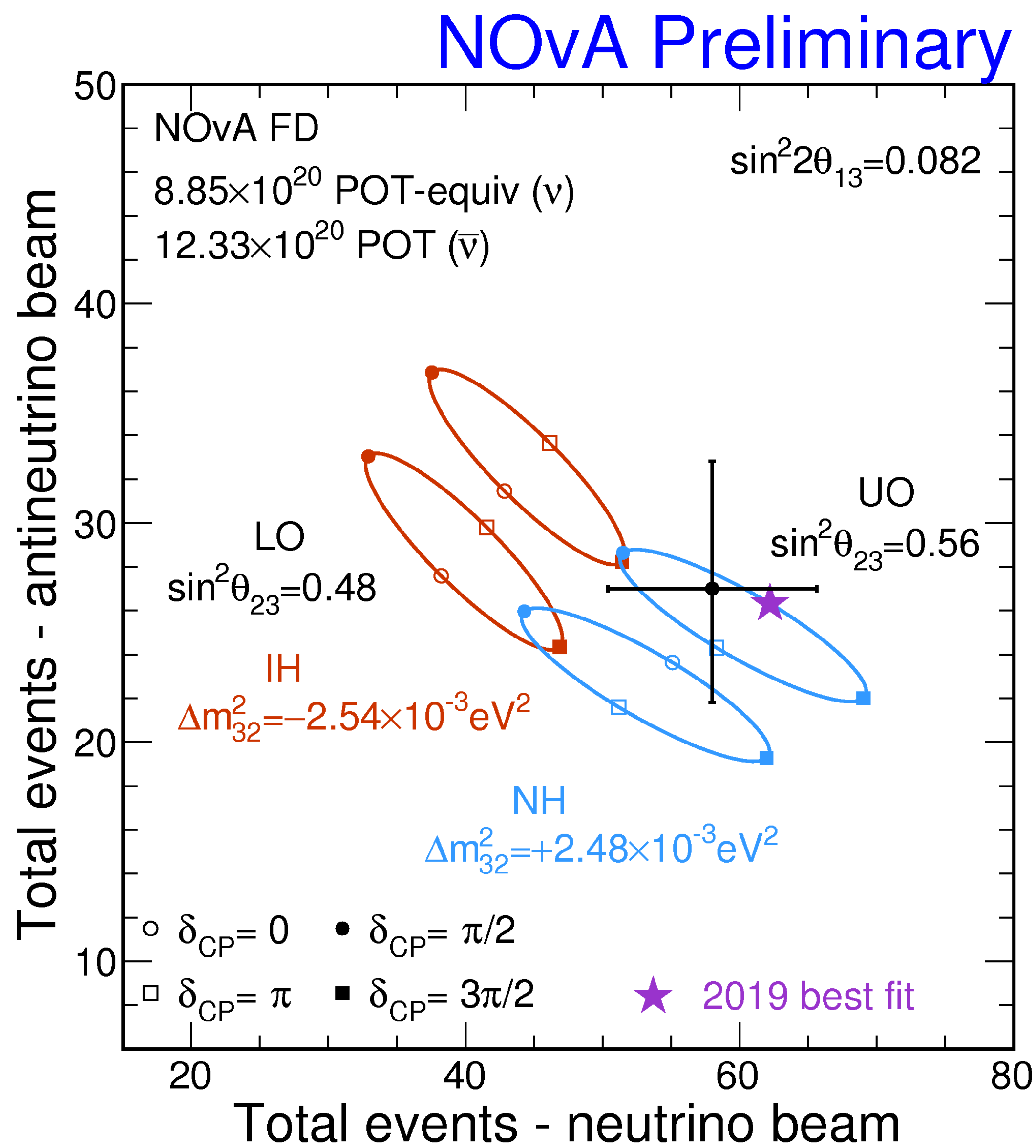


ν_μ disappearance measures $\sin^2(2\theta_{23})$

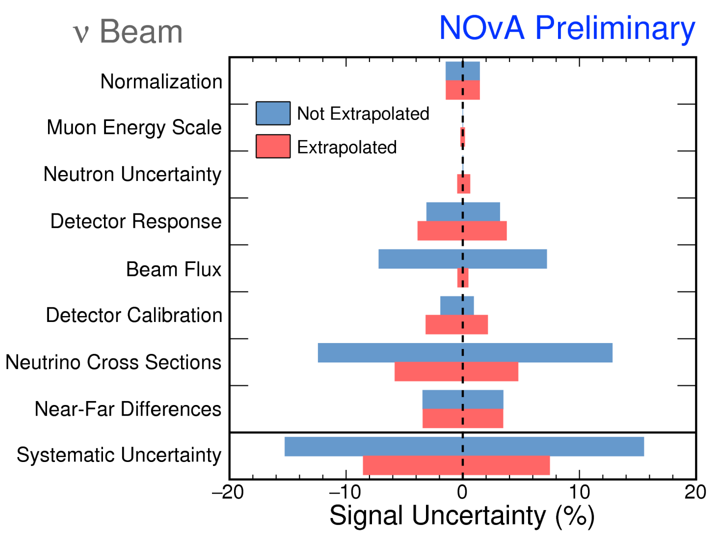
ν_e appearance depends in leading order on $\sin^2(\theta_{23})$

