The NOvA Physics Program

Peter Shanahan, for the NOvA Collaboration

Snowmass Neutrino Frontier Workshop

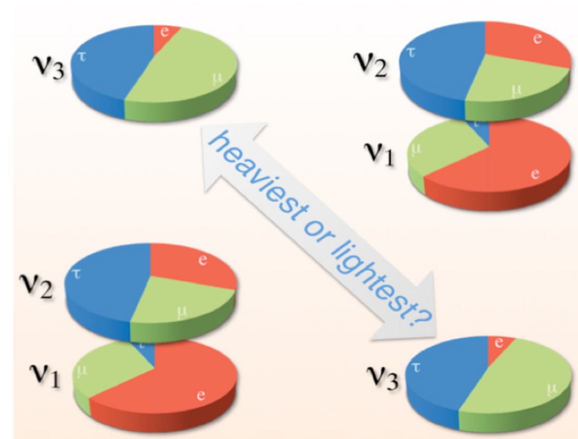
3 September 2020

In partnership with:

Physics with Long Baseline Neutrino Oscillations

- Structure of mixing
  - Is there a new symmetry driving equal ν_μ - ν_τ contributions to ν_3?
    - Maximal mixing, $\theta_{23}=45^o$, $\sin^2(\theta_{23})=0.5$
  - If not, does ν_3 have more ν_τ, or more ν_μ
    - Lower octant vs upper octant of θ_{23}

- Mass Hierarchy
  - Is ν_3 heaviest (normal) or lightest (inverted)?



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta} & c_{13}c_{23} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- CP Violation
  - $P(\nu_\mu \rightarrow \nu_e)$ and $P(\nu_\mu \rightarrow \nu_e)$ differ depending on value of CP violating phase of PMNS matrix, δ

- Is there more to the picture?
  - Is there evidence of oscillations to flavors not participating in Neutral Current interaction?
    - Sterile Neutrinos
  - Non-standard interactions? Etc.?

NOvA

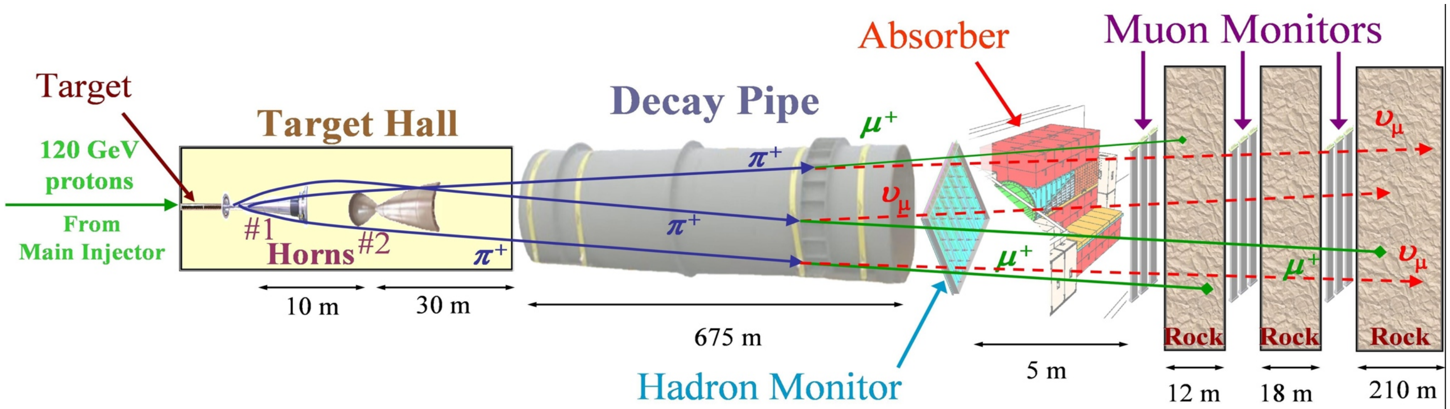
- Measure $\nu_\mu \rightarrow \nu_\mu$, $\nu_\mu \rightarrow \nu_e$, $\nu \rightarrow \nu$, for neutrinos and antineutrinos
  - Mass Hierarchy, Octant/Maximal Mixing, CP Violation
  - Search for phenomena outside 3-flavor mixing framework
    - Sterile Neutrinos, NSI
- Measure sub-dominant (P~0.05) $\nu_\mu \rightarrow \nu_e, \bar{\nu}_\mu \rightarrow \bar{\nu}_e$ 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

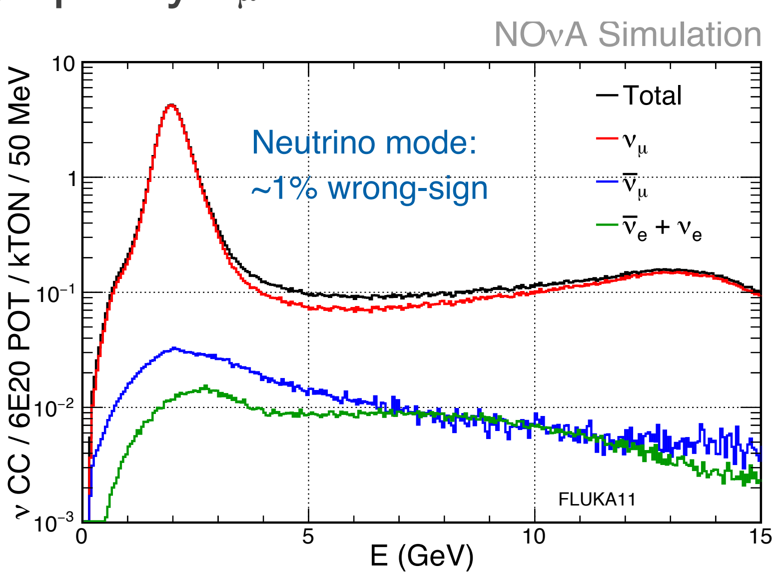
- 200 Collaborators from 50 institutions in 7 countries.
- 24 Remote Operations Centers worldwide.

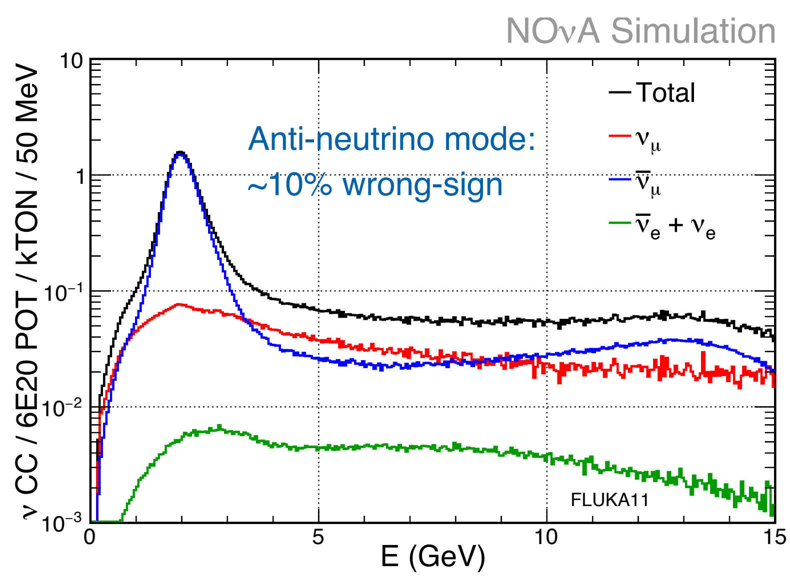
NuMI Beam

- 700 kW design power: O(10^6) ν delivered to Far Detector every 1.2 seconds

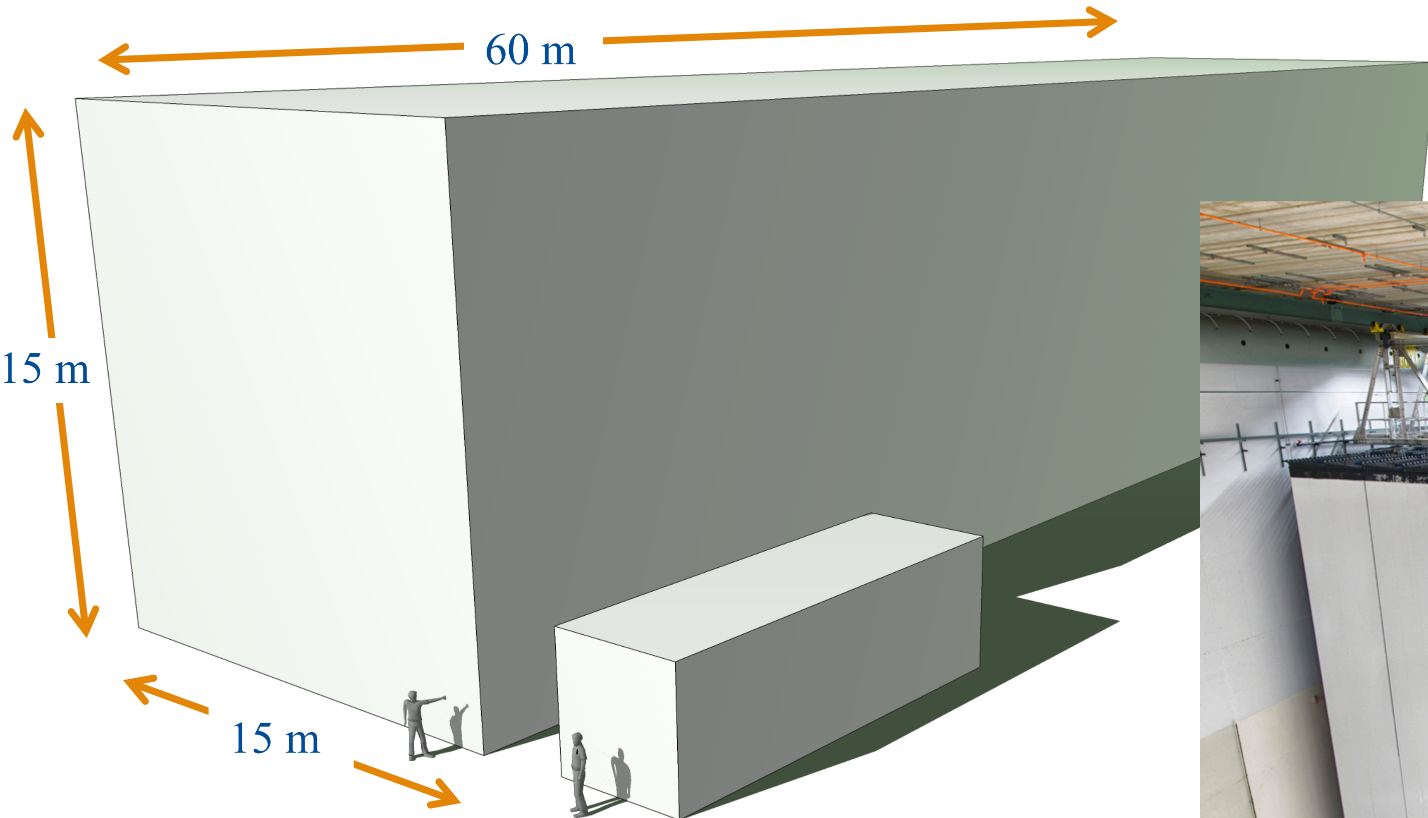


- ν and $\bar{\nu}$ beam modes selected by polarity of focusing horn current
- High purity ν_μ content

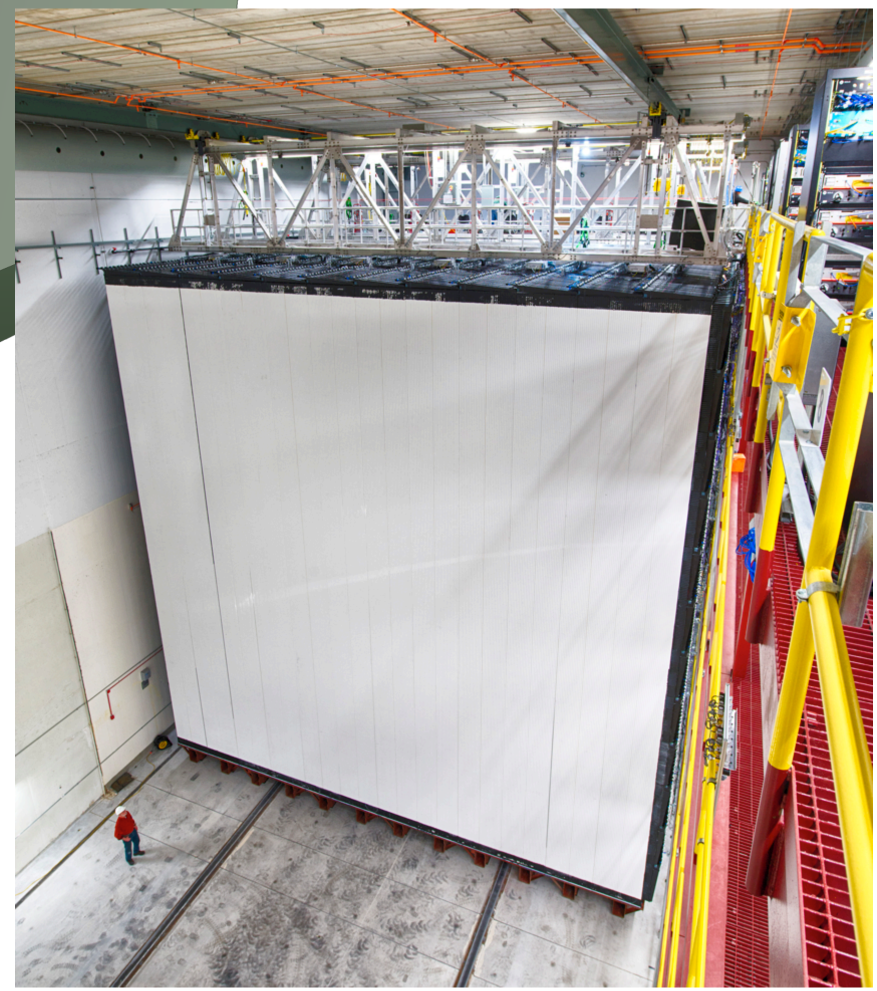




NOvA Detectors



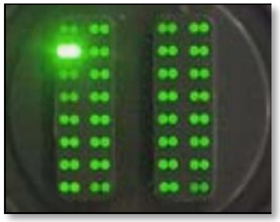
- Far Detector (FD) in Ash River, MN
  - 14 kt, 896 planes

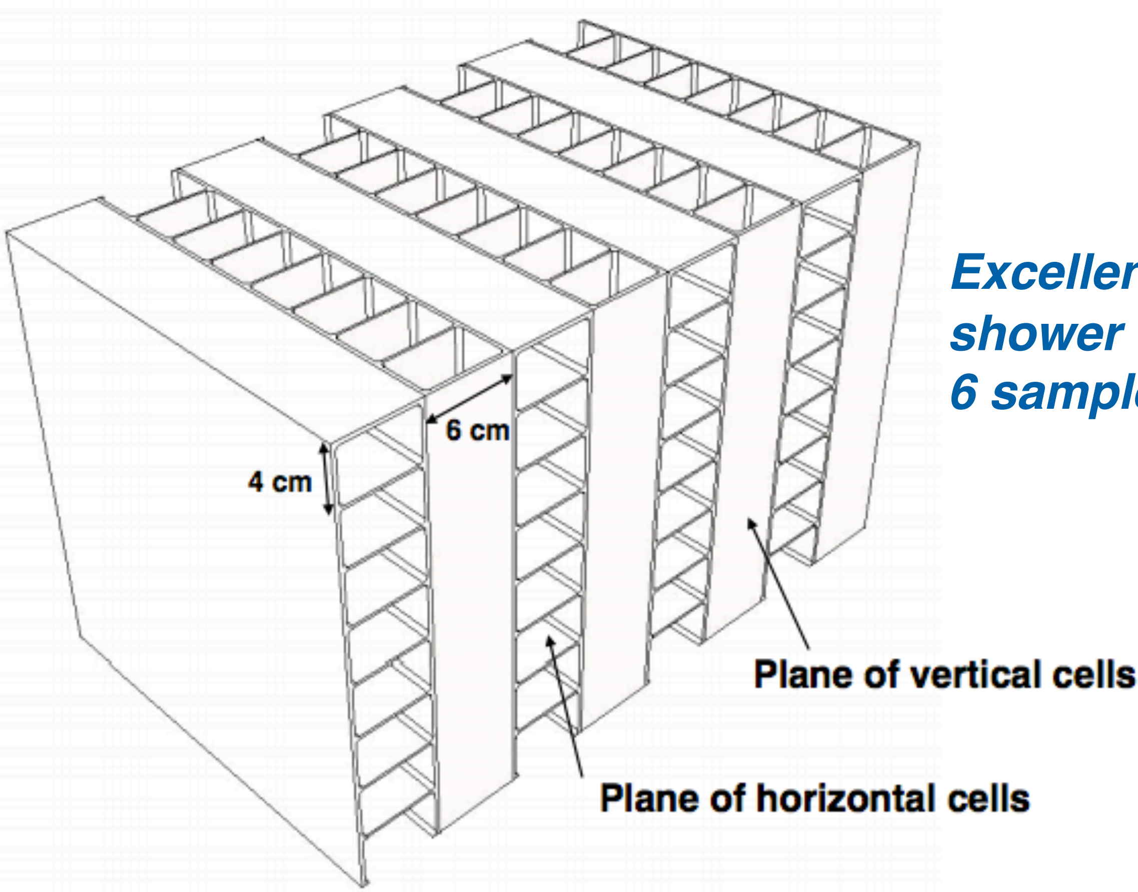


- Near Detector (ND) at Fermilab
  - 293 tons, including muon catcher
  - used to measure neutrino beam flavor and energy spectrum before oscillations

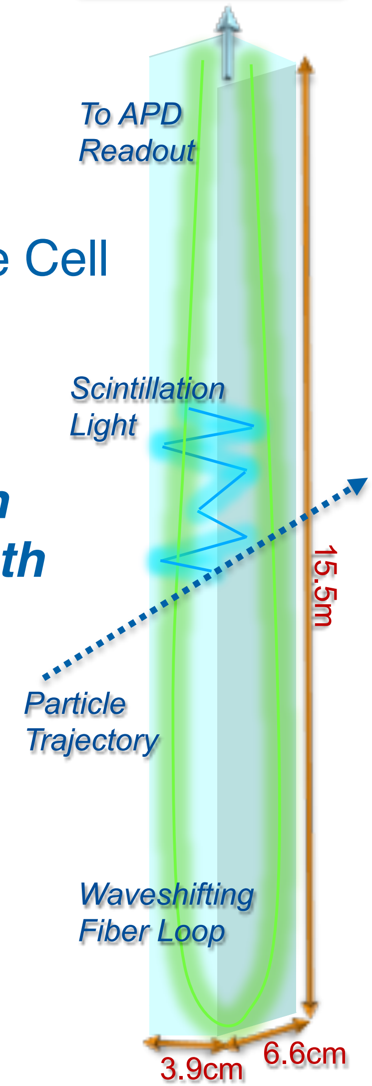
NOvA Detector Technology

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



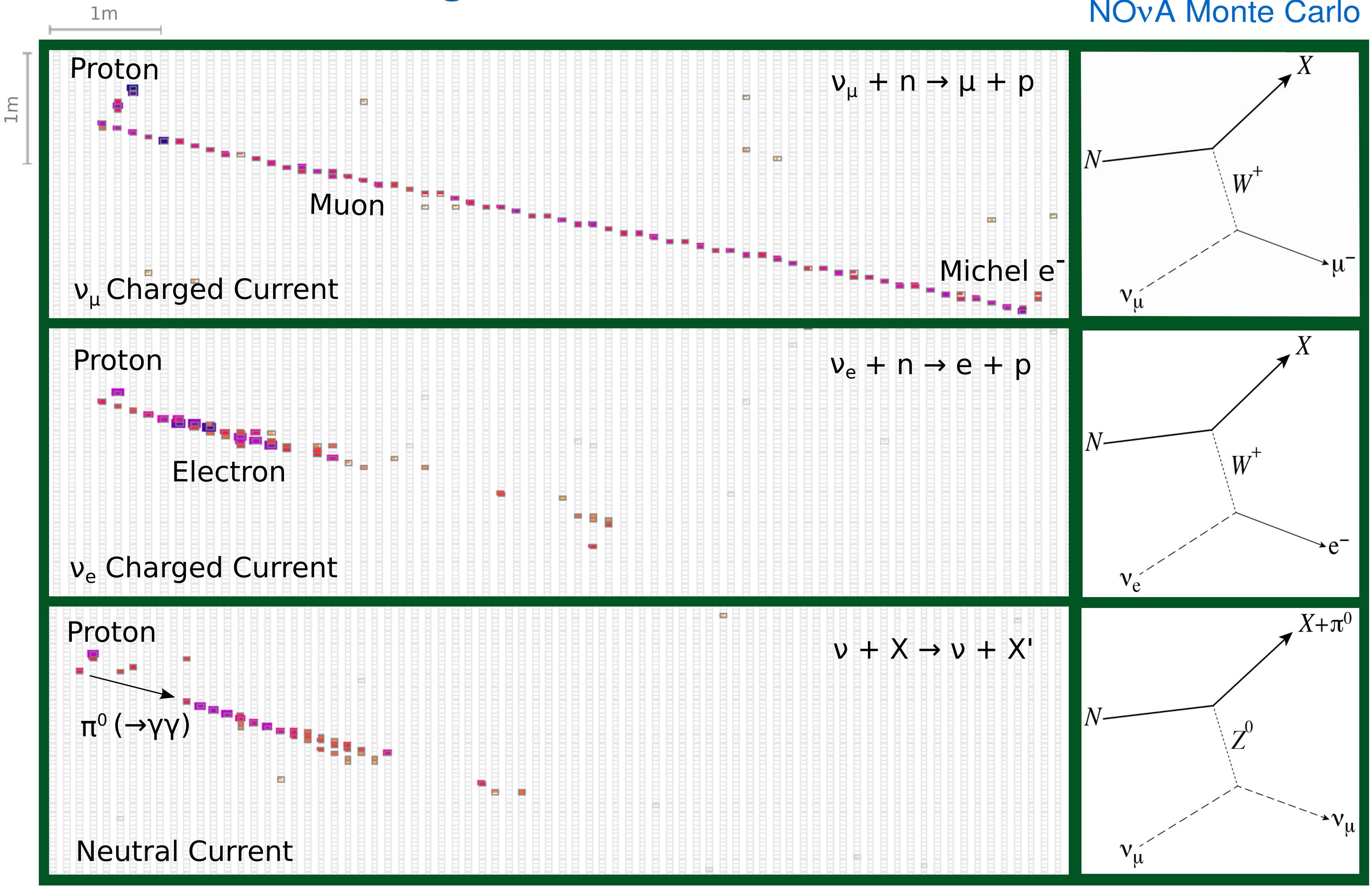


Excellent electromagnetic shower characterization with 6 samples per radiation length



