SEARCHING FOR CP VIOLATION IN NEUTRINOS

Photo credit:
Reidar Hahn

Patricia Vahle, William and Mary

Topics in Cosmic Neutrino Physics, 2019

Neutrinos Have Mass!

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = U^\dagger \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

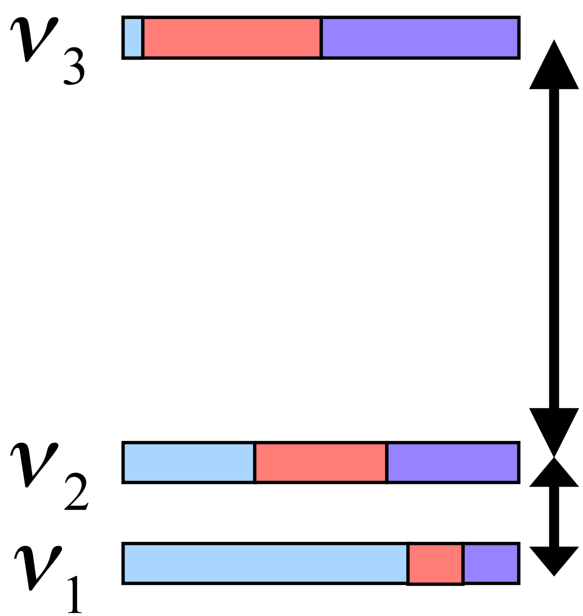
$$P(\nu_\alpha \rightarrow \nu_\beta) = \left| \sum_j U^*_{\beta j} e^{-i\frac{m_j^2 L}{2E}} U_{\alpha j} \right|^2$$

- $\nu_e, \nu_\mu, \nu_\tau \leftrightarrow \nu_1, \nu_2, \nu_3$
  - Flavor States: creation and detection
  - Mass States: propagation
- A neutrino created as one flavor can later be detected as another flavor, depending on:
  - distance traveled (L)
  - neutrino energy (E)
  - difference in the squared masses ($\Delta m^2_{ij} = m^2_i - m^2_j$)
  - The mixing amplitudes ($U_{\alpha j}$)

The PMNS Mixing Matrix

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$\theta_{23} \approx 45°$ $\theta_{13} \approx 9°$ $\theta_{12} \approx 34°$



What we know

$$\Delta m^2_{\text{atm}} \approx 2 \times 10^{-3}\text{eV}^2$$

$$\Delta m^2_{\text{sol}} \approx 8 \times 10^{-5}\text{eV}^2$$

The PMNS Mixing Matrix

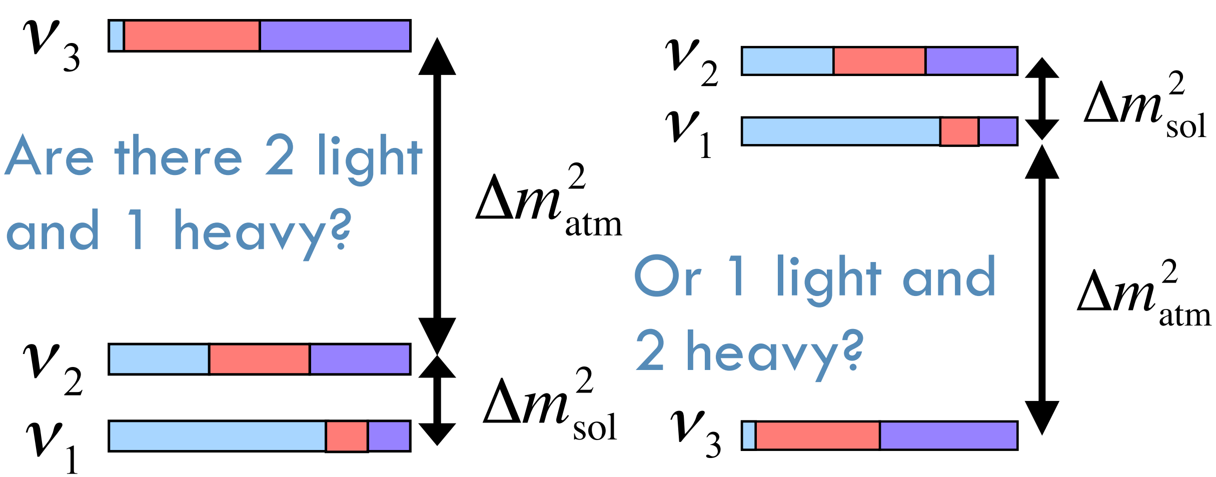
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Is it really 45°?

Is there CP violation?

What we don't know

The Mass Hierarchy



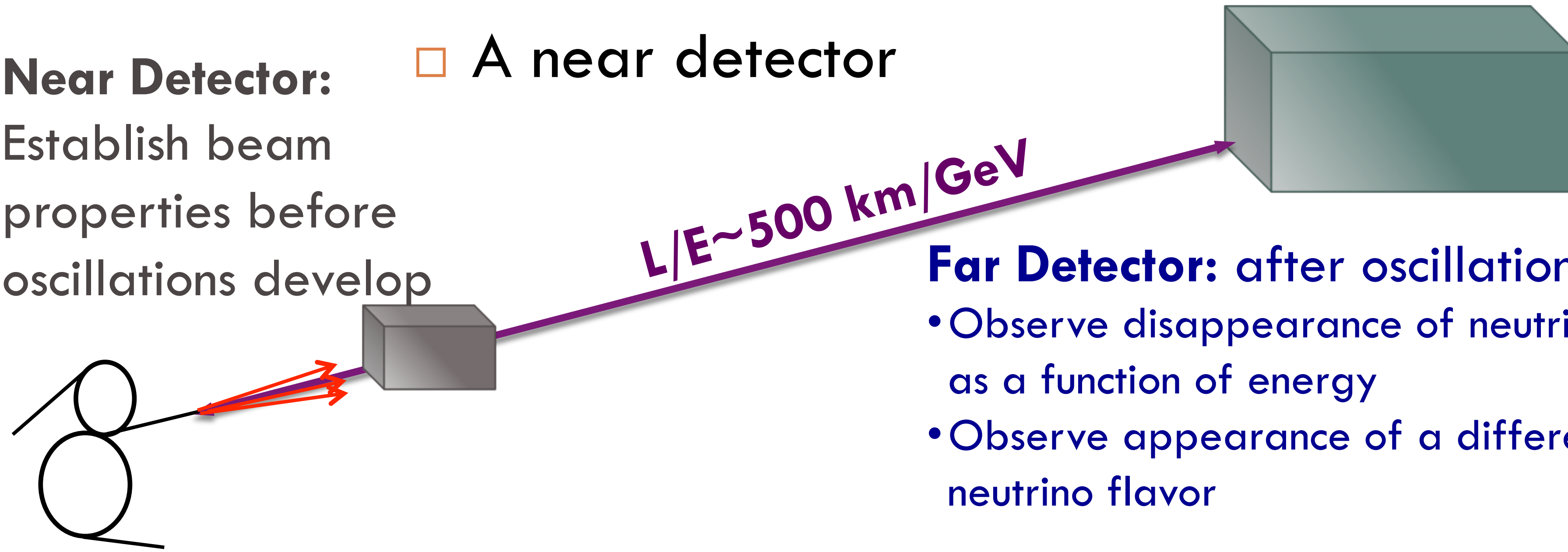
The long baseline experiments: NOvA and T2K

Photo credit:
Caine Delacy, New York Times

The long baseline recipe

- An intense neutrino beam
- A massive far detector
- A near detector

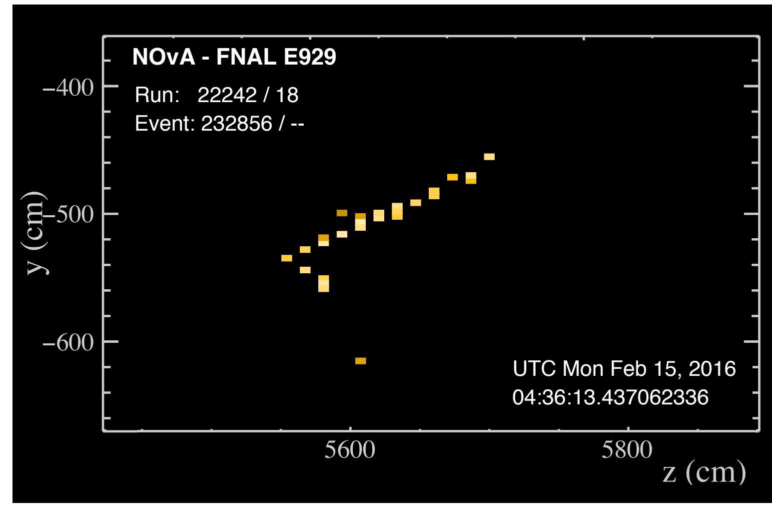
Near Detector: Establish beam properties before oscillations develop

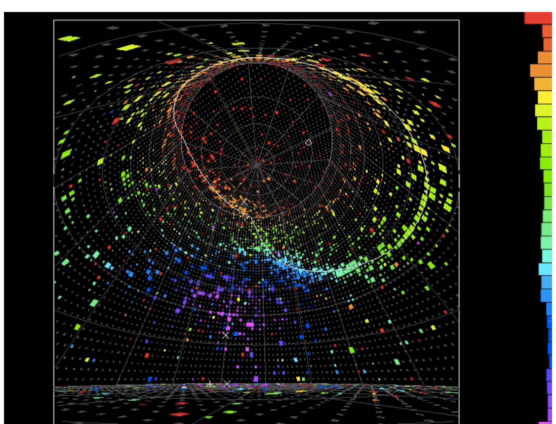


Far Detector: after oscillations
- Observe disappearance of neutrinos as a function of energy
- Observe appearance of a different neutrino flavor

Two detectors → Systematics Cancel
- Neutrino flux uncertainties
- Neutrino interaction uncertainties

Long-baseline experiments





Long-baseline experiments

Study multiple oscillation modes, compare neutrino and antineutrino oscillation probabilities

- ν_μ disappearance
  - clear suppression as a function of energy
  - $|\Delta m^2_{32}|$, $\sin^2(2\theta_{23})$
- ν_e appearance
  - θ_{13}, θ_{23}, δ_{CP}, and mass hierarchy
  - may be different for neutrinos vs. antineutrinos

ν_e Appearance

- At L/E~400 km/GeV, dominant oscillation mode is $\nu_\mu \rightarrow \nu_\tau$
- A few percent of the missing ν_μ could change into ν_e

$$P(\nu_\mu \rightarrow \nu_e) = \left| \sqrt{P_{atm}}\, e^{-i\left(\frac{\Delta m^2_{32} L}{4E} + \delta_{cp}\right)} + \sqrt{P_{sol}} \right|^2$$

$$P_{atm} = \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) \qquad P_{sol} \approx \cos^2\theta_{23} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$$

"Atmospheric" Term

Depends on Δm^2 and θ_{13}

"Solar" Term

<1% for current accelerator experiments

ν_e Appearance

- At L/E~400 km/GeV, dominant oscillation mode is $\nu_\mu \rightarrow \nu_\tau$
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$$P(\nu_\mu \rightarrow \nu_e) = \left| \sqrt{P_{atm}}\, e^{-i\left(\frac{\Delta m^2_{32} L}{4E} + \delta_{cp}\right)} + \sqrt{P_{sol}} \right|^2$$

$$2\sqrt{P_{atm}}\sqrt{P_{sol}} \cos\left(\frac{\Delta m^2_{32} L}{4E}\right) \cos\delta_{CP} \mp 2\sqrt{P_{atm}}\sqrt{P_{sol}} \sin\left(\frac{\Delta m^2_{32} L}{4E}\right) \sin\delta_{CP}$$

Interference Term

\- for neutrinos

\+ for antineutrinos

$$\text{if } \delta_{CP} \neq 0,$$

$$P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$$

ν_e Appearance

- At L/E~400 km/GeV, dominant oscillation mode is $\nu_\mu \rightarrow \nu_\tau$
- A few percent of the missing ν_μ could change into ν_e

$$P(\nu_\mu \rightarrow \nu_e) = \left| \sqrt{P_{atm}}\, e^{-i\left(\frac{\Delta m_{32}^2 L}{4E} + \delta_{cp}\right)} + \sqrt{P_{sol}} \right|^2$$

$$P_{atm} = \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E} - aL\right) \left(\frac{\frac{\Delta m_{31}^2 L}{4E}}{\left(\frac{\Delta m_{31}^2 L}{4E} - aL\right)} \right)^2$$

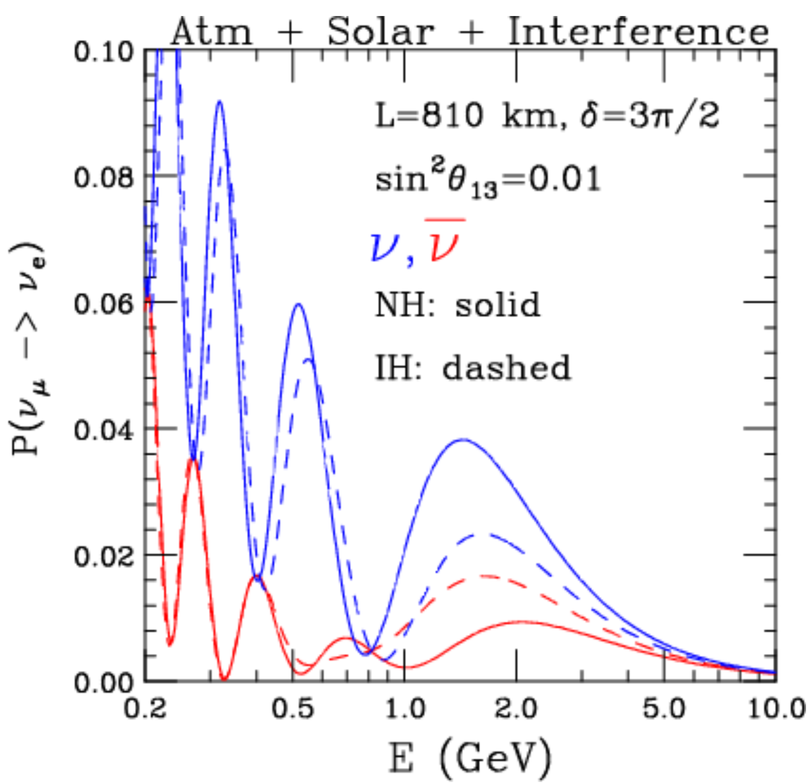
$$P_{sol} \approx \cos^2\theta_{23} \sin^2 2\theta_{12} \sin^2(aL) \left(\frac{\frac{\Delta m_{21}^2 L}{4E}}{aL} \right)^2$$

$$a = \pm \frac{G_F N_e}{\sqrt{2}} \approx (4000\ \text{km})^{-1}$$

In matter, additional term in Hamiltonian from ν_e + e CC scattering modifies oscillation probability, depends on mass hierarchy (ordering), a ~30% effect in NOvA

ν_e Appearance

- At L/E~400 km/GeV, dominant oscillation mode is $\nu_\mu \rightarrow \nu_\tau$
- A few percent of the missing ν_μ could change into ν_e

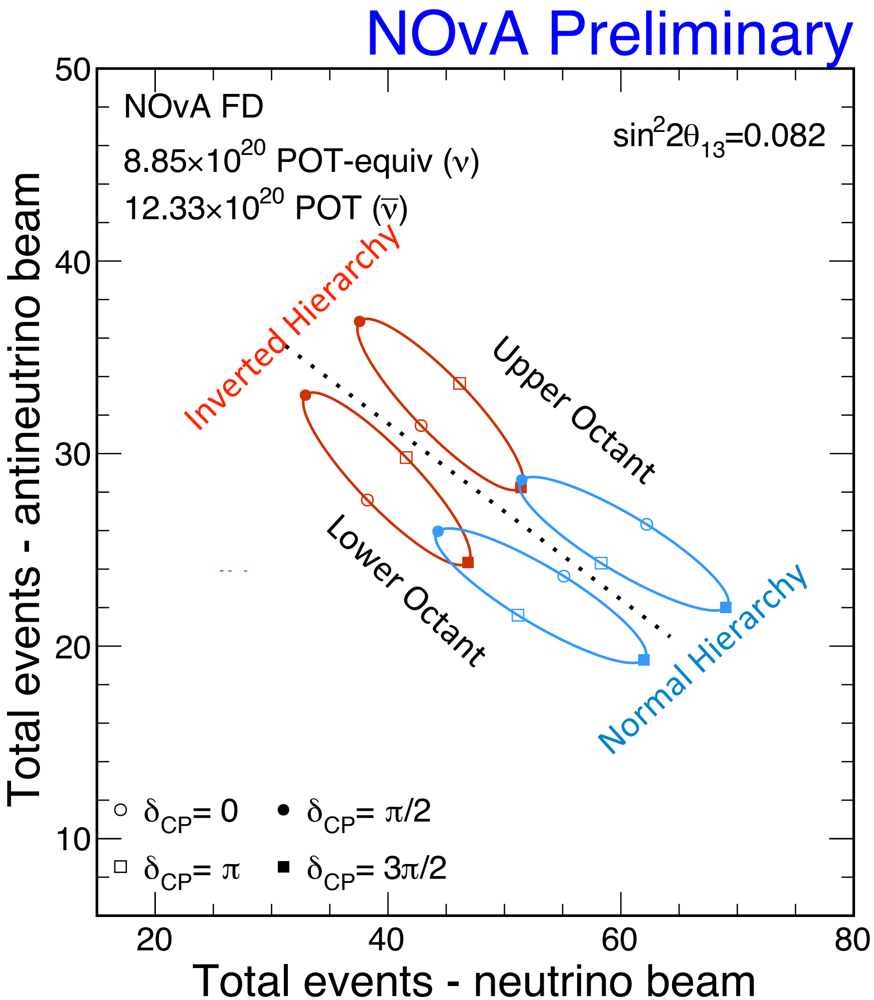


From S. Parke, "Neutrino Oscillation Phenomenology"
in Neutrino Oscillations: Present Status and Future Plans

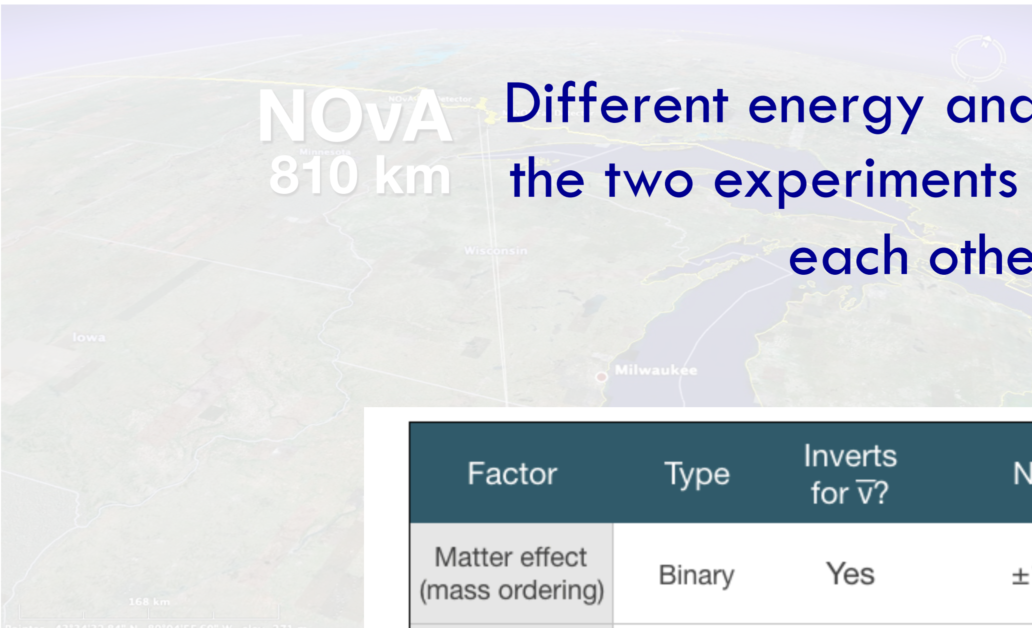
Analysis Basics

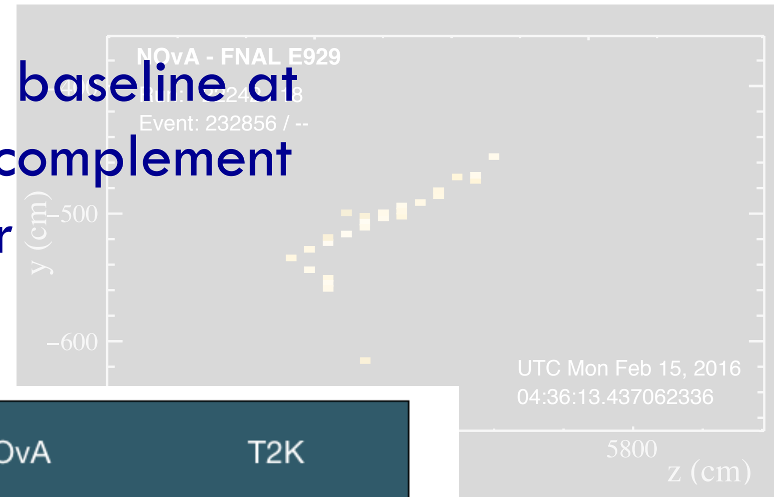
- A few percent of the missing ν_μ could change into ν_e

- 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



Long-baseline experiments





Different energy and baseline at the two experiments complement each other

Factor	Type	Inverts for $\overline{\nu}$?	NOvA	T2K
Matter effect (mass ordering)	Binary	Yes	±19%	±10%
CP violation	Bounded, continuous	Yes	[-22…+22]%	[-29…+29]%
θ_{23} octant	Unbounded, continuous	No	[-22…+22]%	[-22…+22]%

Nota bene:

- Calculations are for rate only; there is some additional information in the energy spectrum
- These estimates neglect non-linearities in combining different effects
- In the calculation of the matter effect and CP violation effects the calculated values account for the fact that T2K runs at an energy on the first oscillation maximum while NOvA runs at an energy slightly above the oscillation maximum
- θ_{23} was varied inside the ±2σ range found by a recent global fit (PRD 90, 093006)