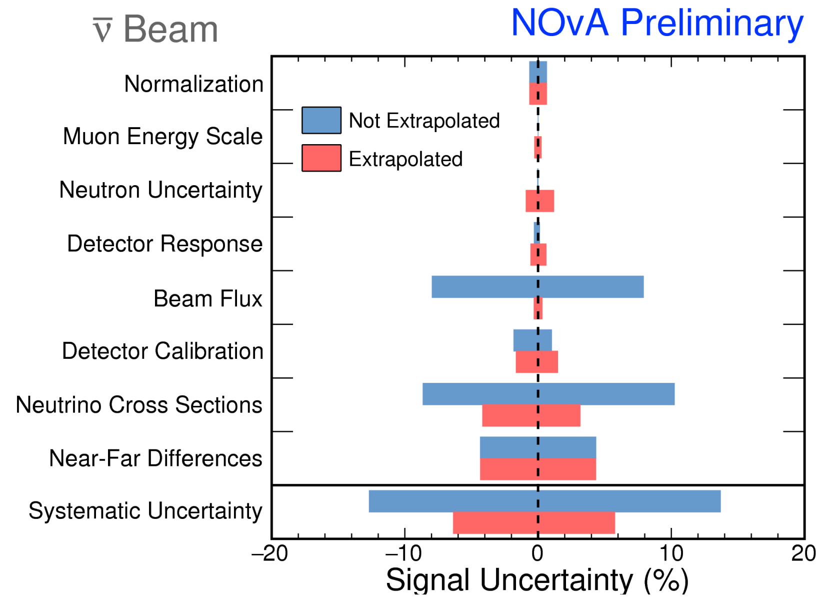
Bi-event rate plot

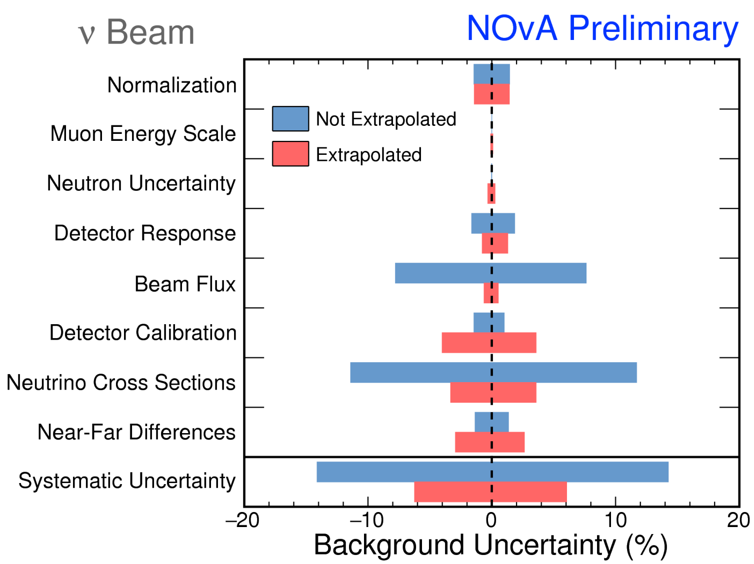
- *Caveat: this picture suppresses energy dependence and other useful variables*

