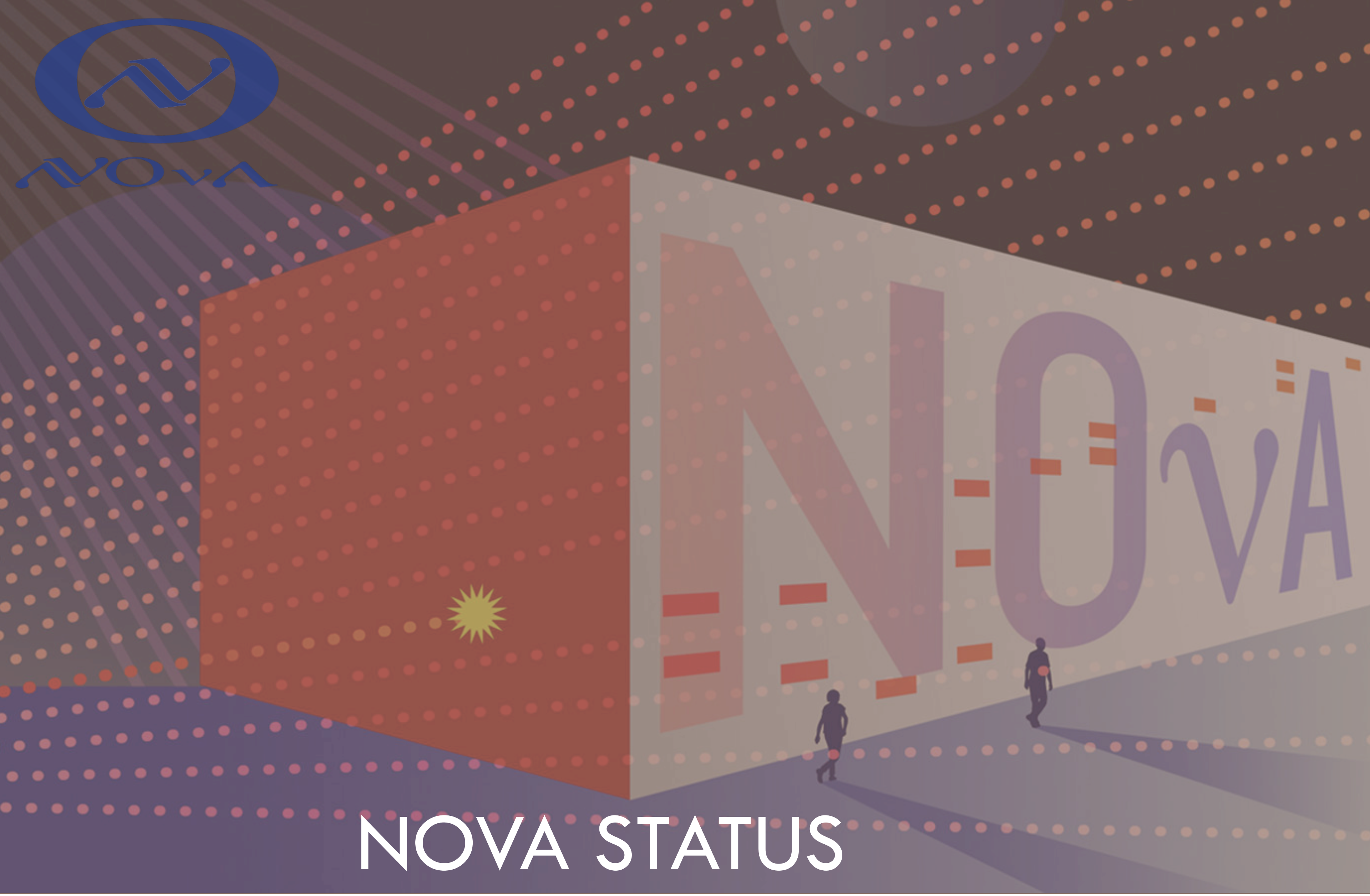
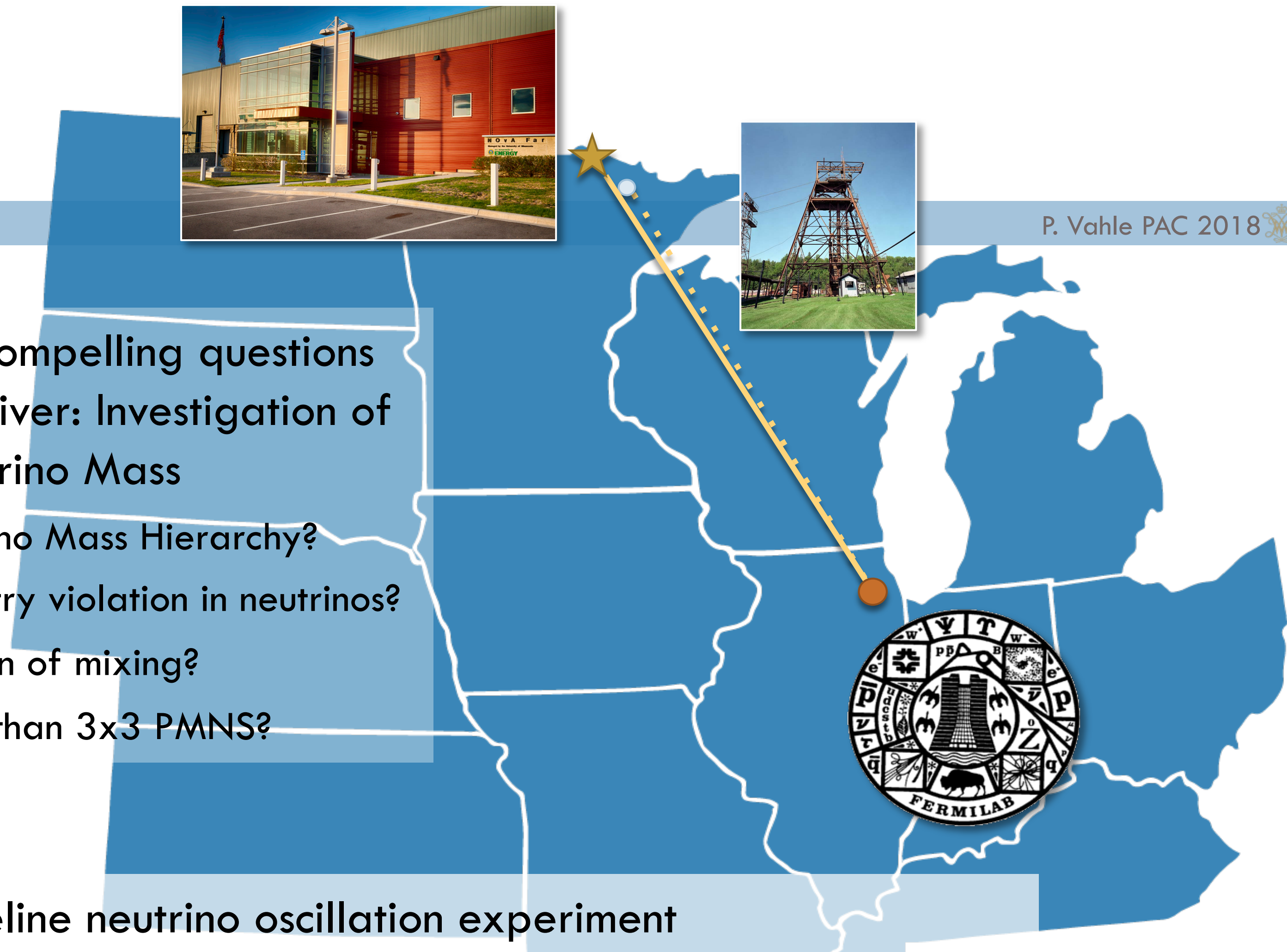


NOVA STATUS

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?

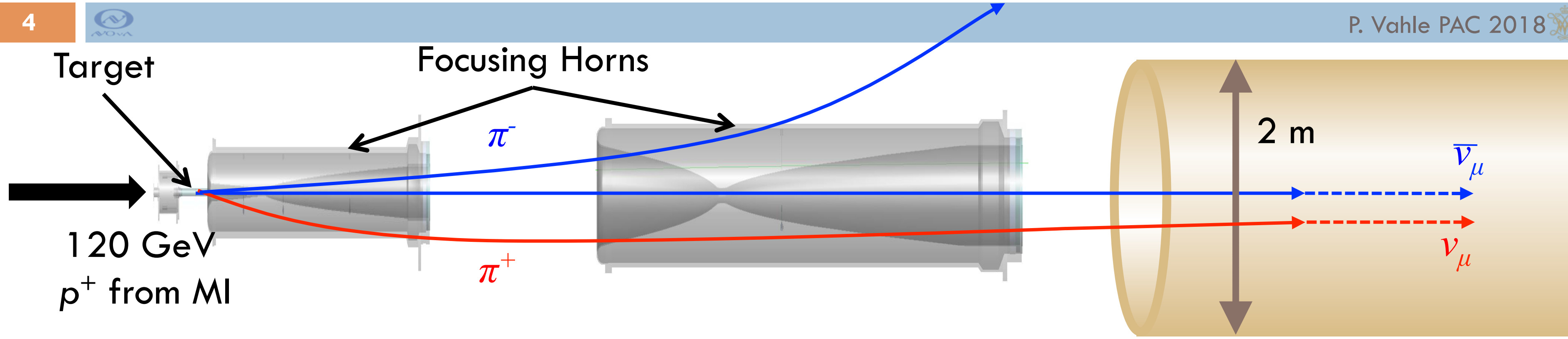
- Long-baseline neutrino oscillation experiment
  - Study muon neutrino disappearance, electron neutrino appearance, and flavor-independent (NC) disappearance with both neutrinos and antineutrinos
  - 2 Detectors separated by 810 km
  - High power and high purity neutrino and antineutrino beams

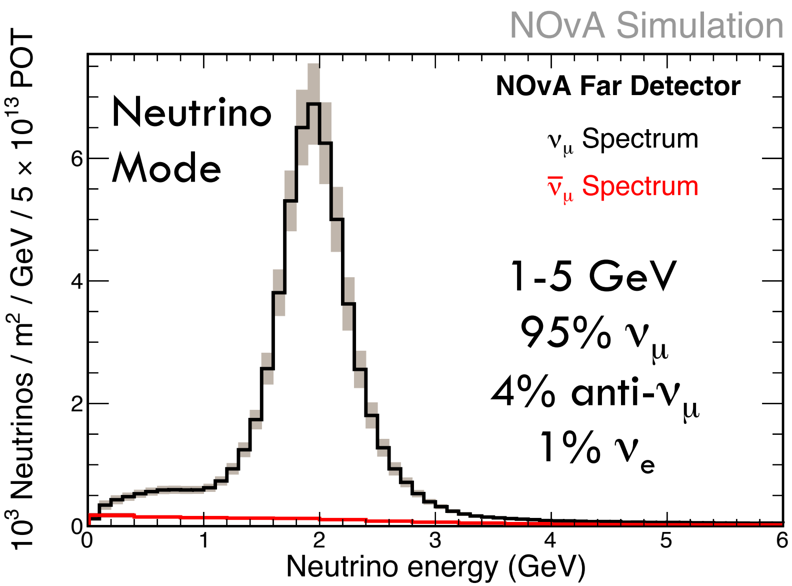
NOvA Collaboration

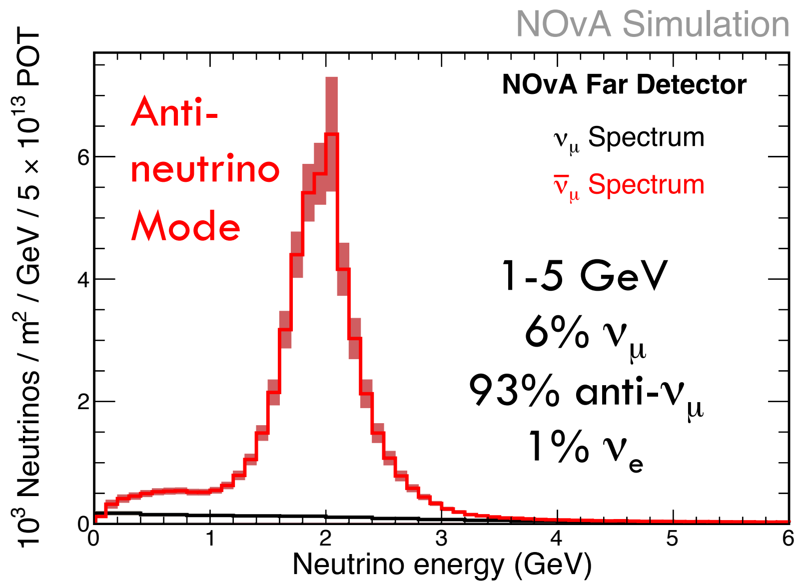
238 collaborators at 49 institutions across 7 countries

19 Remote Control Rooms across the globe

Making an off-axis neutrino beam

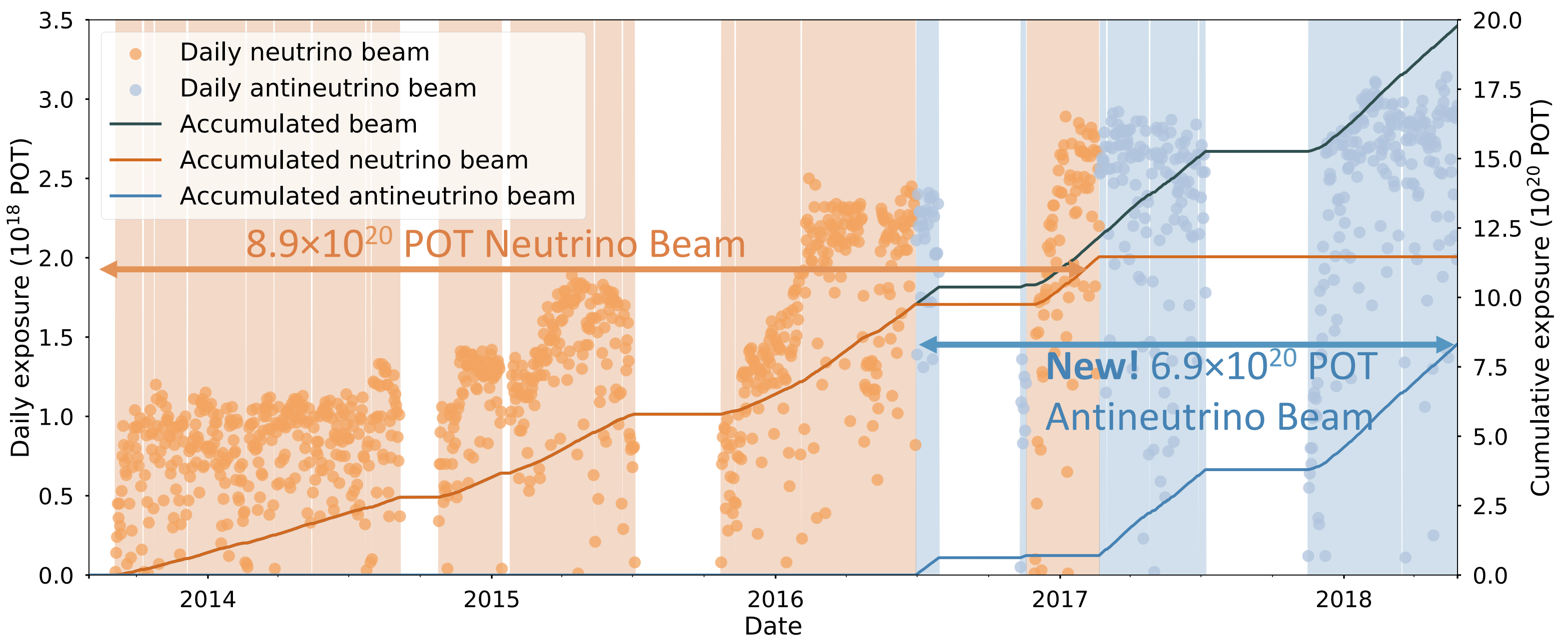




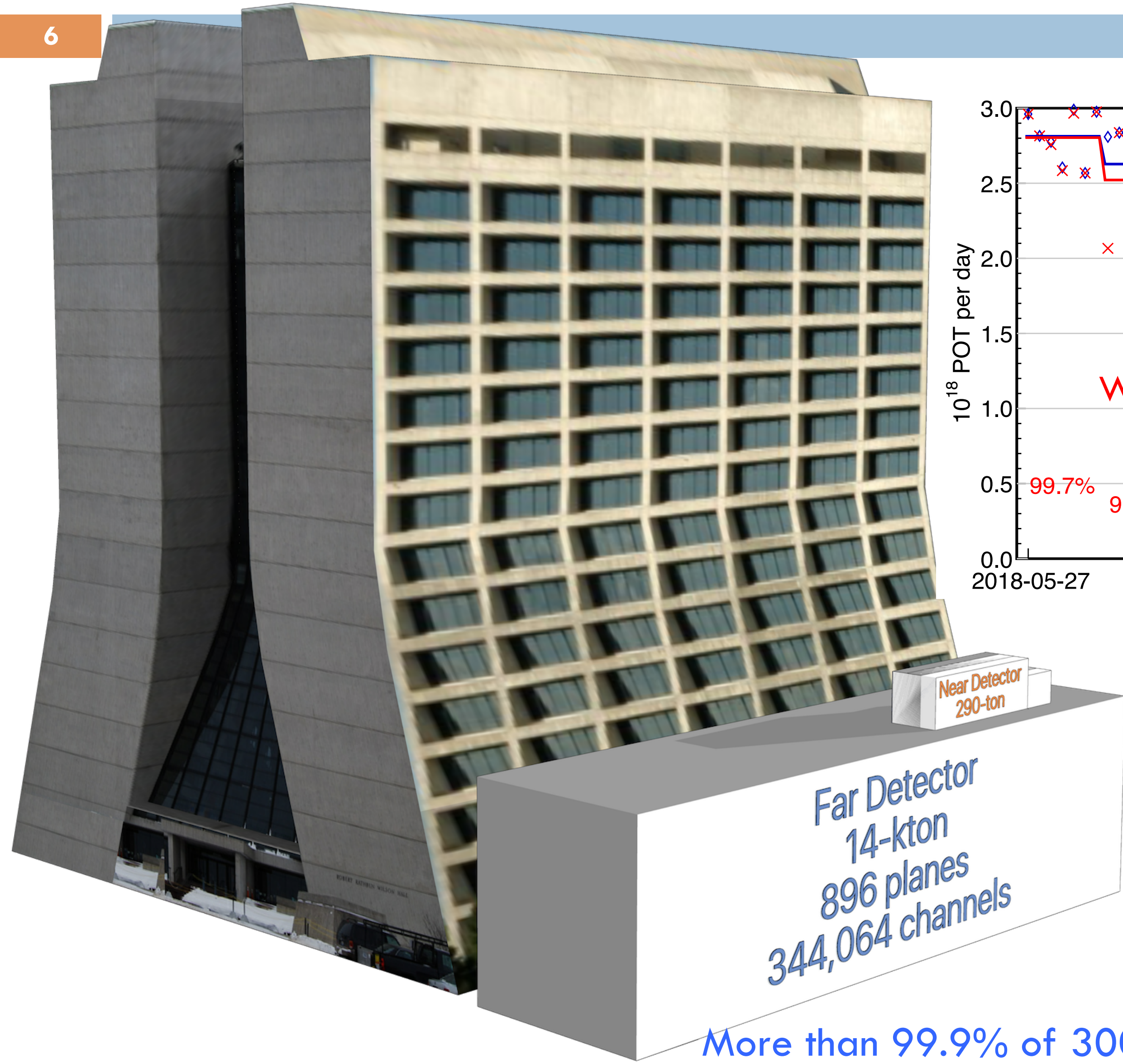


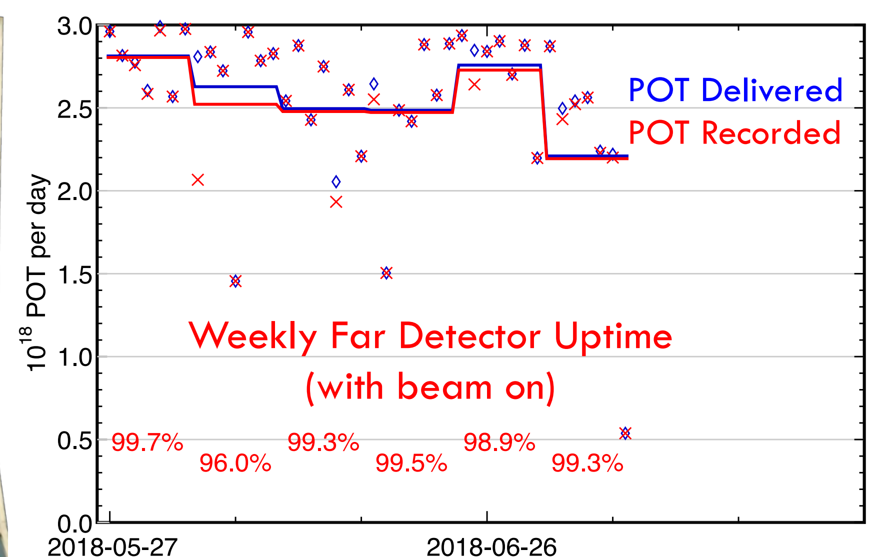
Beam Performance

- 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



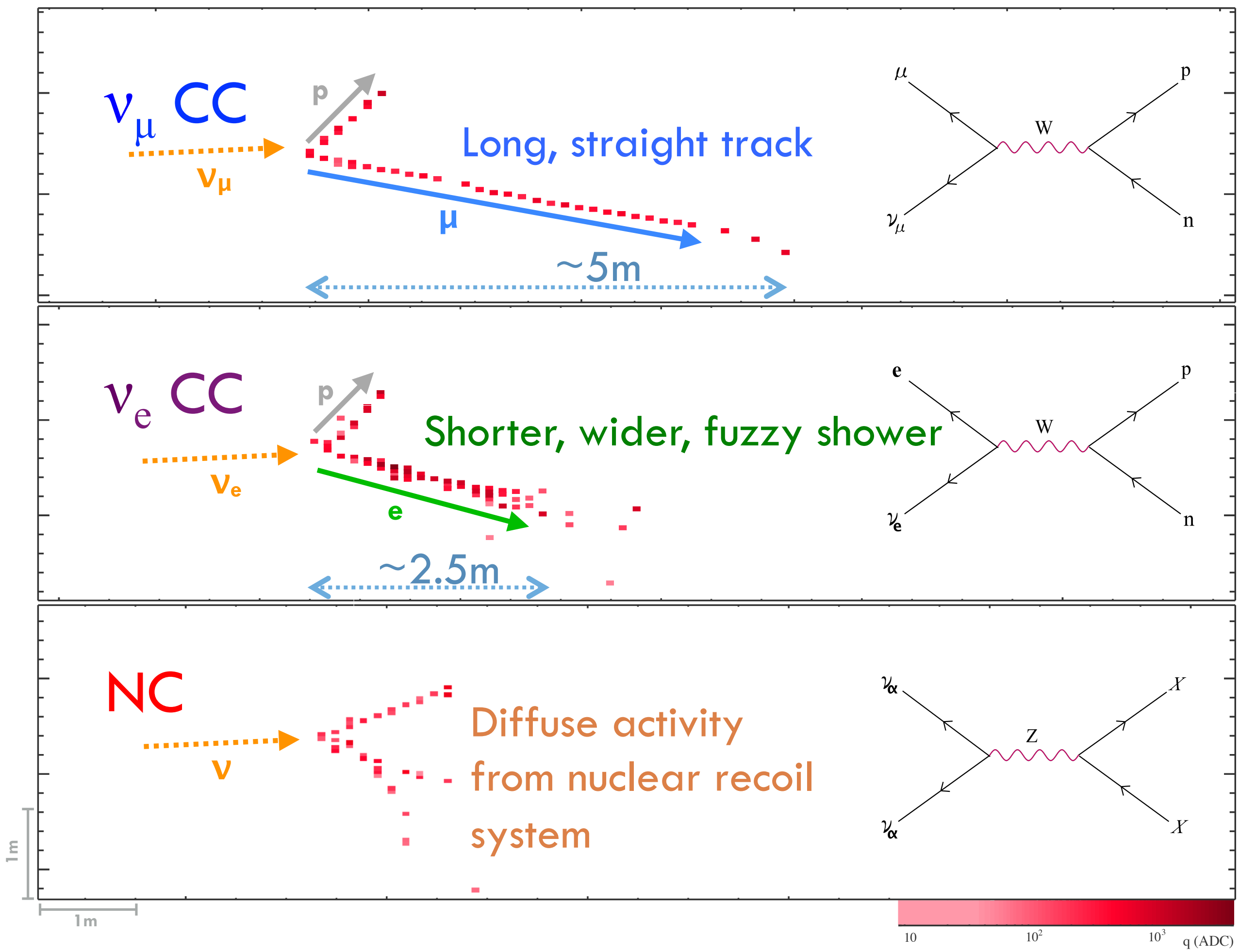


- Functionally identical detectors designed for electron ID
  - Low Z materials (PVC+Liquid Scint.)
  - 65% active
- ND: underground at FNAL
- FD: on the surface in Ash River, MN

