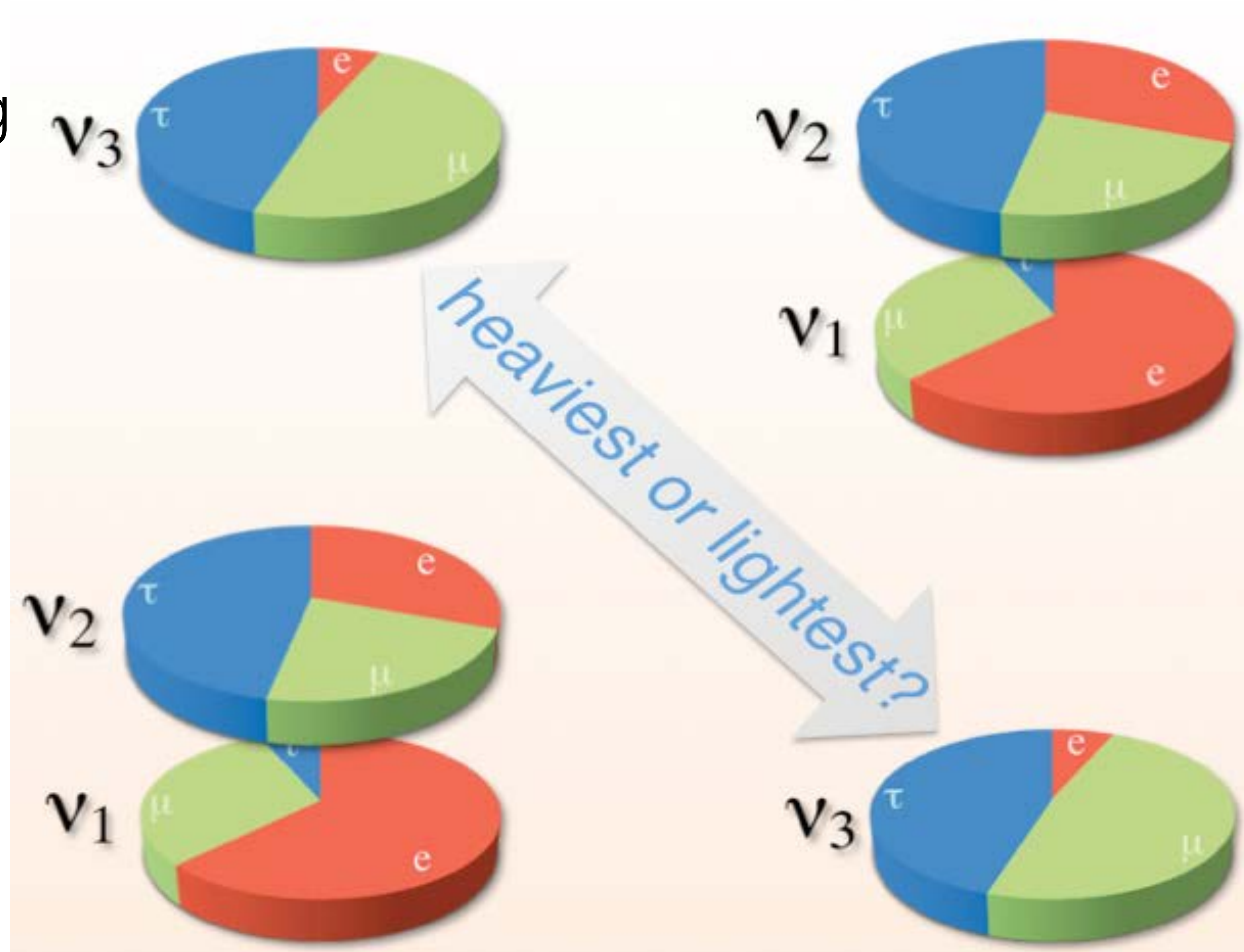
Highlights of new science results: Long-baseline neutrino experiments

Mark Messier
Indiana University

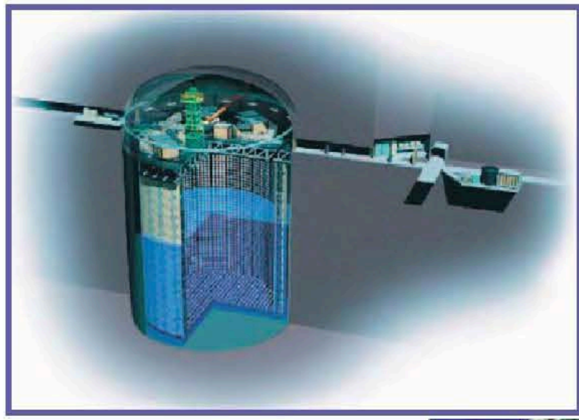
HEPAP Teleconference
September 26, 2017

Next Questions In Neutrino Physics

- Mass ordering
- Nature of ν_3 - θ_{23} octant
- Is CP violated?
- Is there more to this picture?



T2K



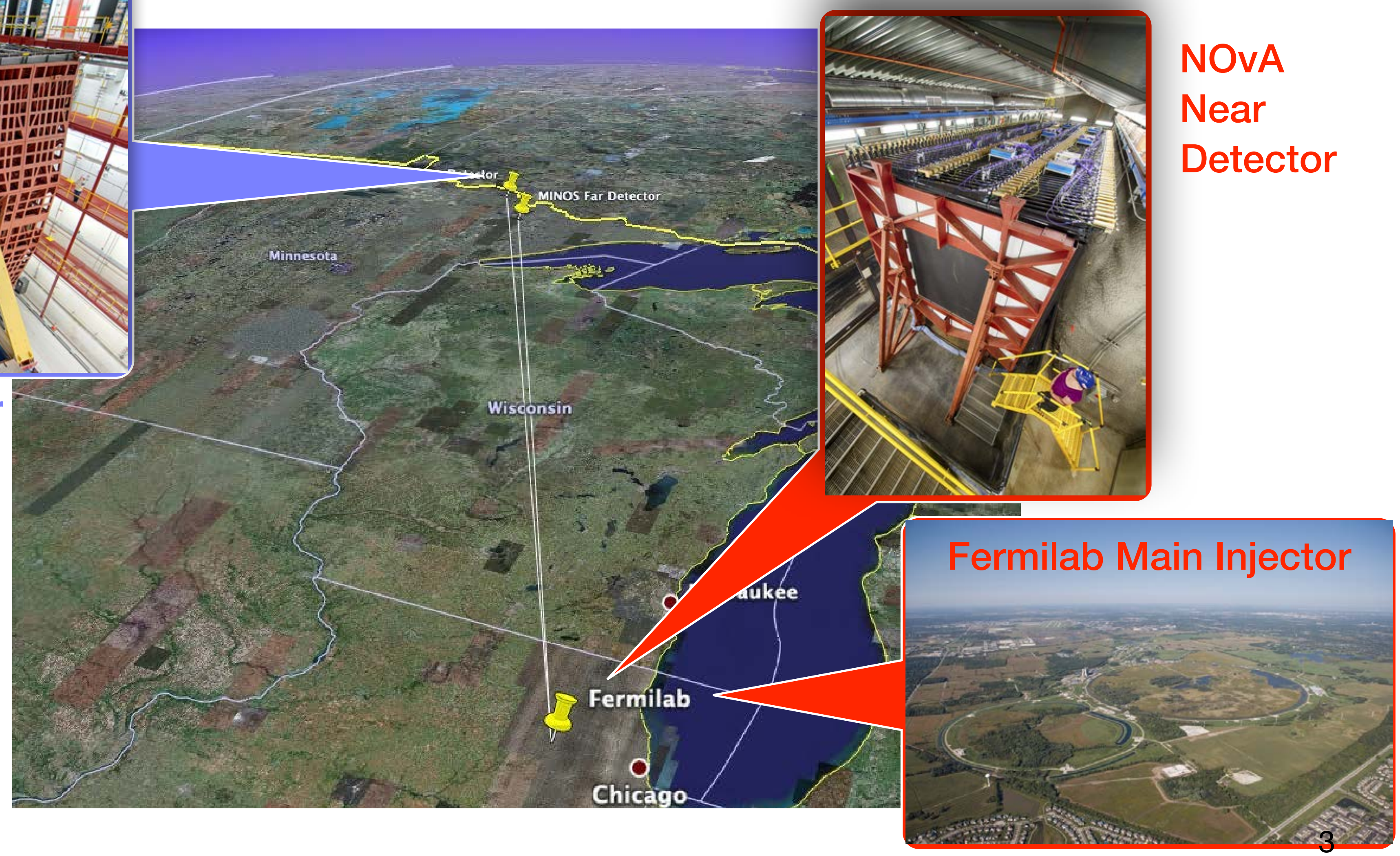
Super-Kamiokande
(ICRR, Univ. Tokyo)

$E_\nu \simeq 0.7$ GeV,

$$\Delta \equiv \frac{1.27 \cdot 0.0025\ \mathrm{eV}^2 \cdot 295\ \mathrm{km}}{0.7\ \mathrm{GeV}} \simeq \frac{\pi}{2}$$

NOvA

NOvA Far Detector



$E_\nu \simeq 2$ GeV,

$$\Delta \equiv \frac{1.27 \cdot 0.0025\ \mathrm{eV}^2 \cdot 810\ \mathrm{km}}{2\ \mathrm{GeV}} \simeq \frac{\pi}{2}$$

Neutrino oscillations at long baseline

Following presentation by Nunokawa, Parke, Valle, in "CP Violation and Neutrino Oscillations", Prog.Part.Nucl.Phys. 60 (2008) 338-402. arXiv:0710.0554 [hep-ph]

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - 4\cos^2\theta_{13}\sin^2\theta_{23}\left[1-\cos^2\theta_{13}\sin^2\theta_{23}\right]\sin^2\Delta_{3i}$$
$$\simeq 1 - \sin^2 2\theta_{23}\sin^2\Delta_{3i}$$

$$P(\nu_\mu \to \nu_e) \simeq |\sqrt{P_{\rm atm}}e^{-i(\Delta_{32}+\delta)} + \sqrt{P_{\rm sol}}|^2$$
$$= P_{\rm atm} + P_{\rm sol} + 2\sqrt{P_{\rm atm}P_{\rm sol}}\,(\cos\Delta_{32}\cos\delta \mp \sin\Delta_{32}\sin\delta)$$

$$\sqrt{P_{\rm atm}} = \sin\theta_{23}\sin 2\theta_{13}\frac{\sin(\Delta_{31}\mp aL)}{\Delta_{31}\mp aL}\Delta_{31}$$

$$\sqrt{P_{\rm sol}} = \cos\theta_{23}\sin 2\theta_{12}\frac{\sin(aL)}{aL}\Delta_{21}$$

$$a = G_F N_e/\sqrt{2} \simeq \frac{1}{3500\ \rm km}$$

$aL = 0.08$ for $L = 295$ km
$aL = 0.23$ for $L = 810$ km
$aL = 0.37$ for $L = 1300$ km