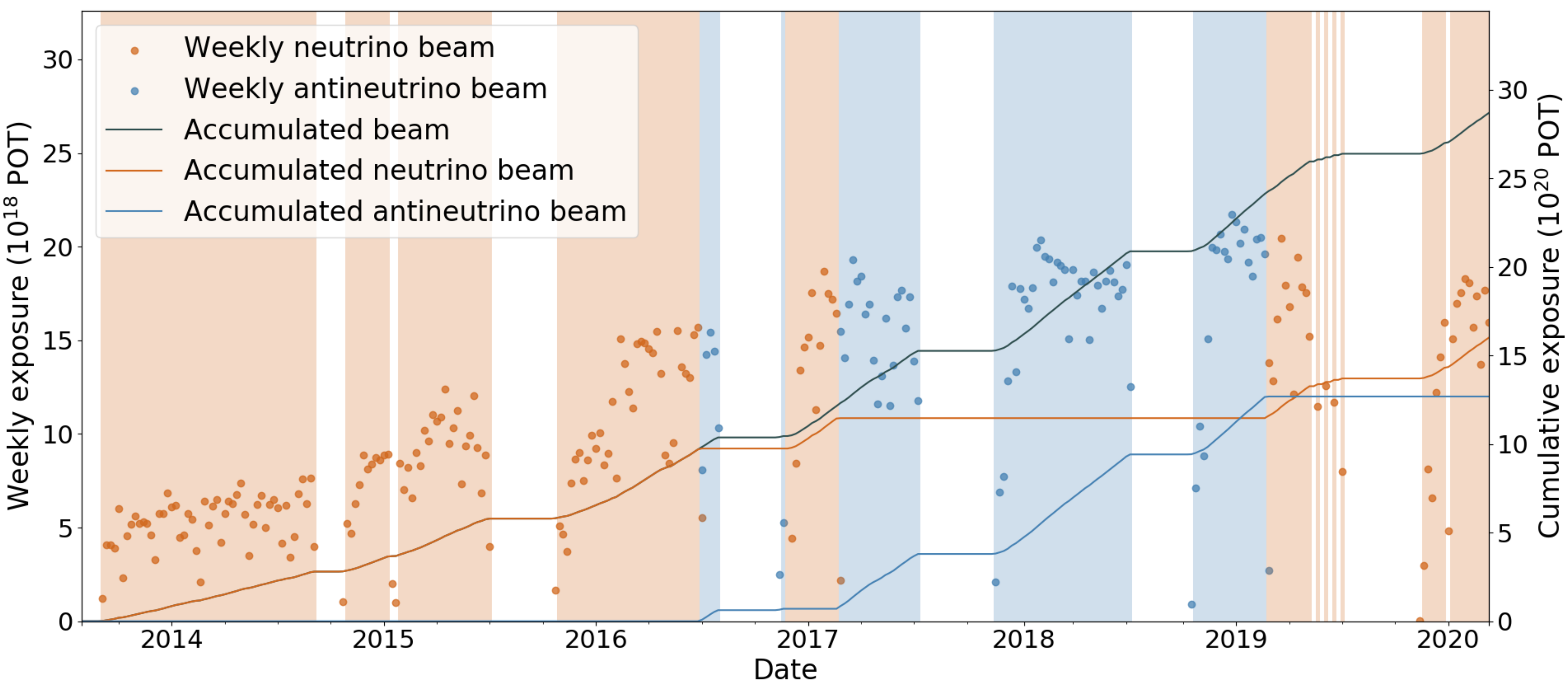
NOvA Detector Design

NOνA Monte Carlo



Data-Taking since 2014

- Far Detector Beam Data Set To Date: Protons-on-target (POT) to NuMI
  - 13.6×10^{20} (14 kt-equivalent) POT Forward Horn Current (neutrino beam)
  - 12.7×10^{20} POT in Reverse Horn Current (antineutrino beam)
- 756 kW hourly beam power record achieved



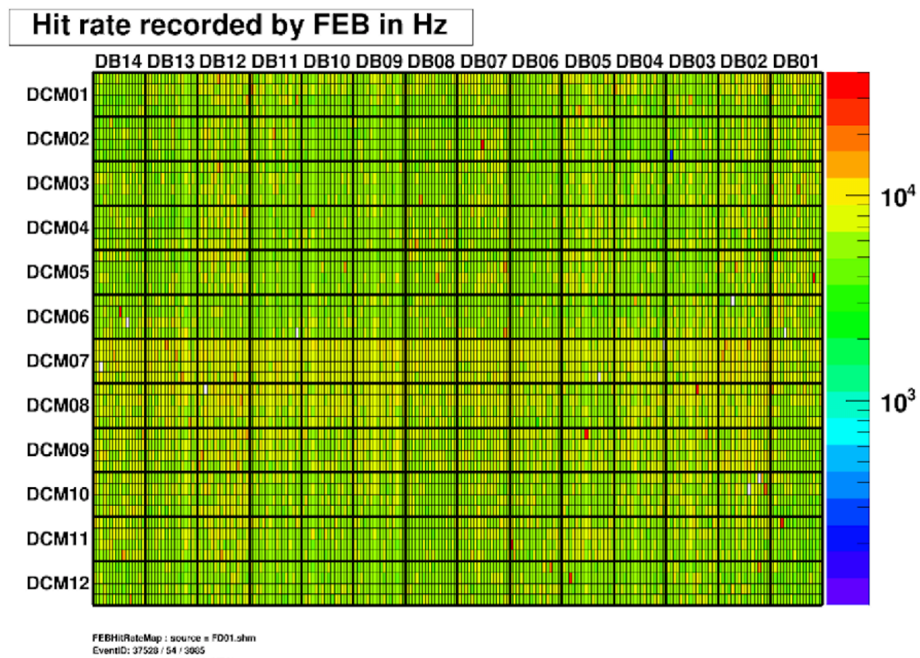
NOvA Milestones

- History
  - First meeting in 2002, collaboration formed in 2004.
  - DOE Project for Detectors & Accelerator/Beam Upgrades 2005-2014
  - Physics data started Feb. 2014, first result 2015.
  - 700 kW beam power achieved in Jan. 2017
- Multiple rounds of 3-flavor oscillation results, with increasing levels of sophistication
  - 1st use in HEP of particle-ID based on convolutional neutral network
  - Strongest evidence (4.4 sigma) for long-baseline electron antineutrino appearance
- Results in cross-sections, sterile neutrino limits, cosmic rays and astrophysics
- Publications
  - 10 Published
    - 3-flavor oscillations using neutrinos and antineutrinos, PRL 123 (2019) 15, 151803
    - Search for Multi-messenger Signals, PRD 101 (2020), 112006
    - Neutral current coherent π^0 production, PRD 102 (2020), 012004
  - 1 Accepted for publication
    - Supernova Neutrino detection in NOvA
  - 1 in journal review
    - Cross-section model tuning, arXiv:2006.08727
- 37 Ph.D.s awarded

NOvA Operations

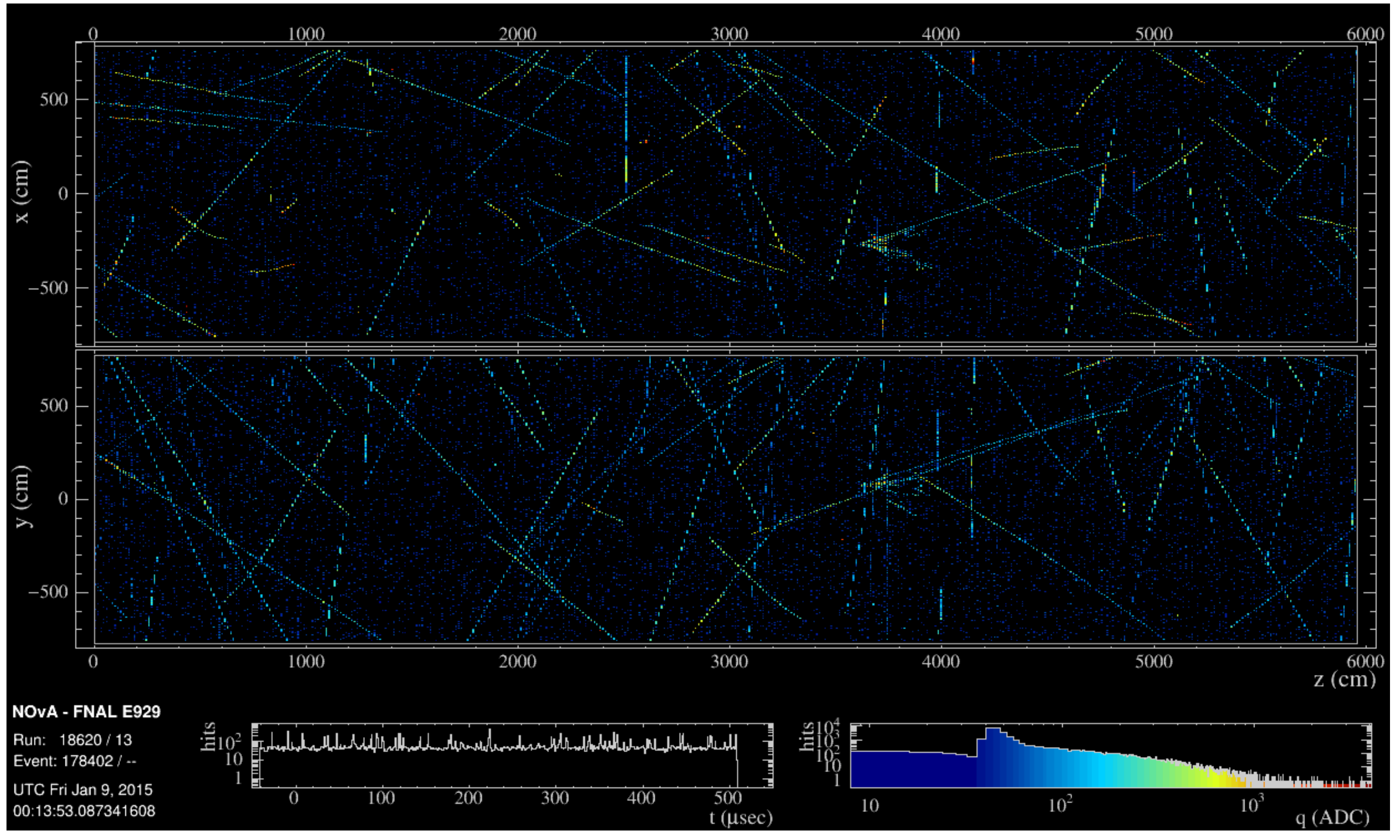
- Shifts taken and expert support provided 24x7 from 25 Remote Operations Centers around the world
  - During Covid-19, web-based shifts run from home
- Far Detector and Laboratory Maintained and Operated by University of Minnesota
- Far Detector annual beam-weighted uptime typically above 99%

99.9% of 344,064 channels are typically active



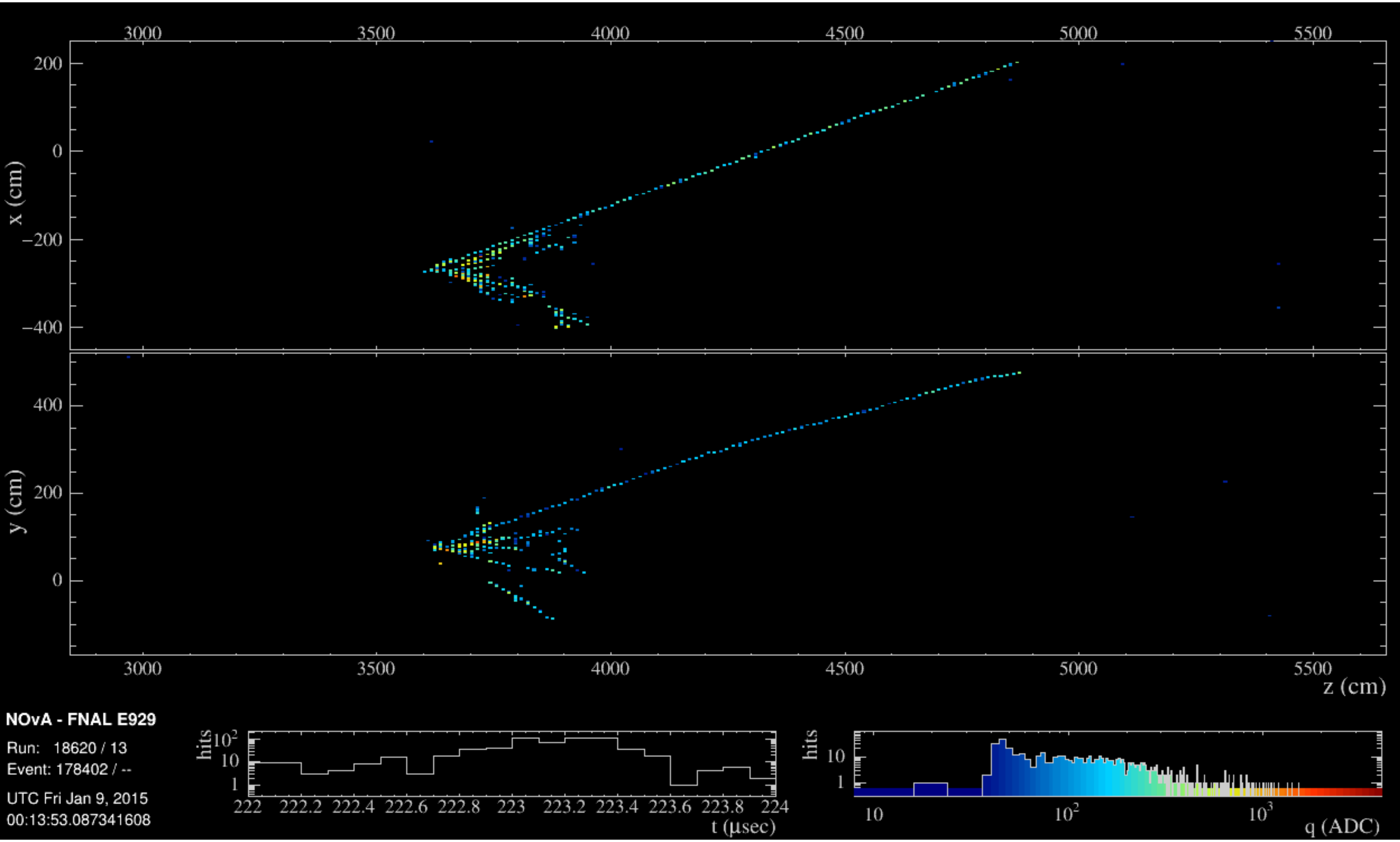
NOvA Event Selection - Cosmic Ray Rejection

- 1st long-baseline neutrino experiment on the surface
  - Effective cosmic ray rejection is critical



  - 6 orders of magnitude rejection achieved with cuts and algorithms using lepton and event characteristics, directions, etc.
- Characterizing remaining background is also important
  - NOvA takes ~50x beam data in beam triggers, and another ~500x in periodic cosmic triggers

Zoom-in: ν_μ candidate event



NOvA Event Selection - Deep Learning

- Convolutional Neural Networks: fully exploit detail of NOvA events.
  - NOvA's Convolutional Visual Network was pioneering use of Deep Learning in HEP.
  - Improvement in signal & background for ν_e was equivalent to 30% increase in exposure.

Aurisano et al., 2016 JINST 11 P09001

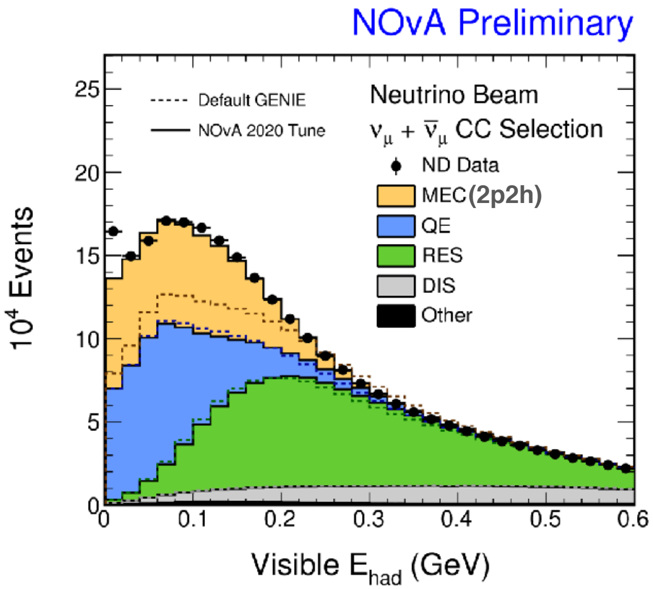
- We continue to gain improvements from Deep Learning in NOvA.
  - Ongoing progress in application of different network types and specific applications.
  - Networks developed for individual prong ID, energy estimation, hit clustering, etc.

3-flavor Oscillation Analysis - Using the Near Detector

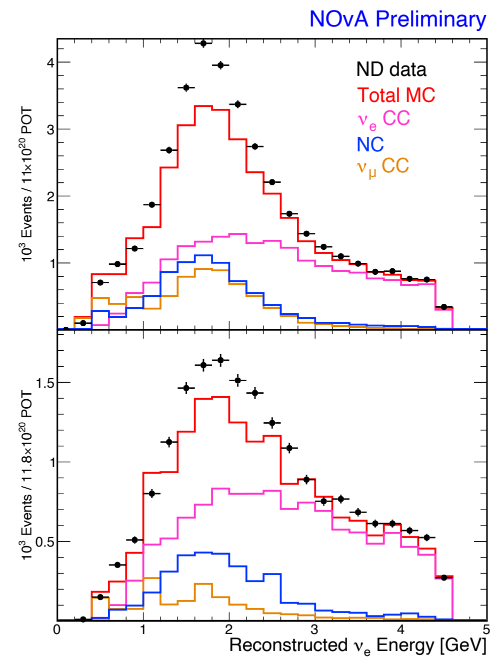
Use ND ν_μ and $\bar{\nu}_\mu$ data to tune custom GENIE 3.0.6 CMC

Importance of multi-nucleon scattering (2p2h) was an early surprise for NOvA

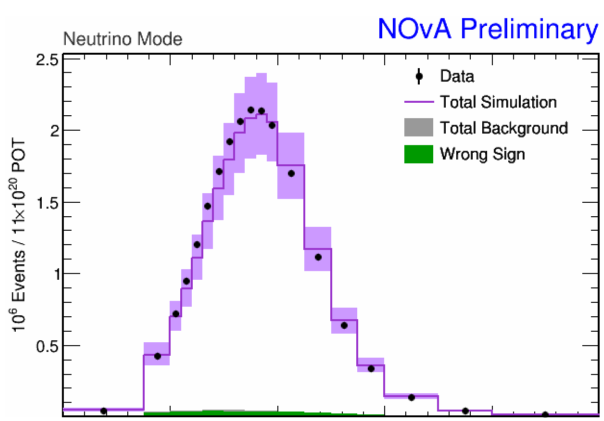
Several cross-section tuning iterations, including as described in arXiv:2006.08727

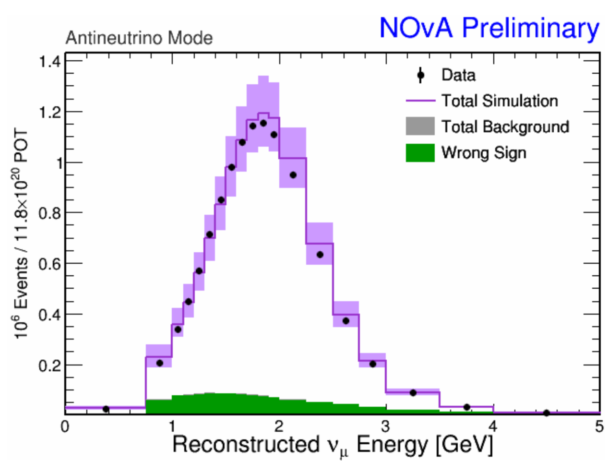


Use ND ν_e-like spectra to improve Far Detector ν_e background prediction.