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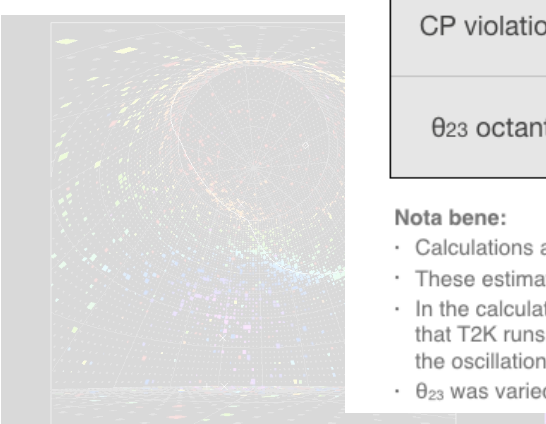
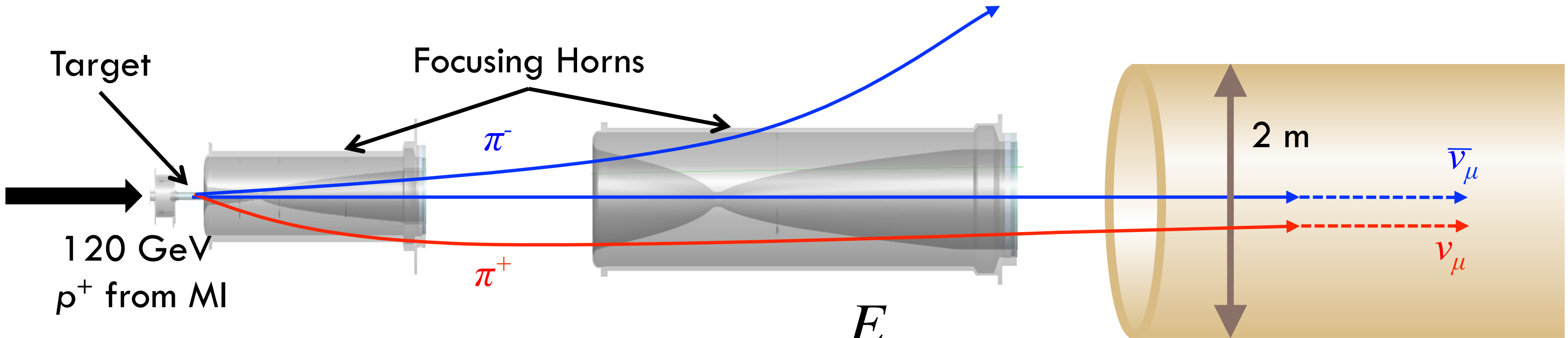
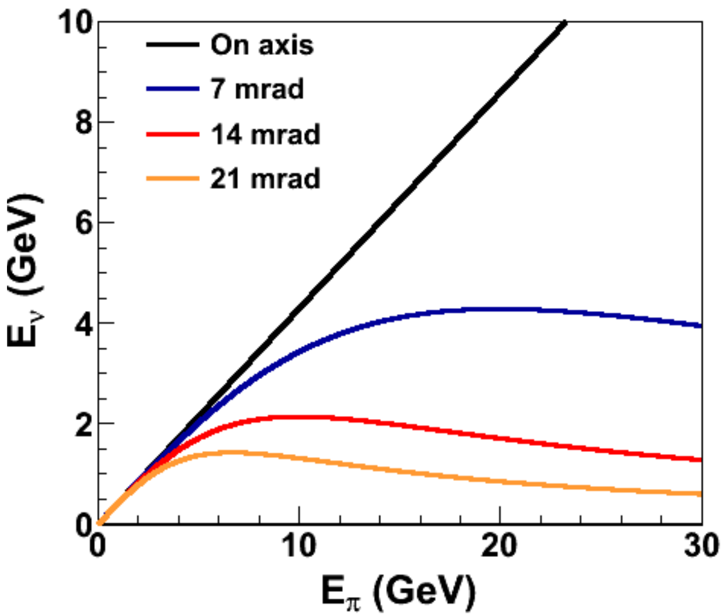


Table courtesy M. Messier

Making a Neutrino Beam



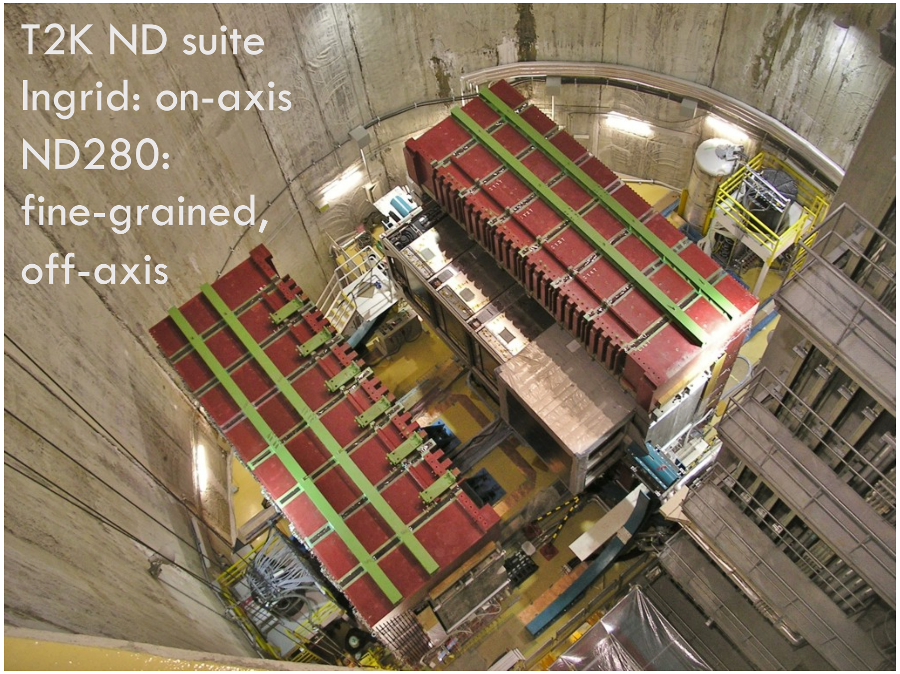
$$E_\nu \approx 0.43 \frac{E_\pi}{1+\gamma^2\theta_\nu^2}$$



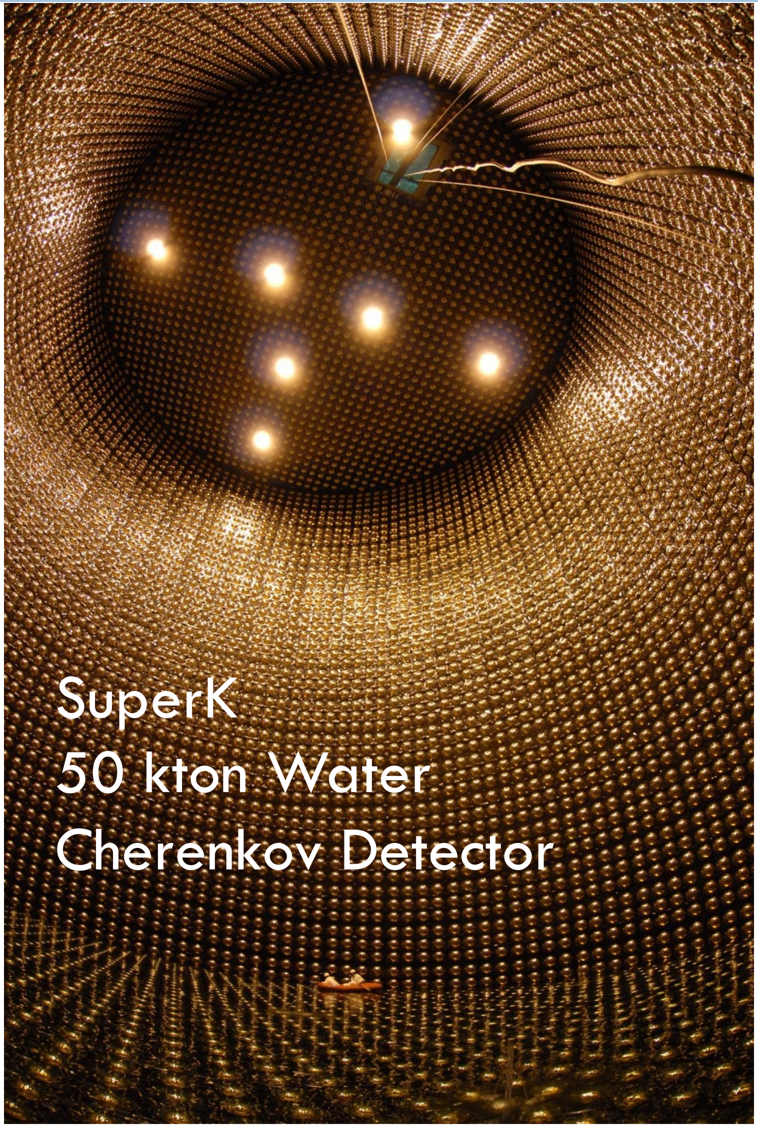
- NOvA is 14 mrad off-axis, sees a narrow band beam peaked at 2 GeV
  - Near (but slightly above) oscillation maximum
  - Few high energy NC background events
- T2K at 2.5° (43 mrad), beam peak 600MeV

Two detector technique

- Near detectors used to predict far expectations and mitigate systematics



Far Detectors



Current Results

Photo credit:
Reidar Hahn

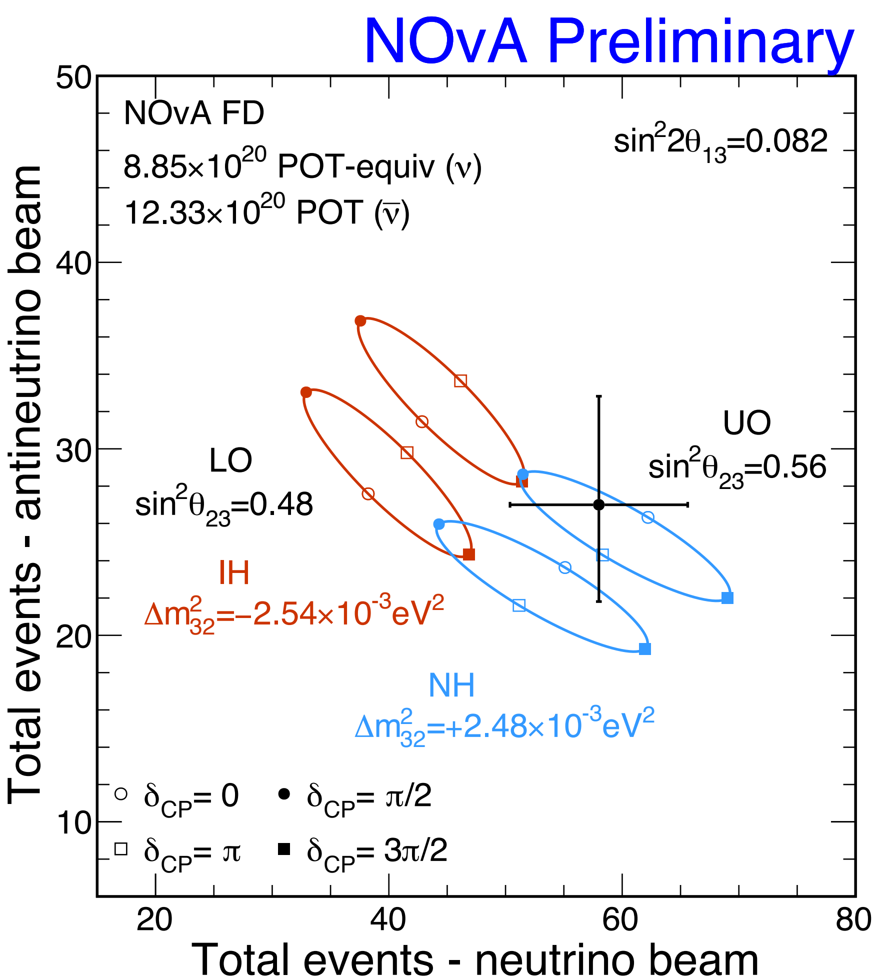
NOvA Appearance Results

arXiv:1906.04907

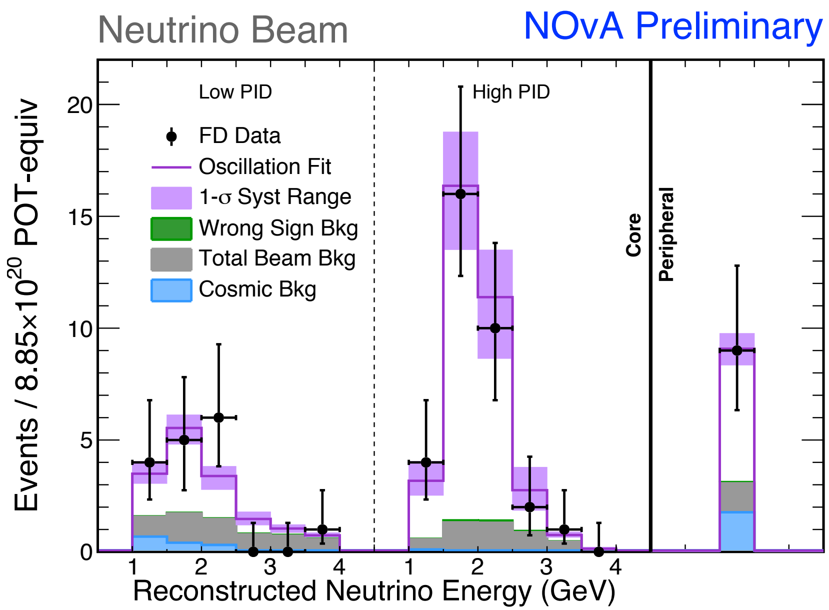
- Neutrino mode
  - 58 events observed
  - 15 bkg expected
- Antineutrino mode
  - 27 events observed
  - 10 bkg expected
  - (including 2 wrong sign)

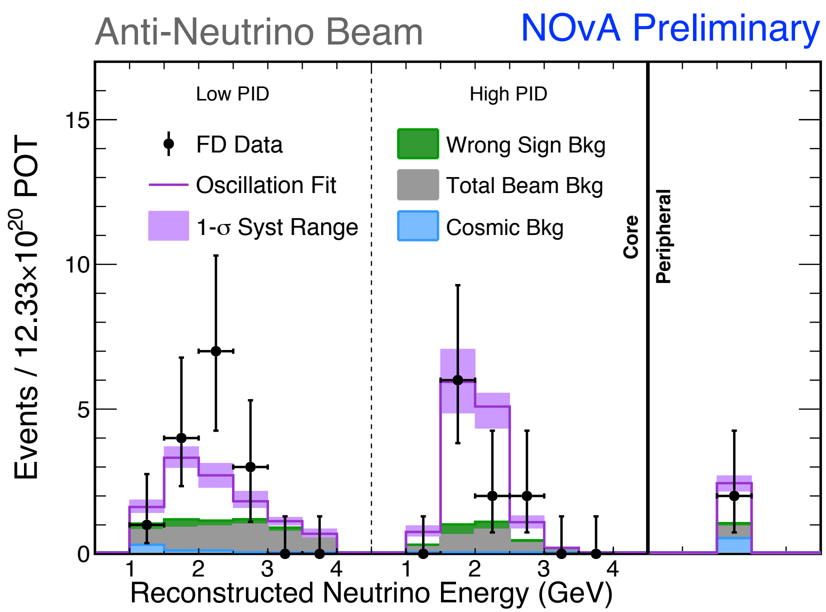
Strong (4.4 sigma) evidence of electron antineutrino appearance

Full analysis power comes from joint fit to ν_e appearance and ν_μ disappearance spectra in both neutrino and antineutrinos



Appearance Spectra





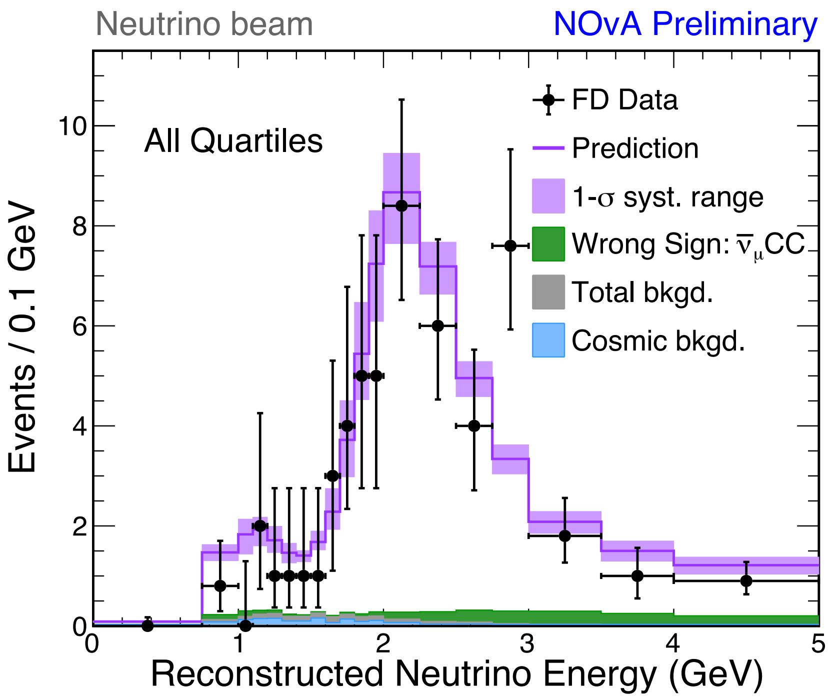
Neutrino Mode

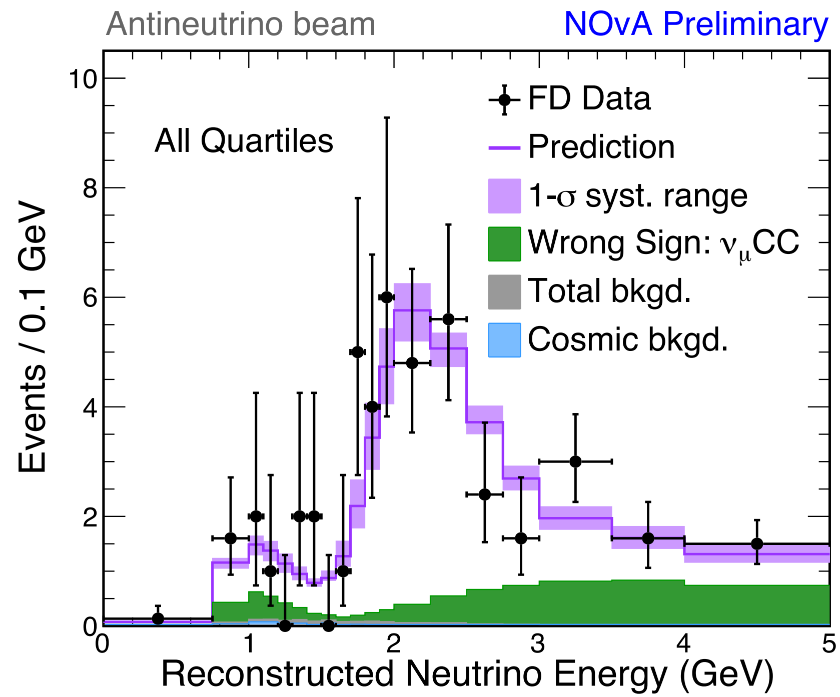
Total Observed	58
Total Prediction	59.3
Wrong-sign	0.6
Beam Bkgd.	11.7
Cosmic Bkgd.	3.3
Total Bkgd.	15.0

Antineutrino Mode

Total Observed	27
Total Prediction	26.8
Wrong-sign	2.2
Beam Bkgd.	9.2
Cosmic Bkgd.	1.1
Total Bkgd.	10.3

Disappearance Spectra



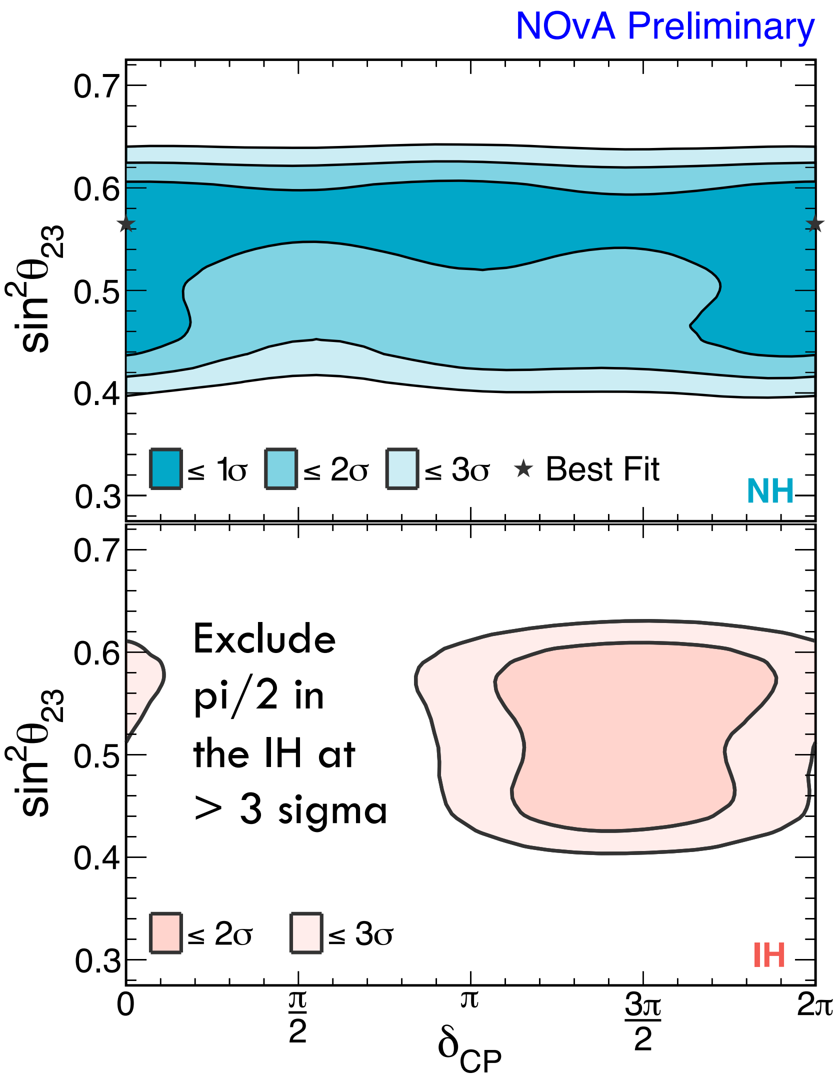


Total Observed	113
Best fit prediction	124
Cosmic Bkgd.	2.1
Beam Bkgd.	2.1
Unoscillated	730