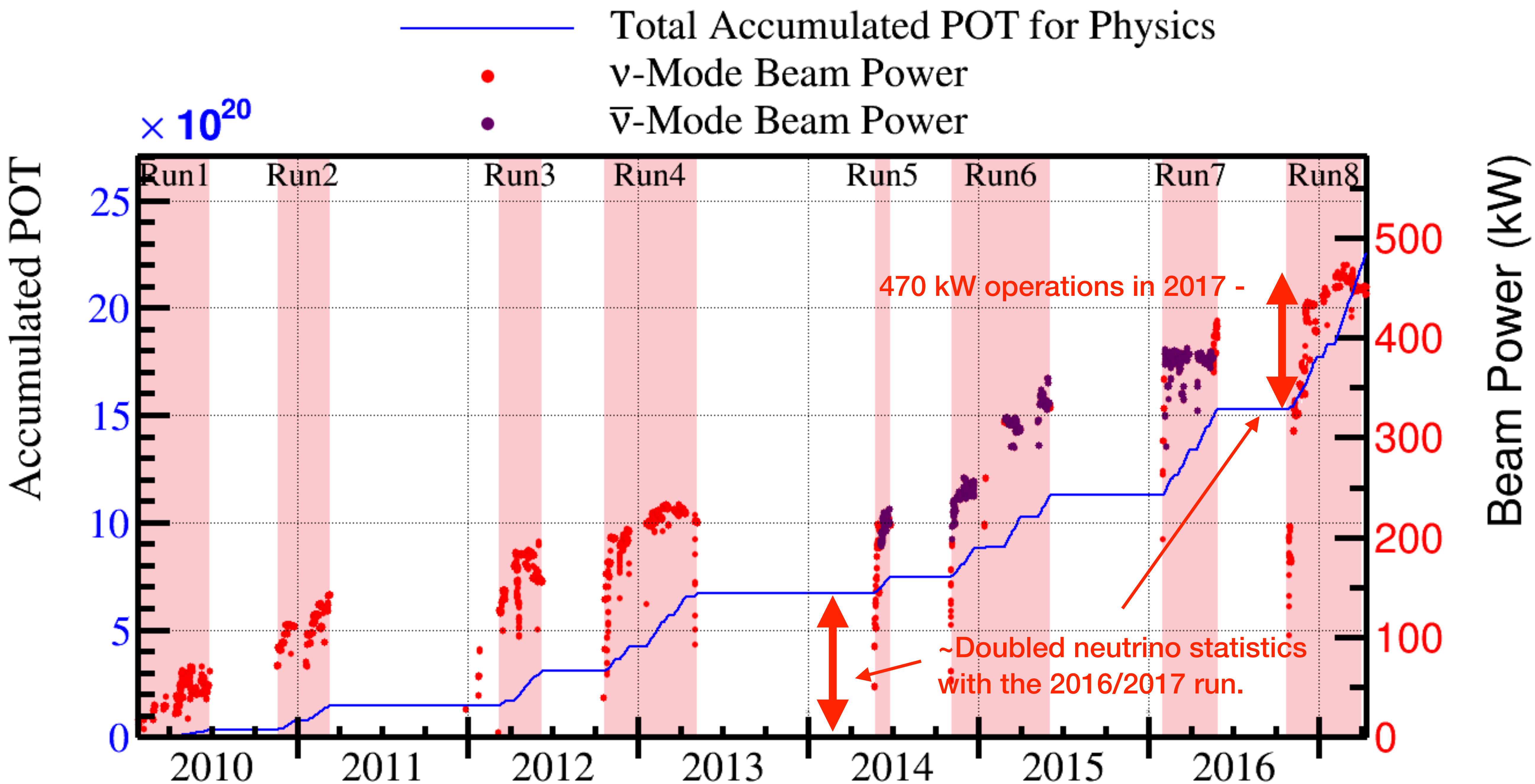
Parameter	Channels	Question
$\sin^2 2\theta_{23}$:	$\nu_\mu \to \nu_\mu$ and $\bar\nu_\mu \to \bar\nu_\mu$:	Is θ_{23} maximal?
$\sin^2\theta_{23}\sin^2 2\theta_{13}$:	$\nu_\mu \to \nu_e$ and $\bar\nu_\mu \to \bar\nu_e$:	Octant of θ_{23}
$\mathrm{sign}\,[\Delta_{31}]$:	$\nu_\mu \to \nu_e$ vs. $\bar\nu_\mu \to \bar\nu_e$:	Neutrino mass hierarchy
$\delta_{\rm CP}$:	$\nu_\mu \to \nu_e$ vs. $\bar\nu_\mu \to \bar\nu_e$:	Is CP violated?

Summary of sensitivity of $\nu_\mu \rightarrow \nu_e$ rates to physics parameters

Factor	Type	Inverts for $\bar{\nu}$?	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:

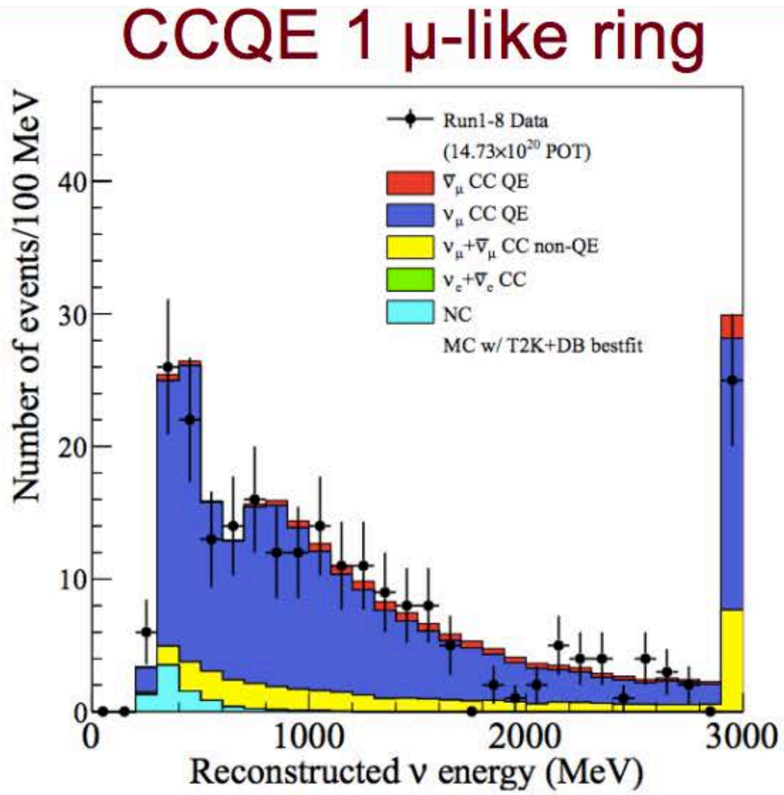
- Calculations are for rate only; there is some additional information in the energy spectrum
- These estimates neglect non-linearities in combining different effects
- In the calculation of the matter effect and CP violation effects the calculated values account for the fact that T2K runs at an energy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

