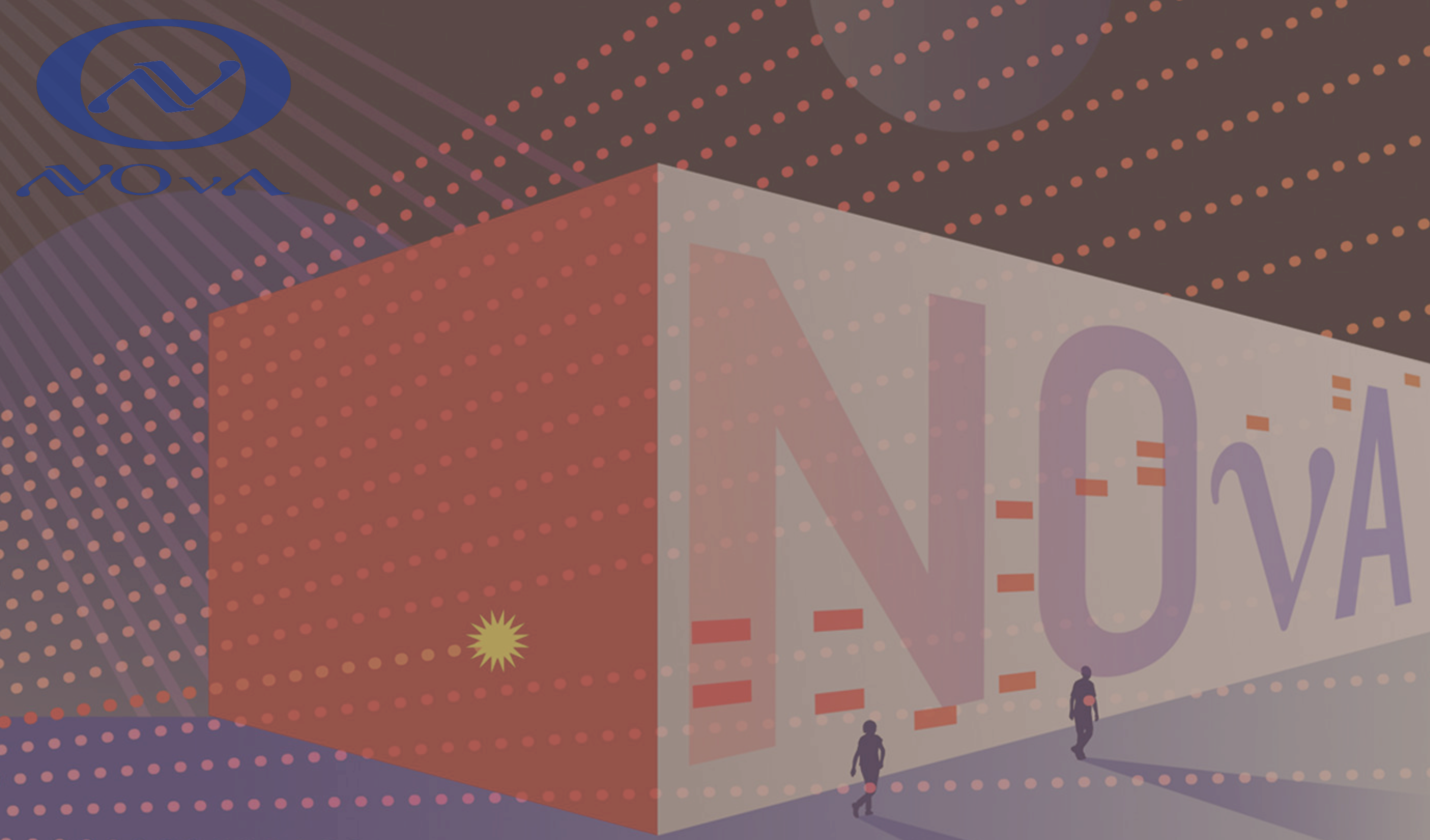


NOVA STATUS

Patricia Vahle, On Behalf of the NOvA Collaboration
William and Mary

NOvA

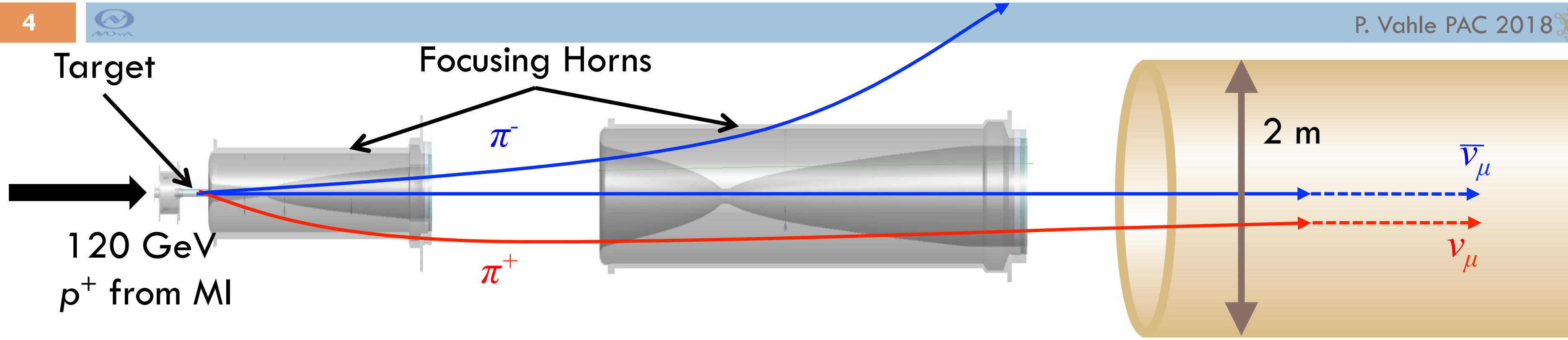
- NOvA addresses compelling questions from P5 Science driver: Investigation of the Physics of Neutrino Mass
  - What is the Neutrino Mass Hierarchy?
  - Is there CP symmetry violation in neutrinos?
  - What is the pattern of mixing?
  - Is there more to it than 3x3 PMNS?

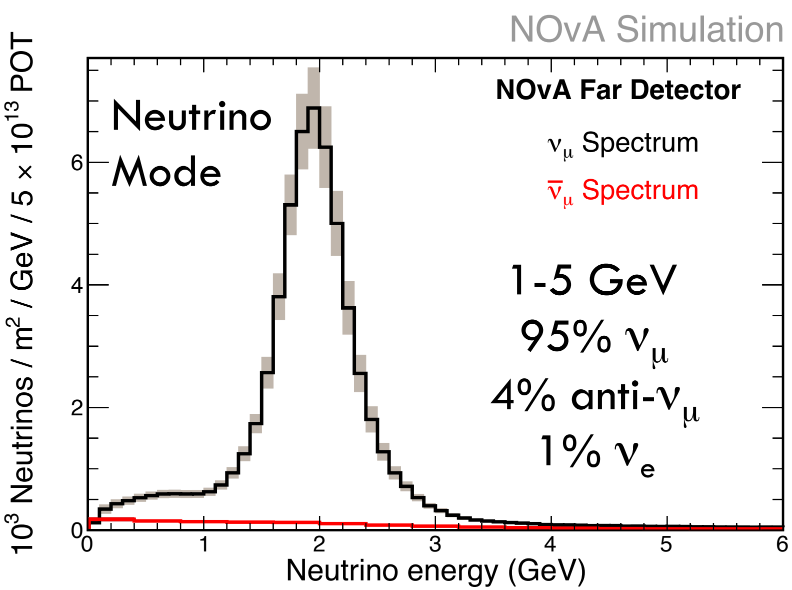
- Long-baseline neutrino oscillation experiment
  - Study muon neutrino disappearance, electron neutrino appearance, and flavor-independent (NC) disappearance with both neutrinos and antineutrinos
  - 2 Detectors separated by 810 km
  - High power and high purity neutrino and antineutrino beams

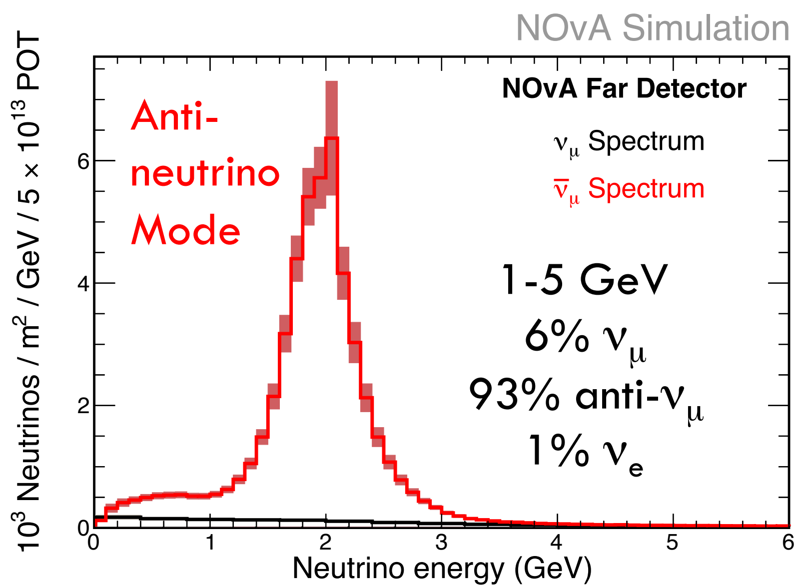
NOvA Collaboration

238 collaborators at 49 institutions across 7 countries

Making an off-axis neutrino beam

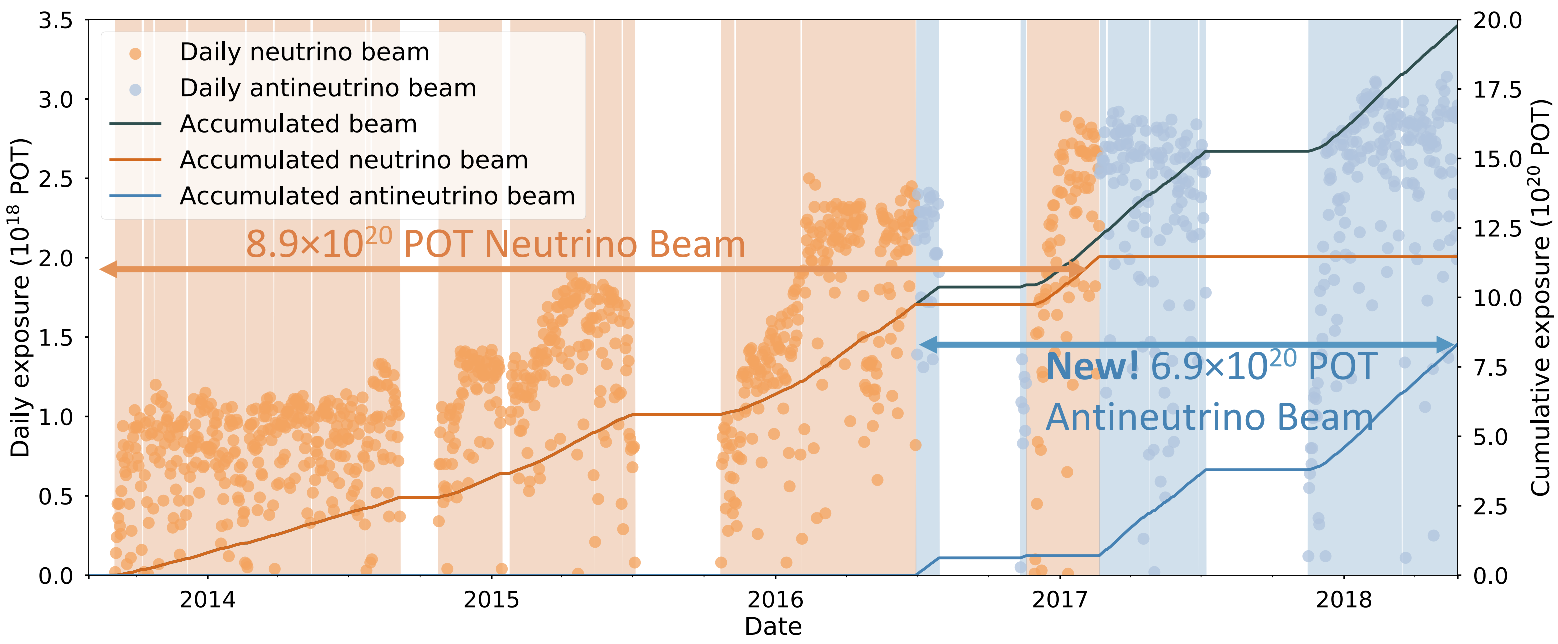




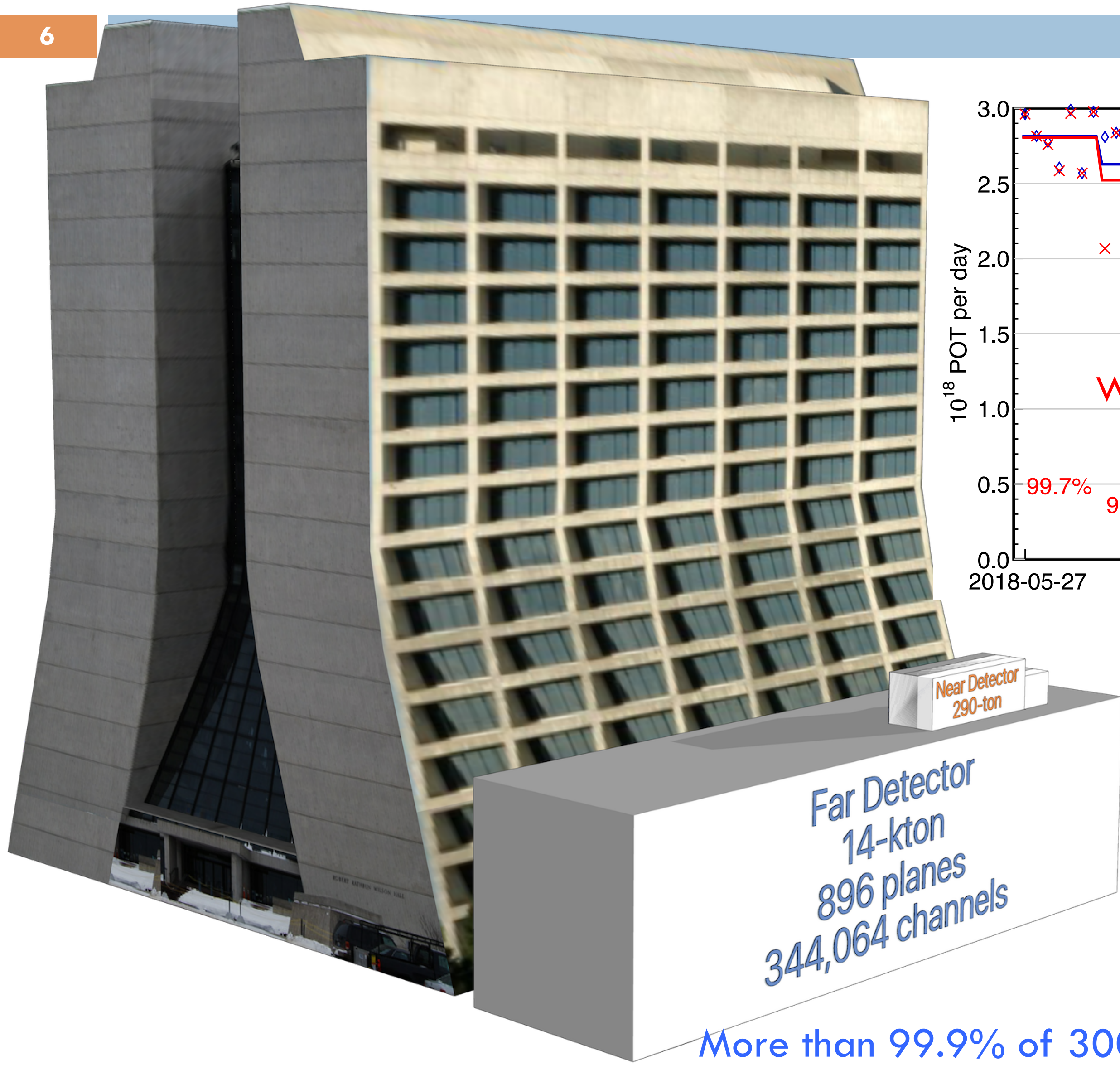


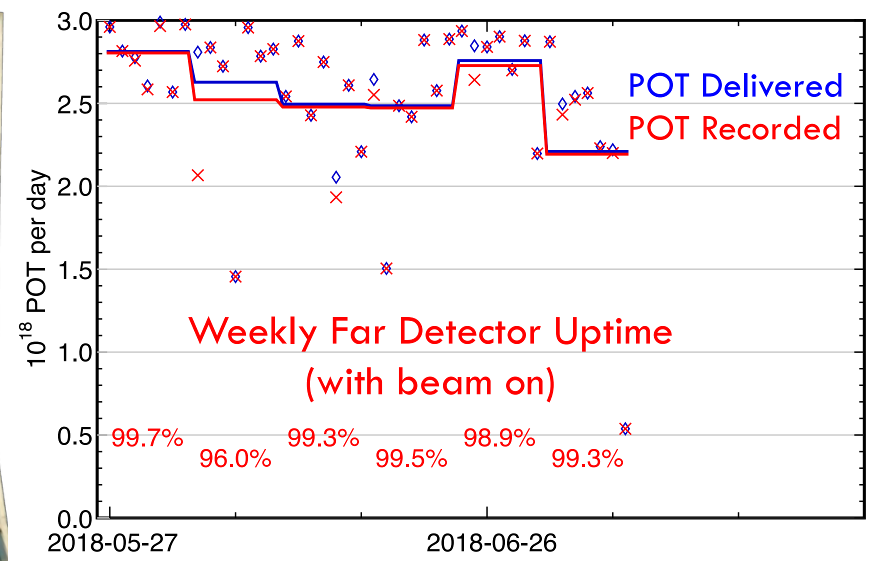
Beam Performance

- Run at 700 kW design goal since January 2017
  - 5.64e20 POT delivered in FY18, exceeding goal, best year so far by 10%
  - 34 weeks of running at 98.7% uptime



NOvA Detectors



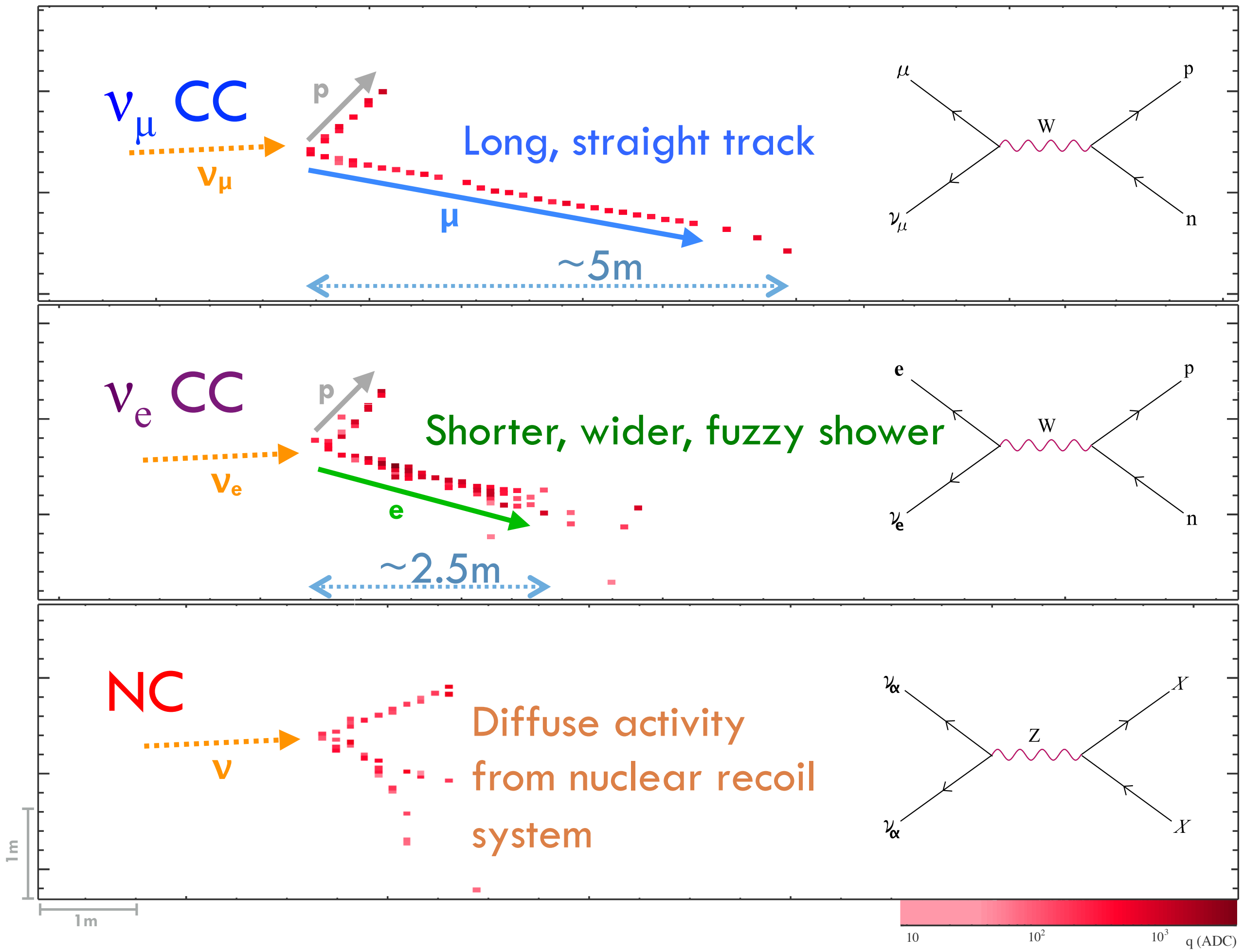


- Functionally identical detectors designed for electron ID
  - Low Z materials (PVC+Liquid Scint.)
  - 65% active
- ND: underground at FNAL
- FD: on the surface in Ash River, MN

More than 99.9% of 300k+ FD channels are operational!