Use ND ν_μ spectra to improve FD ν_μ and ν_e signal predictions

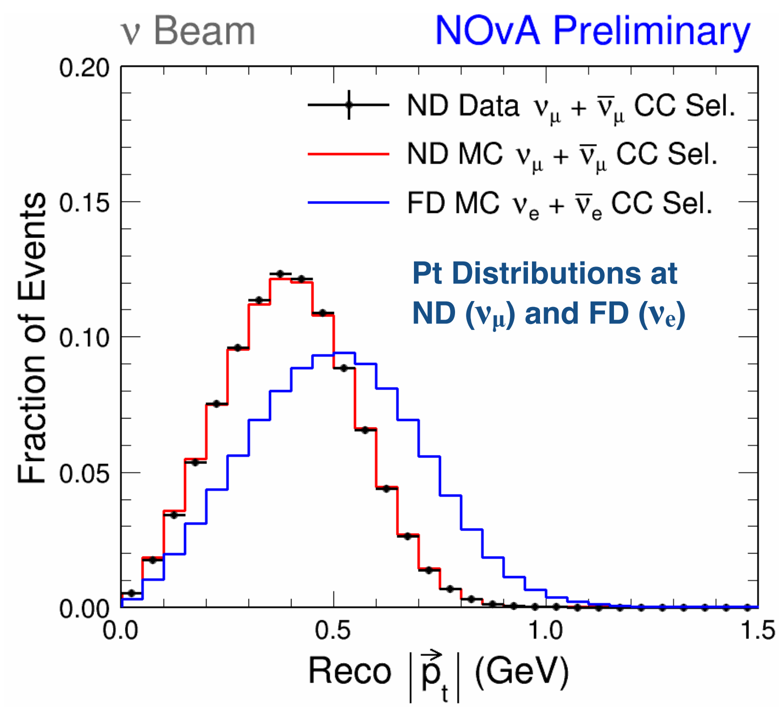




Extrapolation

- Original extrapolation
  - Adjust energy distribution to match ND MC to data, apply same adjustment to FD.

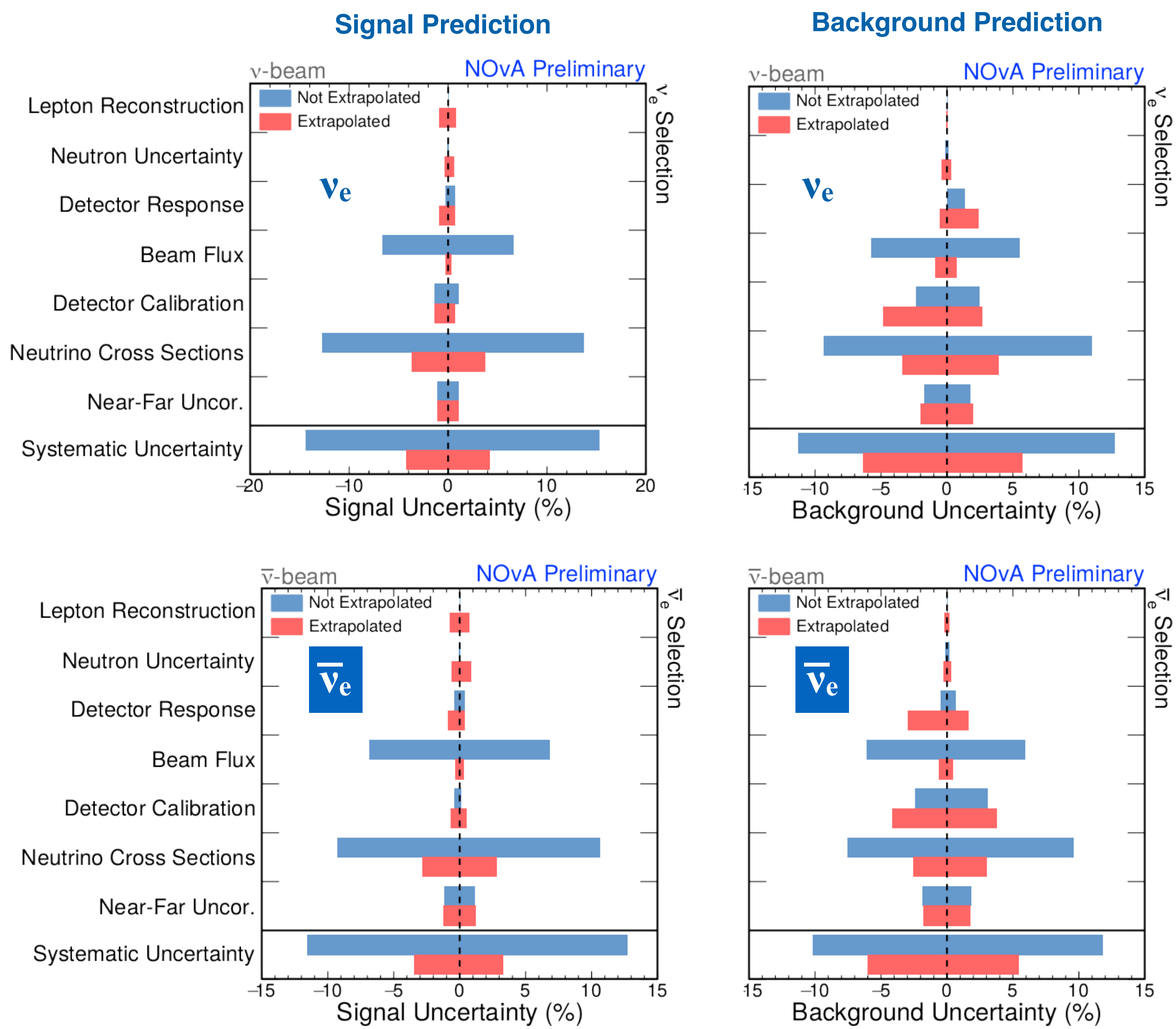
- Improvements
  - Extrapolate and fit ν_μ in bins of reco. hadronic energy fraction (2018)
    - Improves sensitivity of ν_μ fit by grouping events by energy resolution.
    - Improves cross-section uncertainties by isolation of different cross-section effects.
  - Extrapolate in bins of reco. lepton P_t.
    - Improved robustness with respect to effect of ND-FD acceptance differences on neutrino interaction modeling uncertainties.



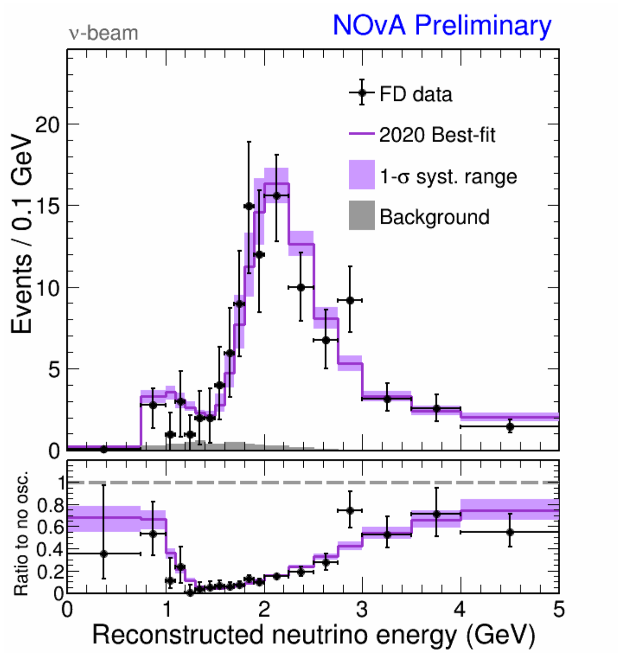
Systematic Uncertainties

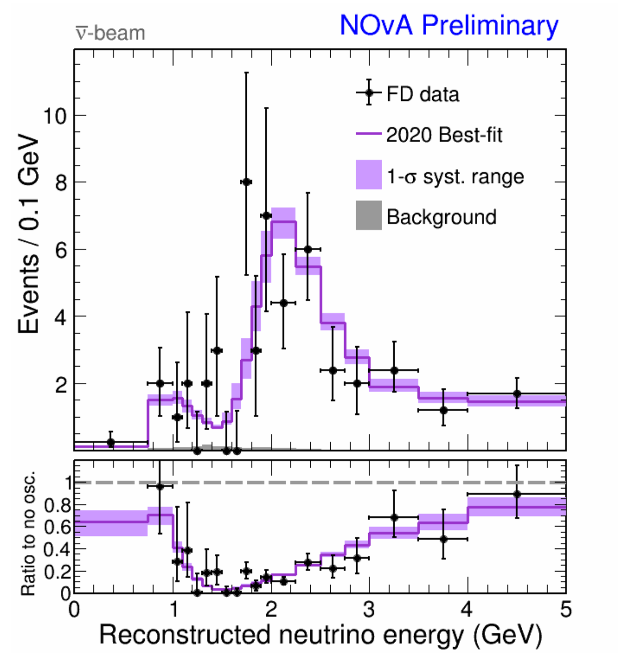
Systematic uncertainties are evaluated by modifying simulation throughout analysis chain.

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



Far Detector Data and Oscillation Fit

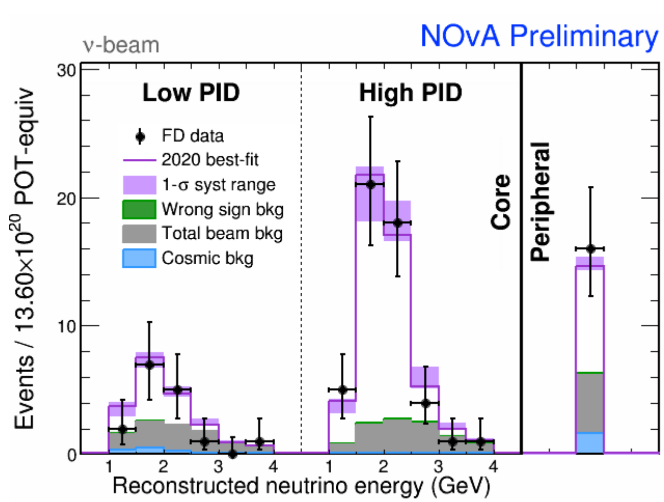


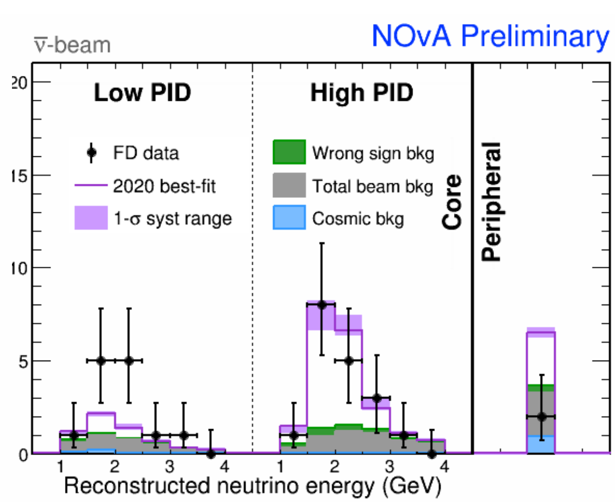


Muon Neutrino Disappearance

	Neutrino	Antineutrino
Observed	211	105
No Disappearance	1156	488
Best Fit Expectation	222	105
Background	8.2	2.1

ν_μ and ν_μ spectra fit in bins of hadronic energy fraction and reconstructed energy



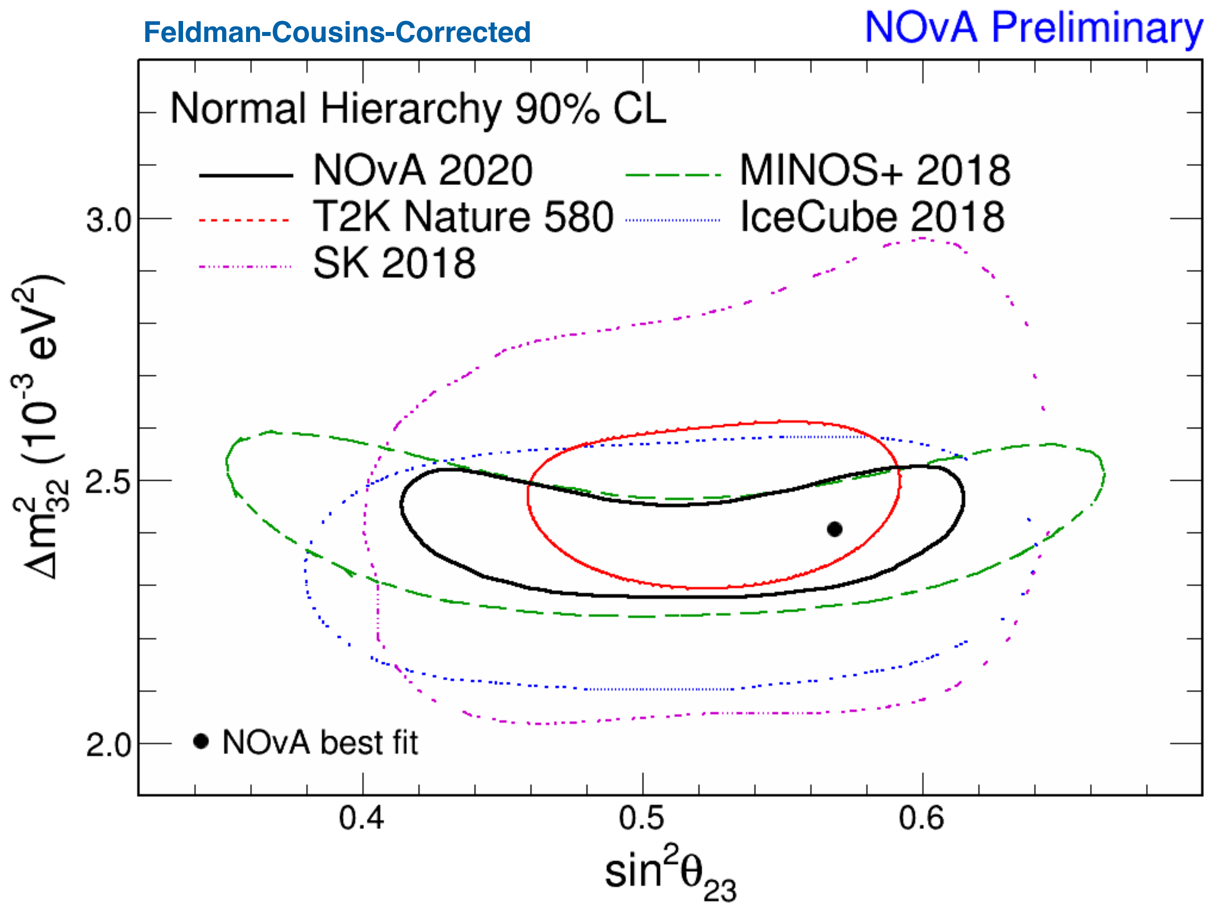


Electron Neutrino Appearance

	Neutrino	Antineutrino
Observed	82	33
Best Fit Expectation	85.8	33.2
Background	26.8	14.0
Wrong-sign	*1.0*	*2.3*
Beam bkgd.	*22.7*	*10.2*
Cosmic bkgd.	*3.1*	*1.6*

ν_e and ν_e spectra fit in bins of selection purity and reconstructed energy

Oscillation Parameters from Joint Fit to Data



Precision measurements of Δm^2_{32} (3%) and $\sin^2\vartheta_{23}$ (6%).

Best Fit

Normal hierarchy

$\Delta m^2 = (2.41 \pm 0.07) \times 10^{-3}$ eV^2

$\sin^2\theta_{23} = 0.57^{+0.04}_{-0.03}$

$\delta = 0.82\,\pi$

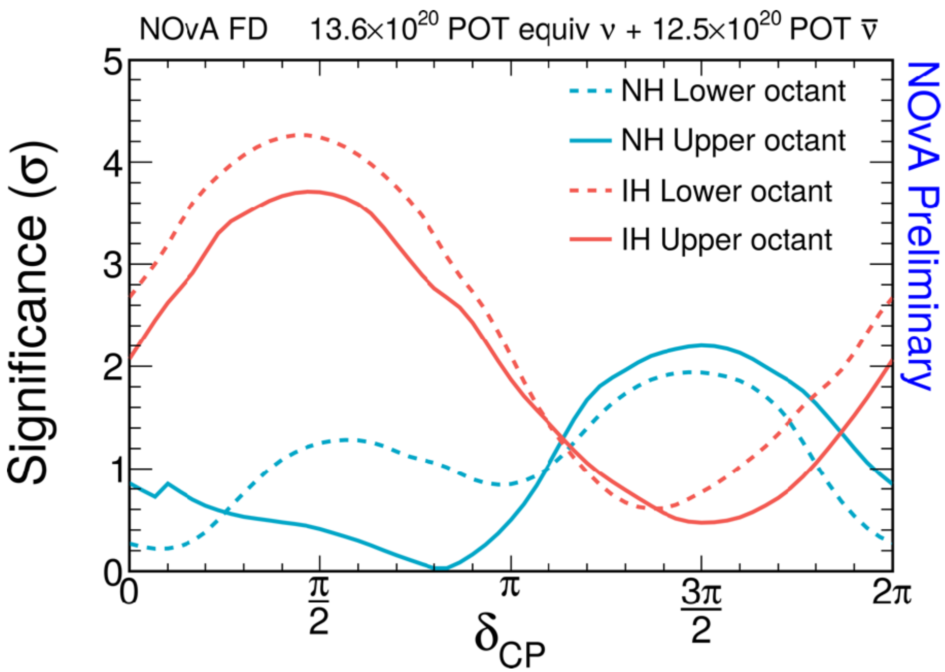
Experiments are in good agreement.

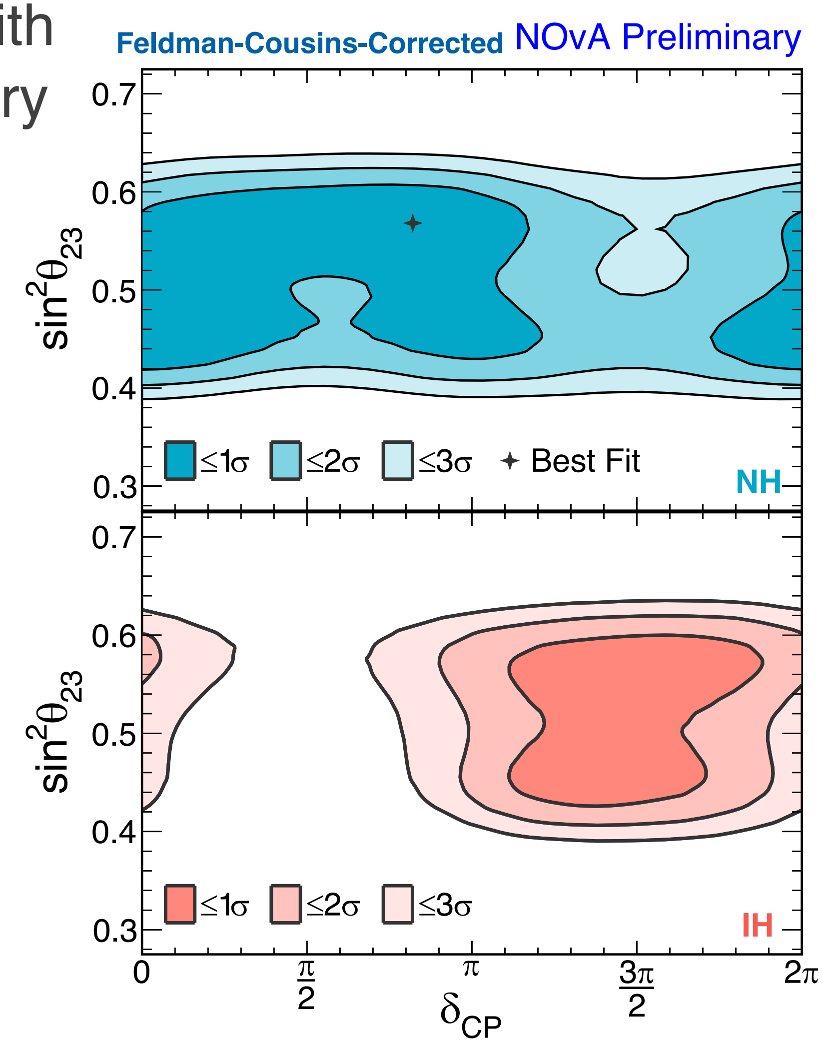
Note: plot does not reflect latest contours from other experiments

Oscillation Parameters from Joint Fit to Data

- Slight (1 sigma) preference for normal hierarchy, upper octant of θ_{23}
- Disfavors combinations of MH and δ_{CP} with strongest neutrino-antineutrino asymmetry in $\nu_\mu \rightarrow \nu_e$ appearance
  - IH + $\delta_{CP} \sim \pi/2$ at > 3 sigma
  - NH+ $\delta_{CP} \sim 3\pi/2$ at > 2 sigma

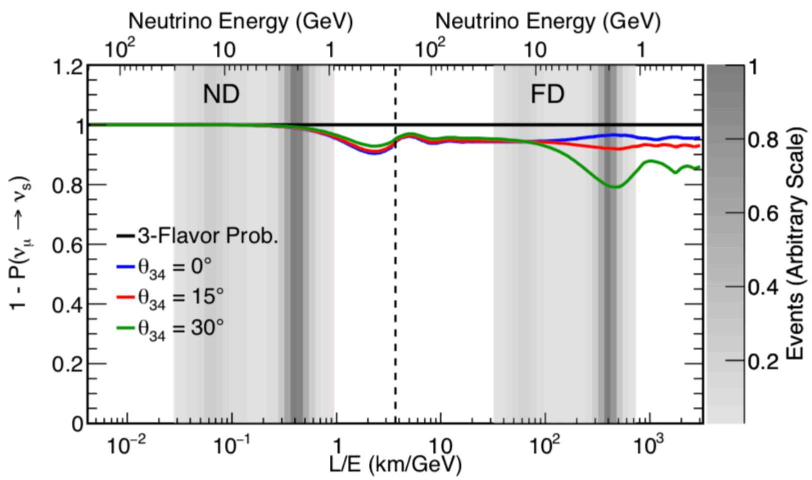
Using θ_{13} from world reactor data.