Total Observed	102
Best fit prediction	96.2
Cosmic Bkgd.	0.8
Beam Bkgd.	1.4
Unoscillated	476

arXiv:1906.04907

NOvA Fit Results: Hierarchy and Delta CP

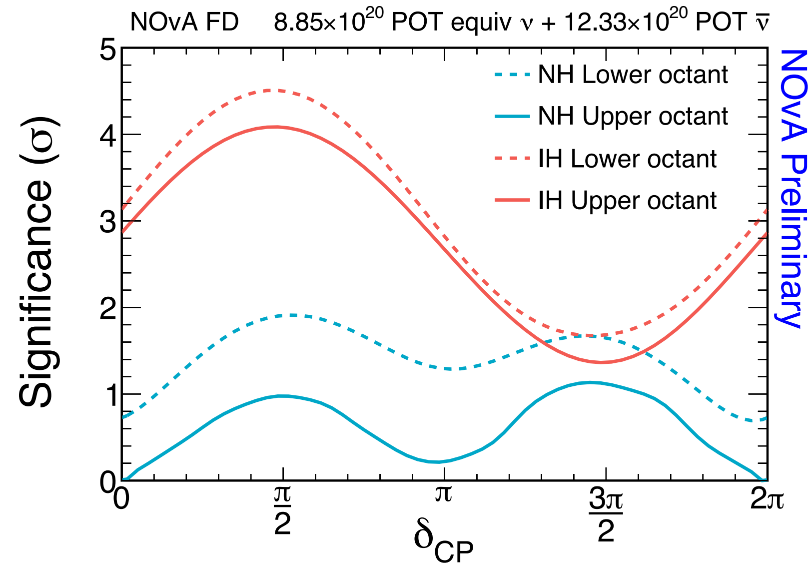


Normal Hierarchy

$$\Delta m^2_{32} = 2.48^{+0.11}_{-0.06} \times 10^{-3}\mathrm{eV}^2$$

$$\sin^2\theta_{23} = 0.56^{+0.04}_{-0.03}$$

$$\delta_{CP} = 0.0\pi$$



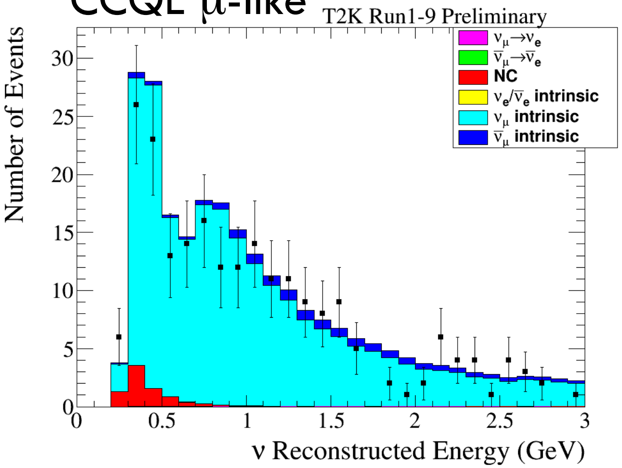
Normal Hierarchy preferred at 1.9 sigma

Upper Octant preferred at 1.6 sigma

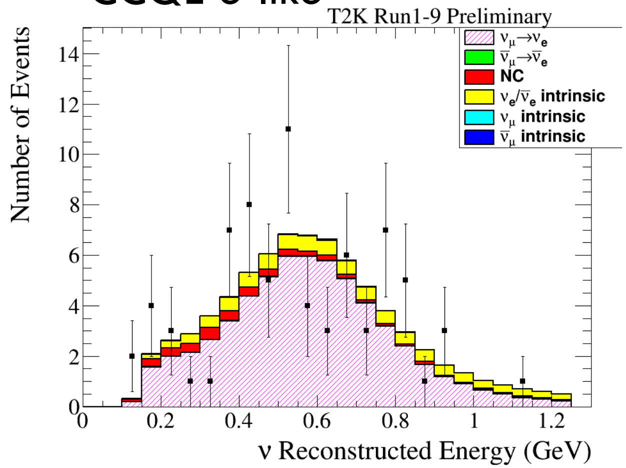
All values of delta consistent at 1.1 sigma

T2K FD Spectra

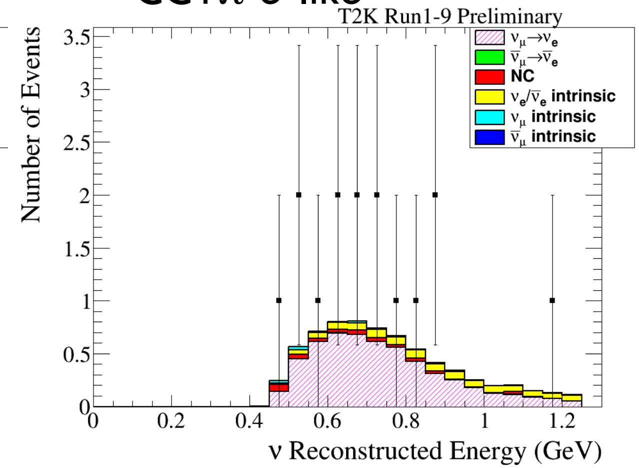
CCQE μ-like



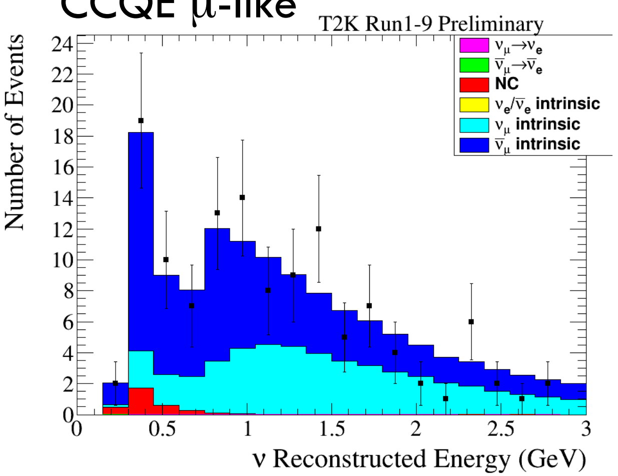
CCQE e-like



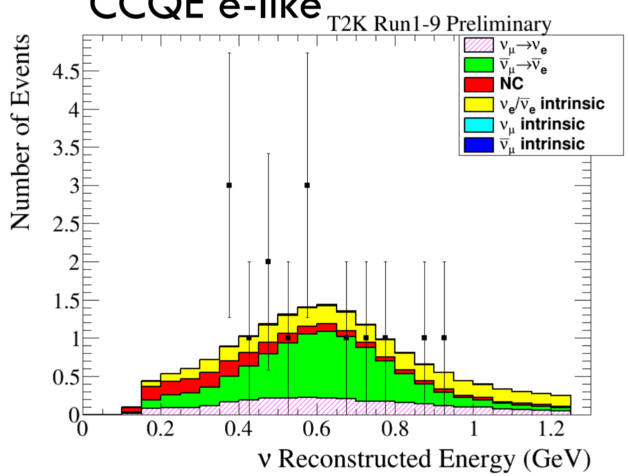
CC1π e-like



CCQE μ-like



CCQE e-like



Top Row—Neutrinos

Bottom Row—Antineutrinos

K. Porwit, NuTelescopes 2019

*Note Phase convention difference

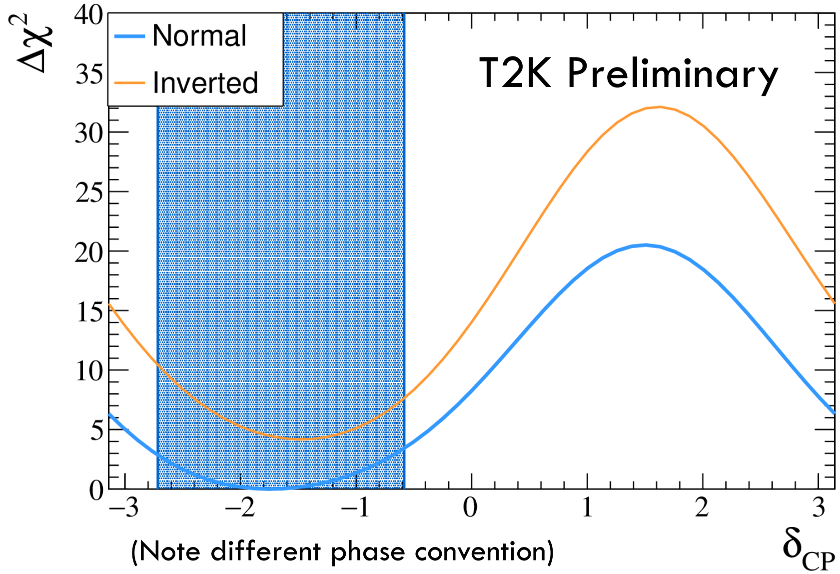
T2K Results: Delta CP

Gzarnecki, LaThuile 2019

Sample	Predicted				Observed	Systematic uncertainty for prediction
	δ_{CP} = -π/2	δ_{CP} = 0	δ_{CP} = +π/2	δ_{CP} = π		
ν mode μ-like	272.4	272.0	272.4	272.8	243	5.1%
$\bar{\nu}$ mode μ-like	139.5	139.2	139.5	139.9	140	4.5%
ν mode e-like	74.4	62.2	50.6	62.7	75	8.8%
$\bar{\nu}$ mode e-like	17.1	19.4	21.7	19.3	15	7.1%
ν mode e-like + $1\pi^+$	7.0	6.1	4.9	5.9	15	18.4%

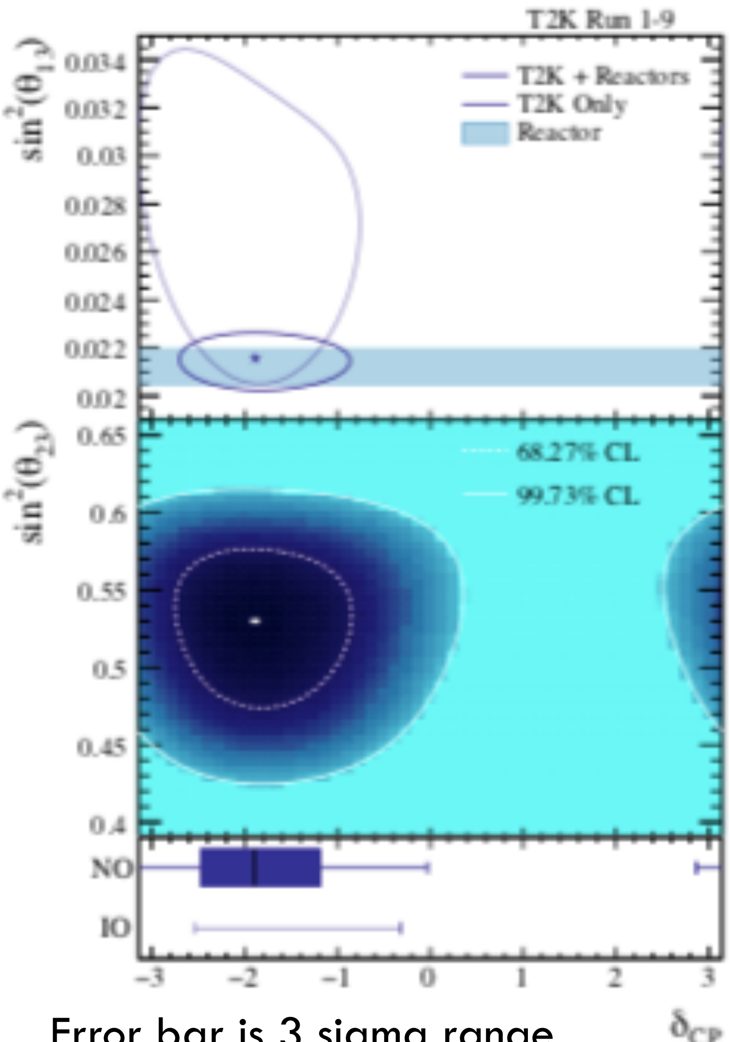
CP conserving values fall outside 2 sigma confidence interval

Normal Hierarchy preferred at 89%



(Note different phase convention)

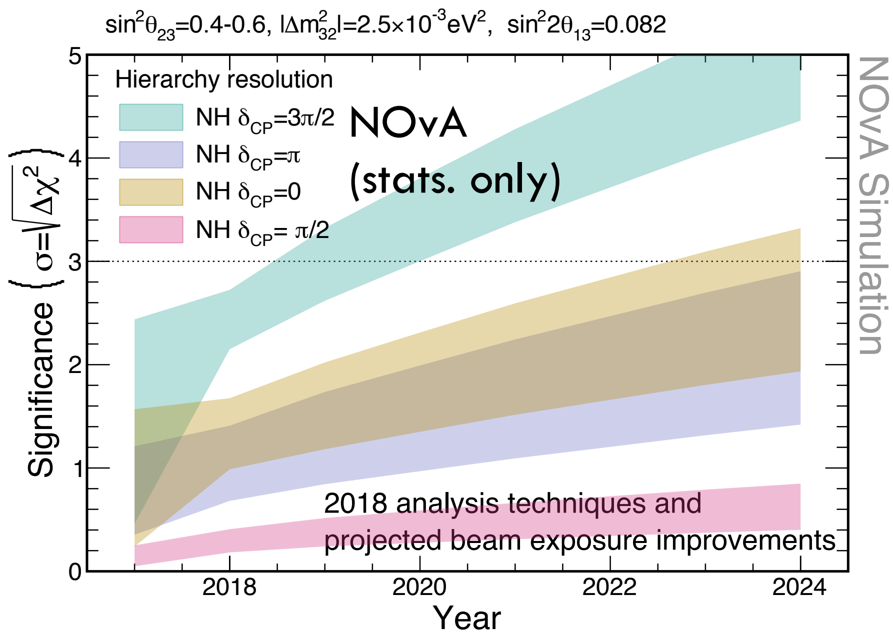
T2K Results—breaking news

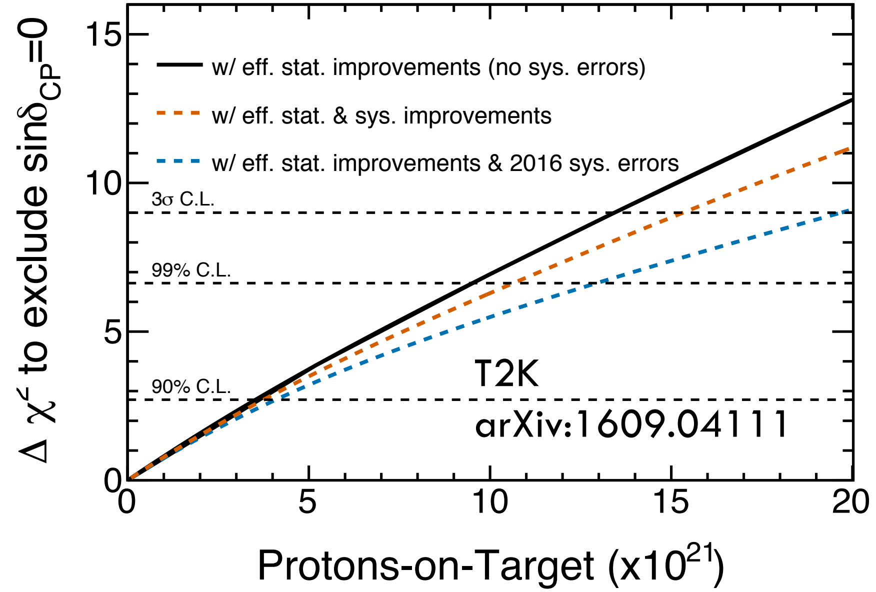


Error bar is 3 sigma range

- arXiv:1910.03887 (released yesterday)
- Quotes a 3sigma range on allowed values of delta CP
  - NH: [-3.41,-0.03]
  - IH: [-2.54,-0.32]
- delta=0 is excluded at 3sigma, but not -pi

Outlook





- For favorable parameters consistent with results, NOvA can achieve 3 sigma mass hierarchy sensitivity by 2020
  - 3 sigma sensitivity for 30-50% of delta CP range by 2025
  - >5 sigma in favorable cases by 2025
- T2K projects 3 sigma sensitivity to CP violation with 20×10^{21} POT, achievable by 2026

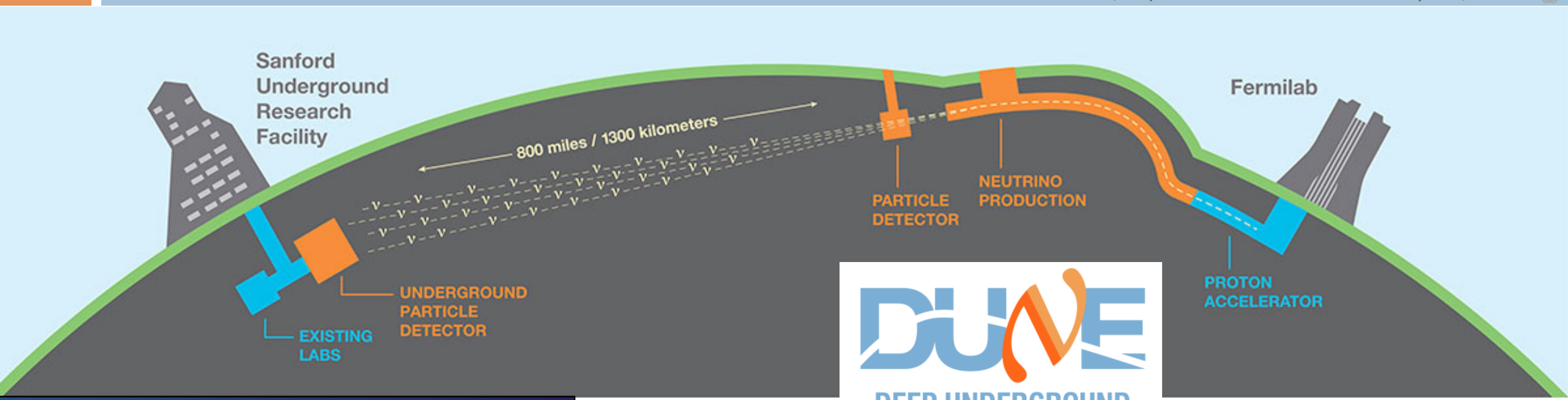
Joint Analysis

- Four joint meetings since 2016
  - laying groundwork for joint fit, meet every 6-9 months.
  - identifying important correlations in systematics
- Targeting first joint fits in 2021, with scope to be clarified summer 2020.

The Future

Photo credit: Reidar Hahn

The Future of Long-baselines: DUNE

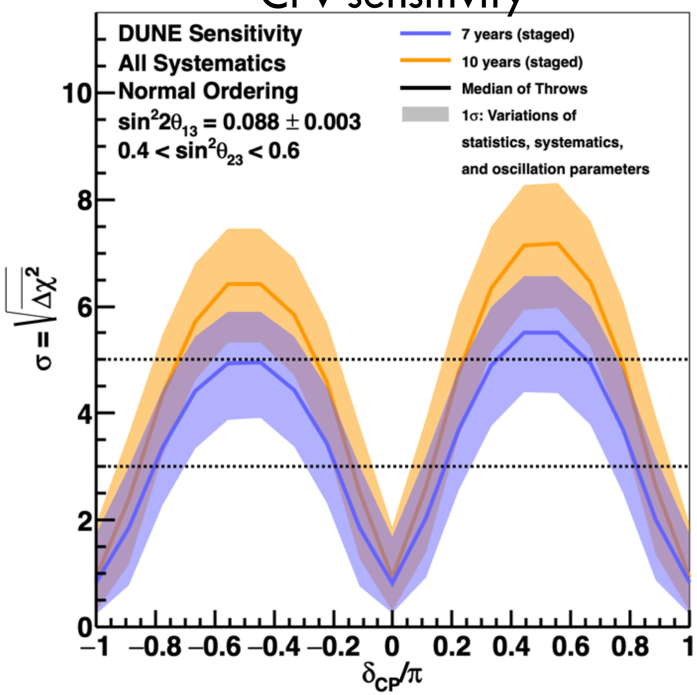


DUNE
DEEP UNDERGROUND NEUTRINO EXPERIMENT

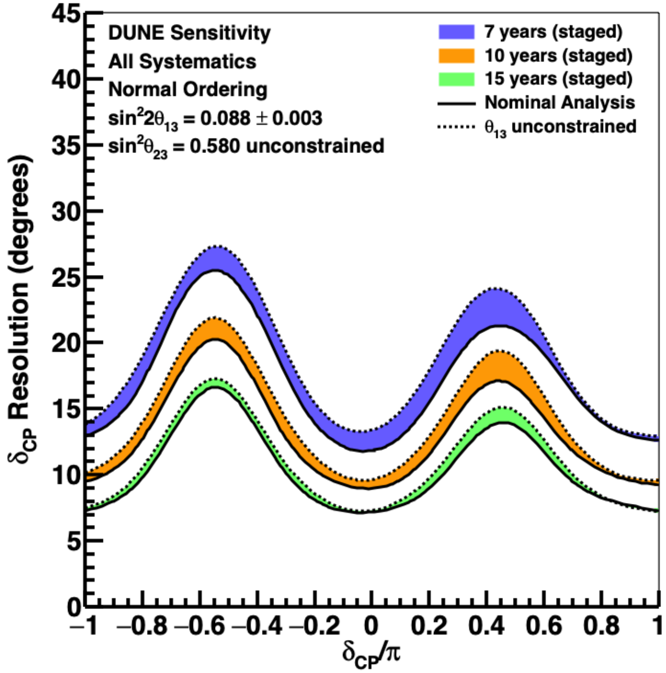
- 1300km baseline
- 1.2 MW neutrino beam, Upgradable to 2.4MW
- 40 kton Liquid Argon Time Projection Detectors

DUNE

CPv sensitivity



Resolution on Delta

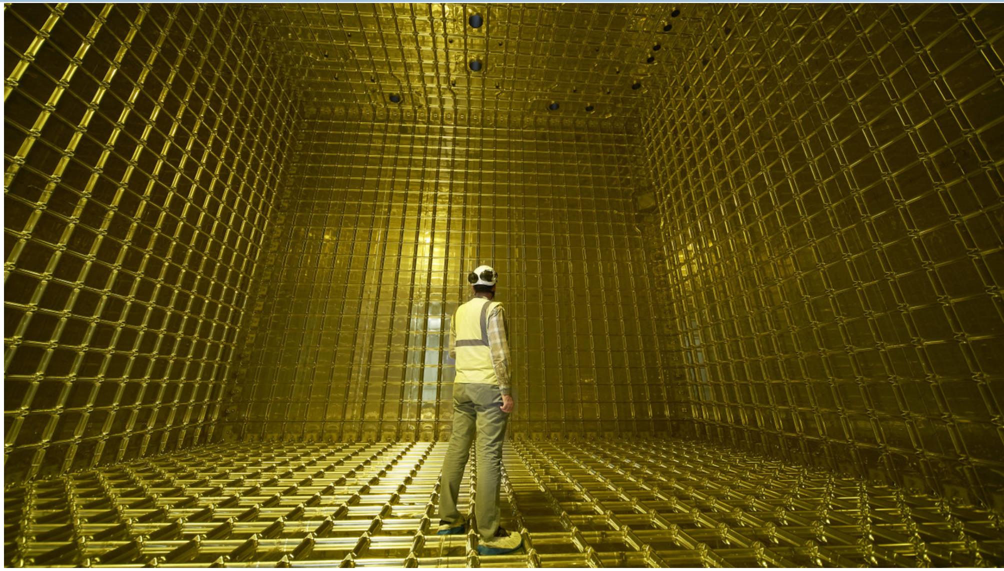


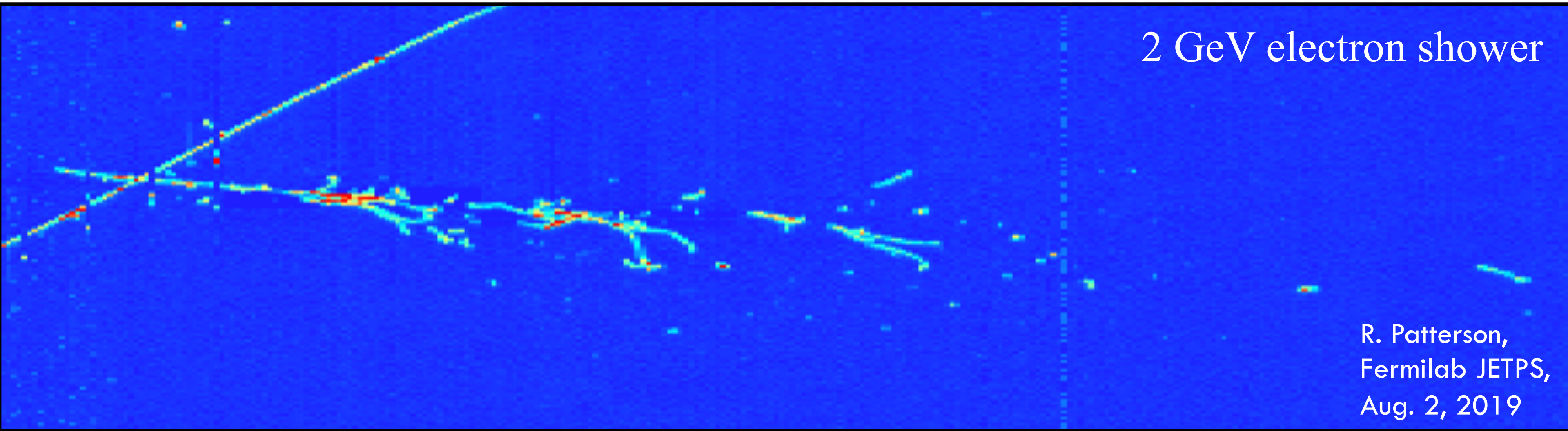
- Within 7 years of running 1000 appeared electron neutrinos!
  - >5 sigma mass ordering resolution, regardless of delta CP
  - 5 sigma sensitivity to maximal CP violation
- Delta CP ultimately measured to 7°-17°