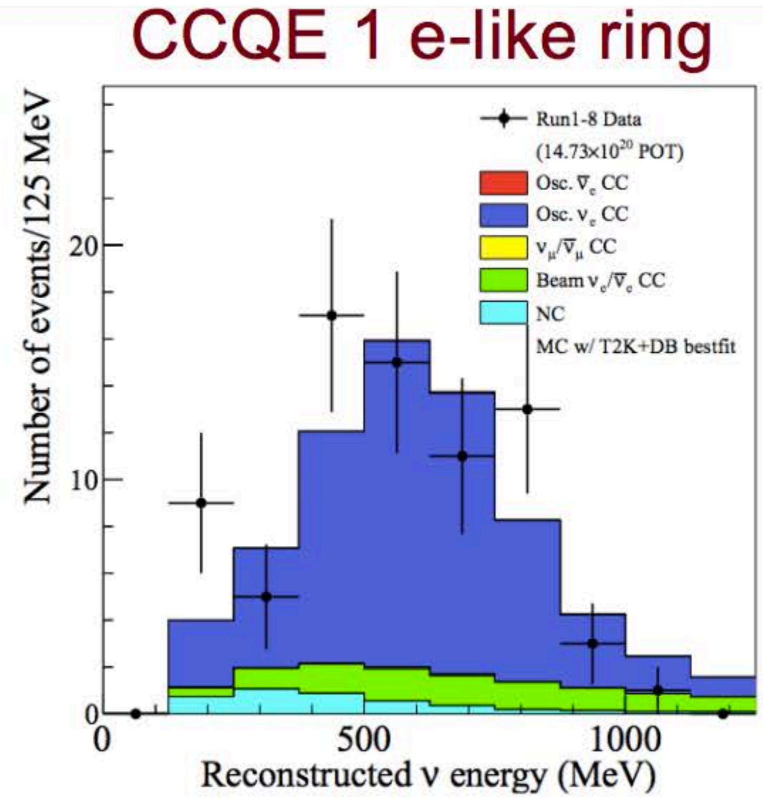


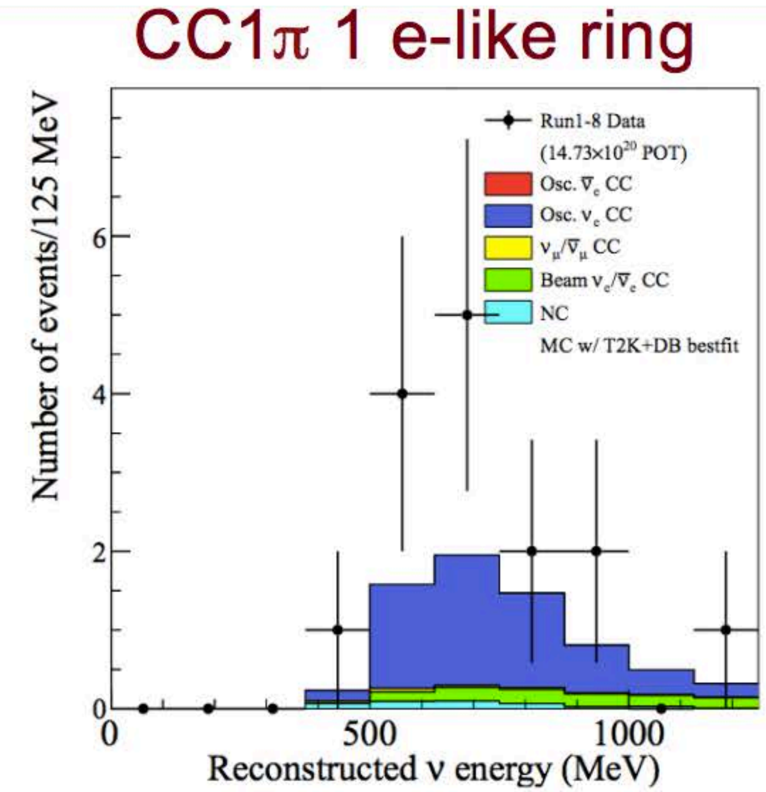
T2K Beam Delivery

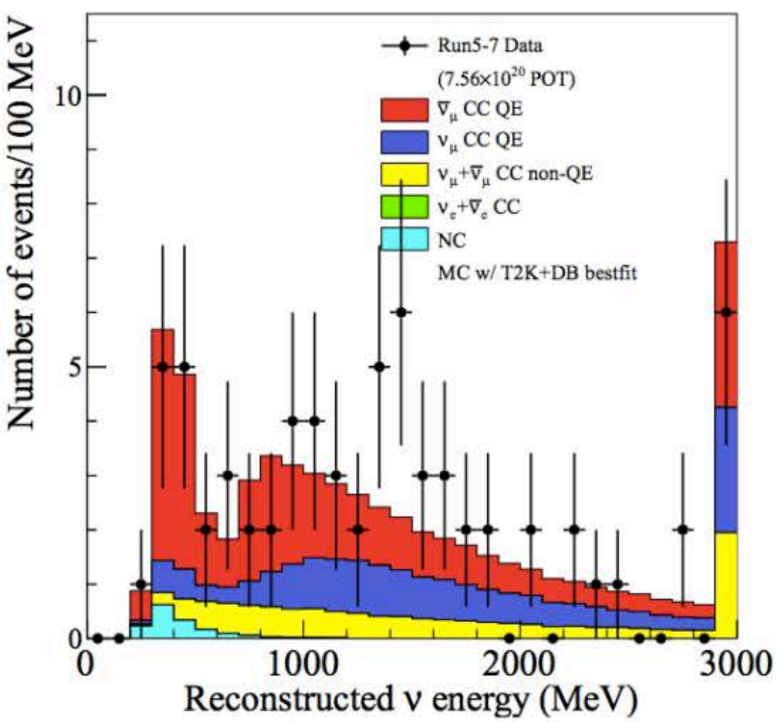
14.7E20 POT in neutrino mode

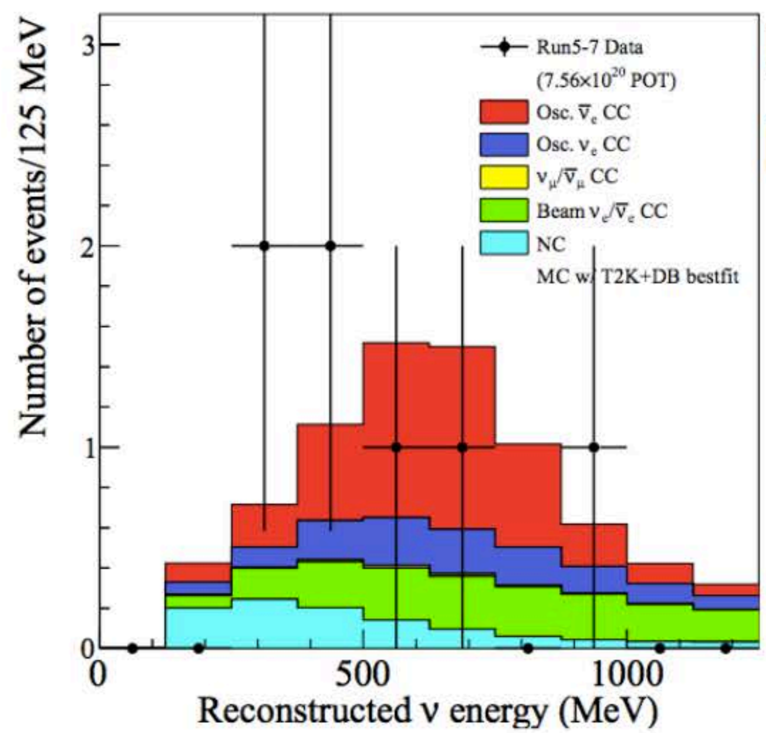
7.6E20 POT in antineutrino mode











Upper panels: nu-mode

Lower panels: antinu-mode

T2K Preliminary

https://www.t2k.org/docs/talk/282

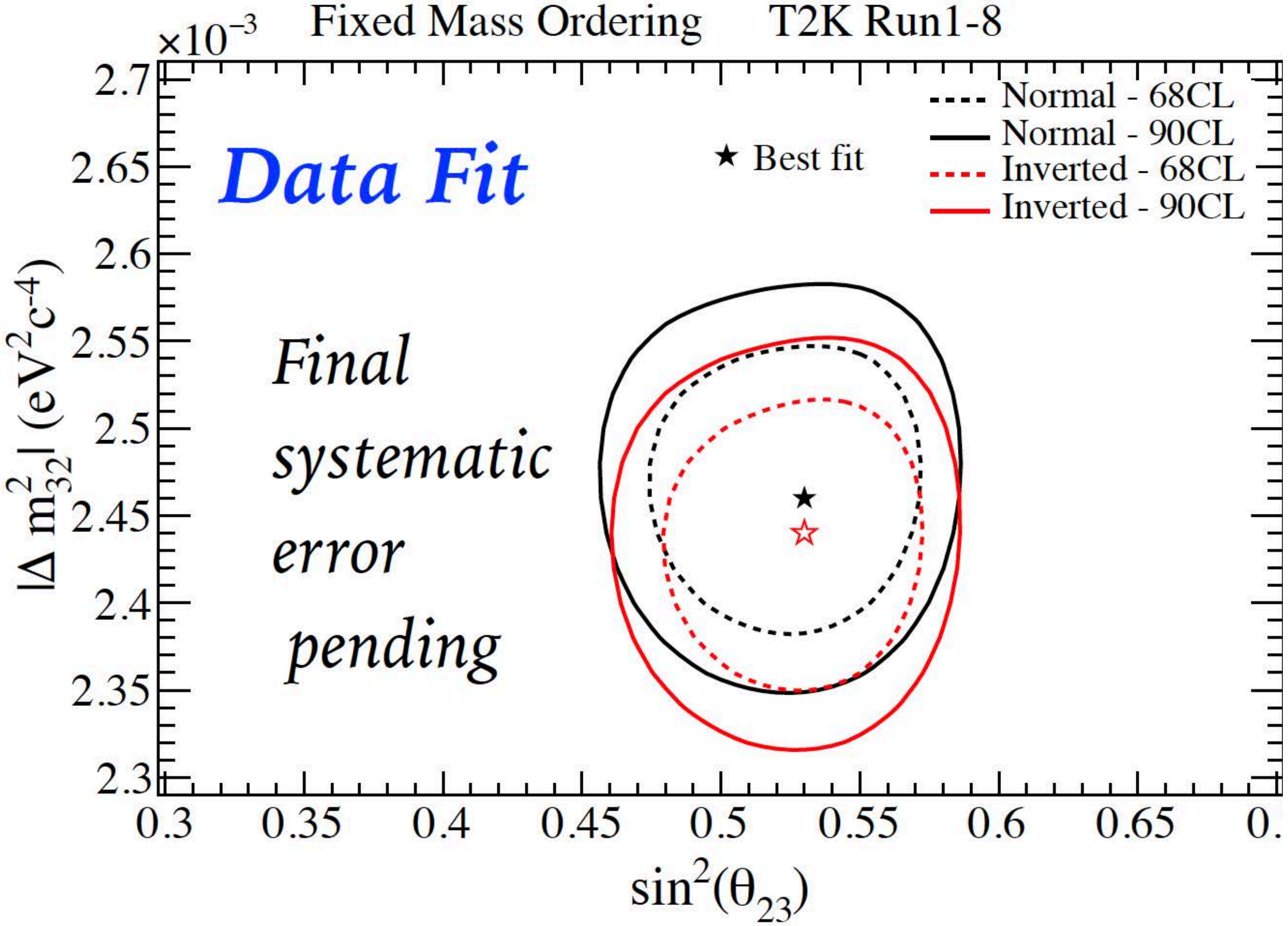
T2K Event Distributions

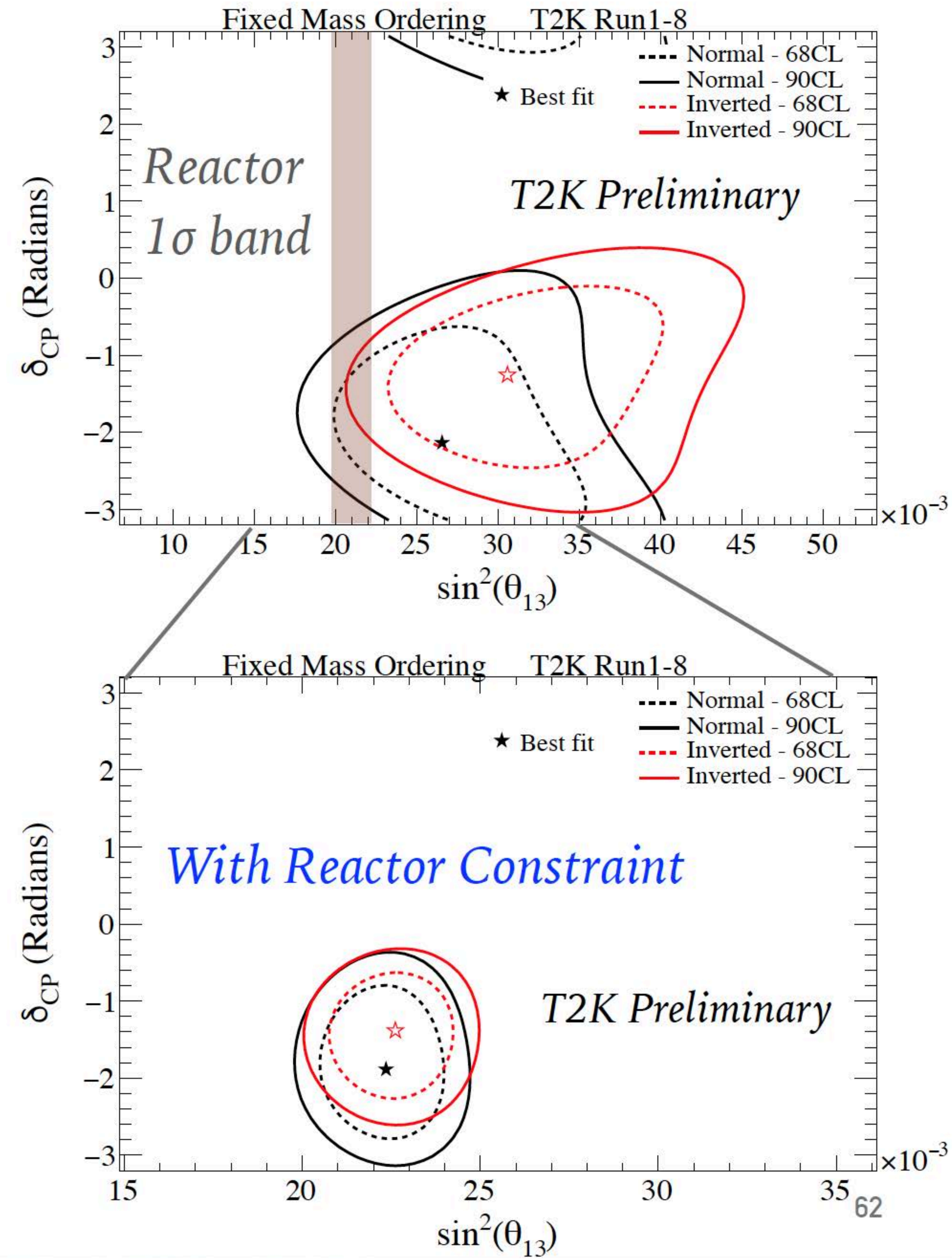
Use of new analysis tools “fiTQun” has increased efficiency and purity of existing samples, allowed for an expansion of fiducial volume, and enabled addition of new sample to the appearance search - produces an effective 30% increase statistics.

T2K Expected and Observed Event Counts

	Predicted Rates				Observed
Sample	$\delta_{cp}=-\pi/2$	$\delta_{cp}=0$	$\delta_{cp}=\pi/2$	$\delta_{cp}=\pi$	Rates
CCQE 1-Ring e-like FHC	73.5	61.5	49.9	62.0	74
CC1π 1-Ring e-like FHC	6.92	6.01	4.87	5.78	15
CCQE 1-Ring e-like RHC	7.93	9.04	10.04	8.93	7
CCQE 1-Ring μ-like FHC	267.8	267.4	267.7	268.2	240
CCQE 1-Ring μ-like RHC	63.1	62.9	63.1	63.1	68

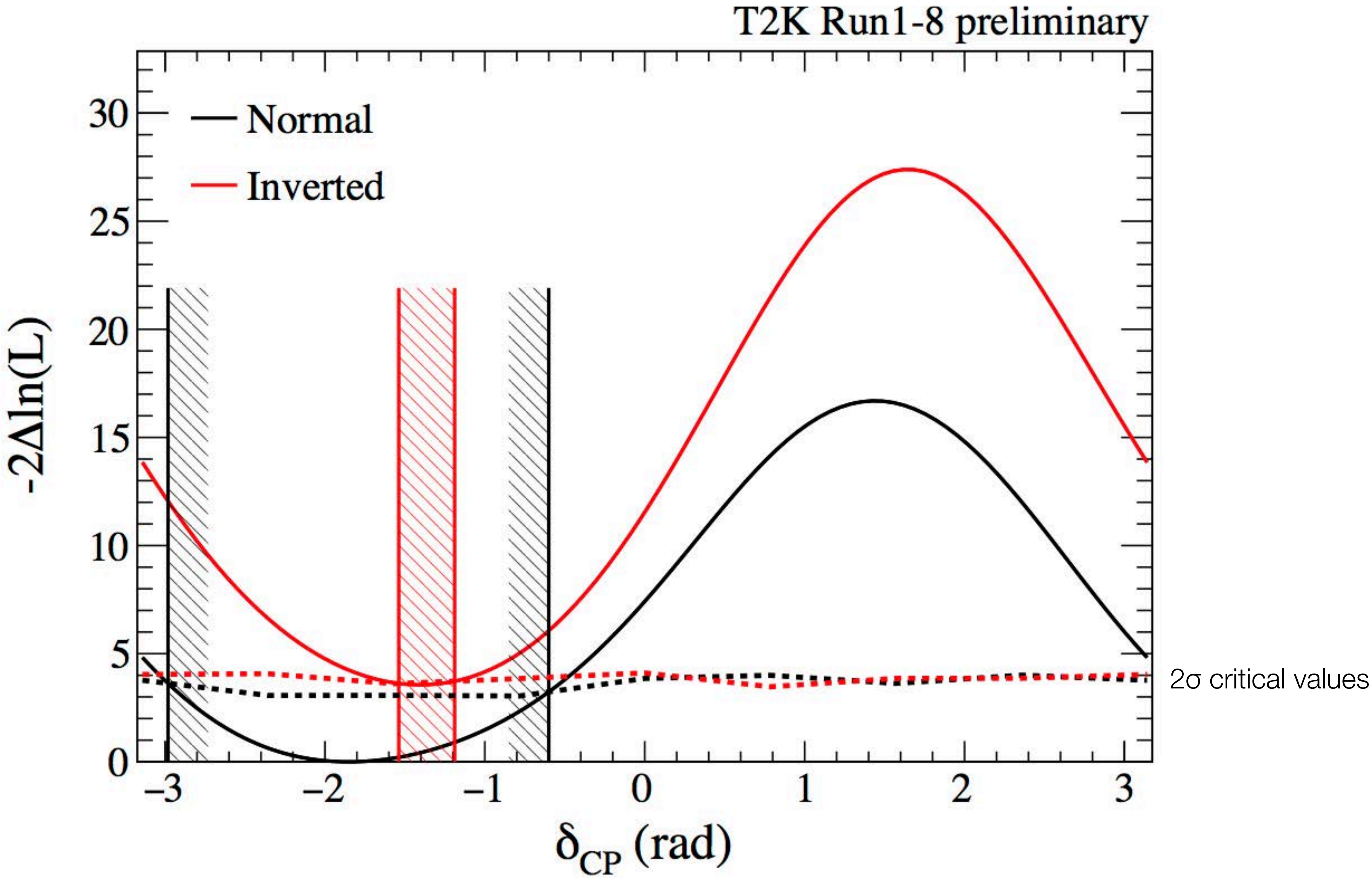
- Event counts favor $\delta_{CP} = -\pi/2$ ($3\pi/2$)
- Excess in the CC1π 1-Ring e-like: 7 expected 15 observed causes results to exceed what is expected from sensitivities.
- P-value for 7 fluctuating to 15 is ~2%; about 12% of random samples have a fluctuation this large in at least one of the 5 samples.