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

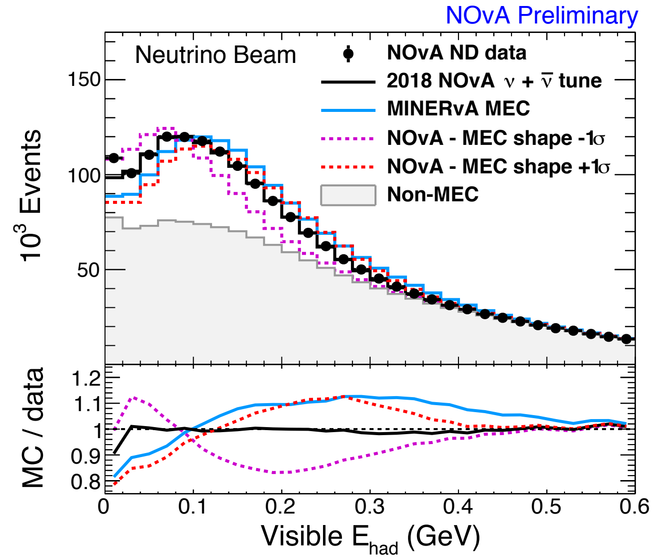
- Calibrated hit maps are inputs to Convolutional Visual Network (CVN)
- Series of image processing transformations applied to extract abstract features
- Extracted features used as inputs to a conventional neural network to classify the event

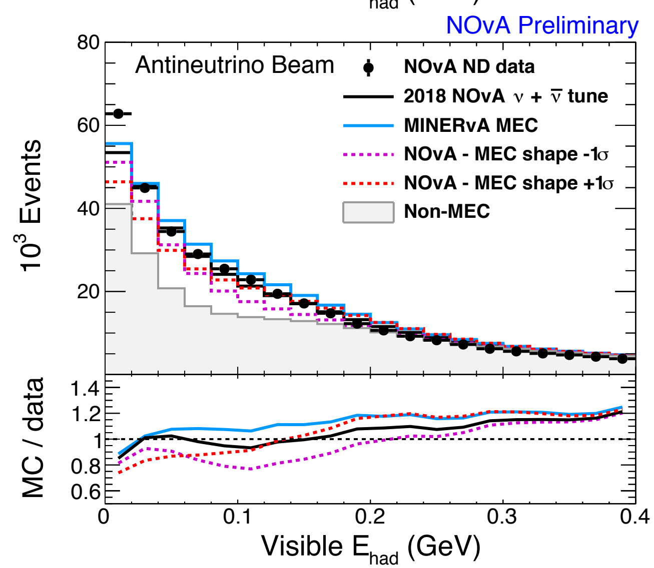
A. Aurisano et al., arXiv:1604.01444

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

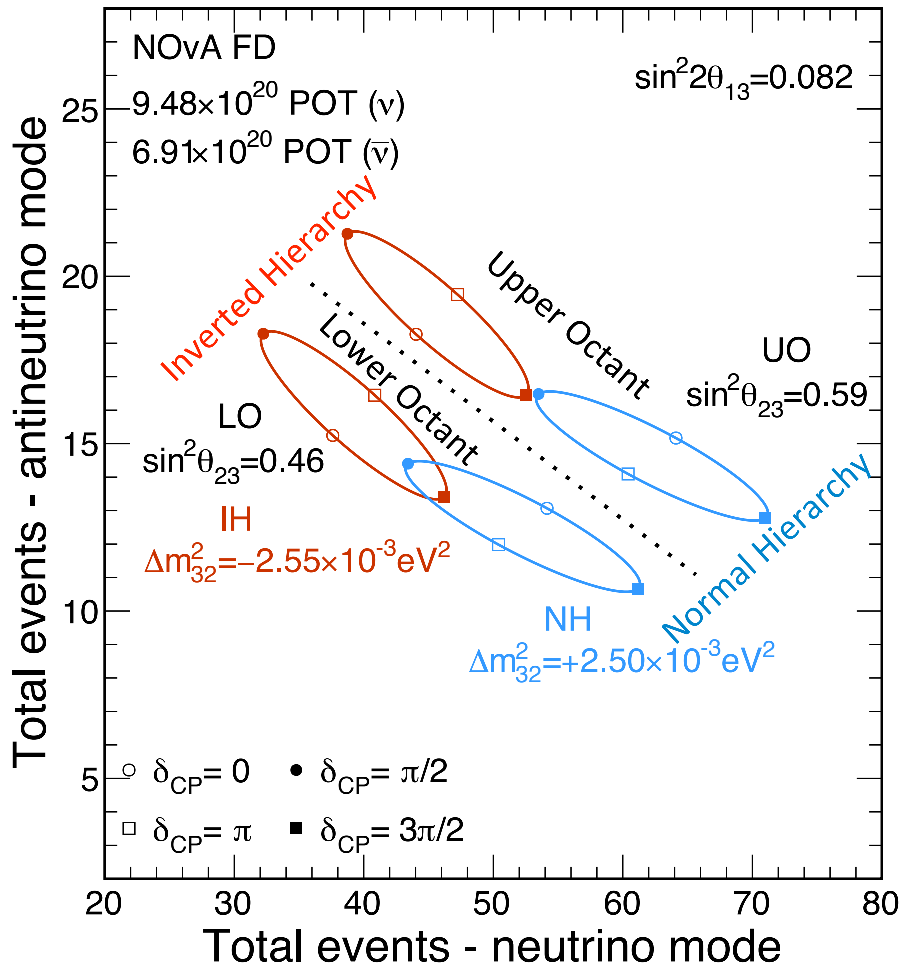
    (Phys. Rev. D 94, 092005. 2016)
  - neutrino interaction tuning guided by MINERvA experience (arXiv:1705.02932 and Eur. Phys. J. C76. 2016.)
  - Custom tuning of GENIE Empirical MEC model
- Workshop with MINERvA planned for this fall to share GENIE tuning techniques





Analysis Basics

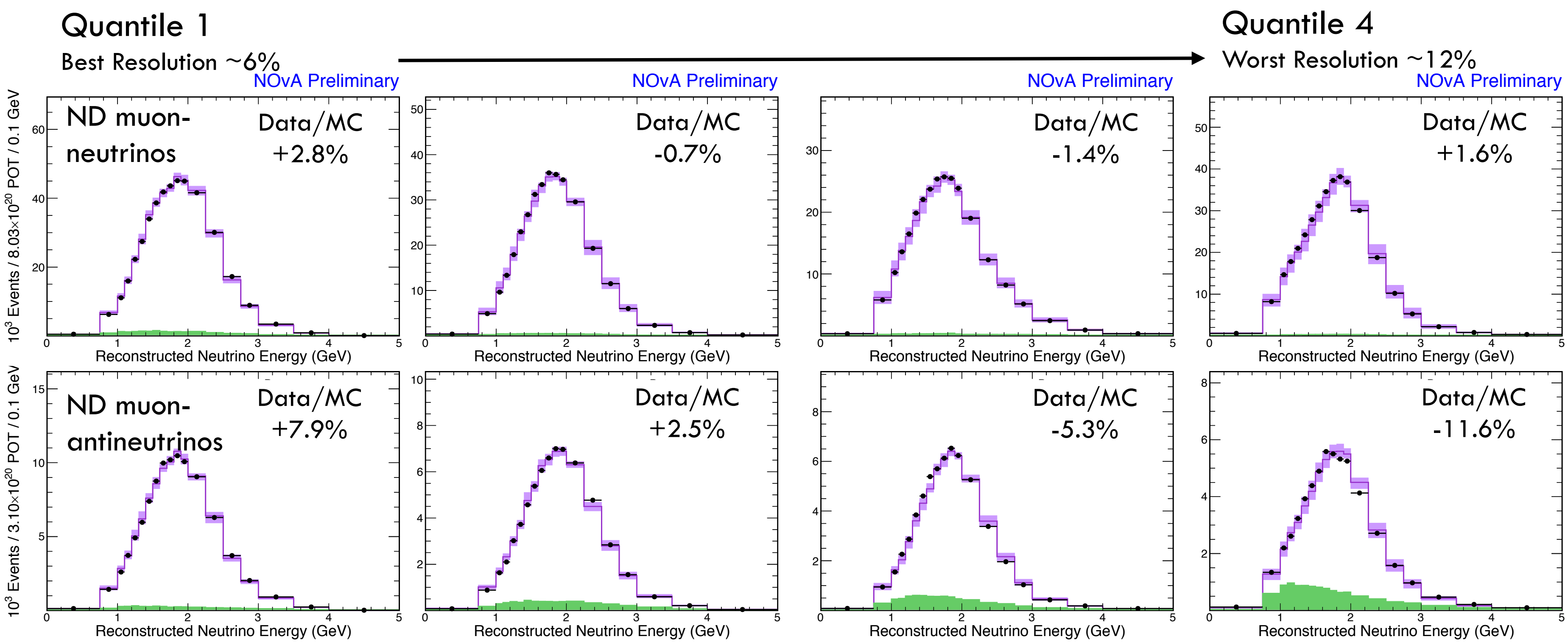
- Compare electron-neutrino appearance probability in neutrinos to antineutrinos
  - in vacuum with no CP violation, the two should be the same
  - CP violation enhances oscillation probability for neutrinos while suppressing it for antineutrinos, or vice-versa
  - matter effects also introduce mass 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

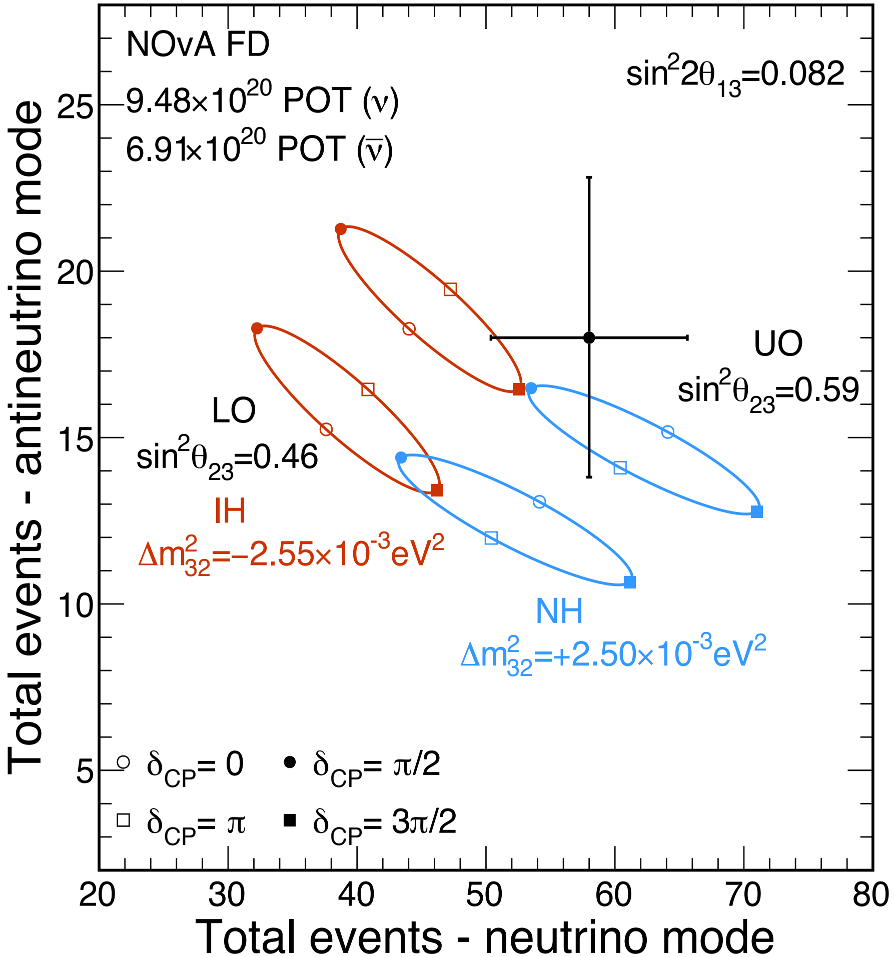


Appearance Results

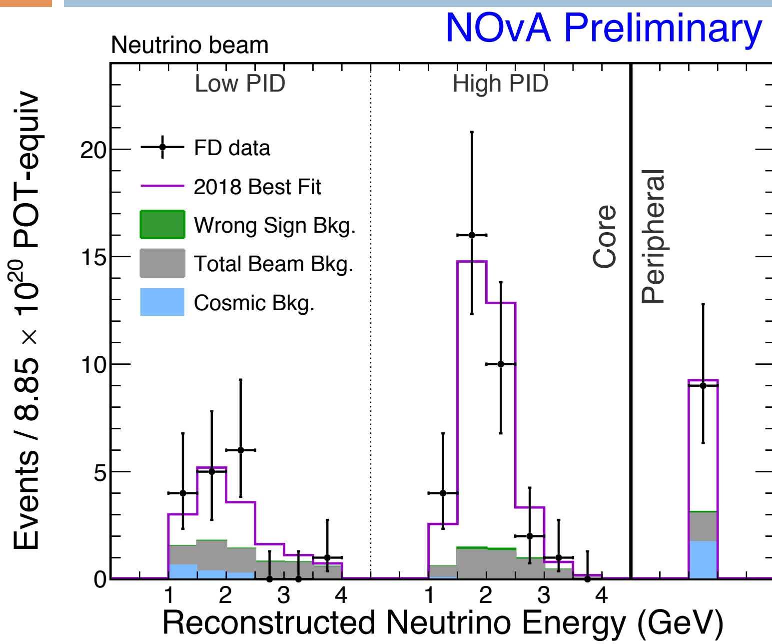
- Neutrino mode
  - 58 events observed
  - 15 bkg expected
- Antineutrino mode
  - 18 events observed
  - 5 bkg expected

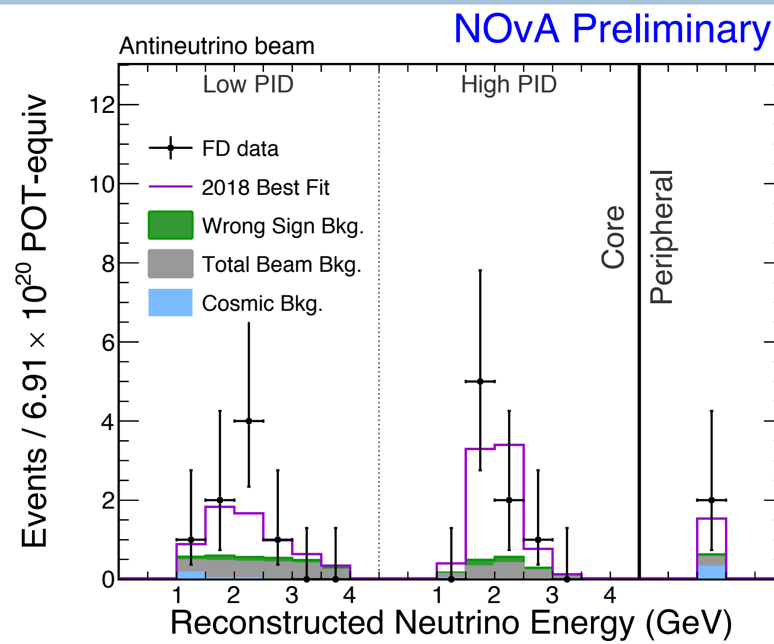
    (including 1 wrong sign)

Strong (>4 sigma) evidence of electron antineutrino appearance



Appearance Spectra





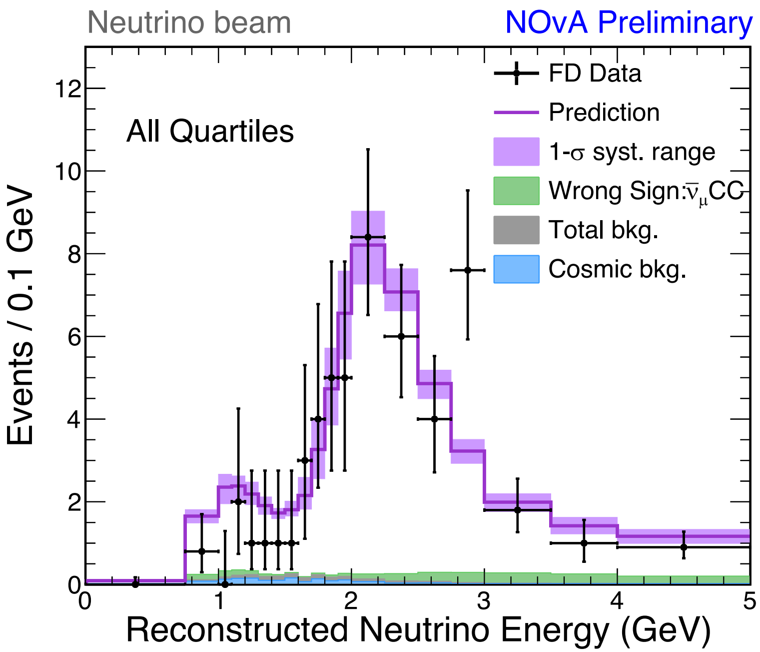
Neutrino Mode

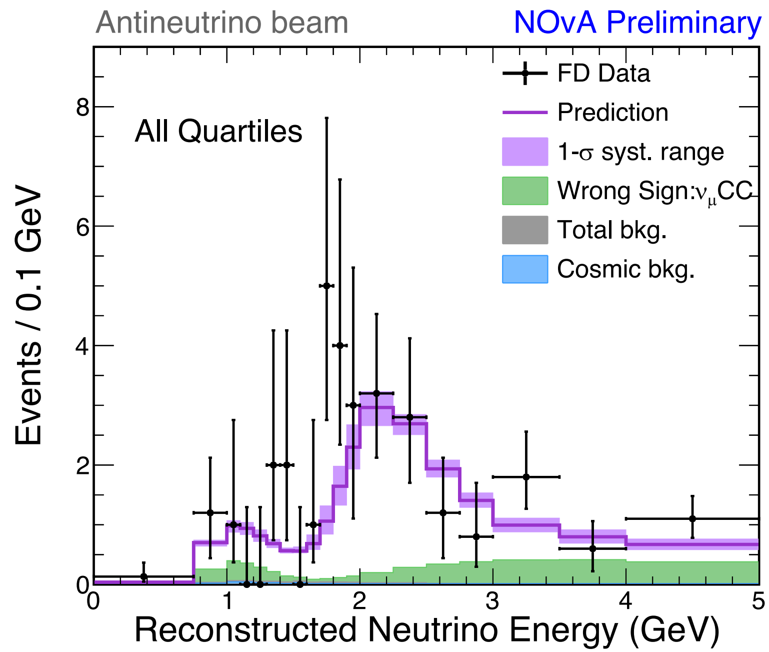
Total Observed	58	Range
Total Prediction	59.0	30-75
Wrong-sign	0.7	0.3-1.0
Beam Bkgd.	11.1	
Cosmic Bkgd.	3.3	
Total Bkgd.	15.1	14.7-15.4