R. Patterson, Fermilab JETPS, Aug. 2, 2019

DUNE Status

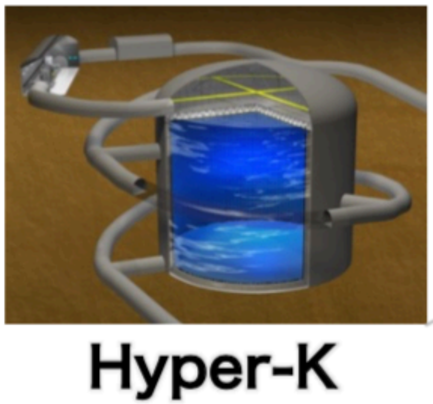
- 2026 expected start of Far Detector operations
  - FD TDR Submitted to review committee in July
  - Working for CD 2/3 in 2020
  - FD installation start 2024
- ProtoDUNE detectors installed at CERN





R. Patterson, Fermilab JETPS, Aug. 2, 2019

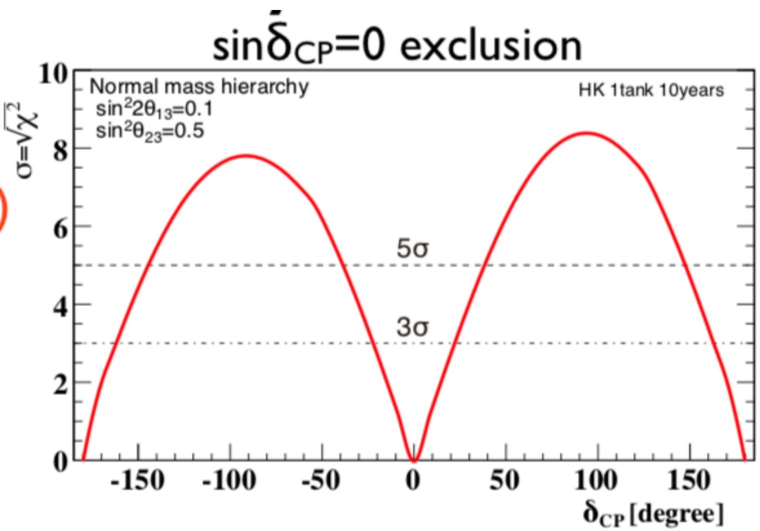
The Future of Long-baselines: HyperK

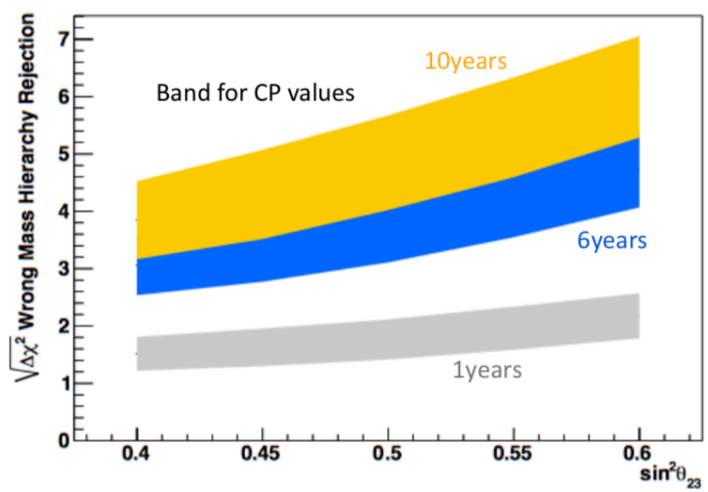


M. Shiozawa, Neutrino 2018

- Gigantic neutrino and nucleon decay detector—10x SuperK
- MW beam from upgraded JPARC complex
- Construction start April 2020*, beam 2026

*Sept. 19, 2018 Press release





Design report, arXiv:1805.04163

Summary

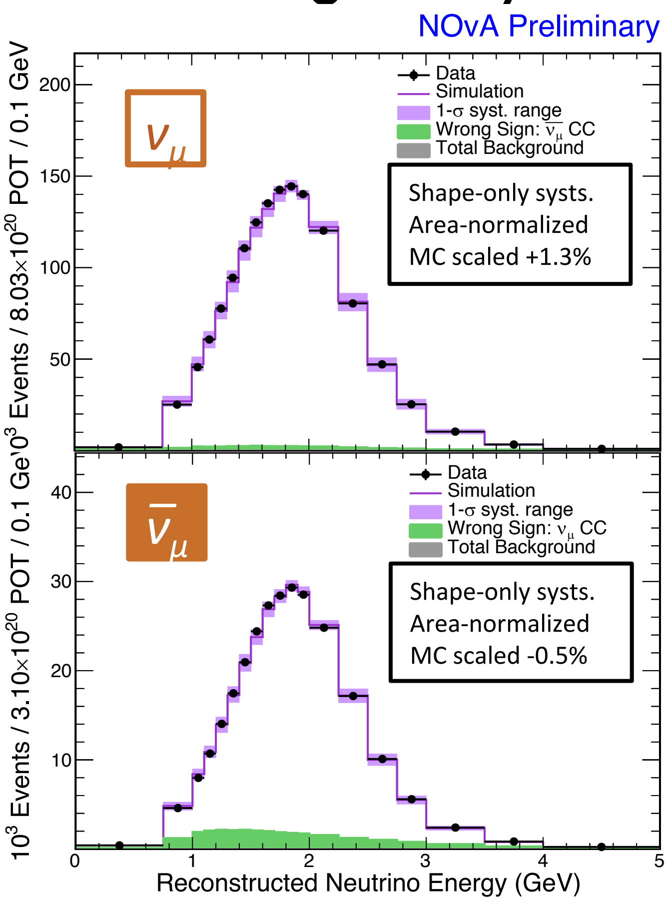
- 20 years from the discovery of neutrino mass and oscillations, we still have exciting discoveries to make.
- Current results from accelerator experiments
  - NOvA has strong evidence of electron-antineutrino appearance
  - T2K favors non-CP conserving values of δ_{CP} at 2σ
- Next generation long-baseline experiments promise exciting CP violation discovery potential

Photo credit:
Reidar Hahn

Backup

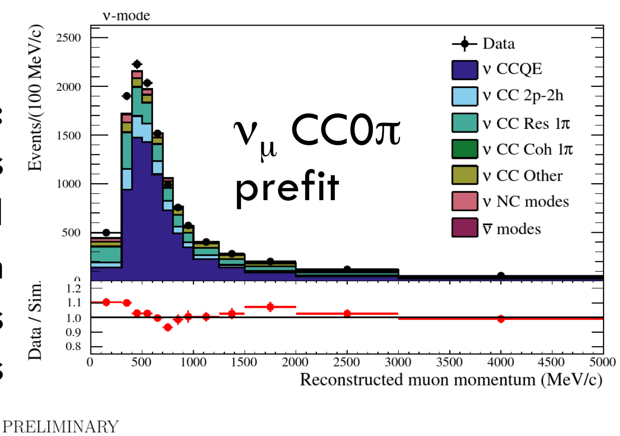
Two detector technique

- Near detectors used to predict far expectations and mitigate systematics



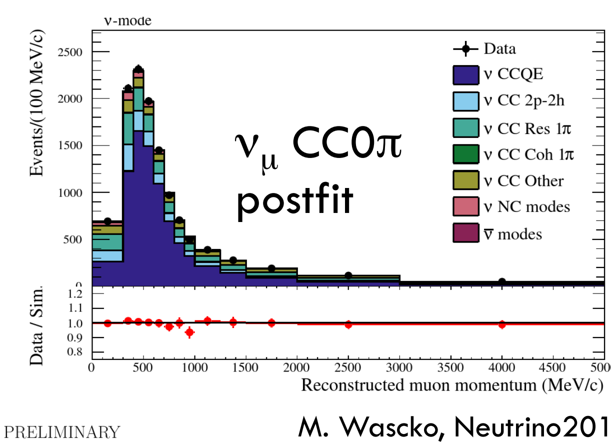
T2K:

Fit 14 different ND280 samples separated by muon charge and pion multiplicity with parameterized flux and cross section models



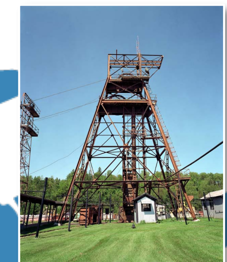
NOvA:

Adjust flux and cross section models guided by external data, adjust empirical MEC model to match data, extrapolate remaining discrepancies in bins of energy resolution using F/N ratio



M. Wascko, Neutrino2018

NOvA



- Long-baseline, off-axis neutrino oscillation experiment
- Study neutrinos from NuMI beam at Fermilab
- At 14 mrad off-axis, energy peaked at 2 GeV
- Functionally identical detectors
  - ND on site at Fermilab
  - FD 810 km away in Ash River, MN
  - Measurement at ND is directly used to predict FD

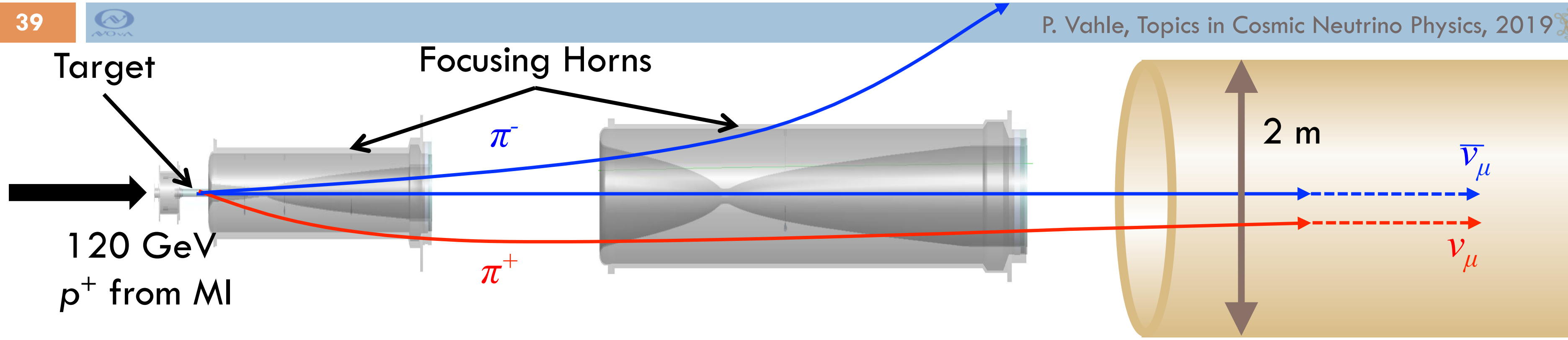
NOvA Collaboration

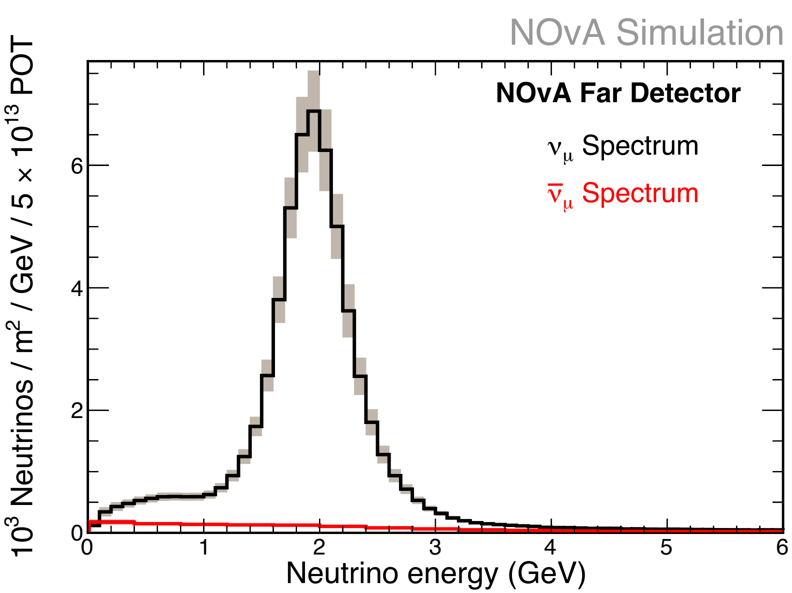
238 collaborators at 49 institutions across 7 countries

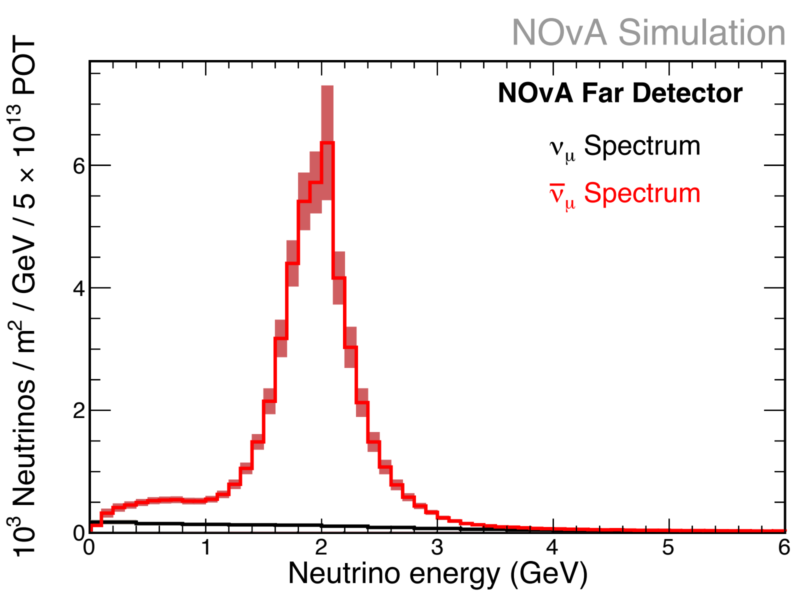
Publications and PhDs

- 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

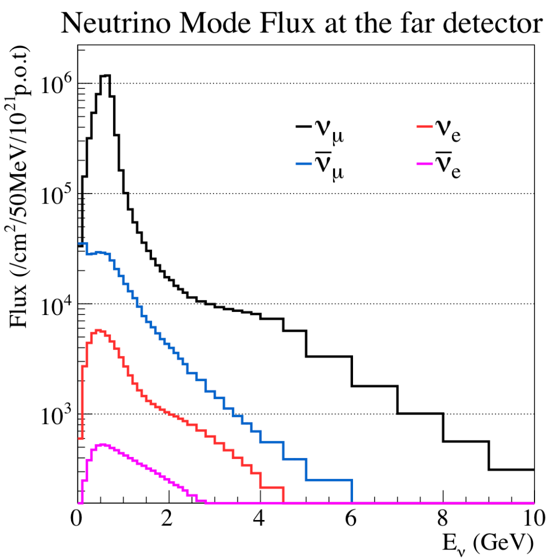
Making an off-axis neutrino beam

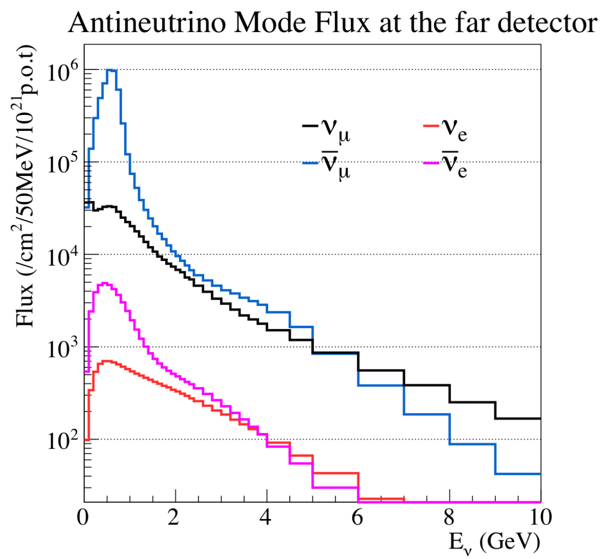




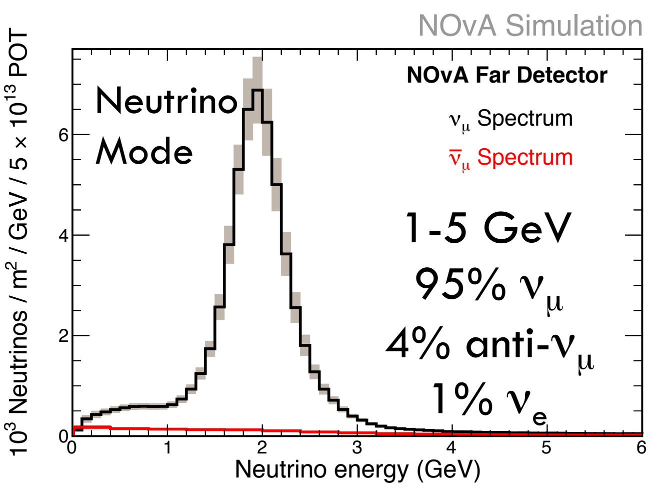


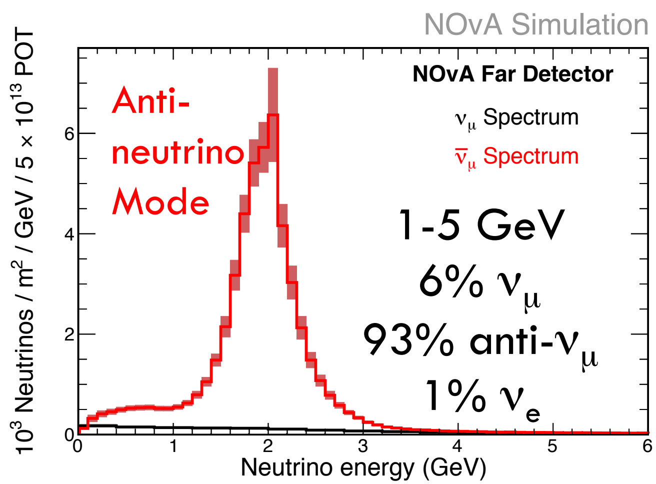
Flux Spectra





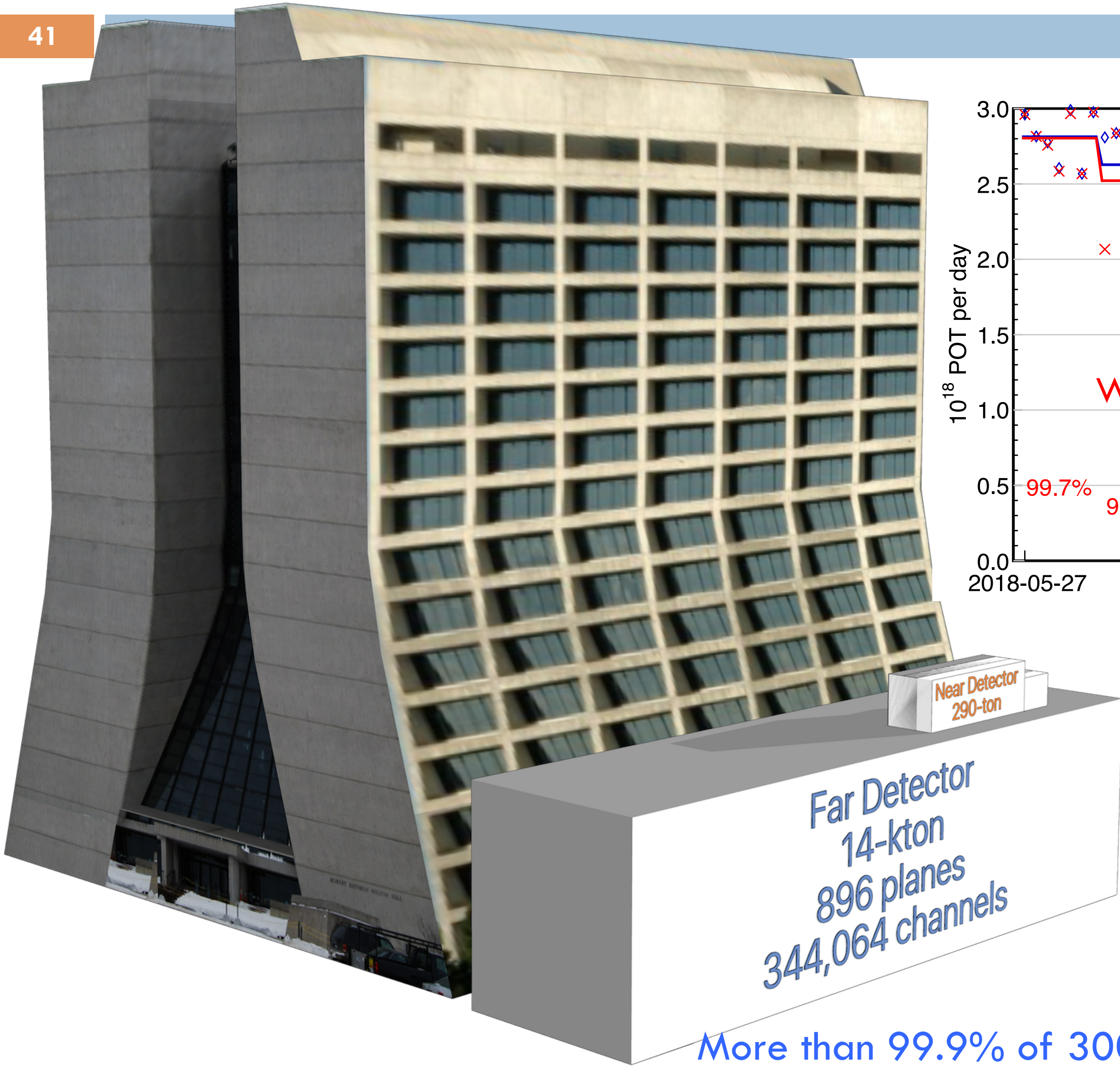
- External Hadron Production data constrain flux uncertainty to ~10%
- Electron neutrino contamination is small
- Wrong sign flux less than 10% in both neutrino and antineutrino beams