Latest T2K Results

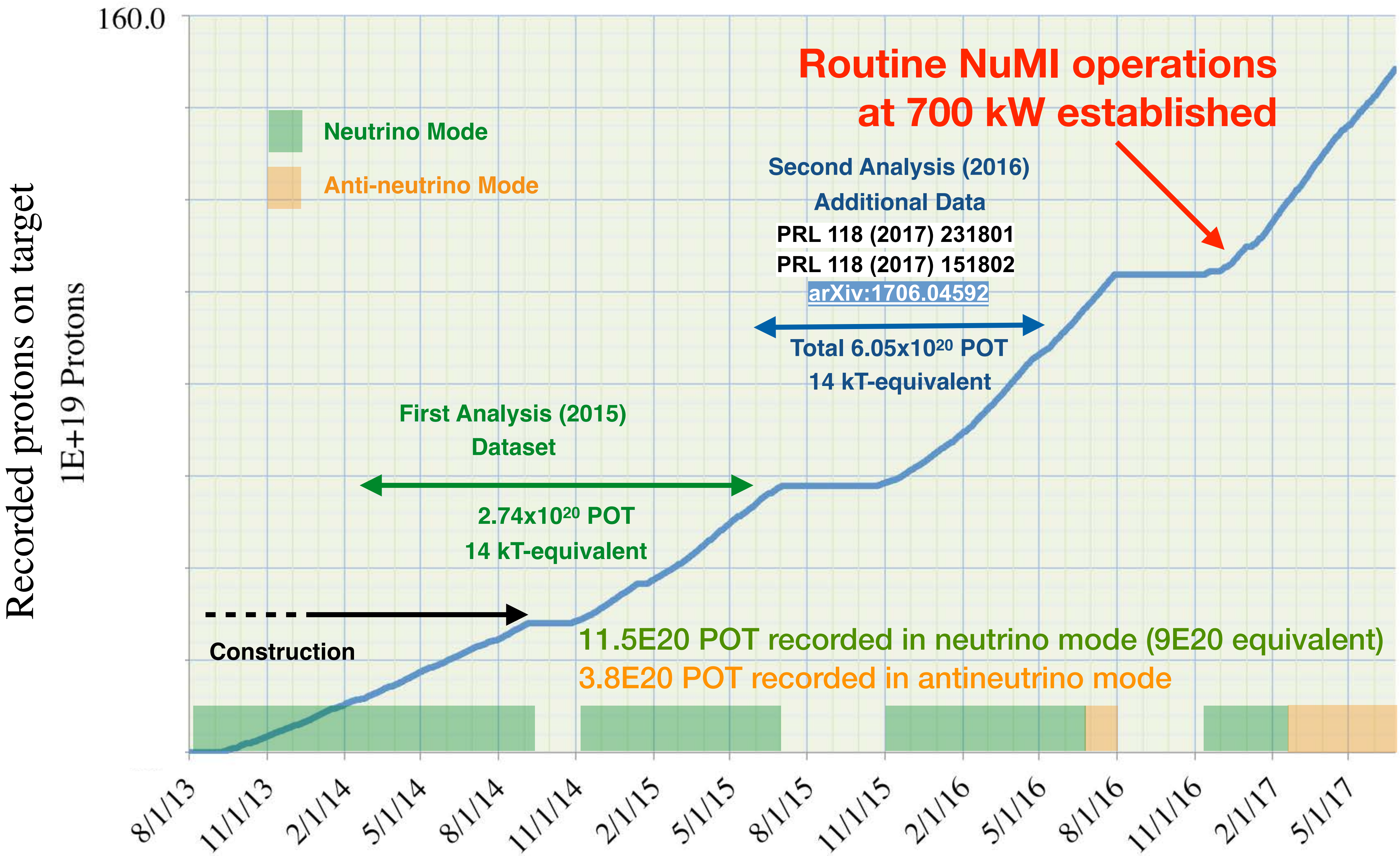
https://www.t2k.org/docs/talk/282



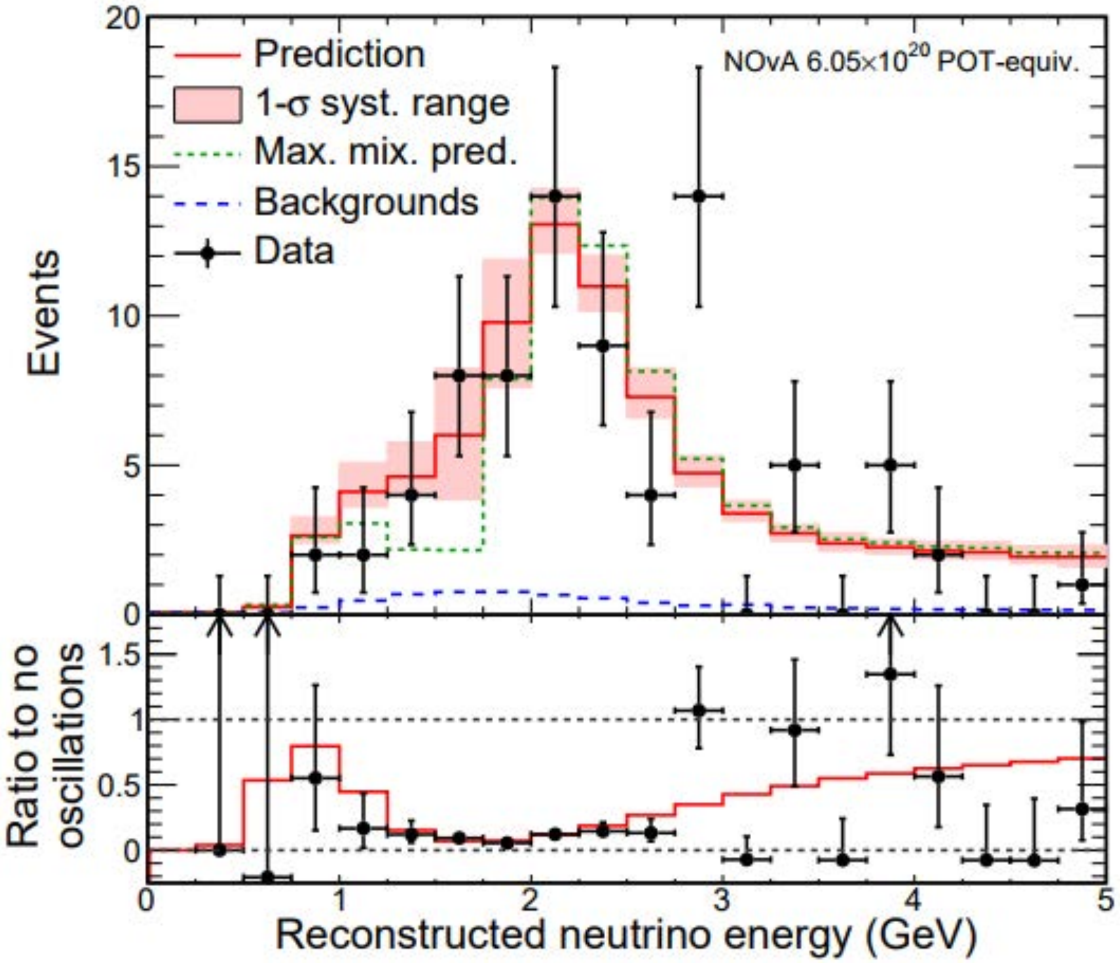
T2K Measurement of δ_{CP}

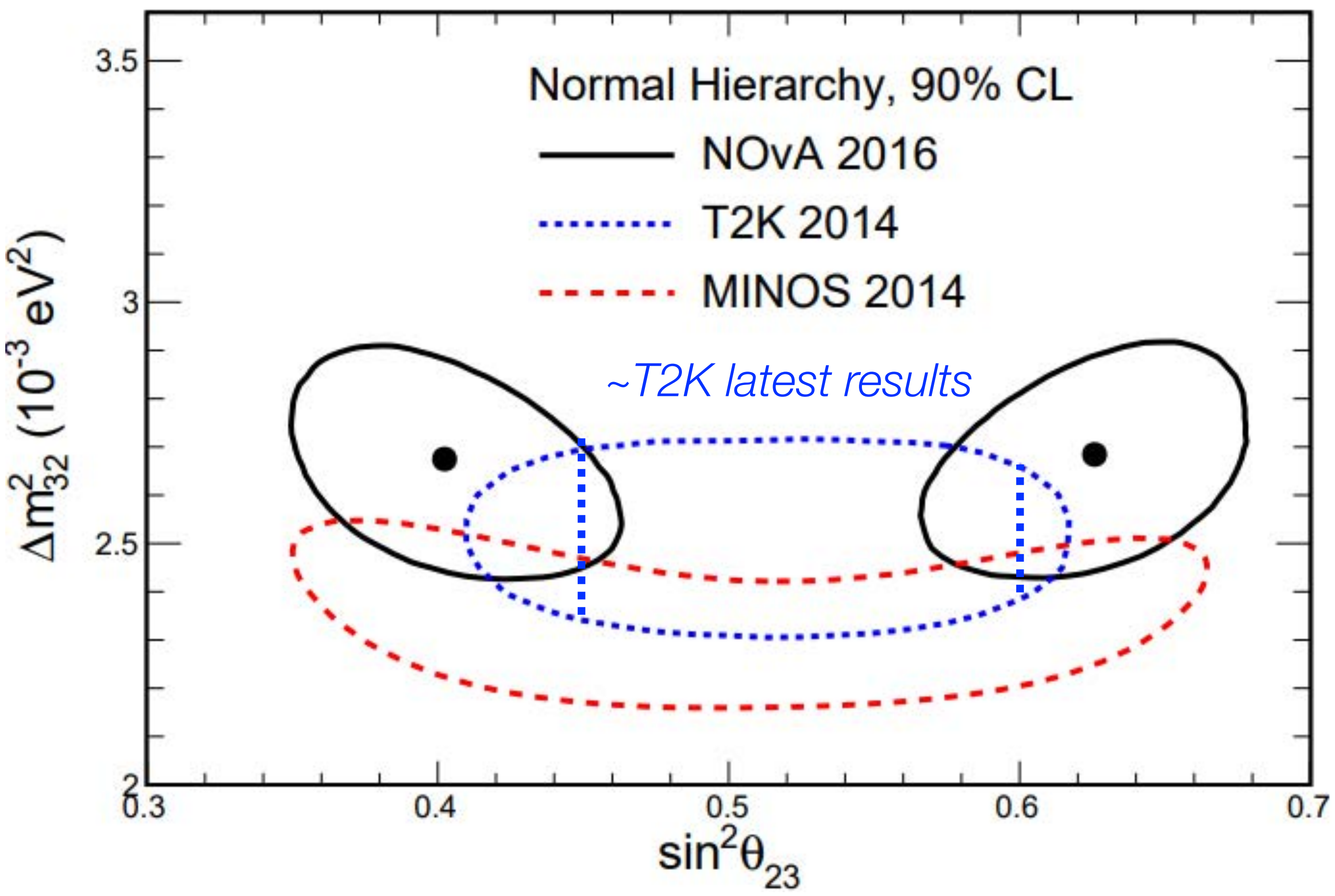
Best fit for nearly maximal value of CP violation, $\delta_{CP}=-\pi/2$
CP conserving values of $\delta_{CP}=0, \pi$ are excluded at 2σ

NOvA Data-taking history



NOvA Muon Neutrino Disappearance





- Based on extrapolation from near detector, expect 473±30 events before oscillations
- **Observe 78 ν_μ charged-current events.**
- Predict 3.9 events of beam backgrounds and 2.9 events from cosmic-ray backgrounds

$$\sin^2\theta_{23} = 0.404^{+0.030}_{-0.022},\quad 0.624^{+0.022}_{-0.030}\quad (68\%\mathrm{C.L.})$$
$$\Delta m^2_{32} = (+2.67 \pm 0.12)\times 10^{-3}\ \mathrm{eV}^2$$

- Find two degenerate best-fits in the upper and lower θ23 octant
- Maximal mixing disfavored at 2.6σ

