# USING ACCELERATORS TO STUDY NEUTRINOS

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ICHEP 2016 - Chicago - August 8, 2016

# STUDYING NEUTRINO OSCILLATIONS

## What do we know?

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

- Where the mixing matrix has 3 mixing angles and one phase (ignoring Majorana):

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

| Atmospheric + Accelerator | Reactor + Accelerator | Solar + Reactor |
|---|---|---|
| L/E 500 km/GeV | L/E 500 km/GeV | L/E 15,000 km/GeV |
| ✓ $\Delta m^2_{32} \sim 2.5 \times 10^{-3}$ eV$^2$ | ✓ $\theta_{13} \sim 9^\circ$ | ✓ $\delta m^2_{21} \sim 8 \times 10^{-5}$ eV$^2$ |
| ✓ $\theta_{23} \sim 45^\circ$ | ★ $\delta_{CP} = ?$ | ✓ $\theta_{12} \sim 34^\circ$ |

As in the quark case, the CP phase can be non-zero if all 3 angles are non-zero.

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**Atmospheric** +
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L/E 500 km/GeV

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**Solar** +
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L/E 15,000 km/GeV

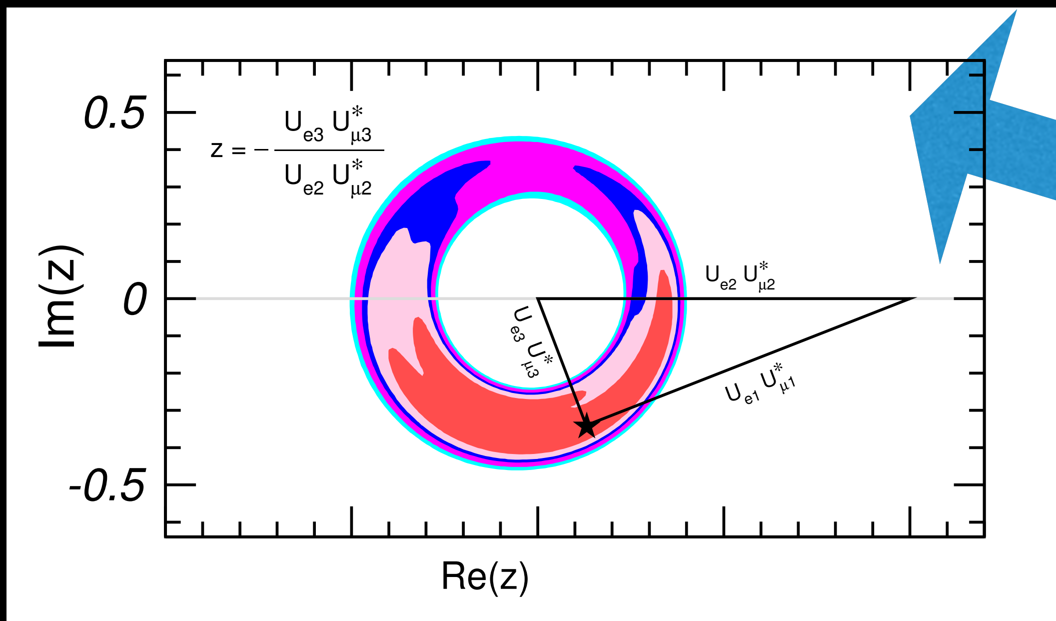
✓ $\delta m^2_{21} \sim 8 \times 10^{-5}$ eV$^2$

✓ $\theta_{12} \sim 34^\circ$

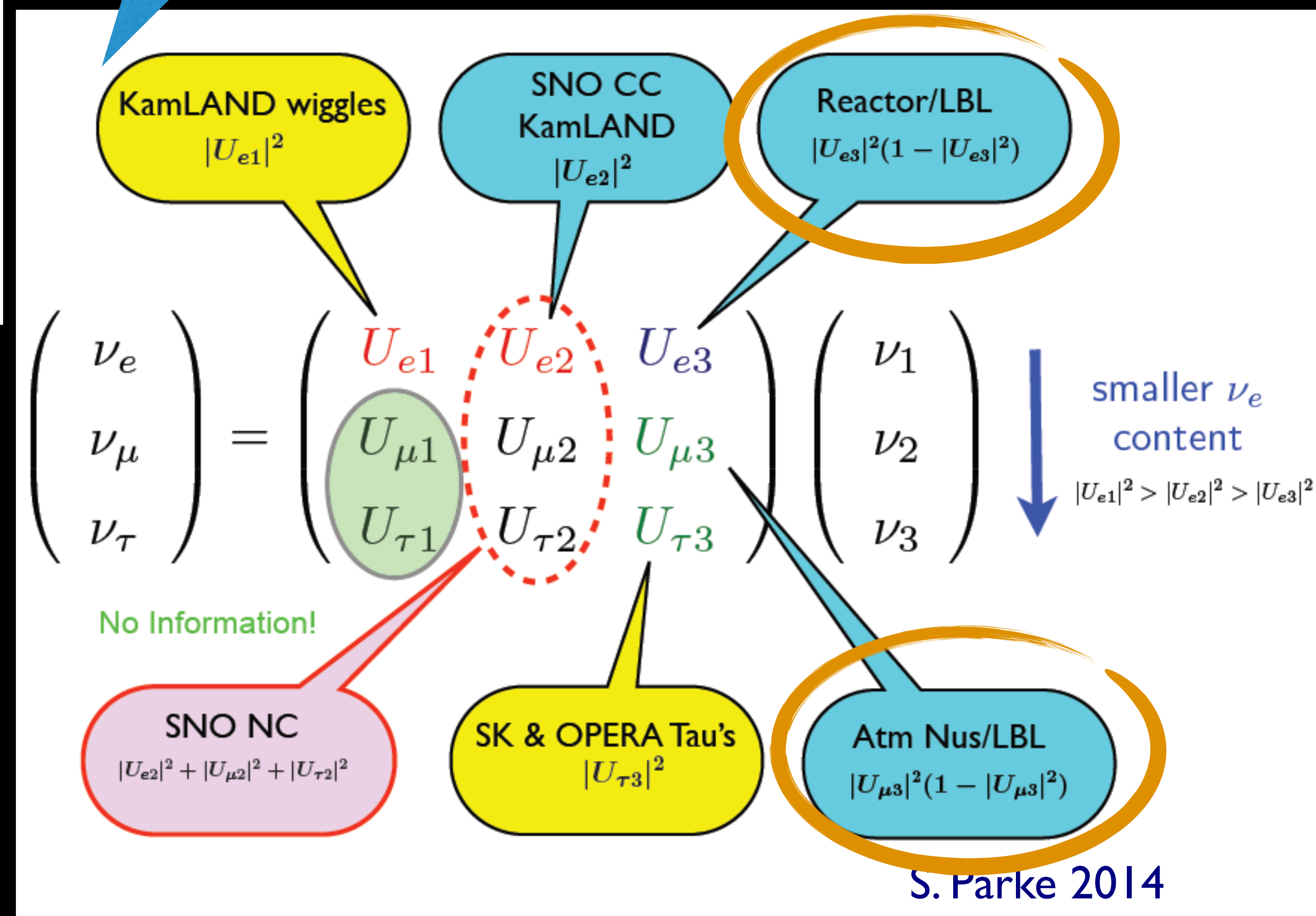
As in the quark case, the CP phase can be non-zero if all 3 angles are non-zero.

# HOW WELL DO WE KNOW IT?

M.C. Gonzalez-Garcia — arxiv:1409.5439




## 3 neutrino paradigm




## leptons

| | | |
|---|---|---|
| SOLAR | $\delta m^2$ | $2.4\%$ |
| ATMOSP. | $\Delta m^2$ | $1.8\%$ |
| SOLAR | $\sin^2\theta_{12}$ | $5.8\%$ |
| REACT. | $\sin^2\theta_{13}$ | $4.7\%$ |
| ATMOSP. | $\sin^2\theta_{23}$ | $\sim 9\%$ |

A. Marrone (Neutrino 2016)

- Most angles and masses have been measured using more than one experimental techniques including accelerator-based experiments.

# NEUTRINOS MASSES AND MIXING

## What we do not know in 3-flavor neutrino mixing?

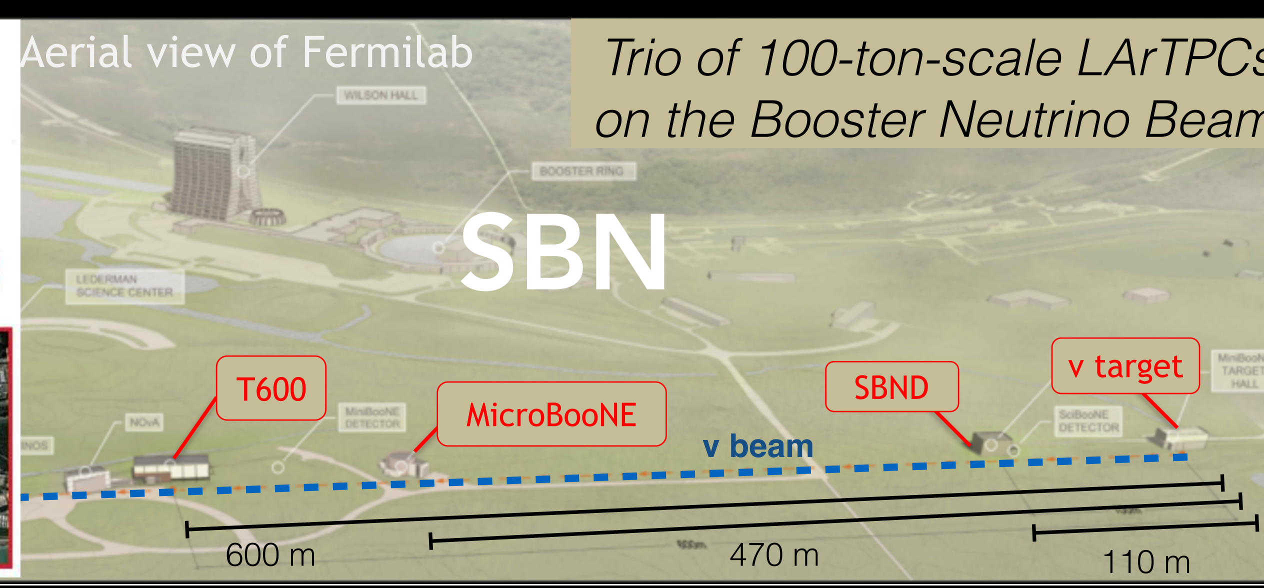
- **CP violation in the lepton sector has NOT been measured.**
  - May explain matter-antimatter asymmetry through leptogenesis.
  - Measuring $\delta_{CP}$ precisely is needed to understand structure of PMNS matrix and underlying symmetries.
- **Mass hierarchy or ordering is NOT known for atmospheric neutrinos.**
  - Important to be able to understand reach of experiments that study if neutrinos are Majorana or Dirac particles.
- **The octant of the large mixing angle is NOT known!**
  - In the case non-maximal mixing this uncertainty impacts our knowledge of mass hierarchy and CP violation.
  - Precision measurements of $\theta_{23}$ are important for testing PMNS unitarity and for model building.

THE NEUTRINO ACCELERATOR EXPERIMENTAL PROGRAM SEEKS TO ANSWER THESE!

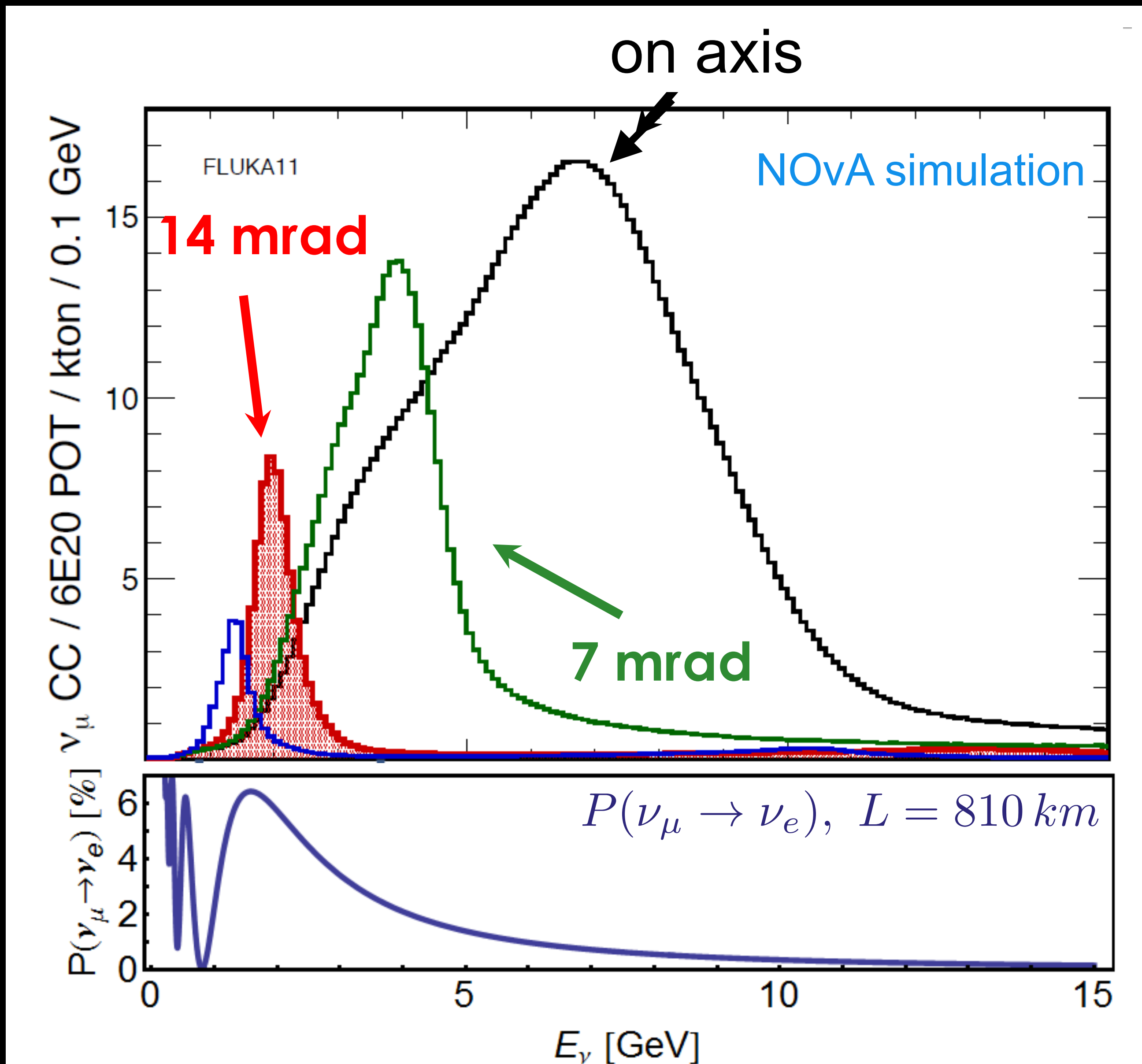
# USING ACCELERATORS FOR NEUTRINOS


- Neutrino oscillation experiments have been built using neutrino beams produced by accelerators around the World: US (NuMI and Booster), Europe (CNGS) and Japan (JPARC).