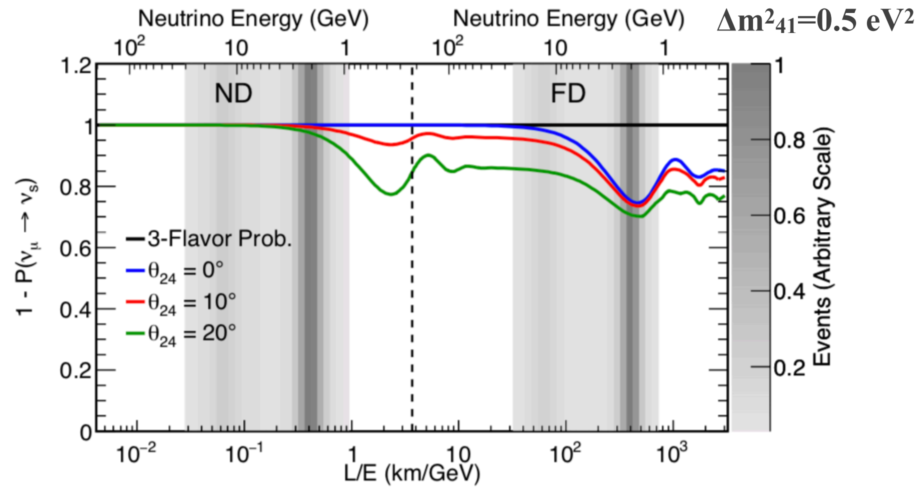




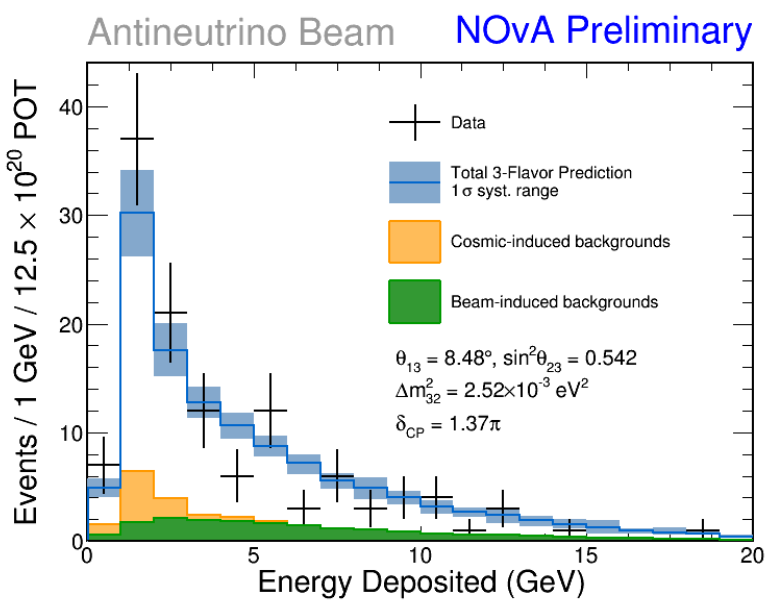
Non-Standard Flavor-Change Phenomena

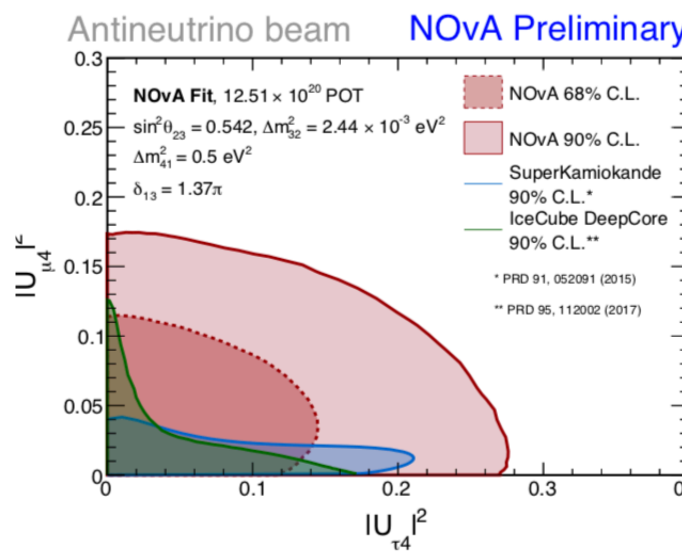
- NC is sensitive to disappearance from 3 active neutrinos - mixing with sterile





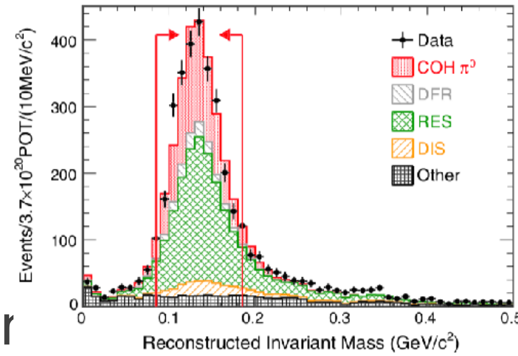
Limits on 3+1 mixing parameters set with both neutrino and antineutrino mode.





NOvA Cross-Section Physics

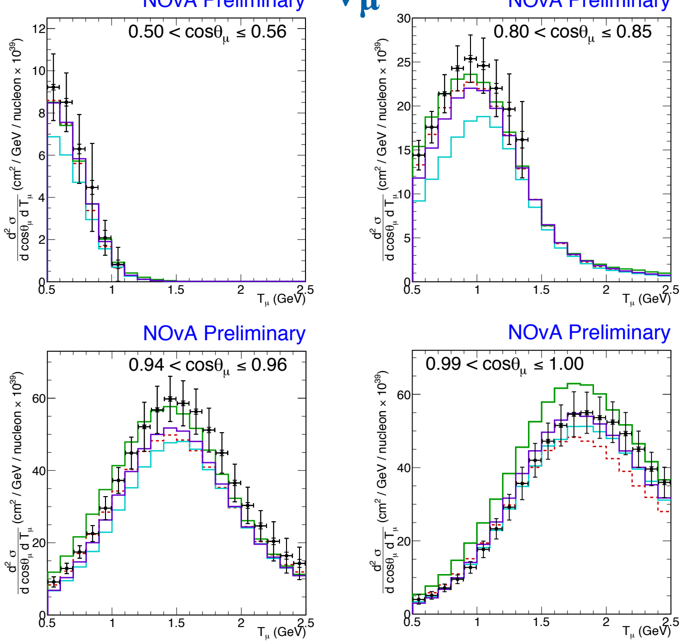
NC Coherent π^0 Production

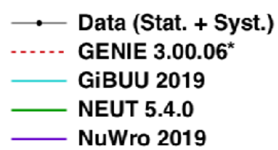


Phys. Rev. D 102 (2020) 012004

- Unique capabilities provided by
  - Narrow-band beam at 2 GeV
  - High-rate of interactions at Near Detector
  - High-purity neutrino and antineutrino modes
- Double-differential inclusive cross-section measuremer
  - ν_μ - more than 1x10^6 events
  - ν_e - more than 10,000 events in sample - first double-differential measurement

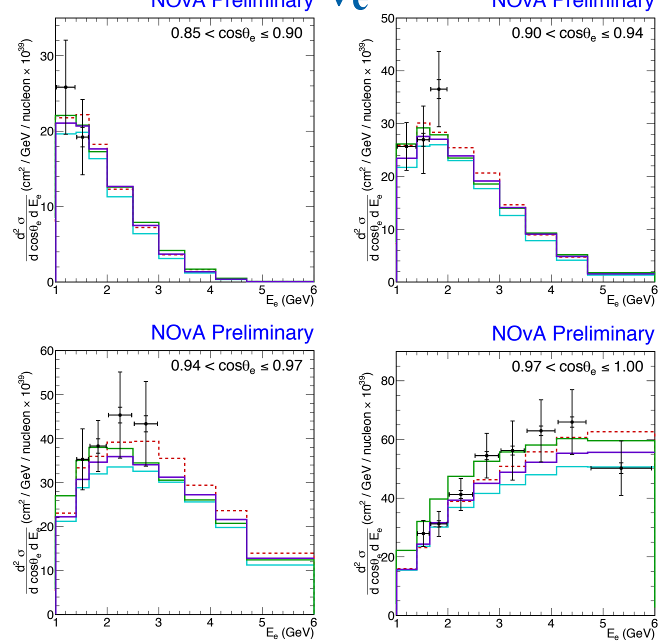
ν_μ





For ν_μ, sample of 4 bins in lepton angle out of 13

ν_e



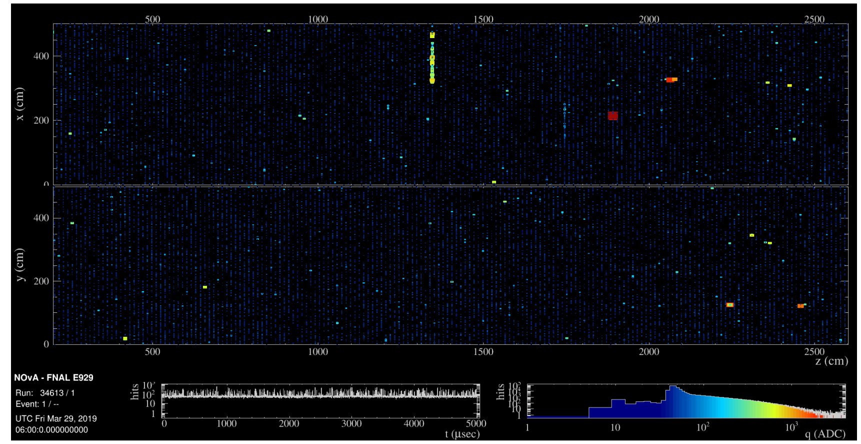
Astrophysics

- NOvA has sensitivity to Supernova Neutrinos at both detectors
  - NOvA subscribes to SNEWS.
  - NOvA internal data-driven trigger 50% efficiency
    - to 6.2 kpc for 9.6 solar-mass progenitor
    - to 10.6 kpc for 27 solar-mass progenitor

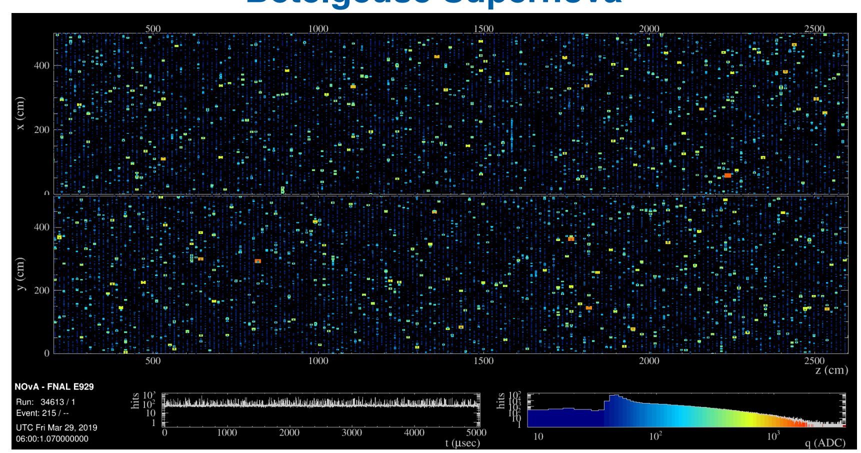
- NOvA has performed a broad search for any signal coincident with 28 gravitational wave alerts from LIGO/VIRO from Sept. 2015 to July 2019.
  - No signal candidates were found.
  - [PRD 101 (2020), 112006]

- NOvA is engaged in a variety of other cosmic-ray studies and searches for Exotic phenomena.

Activity in front-half of NOvA Far Detector in Random 5ms slice



Activity in front-half of NOvA Far Detector in 5ms slice of Betelgeuse Supernova



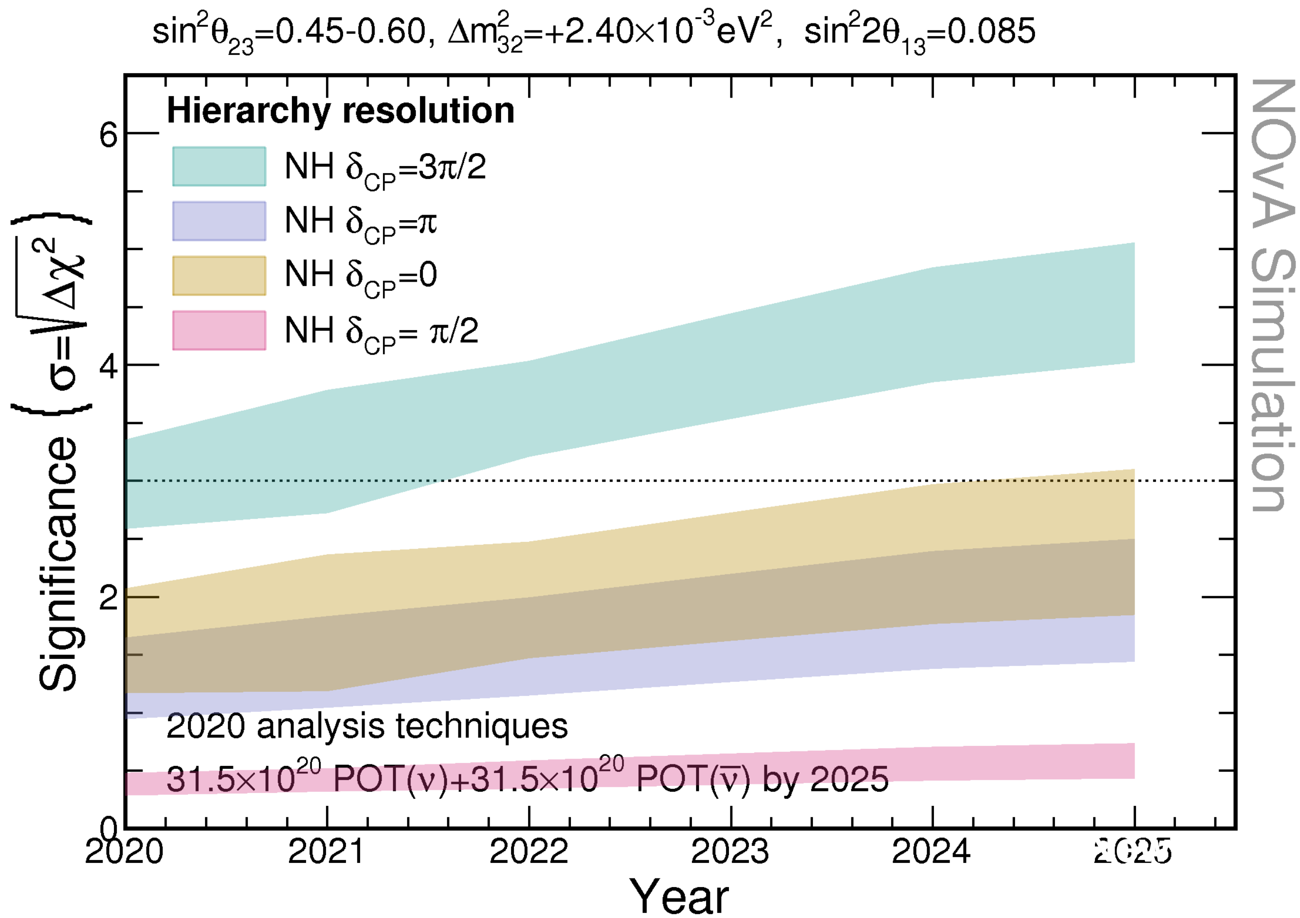
Looking Ahead

- NOvA will run until 2025
- Projections assuming 63×10^{20} protons-on-target
- Beam Improvements
  - 1 MW-capable target recently installed.
  - Further improvements to target system taking place this summer will allow accepting up to 1 MW.
    - New Horn 1, Improvements to air and water handling
  - Planned reduction of losses in 8 GeV Booster may enable beyond 900 kW by 2022/23
    - Dampers and Collimators that are part of PIP-II Scope

Looking Ahead

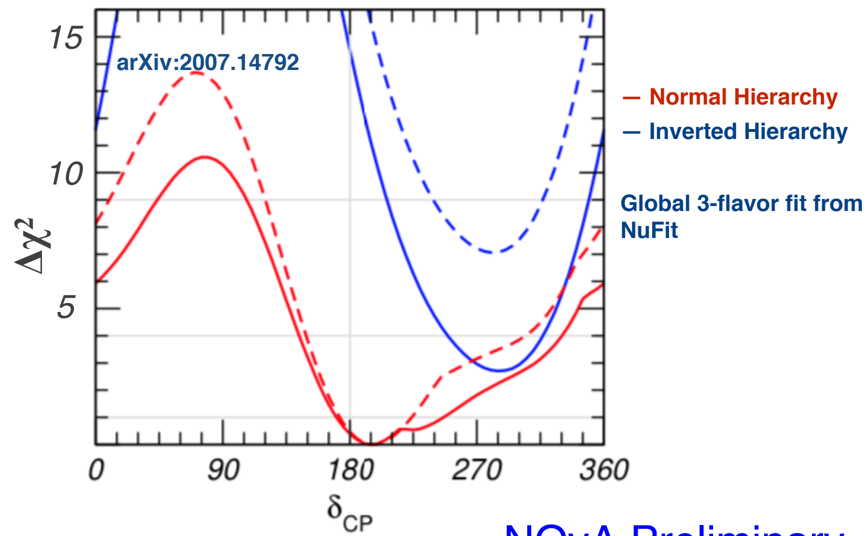
A priori NOvA sensitivity to Mass Hierarchy vs. time

NOvA reaches 3 sigma sensitivity for between 30% and 50% of δ_{CP} values, depending on MH and $\sin^2(\theta_{23})$

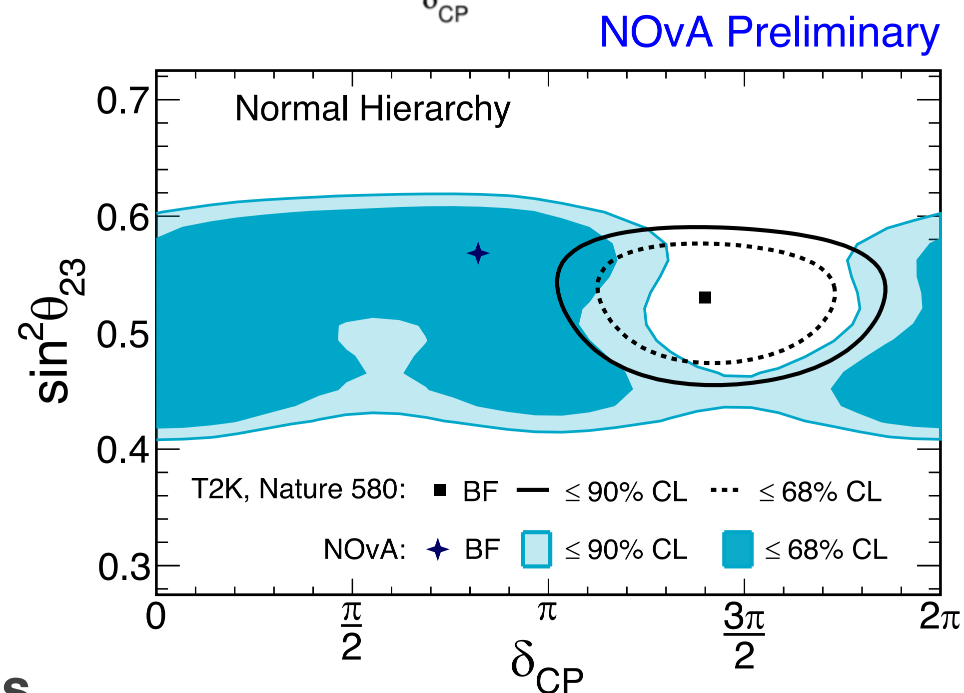


NOvA and the Global Picture

- Preference for CP violation has weakened with new T2K and NOvA Data
  - I. Esteban et al. (NuFit), arXiv:2007.14792



- NOvA result is in slight tension with T2K best-fit point (2 sigma)
- While both NOvA and T2K favor Normal Hierarchy individually, together they prefer Inverted Hierarchy
  - e.g., Kelly, et al., arXiv:2007.08526
- Could this be a hint of new physics?
  - Non-L/E dependent phenomena?
  - E.g., NSI: P. Denton, et al., arXiv:2008:01110, S. Chatterjee & A. Palazzo, arXiv:2008:04161



- **Comparison of 810 km baseline to results from widely different baselines will likely be key to understanding the full picture**

Looking Ahead, cont.