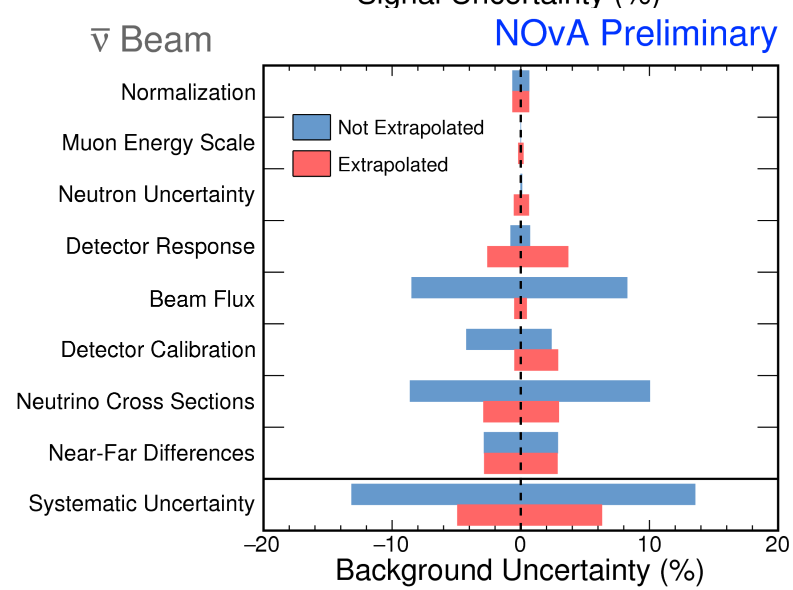


Effect of extrapolation on systematic uncertainties

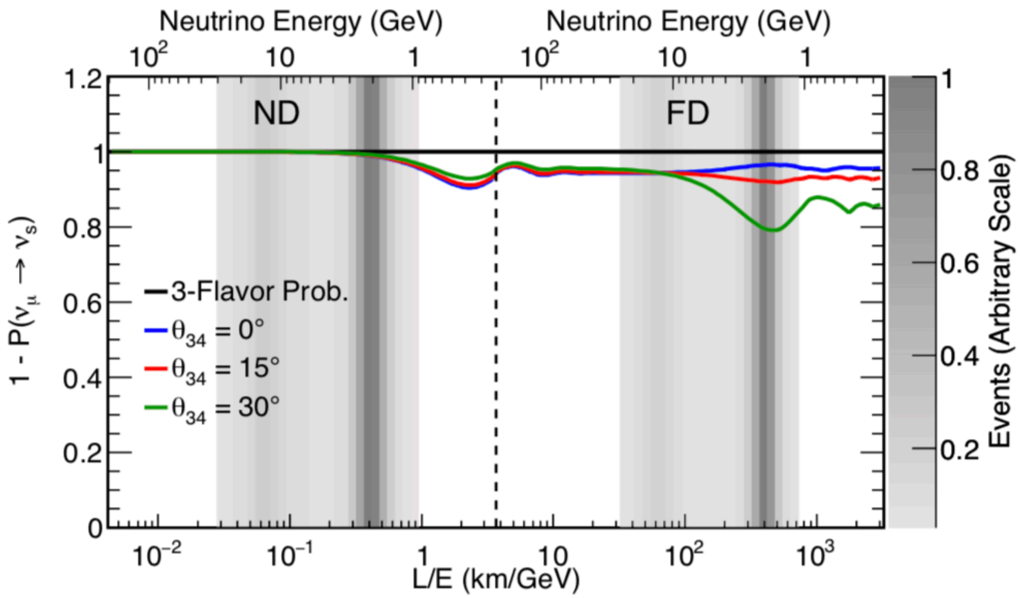


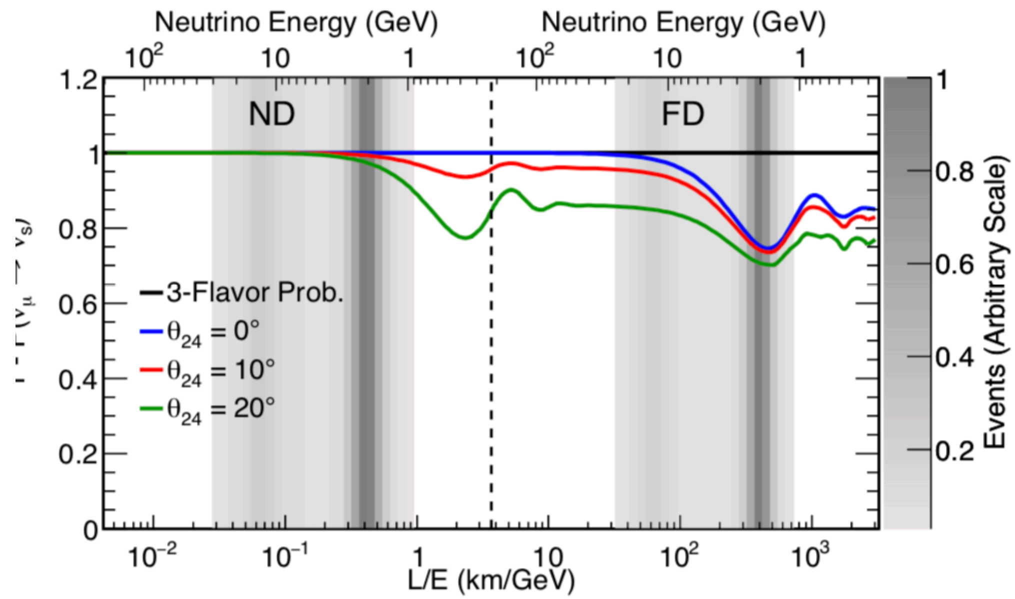




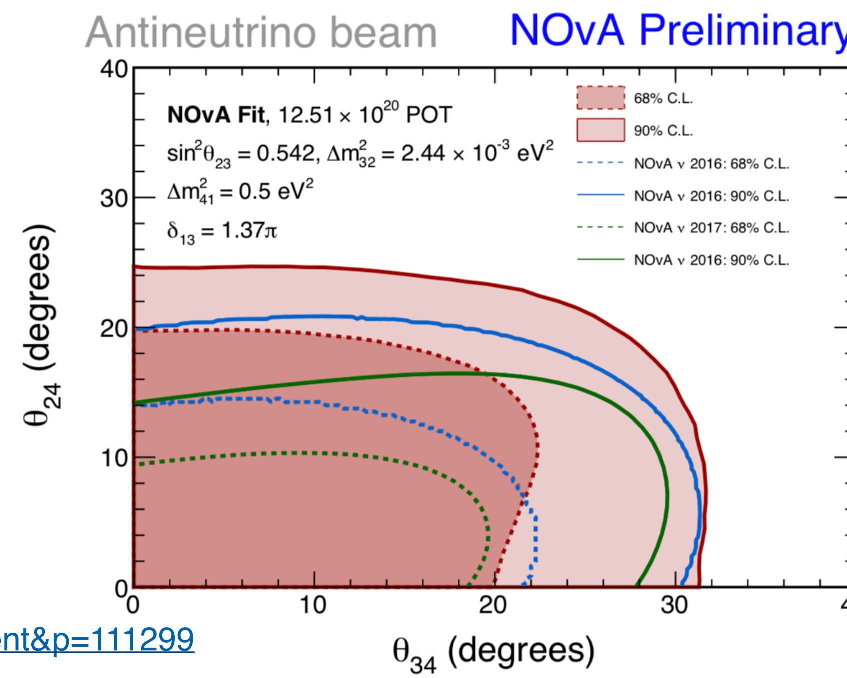