NOvA Electron Neutrino Appearance Results

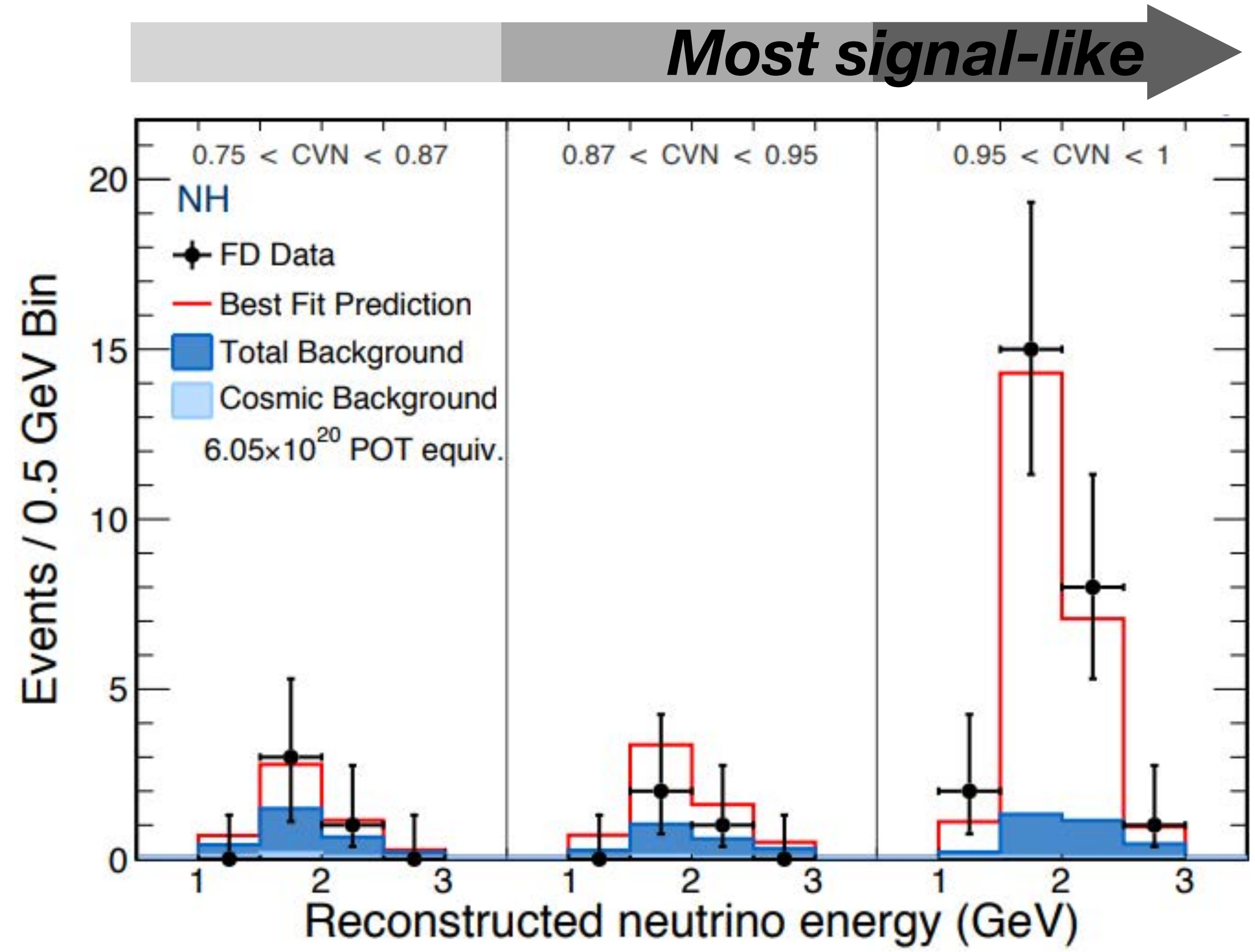
Observed	**33**
NH, δCP=3π/2	36.4
IH, δCP=π/2	19.4
Total Background	**8.2±0.8**
NC	3.7
Beam ν_e CC	3.1
ν_μ CC	0.7
ν_τ CC	0.1
Cosmic	0.5

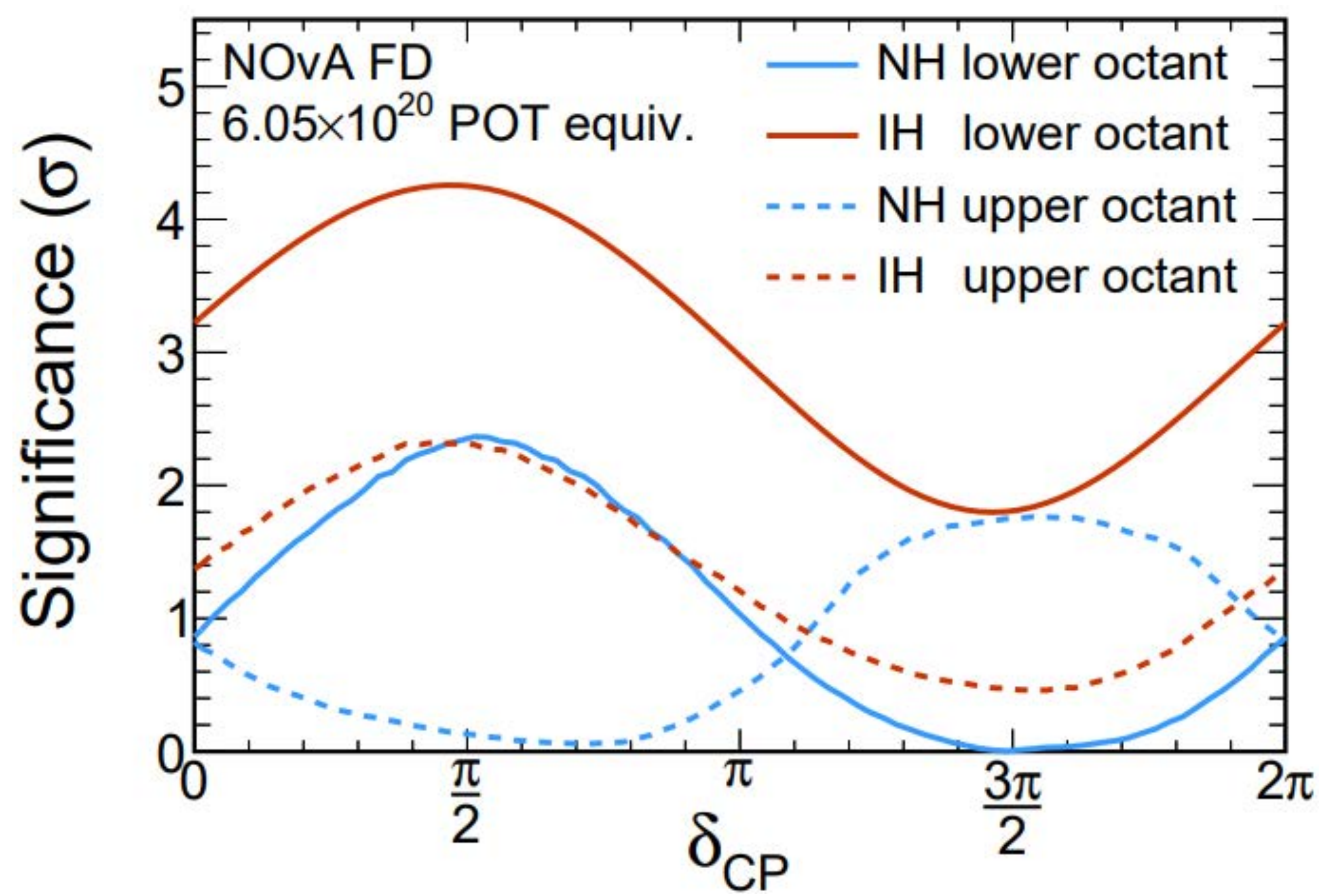
Event counts for 6E20 protons-on-target exposure.

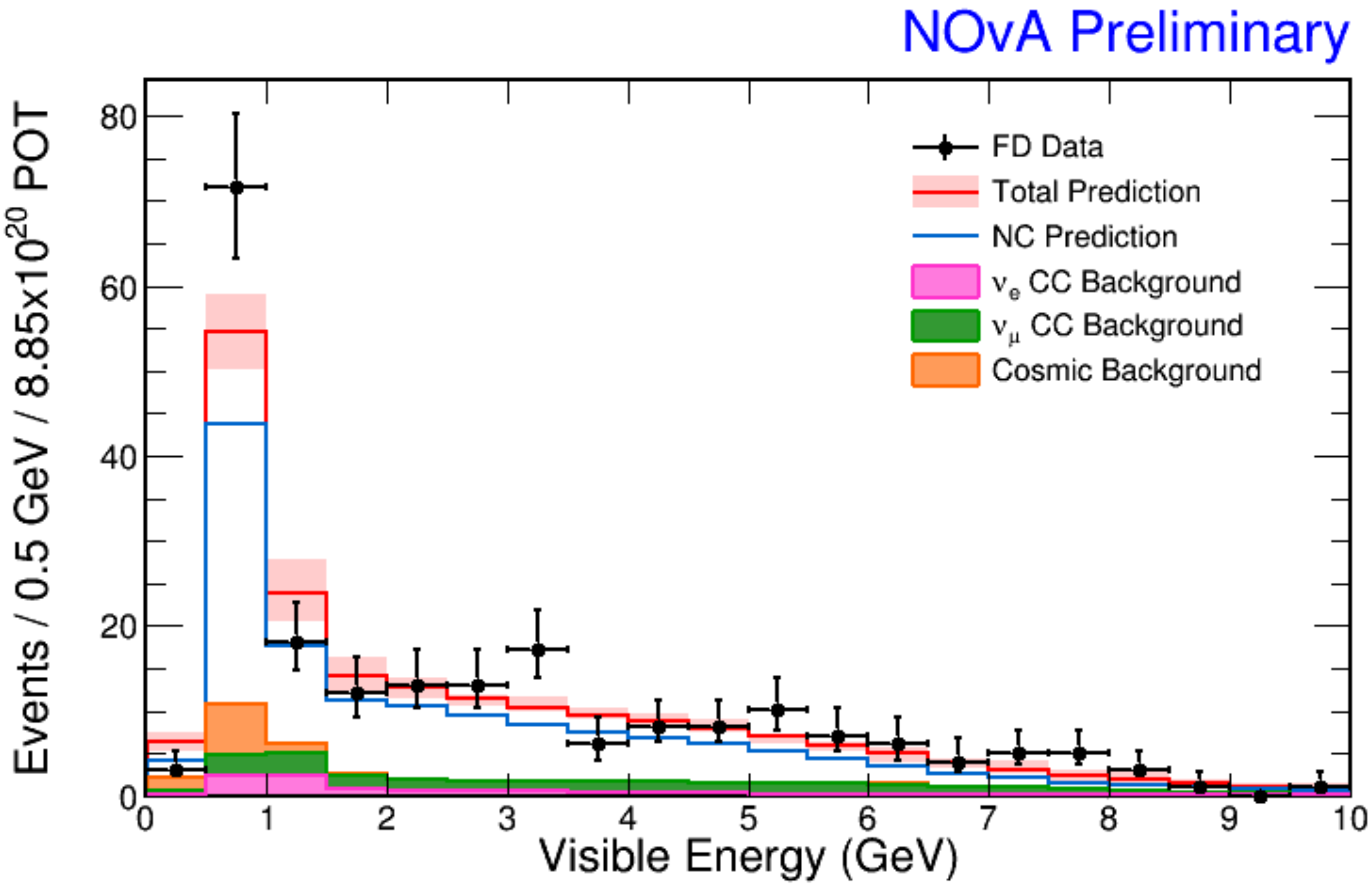
Cutting down on the allowed combinations of oscillation parameters.

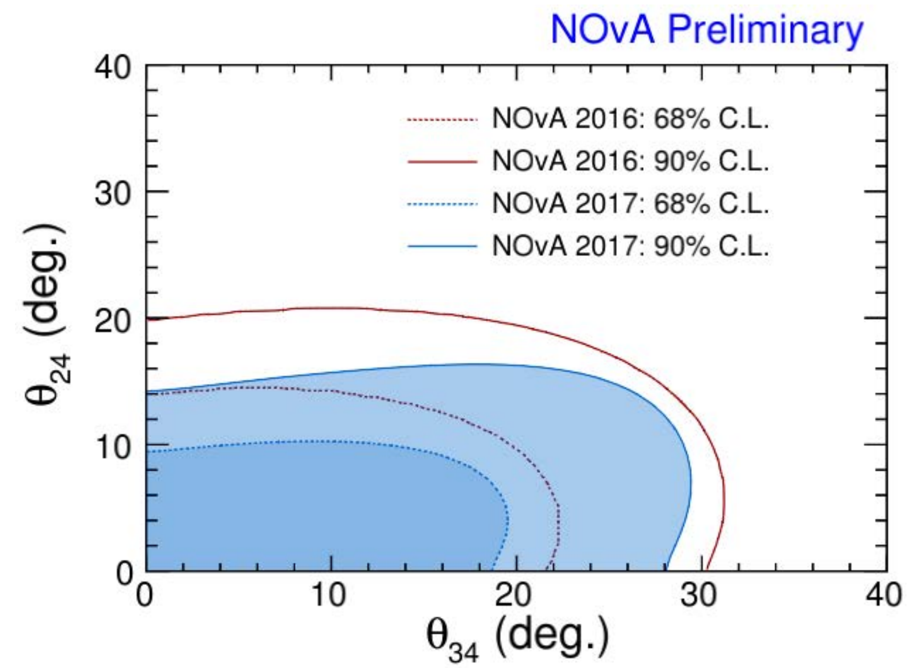
Combination of inverted hierarchy+lower θ_{23} octant is everywhere rejected at >93% C.L.