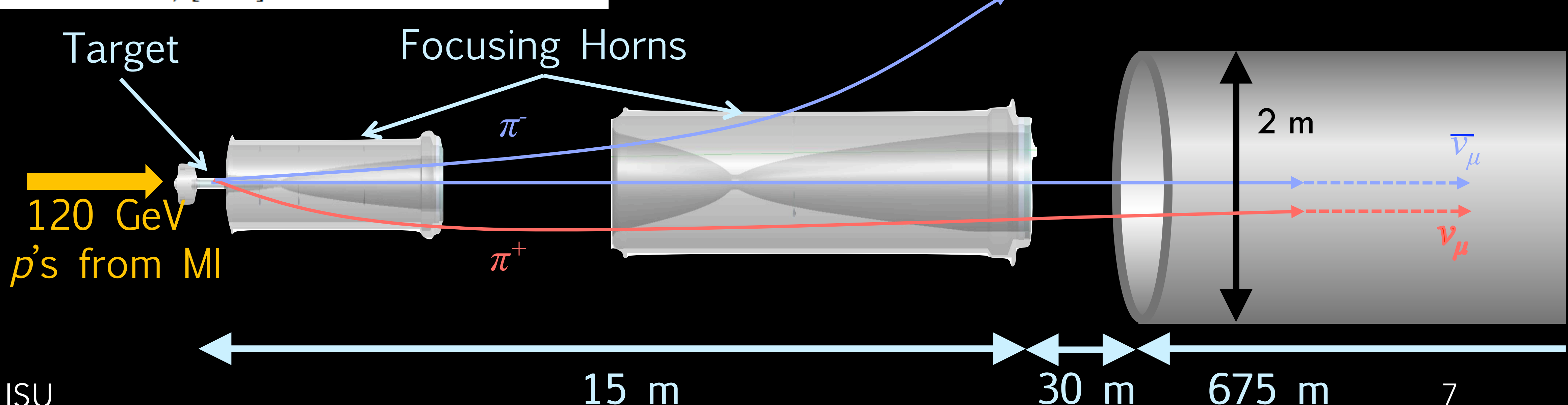
- The baseline of these experiments go from few hundreds of meters (short-baseline) to hundreds (300-1300) of km (long-baseline).

# USING ACCELERATORS FOR NEUTRINOS




- Protons from an accelerator impinge on a target, producing pions and kaons to be focused by horn system. The mesons then decay into mostly muon neutrinos.
- On axis spectrum is broad with higher energy neutrinos arising from very forward mesons.
- Off-axis meson decay kinematics select a narrow band spectrum with energy peak depending on the angle at which the detector(s) is (are) located.



# LONG-BASELINE EXPERIMENTS


- Precision is achieved by placing a detector close to the source (Near Detector) and one at or close to the oscillation maximum (Far Detector).

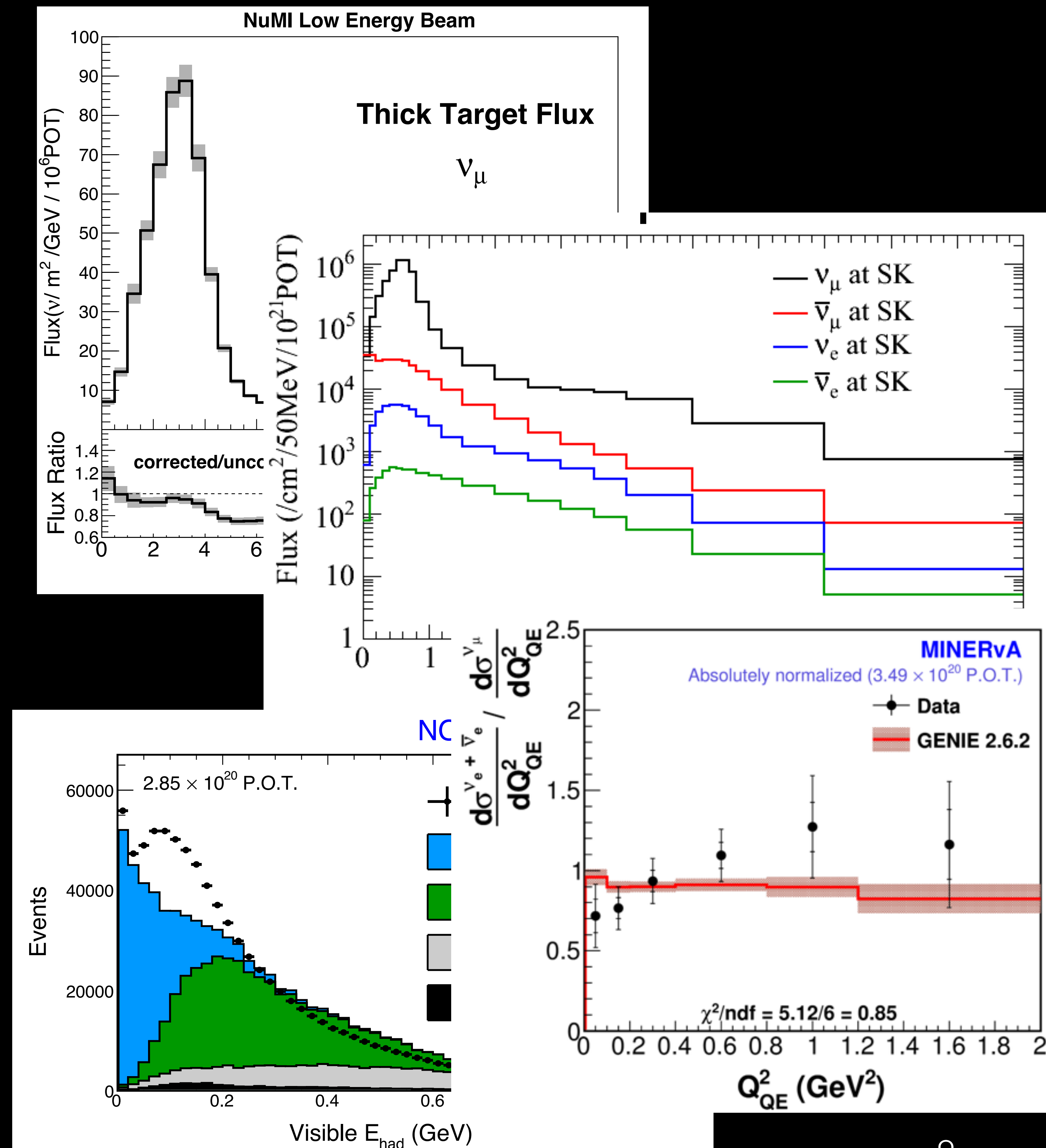
$$ND(\nu_\mu) = \boxed{\Phi(E_\nu) \times \sigma(E_\nu, A)} \times \epsilon_{ND}$$
$$FD(\nu_\mu) = \boxed{\Phi(E_\nu) \times \sigma(E_\nu, A)} \times \epsilon_{FD} \times P_{osc}$$

- The neutrino spectrum is measured at the ND (before oscillations), this is a combination of neutrino flux, cross section and efficiency.
- The measured spectrum is used to make a prediction of the expectation at the FD before considering oscillations.
- In the case of functionally similar detectors the flux combined with the cross sections uncertainties largely cancel.

**UNDERSTANDING THE FLUX, CROSS SECTIONS AND DETECTOR EFFICIENCIES IS ESSENTIAL FOR HIGH PRECISION**

# UNDERSTANDING FLUX AND NEUTRINO INTERACTIONS

- Significant efforts by all long-baseline experiments on a program of understanding the flux and the cross sections.
- The MINERvA experiment is designed to study neutrino interactions. They have produced a wide variety of results on this topic.
- T2K has also pursued this topic aggressively significantly reducing their systematic uncertainties.
- High statistic samples continues to provide evidence for the need for better modeling/data.

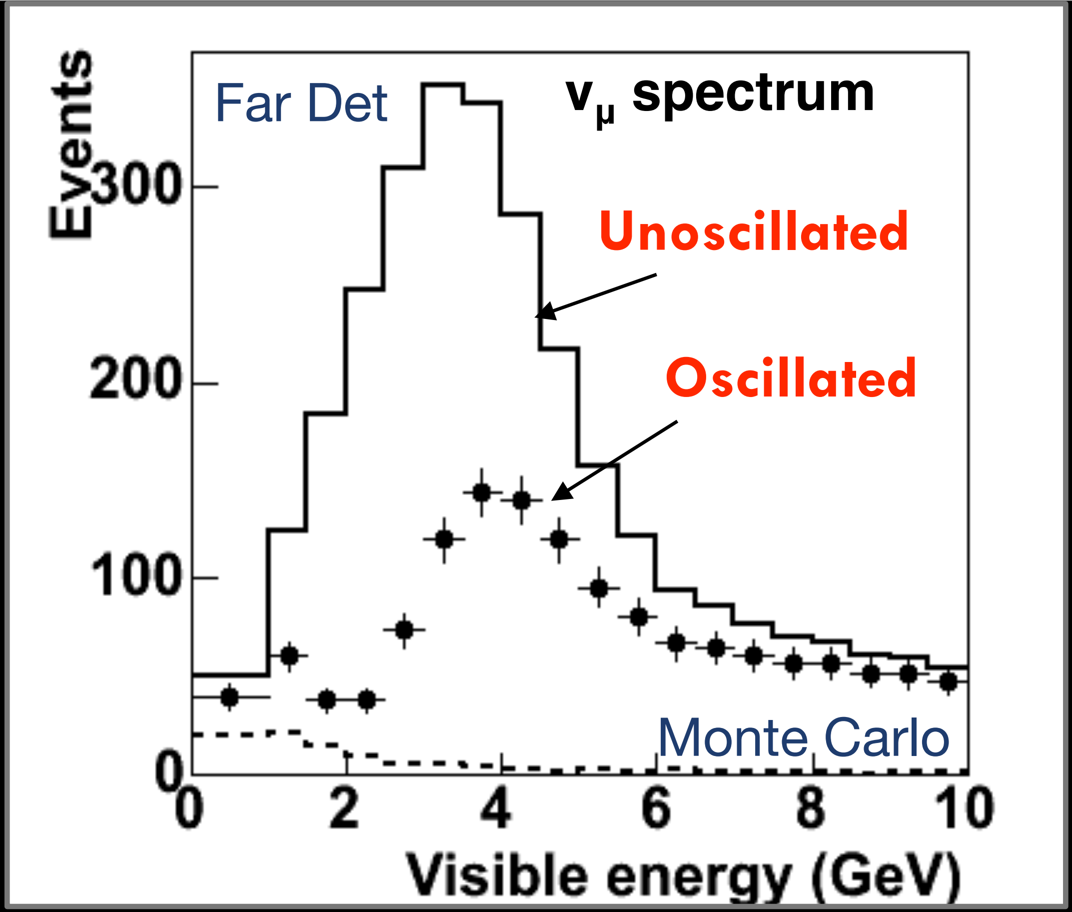


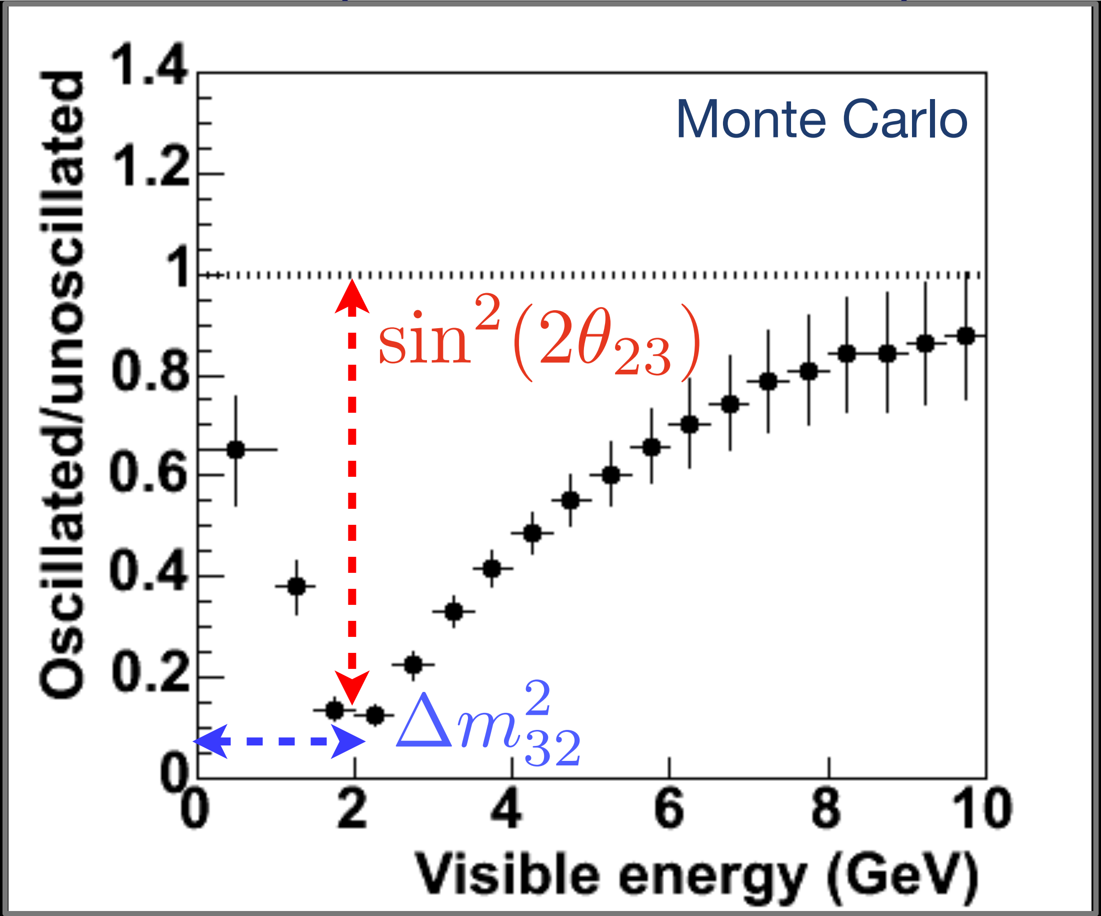
# NEW RESULTS ON MUON NEUTRINO DISAPPEARANCE

# MUON NEUTRINO DISAPPEARANCE

- In long-baseline experiments, neutrino oscillations deplete rate and distort the energy spectrum.