Long Baseline Sterile Neutrinos



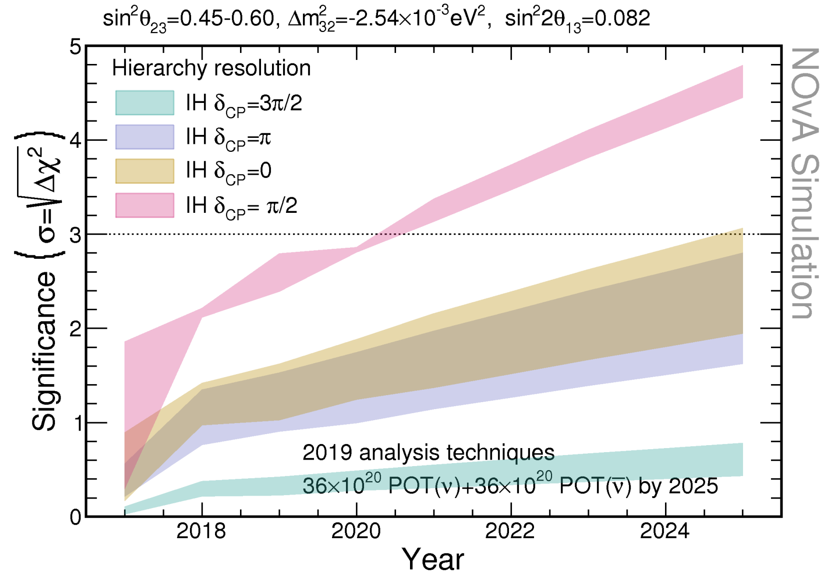


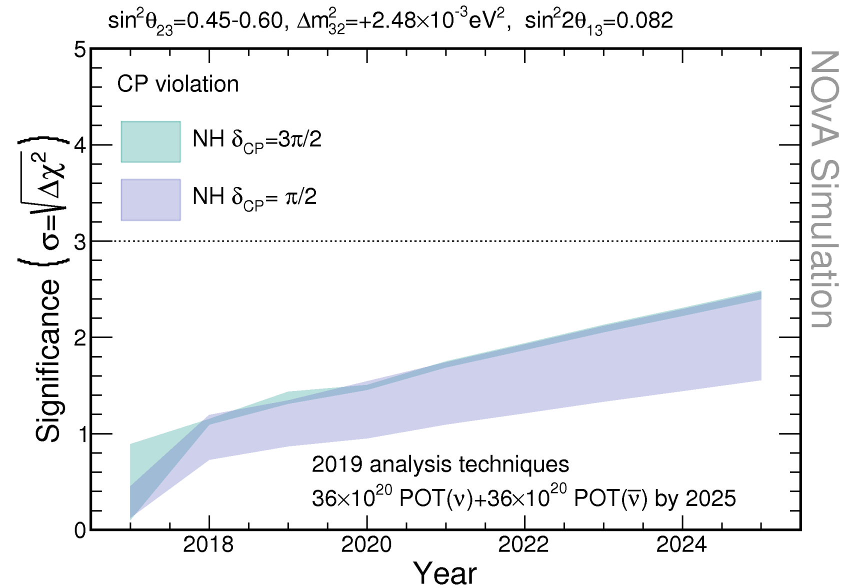
- Search for effector Sterile Neutrinos through disappearance of Neutral Current rate
  - NC = Sum of 3 active flavors
  - In 3+1 model, 3 new angles, 2 new phases, one new mass splitting
  - For now, only consider $0.05 eV^2 < \Delta m^2_{41} < 0.5 eV^2$
- New NOvA result with Antineutrino Beam