- Joint Analysis with T2K
  - The collaborations have been meeting since 2017 to forge an analysis path to understand the significant correlations and make full use of the complementarities.
    - Detector design, beam energy, baseline.
- Non-standard Oscillation Physics
  - Targeting world-leading reach for long-baseline sterile neutrino search with NC-disapp.
  - Long-baseline NSI searches in ν_μ and ν_e channels
- Cross-section measurements
  - A variety of neutrino and antineutrino measurements are in the pipeline.
  - High-statistics will permit triple-differential or quadruple-differential measurements.
- Astrophysics, Cosmic Ray, and Exotic Physics
  - Unique reach for lighter ($<10^{10}$ GeV), slow monopoles thanks to large detector and small overburden
  - Expanded gravitational wave multi messenger search with LIGO/Virgo/KAGRA O4 run
  - n-$\bar{n}$ oscillations

Summary

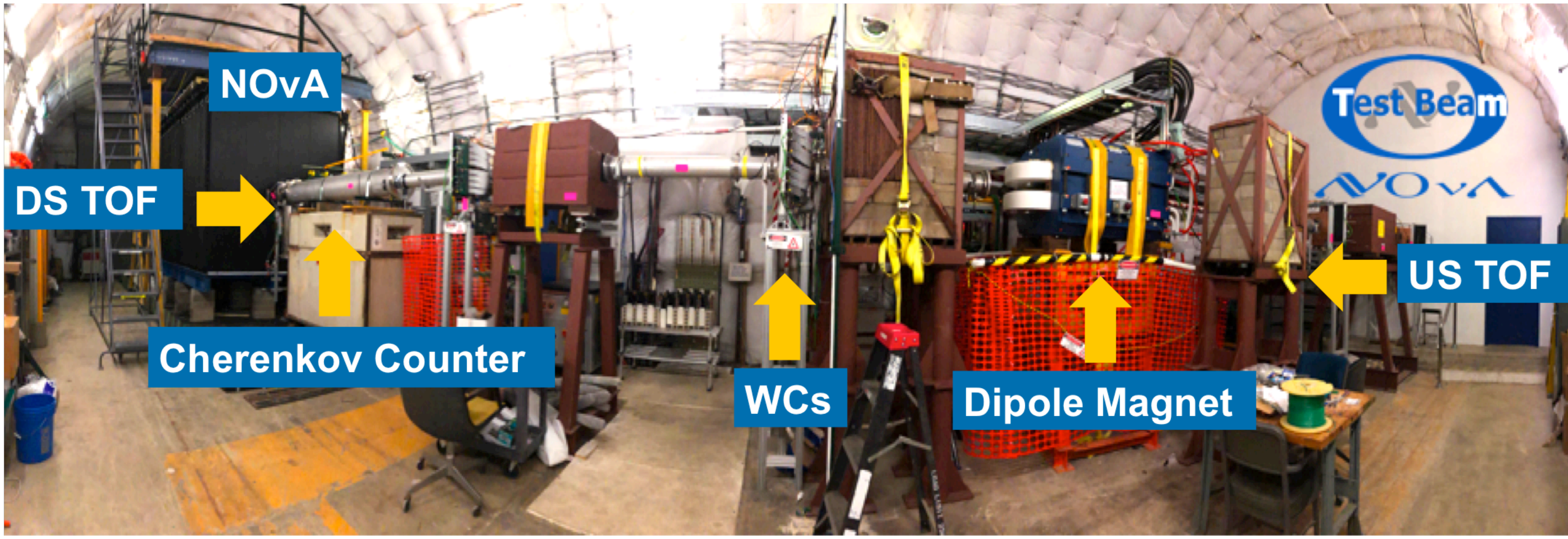
- NOvA has new oscillation results.
  - Hint of tension with T2K
- Our rich and broad physics program will continue to 2025.

- Broadly applicable experience from NOvA
  - Operations
    - High-power target systems, Distributed Remote Operations
  - Computing
    - Handling large datasets, Reliance on HPC for generation of parameter contours
  - Software & Analysis Tools
    - Use of Convolutional Neural Networks for event ID
    - Two-detector Oscillation Analysis framework adopted by DUNE

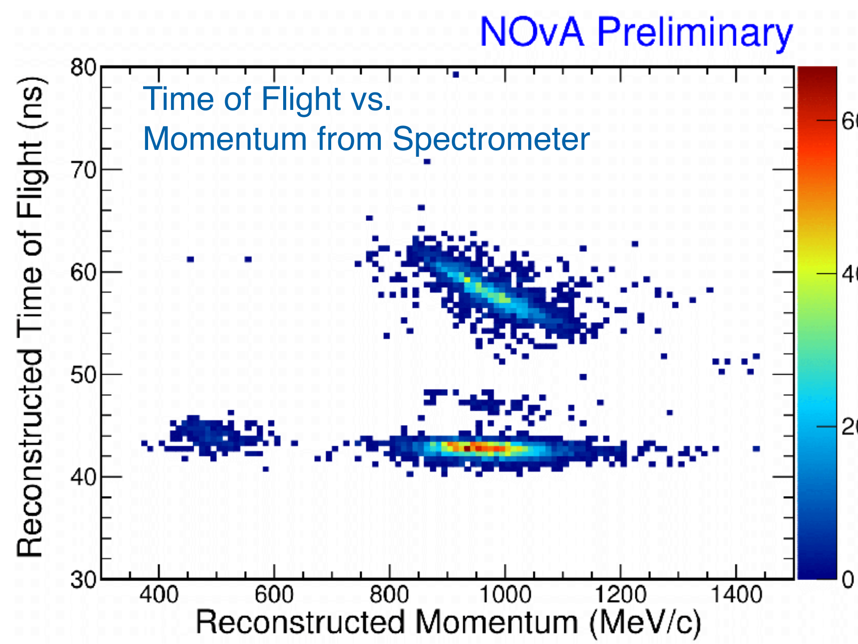
MAY 2020

More details

Coming up: NOvA Test Beam Run

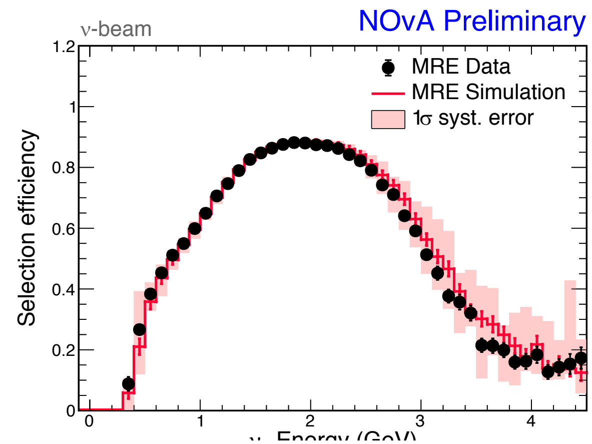


- Targeting reduction of leading detector response and energy calibration uncertainties
- Detector has been filled and commissioned
- New tertiary beamline at FTBF has been commissioned
- We are working on beam improvements and looking forward to coming run.

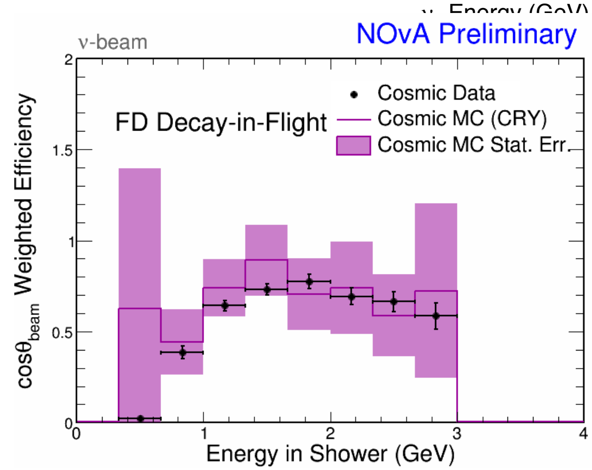


Data-Driven Cross-Checks

- NOvA has employed several data-driven cross-checks on modeling of detector response and physics processes.

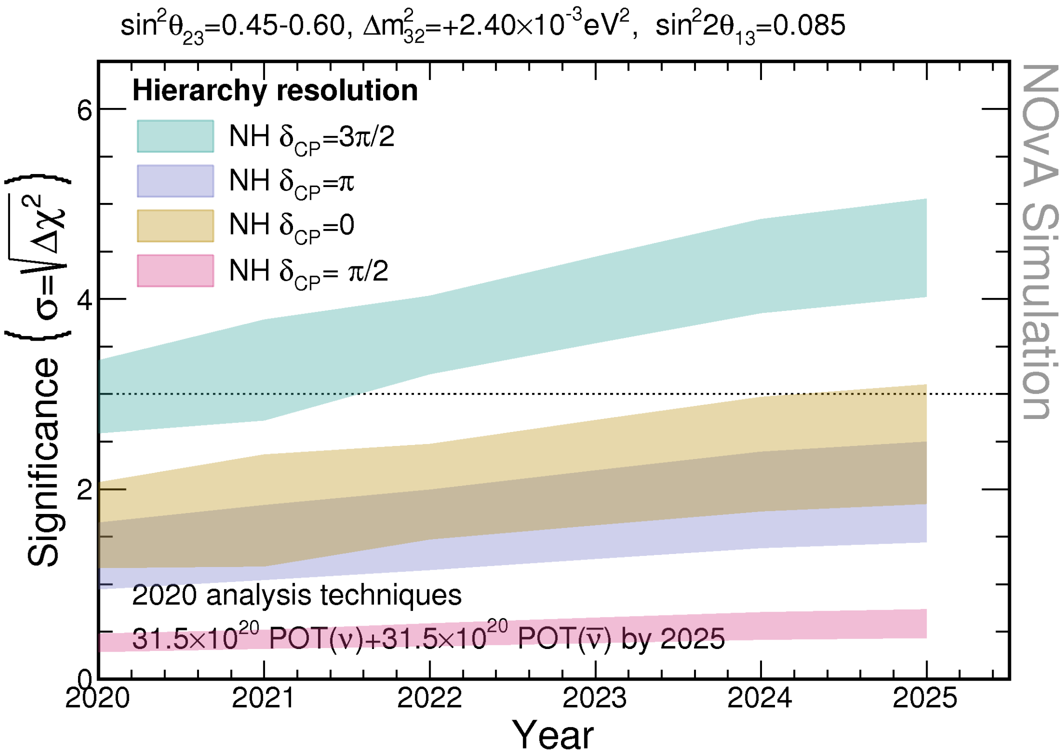


- MRE - Muon Removed, Electron (added)
  - Remove μ track from reconstructed data and MC events, replace with simulated electron

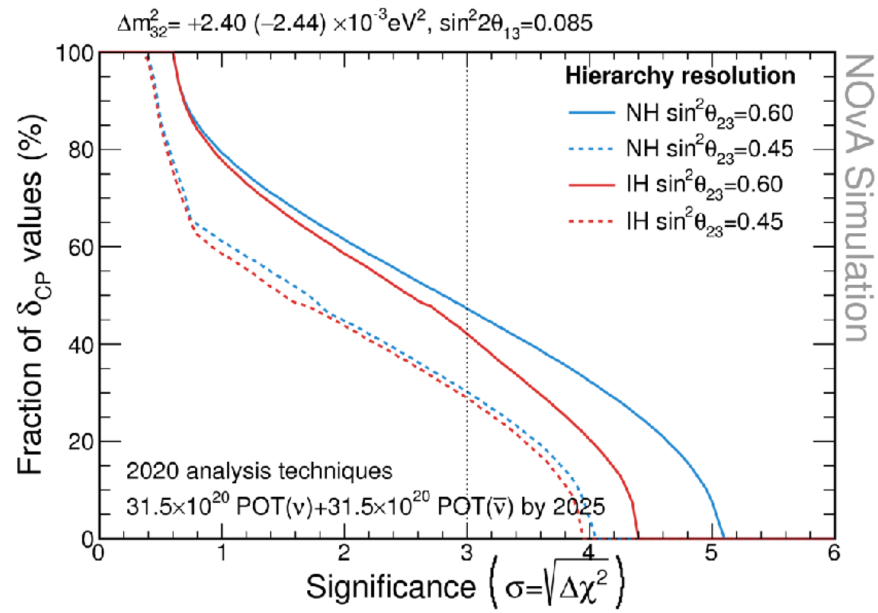


- Cosmic-induced bremsstrahlung, muon decay-in-flight
  - Validate PID performance
- Calibration
  - Detectors calibrated with cosmic-ray muons, checked with Michel Electrons, beam-induced protons, π^0

Future sensitivity to Mass Hierarchy



A priori NOvA Mass Hierarchy Sensitivity

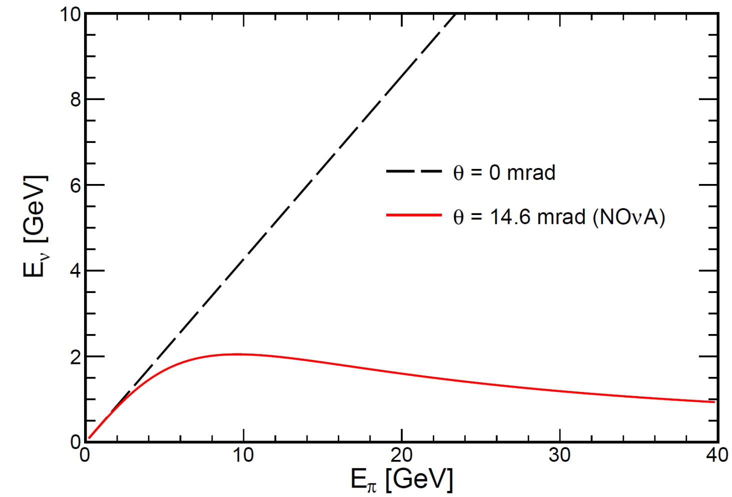


Fraction of values of δ vs a priori sensitivity of resolving Mass Hierarchy

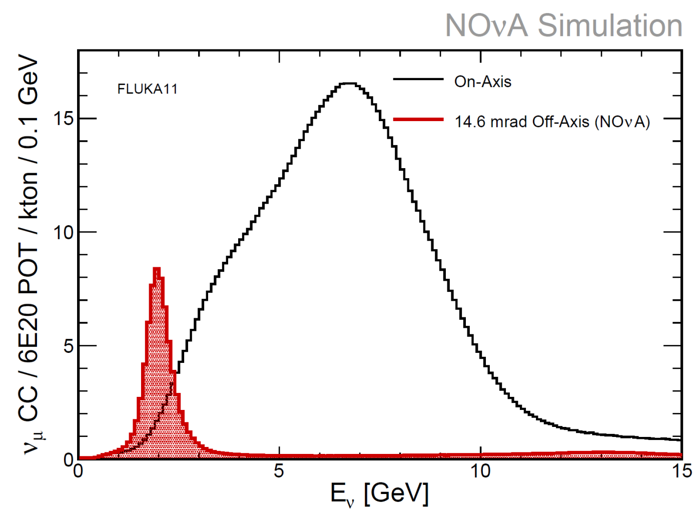
Detector Location

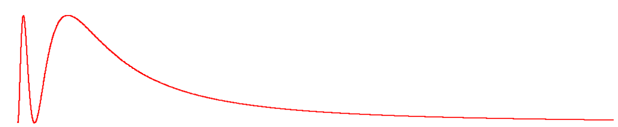
- 14 mrad (11km) off the NuMI beam axis
  - pion 2-body decay kinematics

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



  - 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

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.

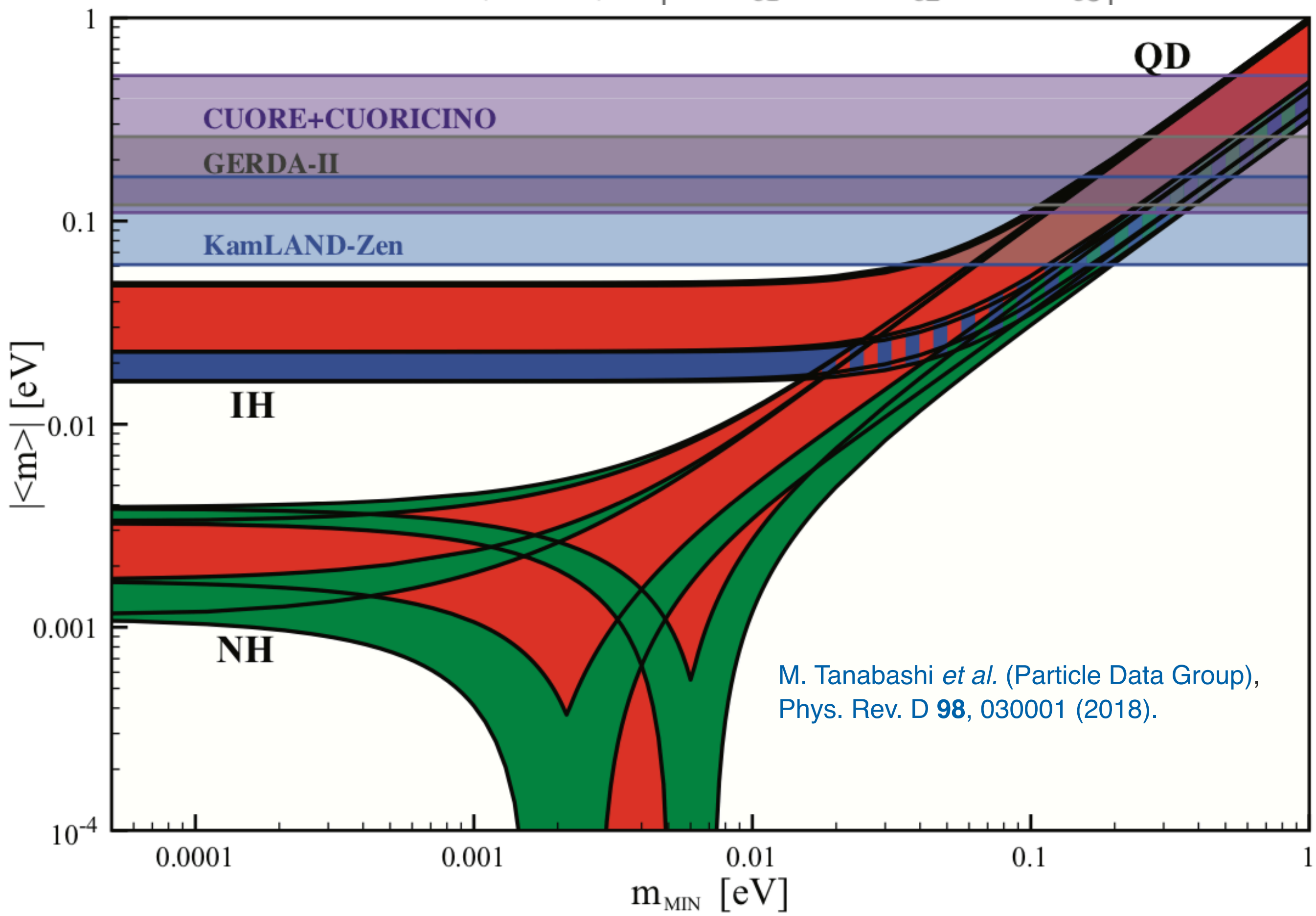
Neutrino Mass Hierarchy (Ordering)

- Discriminator of neutrino mass & mixing models

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

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

⇒ Dirac vs. Marojana Neutrino Mass



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

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: $0 \leq |J_{PMS}| \leq 0.03$

Quark sector: $J_{CKM} \leq 0.00003$

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

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: $P_{Max} \sim 0.05$**

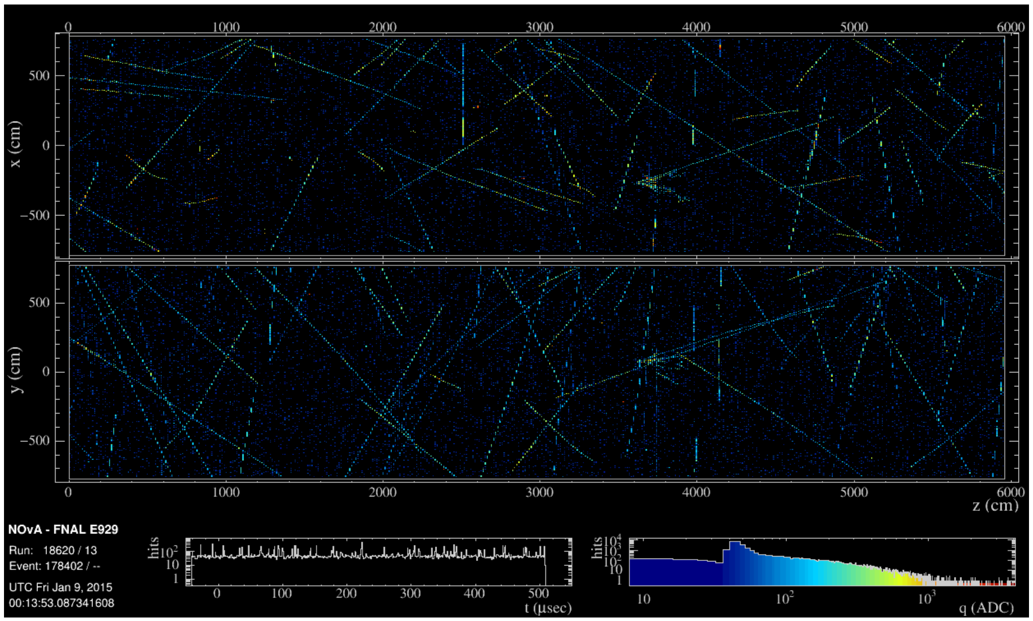
$\sin^2(\theta_{23})$ breaks the $\theta \rightarrow 45^o - \theta$ degeneracy of $\nu_\mu \rightarrow \nu_\mu$
Sensitivity to the Octant of θ_{23}

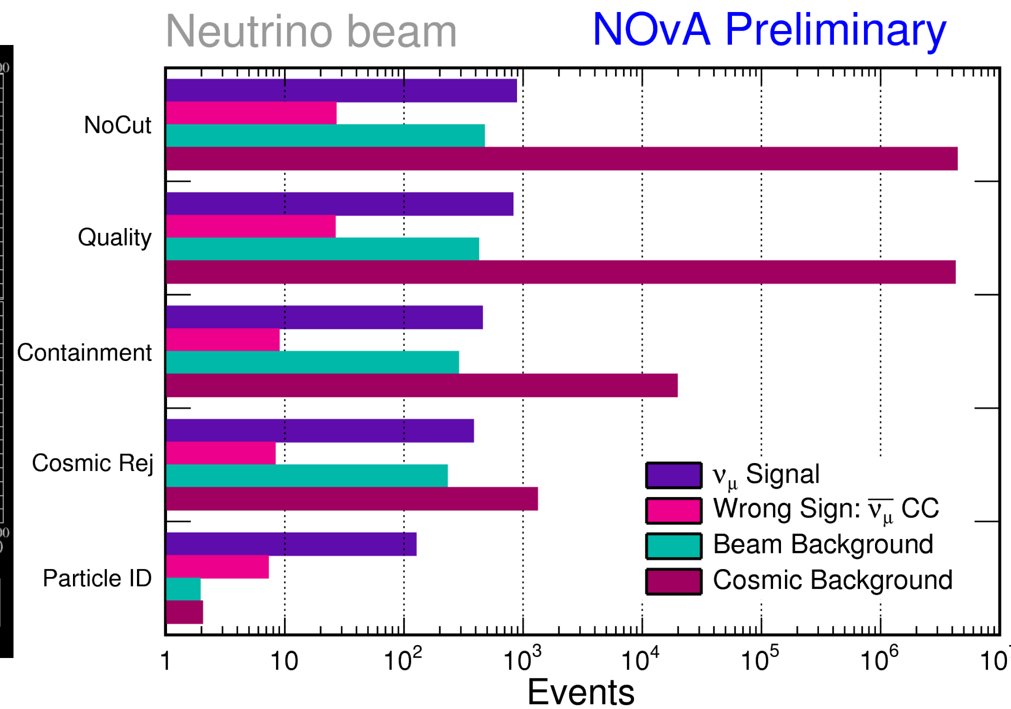
$A = \pm\sqrt{2} G_F N_e 2E/\Delta m^2_{31}$ is Matter Effect: potential shift for ν_e flavor from electrons in matter. + for neutrinos, - for antineutrinos. **Proportional to Δm^2_{31}**
Sensitivity to Mass Hierarchy