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - \sin^2(2\theta_{23}) \sin^2\left(1.267\Delta m^2_{32}\frac{L}{E}\right)$$

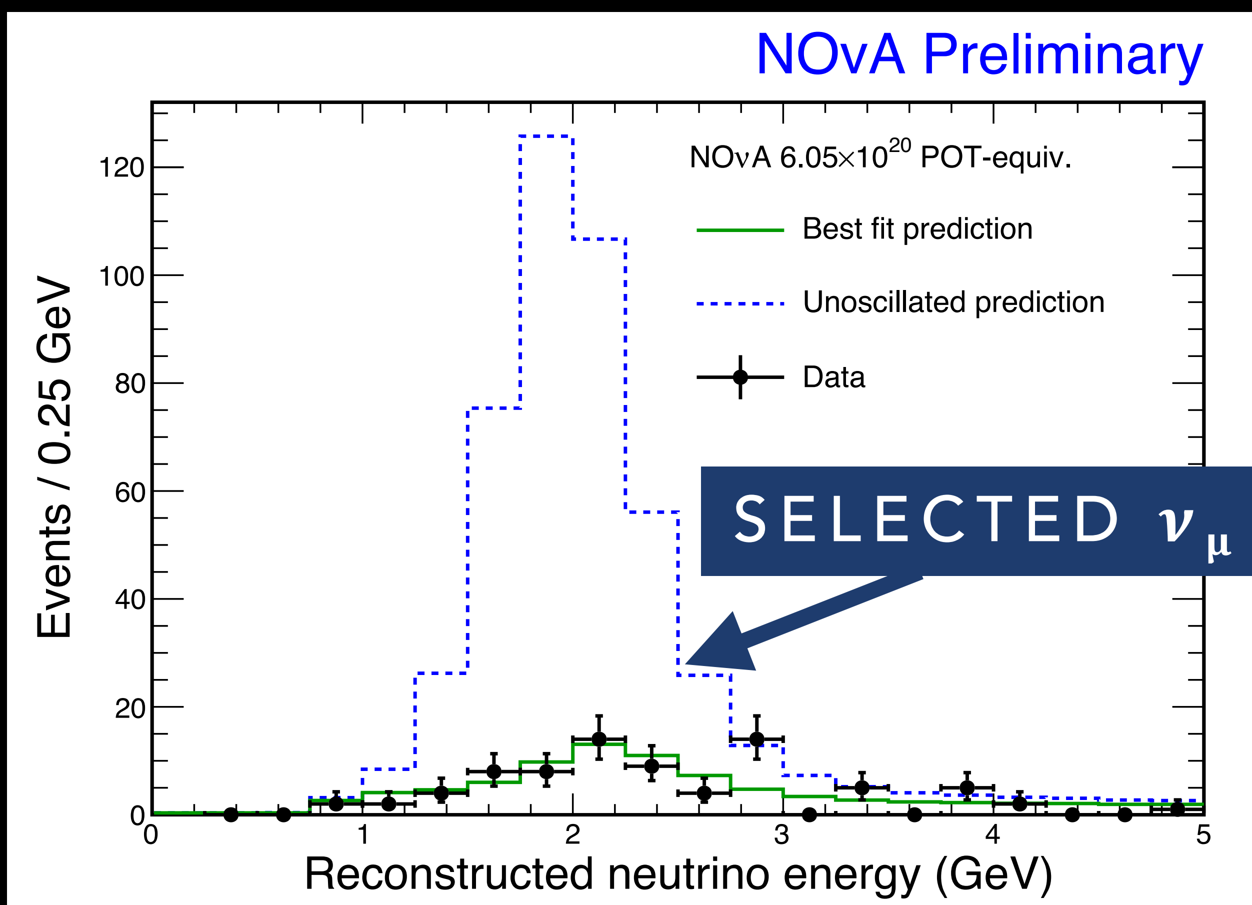


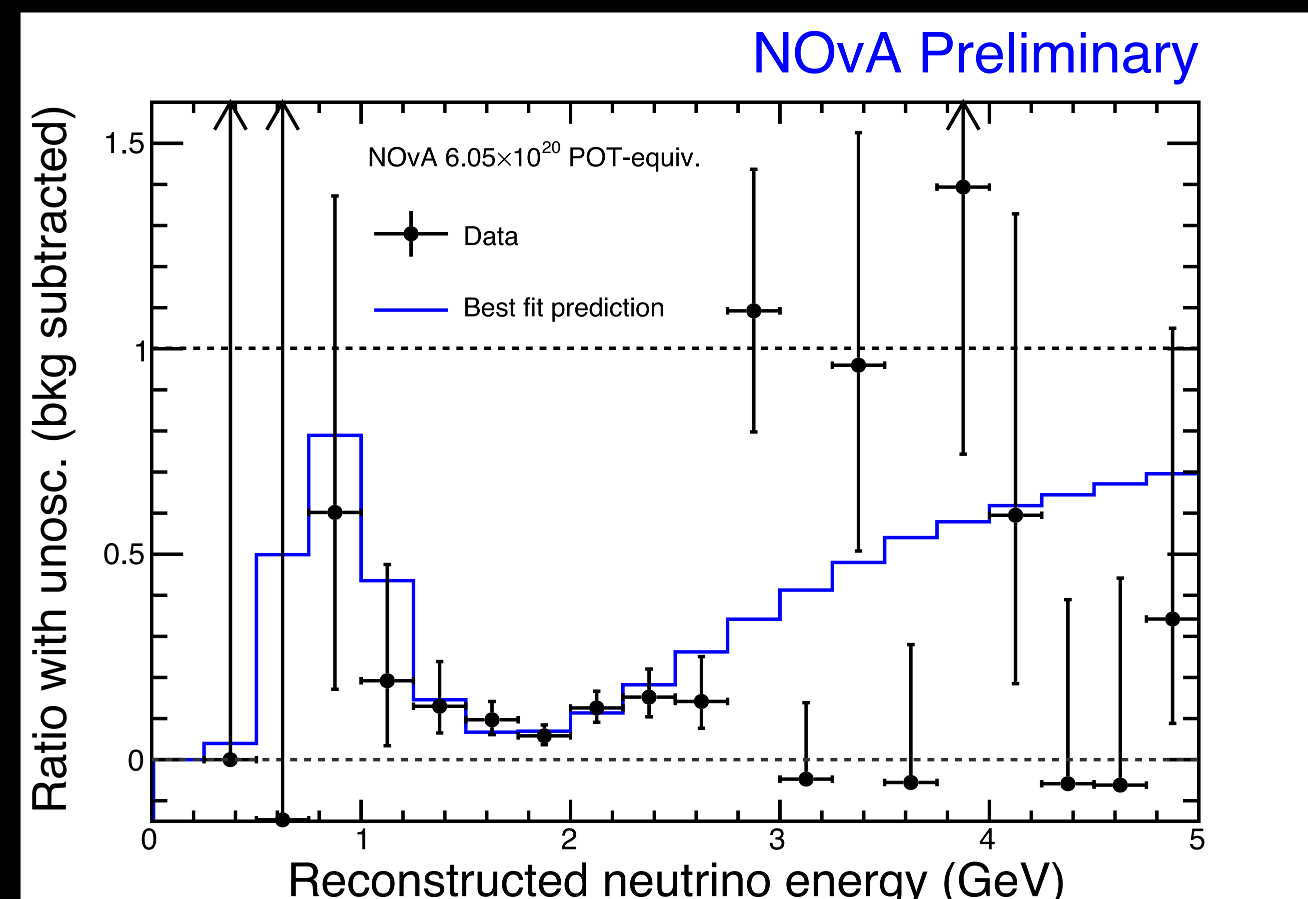




IN AN OFF-AXIS EXPERIMENT NEAR THE OSCILLATION MAXIMUM THE EFFECT IS **EVEN MORE DRAMATIC**

# NOVA: AN OFF-AXIS NEUTRINO EXPERIMENT IN THE NUMI BEAM

- NOvA is on a high intensity off-axis beam (14 mrad) with a 14 kiloton scintillator-filled calorimeter in a 810 km baseline. Running for 2 years.



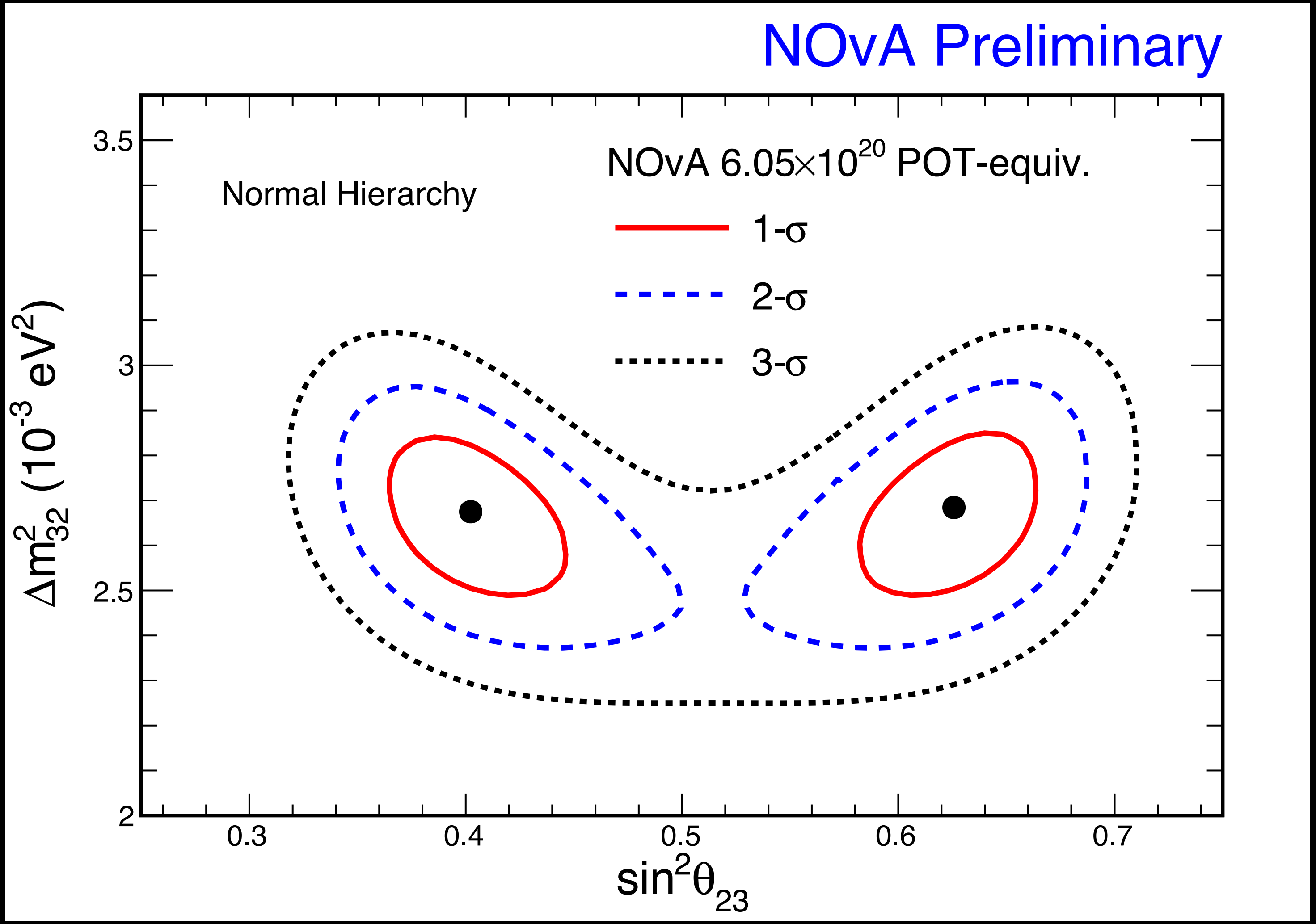




- Expect 473 events before oscillations.
- Observe 78 events (expect 82 at best fit oscillated prediction).