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



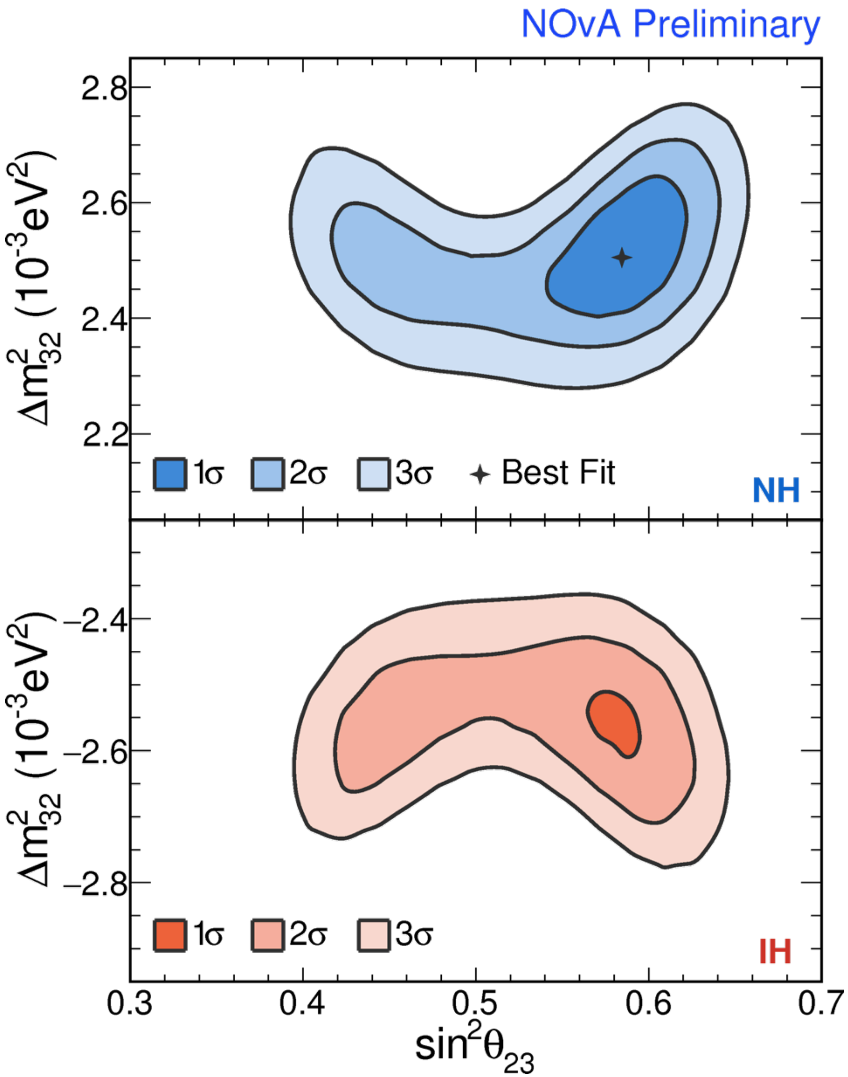


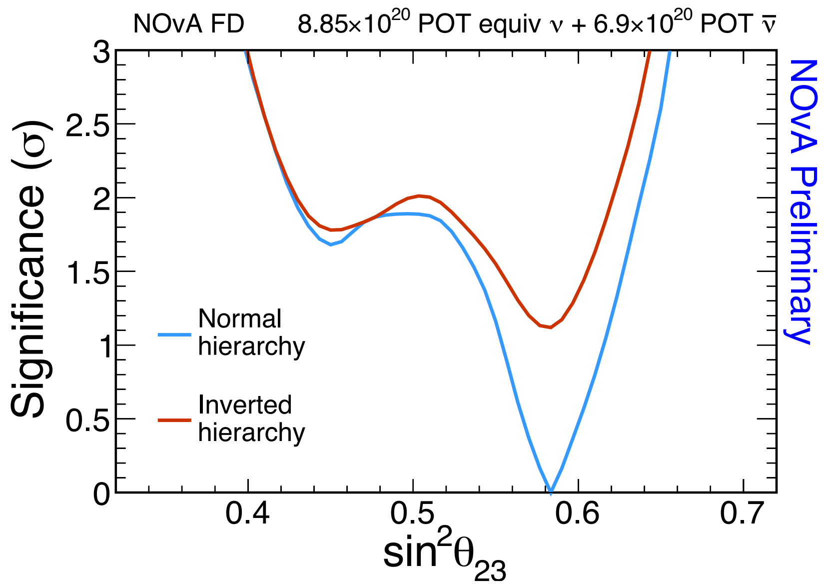
Total Observed	113
Best fit prediction	121
Cosmic Bkgd.	2.1
Beam Bkgd.	1.2
Unoscillated	730

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

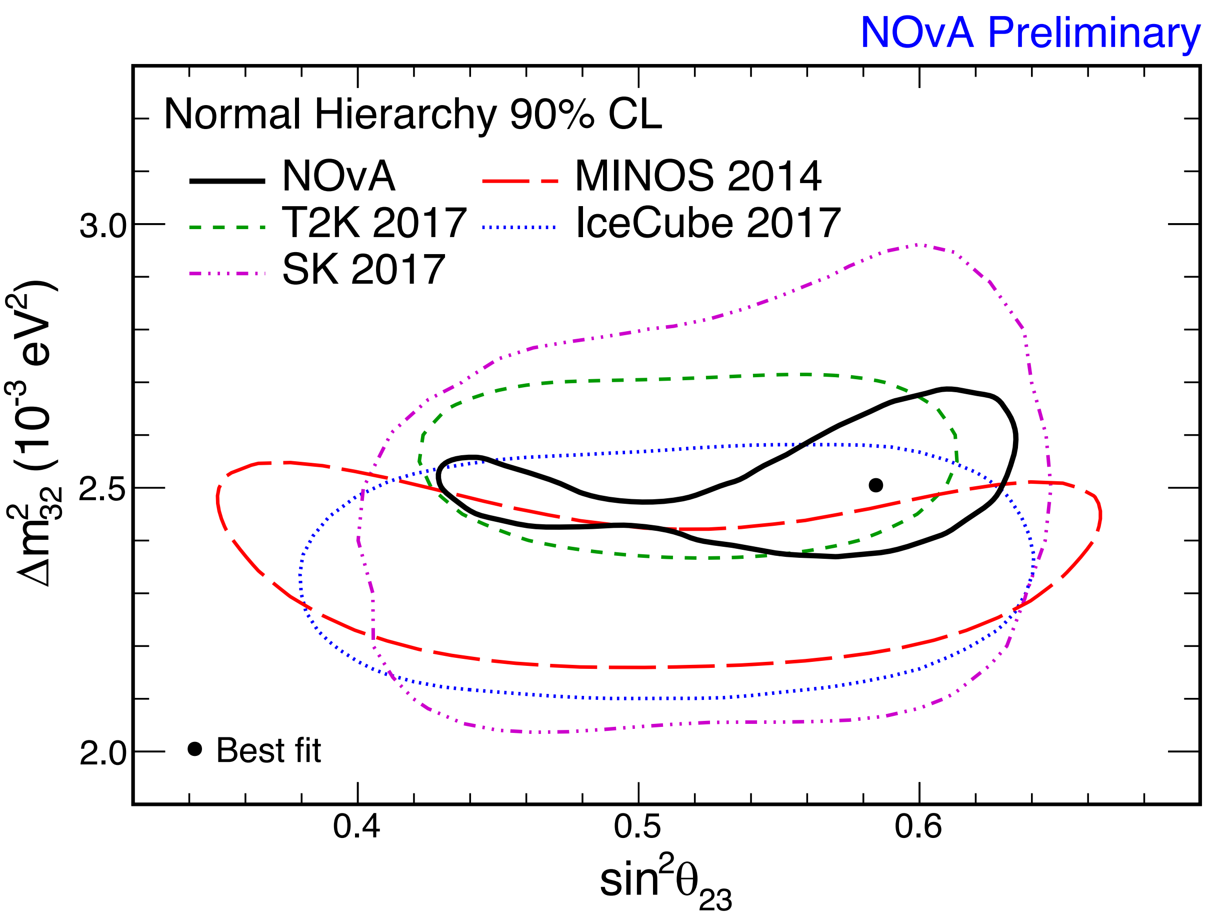
$\Delta m^2_{32} = 2.51^{+0.12}_{-0.08} \times 10^{-3}\text{eV}^2$

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

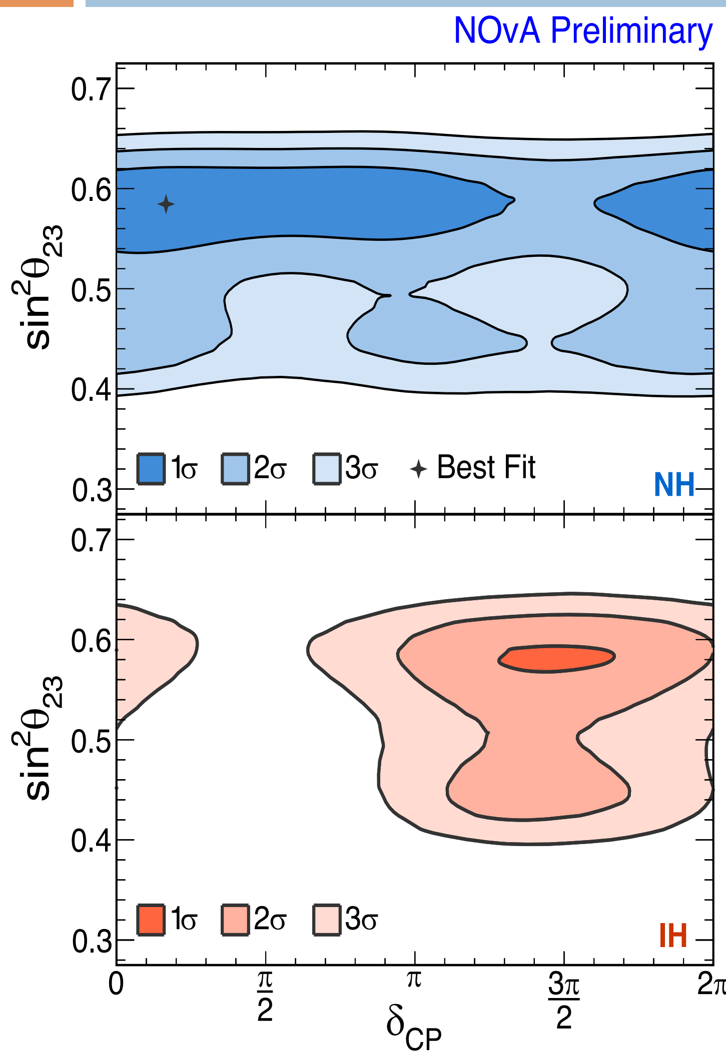
(Upper Octant)

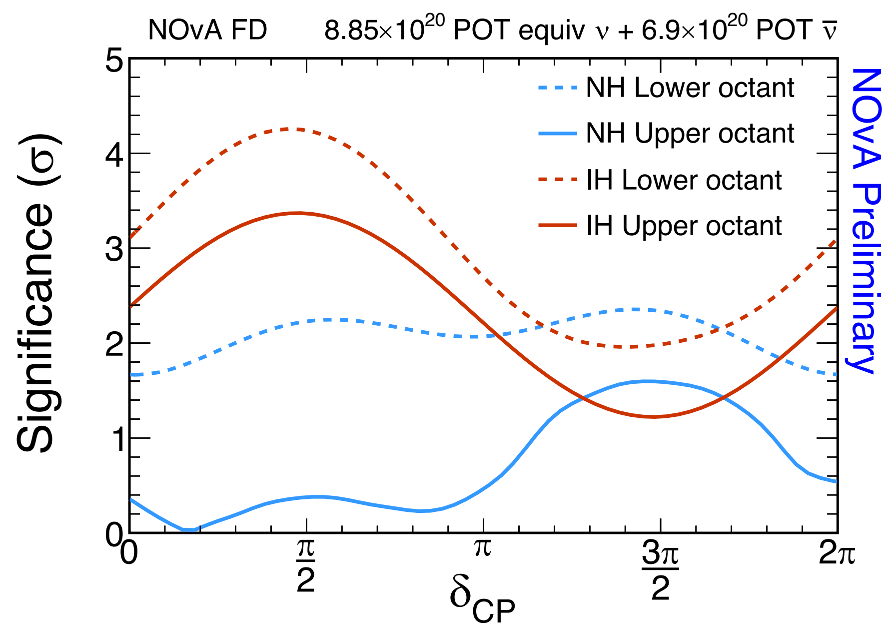
$\delta_{CP} = 0.17\pi$

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

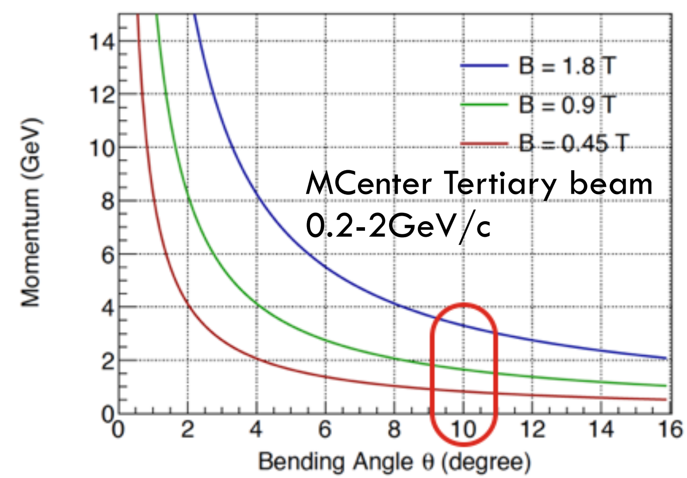
Future Oscillation Analysis Strategy

- 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

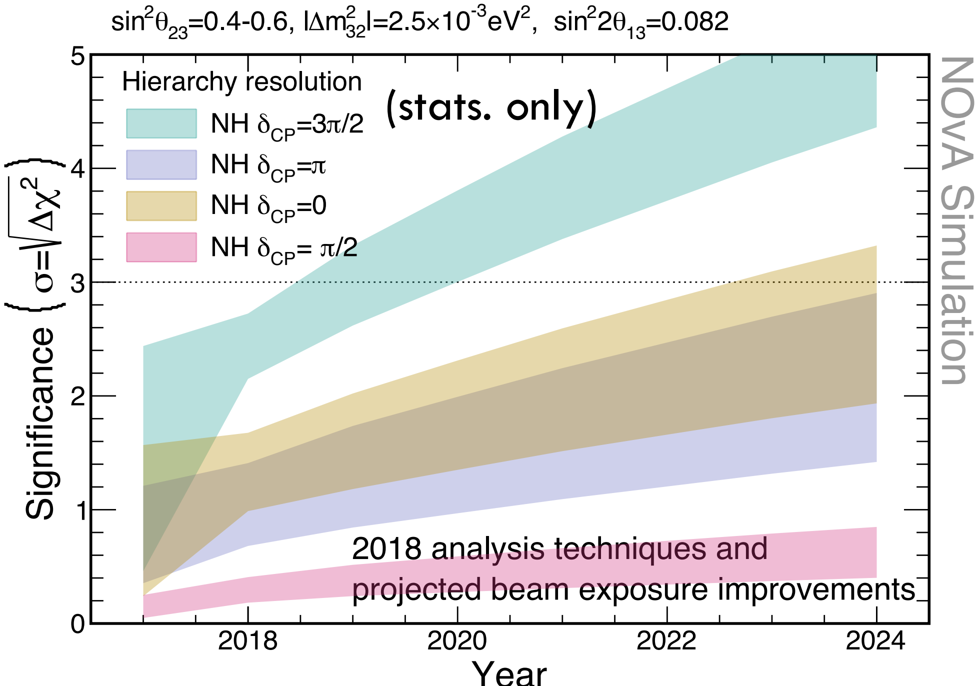
- Testbeam program addresses dominant NOvA systematic errors
  - energy scale for muons, hadrons, EM showers
  - relative calibration
  - light/scintillator response model
- Provides real (tagged) data for sophisticated machine learning particle ID algorithms
- Installation begins this summer
  - Data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

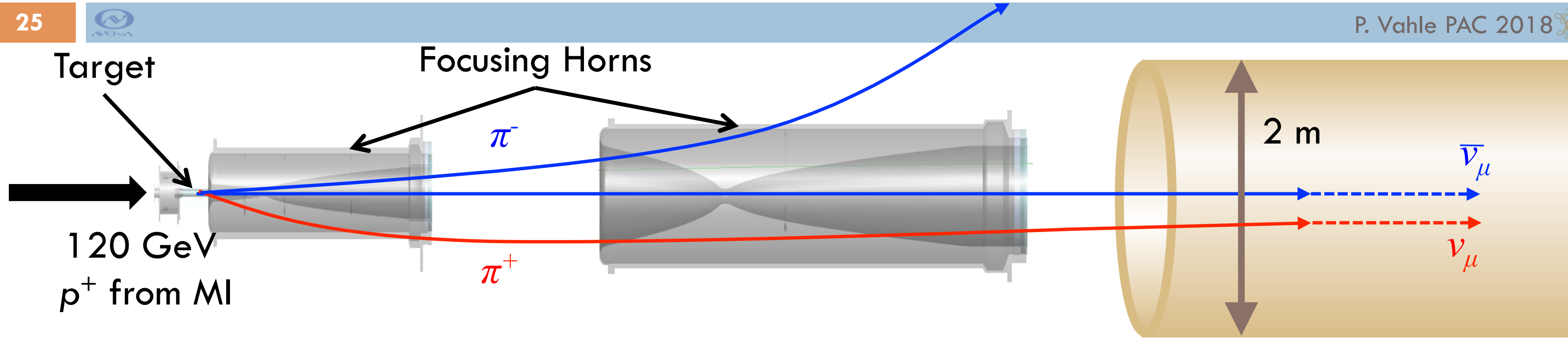
- Sterile Neutrinos
  - NC disappearance/anomalous muon neutrino (antineutrino) disappearance between ND and FD
  - SBL electron neutrino appearance in ND
  - Tau appearance in ND
- Neutrino interaction physics
  - Muon and electron neutrino charged current inclusive cross section
  - COH Pi0
  - CC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

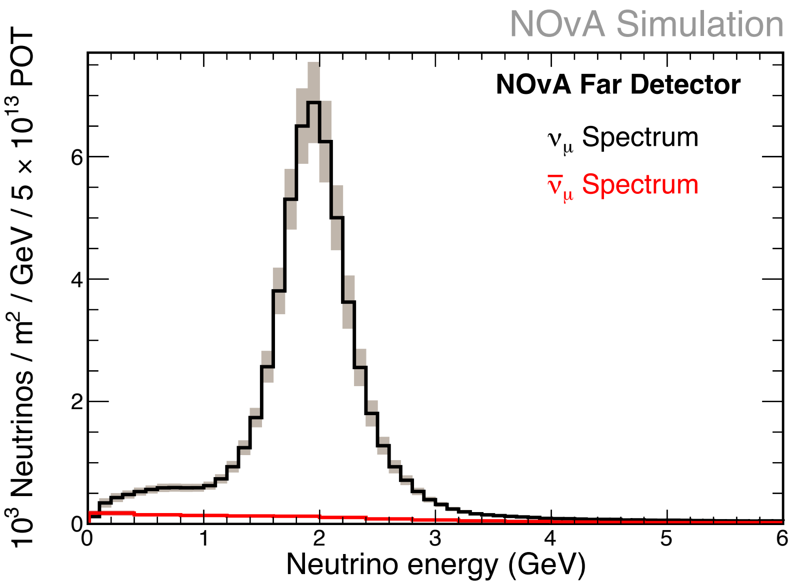
Summary

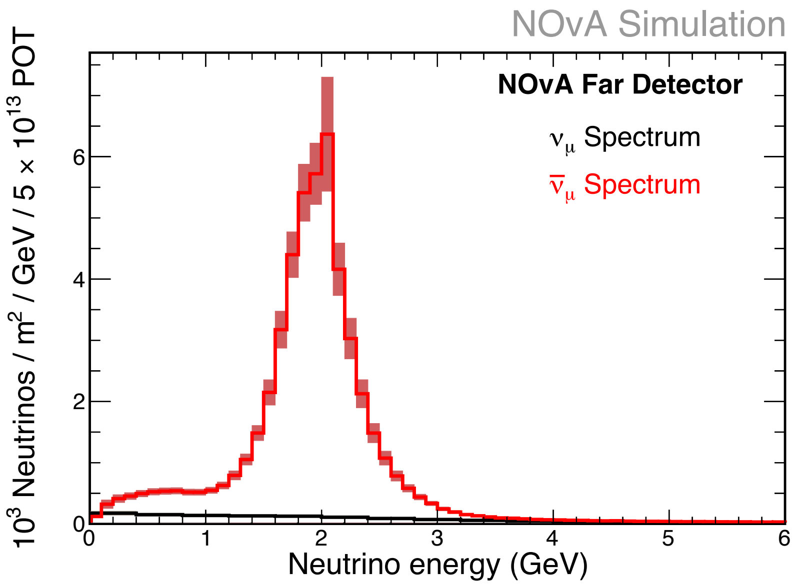
- First antineutrino results released this summer
  - >4 sigma evidence of electron-antineutrino appearance
  - 1.8 sigma preference for Normal Hierarchy
  - 1.8 sigma preference for non-maximal mixing
- Continue to take data in antineutrino mode until 12e20 POT, then switch back to neutrinos
- Can achieve 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