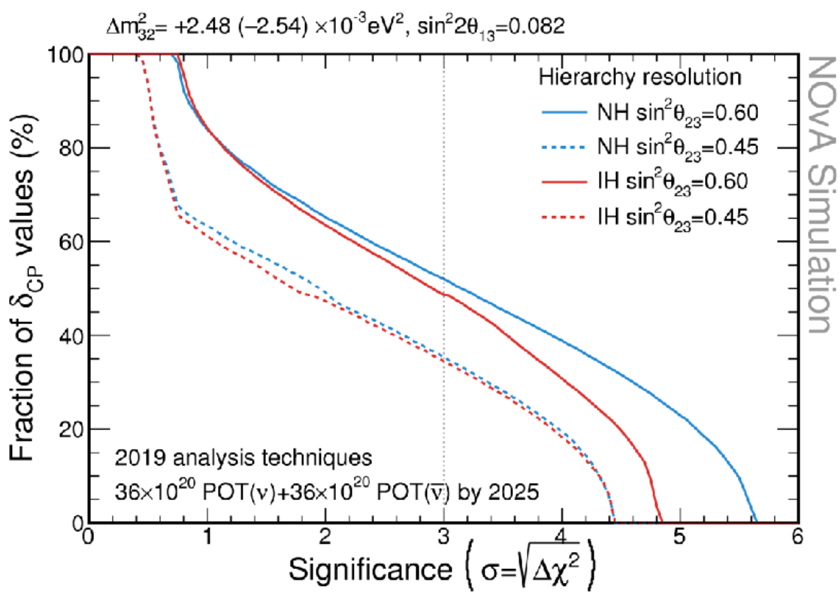


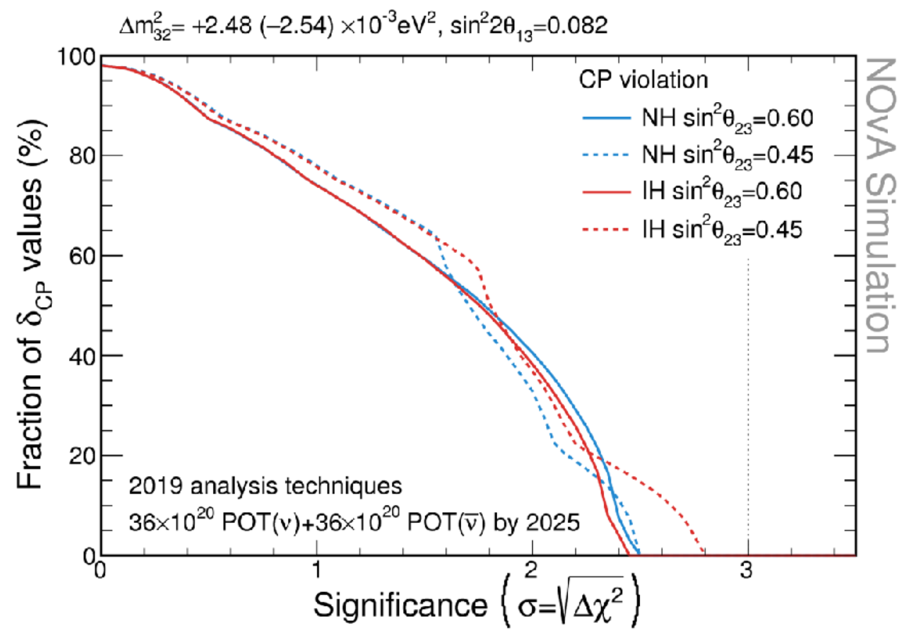
Fermilab "Wine & Cheese Seminar" http://theory.fnal.gov/?post_type=event&p=111299

More sensitivity projections









Sensitivity Projections for Maximal Mixing Rejection and Octant