# NOVA MUON NEUTRINO DISAPPEARANCE RESULTS

- A 3-flavor fit to the $\nu_\mu$ selected spectrum provides the allowed parameter space.
- Dominant systematic effects:
  - Normalization, NC background, flux, muon and hadronic energy scales, cross section, detector response and noise.
- Parameter measurements:

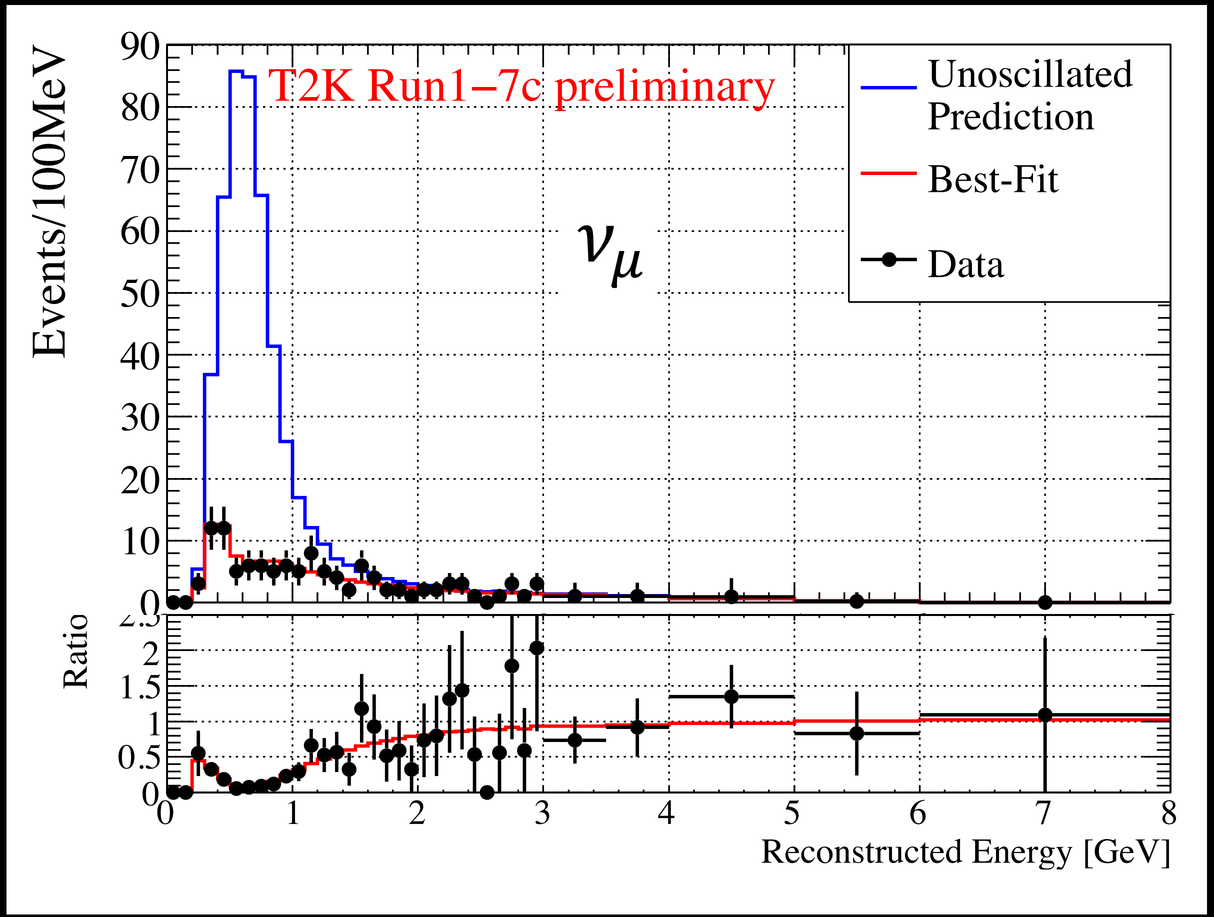
$$\Delta m^2_{32} = (2.67 \pm 0.12) \times 10^{-3} \mathrm{eV}^2 \ (\mathrm{NH})$$
$$\sin^2\theta_{23} = 0.40^{+0.03}_{-0.02} \ (0.63^{+0.02}_{-0.03})$$

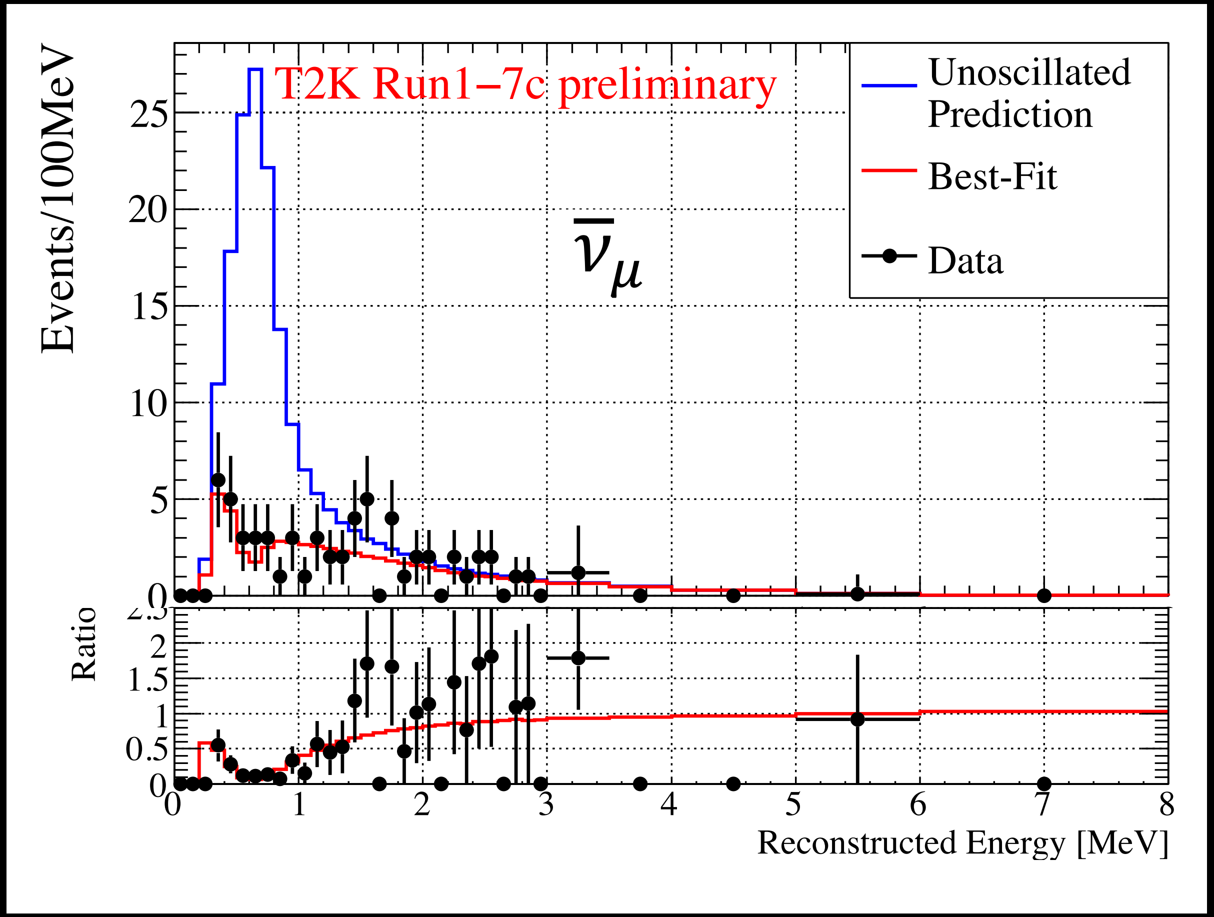



**MAXIMAL MIXING EXCLUDED AT 2.5$\sigma$**

# T2K: AN OFF-AXIS NEUTRINO EXPERIMENT IN THE JPARC BEAM

- T2K uses an off-axis beam (2.5°) with large water Cherenkov detector of SuperK in a 295 km baseline.
  - It has run in both neutrino and anti-neutrino modes.
- They observe:
  - 135 neutrino events with 135.8 expected after oscillations
  - 66 antineutrino events with 64.2 expected after oscillations



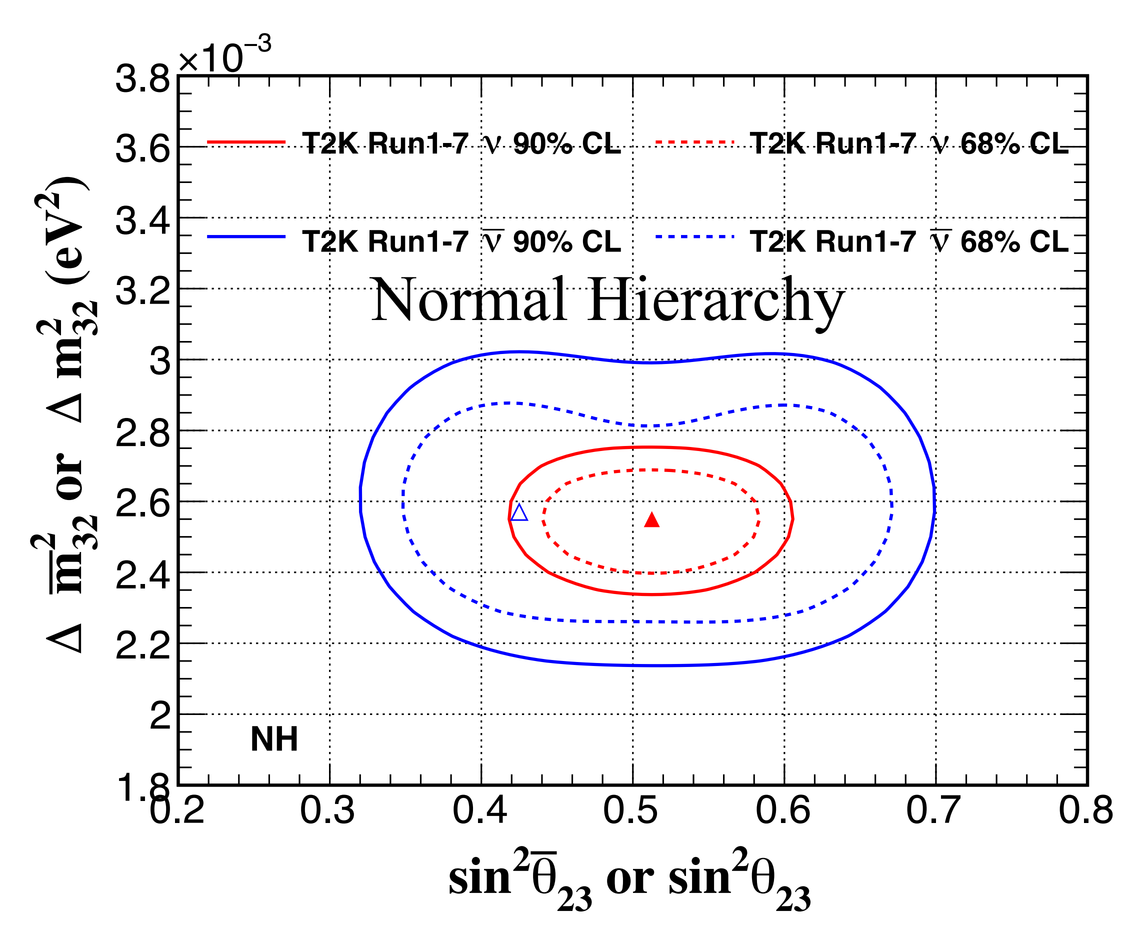



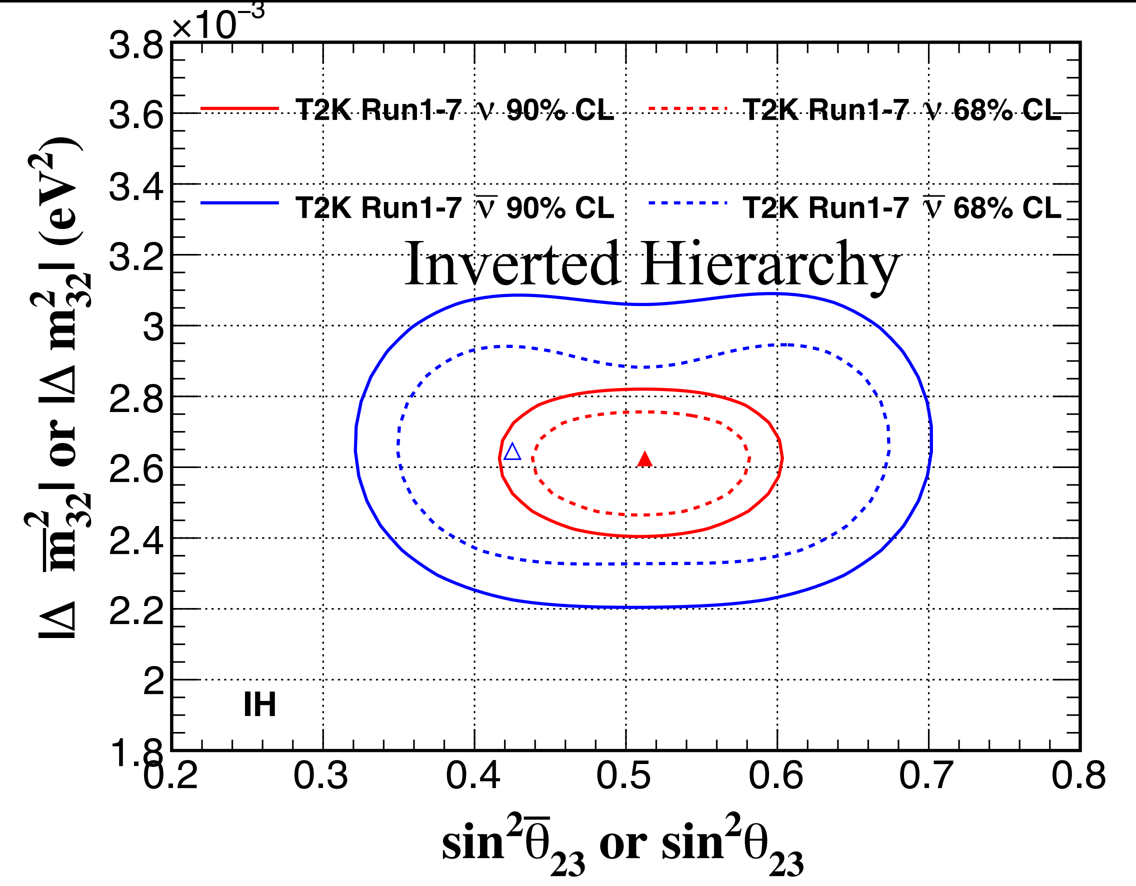

K. Iwamoto - ICHEP 2016

T2K MUON NEUTRINO AND ANTINEUTRINO DISAPPEARANCE RESULTS

- T2K results are consistent with maximal mixing for both neutrinos and antineutrinos.
  - No hint of CPT violation within errors.
  - The best fit for antineutrinos is slightly non-maximal.
- This result agrees with previous MINOS results in Phys. Rev. Lett. 110, 251801 (2013) .