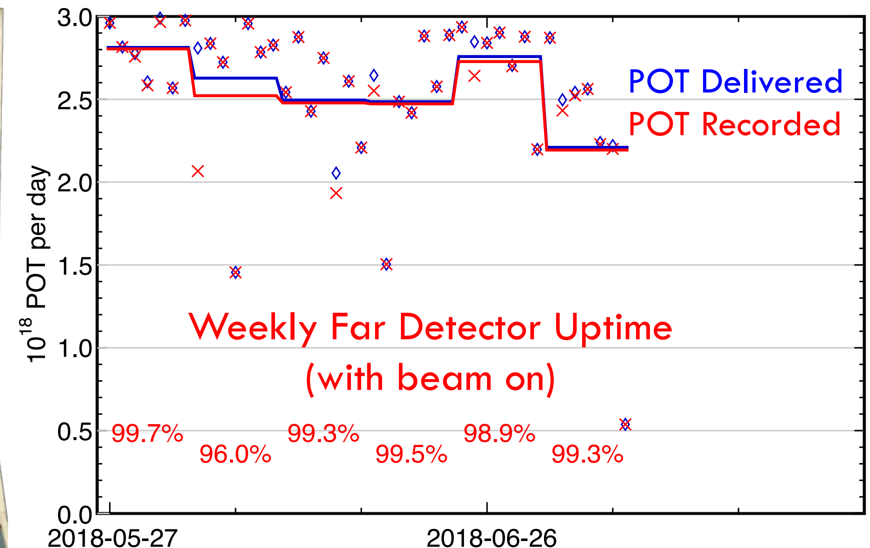




T2K Plots from S. Cao, Moriond 2018

NOvA Detectors



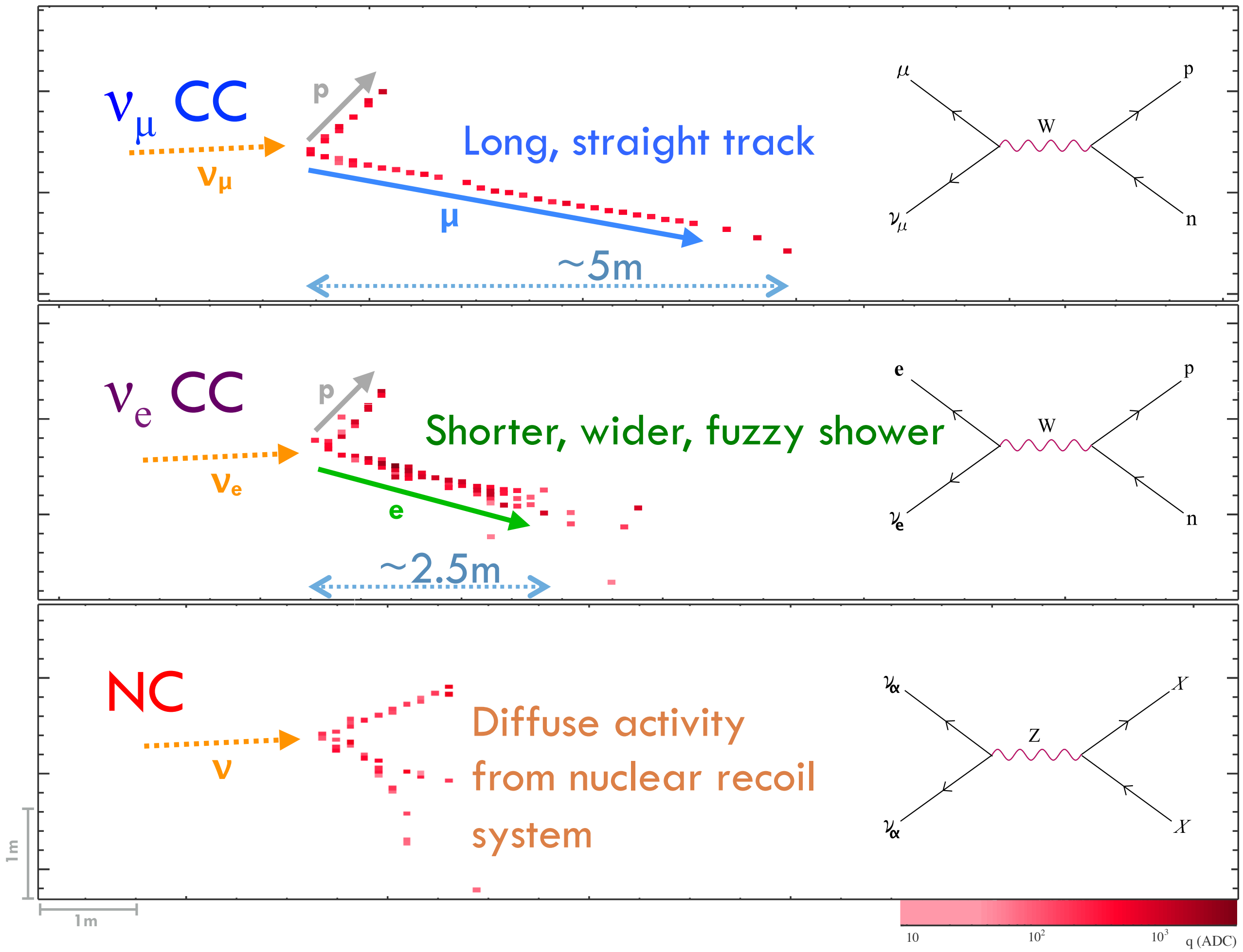


- Functionally identical detectors designed for electron ID
  - Low Z materials (PVC+Liquid Scint.)
  - 65% active
- ND: underground at FNAL
- FD: on the surface in Ash River, MN

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

Improved Event Selection

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

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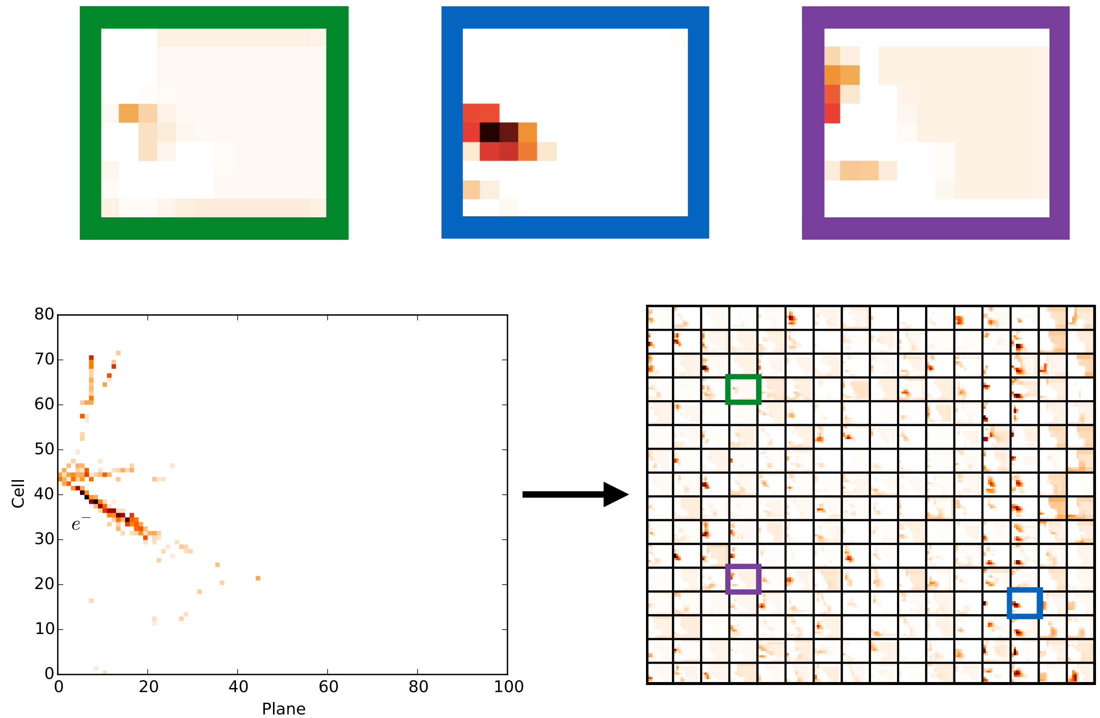

A. Aurisano et al., arXiv:1604.01444
Posters P1.028 by A. Radovic, P1.032 by F. Psihas and A. Himmel for more detail

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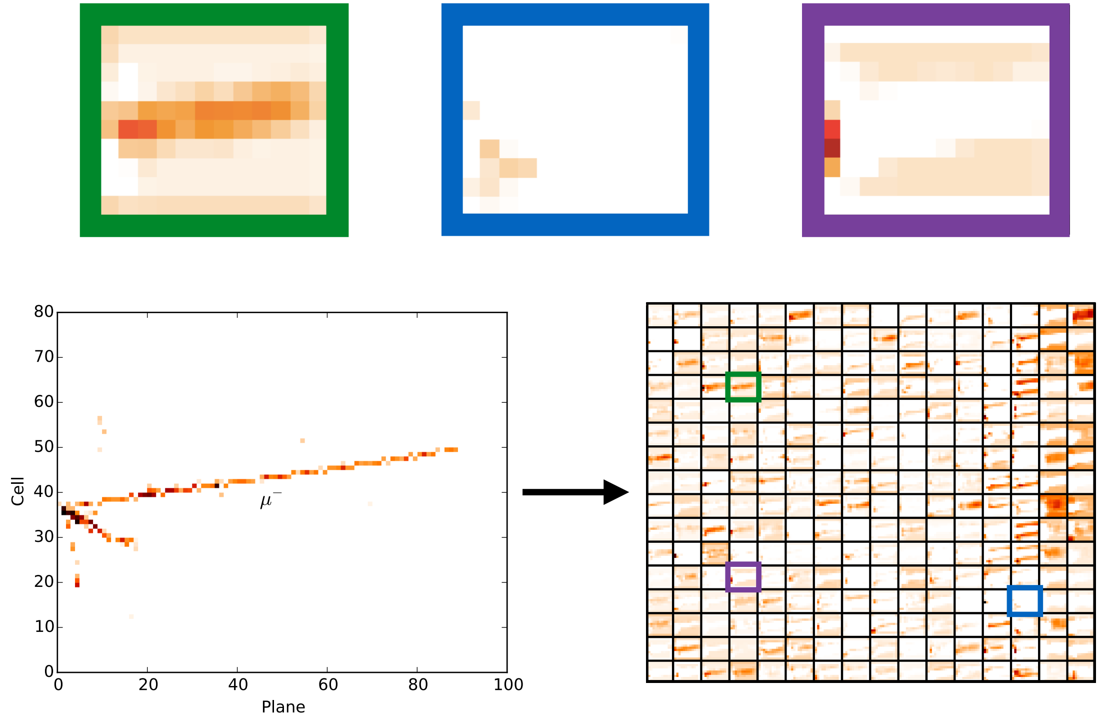

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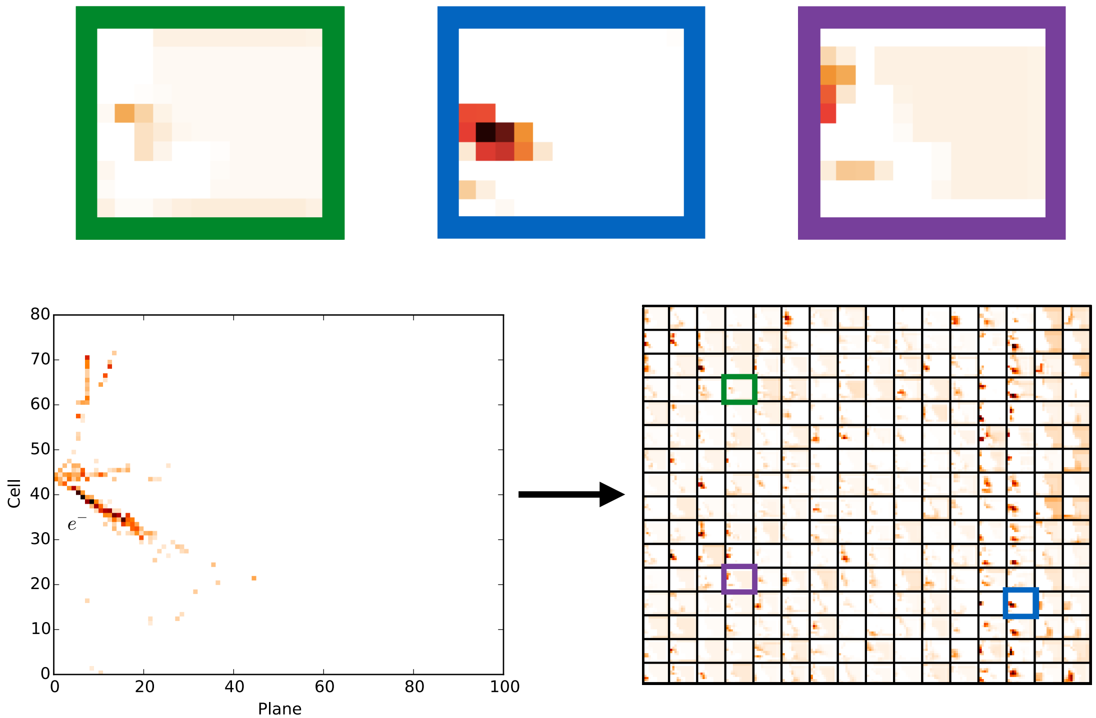


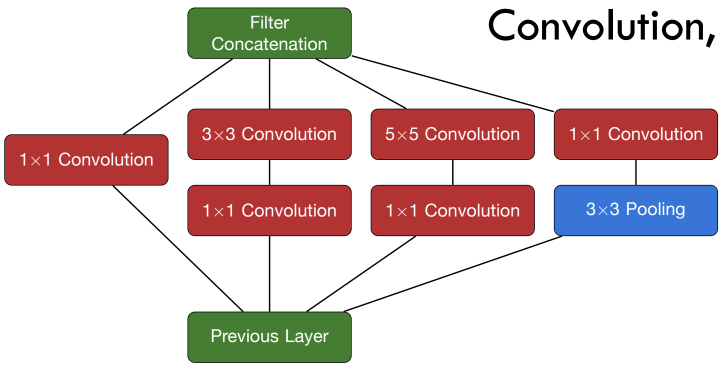
Improvement in sensitivity from CVN equivalent to 30% more exposure

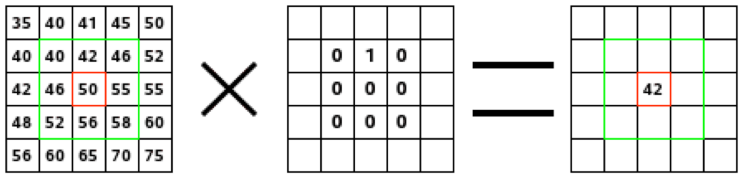
A. Aurisano et al., arXiv:1604.01444

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

CVN Architecture

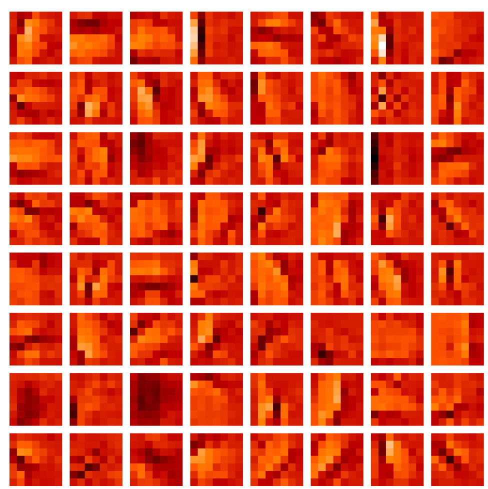
GoogLeNet
Inception Module
C. Szegedy et al.,
arXiv:1409.4842





Example image processing transformation
Convolution, or kernel map

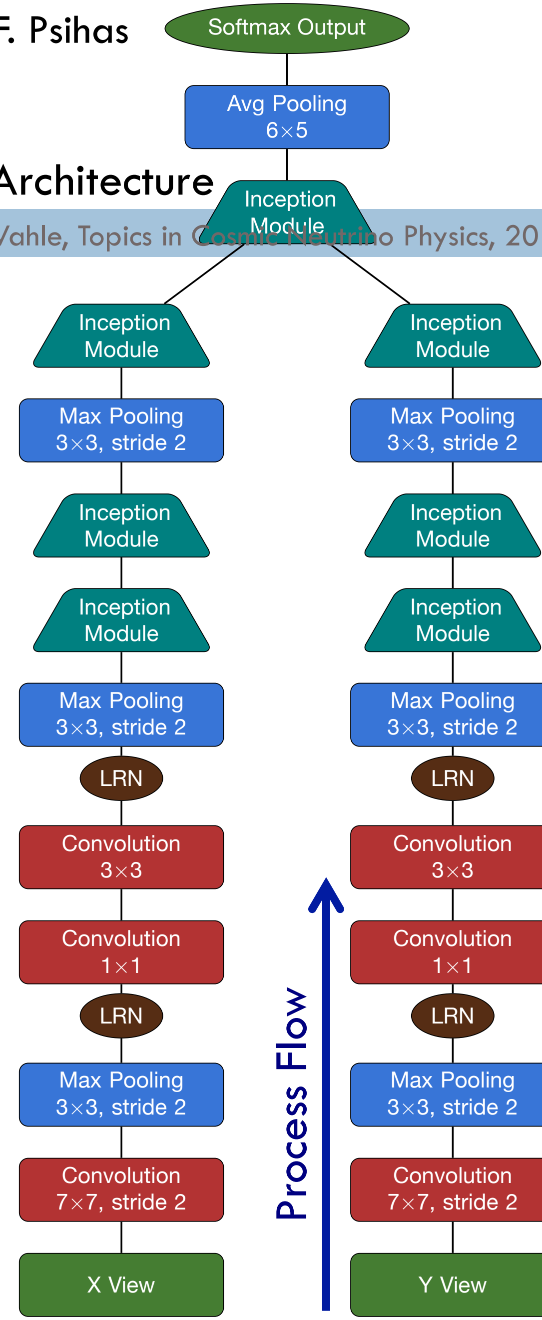
Example Convolutional Filter Layer



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



Backup—Disappearance Results

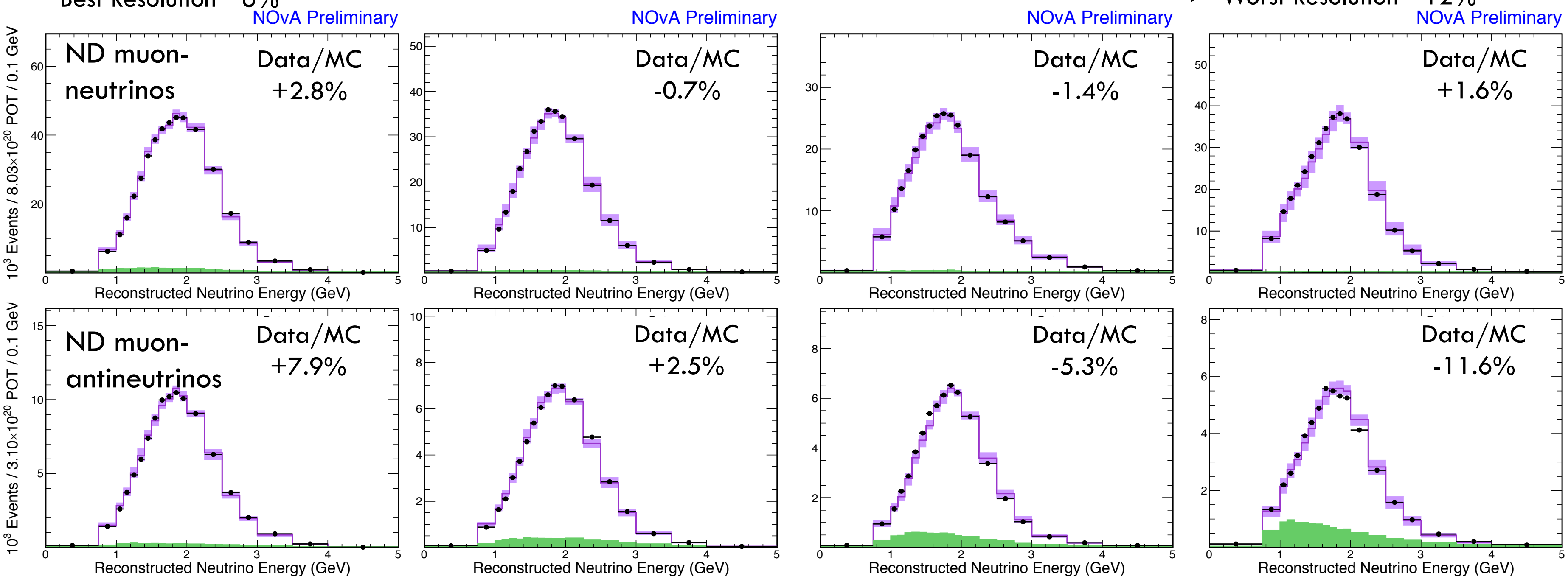
Analysis in more detail

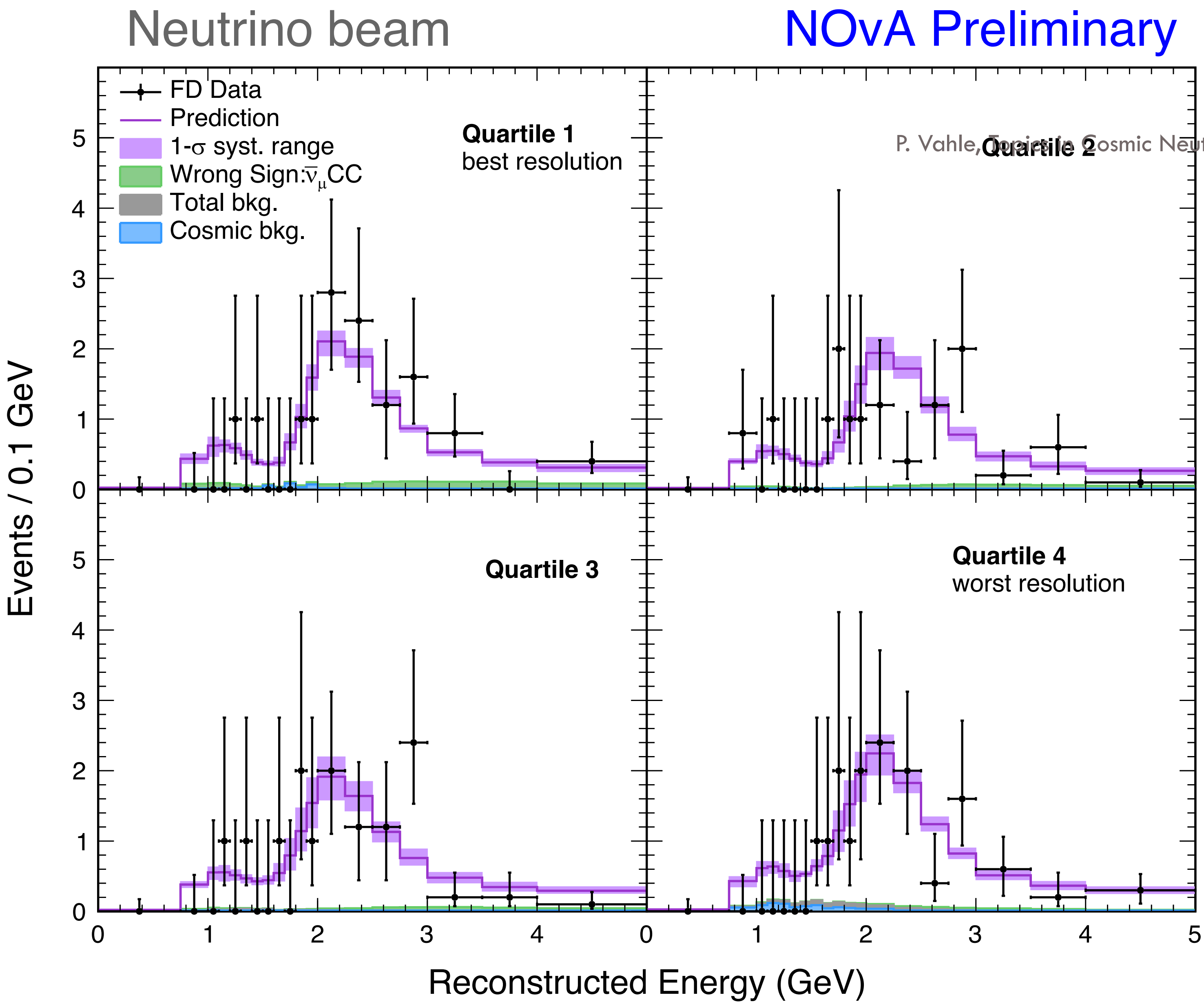
Data
Area-normalized MC
Shape-only systematics
Wrong-sign