Event Selection

Candidate Events from ND data



NOvA has pioneered the use of computer vision and deep learning techniques for event selection

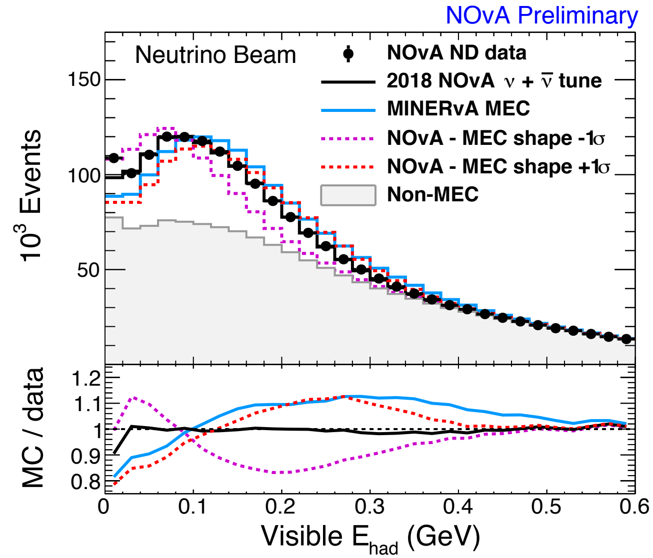
- Calibrated hit maps are inputs to Convolutional Visual Network (CVN)
- Series of image processing transformations applied to extract abstract features
- Extracted features used as inputs to a conventional neural network to classify the event

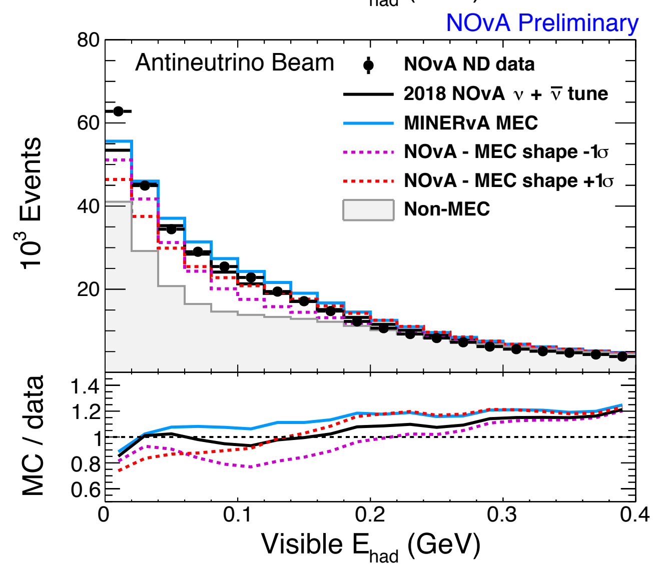
A. Aurisano et al., arXiv:1604.01444

NOvA Simulation

- All NOvA oscillation analyses use ND data to predict FD
  - 2 detector technique naturally mitigates uncertainties on flux and cross sections
  - Simulation used for acceptance and resolution corrections, helps characterize impact of residual systematic uncertainties
- Perfect ND data/mc not required, tuning makes for a more robust prediction
  - Flux from PPFX—package developed on MINERvA based on hadron production data

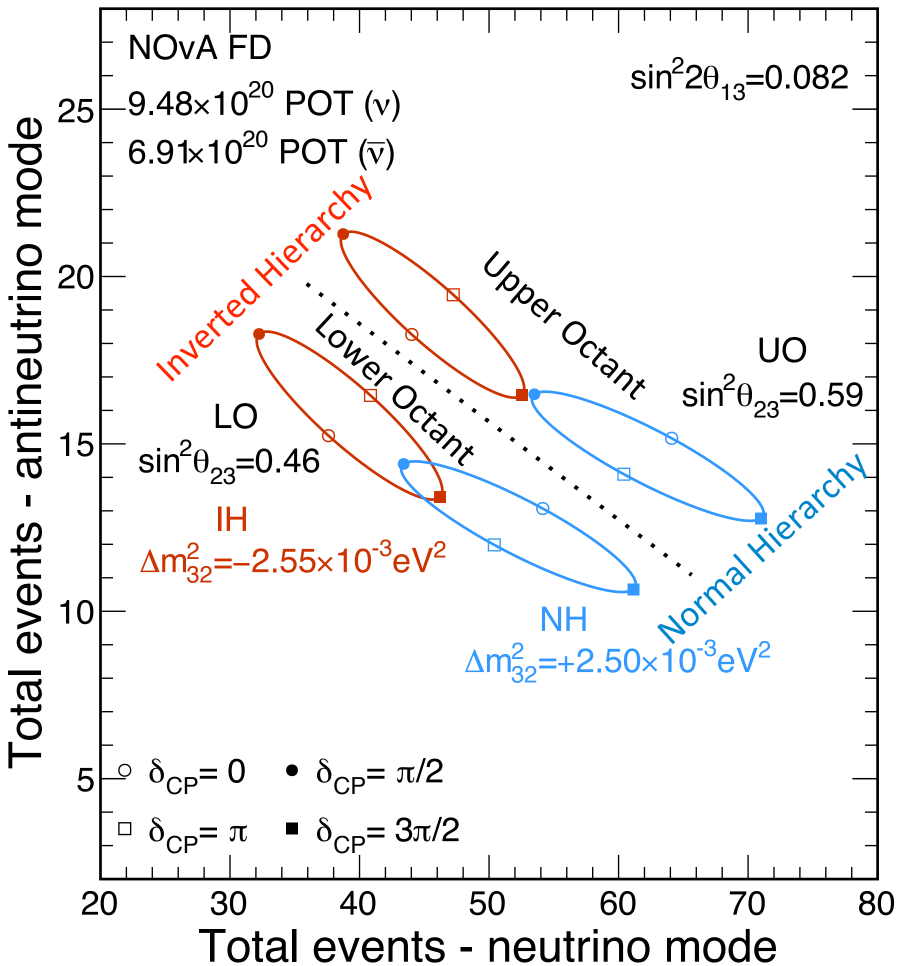
    (Phys. Rev. D 94, 092005. 2016)
  - neutrino interaction tuning guided by MINERvA experience (arXiv:1705.02932 and arXiv:1601.01888)
  - Custom tuning of GENIE Empirical MEC model
- Workshop with MINERvA planned for this fall to share GENIE tuning techniques





Analysis Basics

- Compare electron-neutrino appearance probability in neutrinos to antineutrinos
  - in vacuum with no CP violation, the two should be the same
  - CP violation enhances oscillation probability for neutrinos while suppressing it for antineutrinos, or vice-versa
  - matter effects also introduce mass hierarchy dependent neutrino vs. antineutrino differences
  - upper octant enhances both neutrino and antineutrino oscillation probability, while lower octant suppresses both



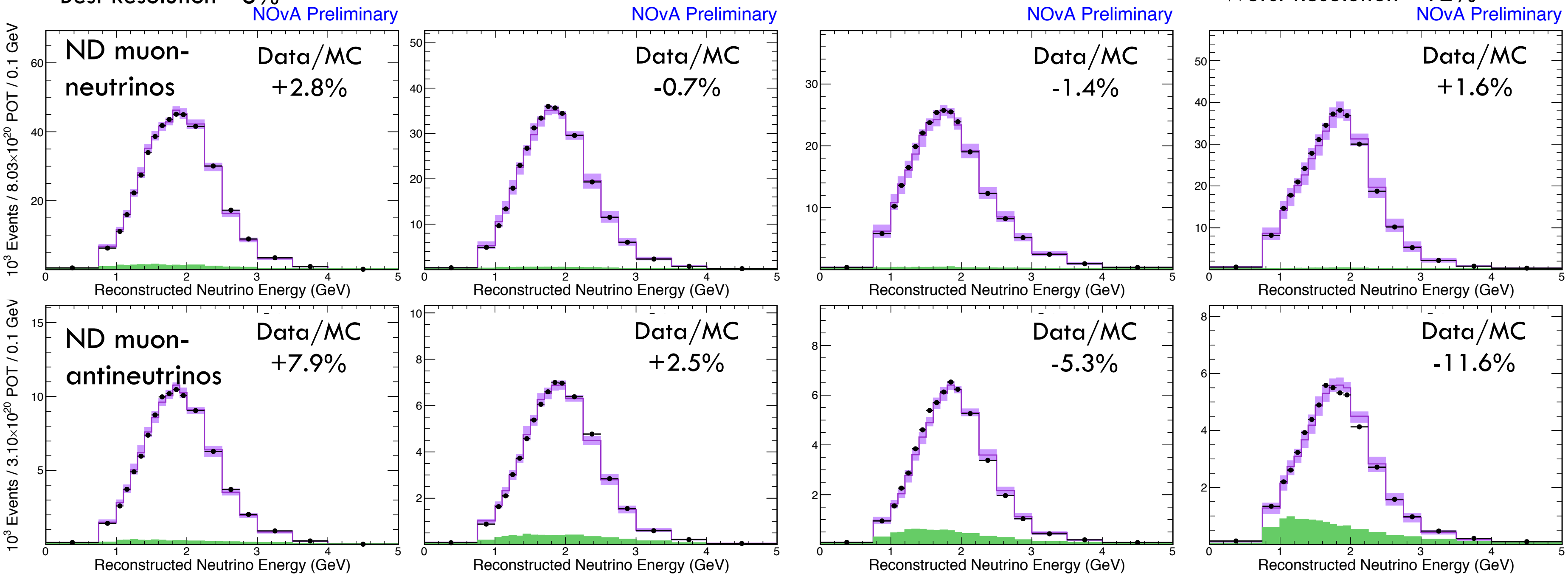
Analysis in more detail

Data
Area-normalized MC
Shape-only systematics
Wrong-sign

- Full power comes from joint fit to energy dependence of both disappearance and appearance in neutrinos and antineutrinos
  - Muon neutrino spectra further separated by energy resolution
  - Electron neutrino spectra further separated by event sample purity

Quantile 1
Best Resolution ~6%

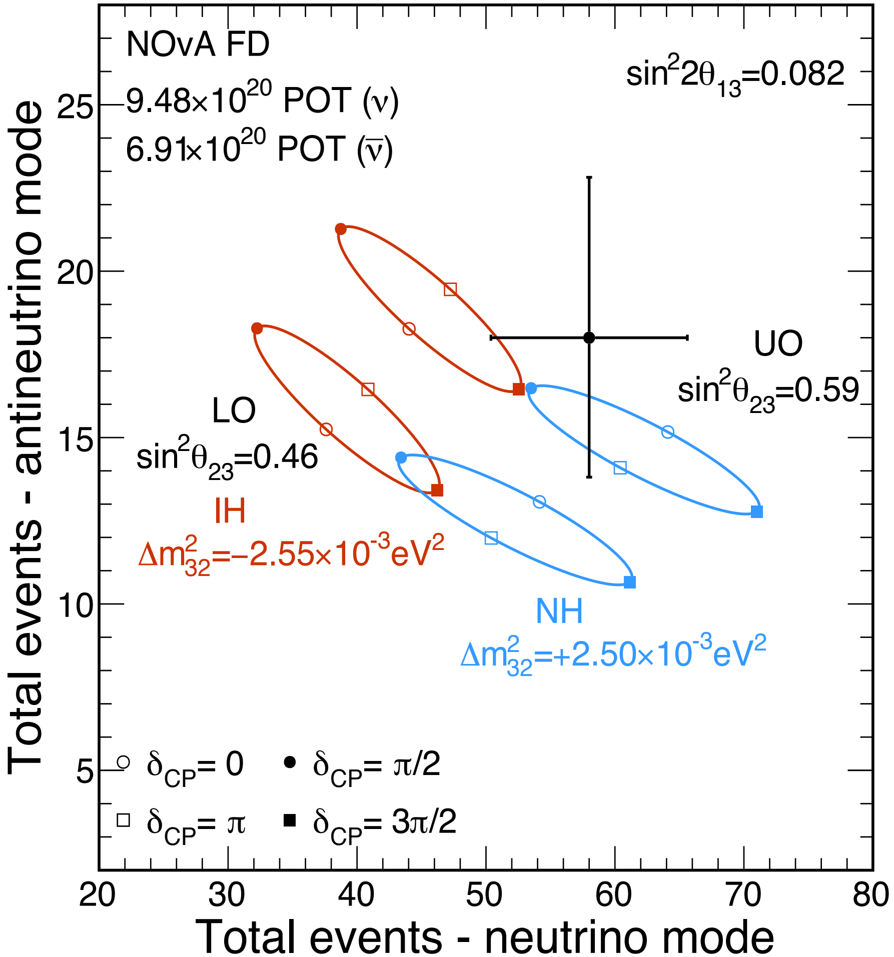
Quantile 4
Worst Resolution ~12%



Appearance Results

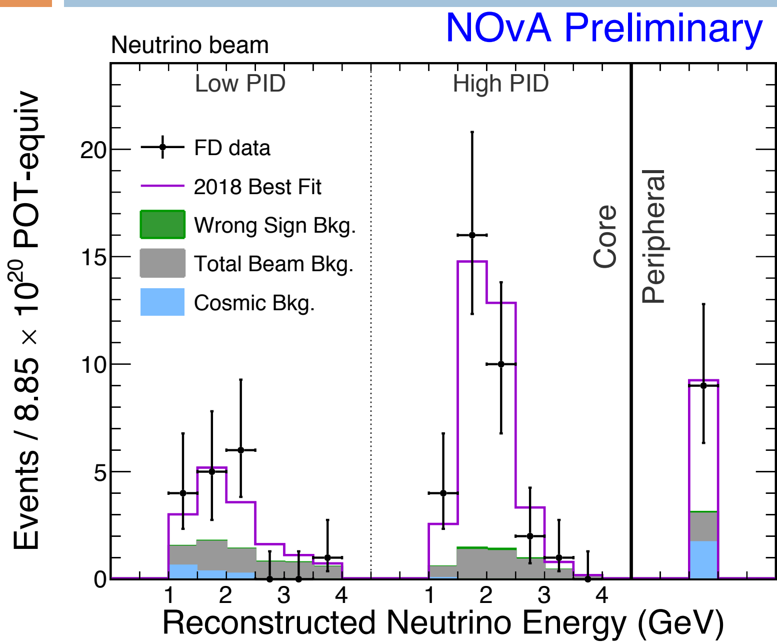
- Neutrino mode
  - 58 events observed
  - 15 bkg expected
- Antineutrino mode
  - 18 events observed
  - 5 bkg expected

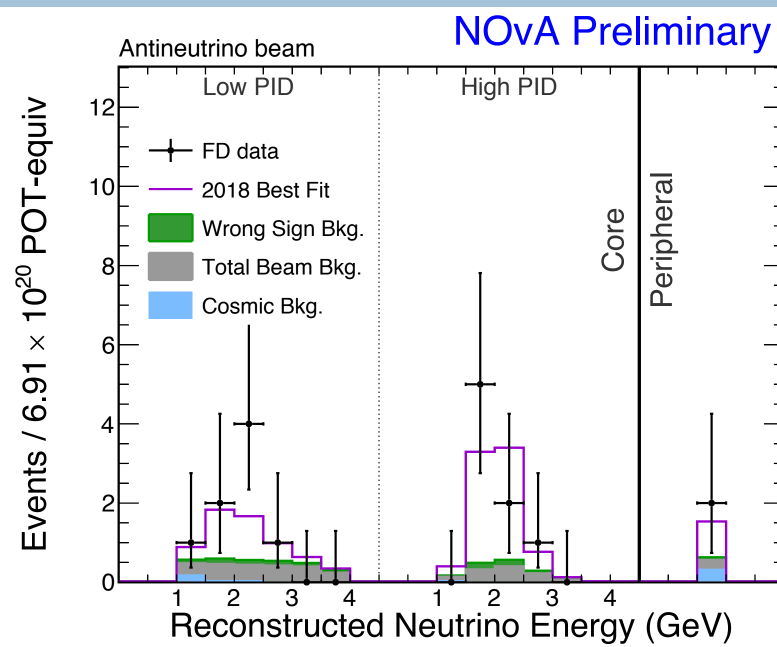
    (including 1 wrong sign)



Strong (>4 sigma) evidence of electron antineutrino appearance

Appearance Spectra





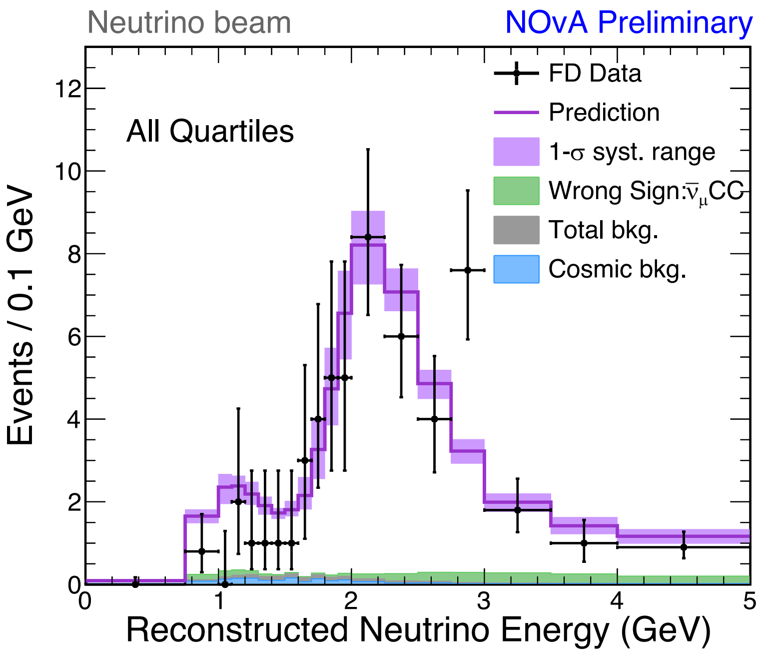
Neutrino Mode

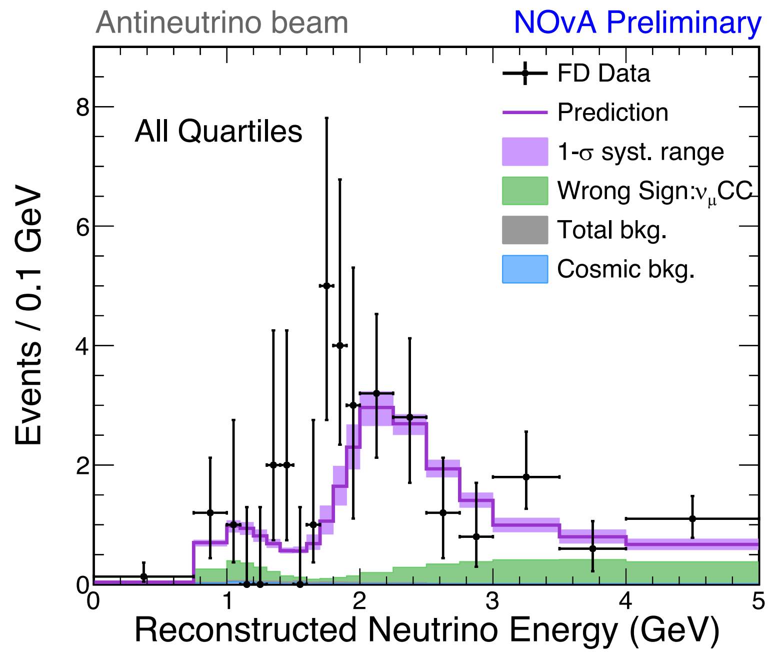
Total Observed	58	Range
Total Prediction	59.0	30-75
Wrong-sign	0.7	0.3-1.0
Beam Bkgd.	11.1	
Cosmic Bkgd.	3.3	
Total Bkgd.	15.1	14.7-15.4

Antineutrino Mode

Total Observed	18	Range
Total Prediction	15.9	10-22
Wrong-sign	1.1	0.5-1.5
Beam Bkgd.	3.5	
Cosmic Bkgd.	0.7	
Total Bkgd.	5.3	4.7-5.7