Phys. Rev. Lett. **118**, 231801 – Published 5 June 2017





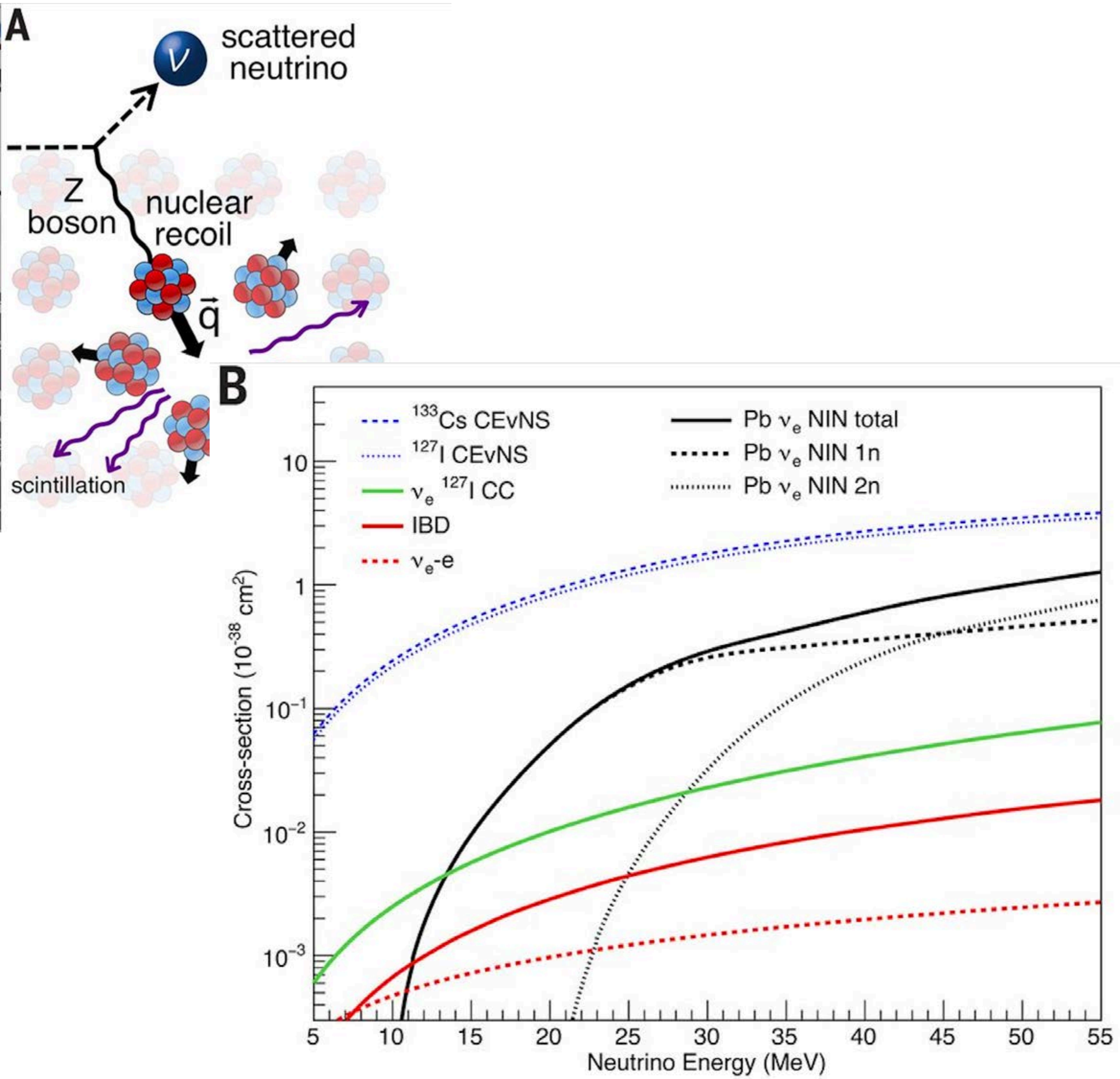


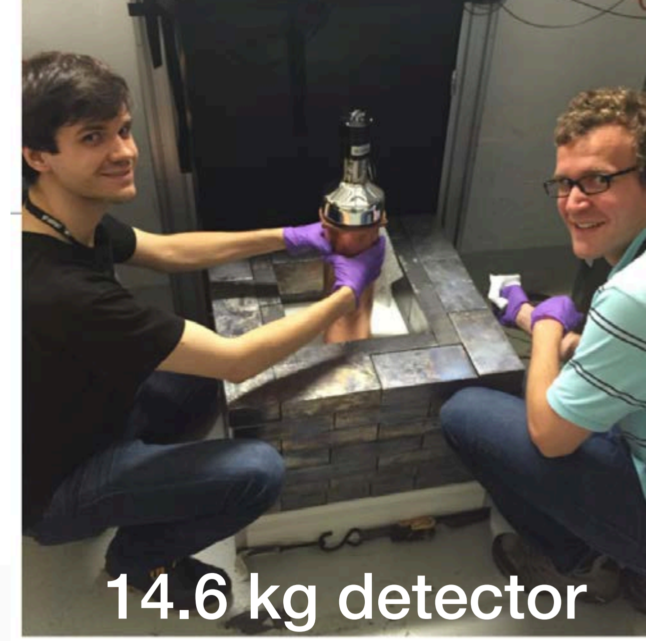


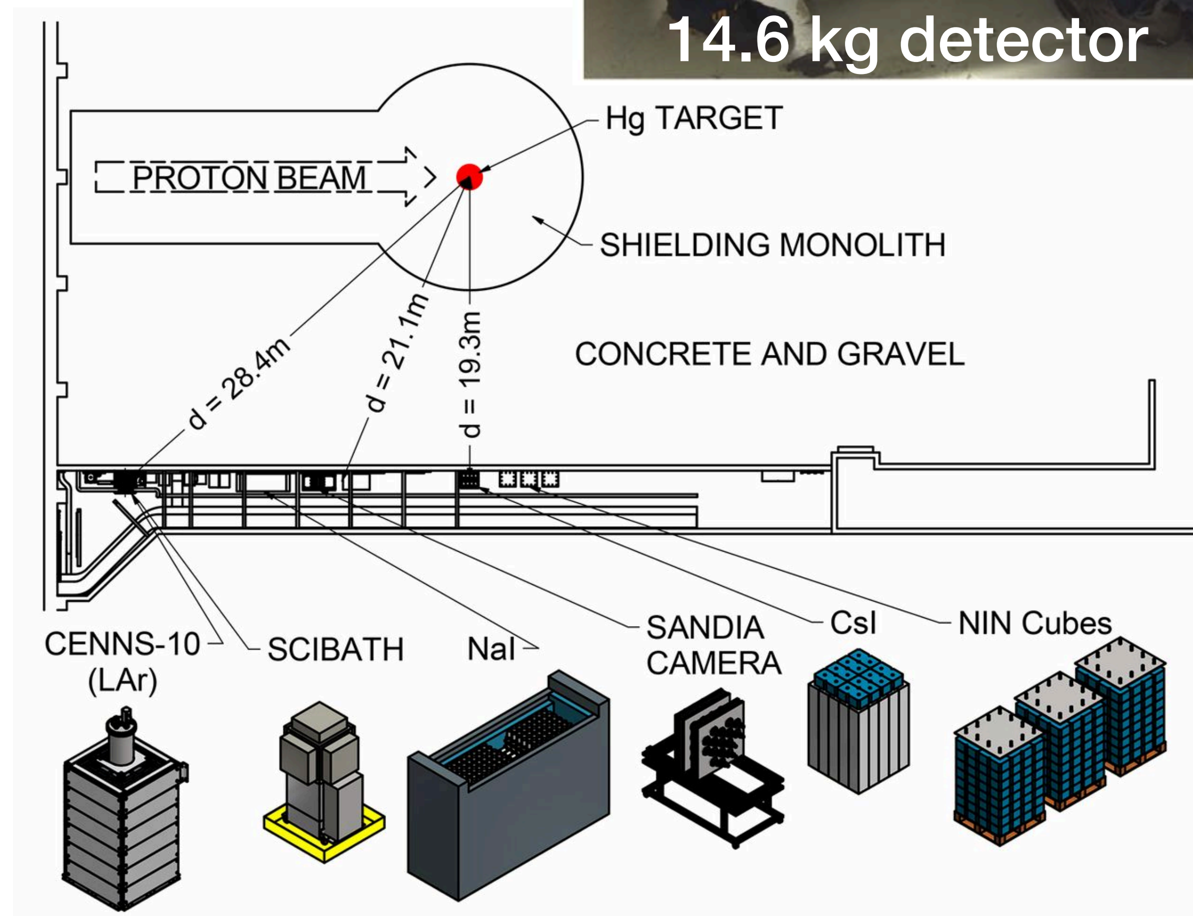
- Standard PMNS neutrino oscillations are expected to modify the flavor content of the beam at the far detector but leave the total neutrino flux unchanged.
- Neutral-current provide a way to measure the total active neutrino flux and search for non-standard oscillations; for example oscillations to a new “sterile” neutrino state.
- We see 214 NC events at the far detector with an expectation of 191. No deficit observed limiting the mixing of active and sterile neutrinos.

NOvA Neutral-Current Spectrum

First 9e20 results shown earlier today in Sweden.







1.4 MW Source
$2x10^{23}$ delivered POT since 2015

REPORT

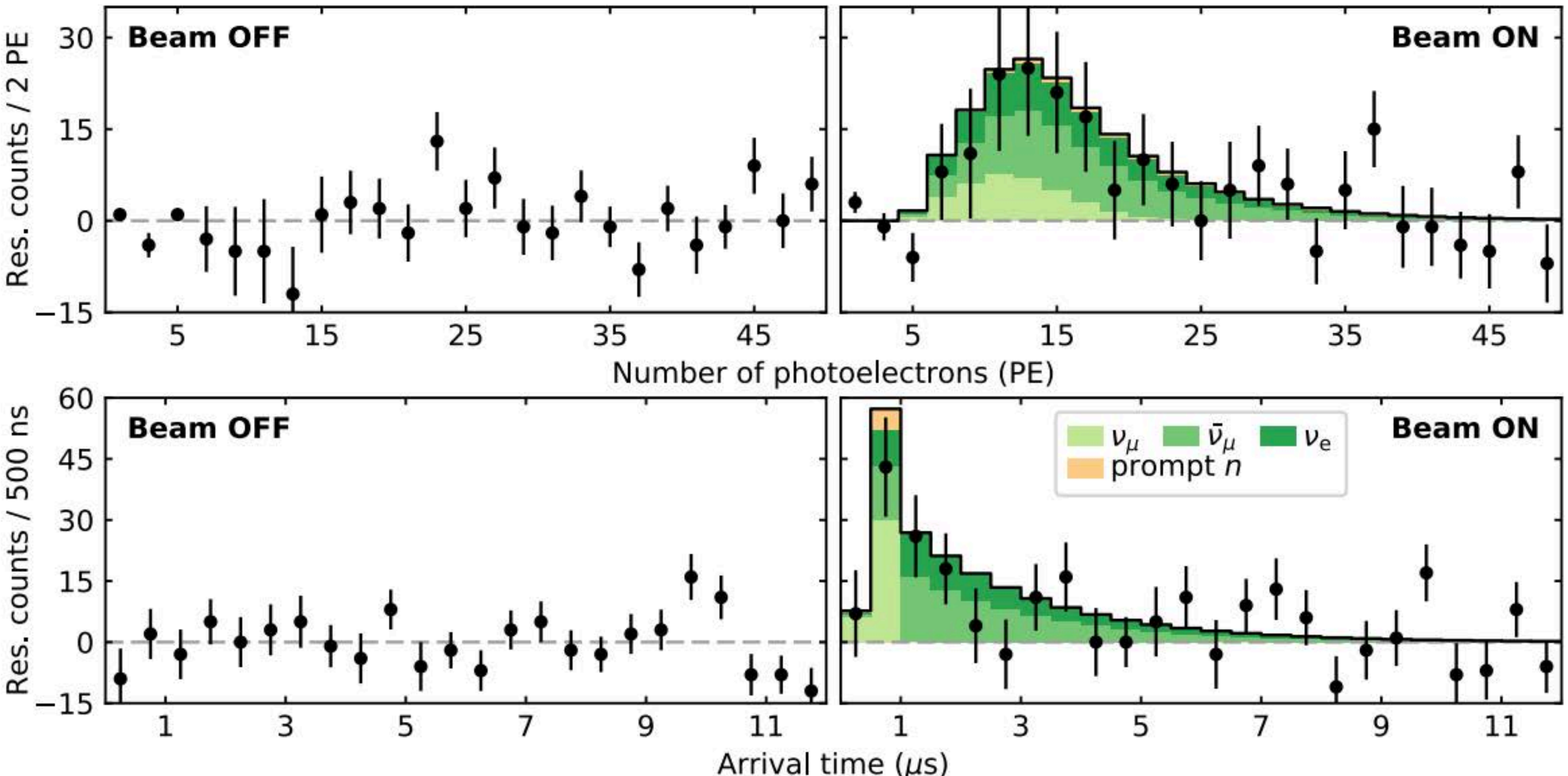
Observation of coherent elastic neutrino-nucleus scattering

D. Akimov[1,2], J. B. Albert[3], P. An[4], C. Awe[4,5], P. S. Barbeau[4,5], B. Becker[6], V. Belov[1,2], A. Brown[4,7], A. Bolozdynya[2], B. Cabrera-...
+ See all authors and affiliations