- 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%

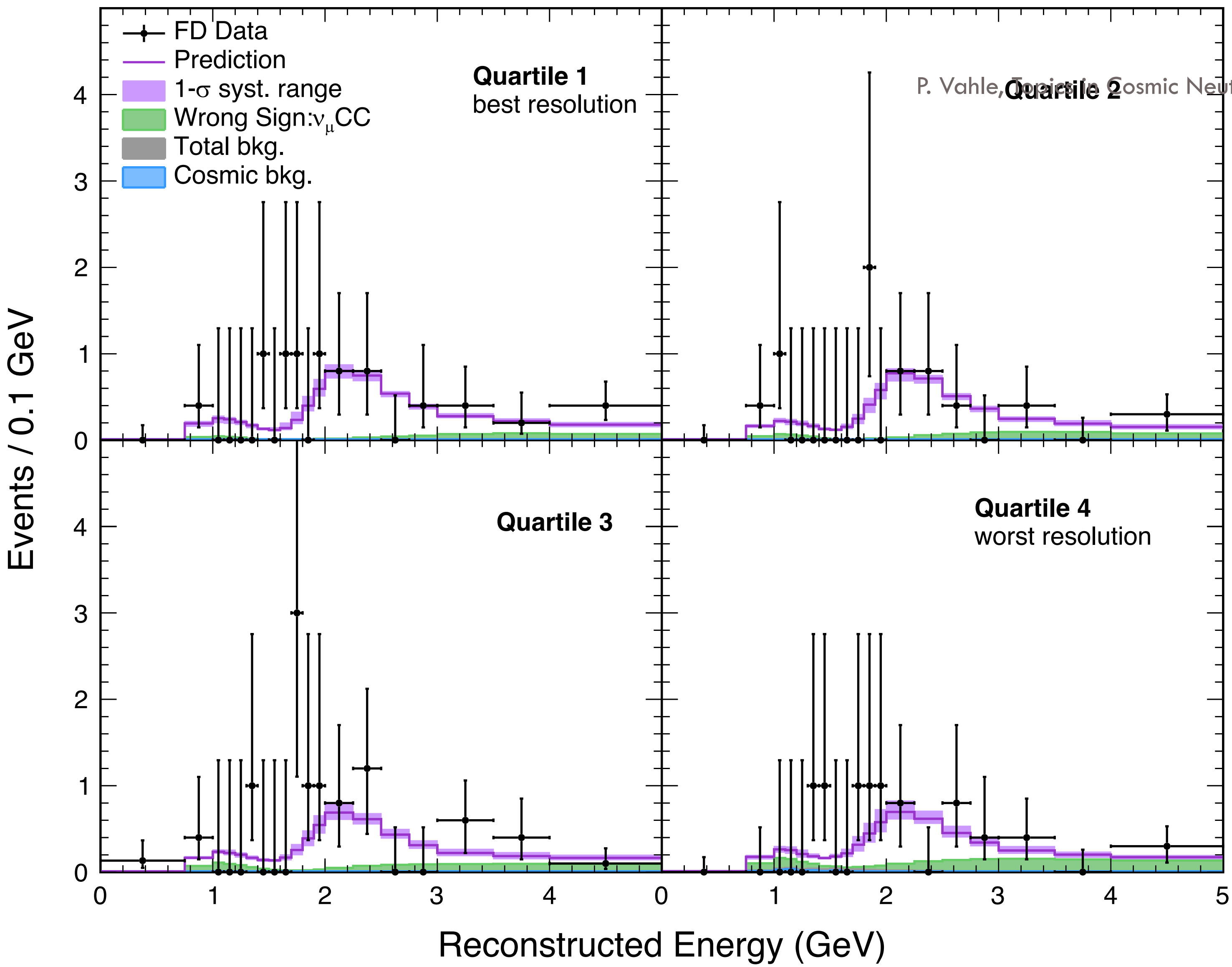
Quantile 4
Worst Resolution ~12%



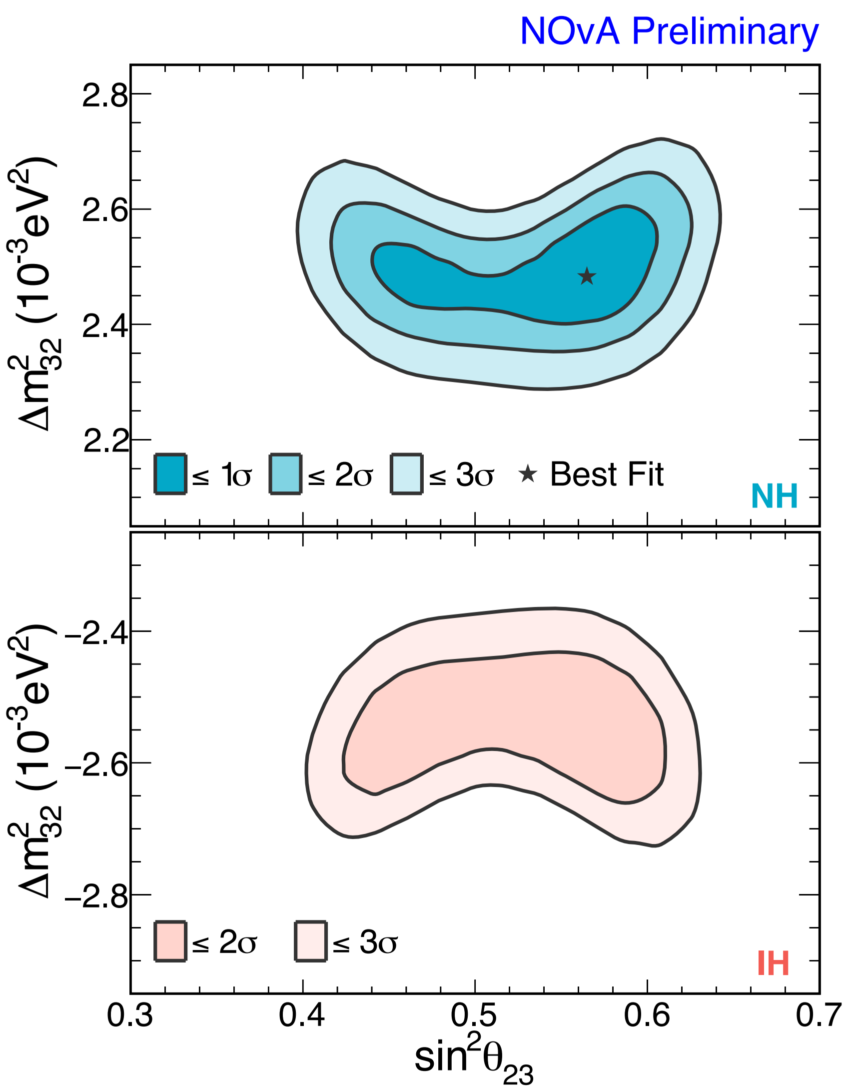

Neutrino beam
NOvA Preliminary
FD Data
Prediction
1-σ syst. range
Wrong Sign: $\bar{\nu}_{\mu}$CC
Total bkg.
Cosmic bkg.
Quartile 1
best resolution
Quartile 2
Quartile 3
Quartile 4
worst resolution
Events / 0.1 GeV
Reconstructed Energy (GeV)
0
1
2
3
4
5

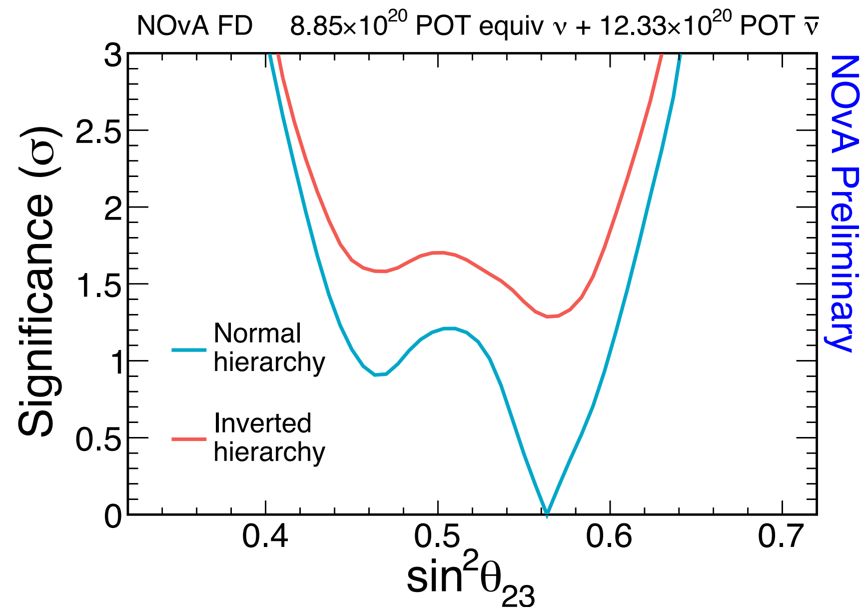
Antineutrino beam

NOvA Preliminary



NOvA Fit Results: Mass splitting and mixing angle





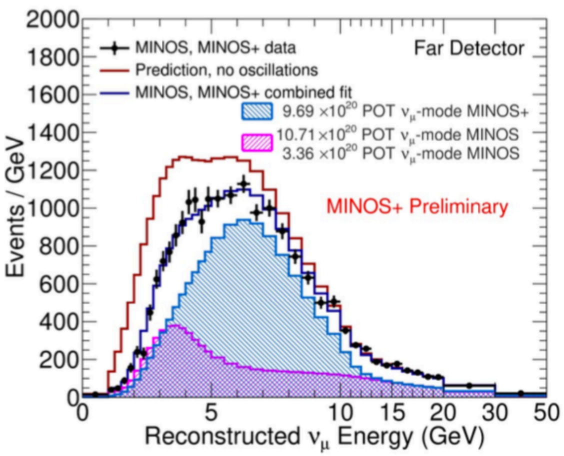
Normal Hierarchy

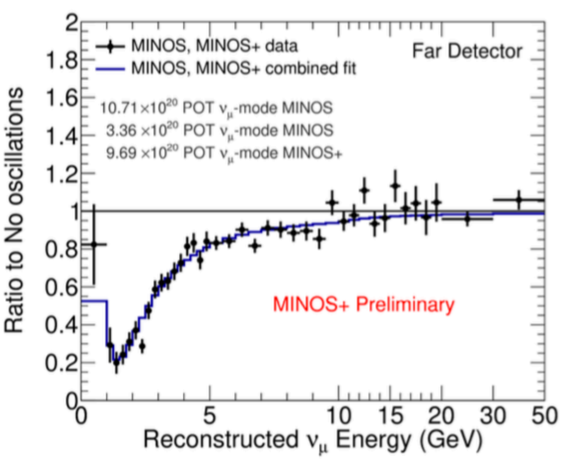
$$\Delta m^2_{32} = 2.48^{+0.11}_{-0.06} \times 10^{-3}\text{eV}^2$$

$$\sin^2\theta_{23} = 0.56^{+0.04}_{-0.03}$$

$$\delta_{CP} = 0.0\pi$$

MINOS+ and OPERA



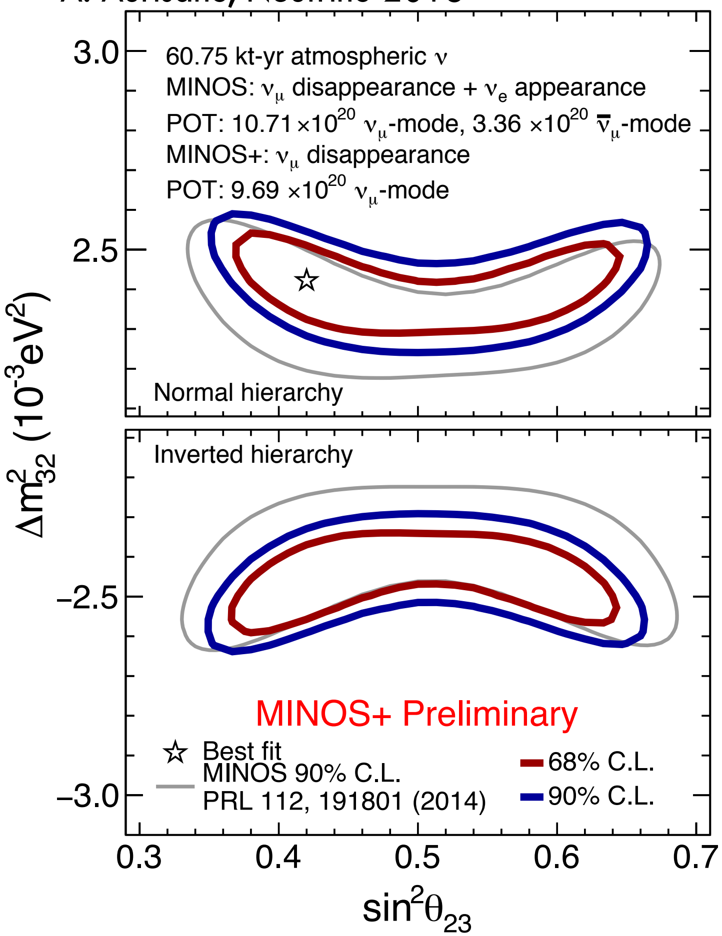


Best fit

$\Delta m^2_{32} = 2.42\text{x}10^{-3}\ \text{eV}^2$

$\sin^2\theta_{23} = 0.42$

A. Aurisano, Neutrino 2018



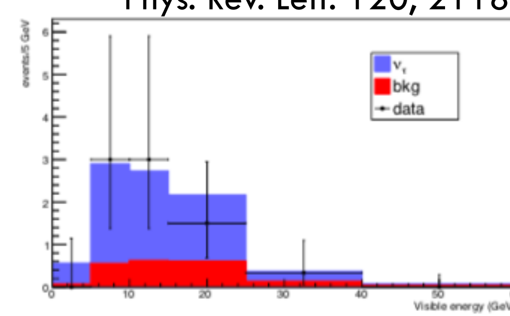
Exclusion of maximal mixing: 1.1σ

Preference for lower octant: 0.8σ

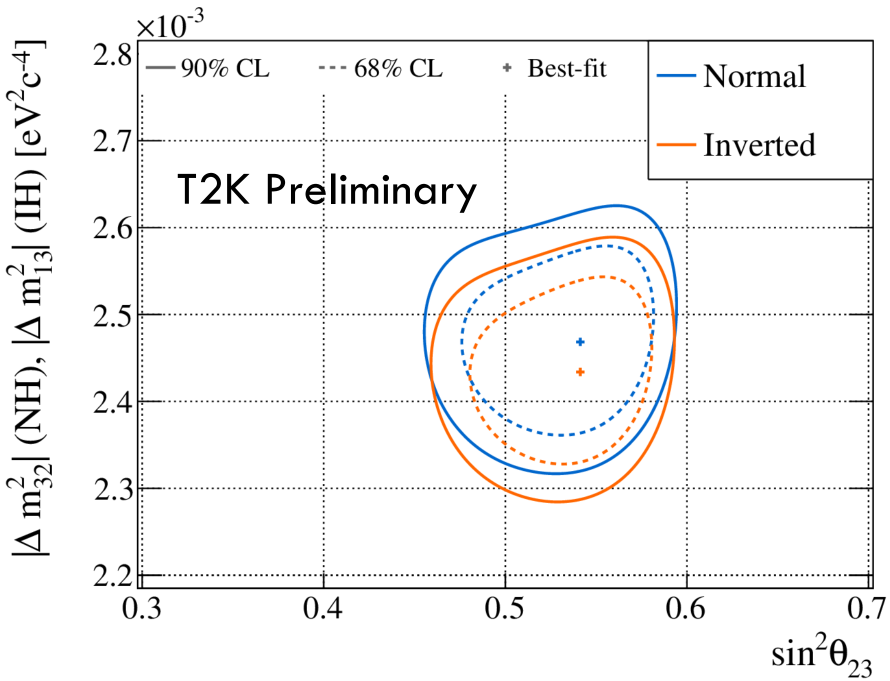
Preference for normal hierarchy: 0.2σ

- Opera final results:
  - 10 tau neutrino candidates
  - 6.1sigma evidence of appearance
  - 20% measurement of mass splitting agrees with disappearance measurements

Phys. Rev. Lett. 120, 211801



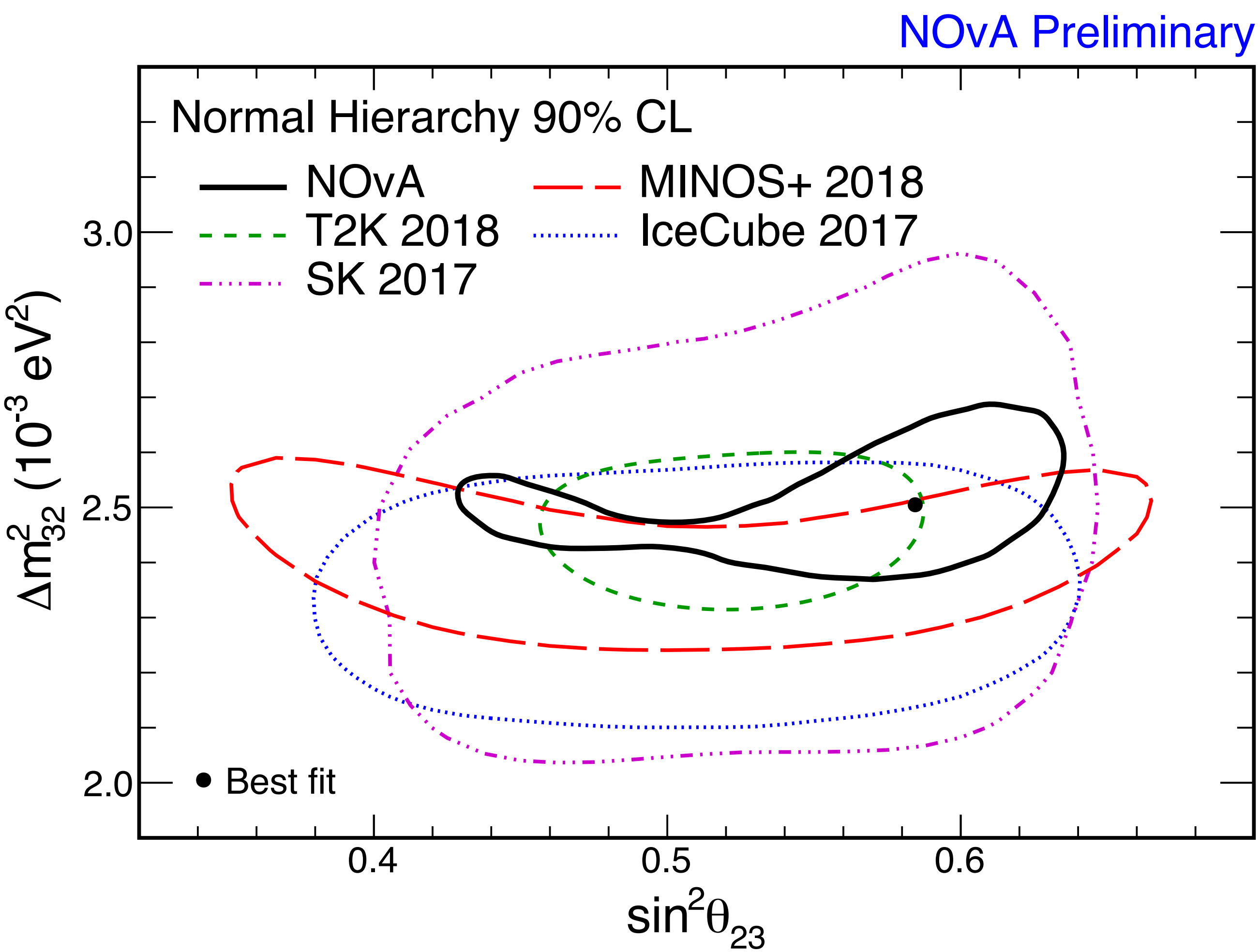
T2K Fit Results: Mass splitting and mixing angle



	Normal Hierarchy	Inverted Hierarchy
$sin^2(\theta_{23})$	$0.532^{+0.030}_{-0.037}$	$0.532^{+0.029}_{-0.035}$
$\|\Delta m^2_{32}\| \times 10^{-3} eV^2$	$2.452^{+0.070}_{-0.071}$	$2.432^{+0.069}_{-0.071}$