Disappearance Spectra



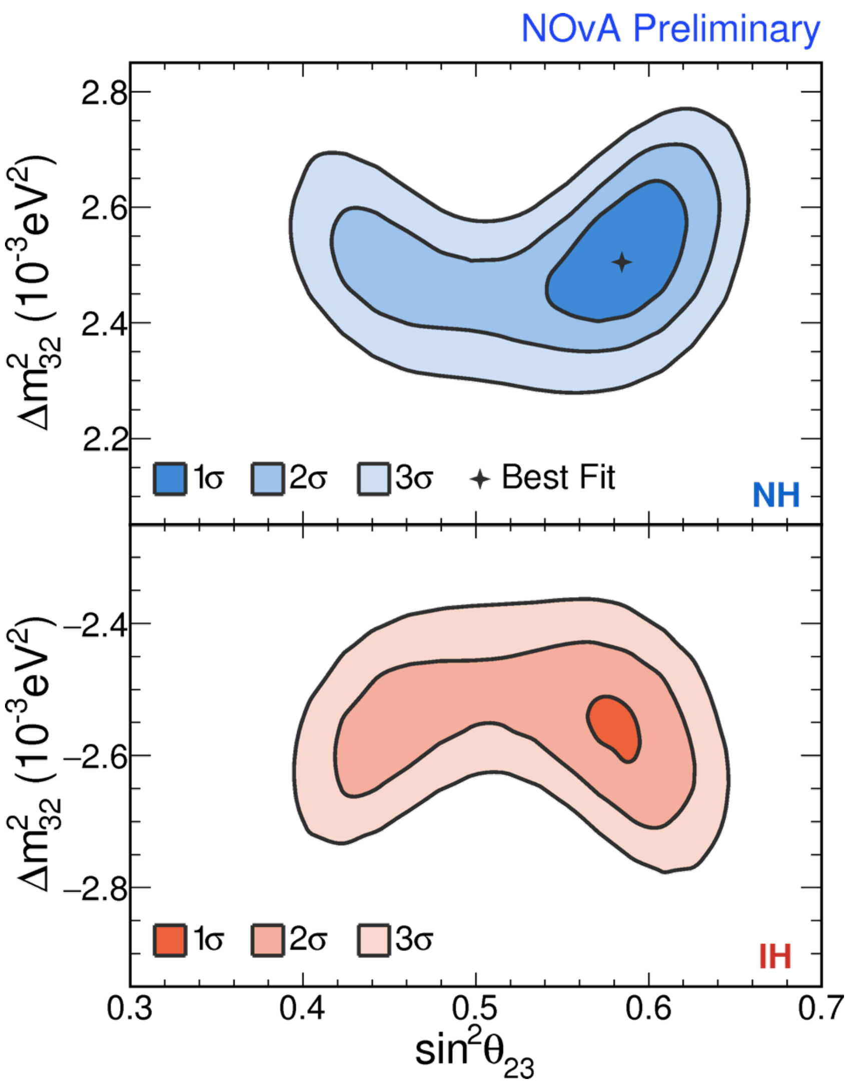


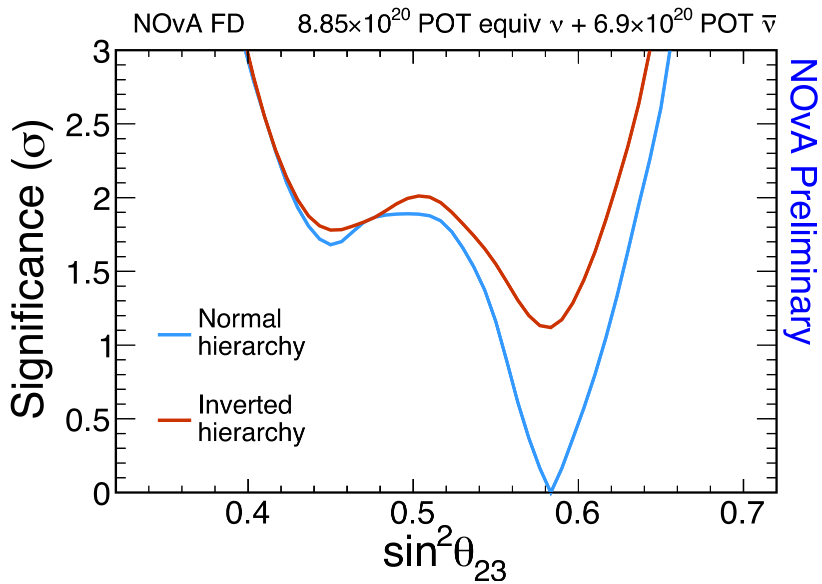
Total Observed	113
Best fit prediction	121
Cosmic Bkgd.	2.1
Beam Bkgd.	1.2
Unoscillated	730

Some tension in disappearance of neutrino vs. antineutrino; Antineutrinos show less disappearance. Results are compatible at better than 4% level.

Total Observed	65
Best fit prediction	50
Cosmic Bkgd.	0.5
Beam Bkgd.	0.6
Unoscillated	266

Appearance and Disappearance Fit Results





Best Fit

Normal Hierarchy

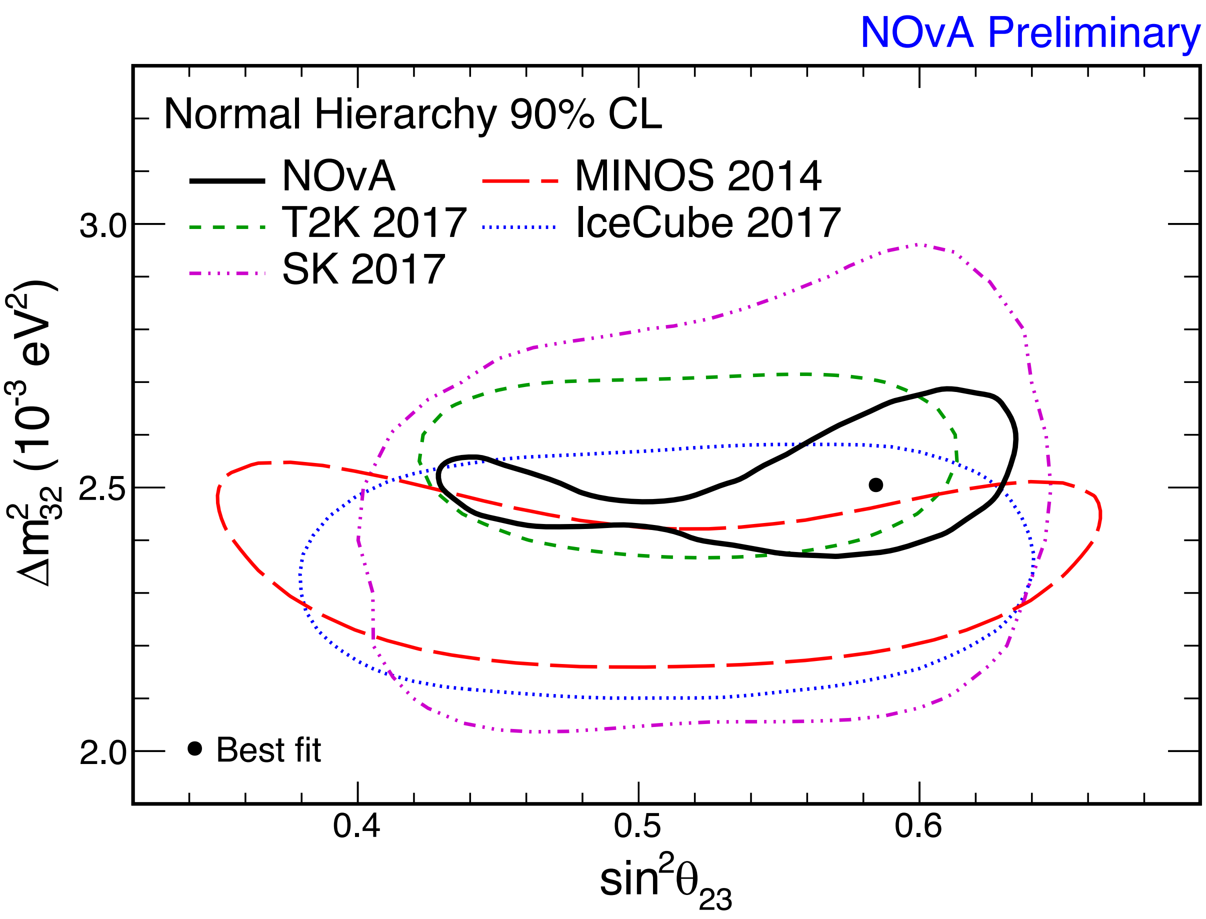
$$\Delta m^2_{32} = 2.51^{+0.12}_{-0.08} \times 10^{-3}\text{eV}^2$$

$$\sin^2\theta_{23} = 0.58 \pm 0.03$$

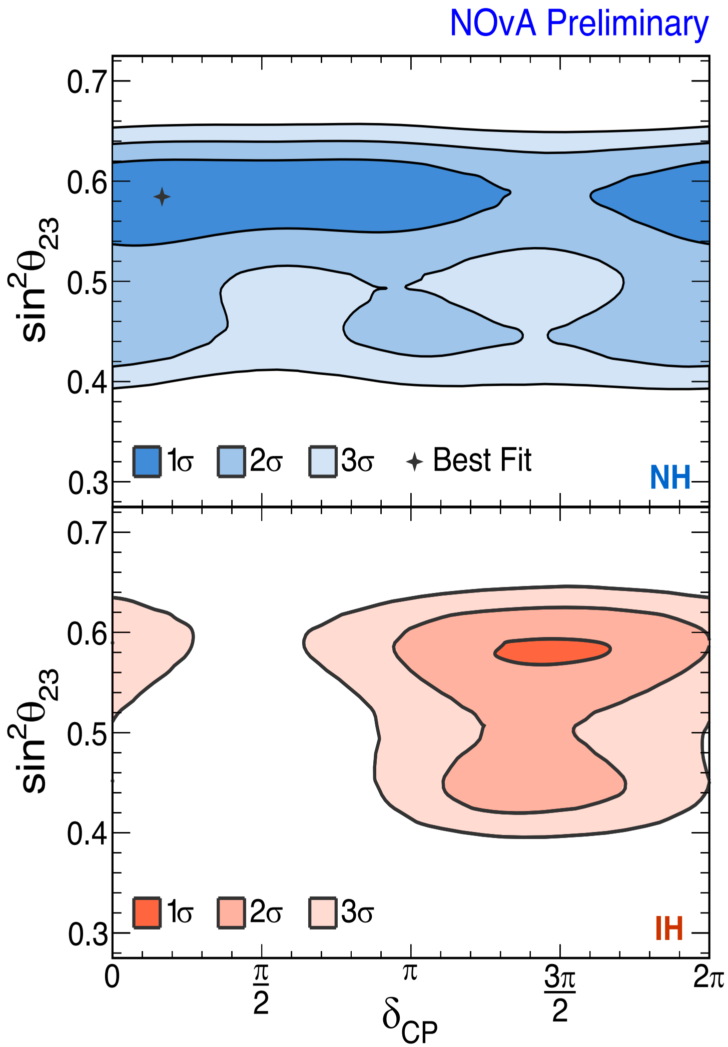
(Upper Octant)

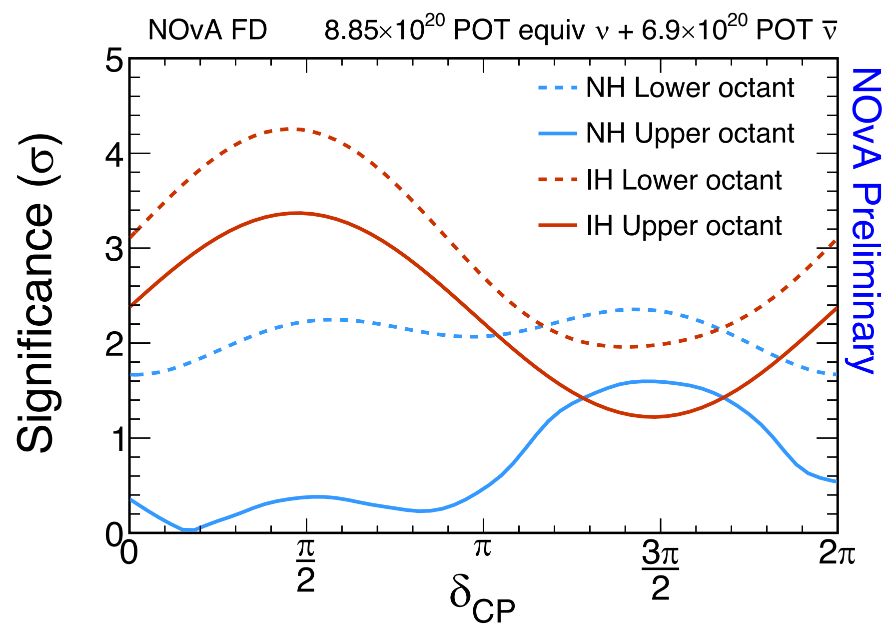
$$\delta_{CP} = 0.17\pi$$

Appearance and Disappearance Fit Results



Appearance and Disappearance Fit Results





Normal Hierarchy preferred at 1.8 sigma

Exclude pi/2 in the IH at > 3 sigma

Significances determined using Feldman-Cousins approach.

Leveraged high performance computing at NERSC

http://news.fnal.gov/2018/07/fermilab-computing-experts-bolster-nova-evidence-1-million-cores-consumed/

Publications and PhDs

- 5 Publications + 1 submitted
  - arXiv:1806.0096 (2 cites)
  - Phys.Rev.D96 (2017) no. 7, 072006 (19 cites)
  - Phys.Rev.Lett. 118 (2017) no. 23, 231801 (83 cites)
  - Phys.Rev Lett. 118 (2017) no. 15, 151802 (83 cites)
  - Phys.Rev.D93 (2016) no. 5, 051104 (102 cites)
  - Phys.Rev. Lett.116 (2016) no. 15, 151806 (167 cites)
- 19 PhDs, 5 since last summer
  - Dan Pershey, CalTech
  - Stefano Tognini, Universidade Federal de Goias, Brazil
  - Fernanda Psihas, Indiana
  - Bio Wang, SMU
  - Luke Vinton, Sussex, UK

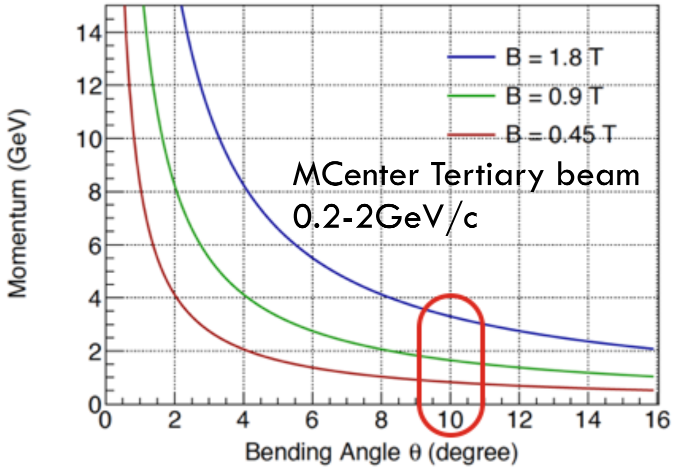
Future Oscillation Analysis Strategy

- Program planning advises us to expect to run to 2024
- Run plan:
  - Antineutrinos until 12e20 POT (fulfills MINERvA request)
  - Approx. 50%-50% neutrino-antineutrino beyond
- Analysis plans
  - 2019: top up on antineutrinos
  - 2020: with ~double neutrino exposure
  - Beyond: Increasing exposure, Joint analysis with T2K
- Analysis improvements in the works
  - More sophisticated cross section tuning
  - Better understanding of neutron response/ simulation
  - More sophisticated ND decomposition for nue
  - More sophisticated treatment of wrong sign
  - Testbeam

so far, 3 joint T2K meetings, with another planned this fall. Gaining mutual understanding of cross section uncertainties, with an eye to developing treatment of correlated systematics in joint fit

Testbeam

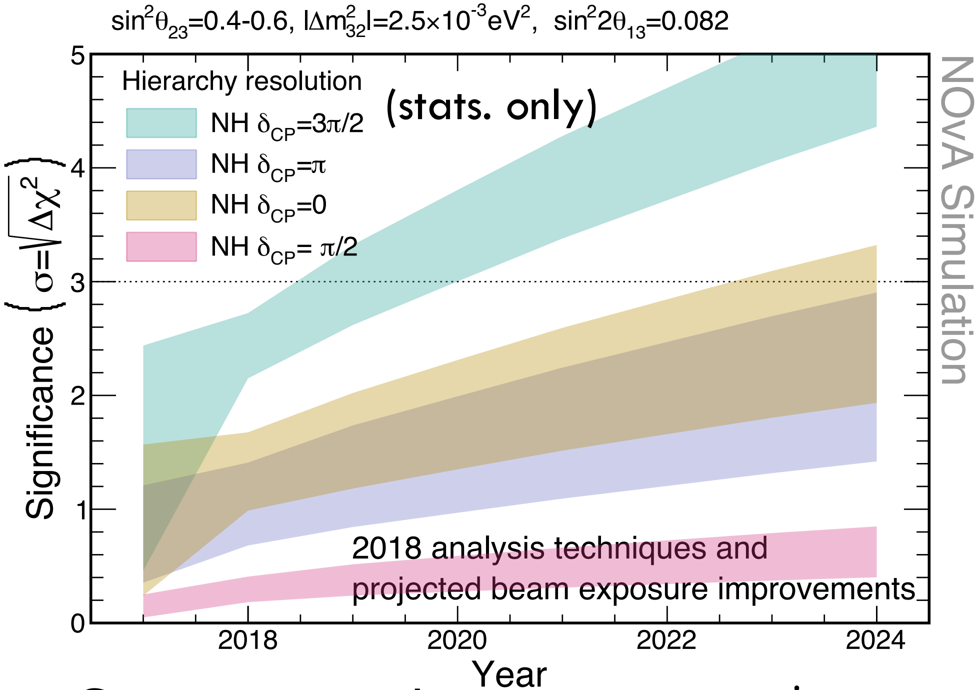
- Testbeam program addresses dominant NOvA systematic errors
  - energy scale for muons, hadrons, EM showers
  - relative calibration
  - light/scintillator response model
- Provides real (tagged) data for sophisticated machine learning particle ID algorithms
- Installation begins this summer
  - Data collection starts end of the calendar year



Proposed Accelerator Improvement Projects

- 2 accelerator improvement projects have the potential to boost NuMI power beyond 700kW (up to 900kW-1MW)
  - Target System
    - New target design rated for 1MW
    - Improved horn stripline cooling
    - Radioactive water system upgrade
    - Target chase chiller and air handling upgrade
  - Intensity
    - Assorted projects to lower Booster losses
- Projects not only enable higher power, but improve reliability, mitigate risk
  - Lifetime extension to 2024
  - Support plan to run 40+ weeks/year (recent experience is 34-40)
- In our projections, we assume:
  - Power at 800 kW in FY19, 900kW in FY20-21, 1MW beyond
  - 40 weeks of running a year with uptime comparable to current running

Future Sensitivity



- Sensitivity dependent on true values in nature
- For favorable parameters consistent with results, we can achieve 3 sigma mass hierarchy sensitivity by 2020
  - 3 sigma sensitivity for 30-50% of delta CP range by 2024
  - >5 sigma in favorable cases by 2024, possible only with POT boosts from AIP work
- Compare to other experiments*:
  - T2K reports Bayes factor NH/IH=7.9 (NH preferred at ~89%)
  - SK prefers NH at at 80.6% to 96.7% (depending on θ_{23})
  - Juno 3-4 sigma sensitivity 6 years after start in 2021(depending on error on $\Delta m^2_{\mu\mu}$)
  - KM3Net/Orca 5 sigma in 2024/2025 (depending on θ_{23})