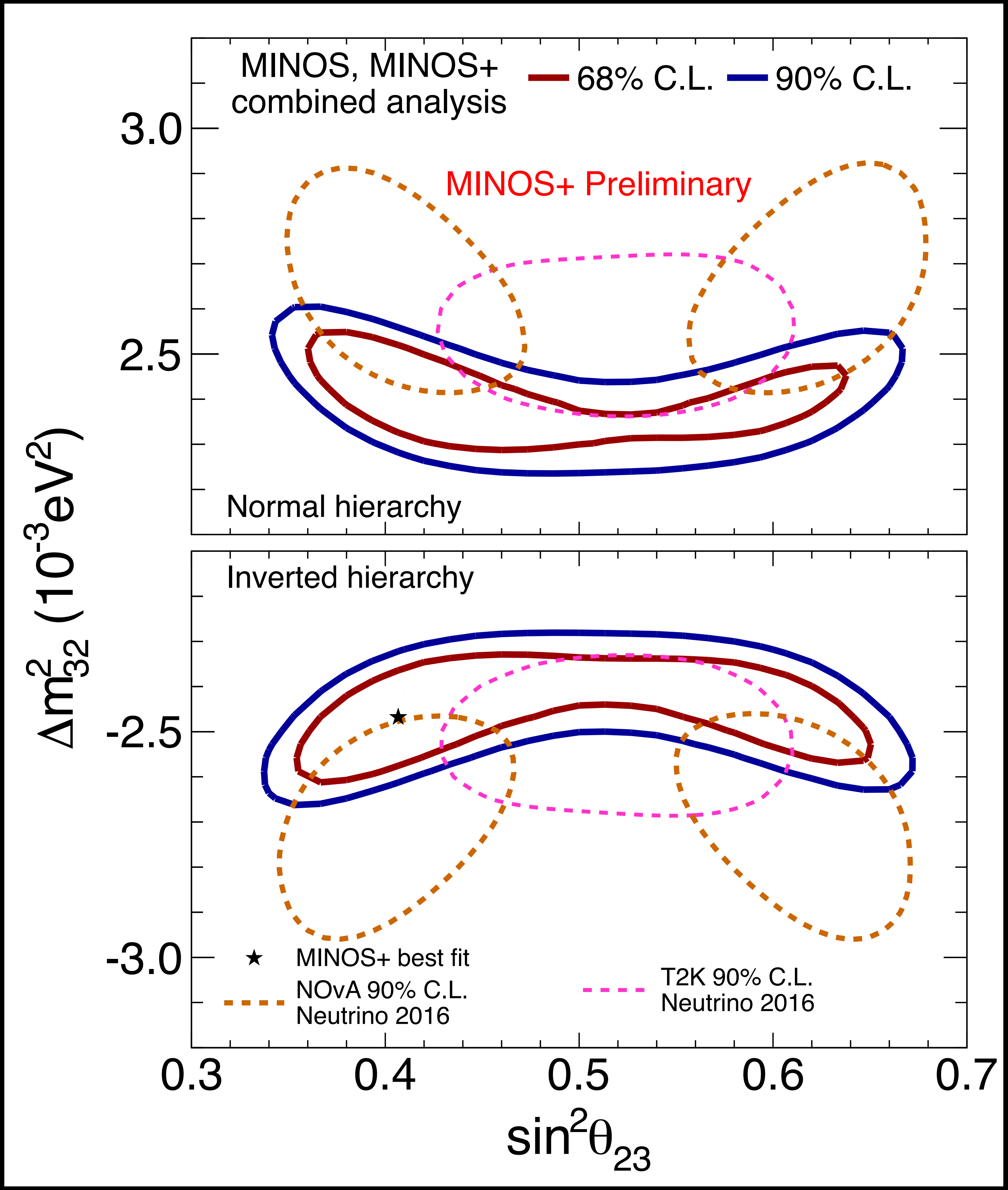
| | NH | IH |
|---|---|---|
| $\sin^2\theta_{23}$ | $0.532^{+0.046}_{-0.068}$ | $0.534^{+0.043}_{-0.066}$ |
| $\lvert\Delta m^2_{32}\rvert [10^{-3} eV^2]$ | $2.545^{+0.081}_{-0.084}$ | $2.510^{+0.081}_{-0.083}$ |



# MINOS: AN ON-AXIS EXPERIMENT ON THE NUMI BEAM

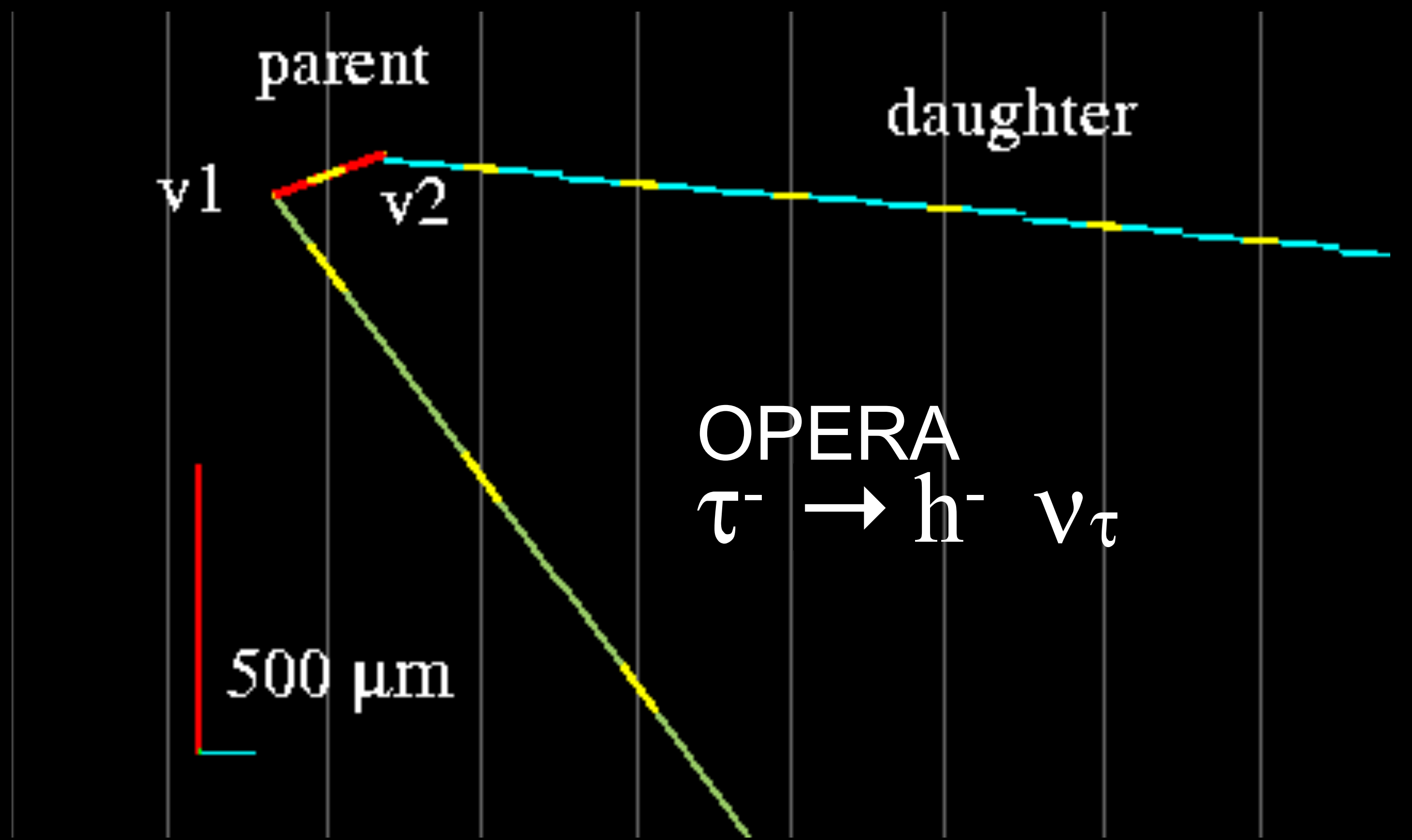
- MINOS/MINOS+ (2005-2016) collected neutrino beam data using an 5.4-kton iron-calorimeter detector in a 735 km baseline.
    - Using muon neutrino disappearance as well as electron neutrino appearance data and atmospheric neutrinos, they observe a slight octant preference.
- Small amount of tension between T2K's maximal and NOvA's non-maximal result. More data should resolve this.

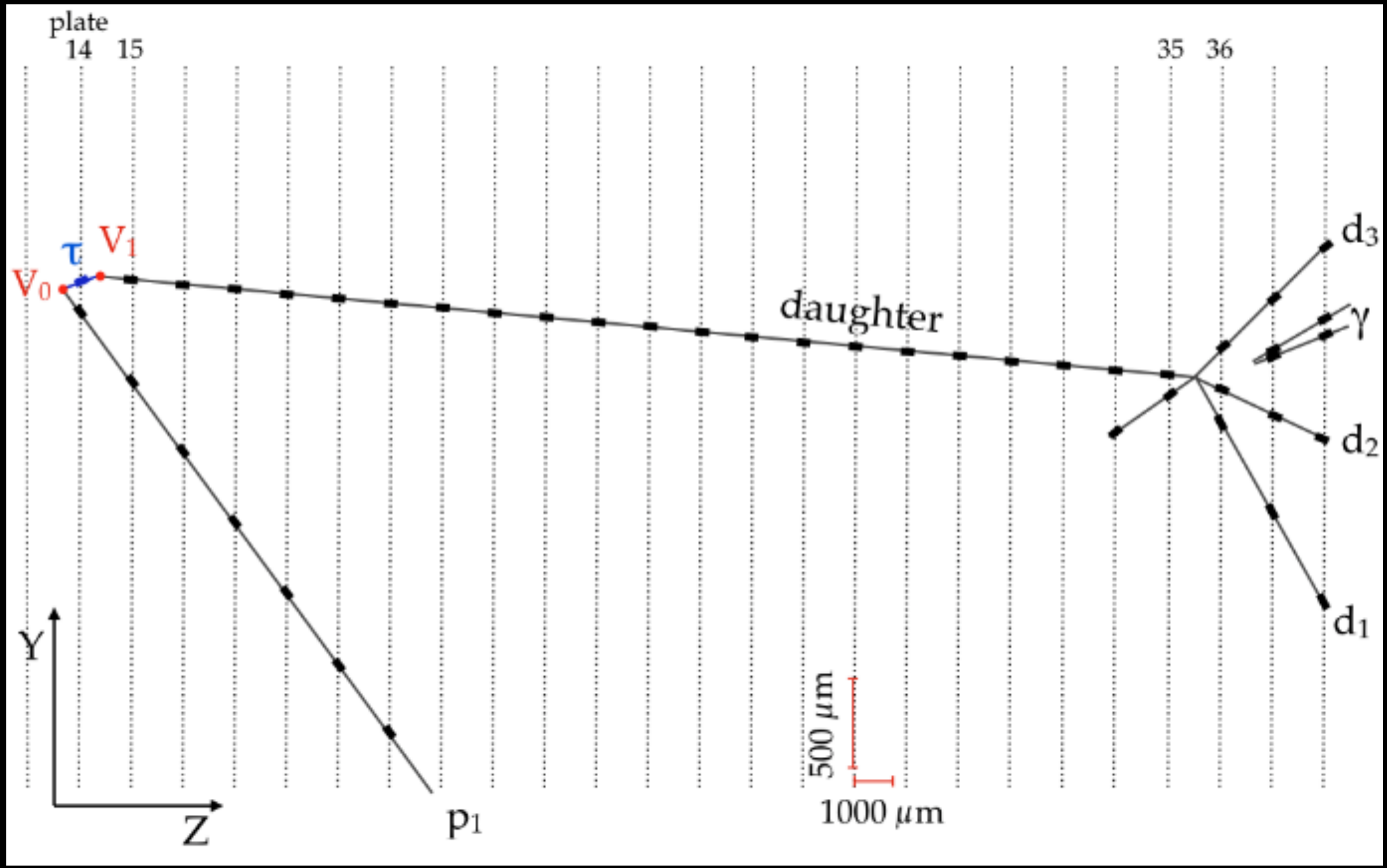



J. Evans - Neutrino 2016

# OPERA: AN ON-AXIS TAU APPEARANCE EXPERIMENT ON THE CERN BEAM

- Most muon neutrinos oscillate to tau neutrinos. However there is a 3.4 GeV threshold to produce a $\tau$ that must be met by the neutrino beam energy.
- With a baseline from CERN to Gran Sasso of 730 km and a higher energy beam, OPERA uses the high resolution of emulsion to find $\tau$s.
- In OPERA 5 candidates have been observed.
- Claim **discovery of $\nu_\tau$ appearance at 5.1 $\sigma$**.
  (Phys. Rev. Lett. 115 (2015) 121802)





D. Duchesneau - ICHEP 2016

# NEW RESULTS ON ELECTRON NEUTRINO APPEARANCE

# ELECTRON NEUTRINO APPEARANCE

- The probability of $\nu_e$ appearance in a $\nu_\mu$ beam:

$$A \equiv \frac{G_f n_e L}{\sqrt{2}\Delta} \approx \frac{E}{11\ \mathrm{GeV}}$$

$$\alpha = \Delta m^2_{12}/\Delta m^2_{31}\ ;\ \Delta \equiv \frac{\Delta m^2_{31} L}{4E}$$