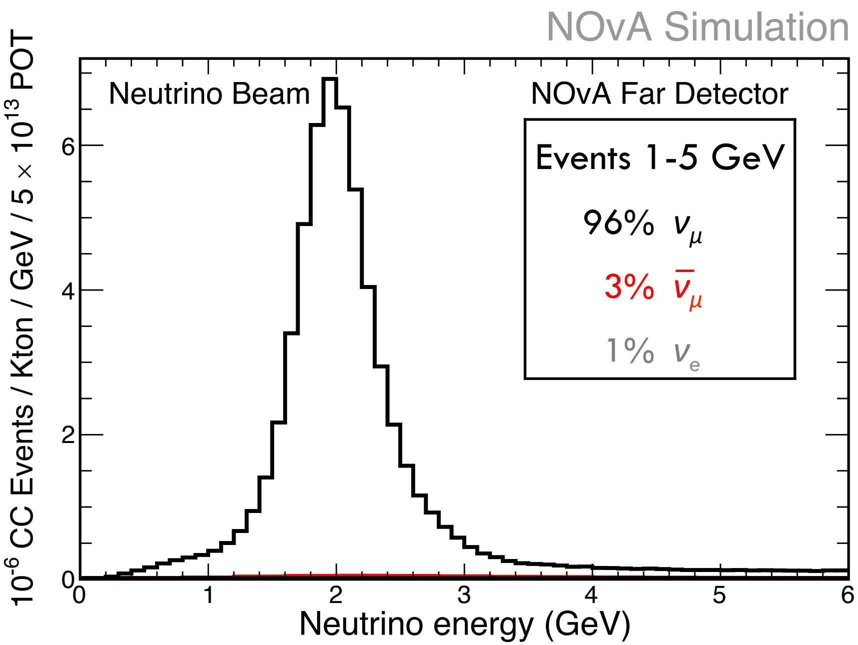
Making an off-axis neutrino beam

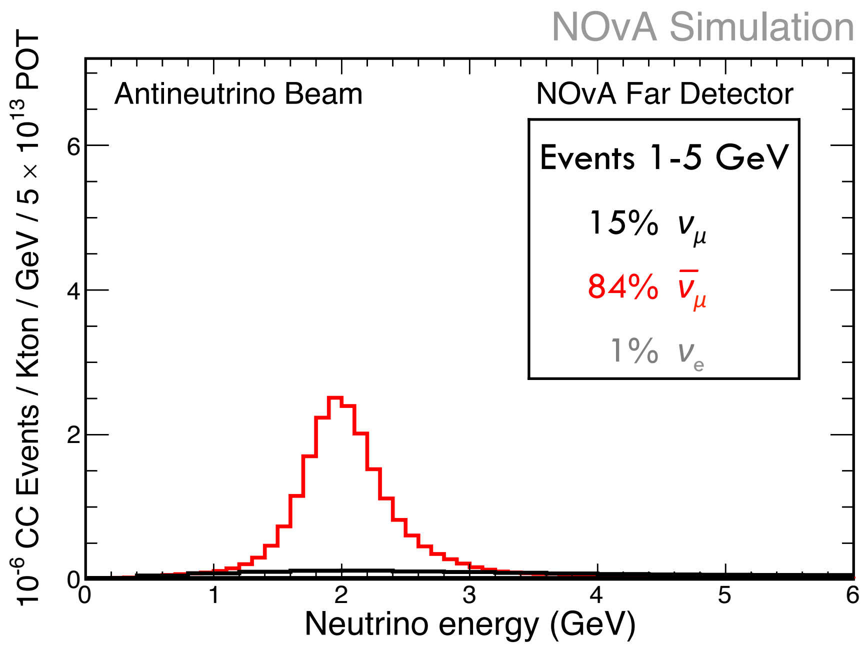






Beam Spectra

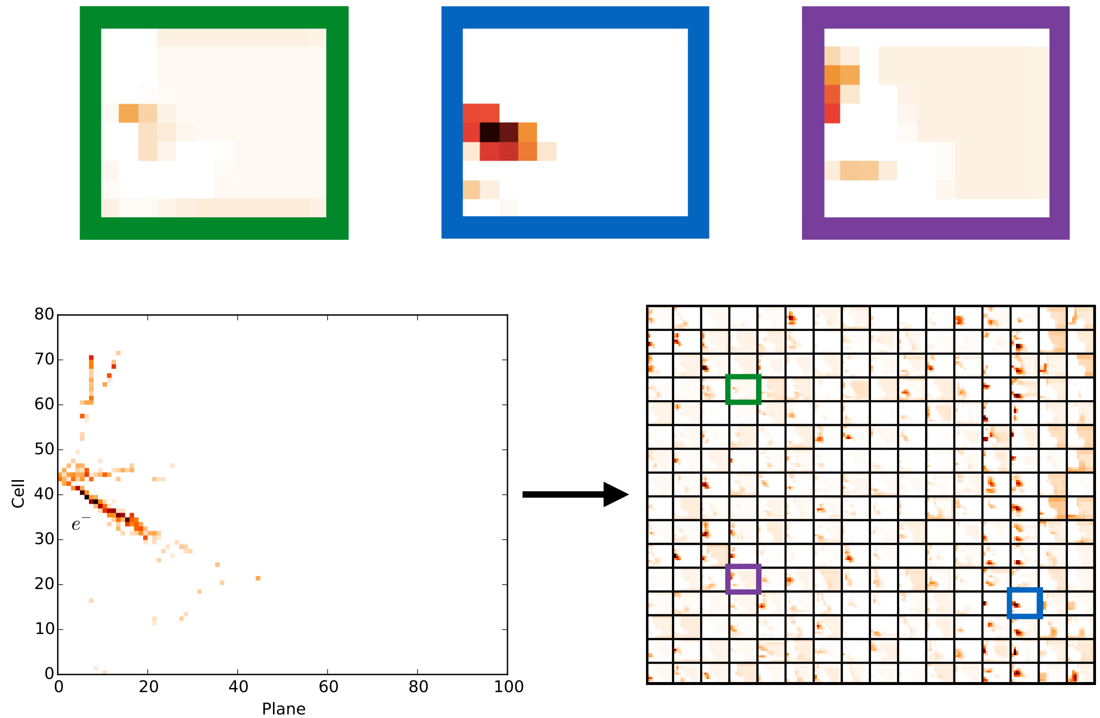




Improved Event Selection

- 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

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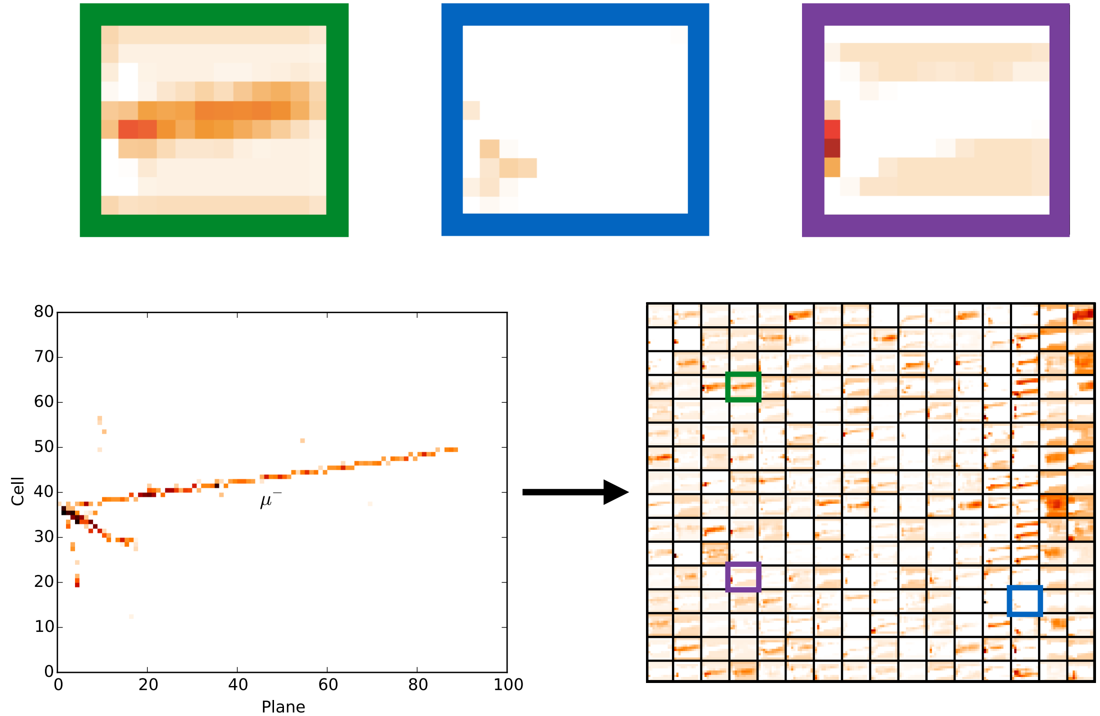

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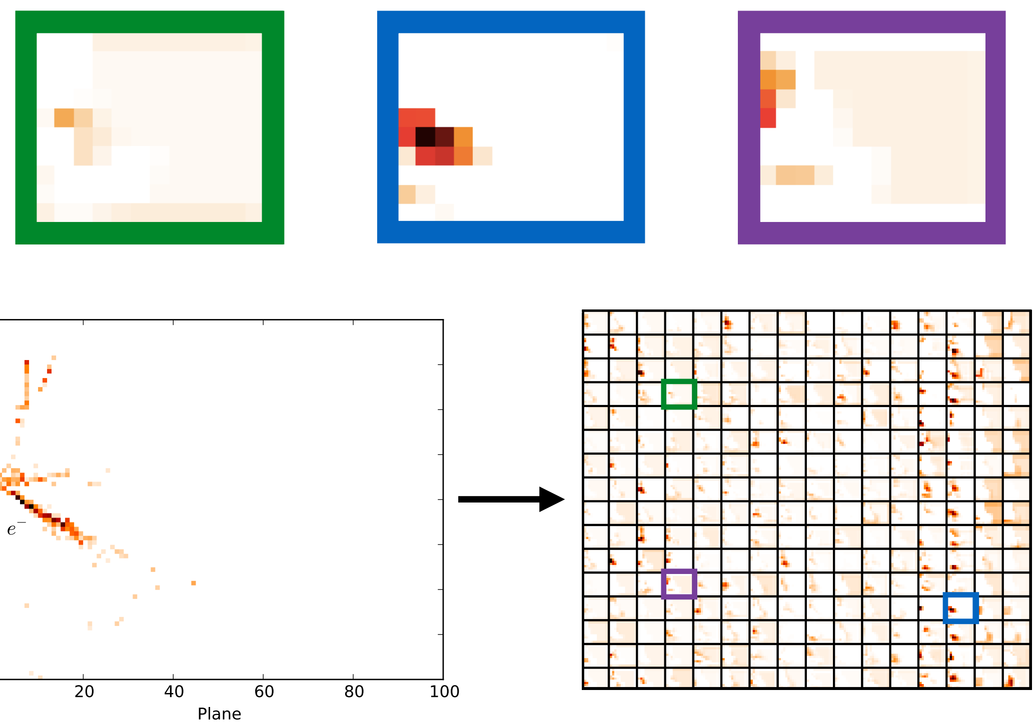


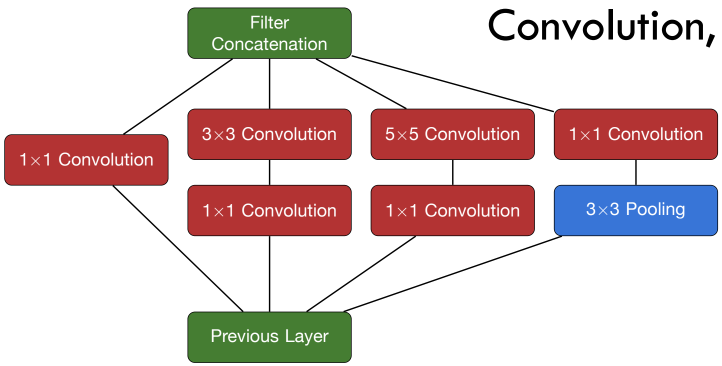
Improvement in sensitivity from CVN equivalent to 30% more exposure

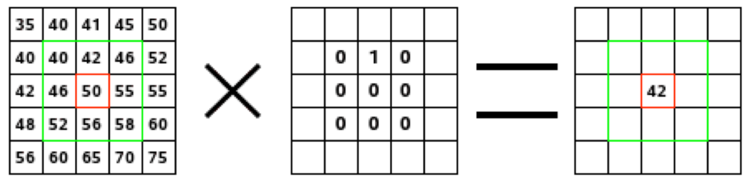
A. Aurisano et al., arXiv:1604.01444

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

CVN Architecture

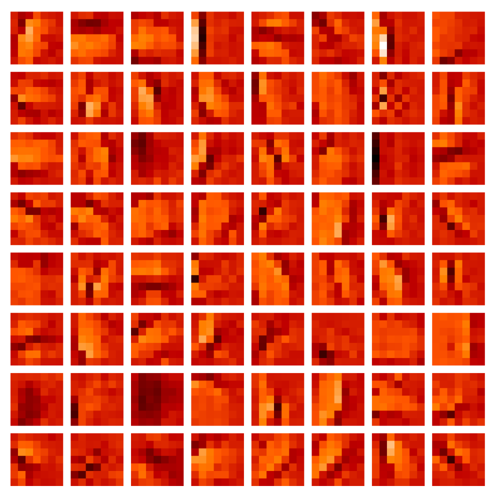
GoogLeNet Inception Module
C. Szegedy et al., arXiv:1409.4842





Example image processing transformation
Convolution, or kernel map

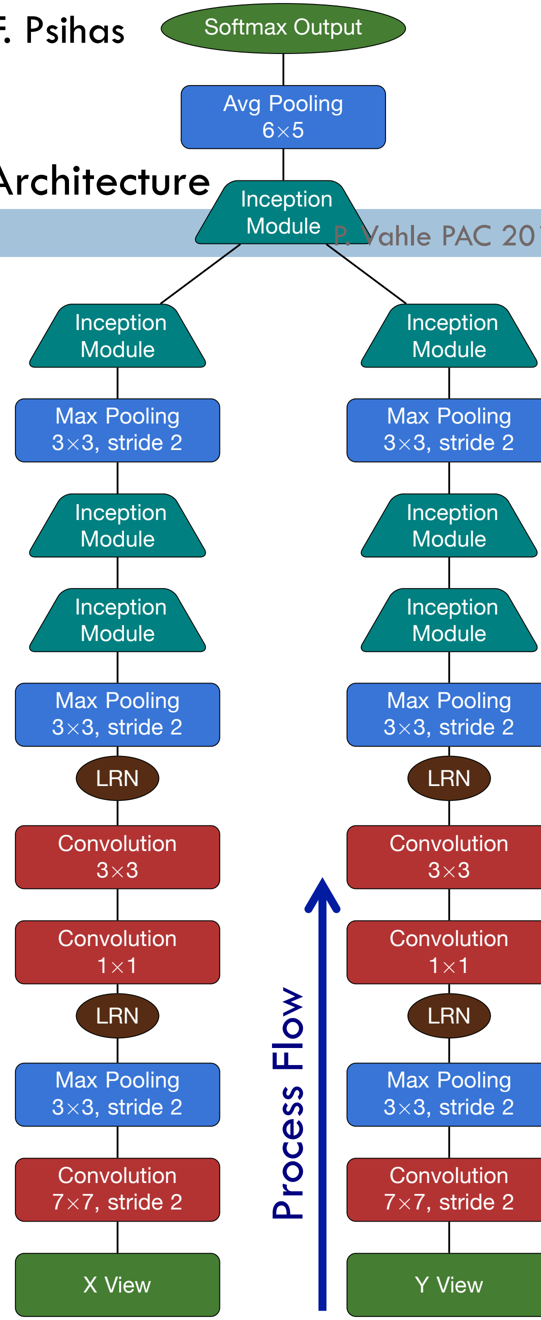
Example Convolutional Filter Layer



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

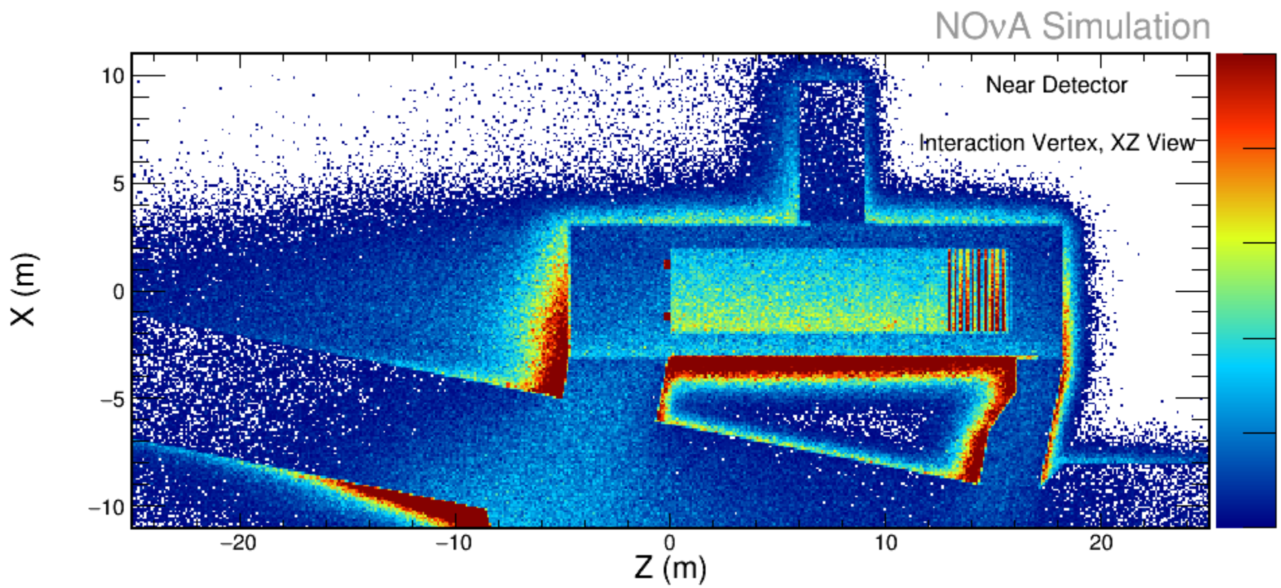
Trained over 4.7M simulated events,
Trained on FNAL GPU farm

CVN Architecture



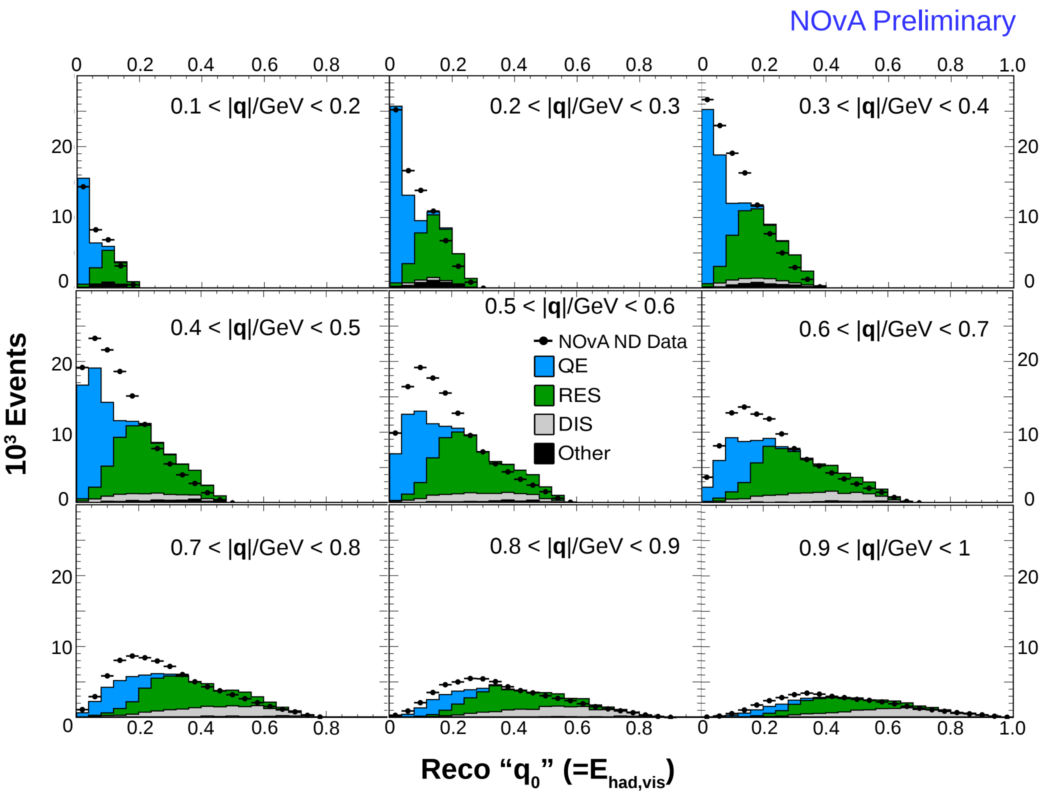
Simulation

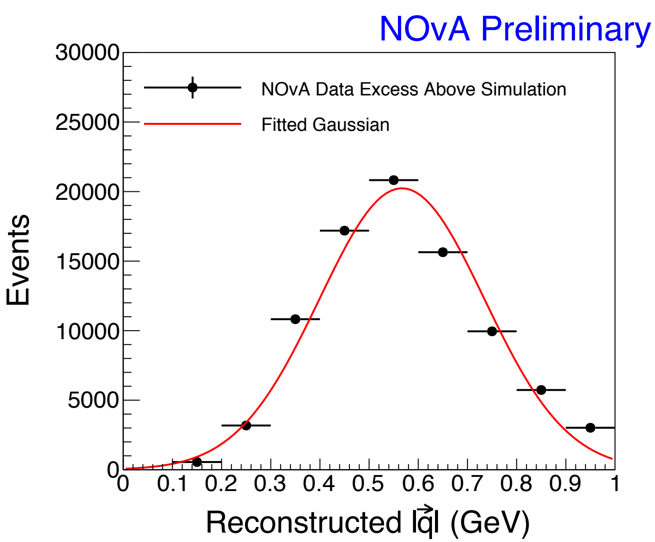
- Beam line production, propagation and neutrino flux: FLUKA/Flugg
- Cosmic Ray flux: CRY
- Neutrino interaction and FSI: GENIE
- Detector: Simulation: Geant4
- Detector response: Custom simulation Routines



Scattering in a Nuclear Environment

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

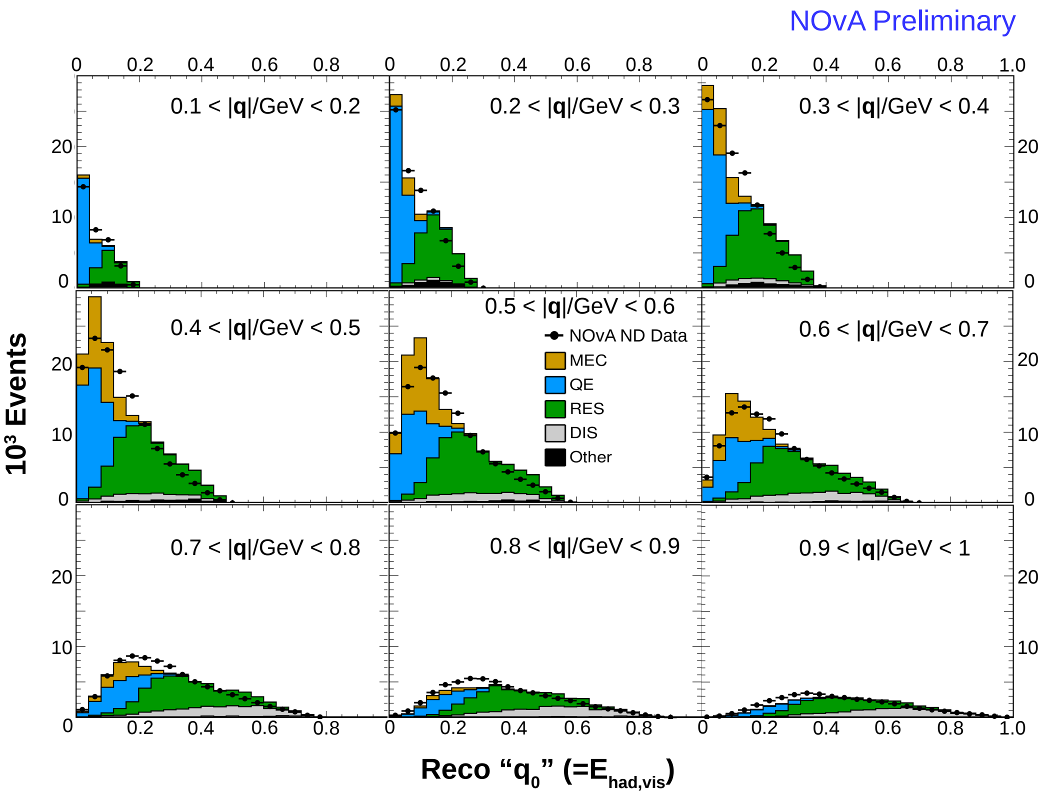




Similar conclusions from MINERvA data reported in P.A. Rodrigues et al., PRL 116 (2016) 071802