*Taken from Neutrino2018 talks by M. Wascko, Y. Hayuto, B. Wonsak, U. Katz

Beyond 3 flavor oscillations

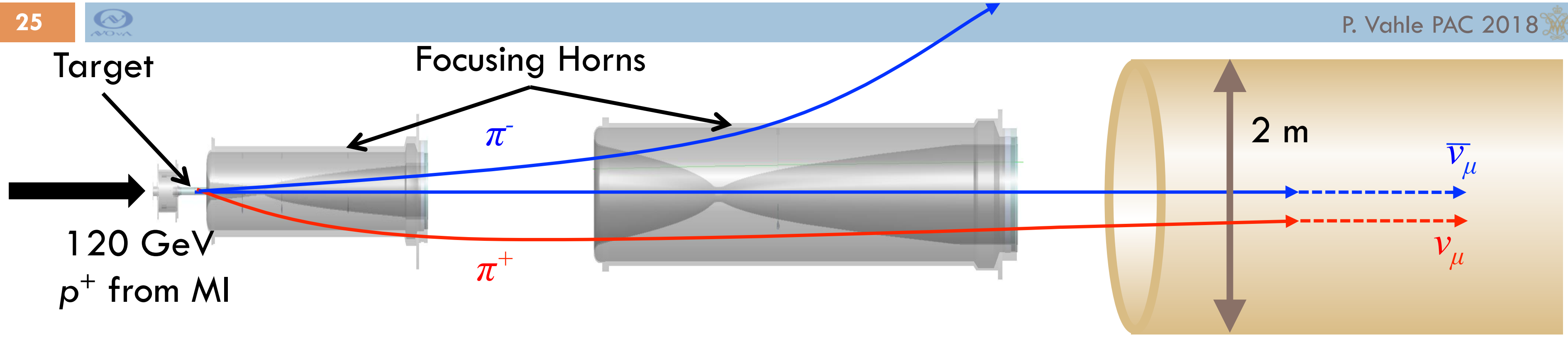
- Sterile Neutrinos
  - NC disappearance/anomalous muon neutrino (antineutrino) disappearance between ND and FD
  - SBL electron neutrino appearance in ND
  - Tau appearance in ND
- Neutrino interaction physics
  - Muon and electron neutrino charged current inclusive cross section
  - COH Pi0
  - CC Pi0 production
  - charged pion production
- Non-beam physics
  - Monopoles
  - Multi-muon cosmic ray events
  - Upward Muons
  - Supernova watch

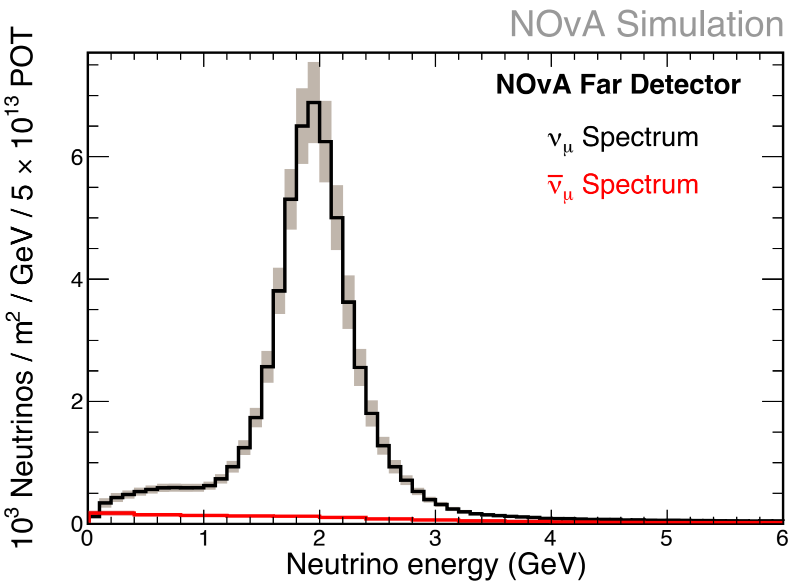
Summary

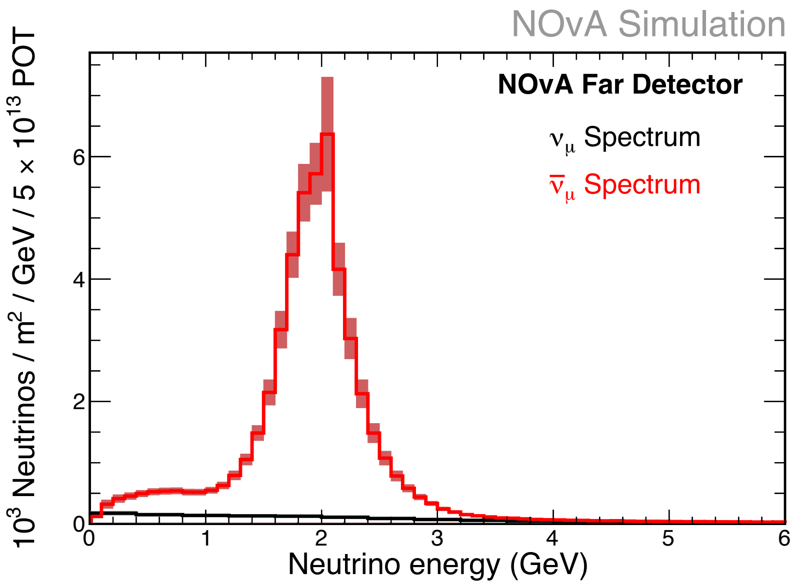
- First antineutrino results released this summer
  - >4 sigma evidence of electron-antineutrino appearance
  - 1.8 sigma preference for Normal Hierarchy
  - 1.8 sigma preference for non-maximal mixing
- Continue to take data in antineutrino mode until 12e20 POT, then switch back to neutrinos
- Can achieve 3 sigma mass hierarchy sensitivity for favorable parameters by 2020
- With beam improvements can reach 3 sigma sensitivity to 30-50% of delta CP range by 2024, >5 sigma for favorable parameters

Backup

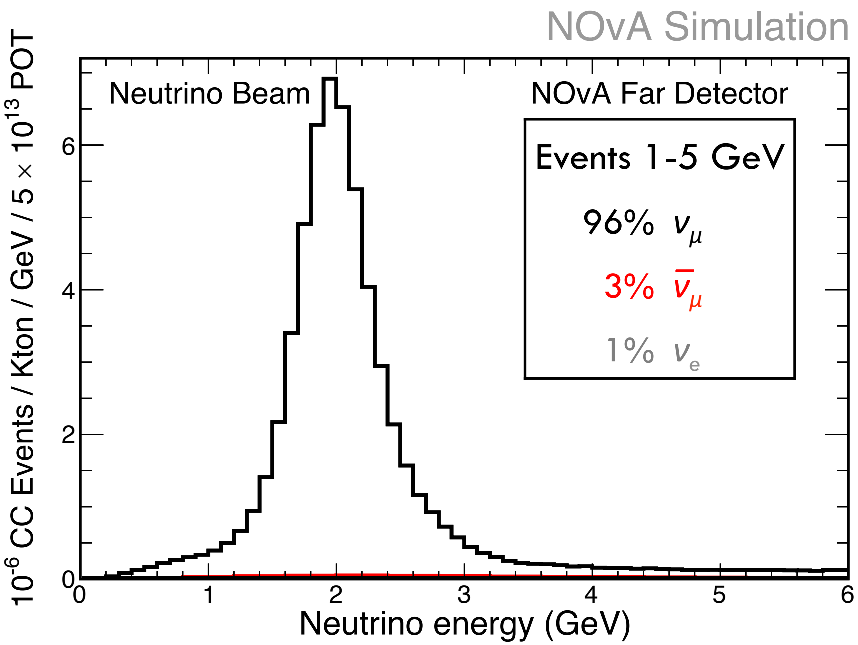
Making an off-axis neutrino beam

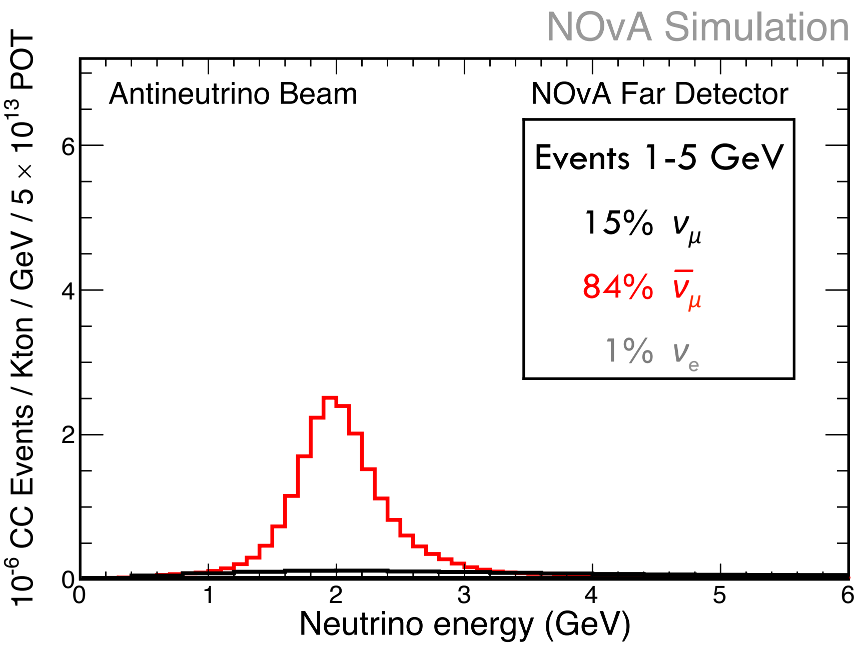






Beam Spectra

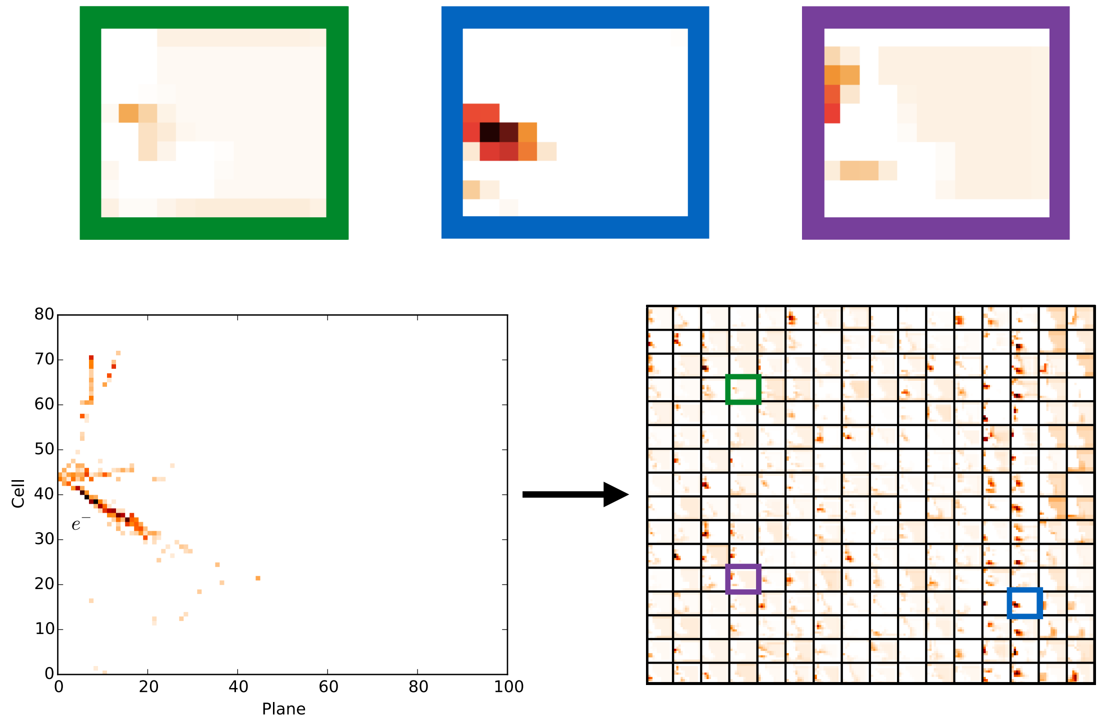




Improved Event Selection

- This analysis features a new event selection technique based on ideas from computer vision and deep learning

- Calibrated hit maps are inputs to Convolutional Visual Network (CVN)
- Series of image processing transformations applied to extract abstract features
- Extracted features used as inputs to a conventional neural network to classify the event

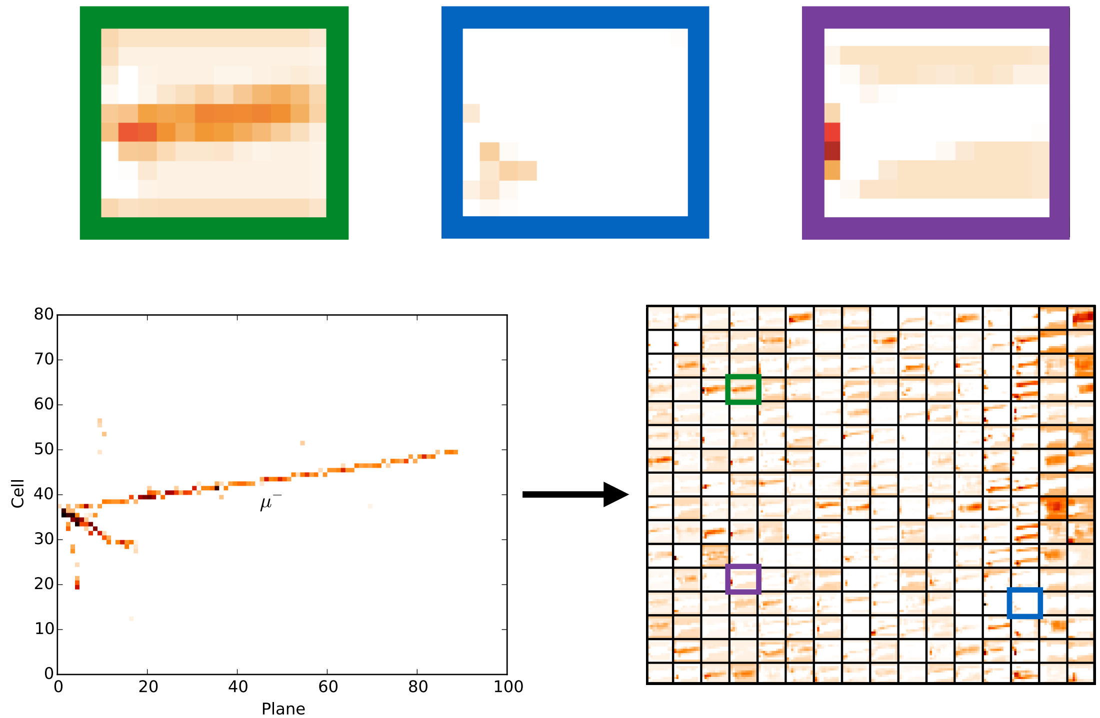


A. Aurisano et al., arXiv:1604.01444
Posters P1.028 by A. Radovic, P1.032 by F. Psihas and A. Himmel for more detail

Improved Event Selection

- This analysis features a new event selection technique based on ideas from computer vision and deep learning

- Calibrated hit maps are inputs to Convolutional Visual Network (CVN)
- Series of image processing transformations applied to extract abstract features
- Extracted features used as inputs to a conventional neural network to classify the event



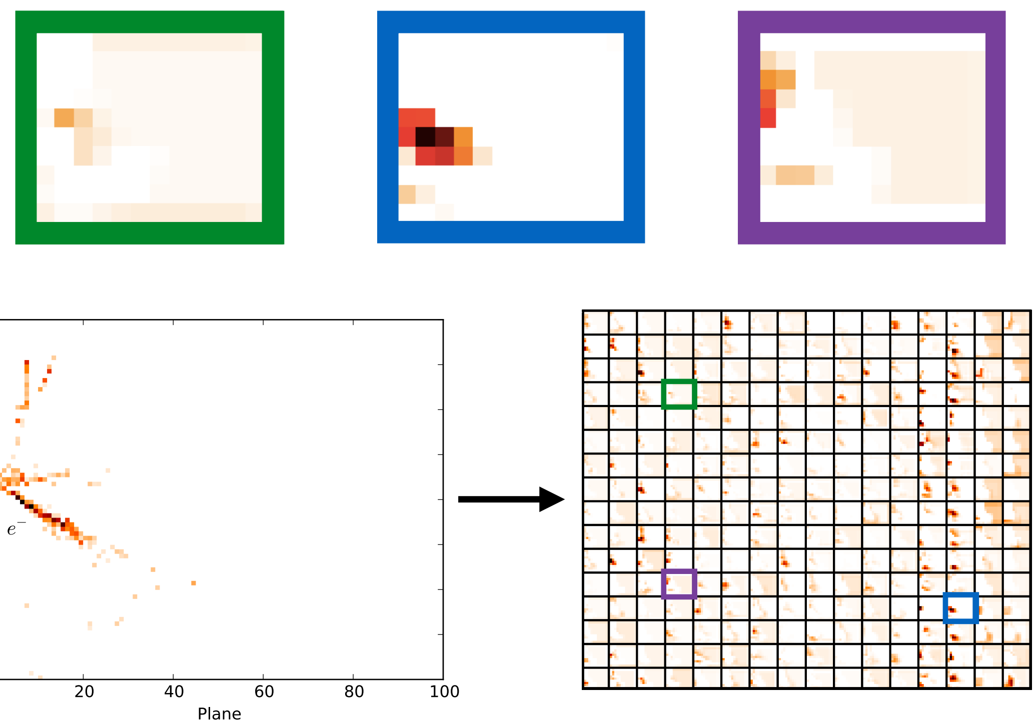
A. Aurisano et al., arXiv:1604.01444

Posters P1.028 by A. Radovic, P1.032 by F. Psihas and A. Himmel for more detail

Improved Event Selection

- This analysis features a new event selection technique based on ideas from computer vision and deep learning

- Calibrated hit maps are inputs to Convolutional Visual Network (CVN)
- Series of image processing transformations applied to extract abstract features
- Extracted features used as inputs to a conventional neural network to classify the event

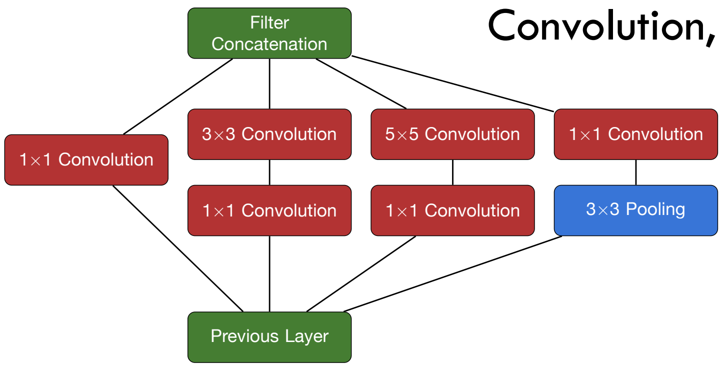


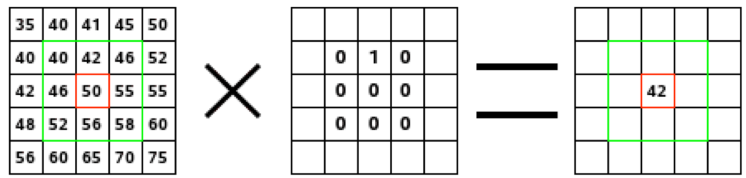
Improvement in sensitivity from CVN equivalent to 30% more exposure

A. Aurisano et al., arXiv:1604.01444
Posters P1.028 by A. Radovic and A. Himmel, P1.032 by F. Psihas

CVN Architecture

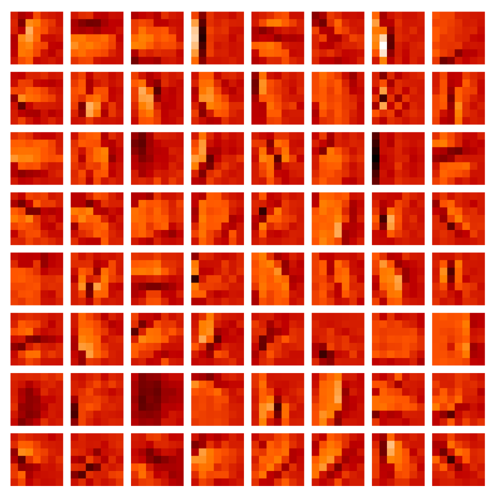
GoogLeNet Inception Module
C. Szegedy et al., arXiv:1409.4842