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

NOvA Event Selection - Cosmic Ray Rejection

- 1st long-baseline neutrino experiment on the surface - effective cosmic ray rejection is critical

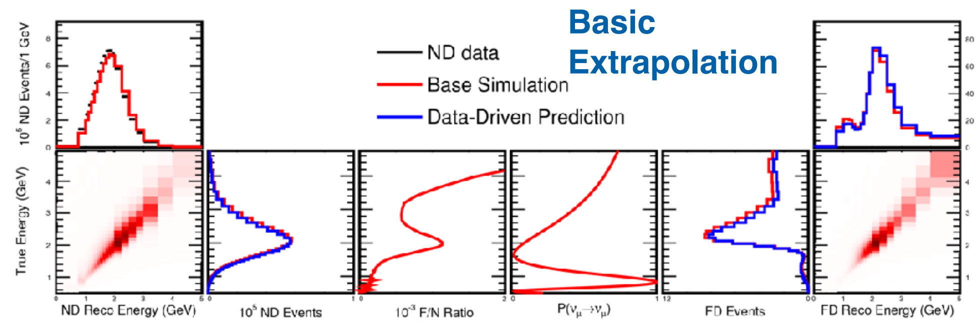




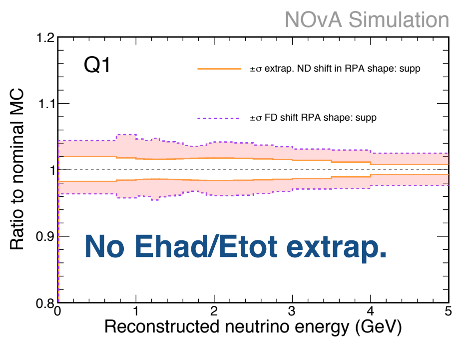
  - 6 orders of magnitude rejection achieved with cuts and algorithms using lepton and event characteristics, directions, etc.
- Characterizing remaining background is also important
  - NOvA takes ~50x beam data in beam triggers, and another ~500x in periodic cosmic triggers

Extrapolation

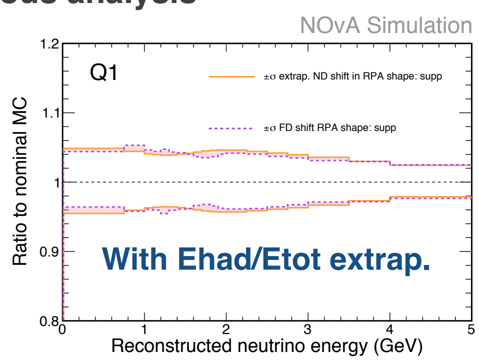
- Original extrapolation
  - adjust true energy distribution to match ND MC to data, apply adjustment to FD.
- Improvements
  - Extrapolate and fit ν_μ in bins of reco. hadronic energy fraction (2018)
    - Improves sensitivity of ν_μ fit by grouping events by energy resolution
    - Isolates different cross-section effects

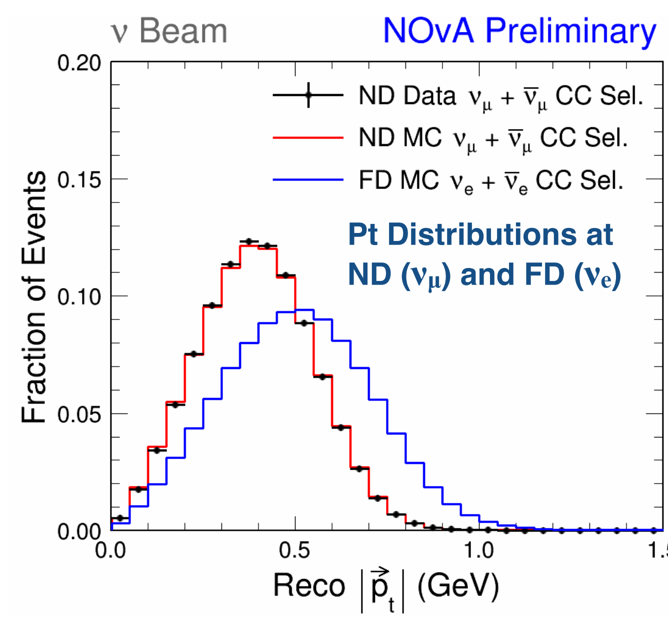


Caveat: example from previous analysis



Example effect of cross-section systematic

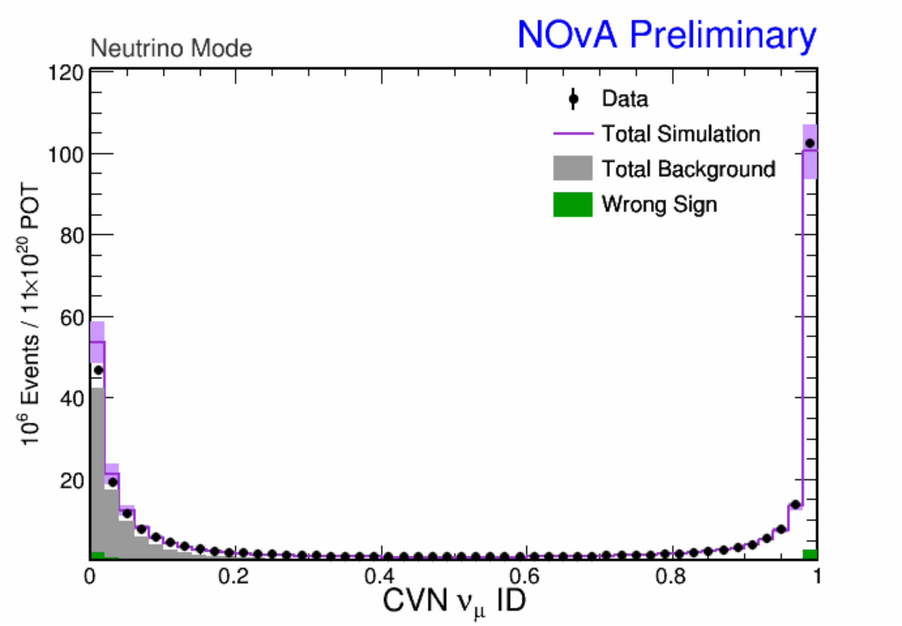




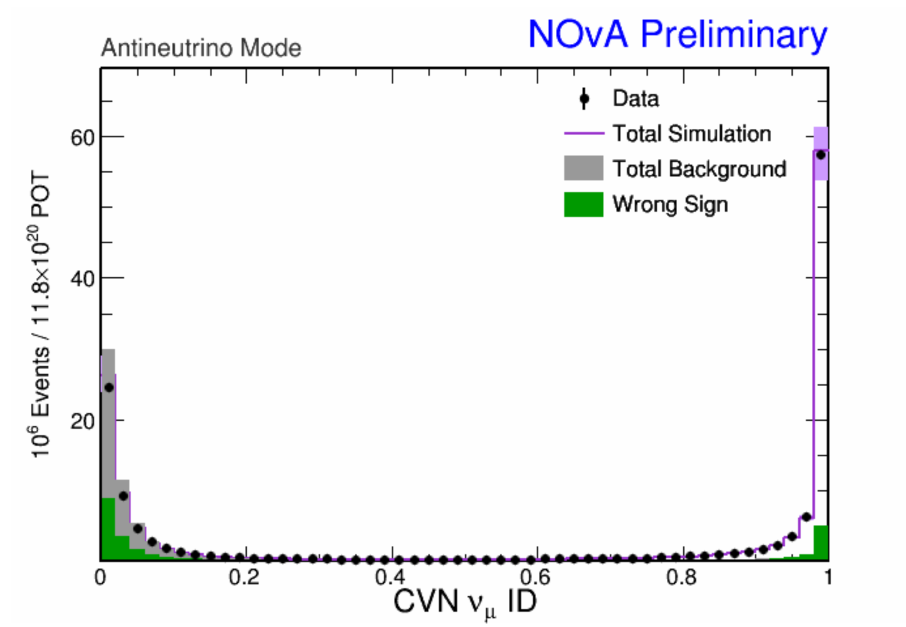
  - Extrapolate in bins of reco. lepton P_t.
    - Improved robustness with respect to effect of ND-FD acceptance differences on neutrino interaction modeling uncertainties.

CVN Neutrino Flavor ID - Data and Simulation in Near Detector

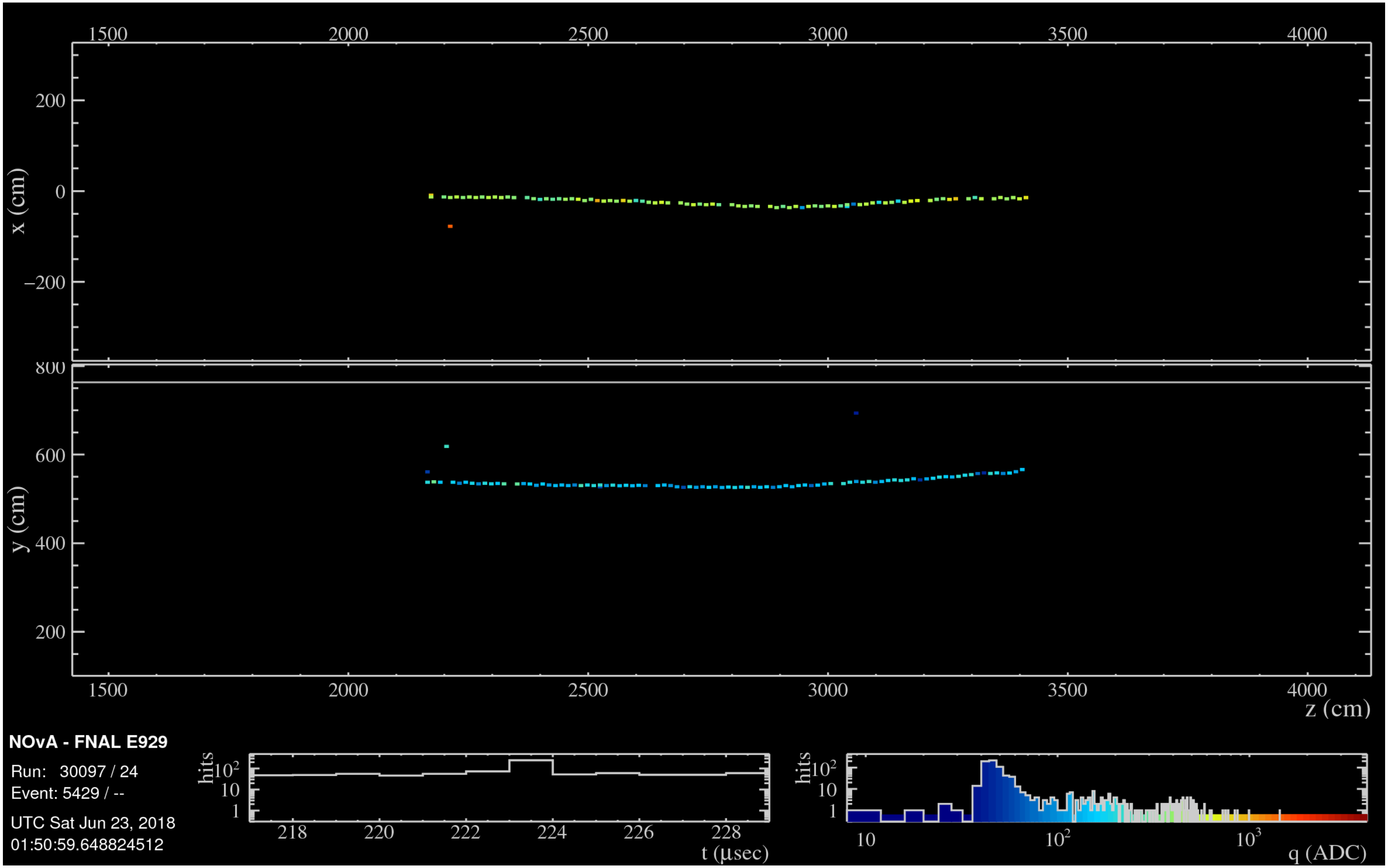
Neutrino



Anti-Neutrino

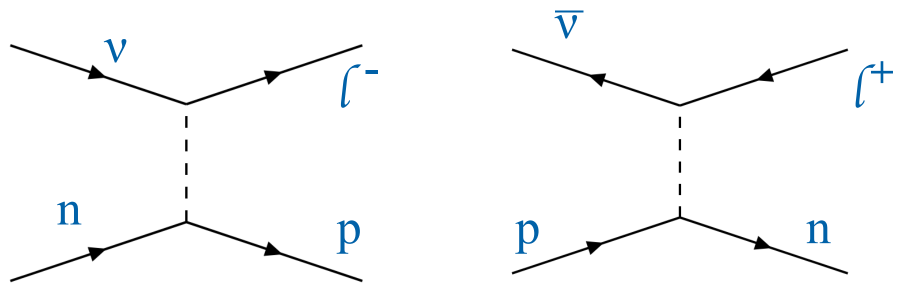


Candidate antineutrino interaction with neutron

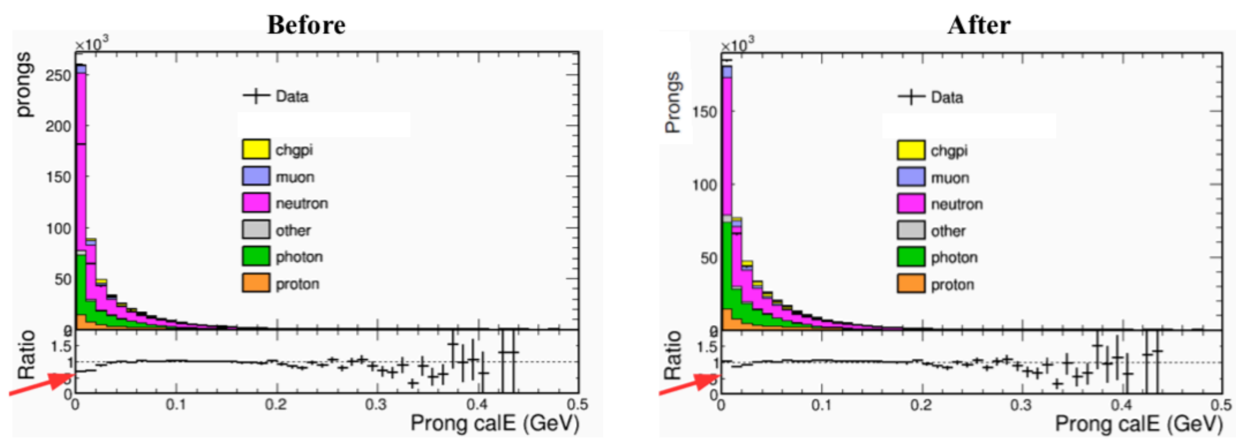


Neutron Systematic

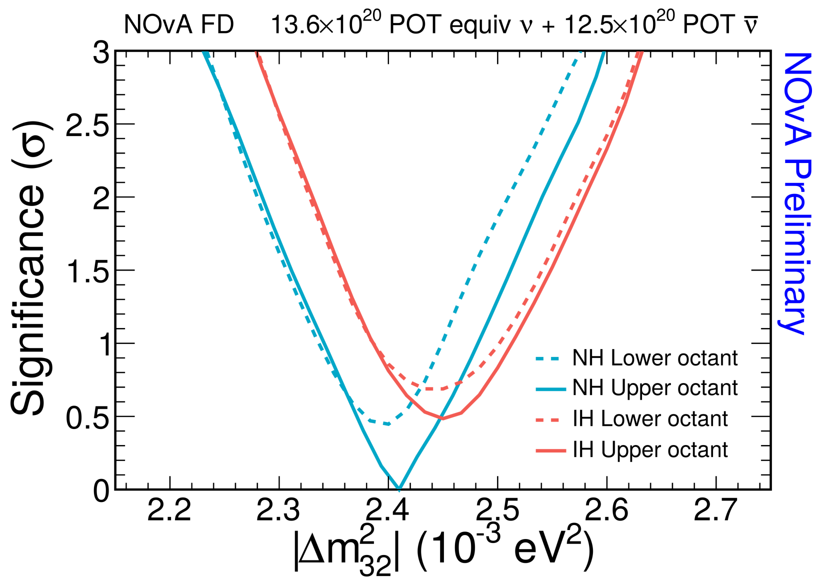
- Antineutrino interactions produce neutrons.



- Energy distribution of neutron candidates predicted in quasi-elastic ν_μ events
- Current evaluation of uncertainty
  - Randomly remove energy for a fraction of lower energy neutron-induced energy depositions to improve data- simulation match.
  - Shifts average $\overset{(-)}{\nu}_\mu$ energy by 0.5% (1%)
  - Studies are ongoing.

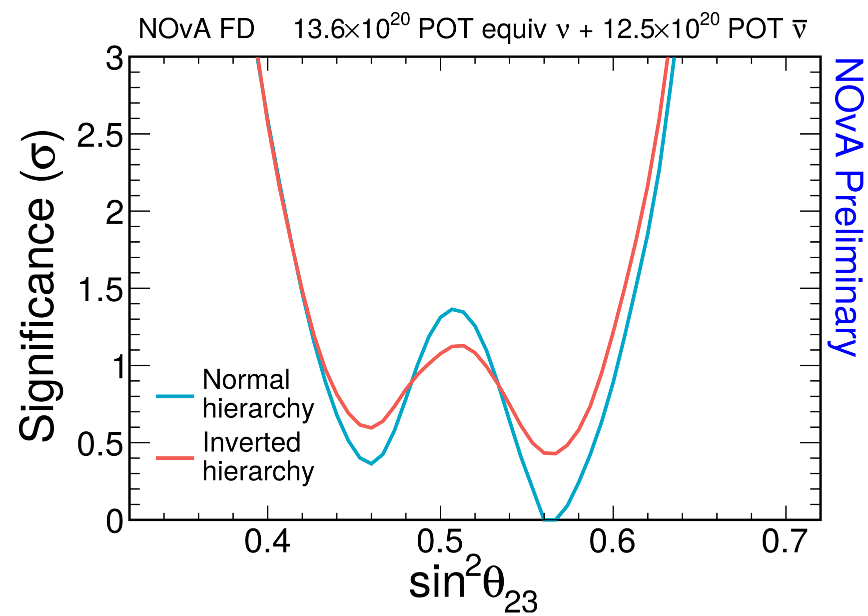


More Fit Results



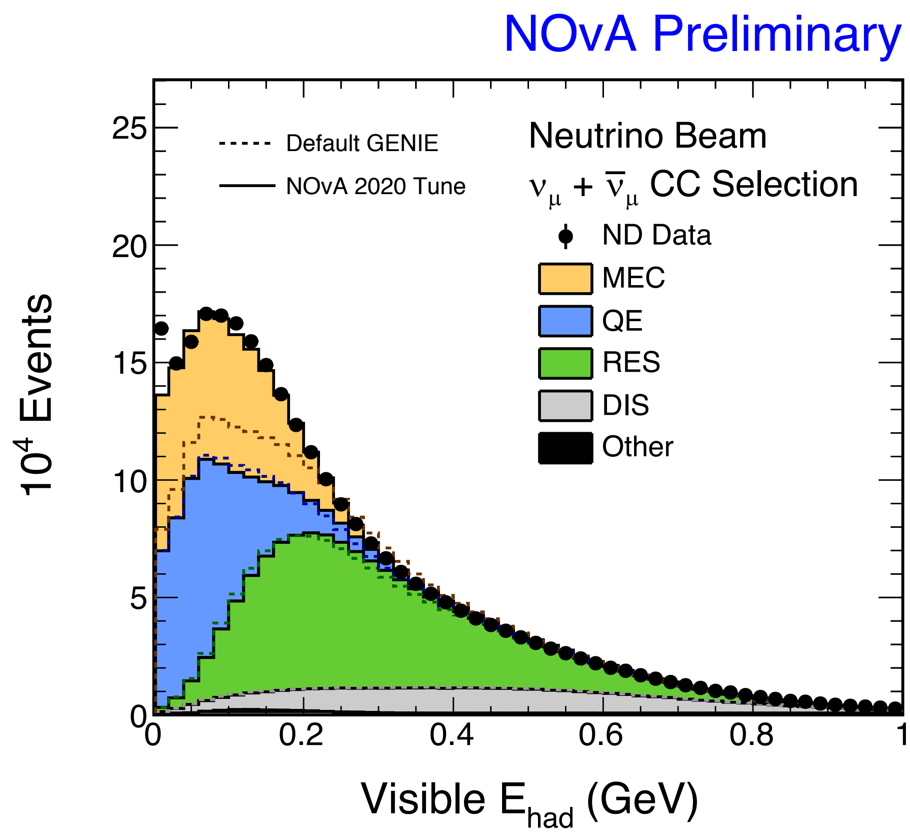
	1-σ range
$\sin^2\theta_{23}$ NH	[0.431 ; 0.487] ∪ [0.530 ; 0.602]
$\sin^2\theta_{23}$ IH	[0.433 ; 0.492] ∪ [0.526 ; 0.595]
Δm^2_{32} NHUO	[2.341 ; 2.482]
Δm^2_{32} NHLO	[2.336 ; 2.449]
Δm^2_{32} IHUO	[2.386 ; 2.513]
Δm^2_{32} IHLO	[2.386 ; 2.502]
δ_{CP} NHUO	[0 ; 1.09] ∪ [1.95 ; 2]
δ_{CP} NHLO	[0 ; 0.37] ∪ [0.84 ; 1.10] ∪ [1.81;2]
δ_{CP} IHUO	[1.22 ; 1.79]
δ_{CP} IHLO	[1.19 ; 1.59]
δ_{CP} NH	[0 ; 1.06] ∪ [1.82 ; 2]
δ_{CP} IH	[1.26 ; 1.73]