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

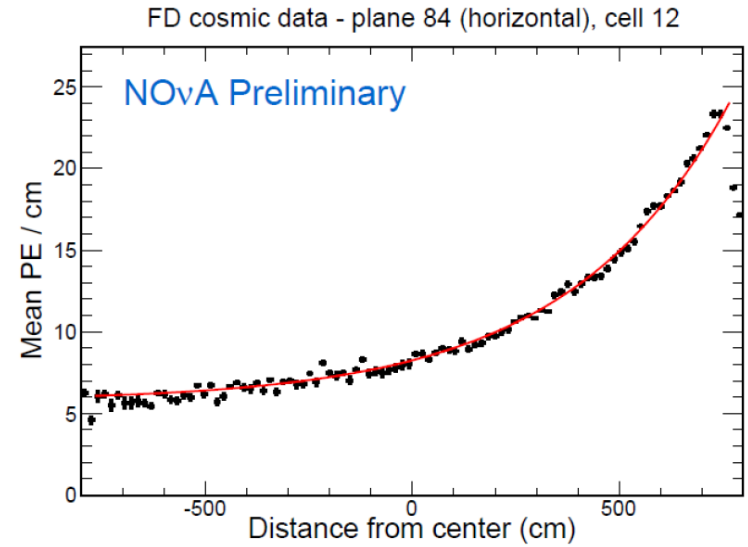


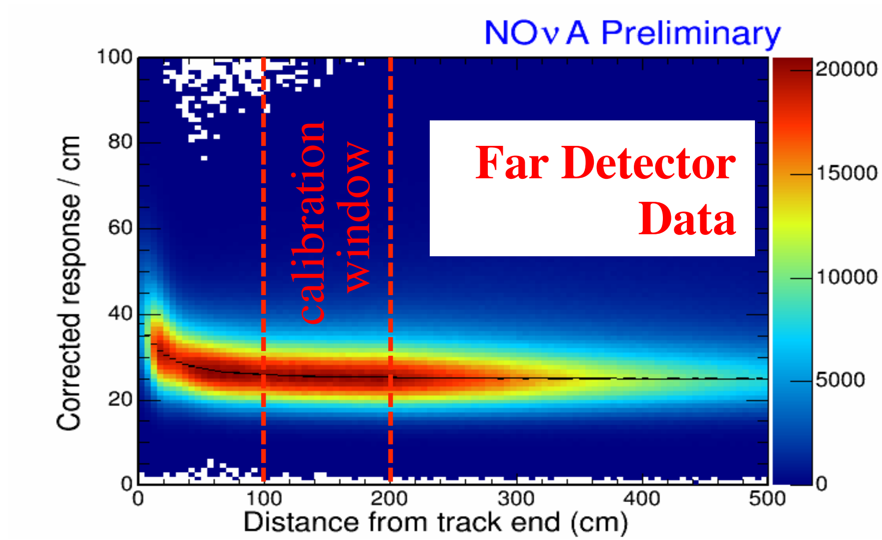
- Eliminate falloff of xsec with energy
- Fix final state nucleon composition
- Match MEC q_0 distribution to quasi-elastic distribution
- scale normalization in bins of 3-momentum transfer to match data/mc disagreement
- Include 50% systematic uncertainty on size of MEC component
- Additionally, reduce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

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

Calibration

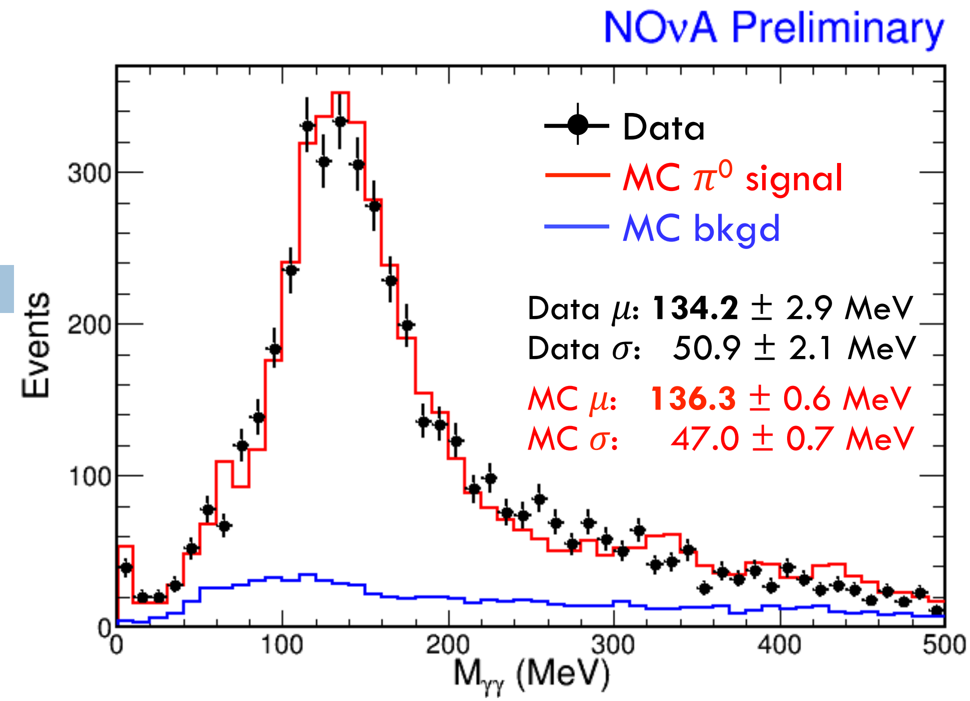
- Calibration achieved using cosmic rays
- Light levels drop by a factor of 8 across a FD cell
- Stopping muons provide a standard candle

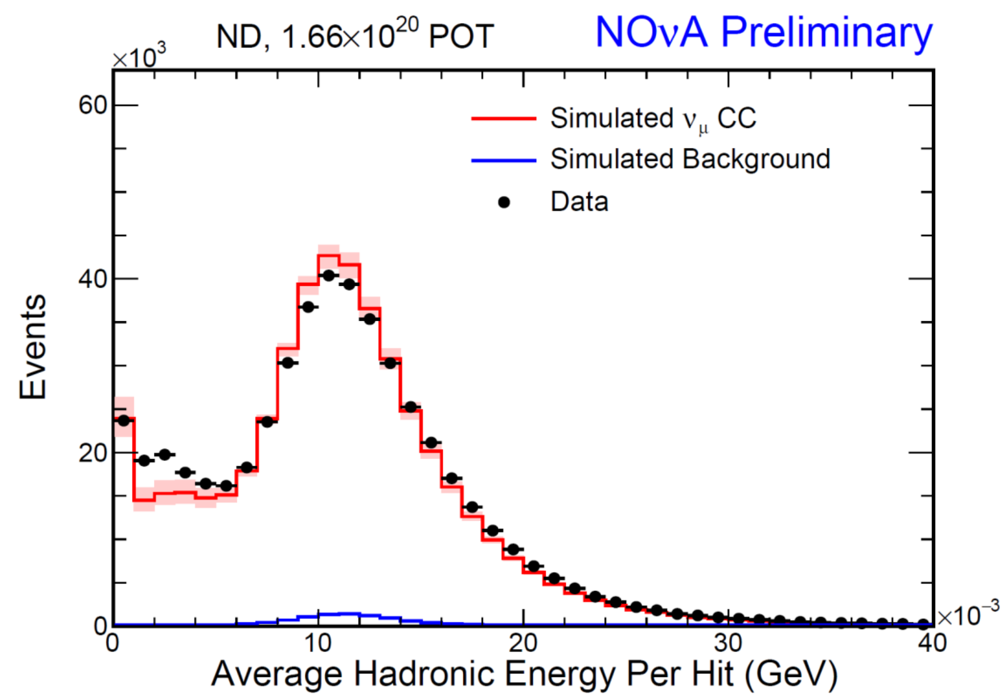




Energy Scale

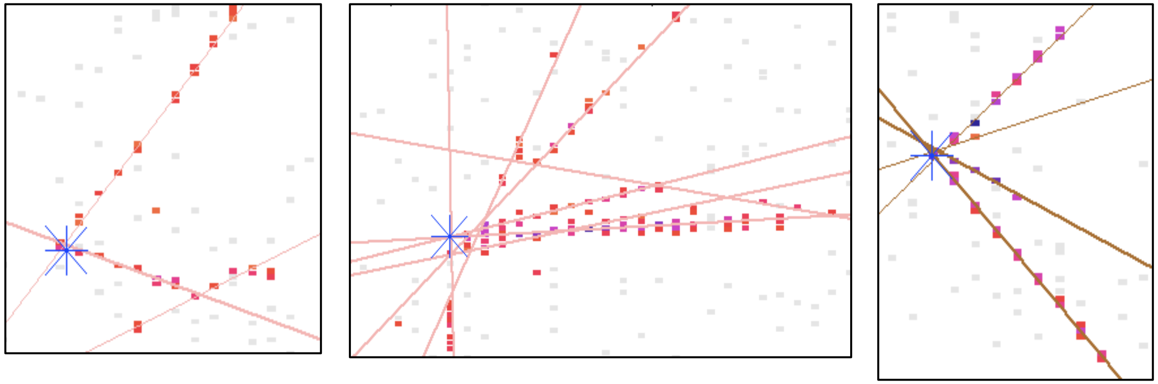
- Near Detector
  - cosmic μ dE/dx [~vertical]
  - beam μ dE/dx [~horizontal]
  - Michel e⁻ spectrum
  - π^0 mass
  - hadronic shower *E*-per-hit
- Far Detector
  - cosmic μ dE/dx [~vertical]
  - beam μ dE/dx [~horizontal]
  - Michel e⁻ spectrum
- All agree to 5%



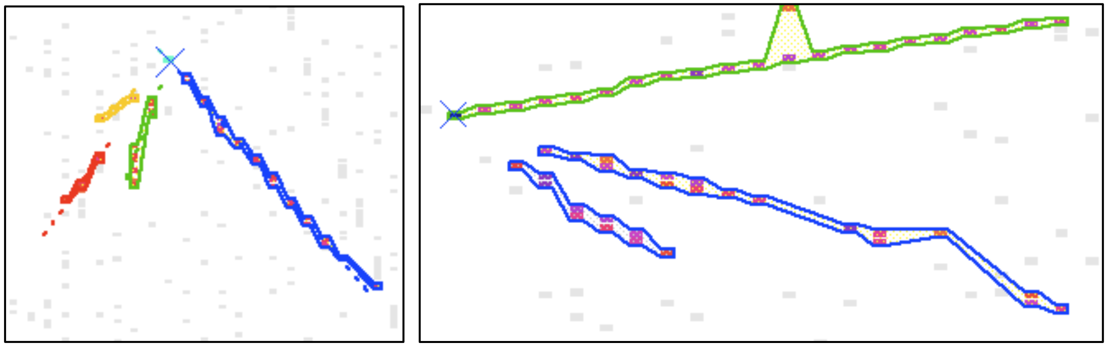


Reconstruction

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

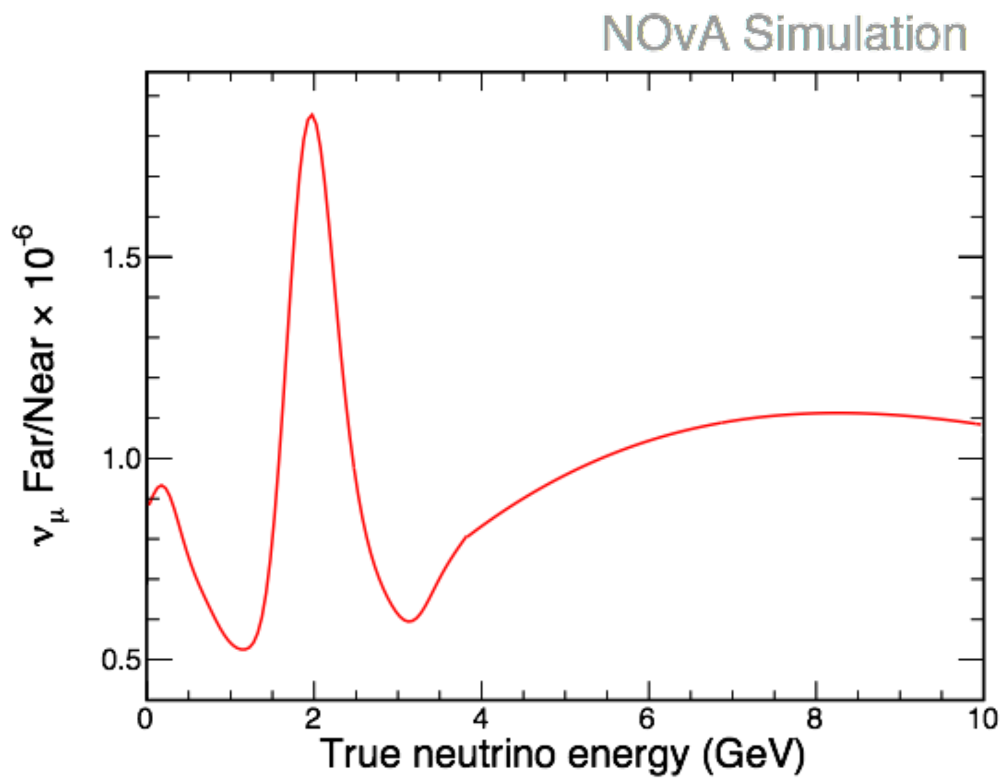


Tracking: Trace particle trajectories with **Kalman filter** tracker.
Also, **cosmic ray tracker:** lightweight, fast, and for large calibration samples, online monitoring.

Extrapolation

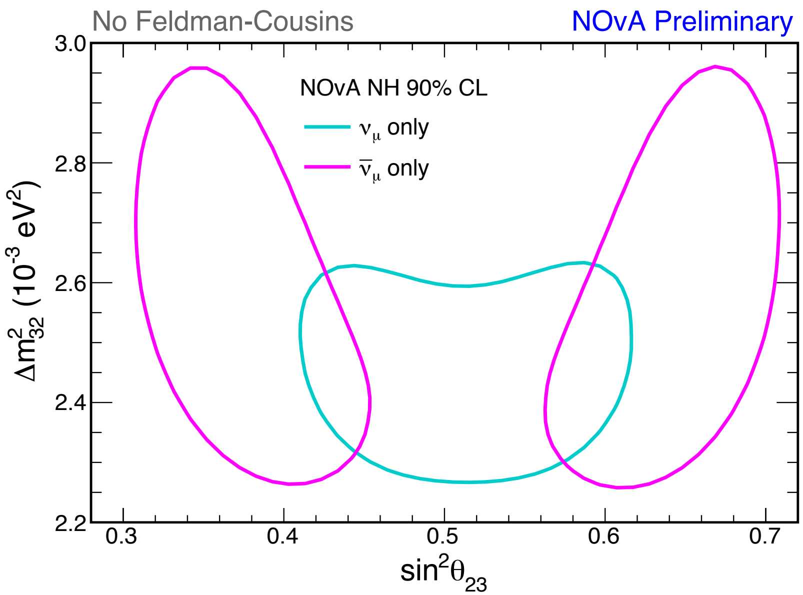
- All NOvA analyses use ND data to predict the FD spectrum

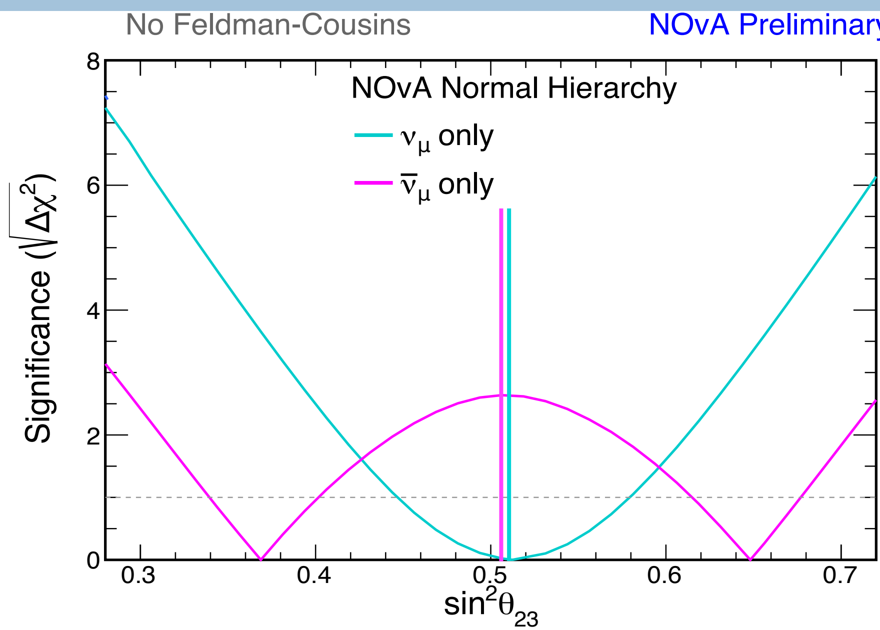
- Muon Neutrino analyses: unfold reco energy, use true F/N ratio for FD prediction of track events
- Electron Neutrino signal: use Muon-neutrino FD prediction
- NC and Electron Neutrino background analyses: Far to Near spectrum in reconstructed energy ratio for FD prediction of shower events