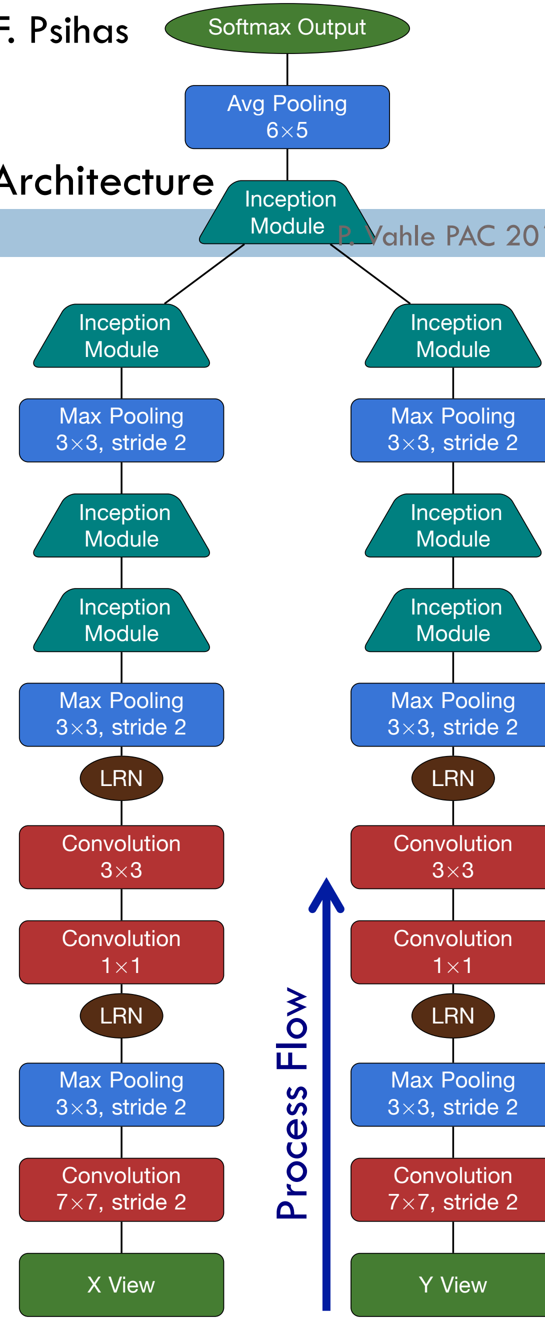


Example image processing transformation
Convolution, or kernel map

Example Convolutional Filter Layer



CVN Architecture

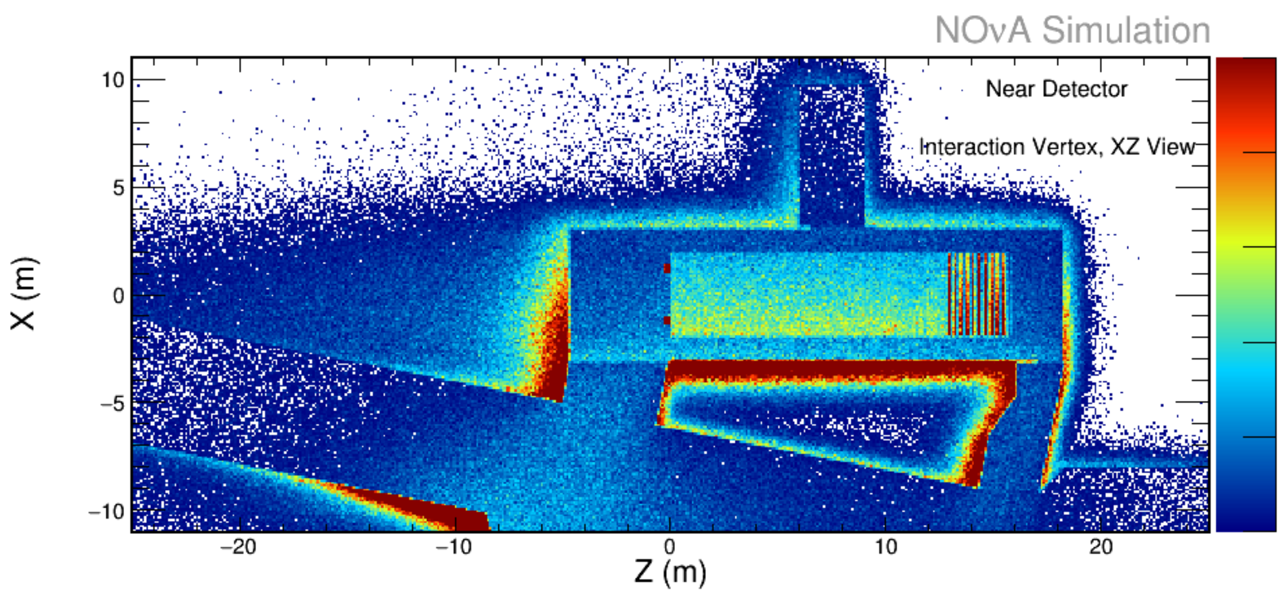


Network implemented and trained in the Caffe Framework
(Y. Jia et al., arXiv:1408.5093)

Trained over 4.7M simulated events,
Trained on FNAL GPU farm

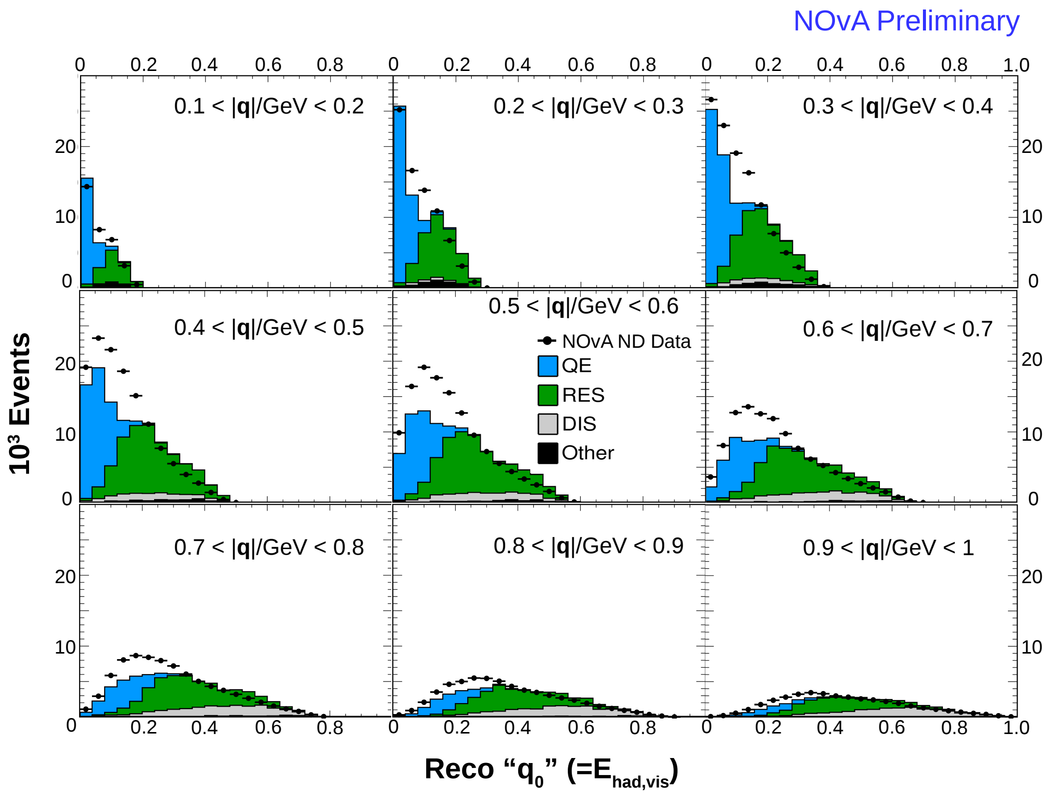
Simulation

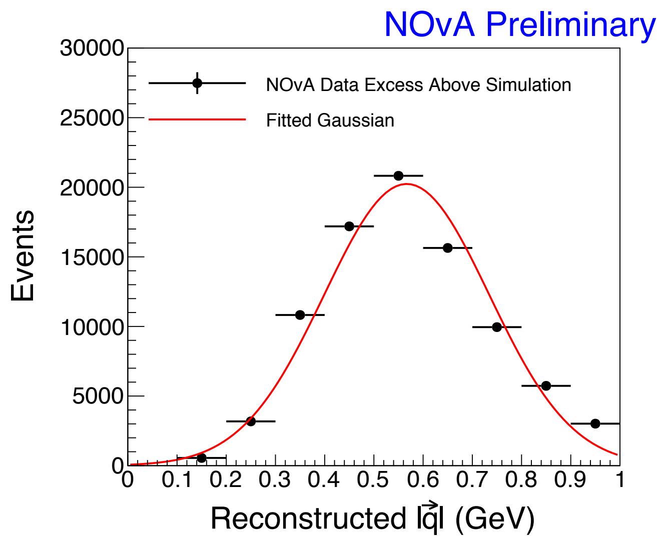
- Beam line production, propagation and neutrino flux: FLUKA/Flugg
- Cosmic Ray flux: CRY
- Neutrino interaction and FSI: GENIE
- Detector: Simulation: Geant4
- Detector response: Custom simulation Routines



Scattering in a Nuclear Environment

- Near detector hadronic energy distribution suggests unsimulated process between quasi-elastic and delta production

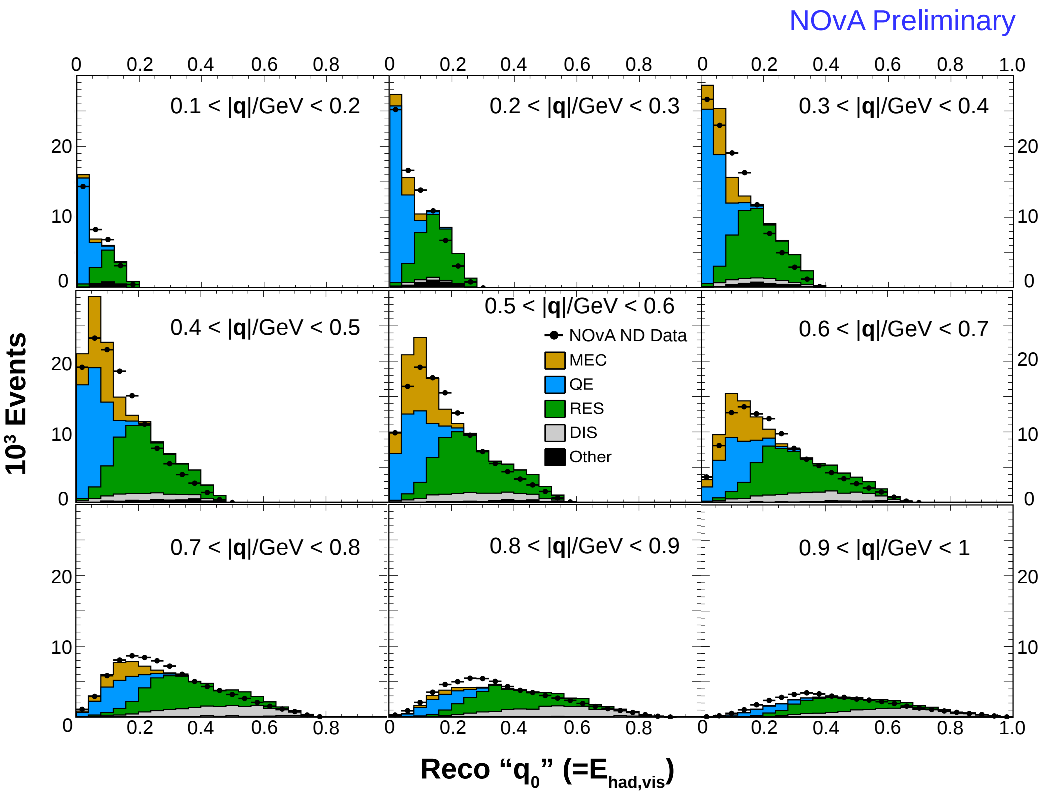




Similar conclusions from MINERvA data reported in P.A. Rodrigues et al., PRL 116 (2016) 071802

Scattering in a Nuclear Environment

- Enable GENIE empirical Meson Exchange Current Model
- Reweight model to match NOvA excess as a function of 3-momentum transfer

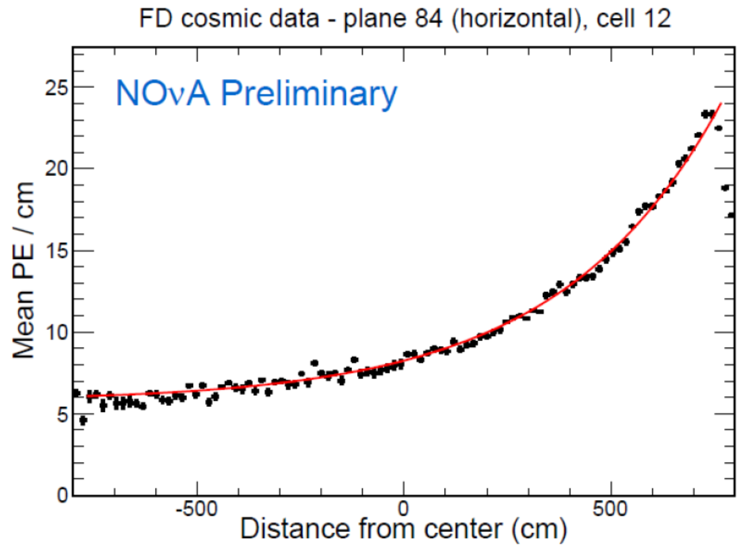


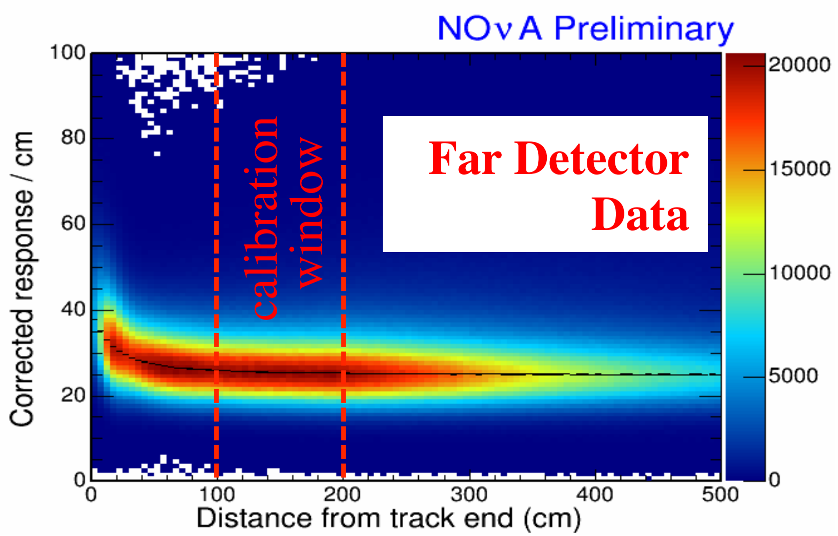
- Eliminate falloff of xsec with energy
- Fix final state nucleon composition
- Match MEC q_0 distribution to quasi-elastic distribution
- scale normalization in bins of 3-momentum transfer to match data/mc disagreement
- Include 50% systematic uncertainty on size of MEC component
- Additionally, reduce single non-resonant pion production by 50%

(P.A. Rodriques et al, arXiv:1601.01888.)

Calibration

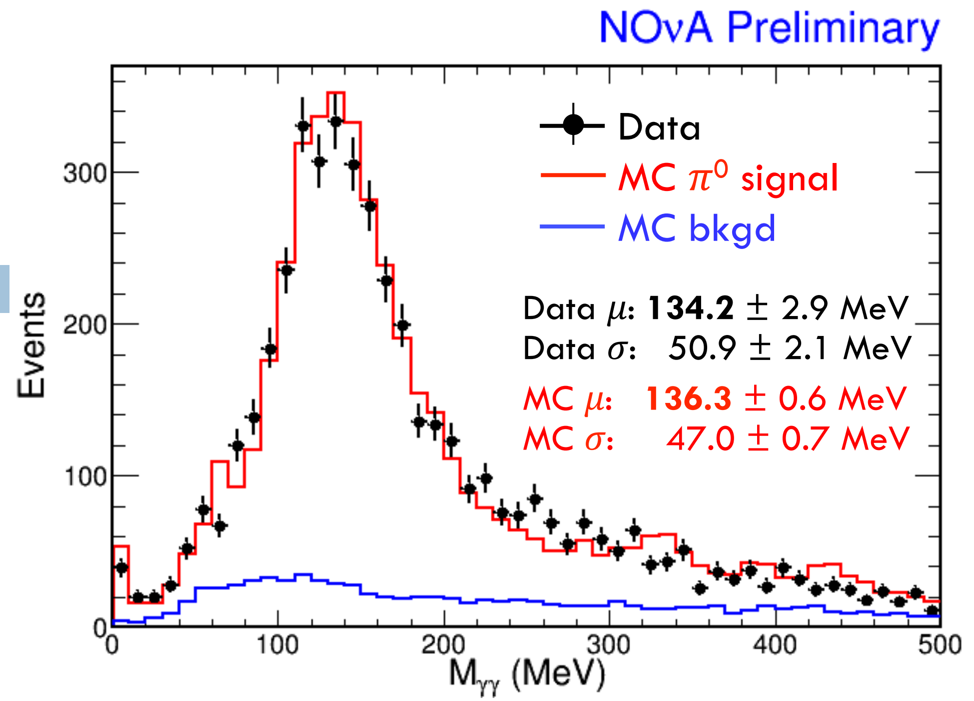
- Calibration achieved using cosmic rays
- Light levels drop by a factor of 8 across a FD cell
- Stopping muons provide a standard candle

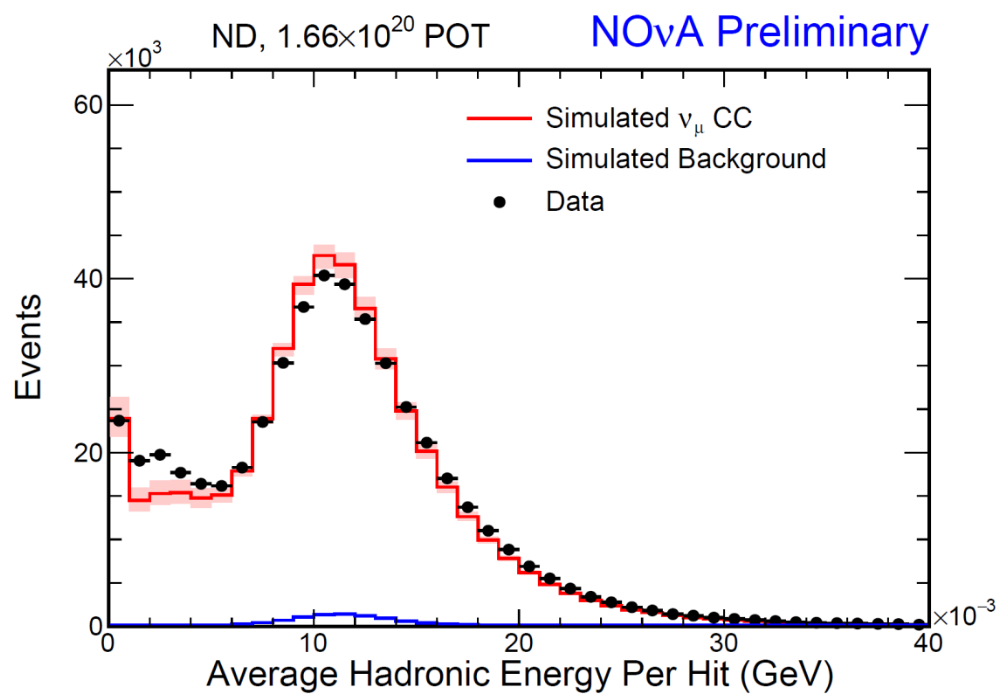




Energy Scale

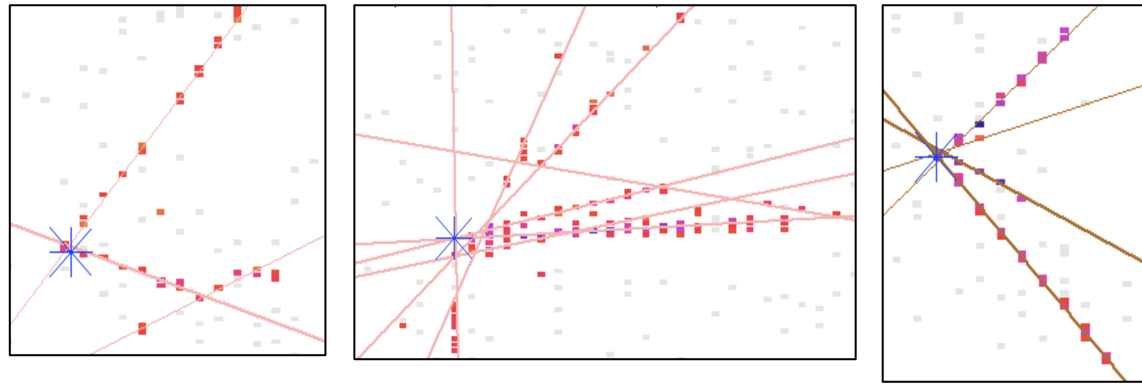
- Near Detector
  - cosmic μ dE/dx [~vertical]
  - beam μ dE/dx [~horizontal]
  - Michel e⁻ spectrum
  - π^0 mass
  - hadronic shower *E*-per-hit
- Far Detector
  - cosmic μ dE/dx [~vertical]
  - beam μ dE/dx [~horizontal]
  - Michel e⁻ spectrum
- All agree to 5%



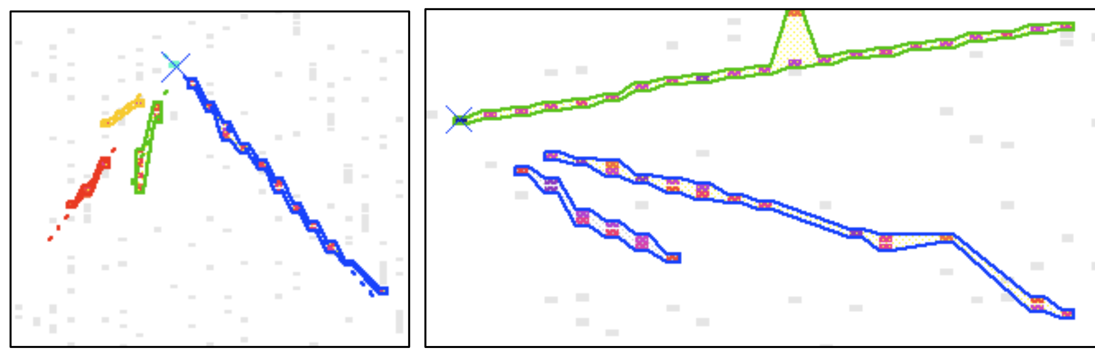


Reconstruction

Vertexing: Find **lines of energy depositions** w/ Hough transform CC events: 11 cm resolution