	Gaus. σ	FC σ	p-value
IH	0.90	1.04	0.300
LO	0.69	1.21	0.224
NHLO	0.69	1.08	0.278
IHUO	0.90	0.94	0.348
IHLO	1.10	1.10	0.272



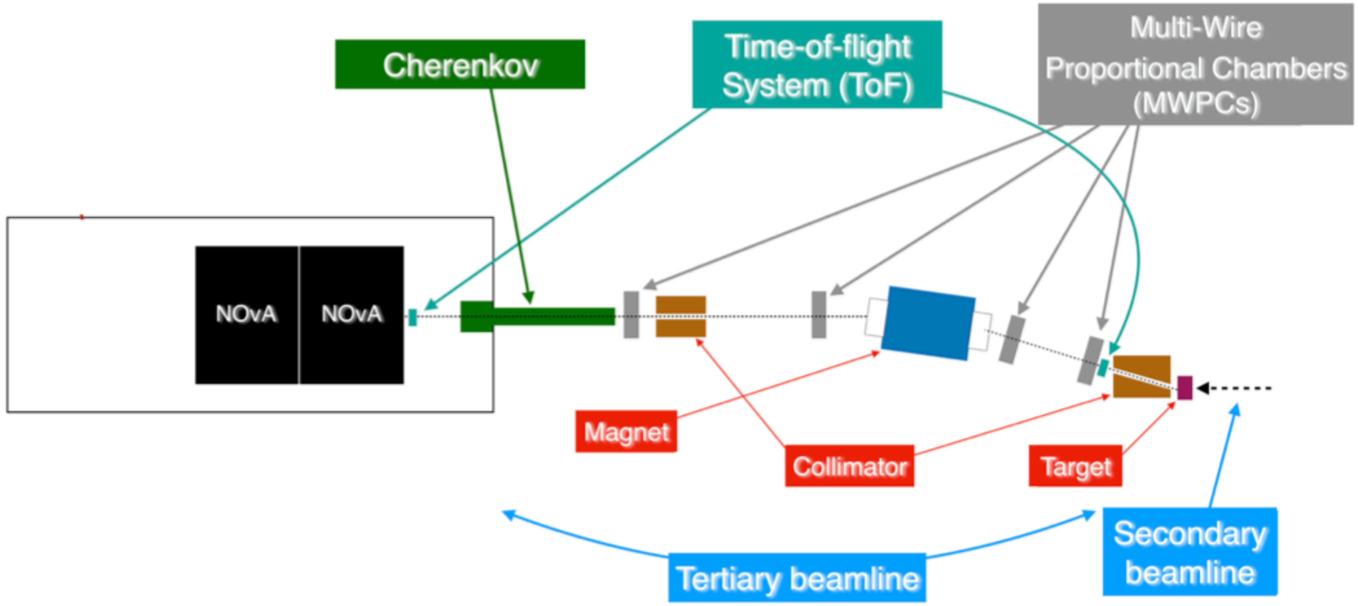
Cross-section Tuning

- 2p2h (Correlated nucleon pairs)
  - Disagreement of multiple experiments with models is well known.
  - Valencia MEC tuned to NOvA ND Data with 2-D gaussians in q_0-$|\vec{q}|$ space
  - Generous systematic uncertainties covering normalization and kinematic shape
- Final State Interactions
  - Use external π scattering data primarily to set uncertainties
  - Required adjusting central value, change in overall cross-section was small

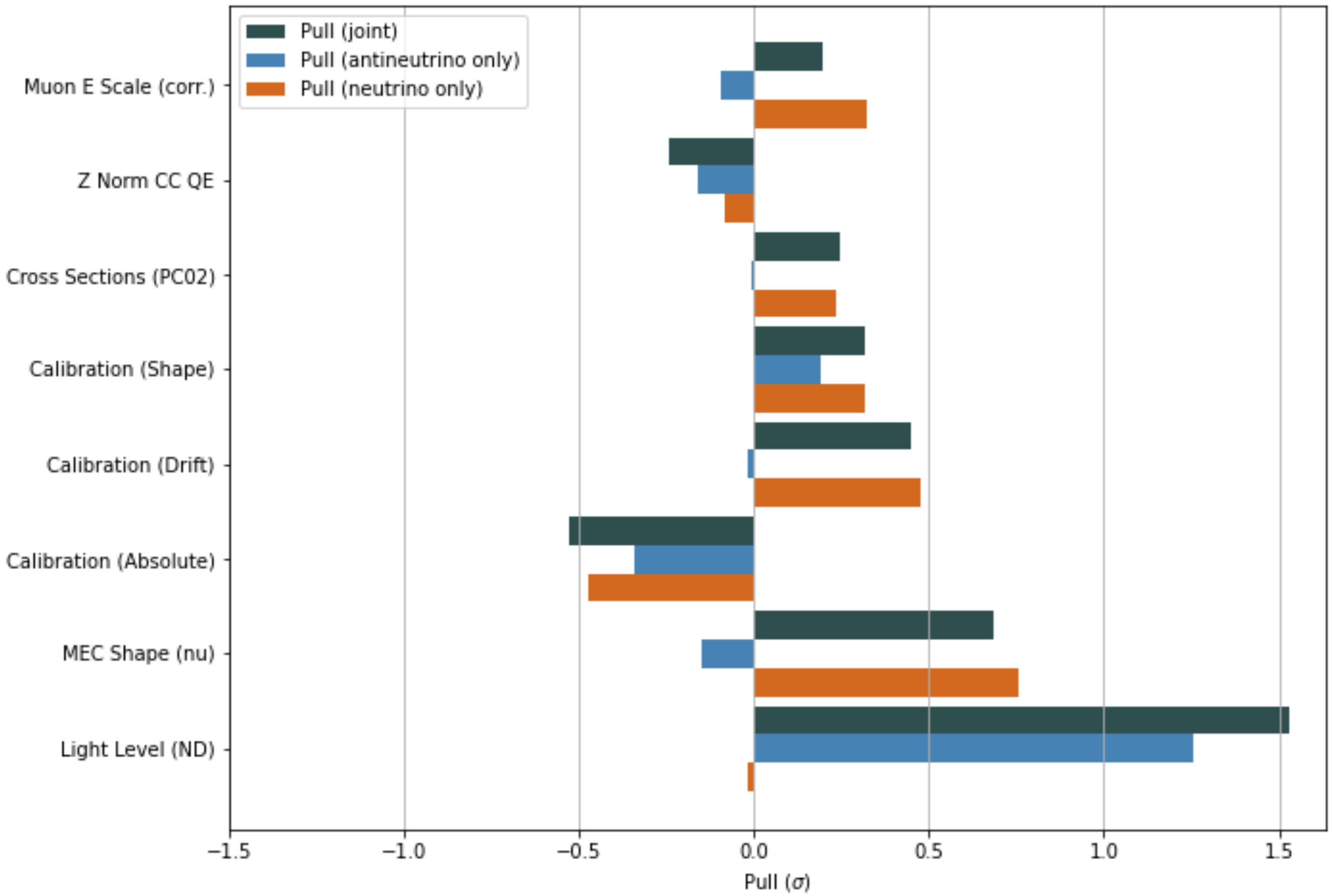


Test beam layout

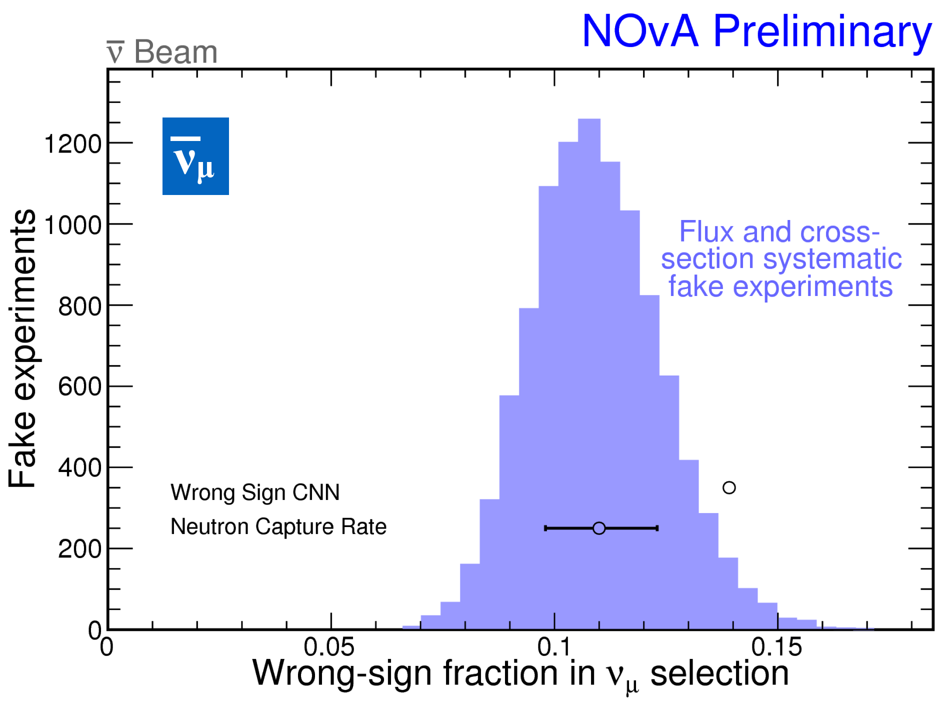
- Detector consists of two 31-plane 2x2 blocks + one horizontal plane at FTBF's MC7
- Exposed to MCenter-sourced e, μ, π, p, K, π^0 tertiary beam with known momentum from 0.2 - 2.0 Gev/c
- Provide absolute measurement of detector response and cross-check of NOvA calibration chain

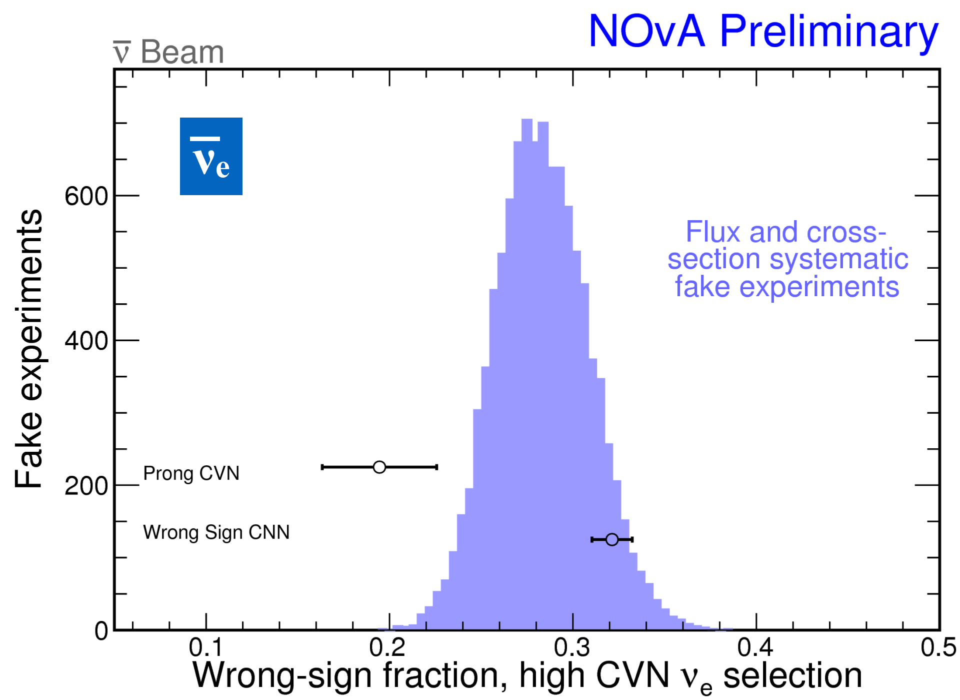


Systematic Pulls



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}

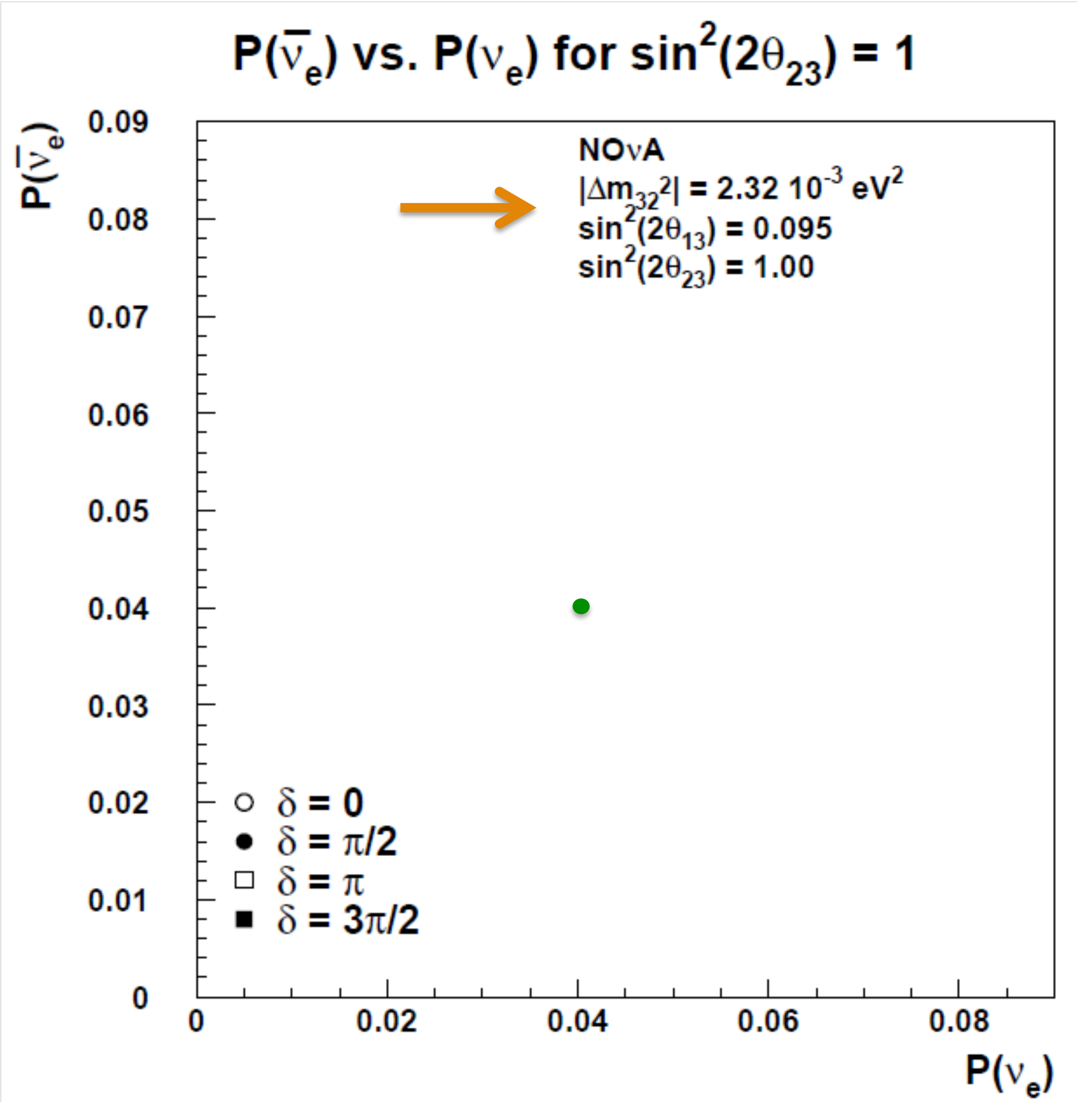
$\Delta = \Delta m^2_{31} L/4E$ $\quad$ $A = \sqrt{2} G_F N_e 2E/\Delta m^2_{31}$ $\quad$ $\alpha = |\Delta m^2_{21}|/|\Delta m^2_{31}|$

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

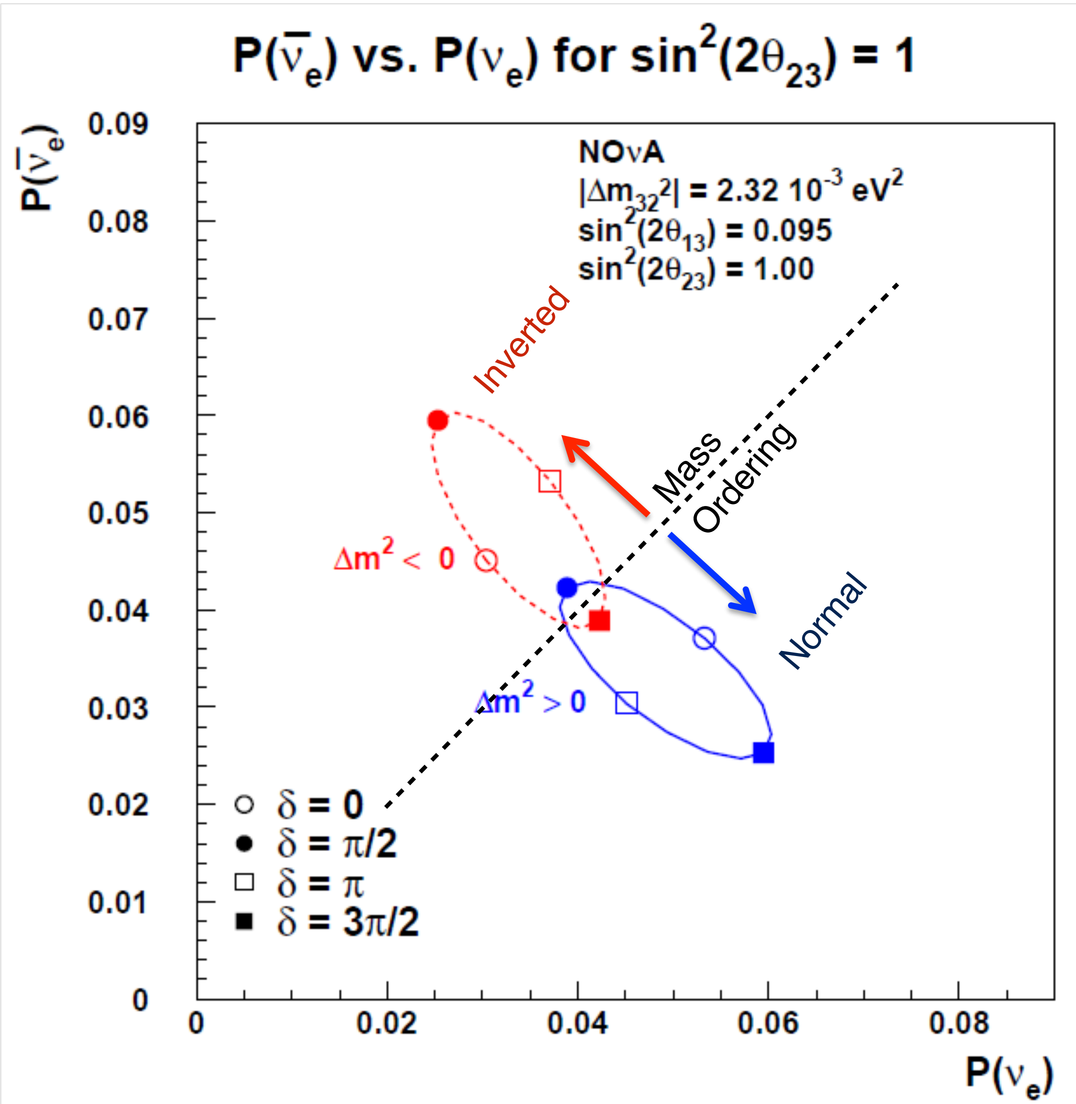


Comparison of neutrino and antineutrino appearance for a specific baseline and energy