Backup—Disappearance Results

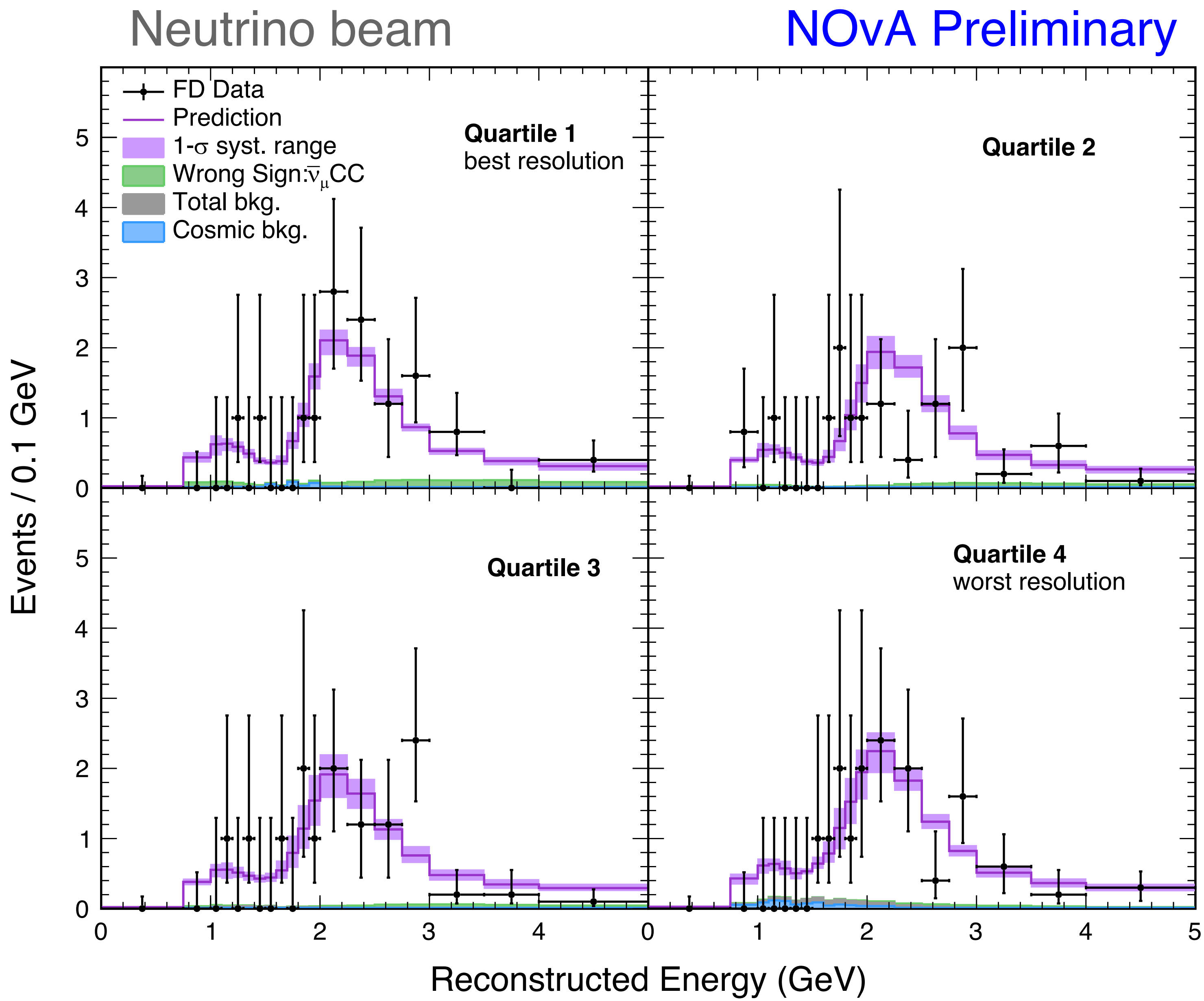
Disappearance

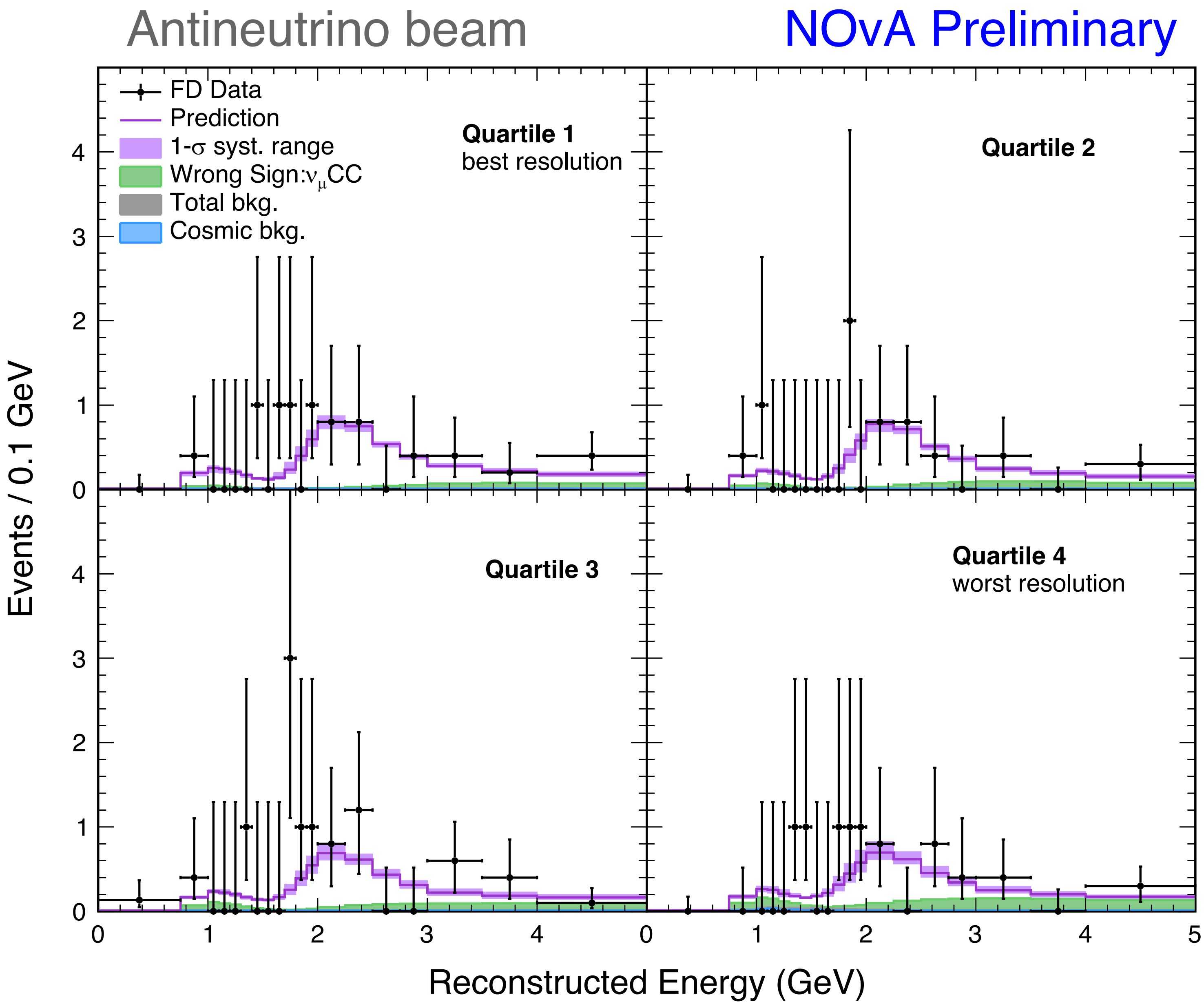




- If fit separately, the $\bar{\nu}_\mu$ data prefers non-maximal while ν_μ prefers maximal.
  - Consistent with joint oscillation parameters to >4%.
- Matter effects introduce a small asymmetry in the point of maximal disappearance.
- Gives a 1.3σ preference for the Upper Octant from *just* the $\nu_\mu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

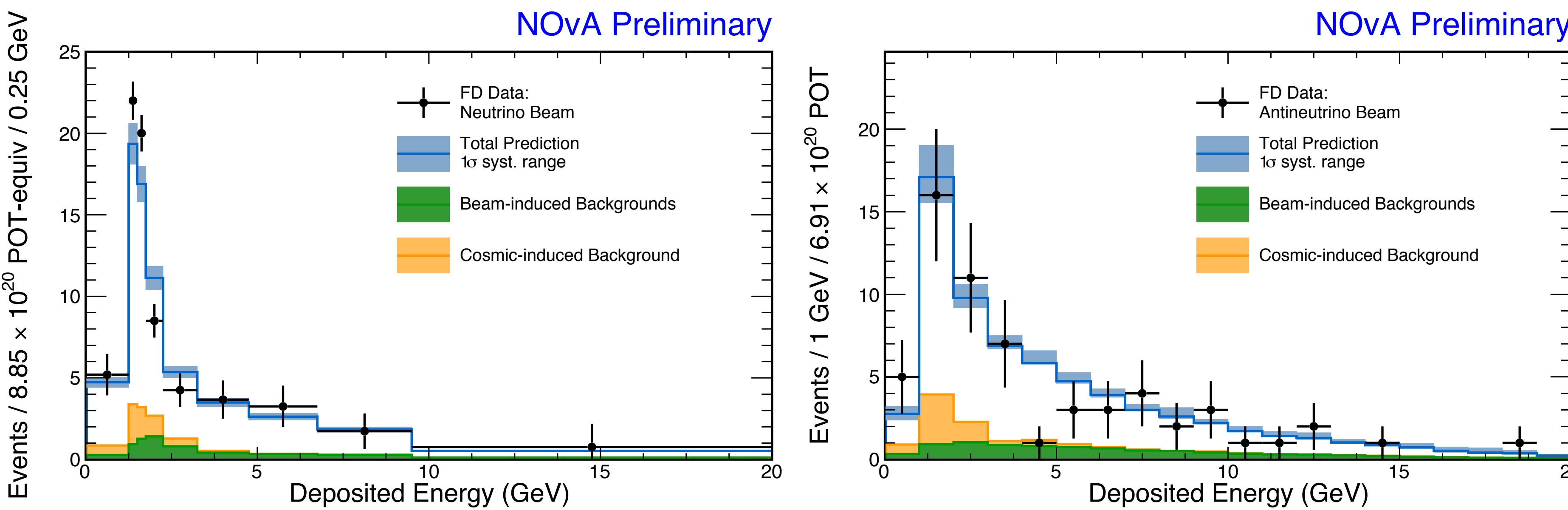
Neutrino beam




Antineutrino beam
NOvA Preliminary
FD Data
Prediction
1-σ syst. range
Wrong Sign:ν_μCC
Total bkg.
Cosmic bkg.
Quartile 1
best resolution
Quartile 2
Quartile 3
Quartile 4
worst resolution
Events / 0.1 GeV
Reconstructed Energy (GeV)
0
1
2
3
4
5

Backup—NC Results

NC Results



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

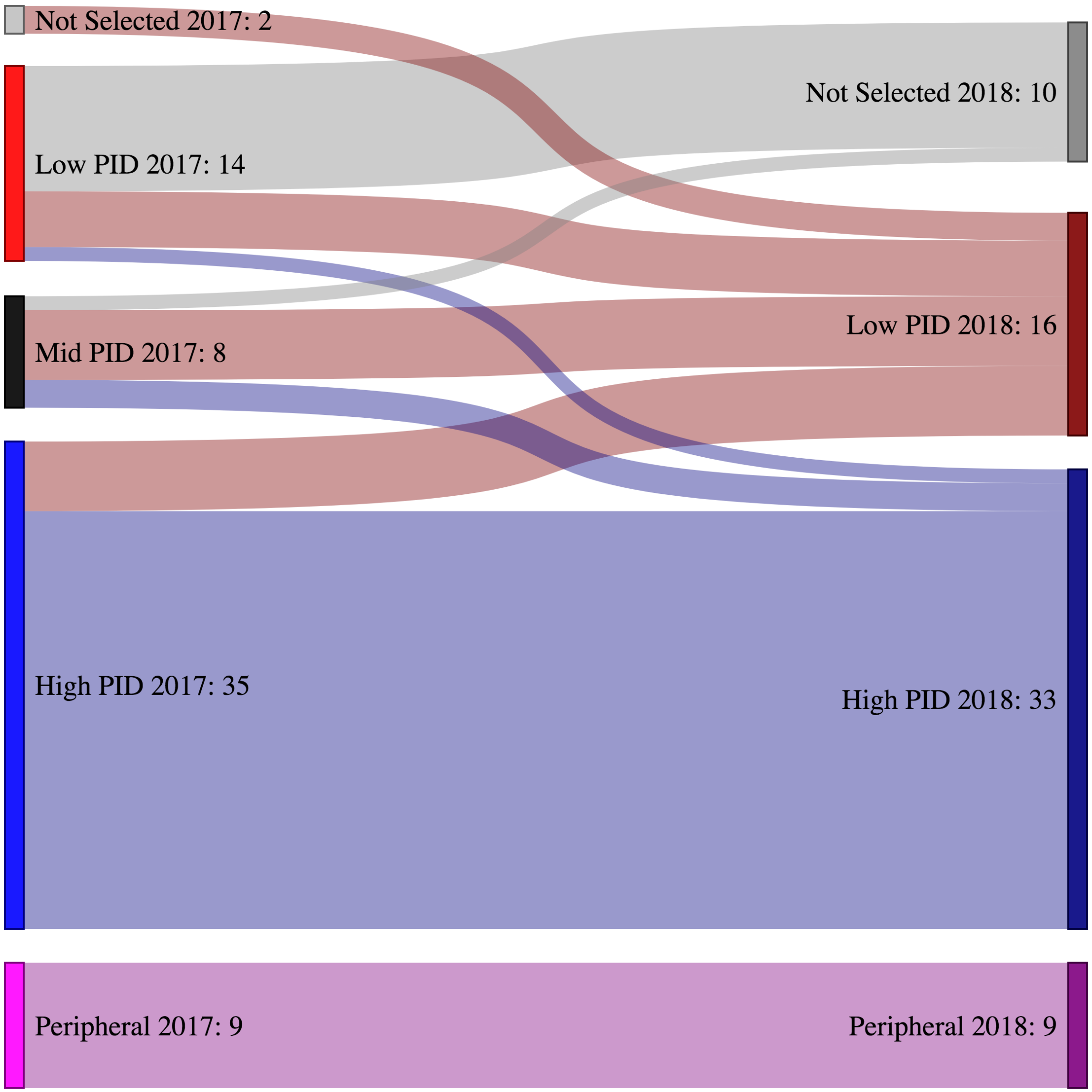
Antineutrino mode:
expect 69+/-8 (syst.) with 16 bkg.
Observe 61 events

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

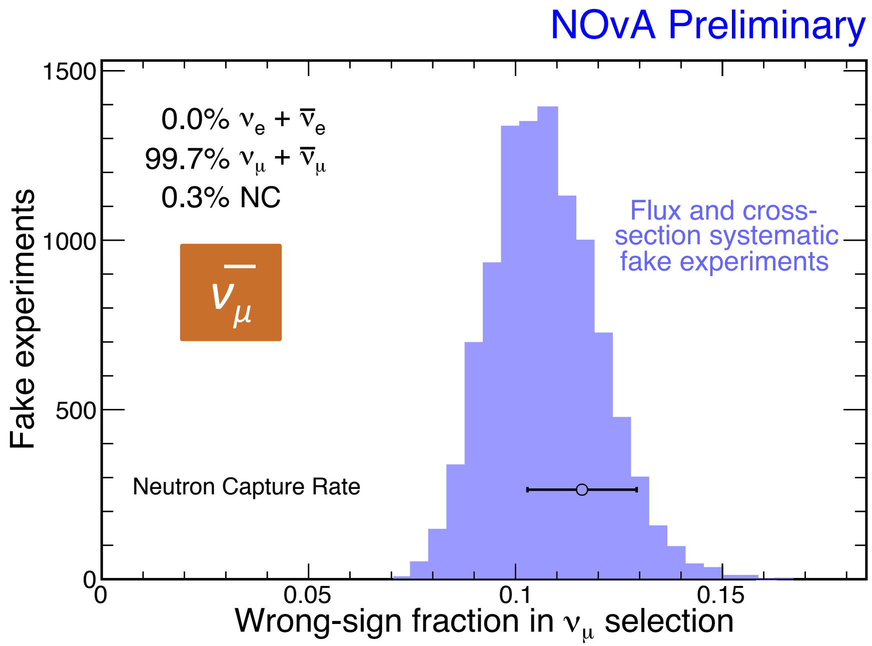
Backup—Appearance Results

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.



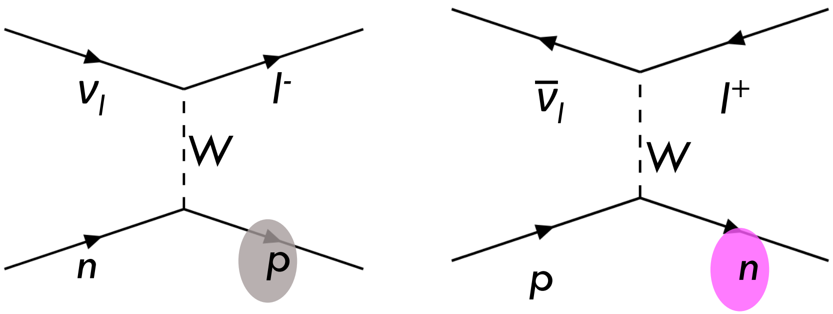
Wrong-sign Background

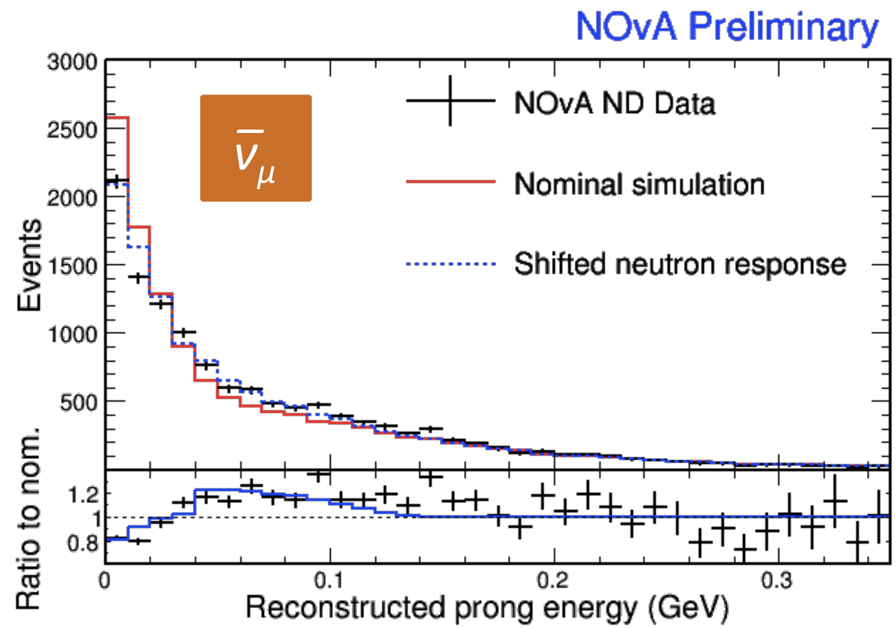


- The 11% wrong-sign fraction of the **$\bar{\nu}_\mu$ events** is important since it becomes the WS background in the **$\bar{\nu}_e$ appearance analysis**.
- ~10% systematic uncertainty on wrong-sign from flux and cross section
  - Does not include uncertainties from detector effects.
- Confirmed using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

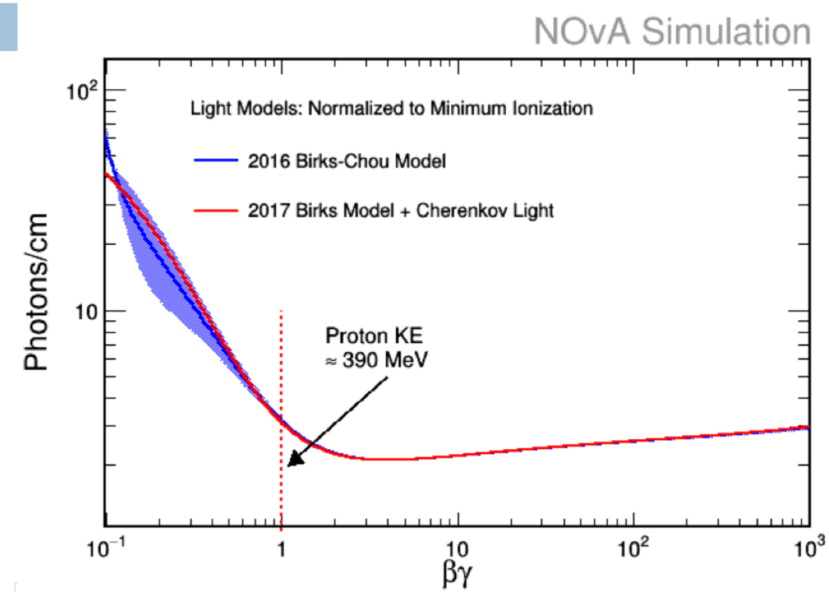


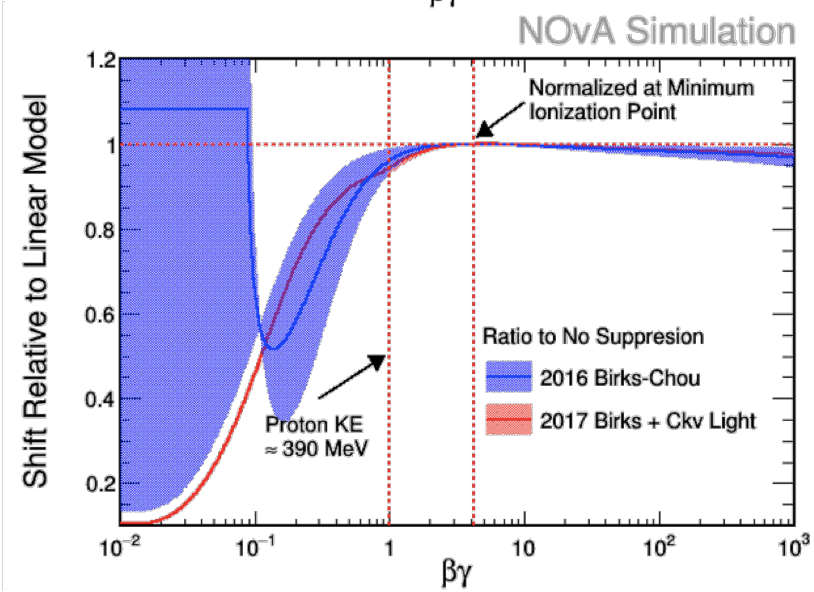


- $\bar{\nu}$'s have neutrons where ν's have protons.
  - Often several hundred MeV of energy.
  - Modeling these fast neutrons is known to be challenging.
- See some discrepancies in an enriched sample of neutron-like prongs.
- New systematic introduced:
  - Scales the amount of deposited energy of 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.

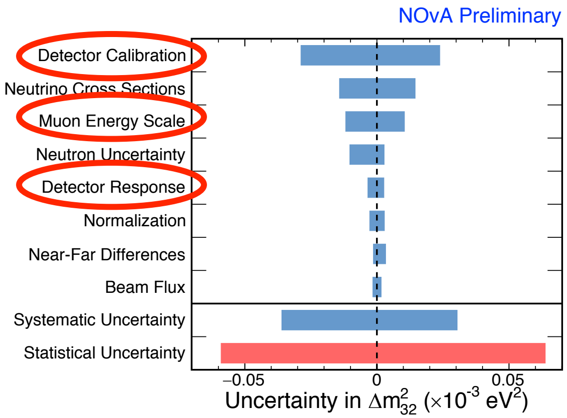
Scintillator Model

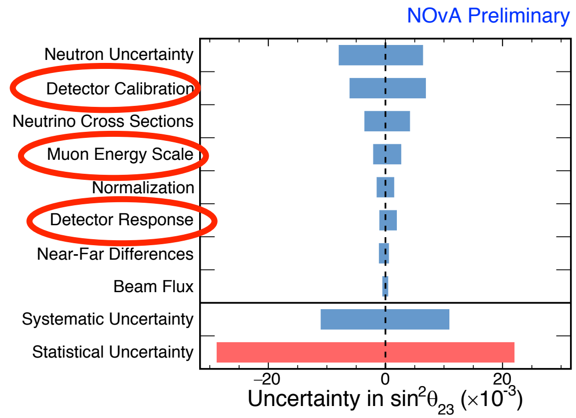
- Absorbed and re-emitted Cherenkov light is a small but important component of our scintillator response.
  - Particularly for low-energy protons in hadronic showers.
- Was one of our largest uncertainties, now reduced by an order of magnitude.
  - Previously accounted for with second order terms in 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%.