Clustering: Find **clusters in angular space** around vertex. **Merge views** via topology and prong dE/dx

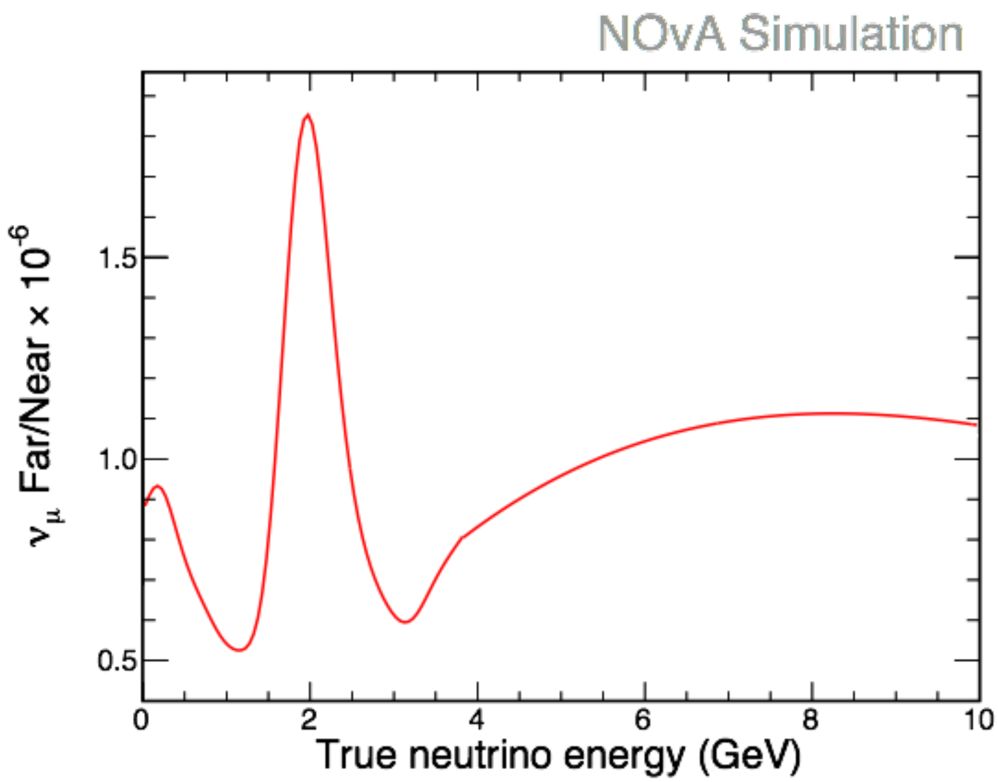


Tracking: Trace particle trajectories with **Kalman filter** tracker.
Also, **cosmic ray tracker:** lightweight, fast, and for large calibration samples, online monitoring.

Extrapolation

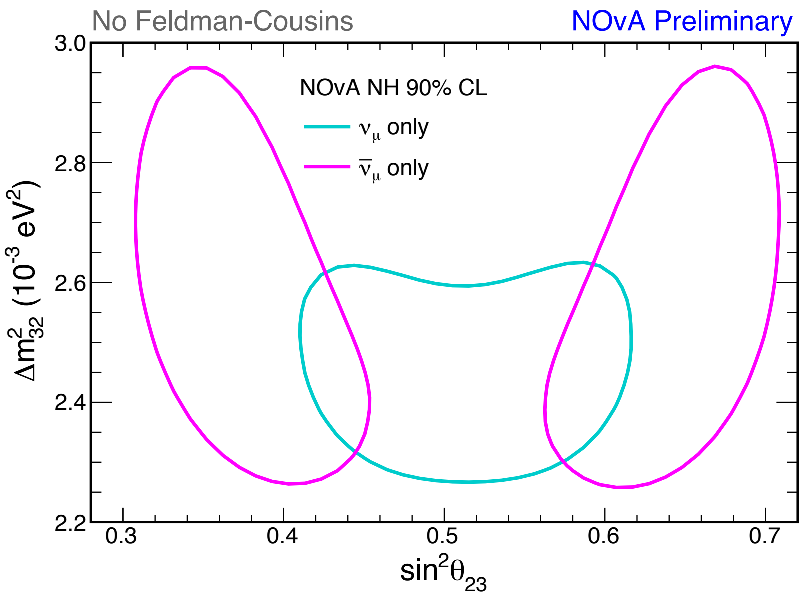
- All NOvA analyses use ND data to predict the FD spectrum

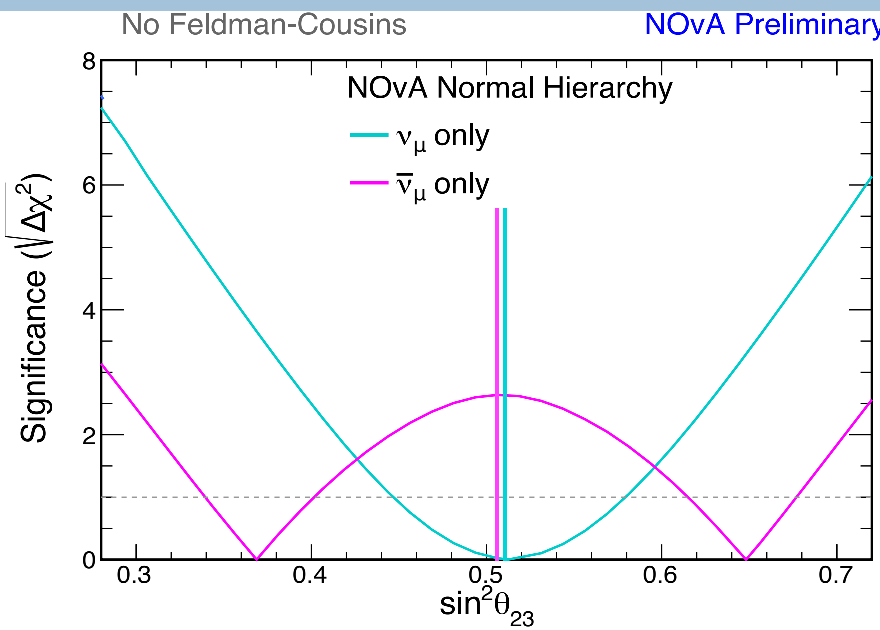
  - Muon Neutrino analyses: unfold reco energy, use true F/N ratio for FD prediction of track events
  - Electron Neutrino signal: use Muon-neutrino FD prediction
  - NC and Electron Neutrino background analyses: Far to Near spectrum in reconstructed energy ratio for FD prediction of shower events



Backup—Disappearance Results

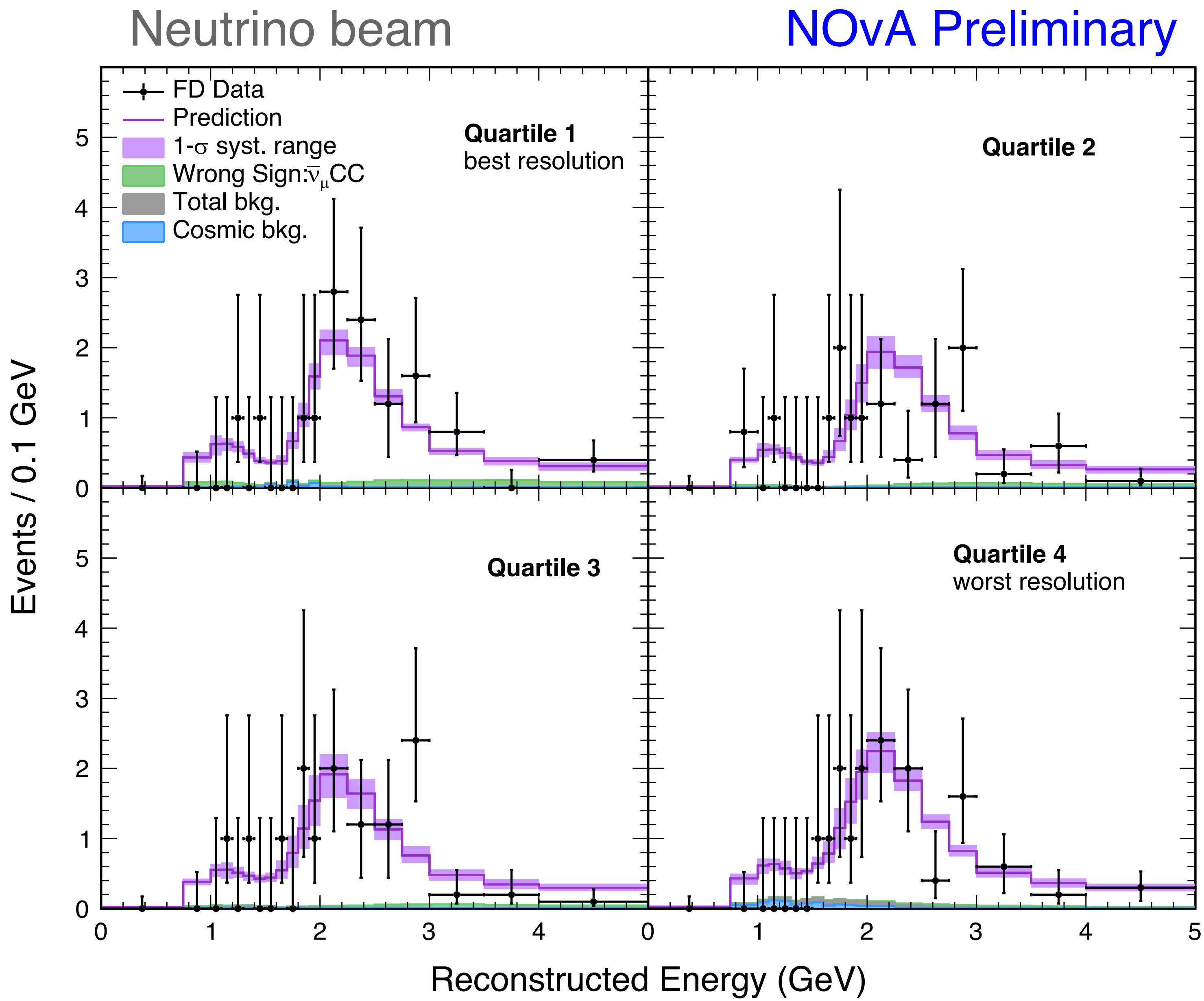
Disappearance





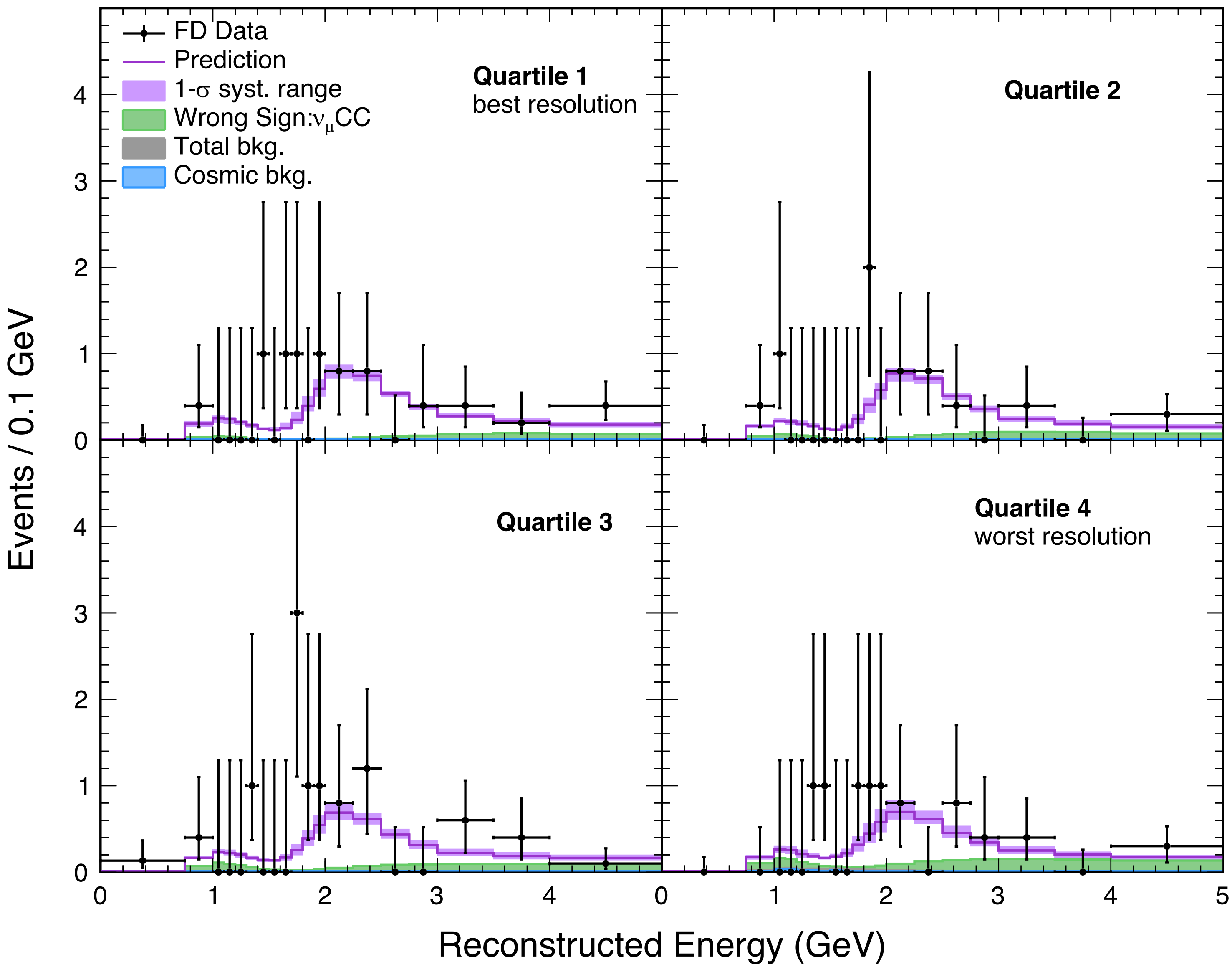
- If fit separately, the $\bar{\nu}_\mu$ data prefers non-maximal while ν_μ prefers maximal.
  - Consistent with joint oscillation parameters to >4%.
- Matter effects introduce a small asymmetry in the point of maximal disappearance.
- Gives a 1.3σ preference for the Upper Octant from *just* the $\nu_\mu + \bar{\nu}_\mu$ fit in NH.
  - The asymmetry is flipped in the Inverted Hierarchy, so there is a similar preference for the lower octant there.

Neutrino beam



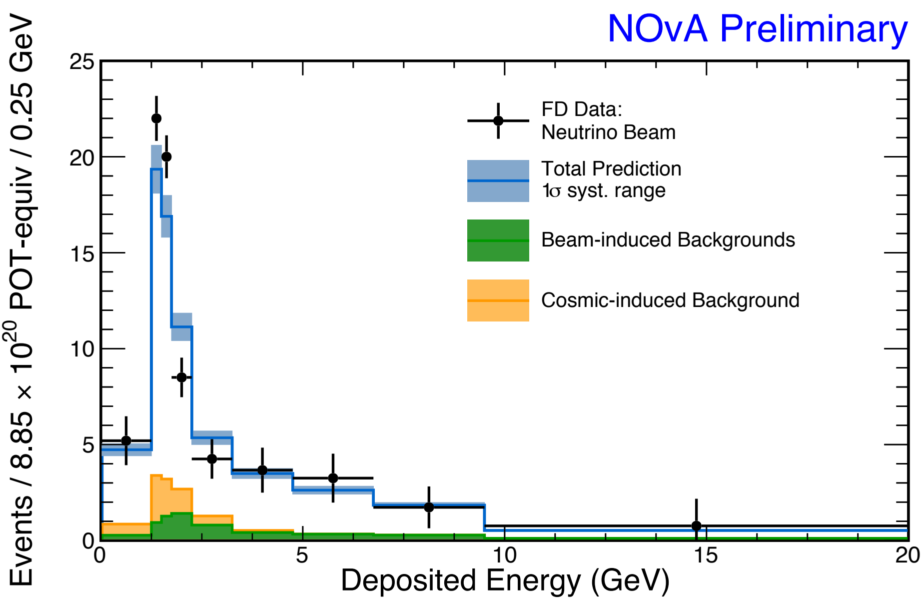
Antineutrino beam

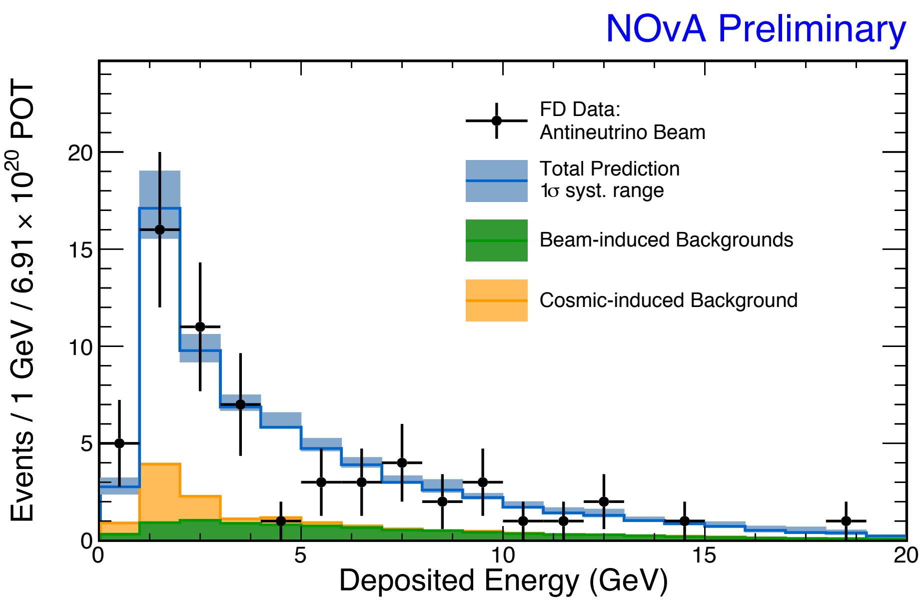
NOvA Preliminary



Backup—NC Results

NC Results





Neutrino mode:
expect 188+/-13 (syst.) with 38 bkg.
Observe 201 events

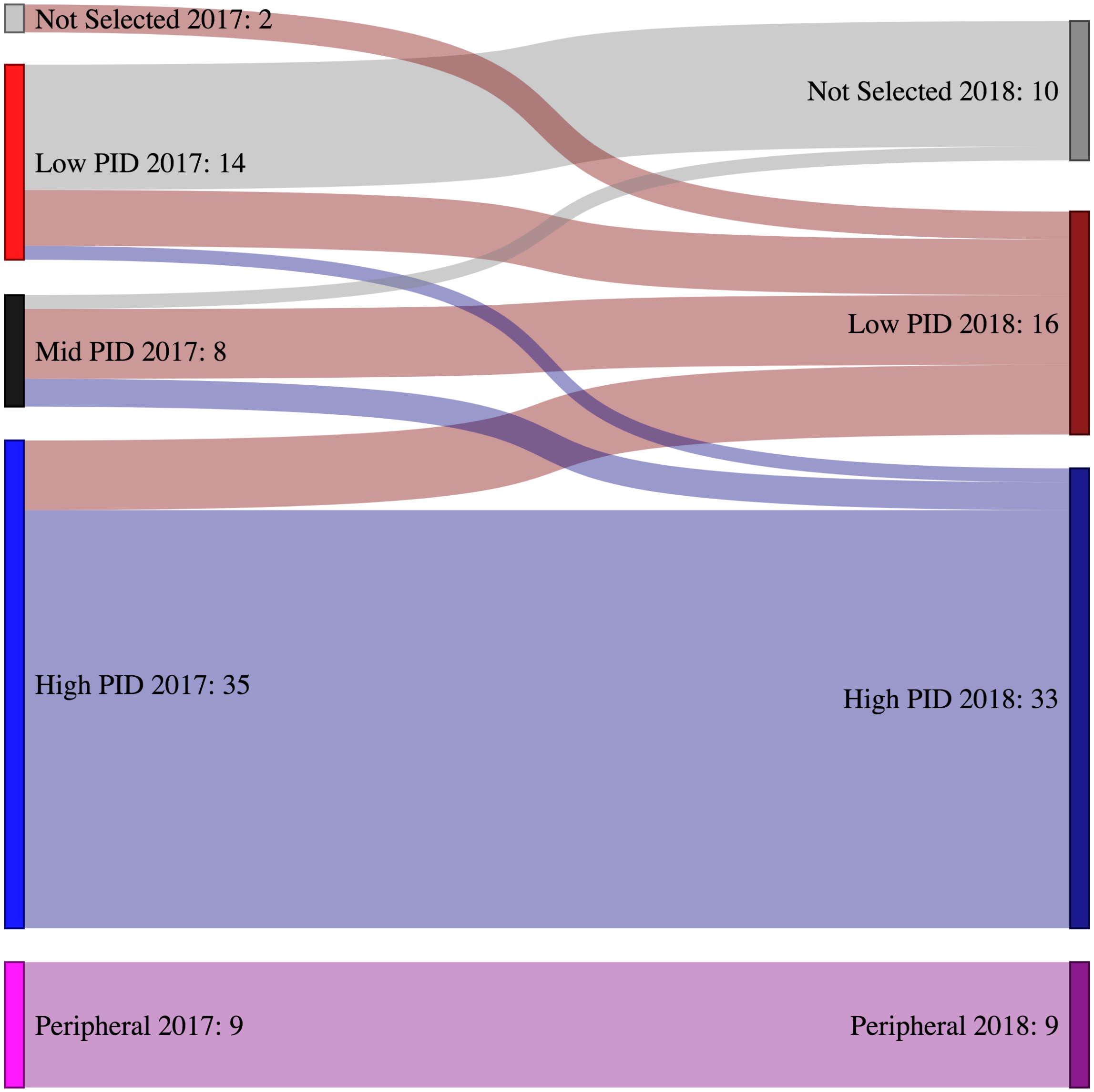
Antineutrino mode:
expect 69+/-8 (syst.) with 16 bkg.
Observe 61 events