Science 03 Aug 2017:
eaao0990
DOI: 10.1126/science.aao0990

Peer Reviewed
← see details

In other news from DPF



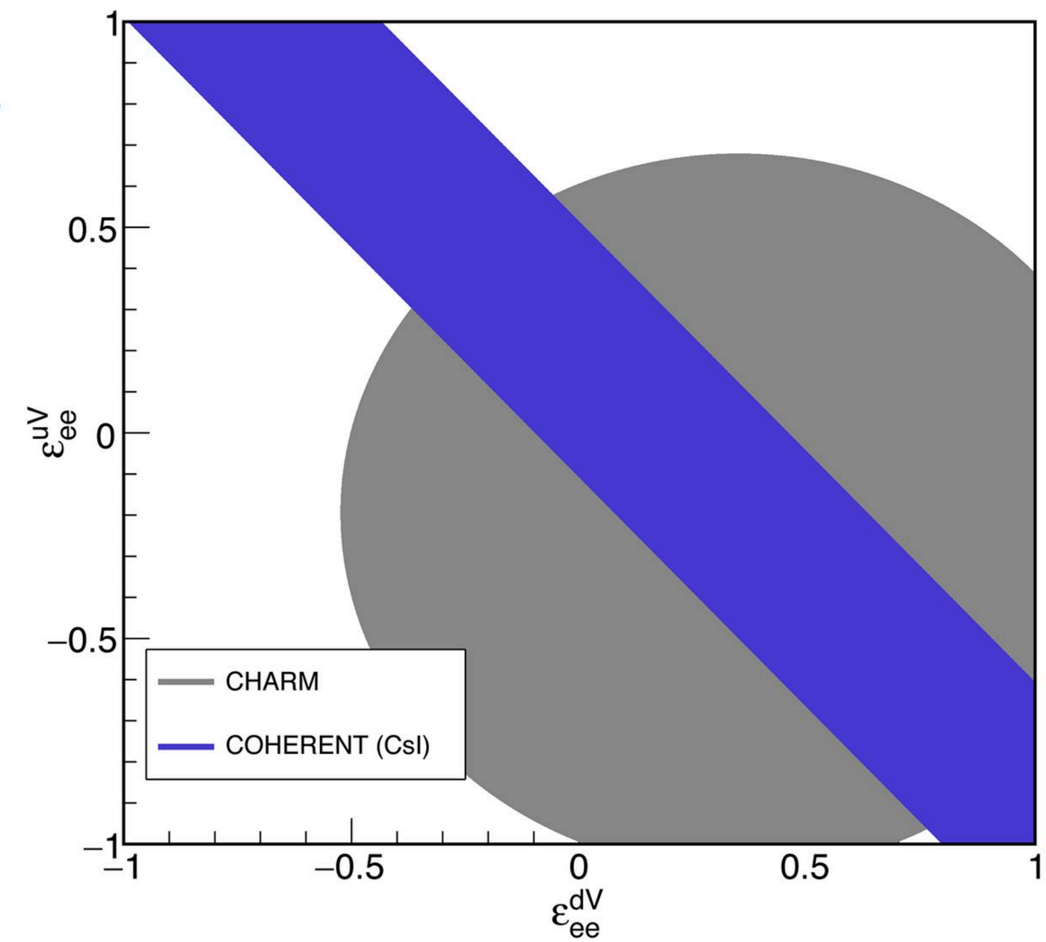
6.7σ observation

D. Akimov et al., Science 10.1126/science.aao0990 (2017).

Constraints on non-standard interactions of neutrinos and quarks

$$\left(\frac{d\sigma}{dE}\right)_{\nu_\alpha A} = \frac{G_F^2 M}{\pi} F^2(2\,\mathrm{ME})\left[1-\frac{ME}{2k^2}\right] \times \{[Z(g_V^p+2\varepsilon_{\alpha\alpha}^{uV}+\varepsilon_{\alpha\alpha}^{dV})+N(g_V^n+\varepsilon_{\alpha\alpha}^{uV}+2\varepsilon_{\alpha\alpha}^{dV})]^2 + \sum_{\alpha\neq\beta}[Z(2\varepsilon_{\alpha\beta}^{uV}+\varepsilon_{\alpha\beta}^{dV})+N(\varepsilon_{\alpha\beta}^{uV}+2\varepsilon_{\alpha\beta}^{dV})]^2\},$$

90% C.L.



Deep Learning Applications

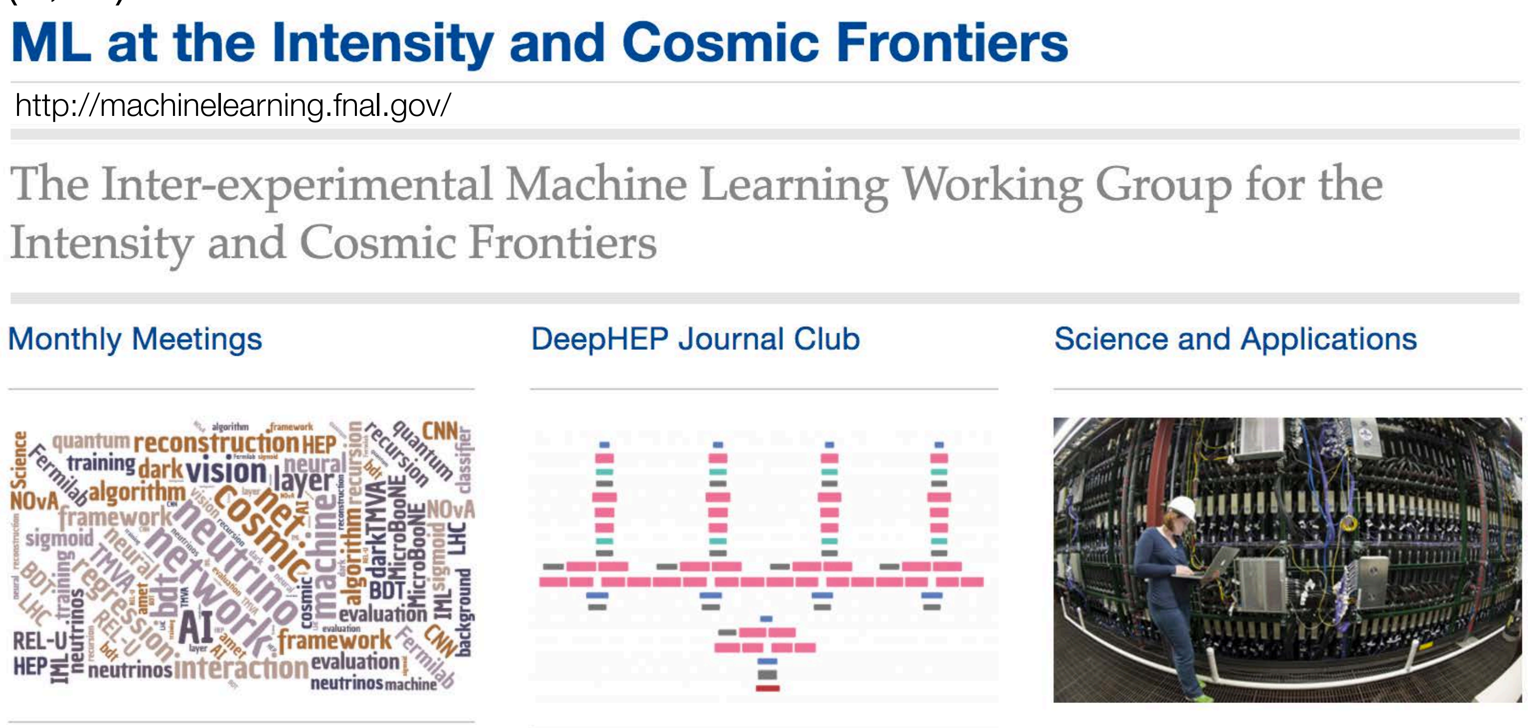
(I) The field of computer vision has made tremendous progress using convolutional neural networks and deep learning algorithms to solve problems of clustering and categorization.

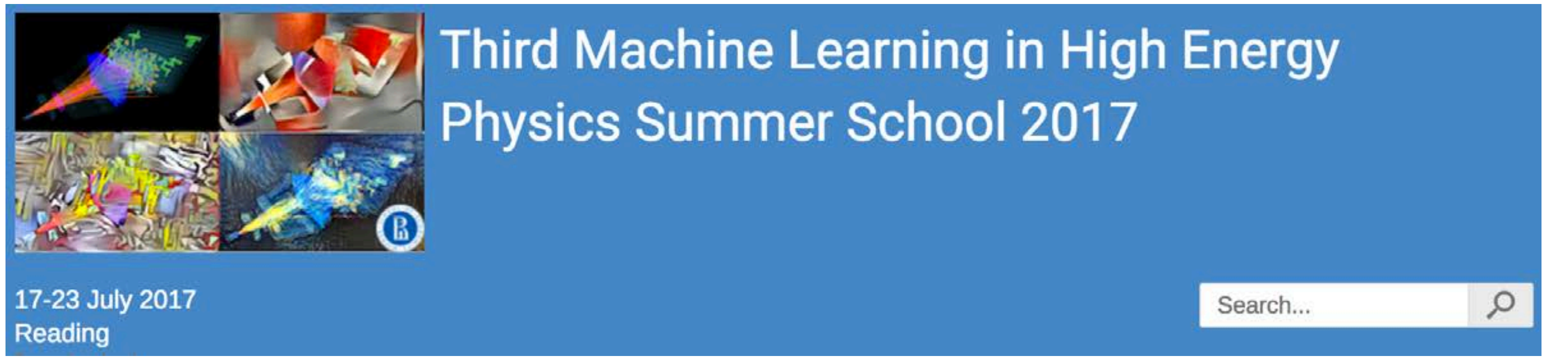
(II) There is lots of interest in the HEP and Cosmic Frontier communities to leverage these advances for our problems of reconstruction and categorization.

(III) On the intensity frontier, researchers from the NOvA and MicroBooNE have been on the forefront.

(IV) There is a lot of top-down and bottom-up organizational activities on-going throughout the community.

(II,IV)





Applications of Convolutional Neutral Networks and Deep Learning to the Intensity Frontier

NOvA

- CVN-based event classification is used to categorize events as cosmic-ray, neutral-current, νe-charged-current, νμ-CC, and ντ-CC.
- CVN-based algorithms contributed one of the most important improvements in our recent electron neutrino appearance results; equivalent to a 30% increase in statistics.
- Now exploring impacts of these methods elsewhere in reconstruction: clustering, prong-by-prong particle identification, and energy estimation.

MicroBooNE

- Potential for applications to highly-granular liquid argon TPC detectors is huge and is being vigorously explored.

A convolutional neural network neutrino event classifier

A. Aurisano[a], A. Radovic[b], D. Rocco[c], A. Himmel[d], M.D. Messier[e], E. Niner[d], G. Pawloski[c], F. Psihas[e], A. Sousa[a] and P. Vahle[b]

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Journal of Instrumentation, Volume 11, September 2016

Editors' Suggestion

Constraints on Oscillation Parameters from ν_e Appearance and ν_μ Disappearance in NOvA

P. Adamson *et al.* (NOvA Collaboration)

Phys. Rev. Lett. **118**, 231801 – Published 5 June 2017

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arXiv.org > hep-ex > arXiv:1706.04592

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High Energy Physics – Experiment

Search for active-sterile neutrino mixing using neutral-current interactions in NOvA

NOvA Collaboration: P. Adamson, L. Aliaga, D. Ambrose, N. Anfimov, A. Antoshkin, E. Arrieta-Diaz, K. Augsten, A.