$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2(A-1)\Delta}{(A-1)^2}$$
$$+2\alpha \sin\theta_{13}\cos\delta \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \cos\Delta$$
$$-2\alpha \sin\theta_{13}\sin\delta \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \sin\Delta + O(\alpha^2)$$

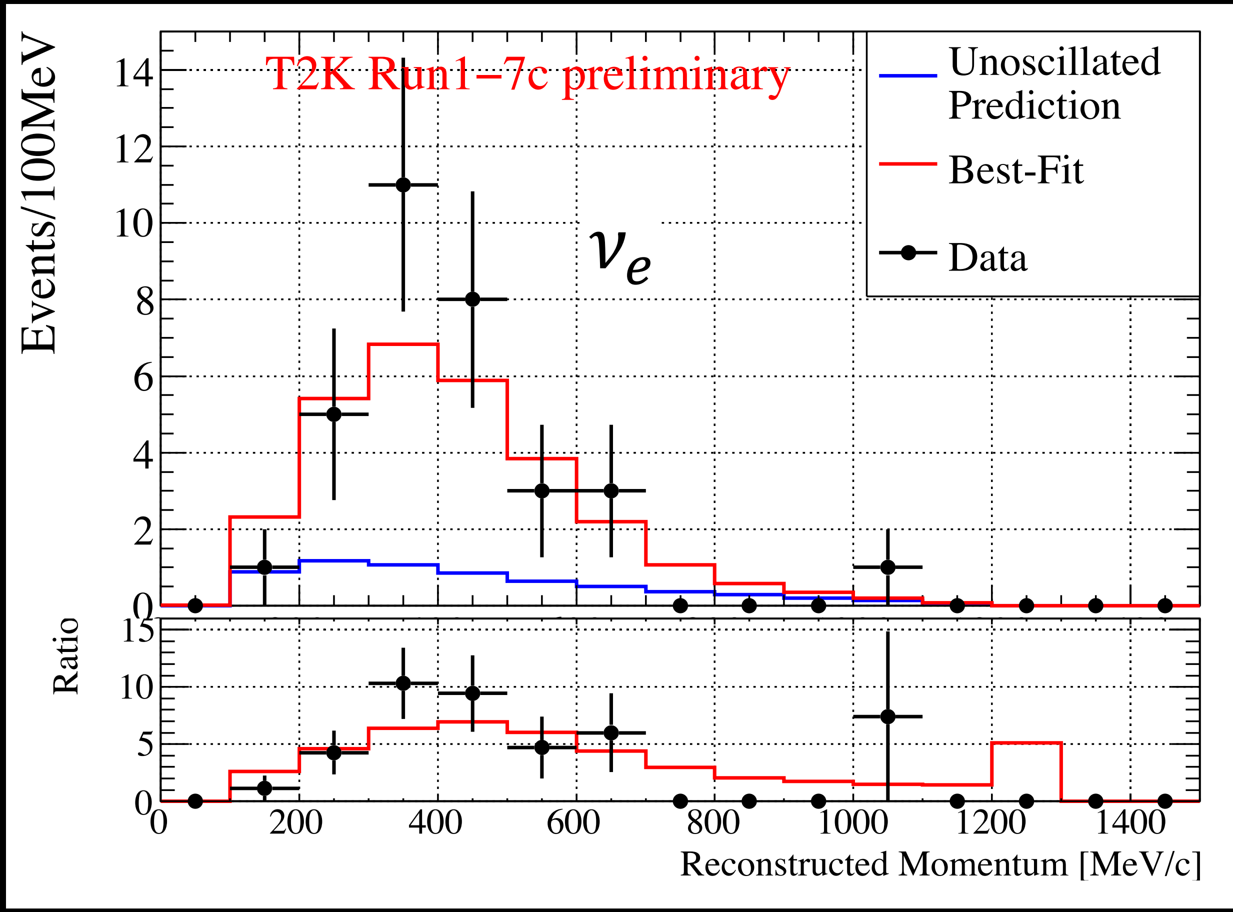
**M. Freund, Phys.Rev. D64 (2001) 053003**

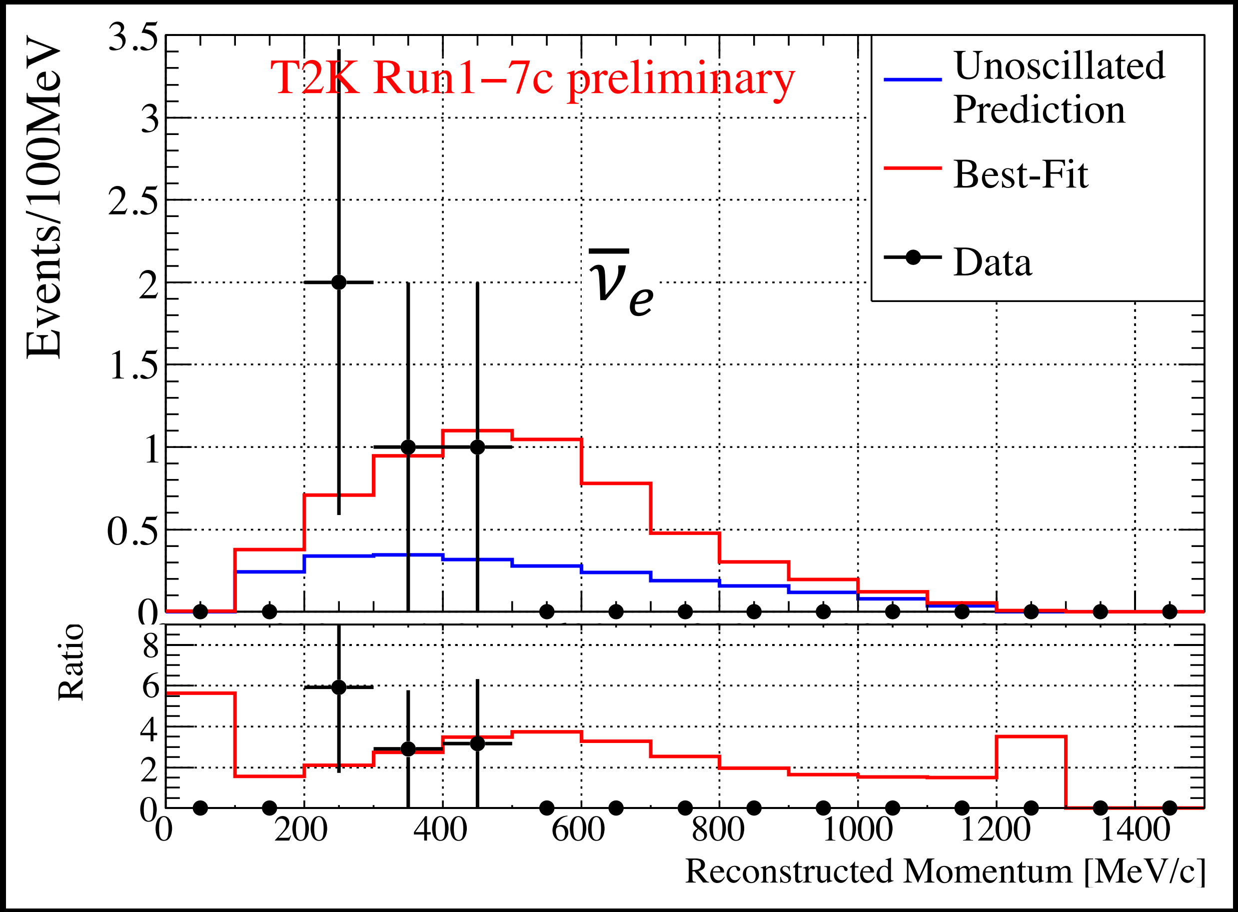
- Searching for $\nu_e$ appearance in a $\nu_\mu$ beam, we can access **$\sin^2(2\theta_{13})$**.
- Probability depends not only on **$\theta_{13}$ but also on $\delta_{CP}$** which enhances or suppresses it.
- Probability is enhanced or suppressed due to **matter effects** which depend on the mass hierarchy as well as neutrino vs anti-neutrino running.
- In addition, the probability depends on the octant of **$\theta_{23}$**.

**PROBE THE MASS HIERARCHY, CP VIOLATION AND OCTANT SPACE**

# T2K ELECTRON NEUTRINO APPEARANCE RESULTS

- T2K has observed 32 neutrinos and 4 antineutrinos.
- There are 29 and 6 expected at NH, $\delta_{CP} = -\pi/2$ (or $3\pi/2$) which is the largest asymmetry.
- More $\nu_e$ candidates than predicted and fewer $\overline{\nu}_e$ candidates than predicted.



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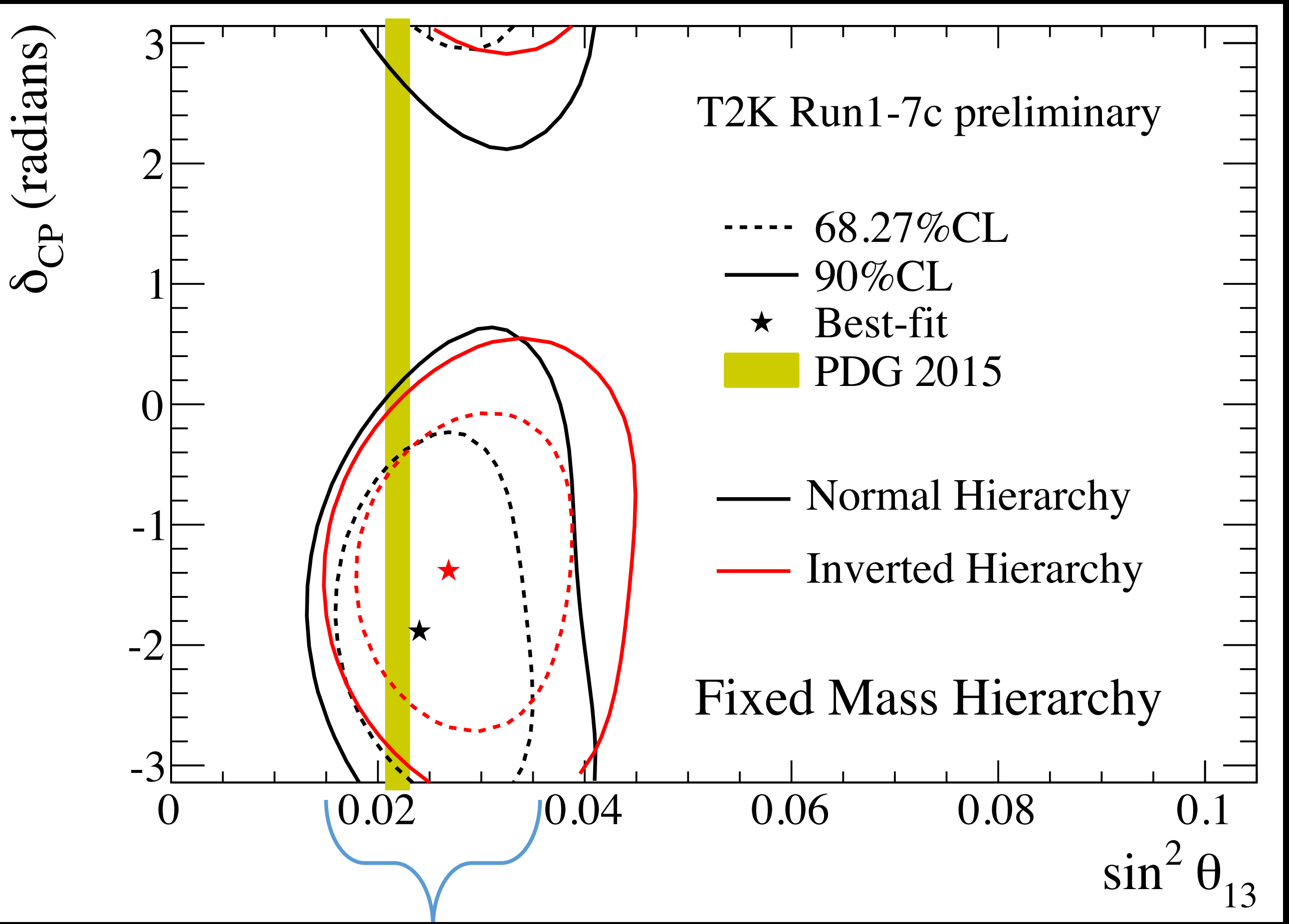
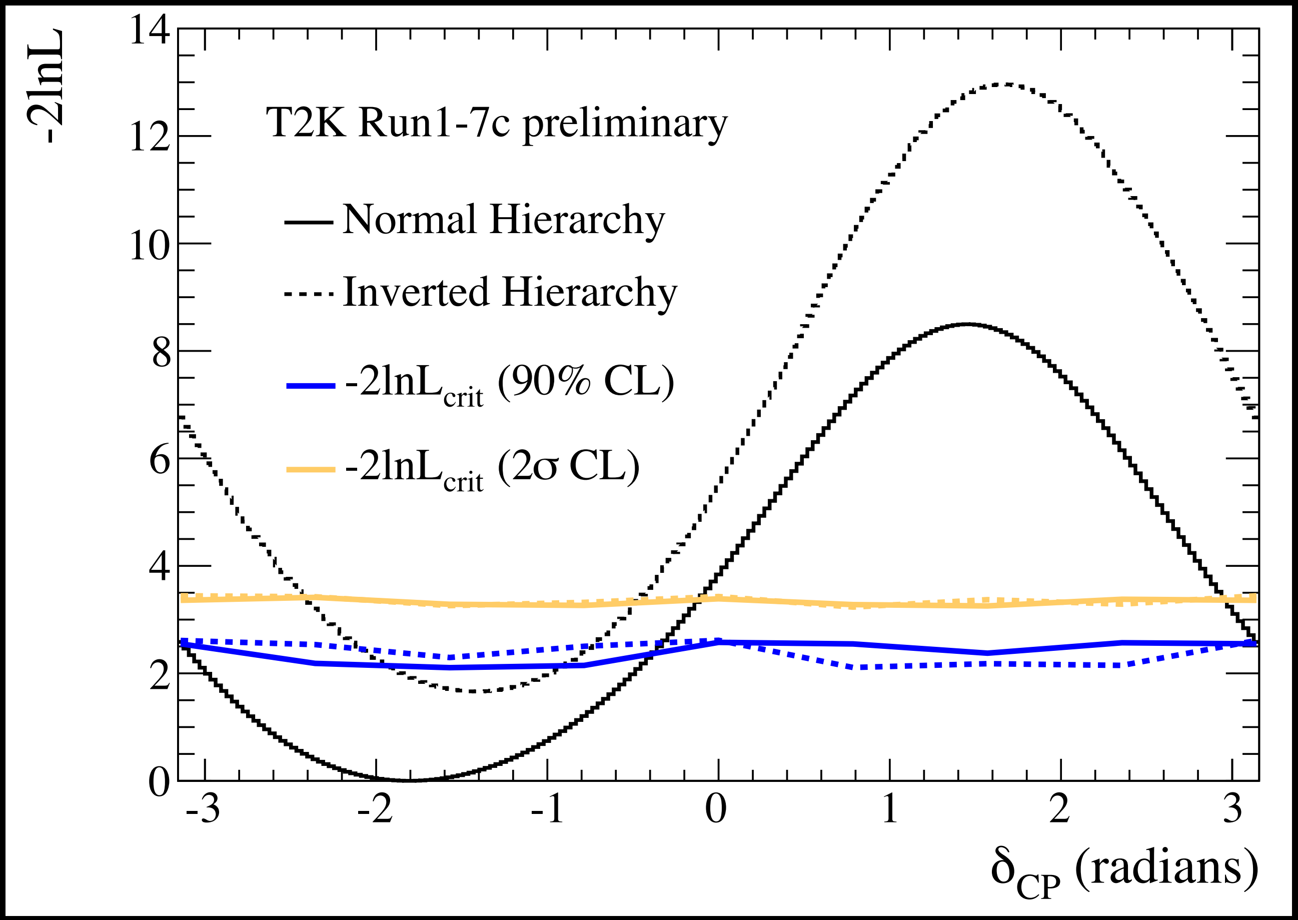
# T2K ELECTRON NEUTRINO APPEARANCE RESULTS