No significant suppression of Neutral Current interactions in either neutrino or antineutrino mode

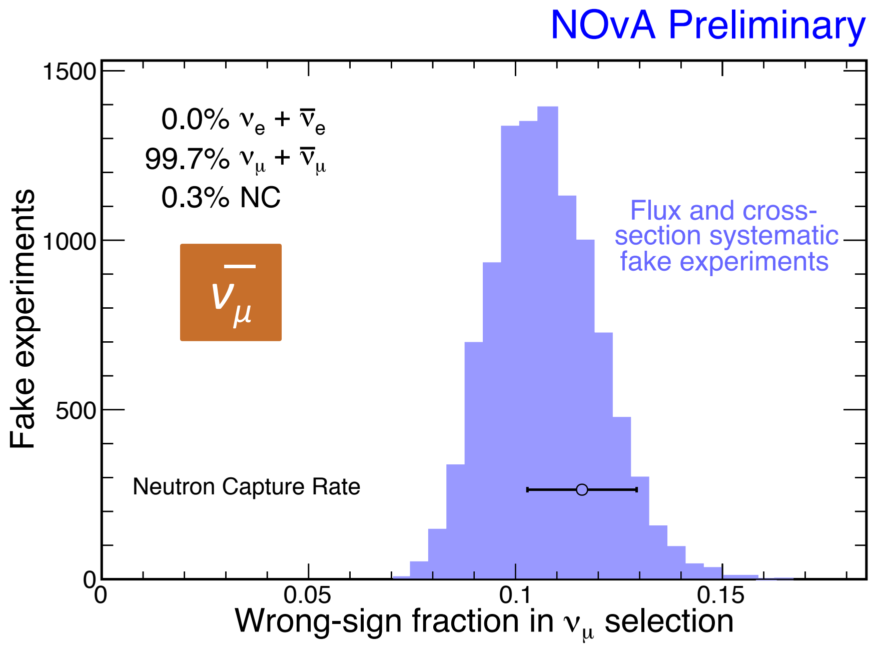
Backup—Appearance Results

Event Migration

- Core:
  - Expected to lose 7 and gain 3.5 vs. 2017.
  - Actually lost 10 and gained 2.
  - No events lost or gained in the high PID bin, but some did move from/to lower PID bins.
- Peripheral:
  - Expected to gain and lose 2.5 events.
  - Actually no events lost or gained.



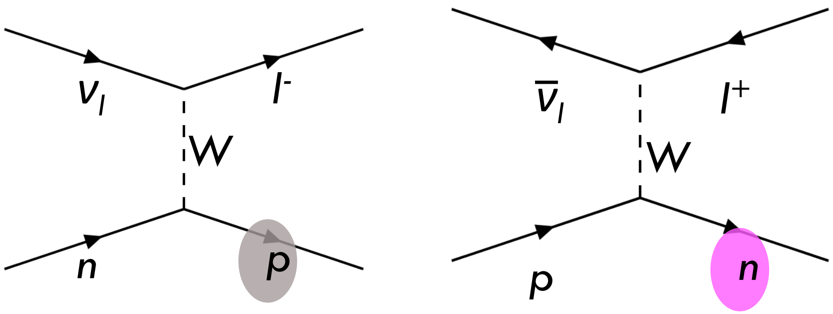
Wrong-sign Background

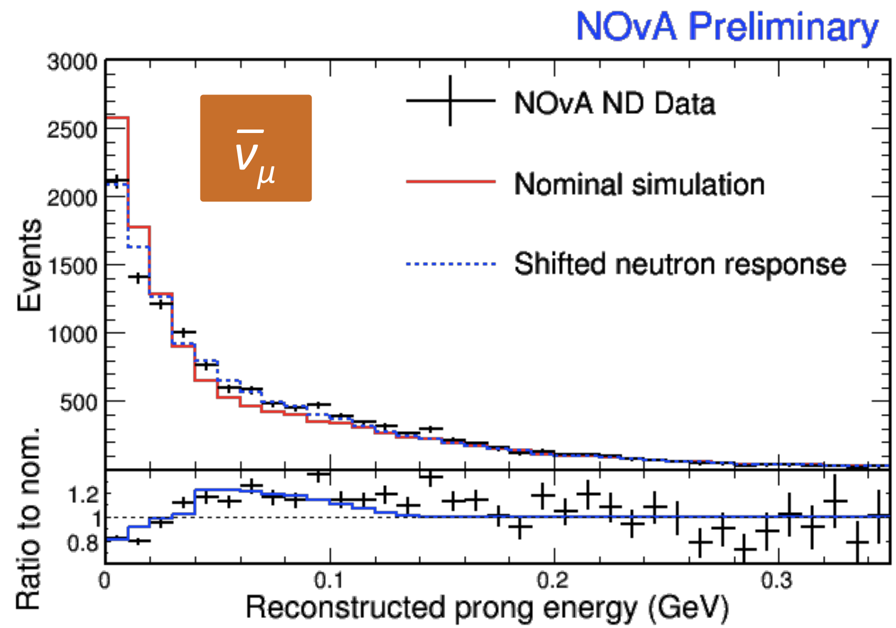


- The 11% wrong-sign fraction of the **$\bar{\nu}_\mu$ events** is important since it becomes the WS background in the **$\bar{\nu}_e$ appearance analysis**.
- ~10% systematic uncertainty on wrong-sign from flux and cross section
  - Does not include uncertainties from detector effects.
- Confirmed using data-driven cross-check of the wrong-sign contamination
  - 11% wrong-sign in the $\bar{\nu}_\mu$ sample checked using neutron captures in the neutrino and antineutrino beams.

Backup—TestBeam

New neutron response systematic

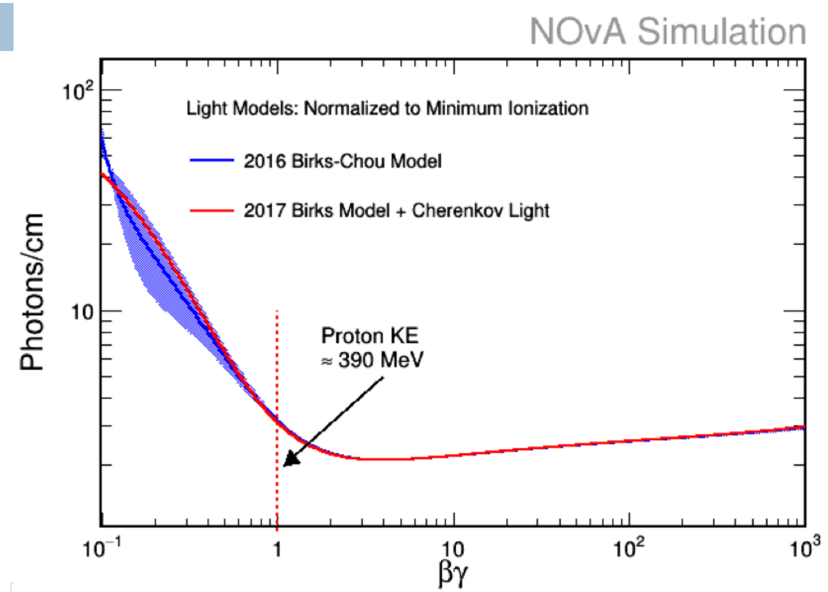


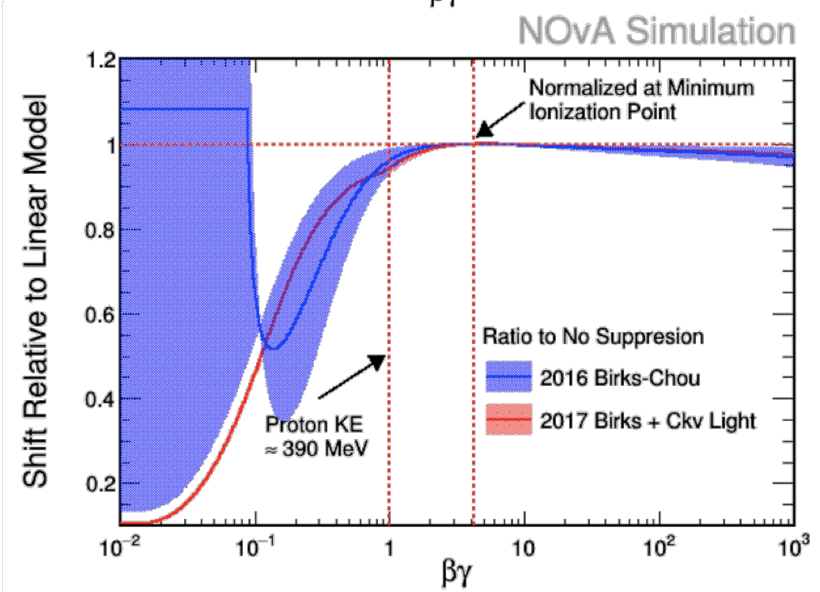


- $\bar{\nu}$'s have neutrons where ν's have protons.
  - Often several hundred MeV of energy.
  - Modeling these fast neutrons is known to be challenging.
- See some discrepancies in an enriched sample of neutron-like prongs.
- New systematic introduced:
  - Scales the amount of deposited energy of some neutrons to cover the low-energy discrepancy.
- Shifts the mean ν_μ energy by 1% in the antineutrino beam and 0.5% in the neutrino beam.
  - Negligible impact was seen on selection efficiencies.

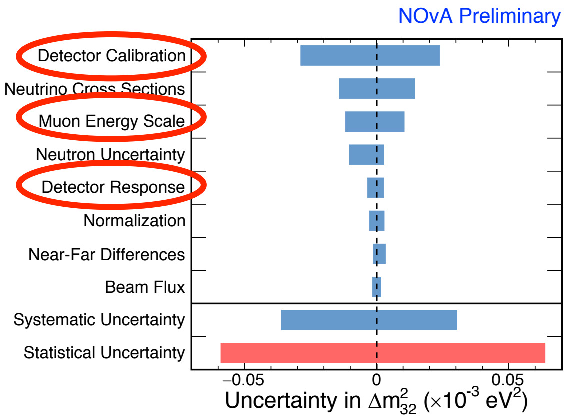
Scintillator Model

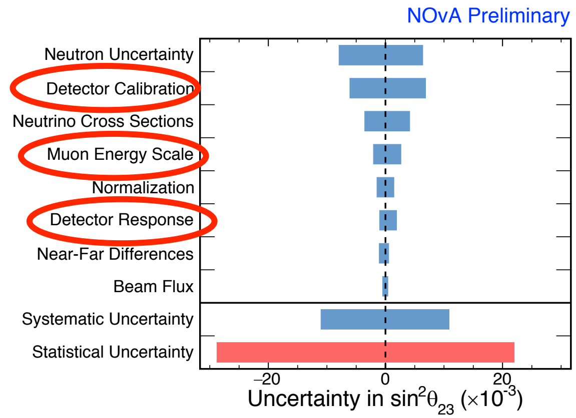
- Absorbed and re-emitted Cherenkov light is a small but important component of our scintillator response.
  - Particularly for low-energy protons in hadronic showers.
- Was one of our largest uncertainties, now reduced by an order of magnitude.
  - Previously accounted for with second order terms in our scintillator model.
  - Those terms were unusual, so we placed large systematics.
- Expected energy resolution for ν_μ CC events increased from 7% to 9%.

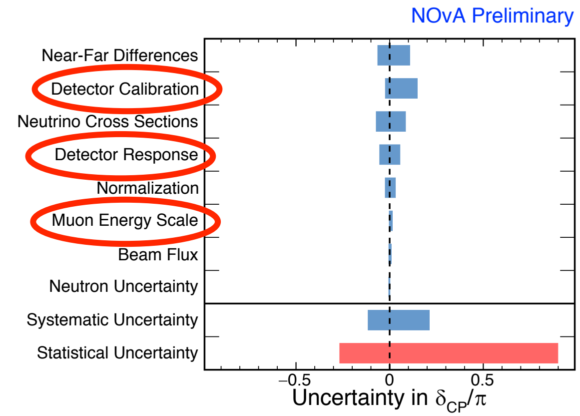


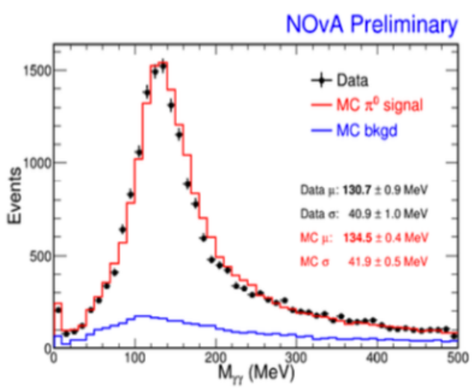


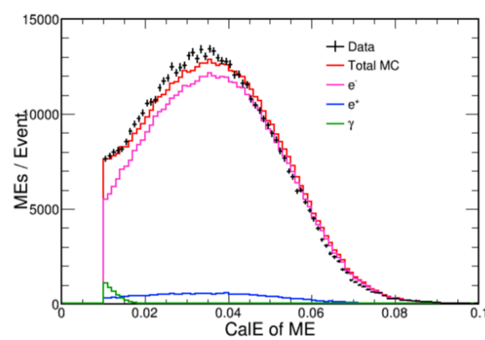
Systematics and Testbeam Motivation









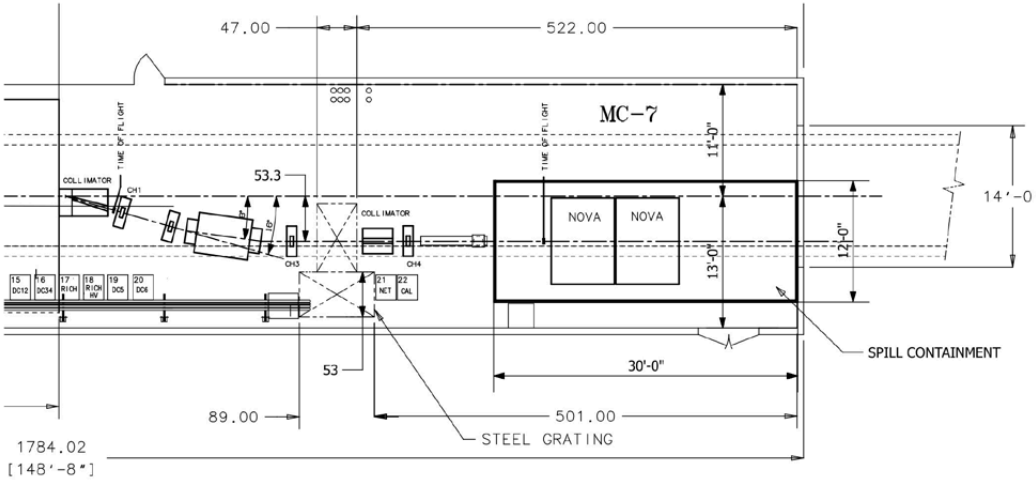


- Testbeam effort affords detailed understanding of detectors energy scale (muon, electromagnetic, and hadronic)
- Allows study of light model, scintillator quenching
- Provides real data for study of particle identification techniques

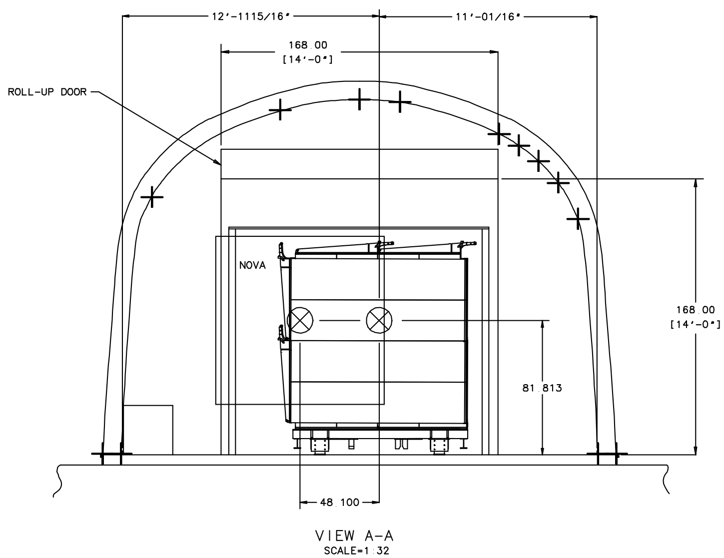
- Estimate of energy/calibration uncertainty comes from ~5% difference in data vs. MC when comparing pi0 mass and Michel e distributions
- Testbeam data decouples detector response from hadronic final state, neutrino cross section, flux uncertainties

Testbeam

- Installed in the MCenter Beamline
  - MC7
  - Space formerly used by MIPP
  - Downstream of Lariat
- Tertiary beam
  - e, mu, pi, p, K
  - momentum 0.2-2GeV/C