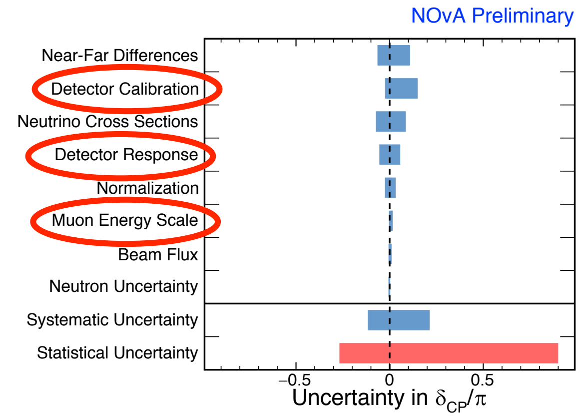


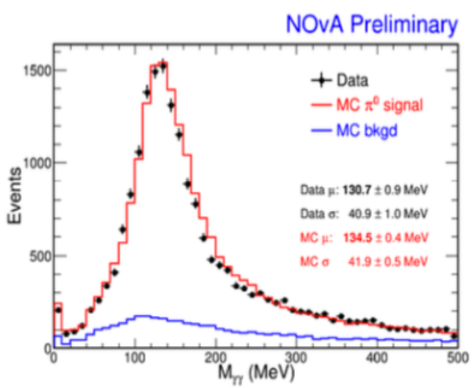


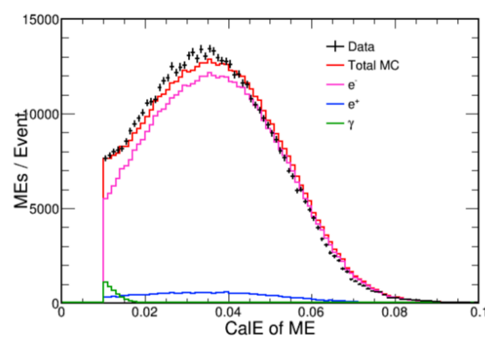
Systematics and Testbeam Motivation









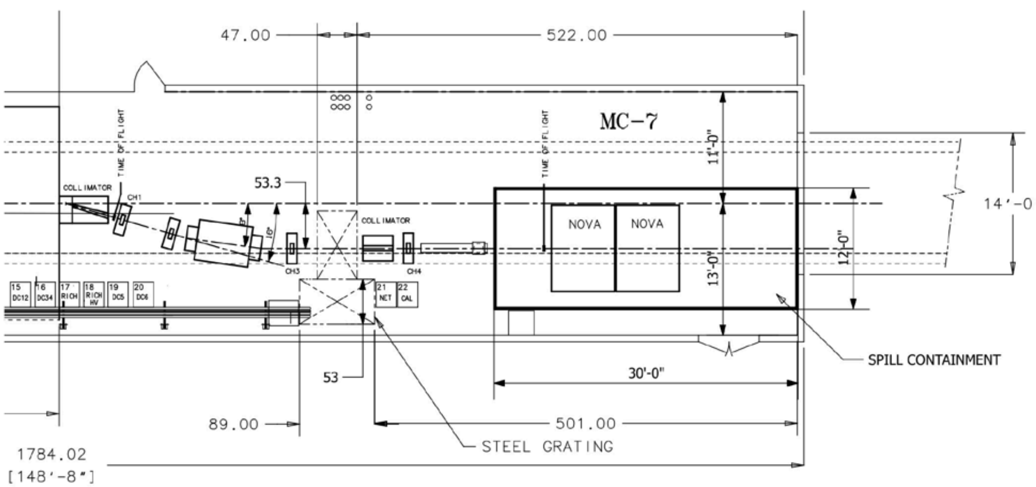


- Estimate of energy/calibration uncertainty comes from ~5% difference in data vs. MC when comparing pi0 mass and Michel e distributions
- Testbeam data decouples detector response from hadronic final state, neutrino cross section, flux uncertainties

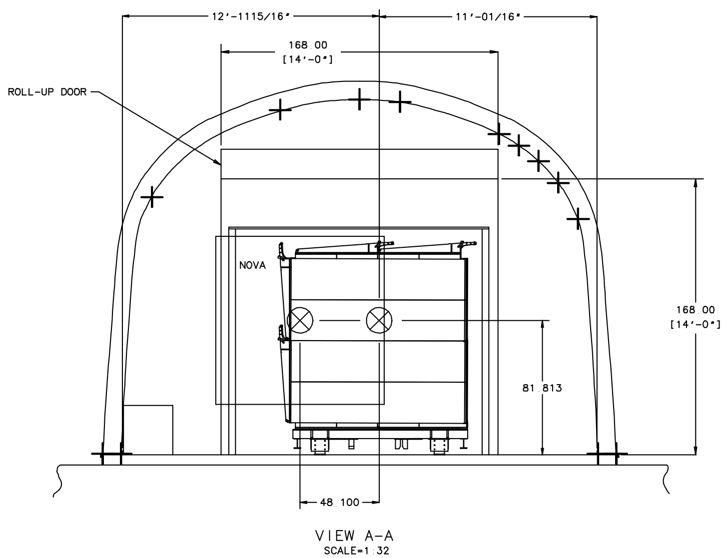
- Testbeam effort affords detailed understanding of detectors energy scale (muon, electromagnetic, and hadronic)
- Allows study of light model, scintillator quenching
- Provides real data for study of particle identification techniques

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



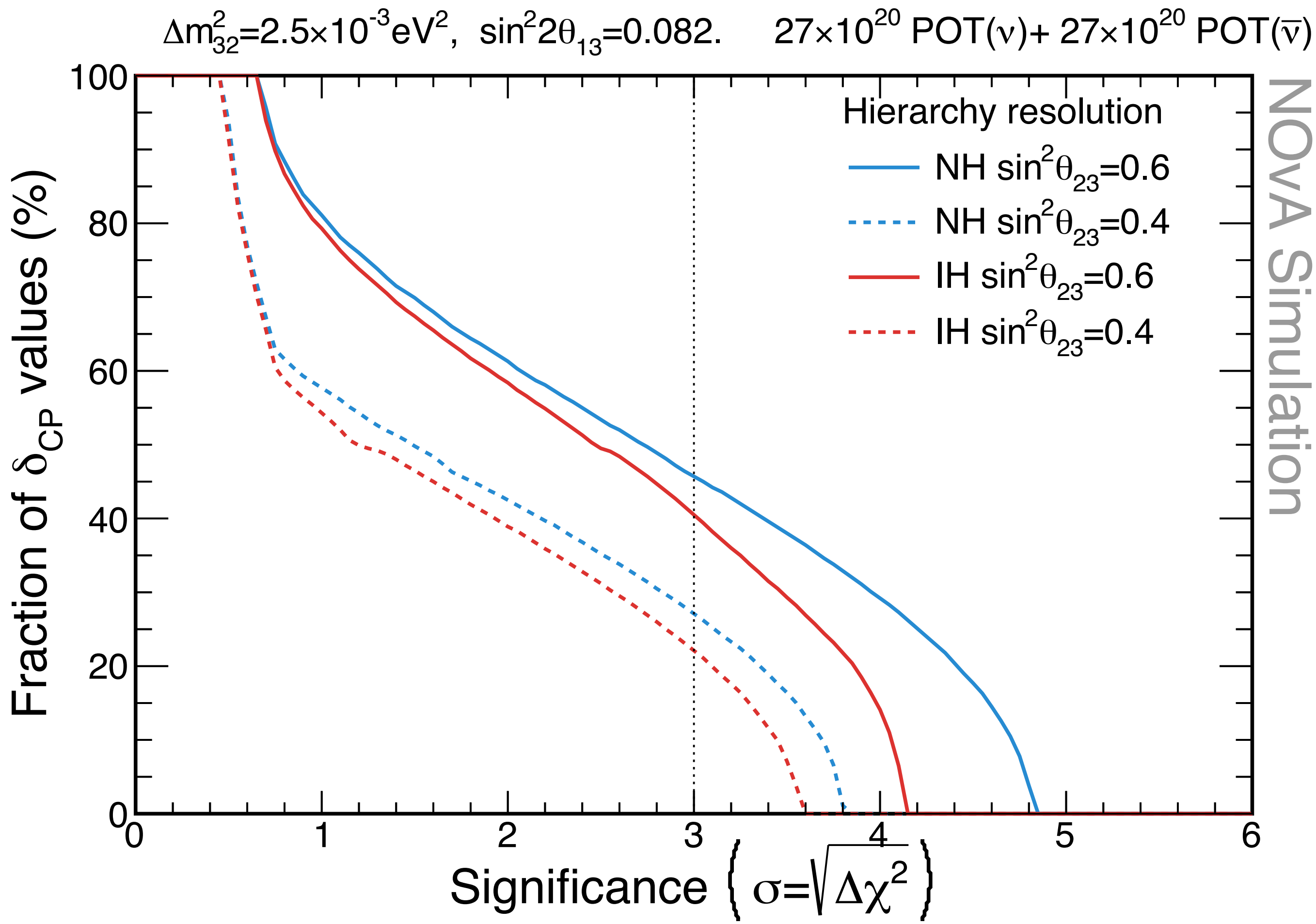
Testbeam



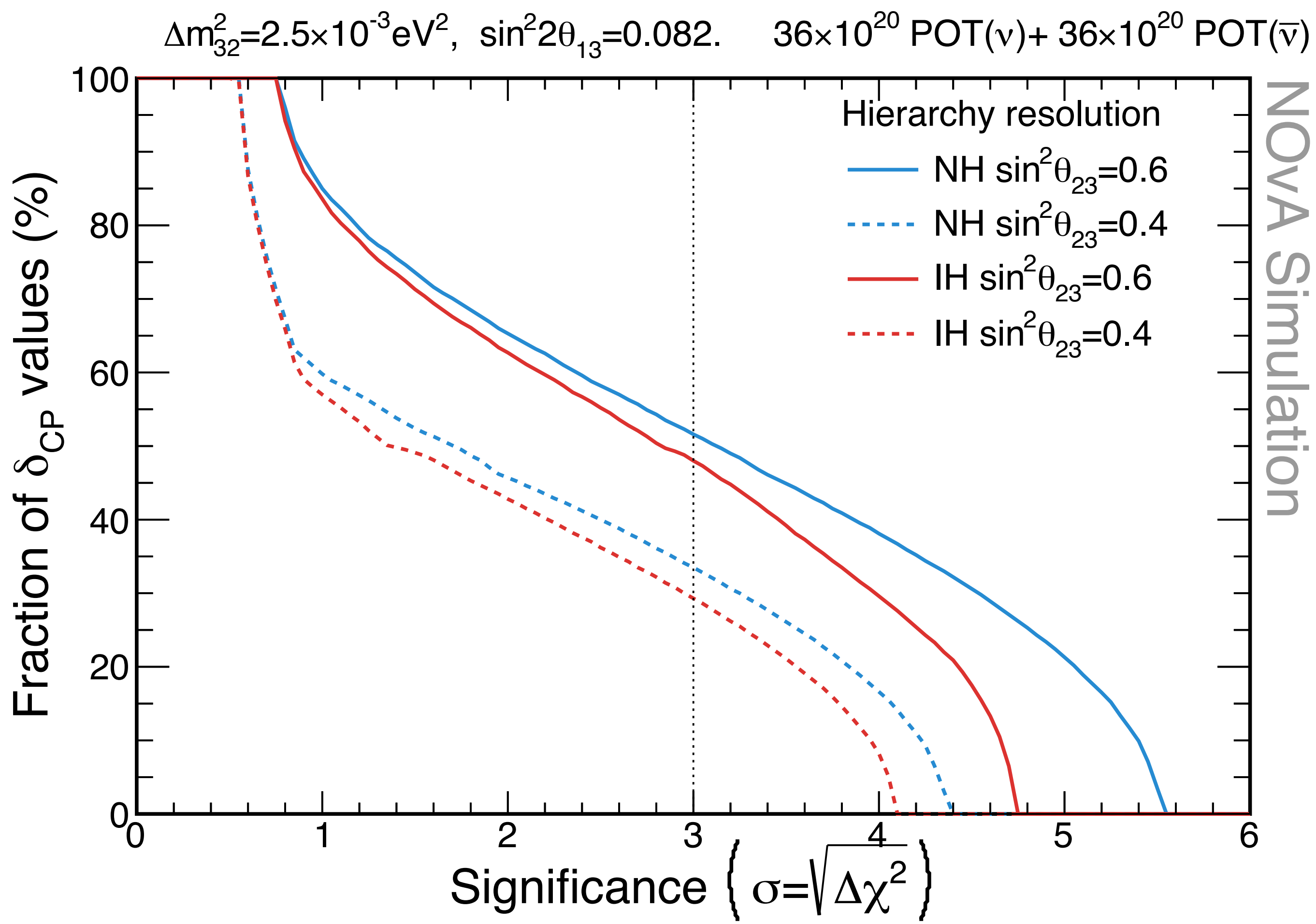
Detector Configuration	Two 2×2 31-plane blocks + One horiz. plane
Dimensions W(m)× H(m)× L(m)	2.6×2.6×4.1
Scintillator/plane (gallons)	86
Total Scintillator Volume (gallons)	5418
PVC Mass/plane (kg)	171.2
Adhesive Mass/plane (kg)	3.1
Total Empty Mass (kg)	10981
Total Scintillator Mass (kg)	17608
Total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

Backup—Sensitivity

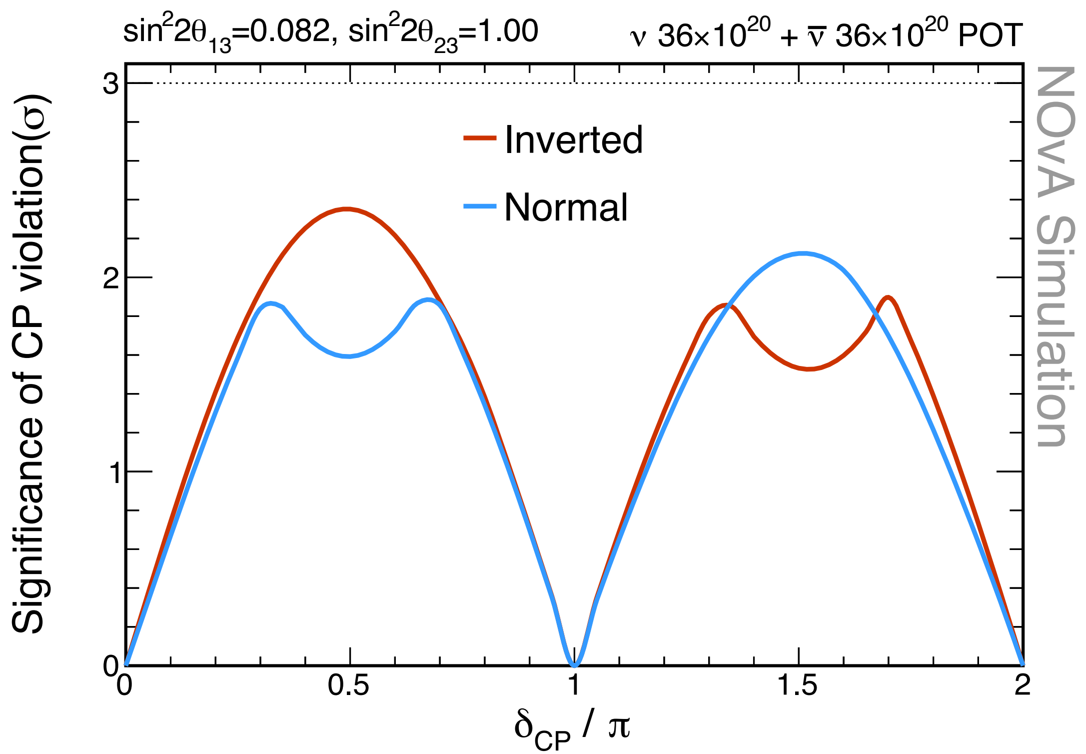
AIP Sensitivity Gain



AIP Sensitivity Gain



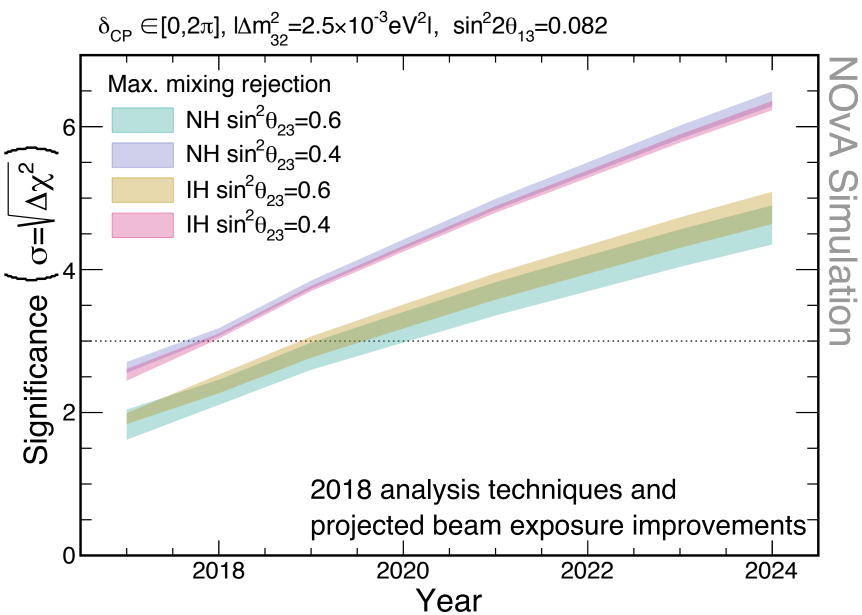
CP Violation Sensitivity



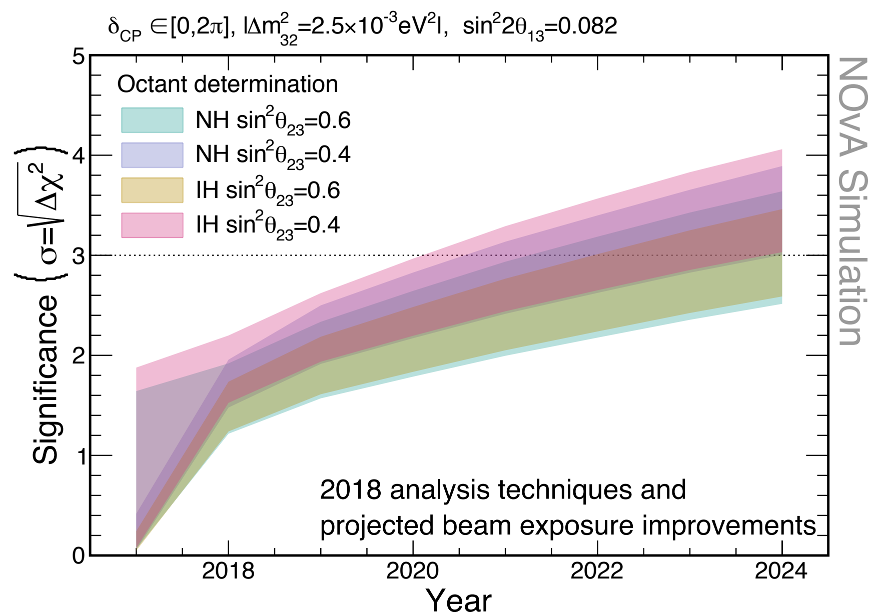
2+ σ sensitivity for CP violation in both hierarchies at $\delta_{CP}=3\pi/2$ or $\delta_{CP}=\pi/2$ (assuming unknown hierarchy) by 2024

Future Sensitivity

Max mixing rejection



Octant

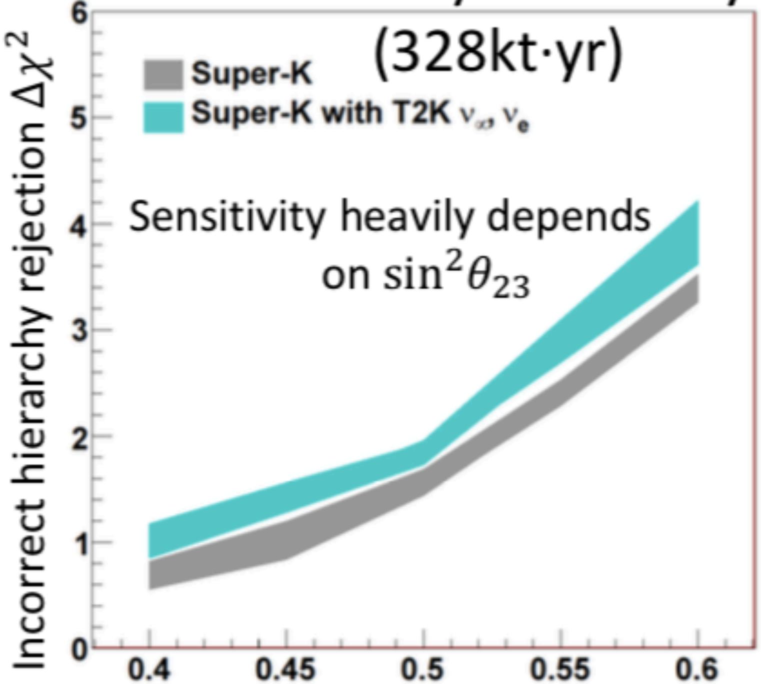


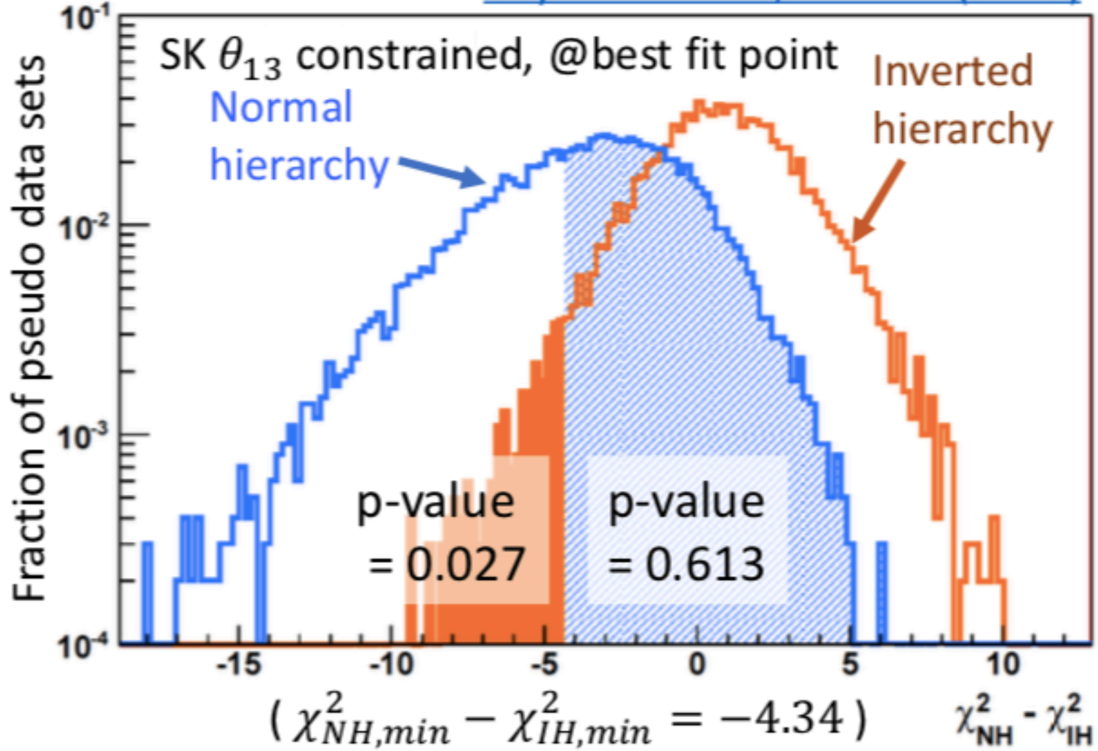
Other Experiments

- 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





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

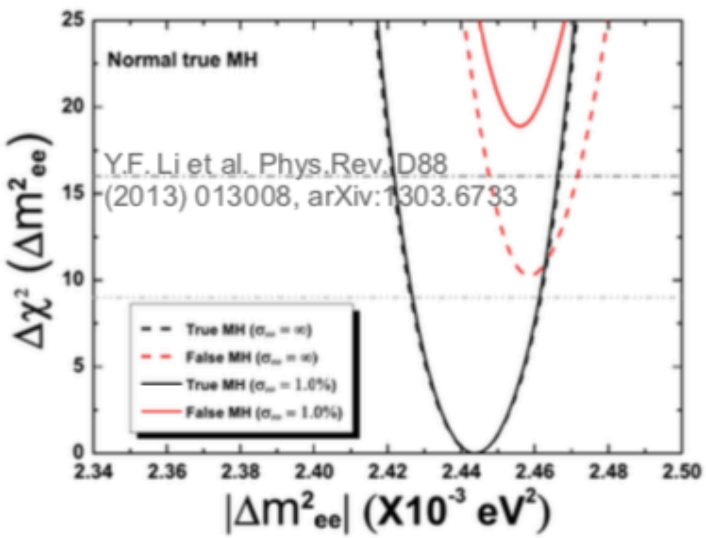
Hypothesis test ~ CL_s method : $\mathrm{CL_s(IH\ rejection)} \equiv \frac{p_{0(IH)}}{1-p_0(NH)}$