Assuming

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

CP Violation and Neutrino Mass Ordering



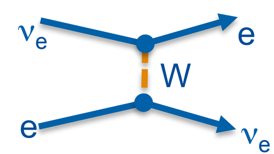
CP Violation

» *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

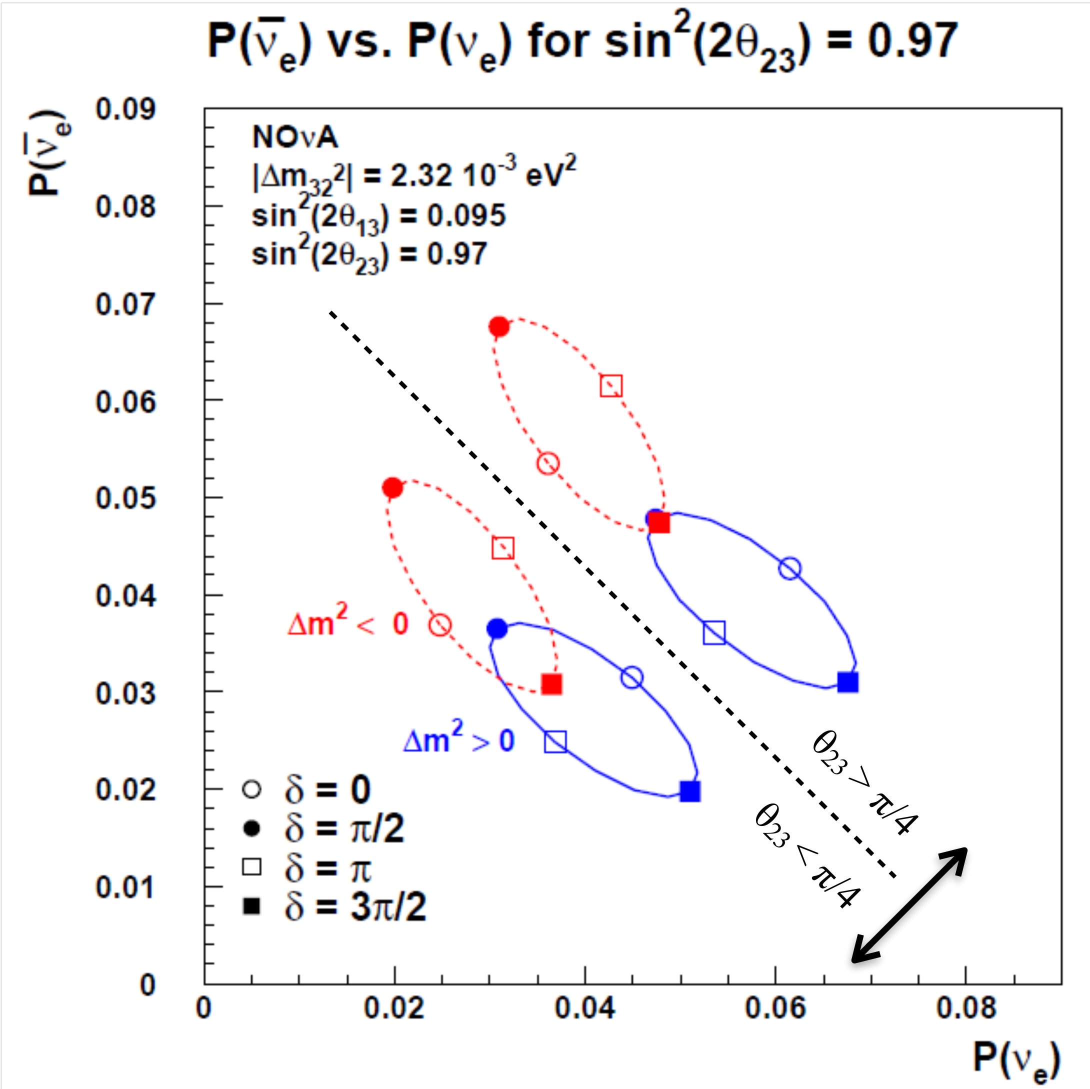


$\sqrt{2} G_F N_e 2E / \Delta m^2_{31}$

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

Shown for maximal θ_{23}

θ_{23} Octant



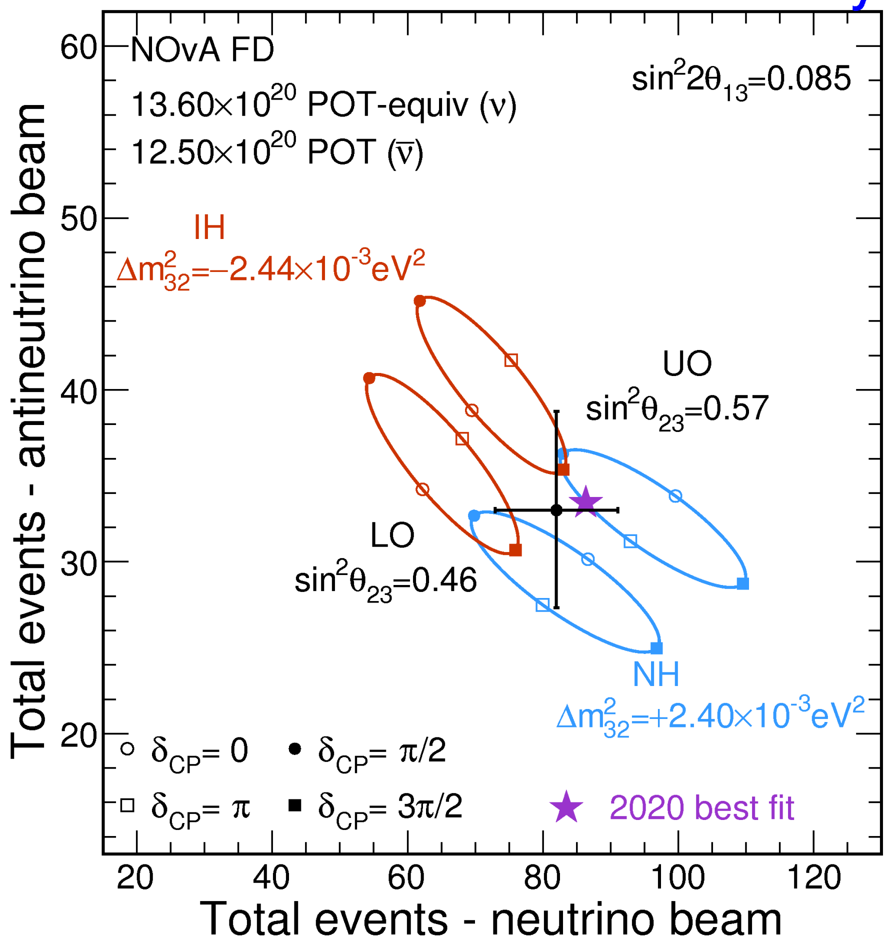
ν_μ disappearance measures $\sin^2(2\theta_{23})$

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

Bi-event rate plot

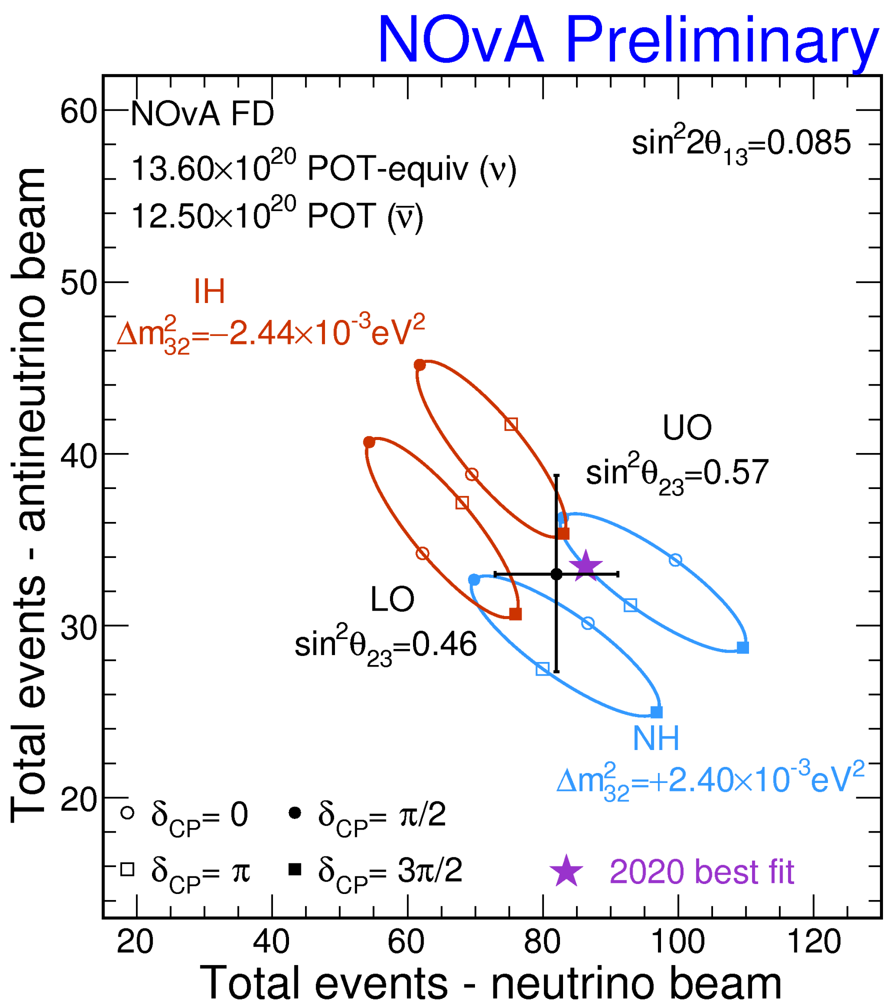
- *Caveat: this picture suppresses energy dependence and other useful variables*

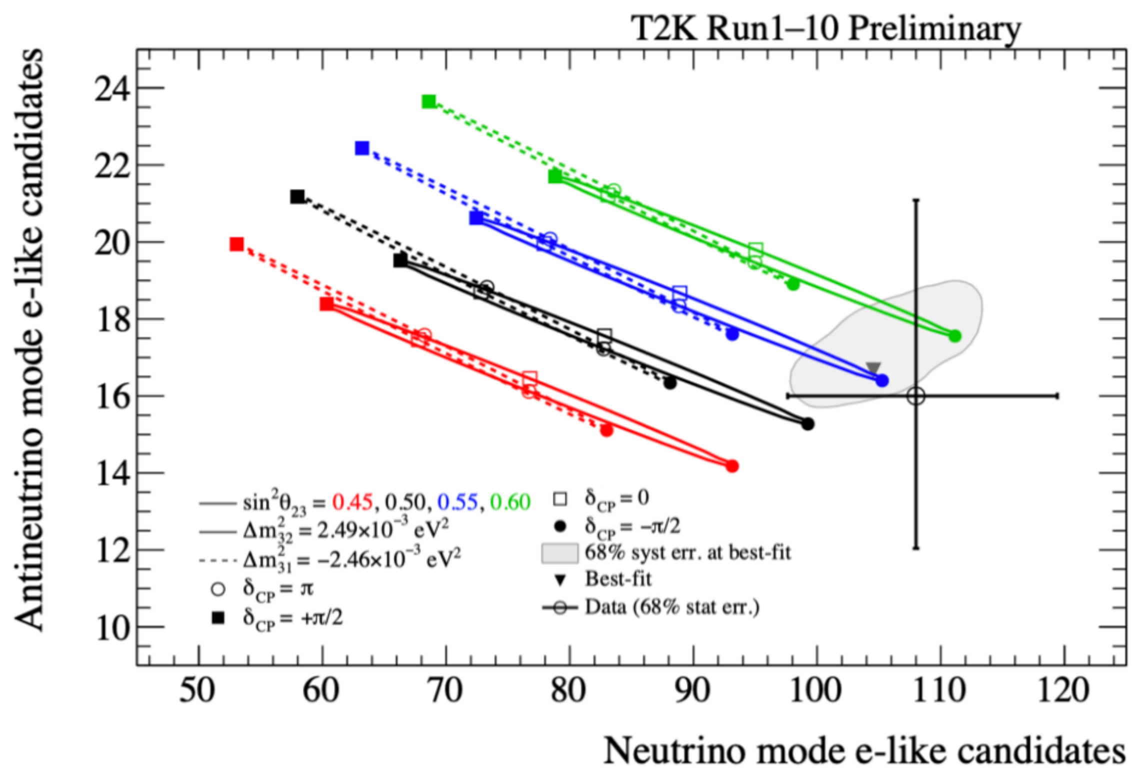
NOvA Preliminary



Bi-event rate plot

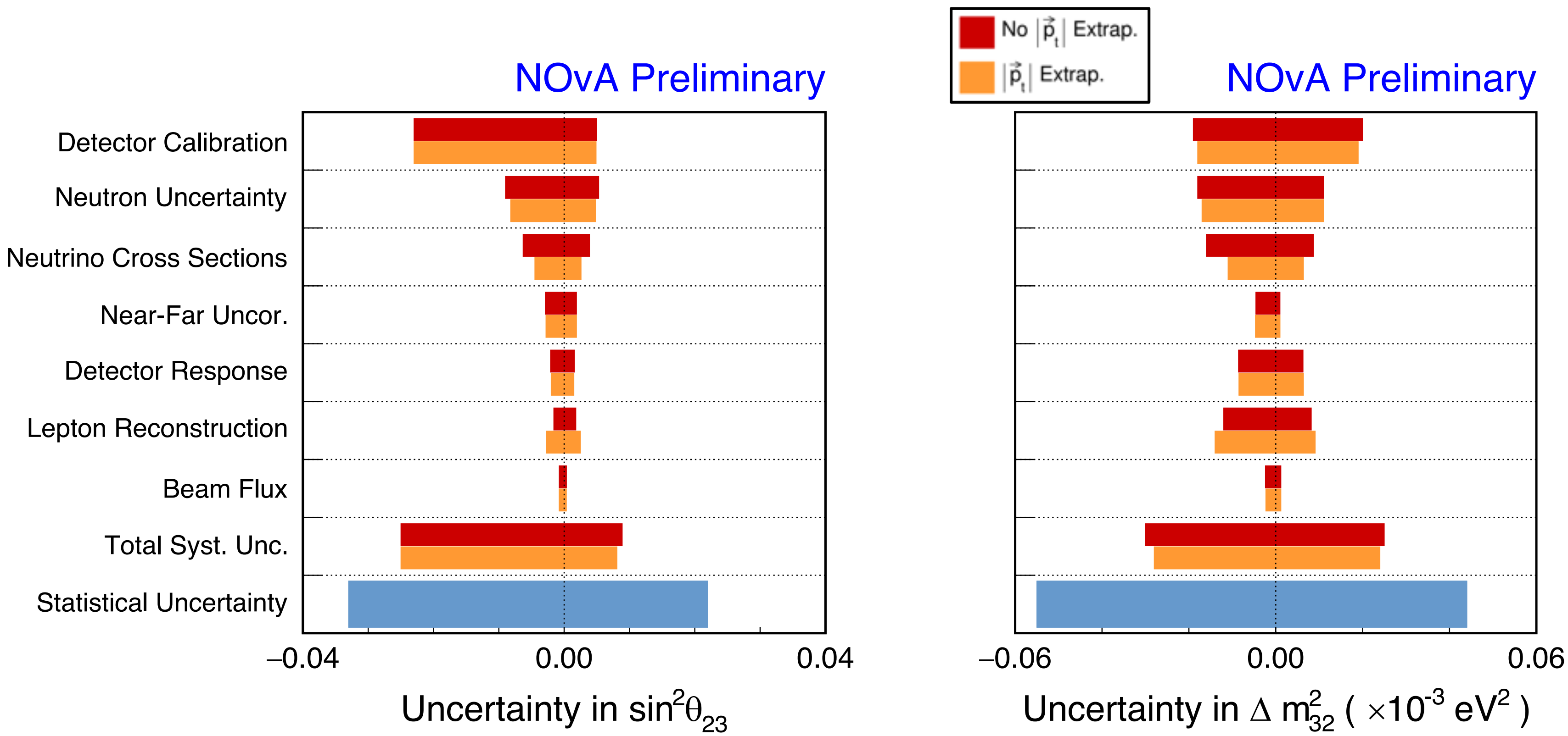
- *Caveat: this picture suppresses energy dependence and other useful variables*



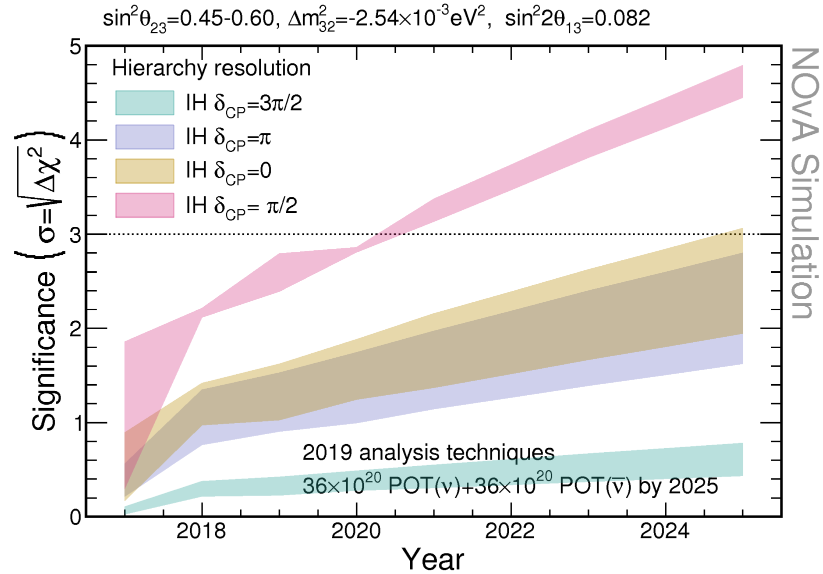


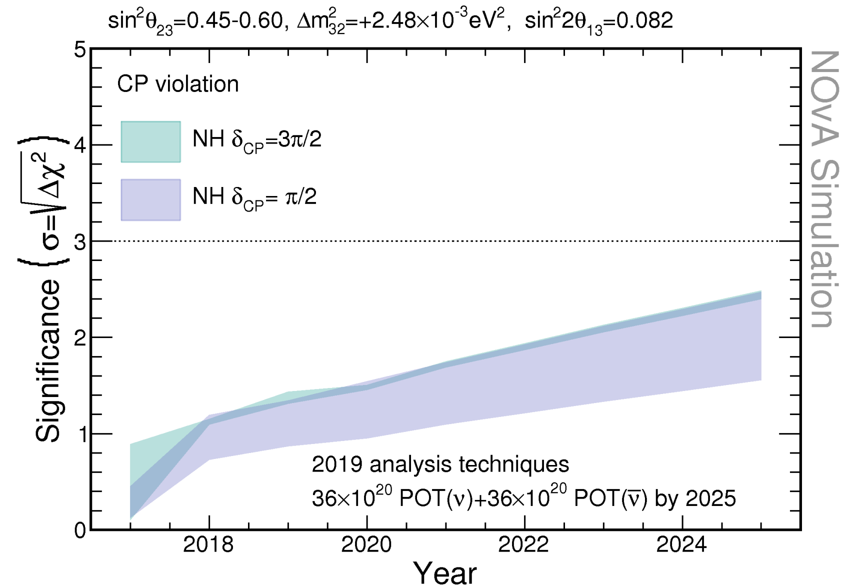
P. Dunne, Neutrino 2020, https://doi.org/10.5281/zenodo.3959558

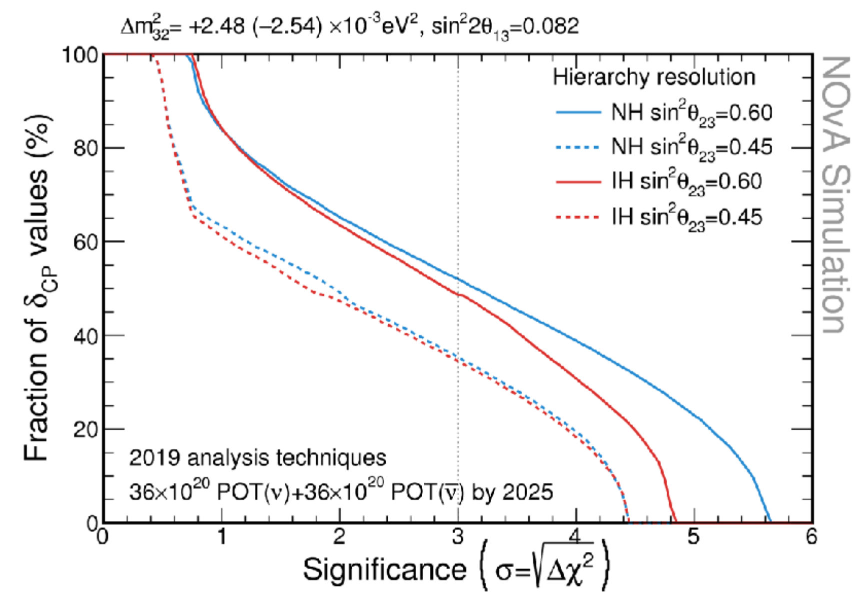
Systematic Uncertainties and P_t Extrapolation

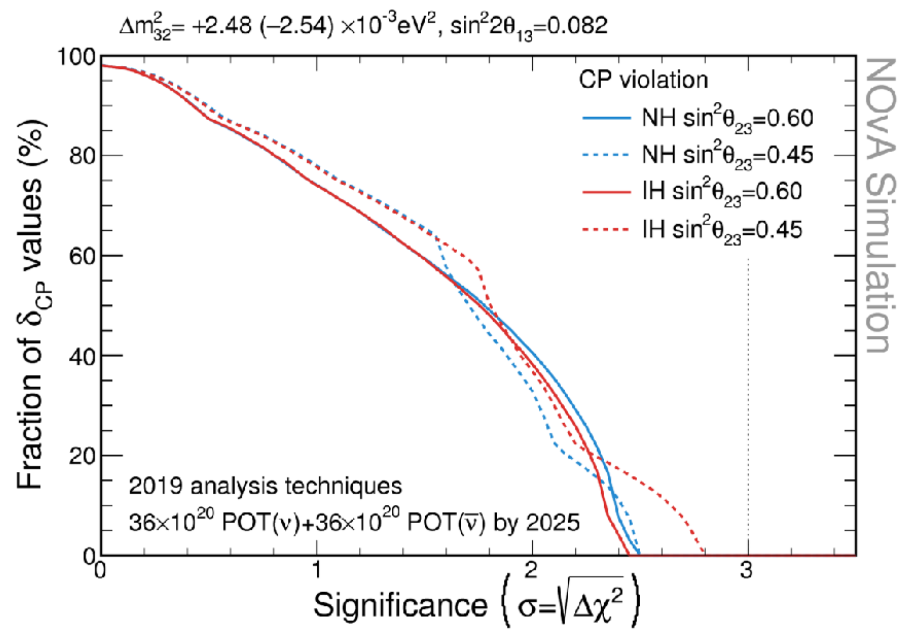


More sensitivity projections









More sensitivity projections