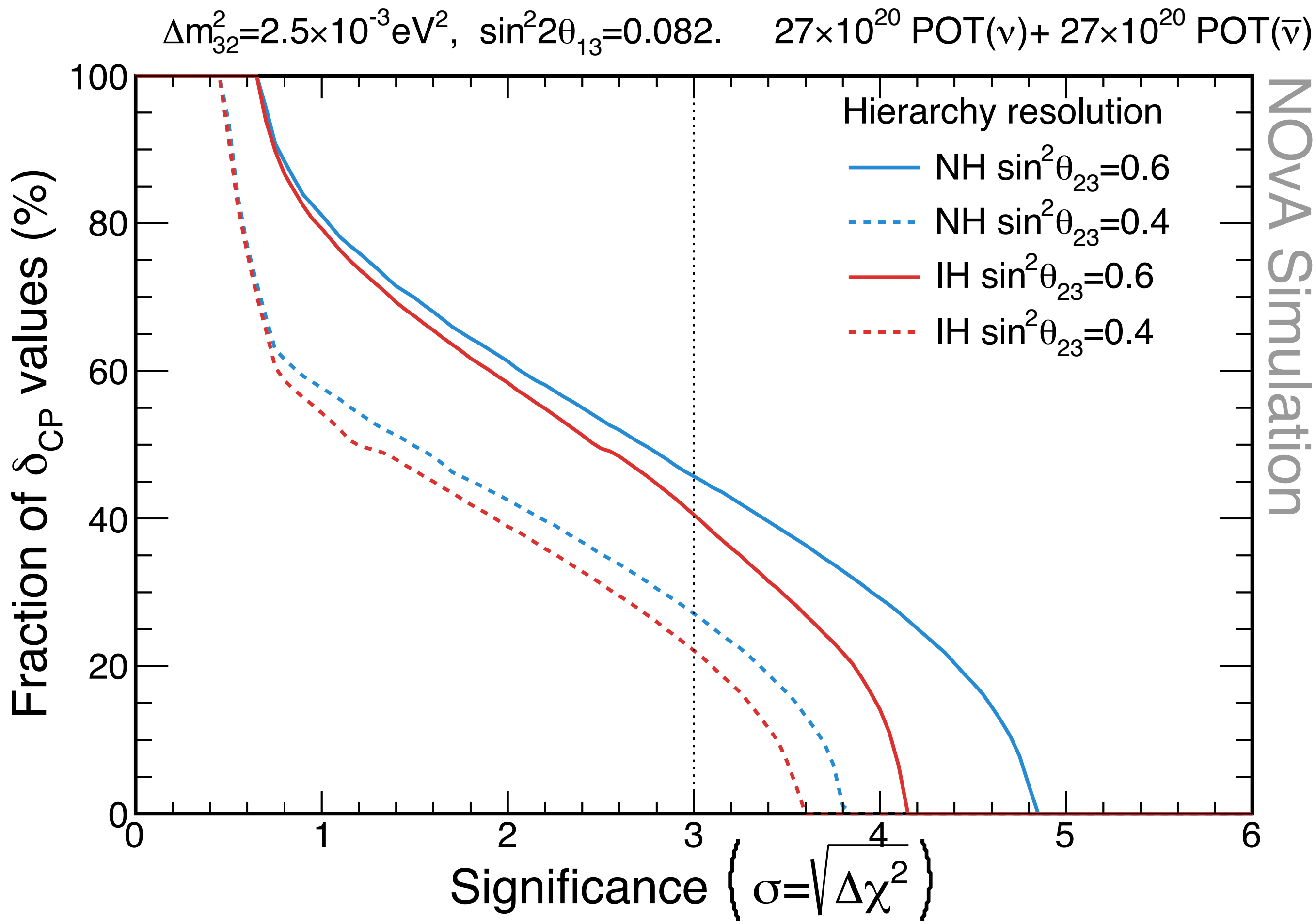
Testbeam



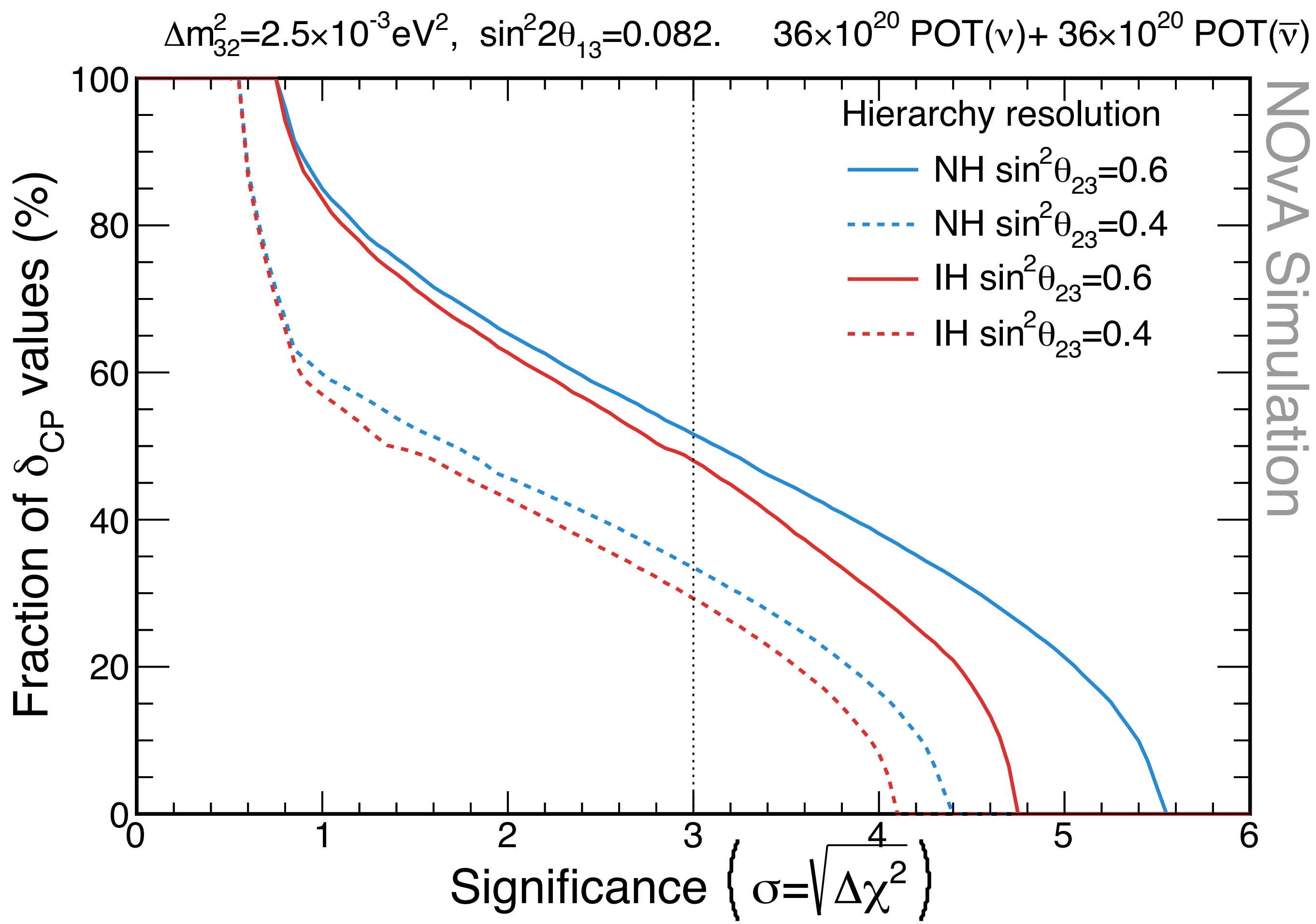
Detector Configuration	Two 2×2 31-plane blocks + One horiz. plane
Dimensions W(m)× H(m)× L(m)	2.6×2.6×4.1
Scintillator/plane (gallons)	86
Total Scintillator Volume (gallons)	5418
PVC Mass/plane (kg)	171.2
Adhesive Mass/plane (kg)	3.1
Total Empty Mass (kg)	10981
Total Scintillator Mass (kg)	17608
Total Detector Mass (kg)	28582
#APDs = #FEBs	126 (118 FEB 4.1 + 8 FEB 5.2)
#DCMs	3

Backup—Sensitivity

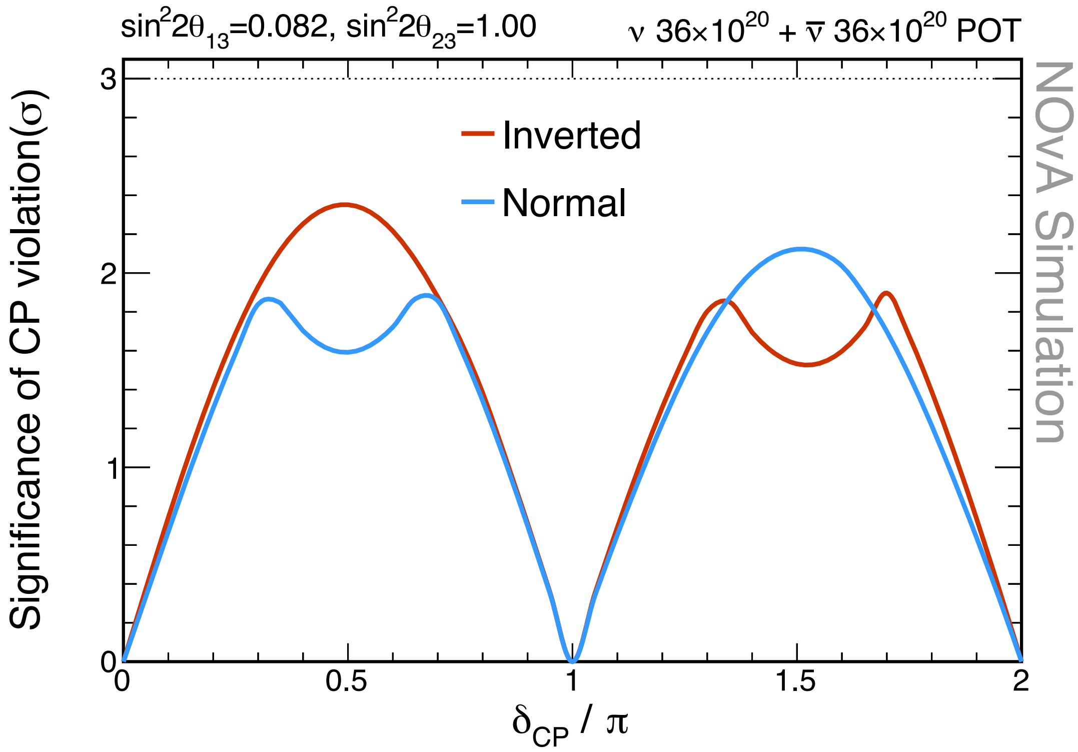
AIP Sensitivity Gain



AIP Sensitivity Gain



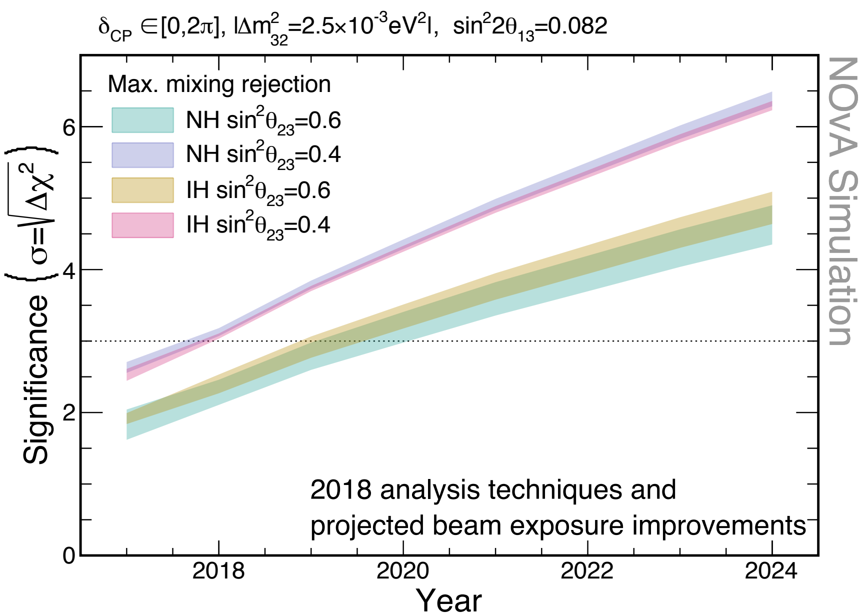
CP Violation Sensitivity



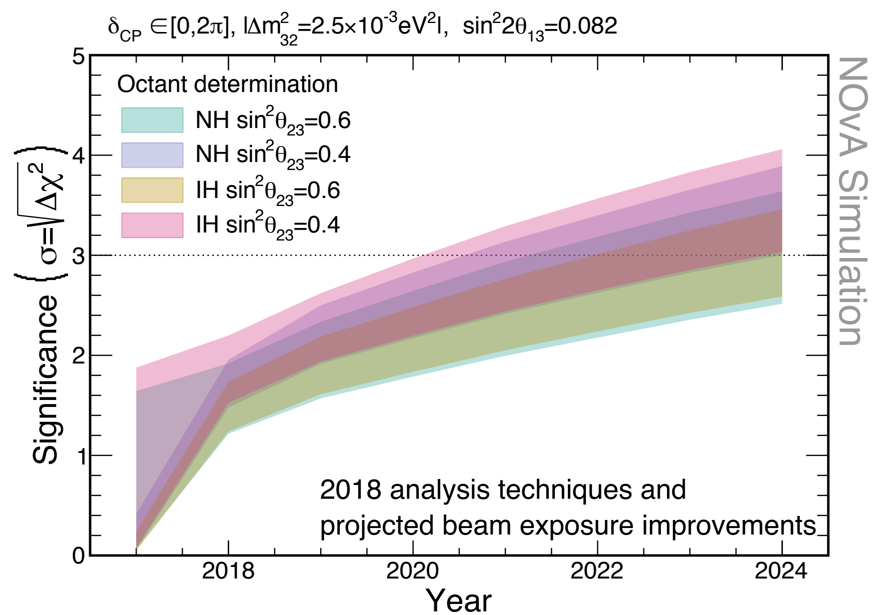
2+ σ sensitivity for CP violation in both hierarchies at $\delta_{CP}=3\pi/2$ or $\delta_{CP}=\pi/2$ (assuming unknown hierarchy) by 2024

Future Sensitivity

Max mixing rejection



Octant



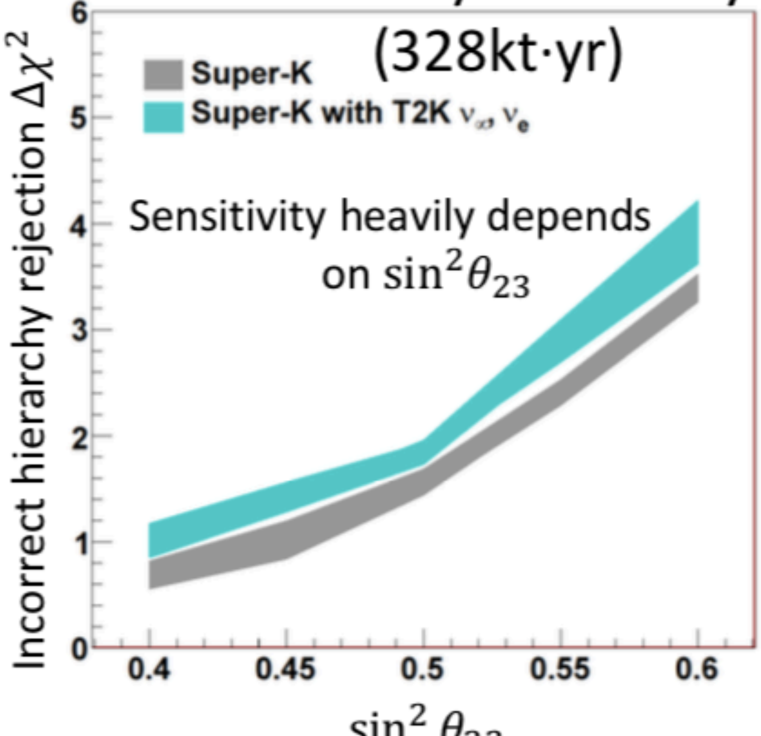
Other Experiments

- T2K
  - M. Wascko—Nu2018
  - Bayes factor for NH/IH=7.9->NH prefered at 89%
- SuperK
  - Y. Hayuto—Nu2018
  - NH favored at 80.6 to 96.7% depending on theta_23
  - Expanding the fiducial volume
- Juno
  - Bjorn Wonsak—Nu2018
  - Start datataking in 2021
  - after 6 years, 3sigma or 4sigma MH resolution depending on constraint on dm_mumu
- KM3Net/Orca
  - U. Katz—Nu2018
  - 5sigma by 2024 at nova favored theta_23

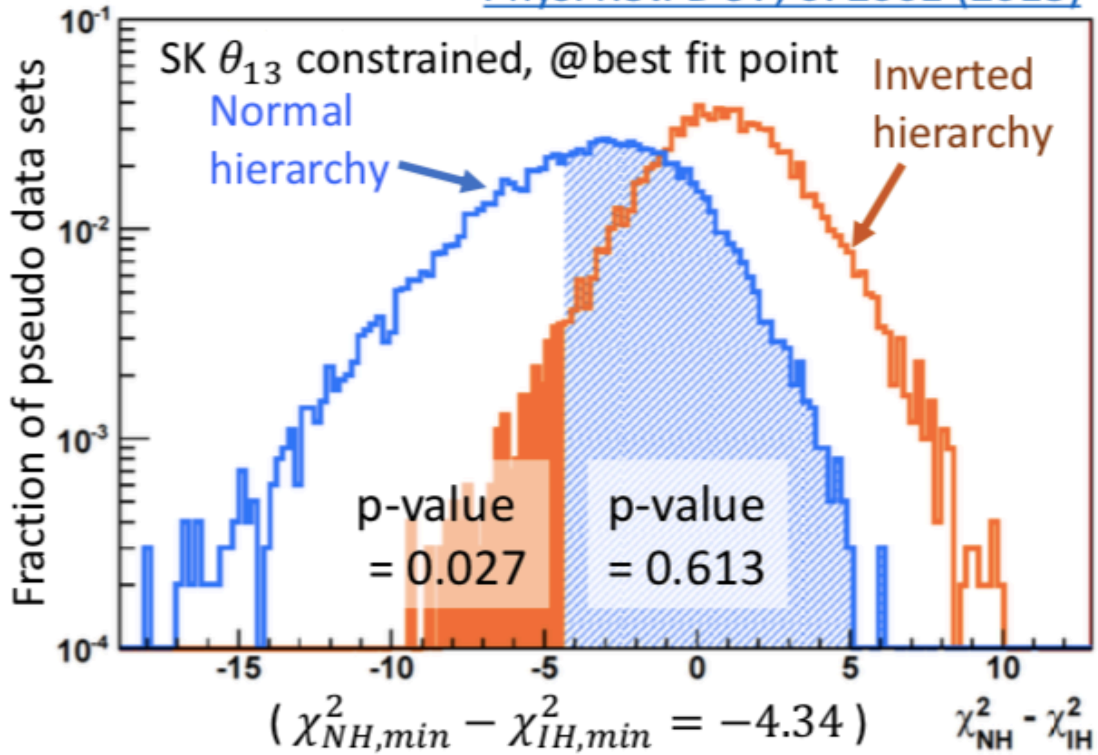
Determination of hierarchy determination

Y. Hayato, Nu2018

Mass hierarchy sensitivity



Phys. Rev. D 97, 072001 (2018)



Estimate p-values using pseudo-data for the smallest and largest $\sin^2\theta_{23}$.

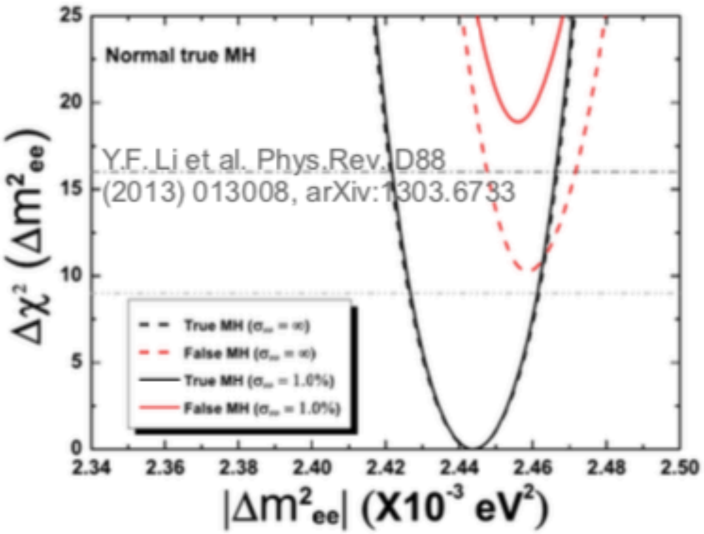
Hypothesis test ~ CL_s method : $\mathrm{CL_s(IH\ rejection)} \equiv \frac{p_0(IH)}{1-p_0(NH)}$

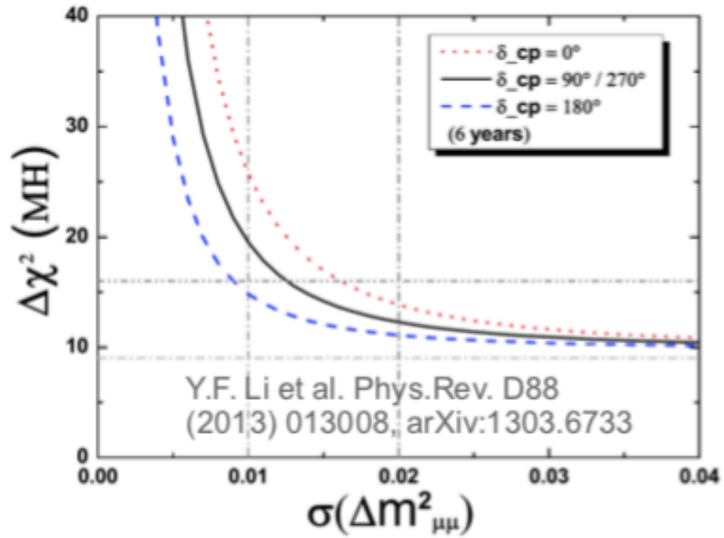
Normal hierarchy is favored ➡

SK only	80.6 ~ 96.7%
SK + T2Kmodel	91.5 ~ 94.5%

Mass Hierarchy Sensitivity

- **Measurement with or without constraint on $\Delta m^2_{\mu\mu}$**





- **Sensitivity with 100k events (~6 yrs):**
  - No constraint: $\overline{\Delta\chi^2} > 9$
  - With 1% constraint: $\overline{\Delta\chi^2} > 16$
- **Reason for synergy:**

$$|\Delta m^2_{ee}| - |\Delta m^2_{\mu\mu}| = \pm \Delta m^2_{21} \cdot (\cos(2\theta_{12}) - \sin(2\theta_{12})\sin(\theta_{13})\tan(\theta_{23})\cos(\delta))$$

Sign defined by MH

See H. Nunokawa et al, Phys.Rev. D72 (2005) 013009

NMO measurement

- Primary signature: Energy-zenith distribution
- Inverse signatures for ν and $\bar{\nu}$, but signal measurable since $\sigma(\nu) \approx 2\,\sigma(\bar{\nu})$ and $\Phi(\nu) > \Phi(\bar{\nu})$
- Measurement requires
  - best possible resolution in energy and zenith
  - separation ν_e/ν_μ
  - detailed understanding of systematics
- In-depth studies by KM3NeT and IceCube, extensive cooperation
- Results very similar

P[2/161] S. Bourret