- Results consistent with the amount of appearance expected from information in reactors.
- Combining with reactor and T2K's own muon neutrino disappearance data.
- **Claim a 90% exclusion of δcp = 0 and π.**
    - Exclusion depends on T2K's observed maximal mixing angle.

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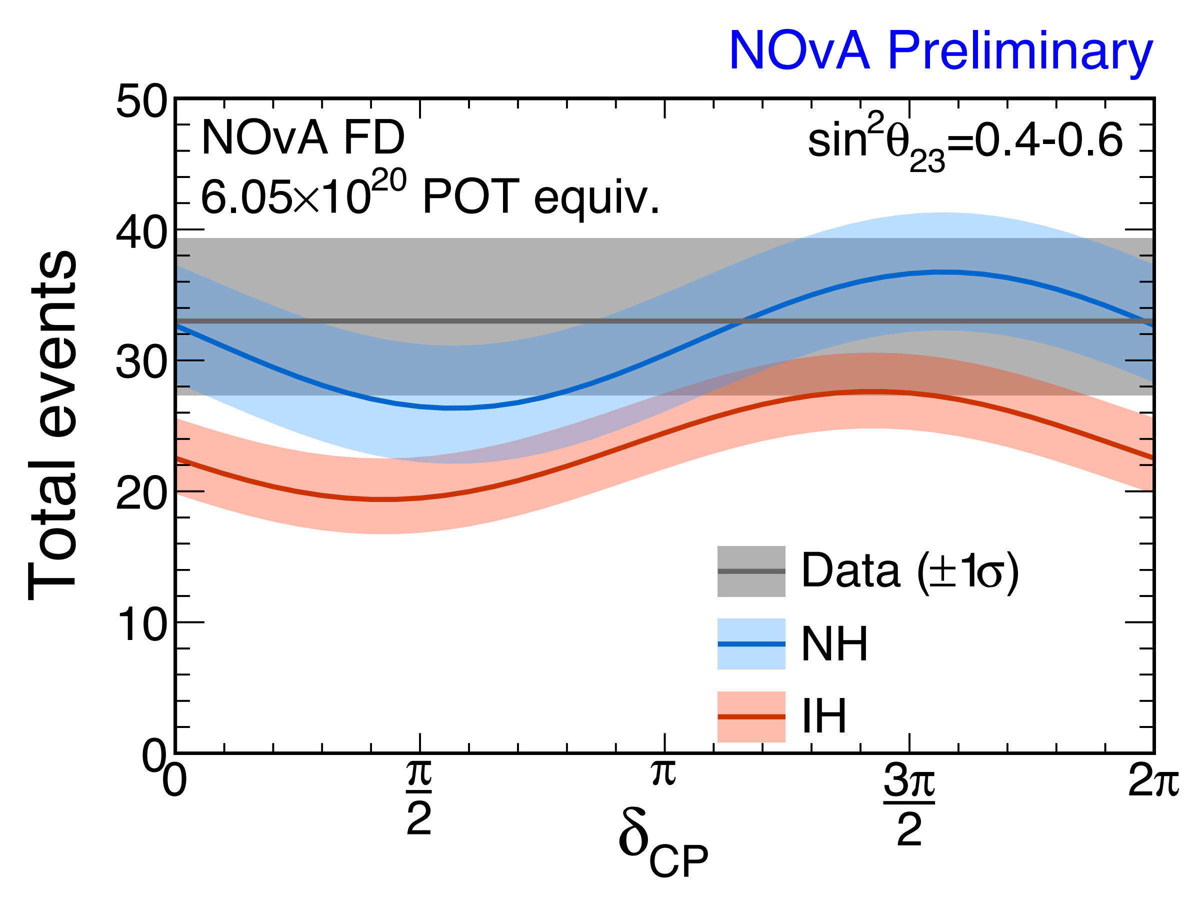
# NOVA ELECTRON NEUTRINO APPEARANCE RESULTS

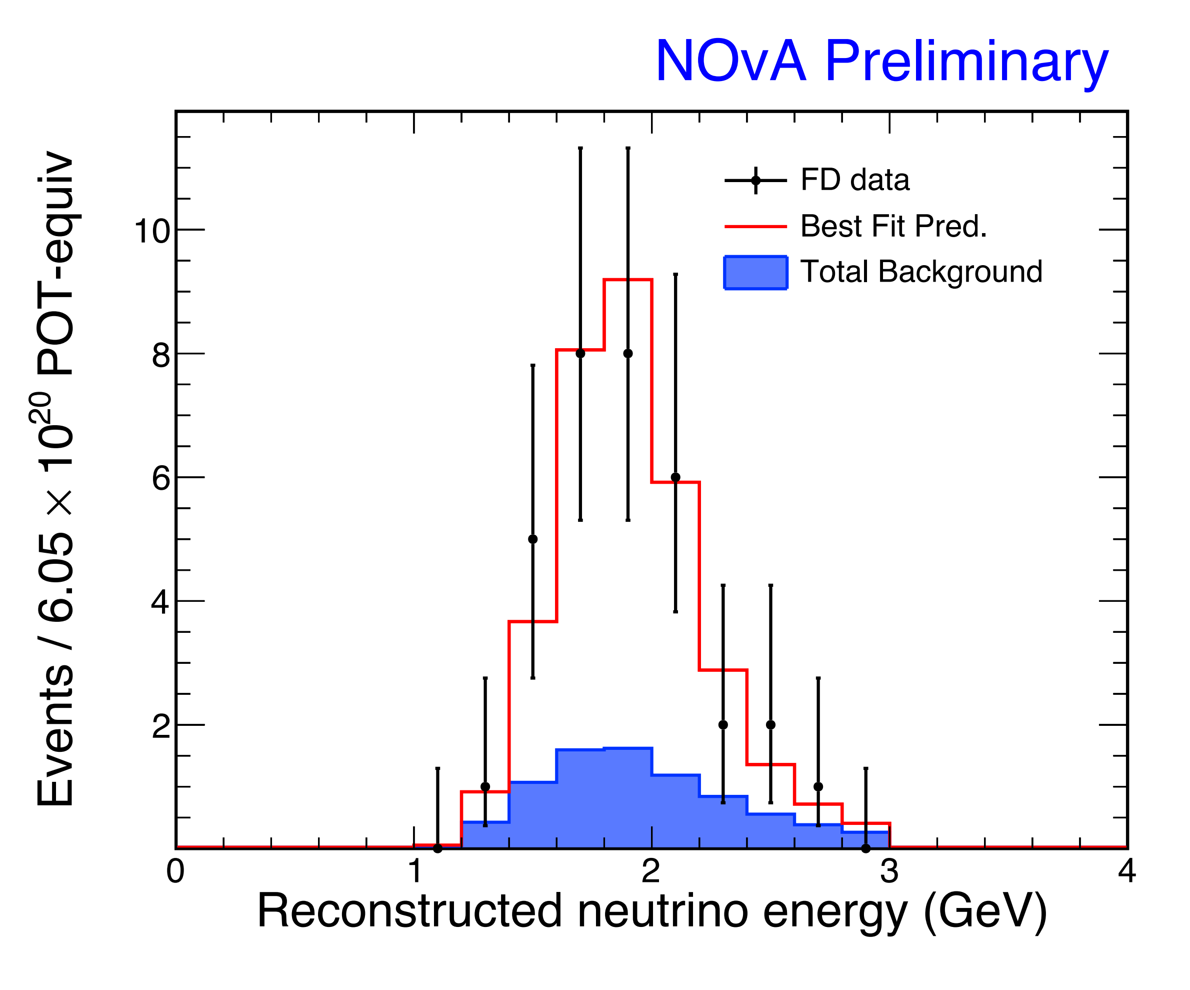
- Observe 33 events for 8.2 expected background events.

- Range of expectation (for maximal mixing):

| NH, 3π/2, | IH, π/2, |
| --- | --- |
| 36 | 19 |

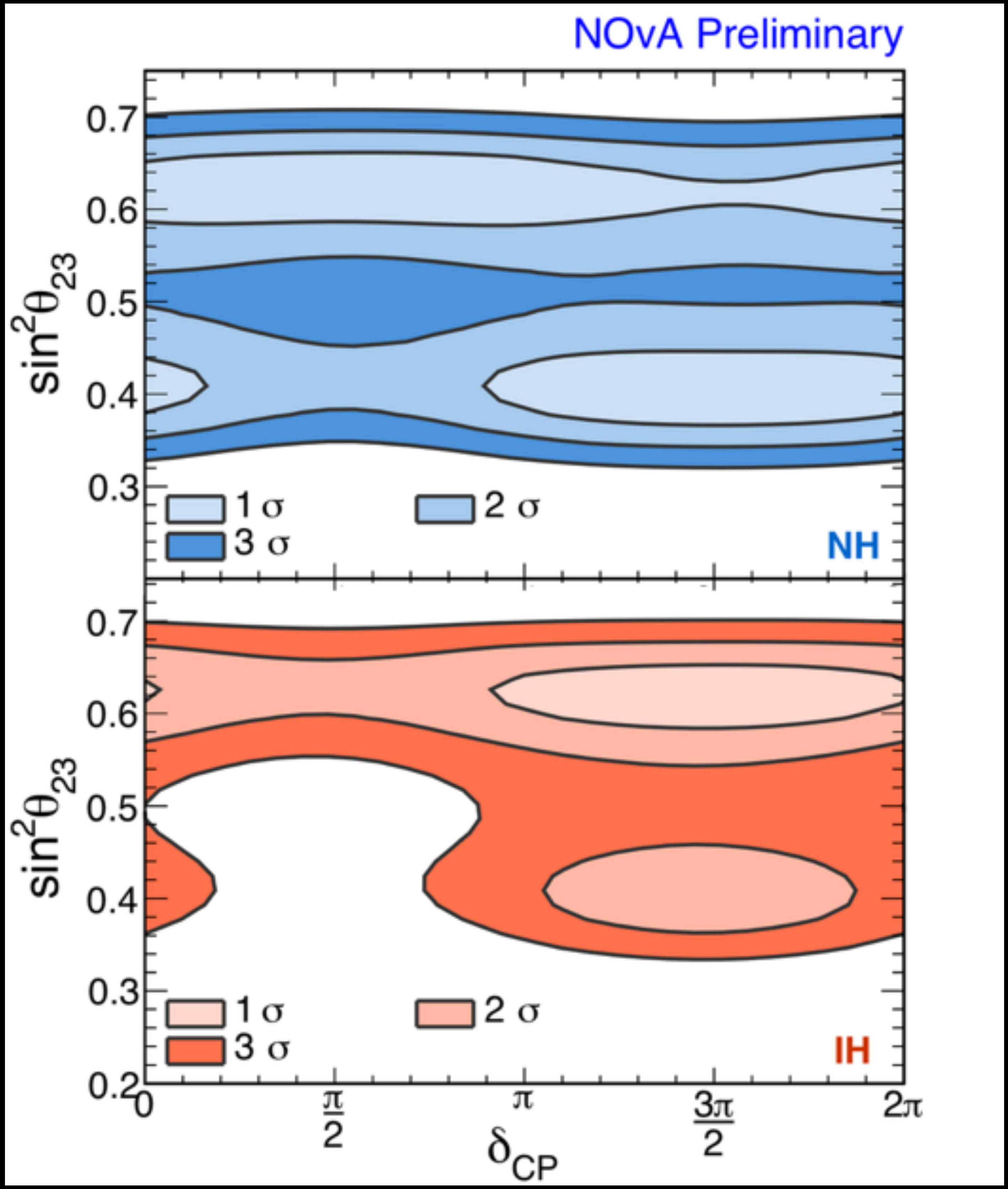
- **Electron neutrino appearance observed at > 8 σ.**



# NOVA ELECTRON NEUTRINO APPEARANCE RESULTS

- Fitting the electron neutrino appearance spectrum with muon neutrino disappearance data which for NOvA hints at a non maximal mixing angle.
- Both octants and hierarchies are allowed at 1σ.
  - Very small $\chi^2$ difference between IH and NH and both octants.
- **NOvA sees a 3σ exclusion at IH, lower octant around $\delta_{CP}$=π/2.**