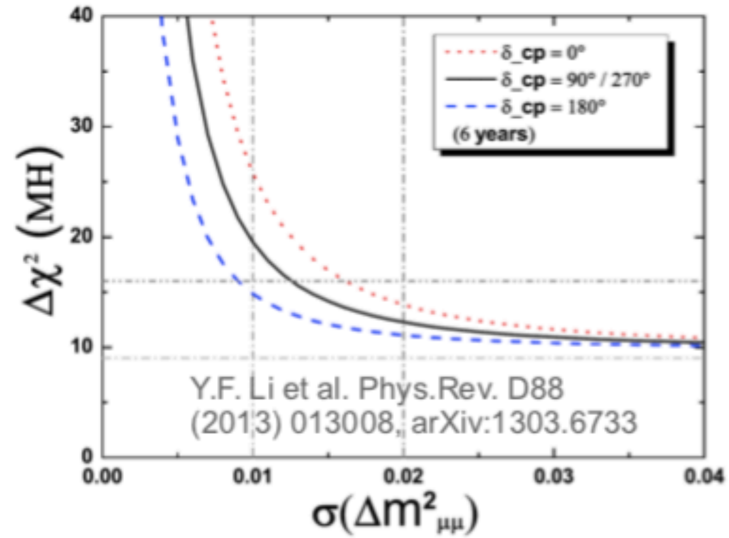
Normal hierarchy is favored ➡

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:**

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

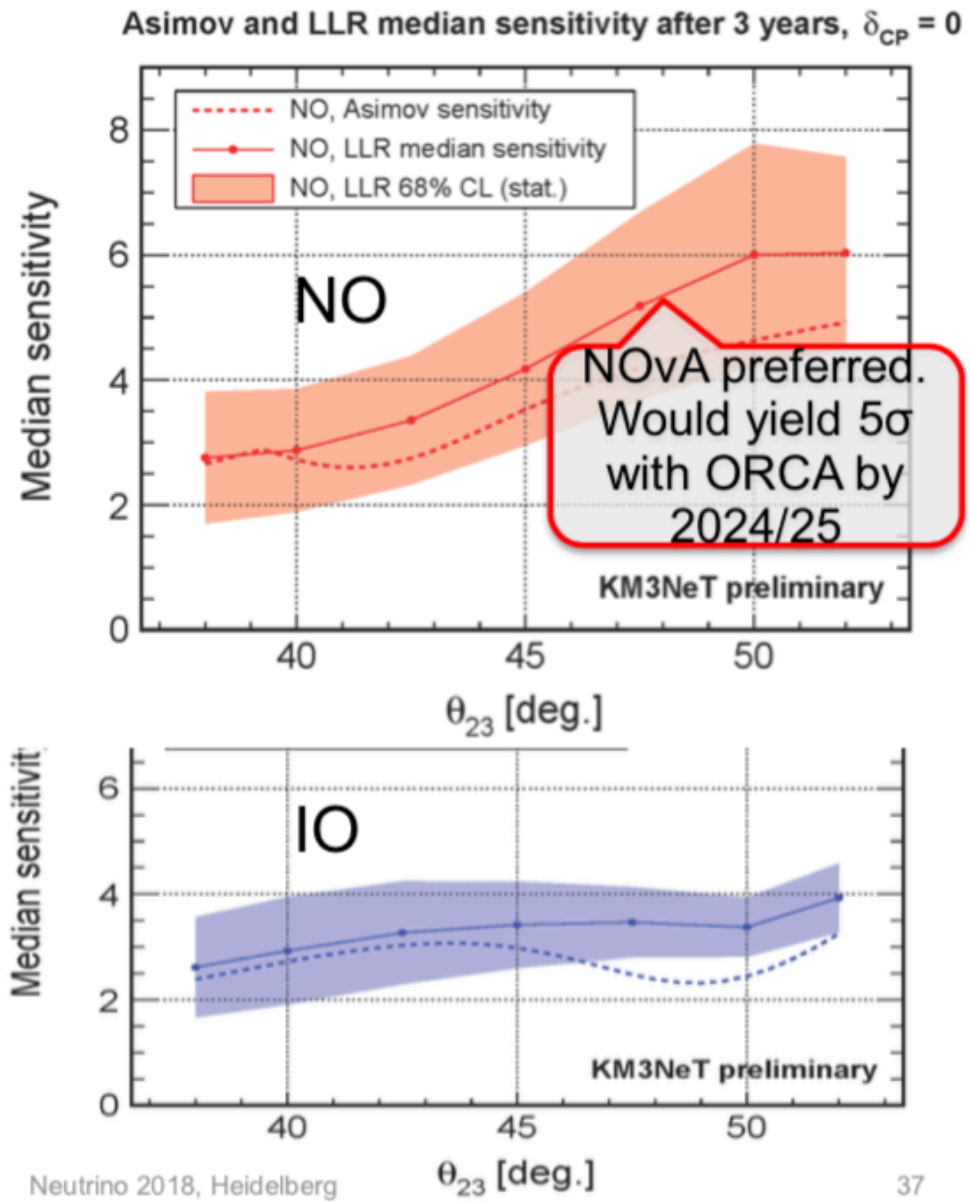
Sign defined by MH

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



Follow-up Questions

July 18, 2018

Question #1-Genie Tune

- Would it be possible to consider publishing your generator tune soon? When is it reasonable to expect this? As we discussed during your presentation this is useful and highly anticipated by the community.
  - We intend to prepare a paper describing the tune we implemented for the Summer 2018 analyses. The authorship committee of this paper is in place and an internal draft is progressing.
  - In addition to the paper, we can also release instructions to implement our tune of the GENIE generator. We are planning a workshop with MINERvA Sept 12-13. A major goal of that workshop is to evaluate how each experiment's tune compares with the other's data. That will be a good venue to figure out what is required for others to implement our tuning procedure.

Question #2-Systematics (part 1)

- You showed your test beam plans to address various systemic errors. Could you quantify the expected impact of the test beam results on these?
  - Nue appearance systematics are dominated by 4 sources of systematic errors: Cross-sections, detector response, acceptance differences, calibration. Testbeam will impact the final 3.
  - An analysis goal for this Fall is to quantify the potential impact of the testbeam and define physics milestones.
  - Testbeam, along with ongoing scintillator studies at Dubna, should also allow us to better tune our light model (ratio of scintillation to cherenkov light), which should improve our detector response systematic
  - Testbeam data allows us to benchmark our CVN selection algorithms, building confidence in prong based identifiers that have the potential to improve/refine our event selection techniques. These prong based selectors might allow us to better match the kinematics of the selection of numu events in the ND to nue events in the ND, allowing us to reduce the "Near/Far differences" systematic in the nue appearance analysis
  - Our calibration systematics are dominated by a 5% uncertainty in the absolute calibration and a 5% Far-to-Near relative energy calibration. This estimate comes from data/MC comparisons of the pi0 mass peak, Michel electrons, and dE/dx of protons identified in QE numu neutrino interactions
    - Testbeam data gives us a clean source of known single particles at known energies that will clarify the source of observed discrepancies and allow us to set our energy scale.
    - Testbeam muons allow us to validate our relative calibration (done with cosmic muons in large dets)
  - We expect a 50% reduction in calibration uncertainty should be feasible

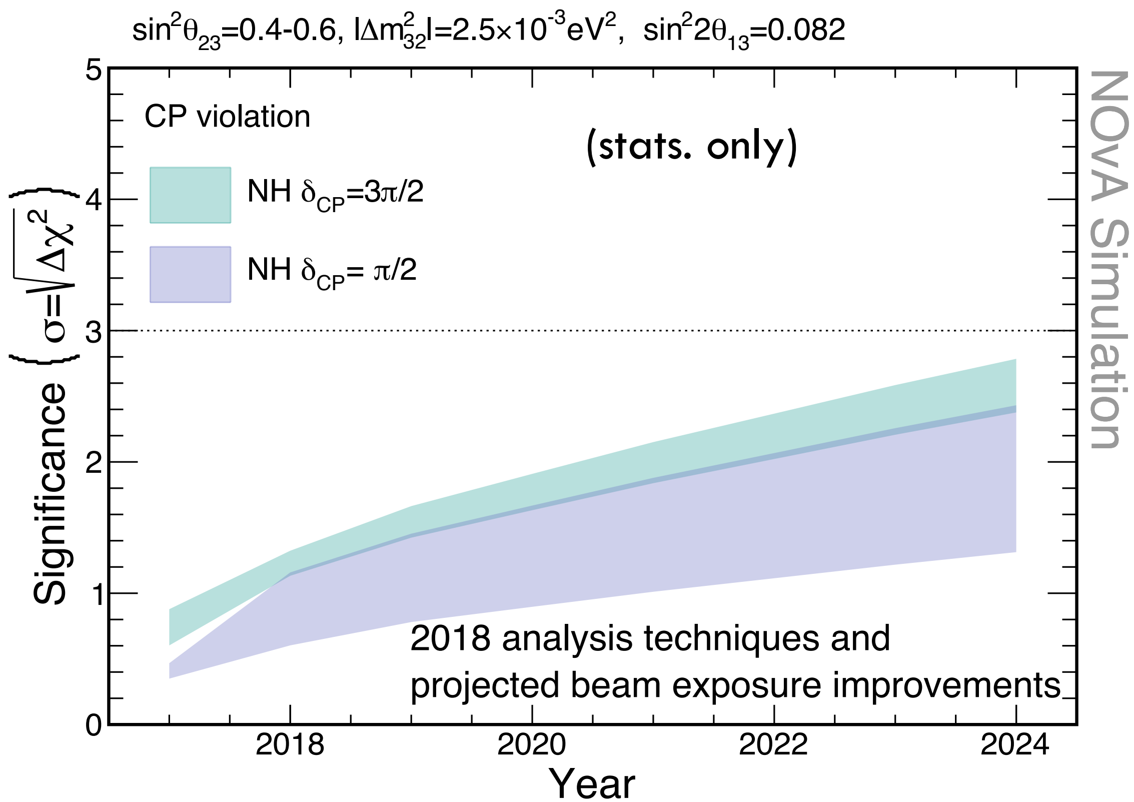
Question #2-Systematics (part 2)

- Neutrons could also turn out to be an important systematic -- how will you characterize their interactions in the detector and validate the existing models? (beyond the ad-hoc tune you explain on page 48)
  - The tune on p48 is based on our sample of numu-antineutrino QE events in the ND which gives us a high stats, clean sample of neutrons. We have only begun to exploit this sample. In the run up to Neutrino2018, we emphasized rapid turn around studies; results from longer term studies requiring re-simulation are starting to appear now.
  - We have formed a task force to study the simulation of neutrons (R. Patterson and M. Wetstein, co-chairs). This group is charged with understanding the source of the discrepancy, suggest changes to our simulation to improve the situation, and determine an updated systematic uncertainty.
  - We may be able to exploit cosmogenic neutrons in the FD by selecting events based on the fall off rate with depth in the detector.
  - We have discussed exposing our detectors to a neutron source. While there are difficult logistics to solve, it is a potential avenue to pursue if the first two samples prove not to be enough.

Question #3—Delta CP

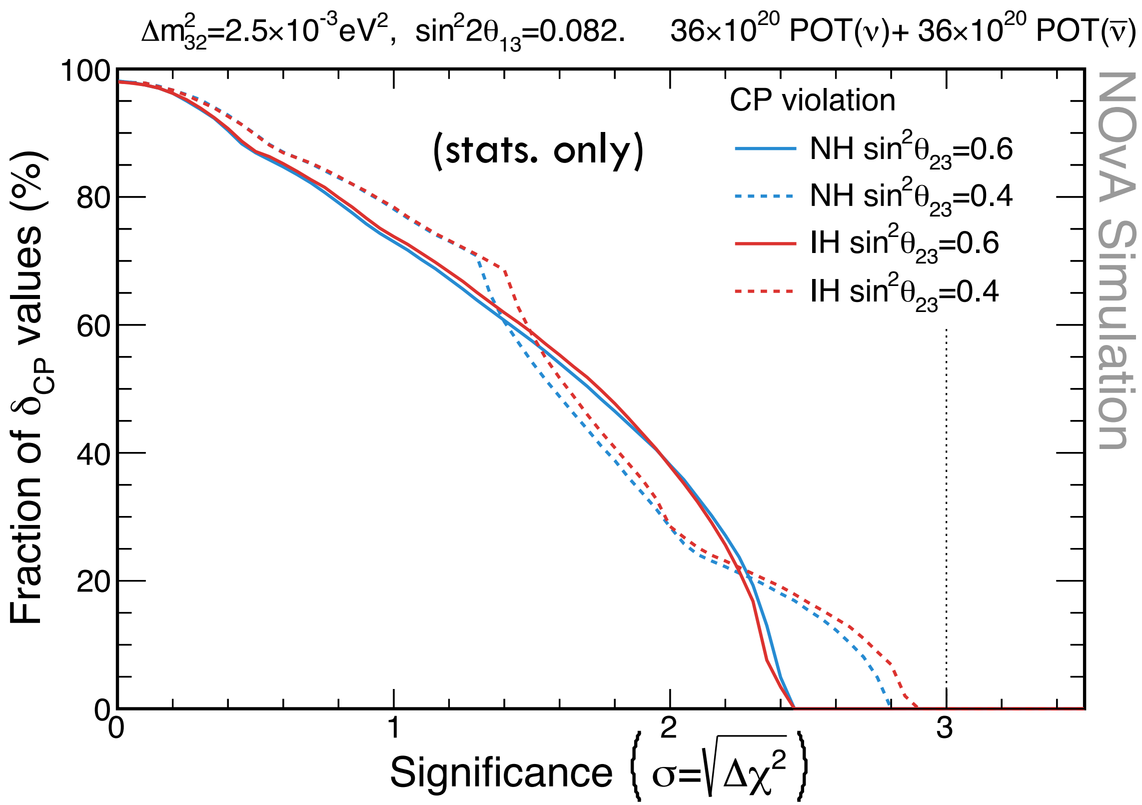
- Do you have the delta CP corresponding plot to the one you show on page 57 for the mass ordering expectations as a function of time? also is there any such projections from T2K you can point us to?
  - Yes, we have projections for our sensitivity to delta CP vs. time (See next slide). We assume the same power profile as described for the MH sensitivity (800kW FY19, 900kW FY20-21, 1MW beyond, 40 weeks of running each FY).
  - T2K have CP sensitivity projections as a function of POT, and a projection of POT/year assuming beam upgrades. These were presented in M. Wascko's talk at Neutrino 2018. More details of what assumptions went into these plots are available at https://arxiv.org/pdf/1609.04111.pdf

Question #3—Delta CP



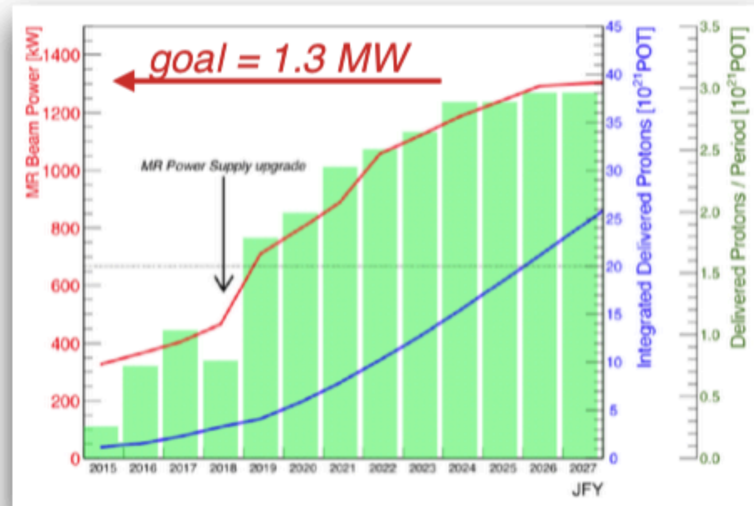
Sensitivity to CP violation for representative values of delta CP. Shaded region represents the range spanned for different true values of the theta_23 mixing angle.

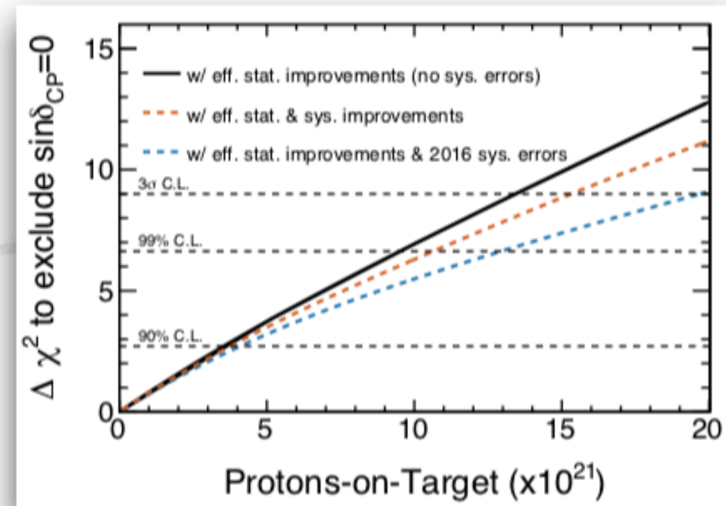
Question #3—Delta CP



Fraction of delta CP range for which NOvA can achieve the desired sensitivity to CP violation by 2024 (72e20 POT)

Question #3—Delta CP

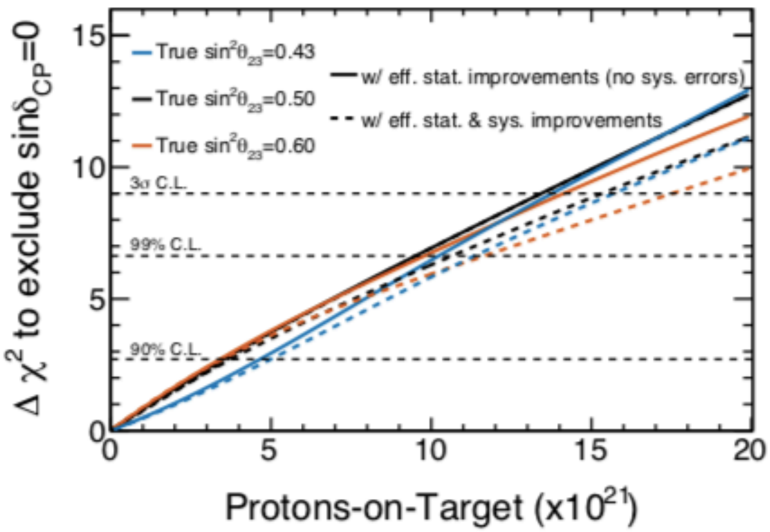




- T2K's long term goal is the pursuit of CP Violation in the neutrino sector.
- In 2016, T2K phase 2 run extension given Stage-1 status by KEK/J-PARC.
- Proposal to collect 20×10^{21} POT by ~2026 (arXiv:1609.04111 [hep-ex]).
- With 20×10^{21} POT, T2K has up to 3σ (median) CPV sensitivity:
  - Sensitivity improves beyond 3σ with reduced systematic errors.
- T2K initiated Near Detector upgrade project in January 2016.
  - "The T2K ND280 Upgrade Proposal", submitted to CERN SPSC in Jan. 2018.

Question #3—Delta CP

arXiv:1609.04111



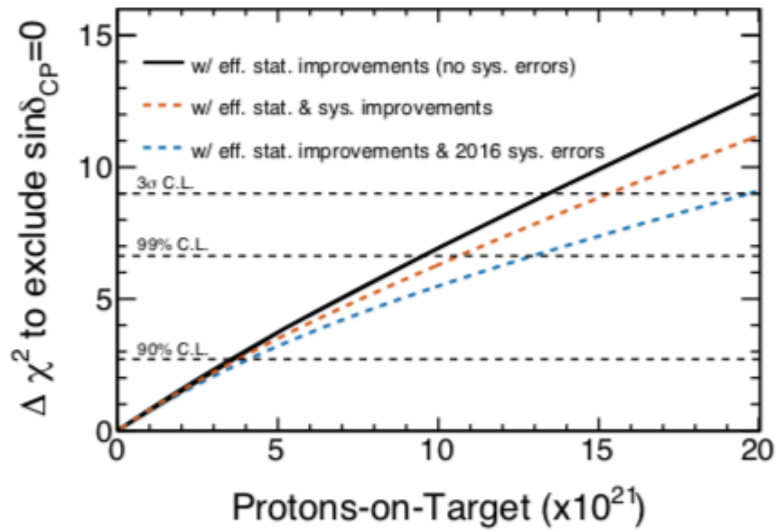


FIG. 25: Sensitivity to CP violation as a function of POT with a 50% improvement in the effective statistics, assuming the true MH is the normal MH but unknown and the true value of $\delta_{CP} = -\pi/2$. The plot on the left compares different true values of $\sin^2\theta_{23}$, while that on the right compares different assumptions for the T2K-II systematic errors with $\sin^2\theta_{23} = 0.50$.