K. Porwit, NuTelescopes 2019

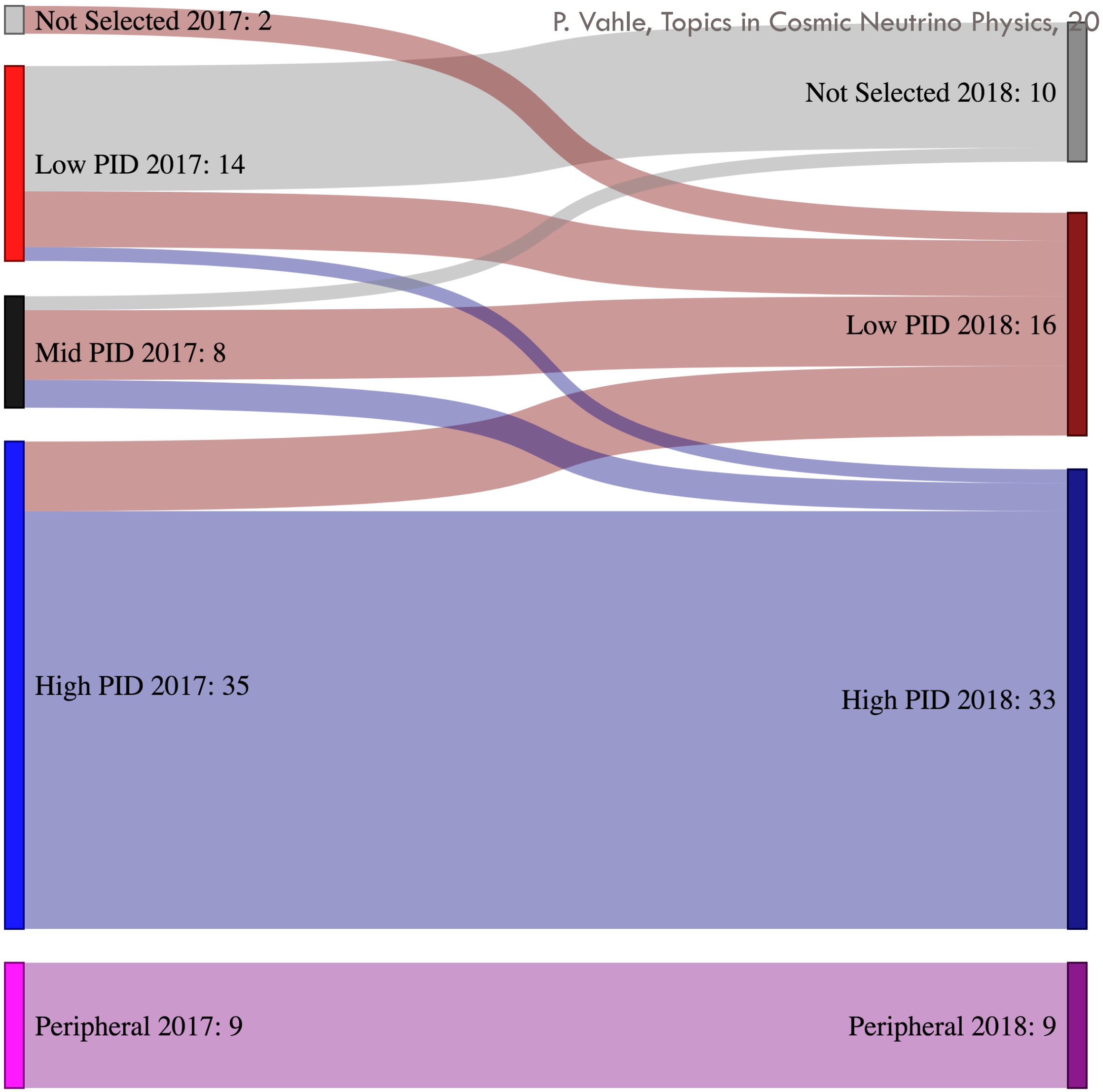
Comparisons



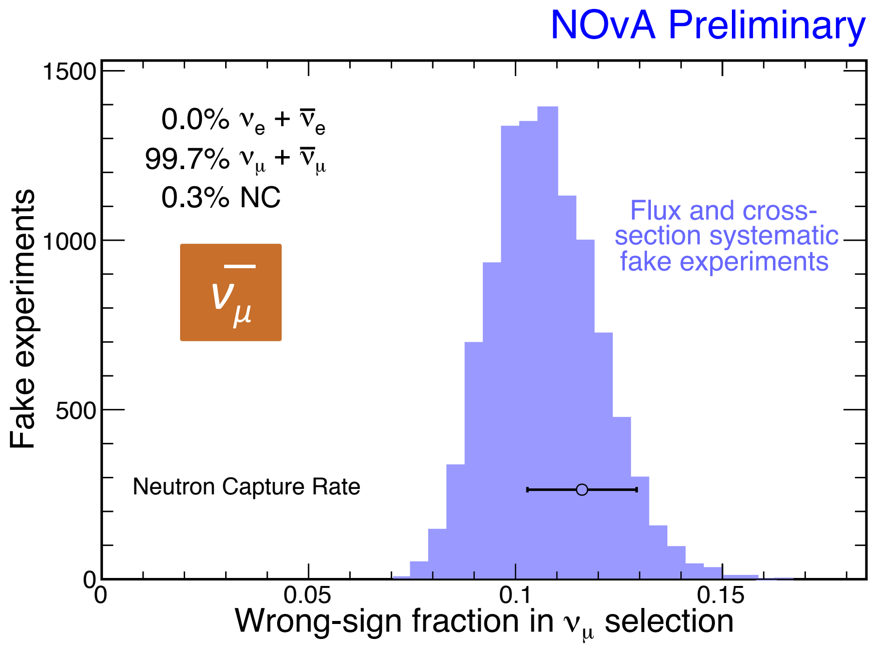
Backup—Appearance Results

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



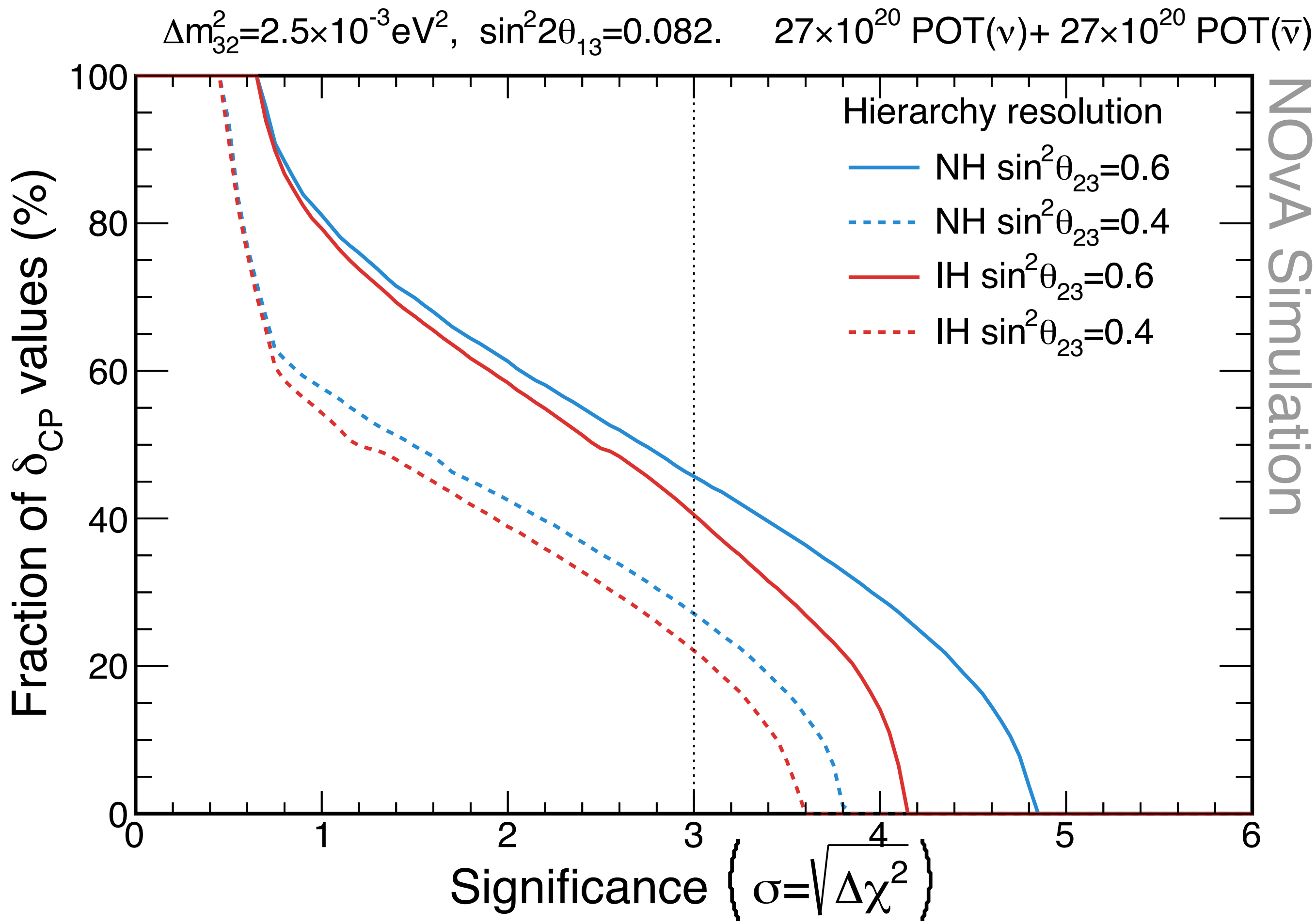
- The 11% wrong-sign fraction of the $\bar{\nu}_\mu$ **events** is important since it becomes the WS background in the $\bar{\nu}_e$ **appearance analysis**.
- ~10% systematic uncertainty on wrong-sign from flux and cross section
  - Does not include uncertainties from detector effects.
- Confirmed using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

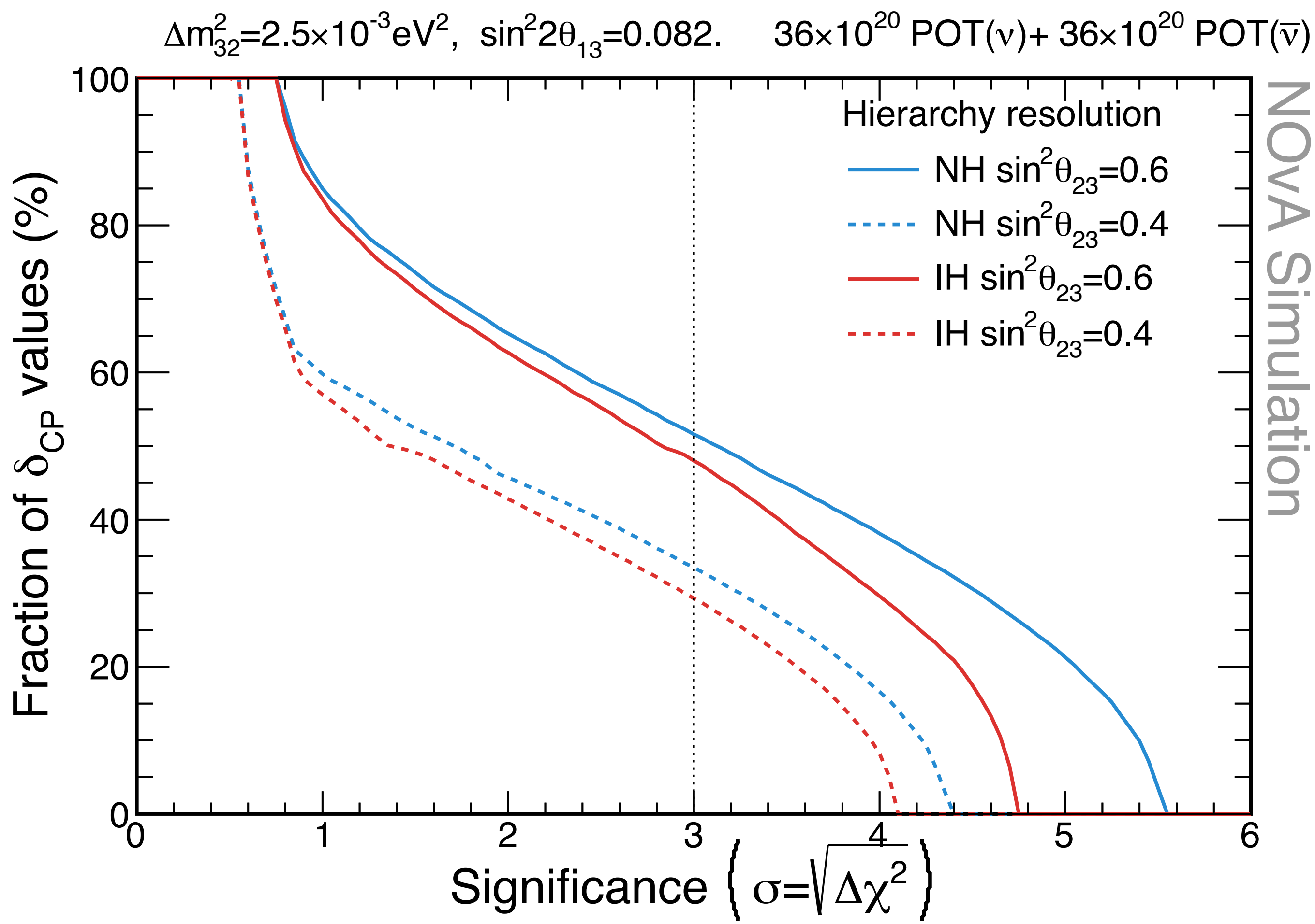
Proposed Accelerator Improvement Projects

- 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

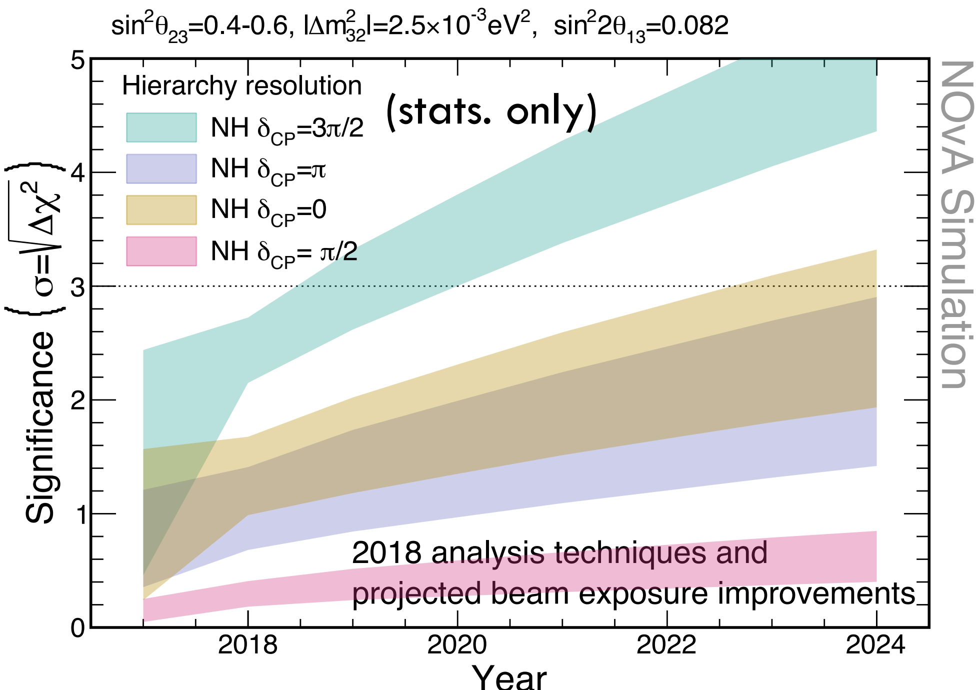
AIP Sensitivity Gain



AIP Sensitivity Gain



Future Sensitivity

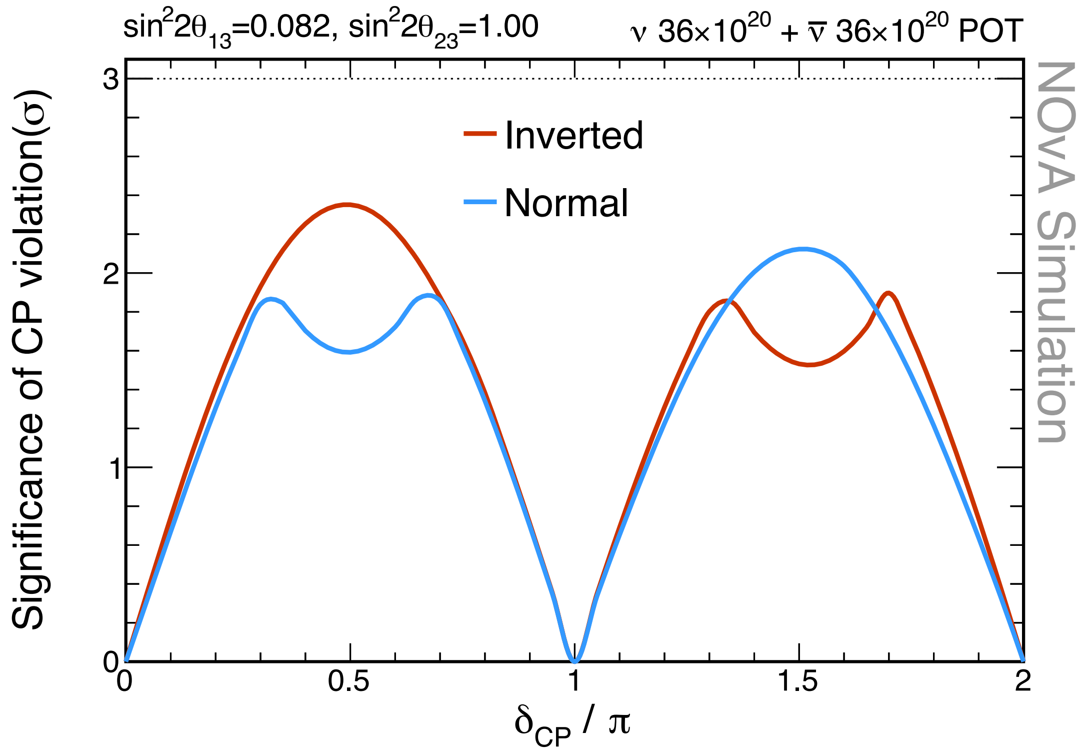


- Sensitivity dependent on true values in nature
- For favorable parameters consistent with results, we can achieve 3 sigma mass hierarchy sensitivity by 2020
  - 3 sigma sensitivity for 30-50% of delta CP range by 2024
  - >5 sigma in favorable cases by 2024, possible only with POT boosts from AIP work

- 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

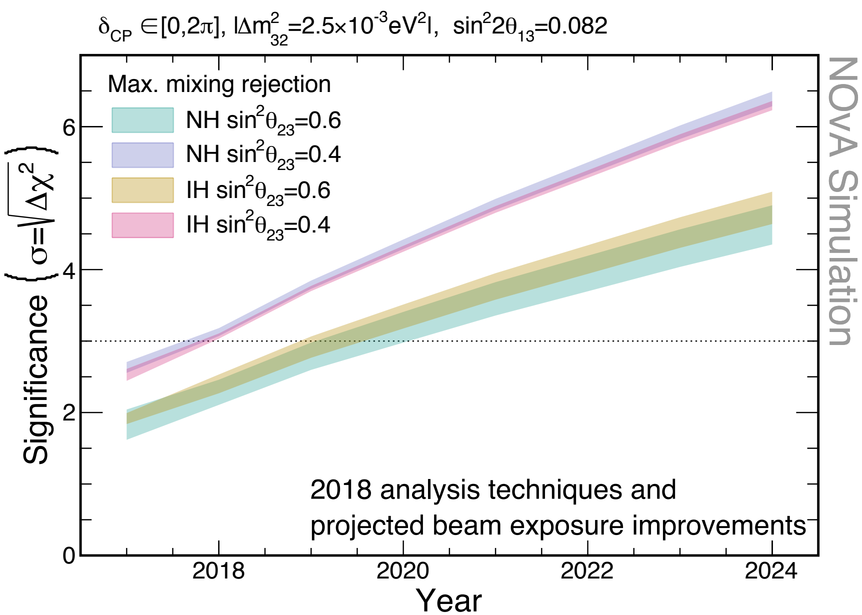
CP Violation Sensitivity



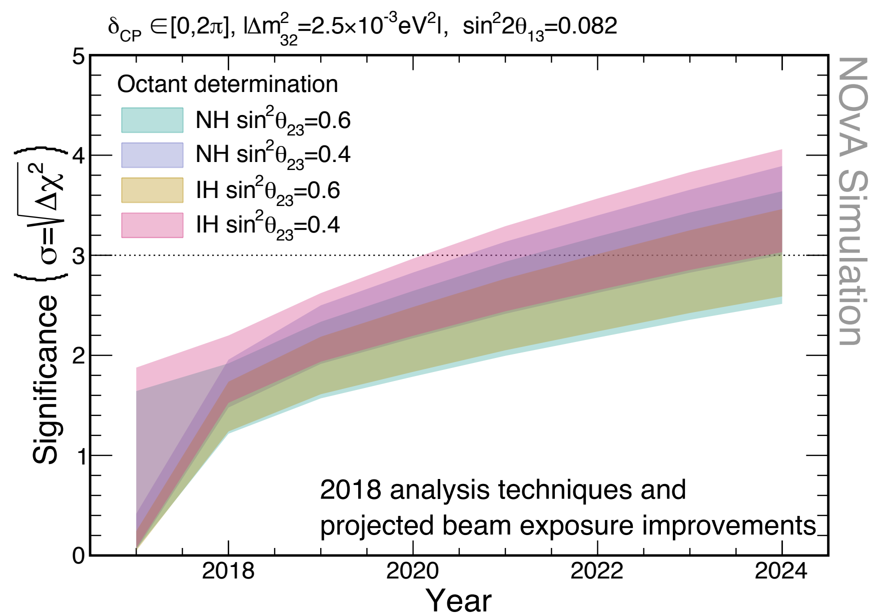
2+ σ sensitivity for CP violation in both hierarchies at $\delta_{CP}=3\pi/2$ or $\delta_{CP}=\pi/2$ (assuming unknown hierarchy) by 2024