Convolutional neural networks applied to neutrino events in a liquid argon time projection chamber

R. Acciarri[g], C. Adams[z], R. An[h], J. Asaadi[w], M. Auger[a], L. Bagby[g], B. Baller[g], G. Barr[q], M. Bass[q], F. Bay[x] +Show full author list

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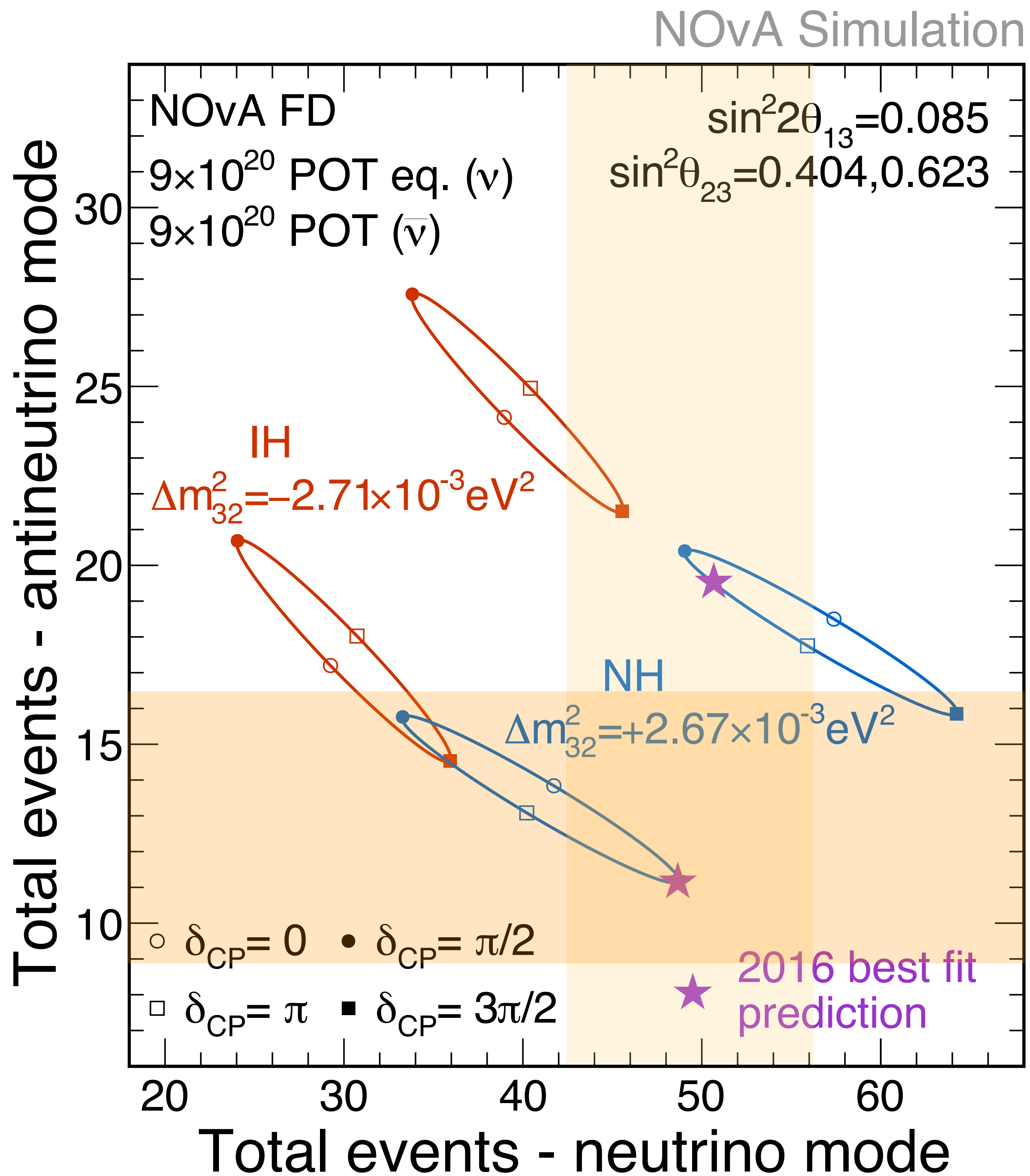


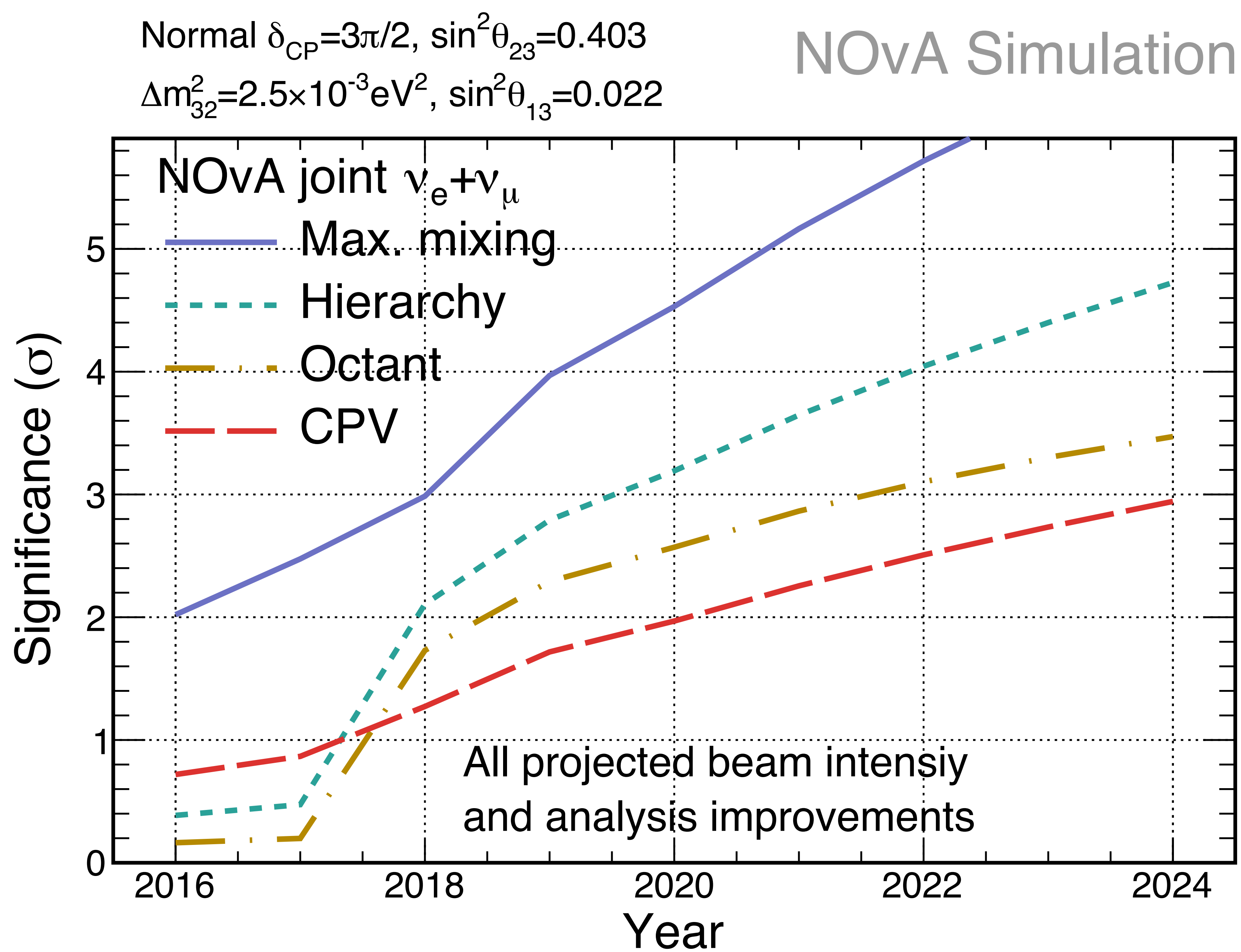
Near future: Heading into Neutrino 2018 conference

T2K will run in neutrino mode this year.

NOvA will run in antineutrino mode until the neutrino and antineutrino data sets have equal exposure (9E20 POT + 9E20 POT)

The important role of antineutrino running to the NOvA program is illustrated in the figure to the left which shows the expected event rates in neutrino mode and antineutrino mode based on the current measurements.

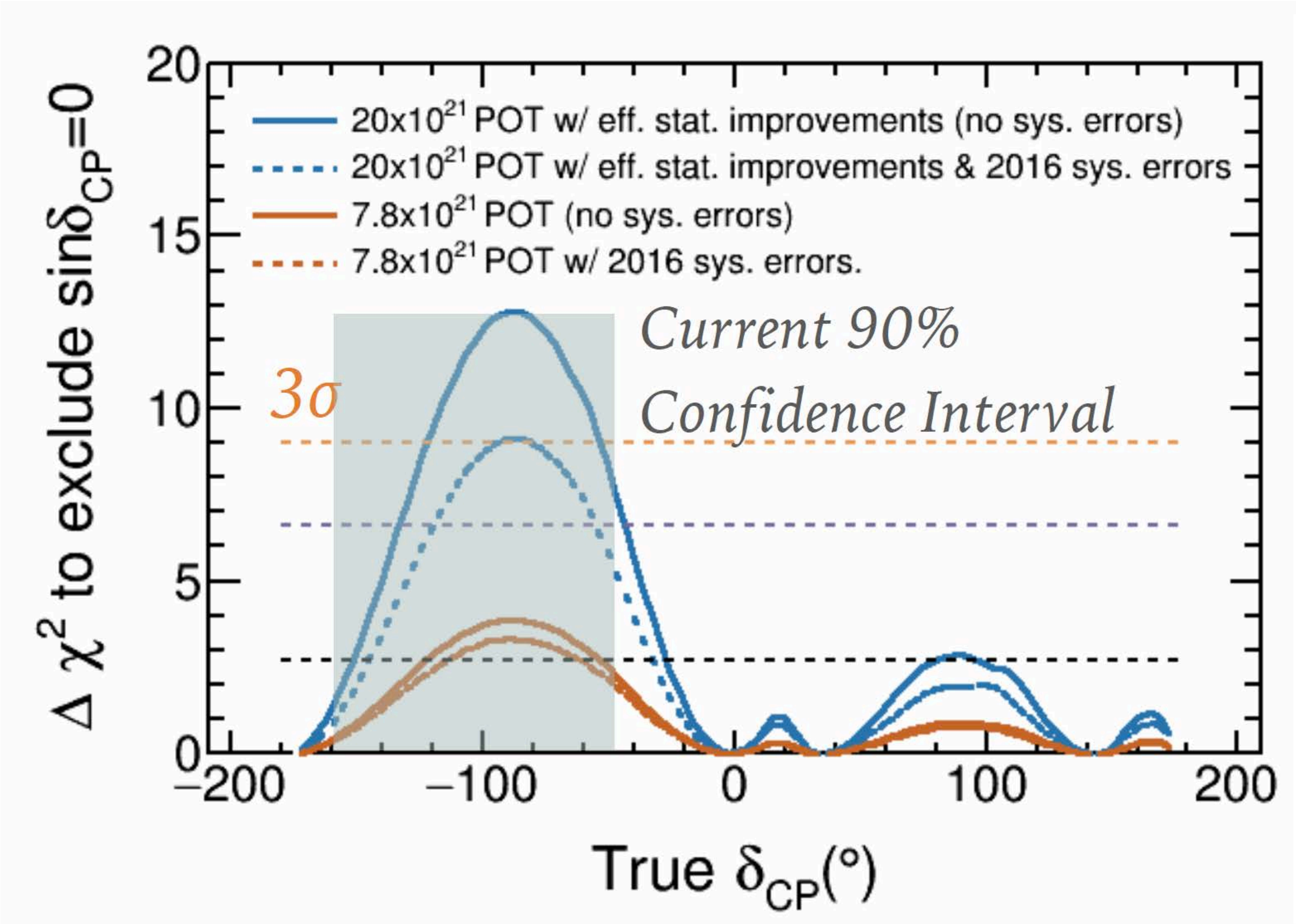
NOvA's neutrino data currently fits best to two solutions which are resolved by antineutrino data.



If PIP-I can increase the NuMI intensity to 900 kW by 2021 and the collaboration can deliver other improvements to the analysis (higher neutrino yield, improved reconstruction, expansion of data set ~50% improvements) and a reduction of systematics through test beam and cross-section measurements NOvA can reach 3 σ CPV measurement in 2024.

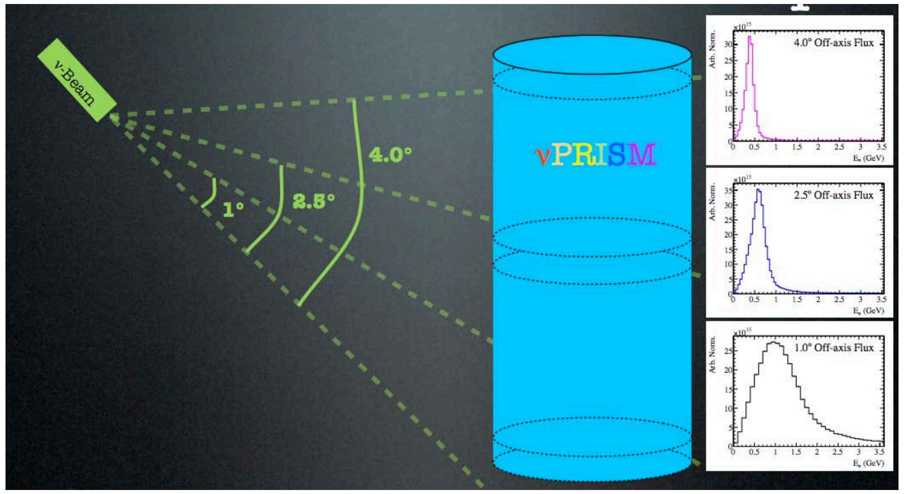
NOvA Extended Running

- >5 σ test of μ-τ symmetry
- >4 σ resolution of mass hierarchy
- >3 σ resolution of θ23 octant
- ~3 σ measurement of CP violation



If T2K beam power is upgraded to 1.3 MW and collaboration can deliver 20% analysis improvements over current analysis and an improvement in systematics, T2K can reach 3 σ CPV measurement in 2026 (arXiv: 1609.04111), has stage-1 approval at J-PARC)

NuPRISM (arXiv:1412.3086) is a novel concept for measuring neutrino event rate at multiple off-axis angle at near site to greatly improve the quality of the near-to-far extrapolation



T2K Extended Run

Working together

- Due to the difference in beam energies, baselines, and detector technologies T2K and NOvA are naturally complementary.
- Beginning last year the T2K and NOvA collaborations have begun discussions working toward a framework for the experiments to eventually produce a joint fit for oscillation parameters.
- Neutrino cross-sections are an obvious place where the experiments can learn from one another and are the main topic of our upcoming meeting in Japan