Future Sensitivity

Max mixing rejection



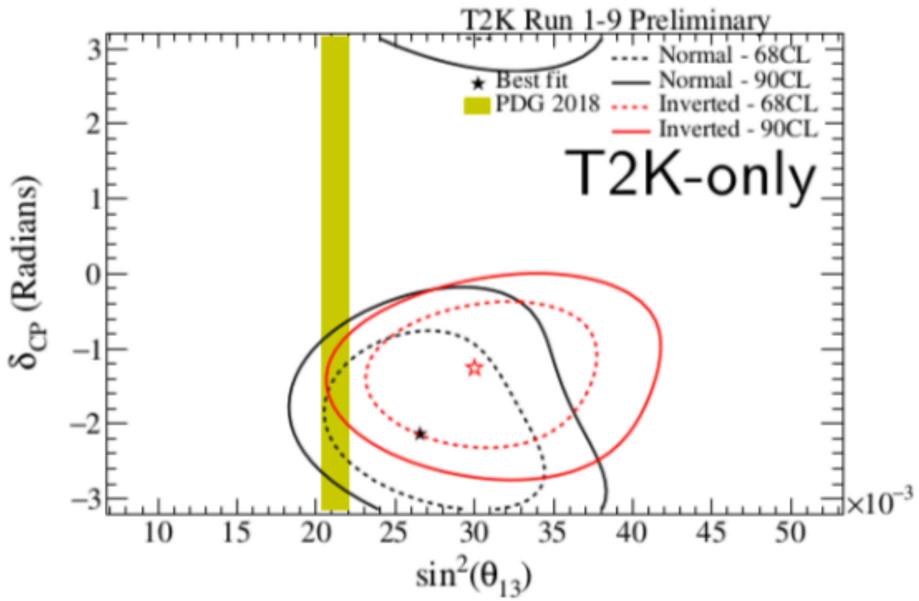
Octant

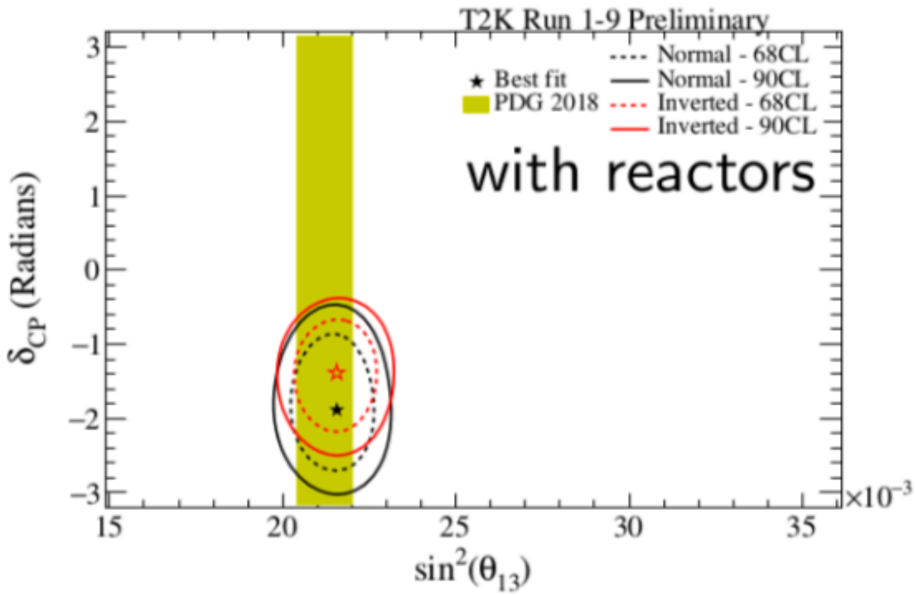


Other Experiments

- 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

T2K Fit Results



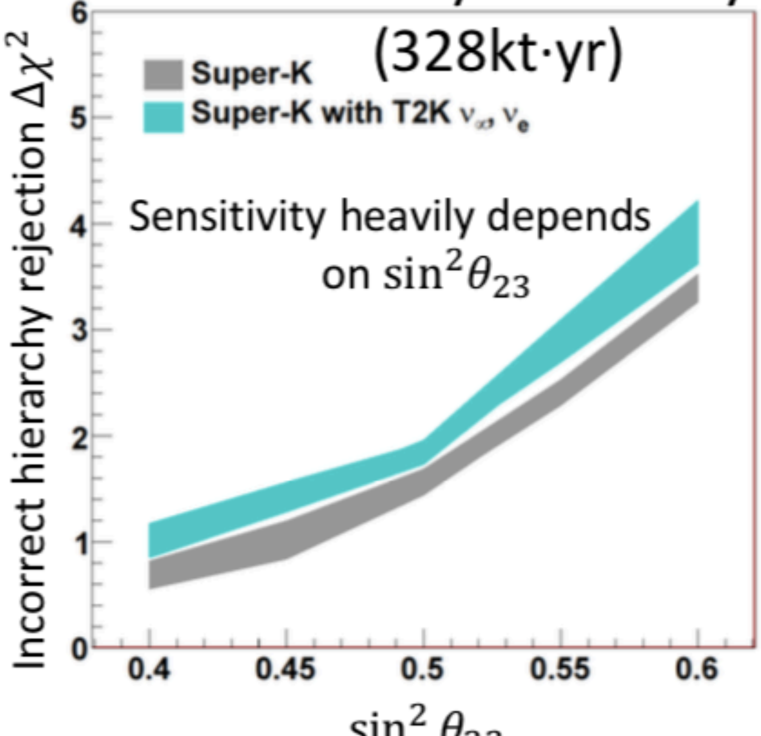


(Note different phase convention)

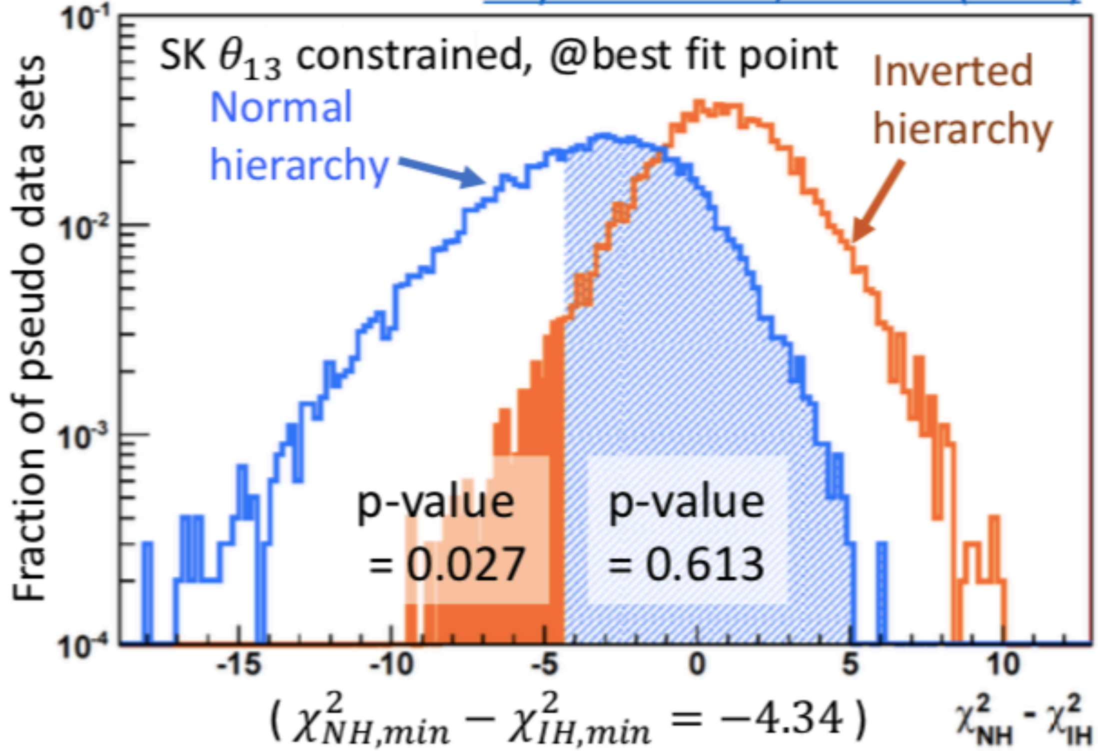
Determination of hierarchy determination

Y. Hayato, Nu2018

Mass hierarchy sensitivity



Phys. Rev. D 97, 072001 (2018)



Estimate p-values using pseudo-data

for the smallest and largest $\sin^2\theta_{23}$.

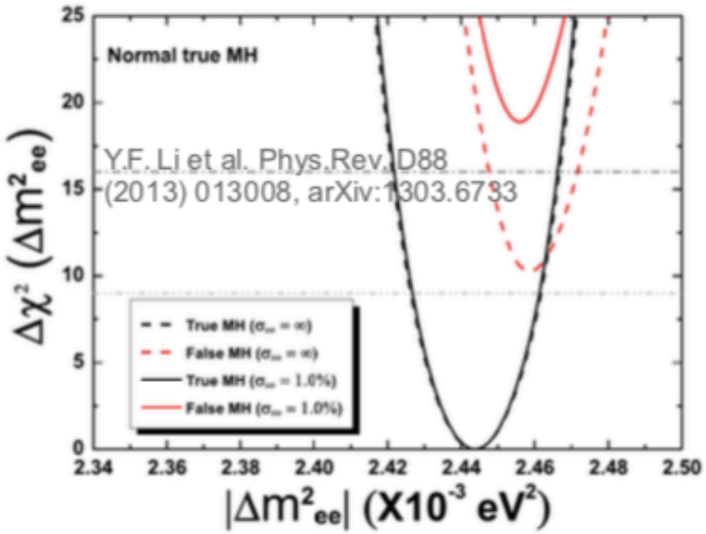
Hypothesis test ~ CL_s method : $\mathrm{CL_s(IH\ rejection)} \equiv \frac{p_{0(IH)}}{1-p_0(NH)}$

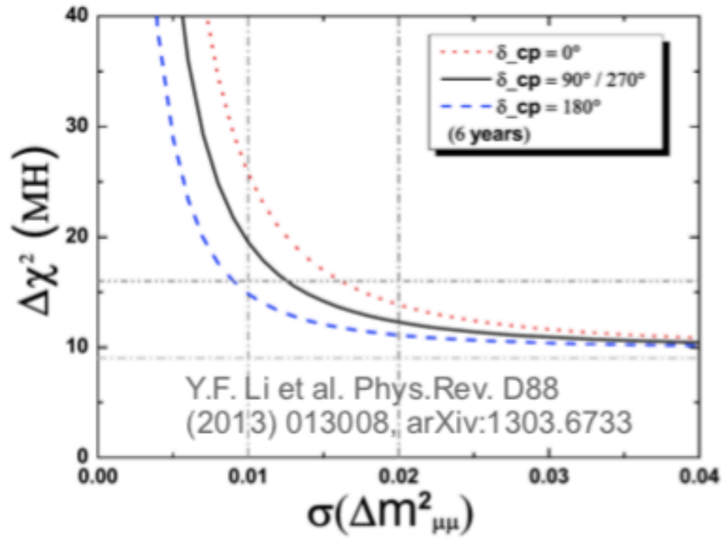
Normal hierarchy is favored ➡

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:**

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

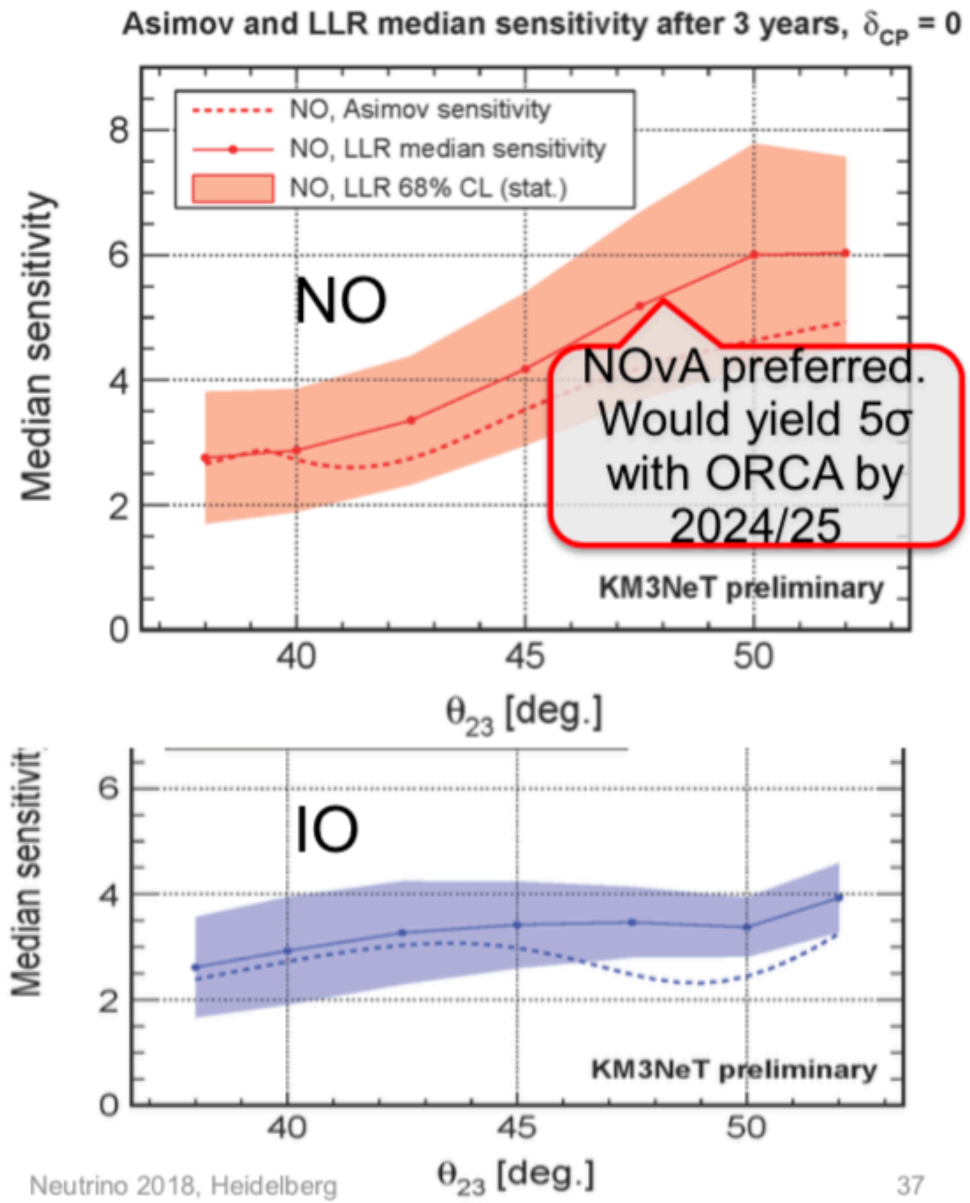
Sign defined by MH

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

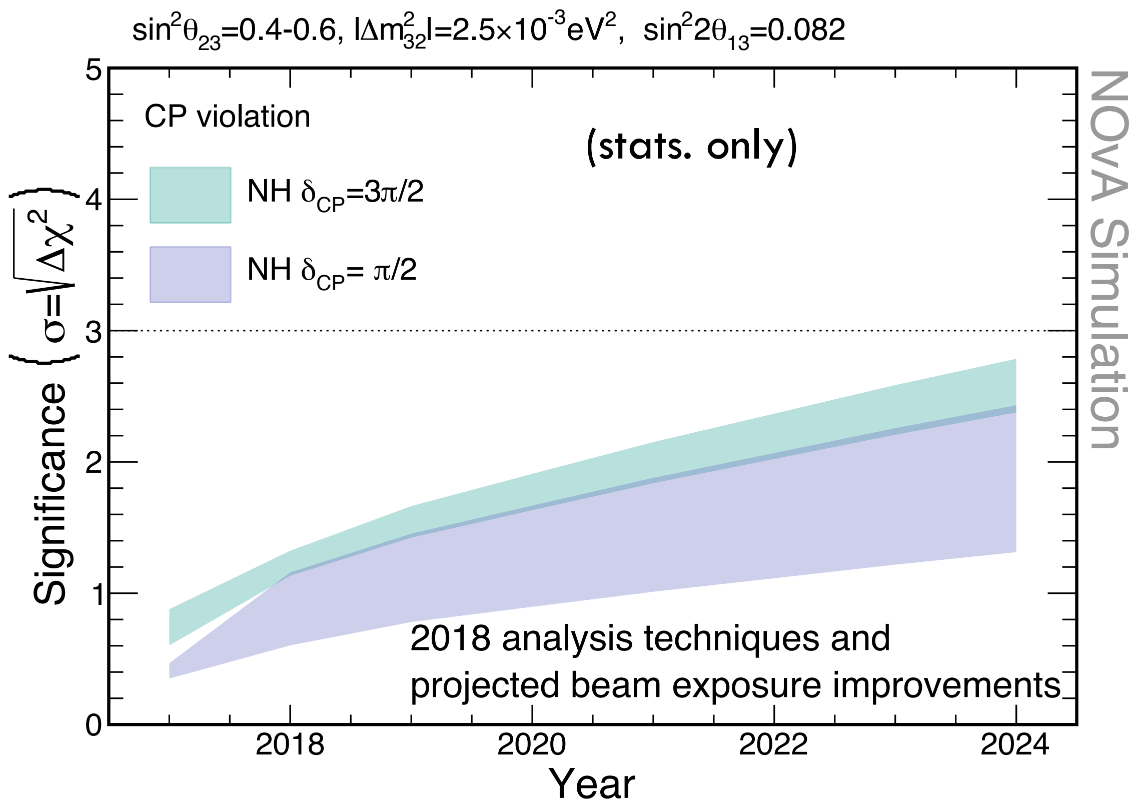
NMO measurement

- 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

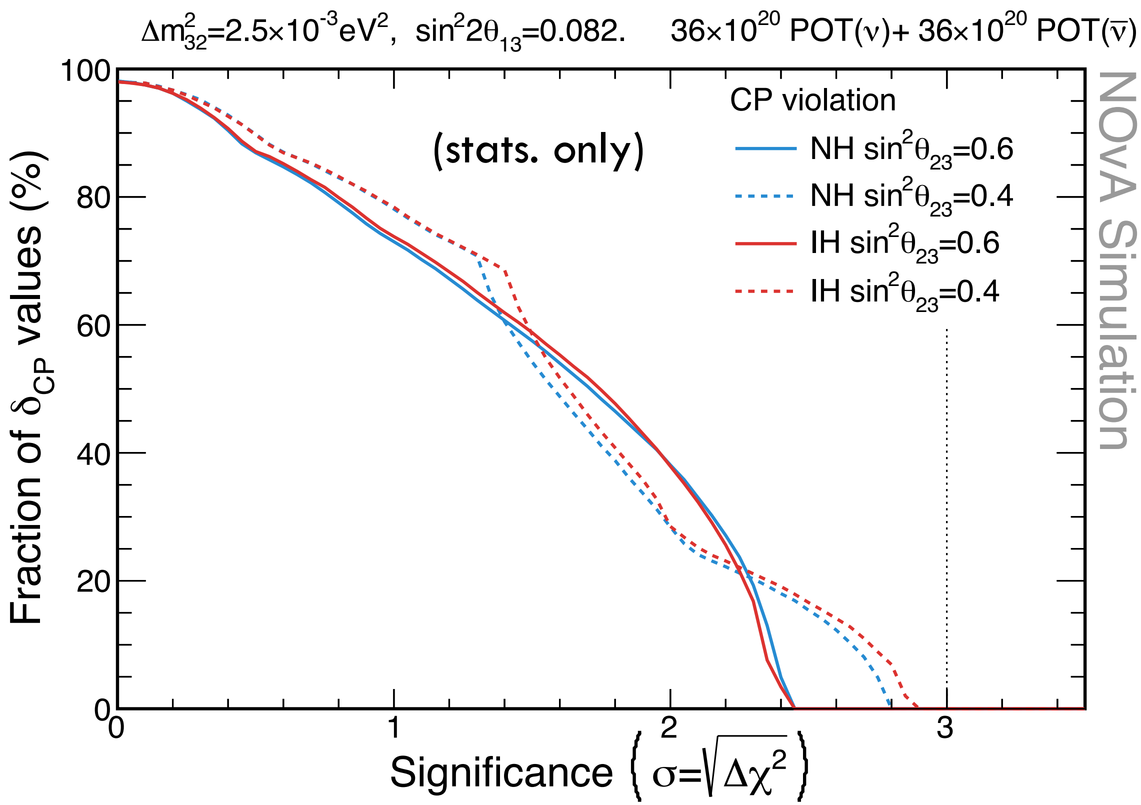


Delta CP



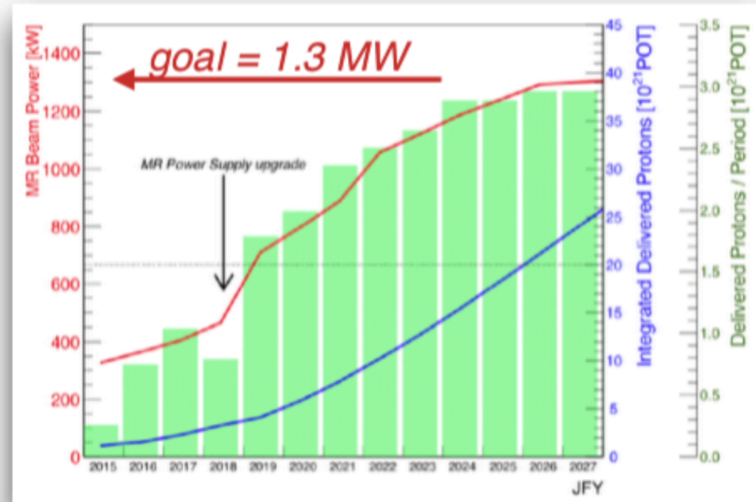
Sensitivity to CP violation for representative values of delta CP. Shaded region represents the range spanned for different true values of the theta_23 mixing angle.

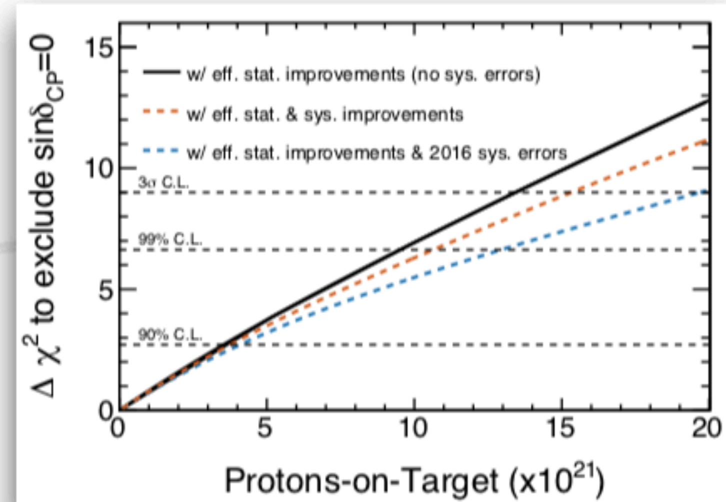
Delta CP



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

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.

Delta CP

arXiv:1609.04111

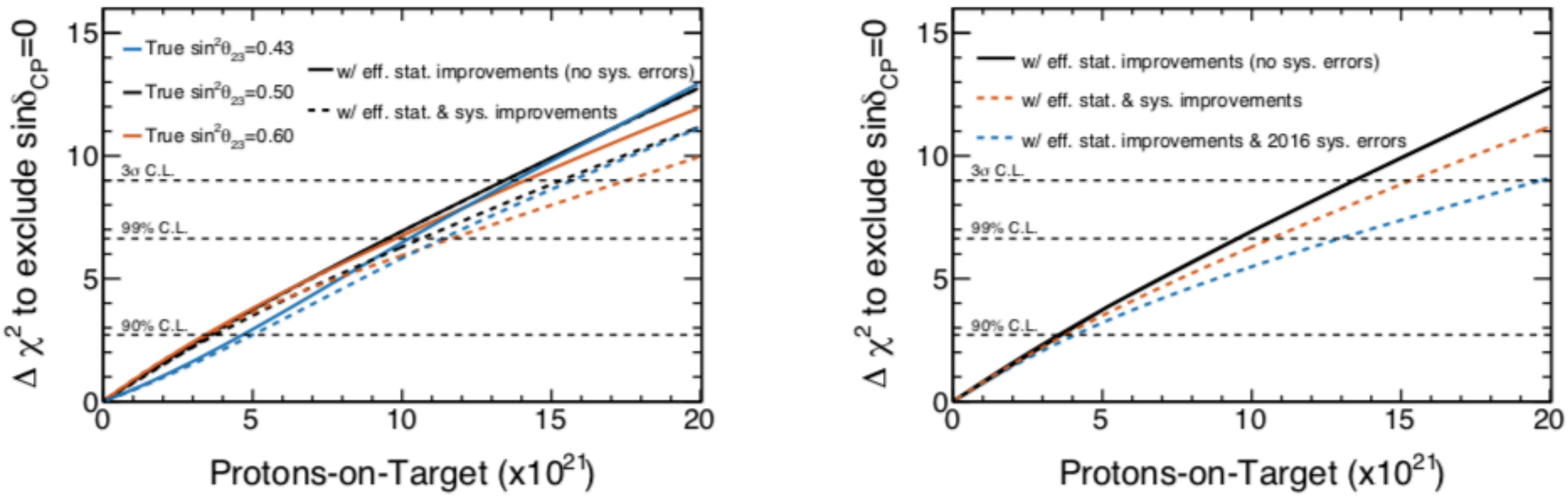


FIG. 25: Sensitivity to CP violation as a function of POT with a 50% improvement in the effective statistics, assuming the true MH is the normal MH but unknown and the true value of $\delta_{CP} = -\pi/2$. The plot on the left compares different true values of $\sin^2\theta_{23}$, while that on the right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