# THE NEXT GENERATION EXPERIMENTS

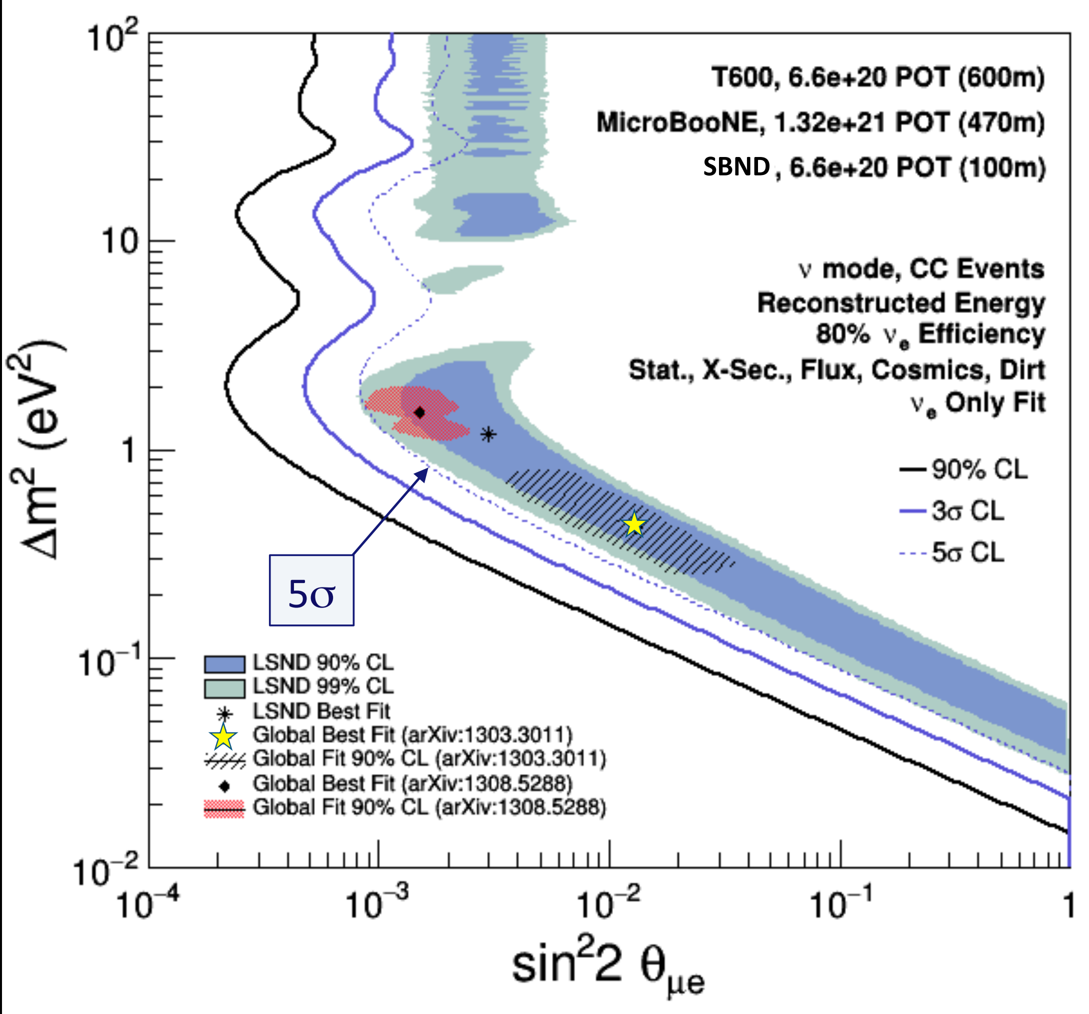
# BEYOND 3 NEUTRINOS

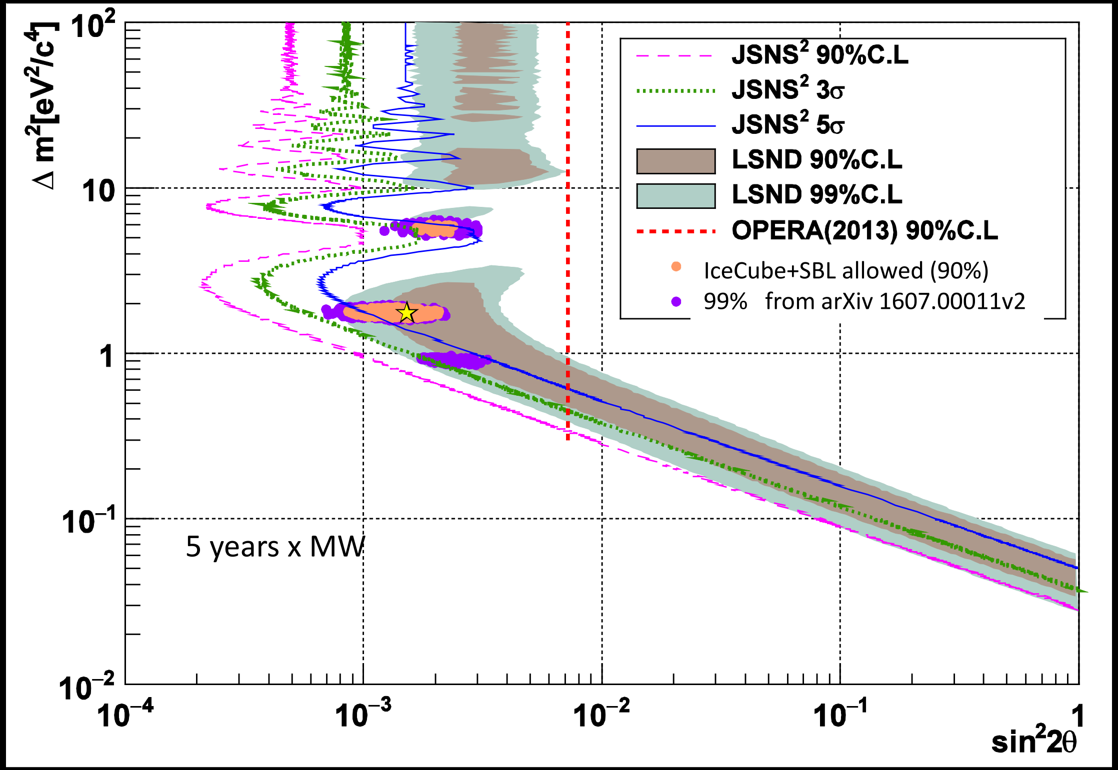
- Evidence for additional neutrinos, that do not interact via the weak current, comes from accelerator short-baseline experiments: LSND (decay at rest) and MiniBooNE (decay in flight). No evidence from long-baseline experiments.

- A short-baseline program (SBN) has begun construction at Fermilab using the booster beam. A 3-detector system (all liquid argon-based) will explore the anomalous hints with coverage of the LSND allowed oscillation parameters in neutrinos at >5$\sigma$.

- In Japan, $JSNS^2$ will seek to use a decay at rest beam to reproduce LSND results directly. Expecting exclusion at 3$\sigma$ of the allowed LSND region.

D. Schmitz - Neutrino 2016

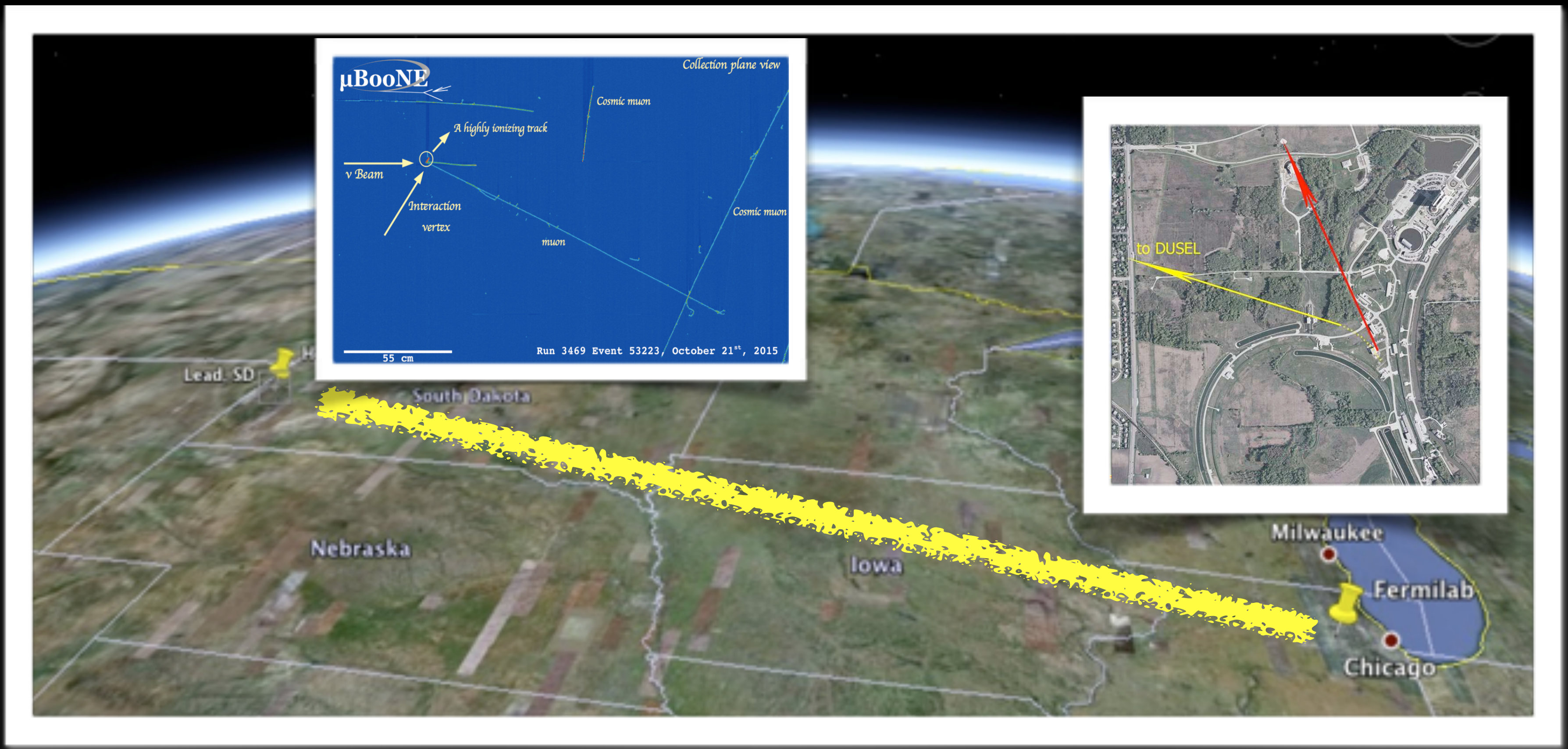



T. Maruyama - ICHEP 2016

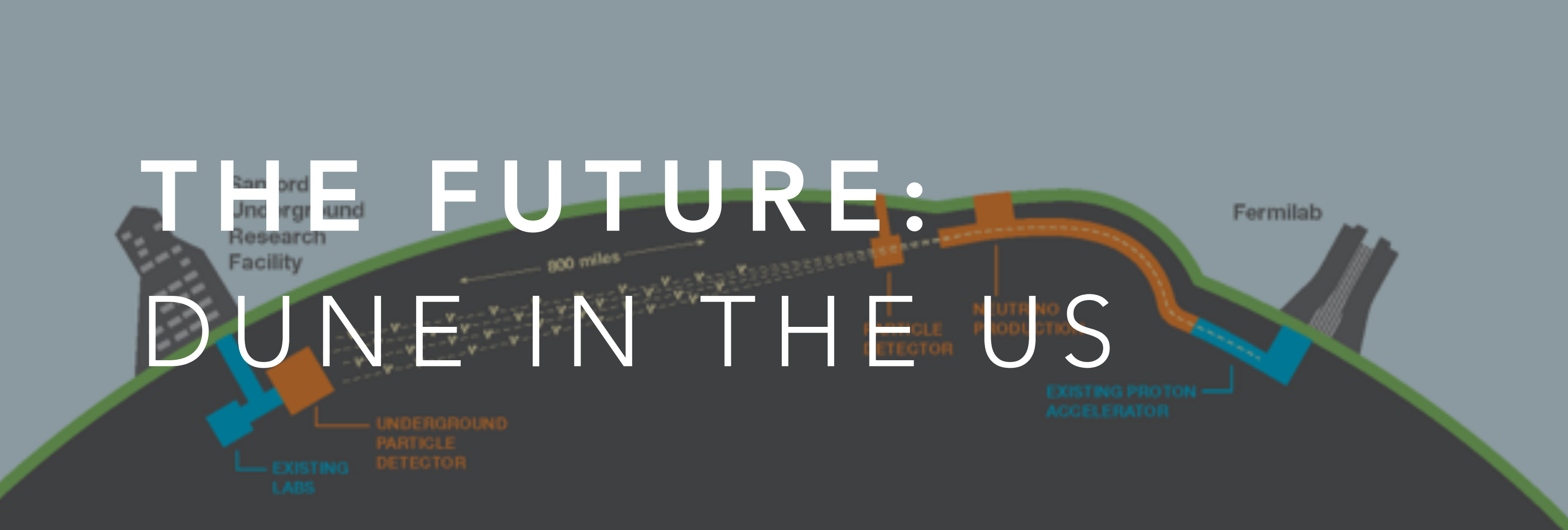
# NEXT GENERATION EXPERIMENTS

- Higher intensity beams can provide more neutrinos and allow for a longer baseline.
- Similarly larger mass can allow to collect more neutrinos.
- Finally higher detector resolution can allow for better background rejection.




- In the US a new experiment (DUNE) is being planned with a baseline of 1300km, a new beam to reach 2.3 MW and  high resolution liquid argon detectors.
- In Japan, an upgrade to the beam to 1.3 MW and a new 500 kton scale detector system is also being planned as part of the T2HK program.

# THE FUTURE: DUNE IN THE US




2017: Far Site Construction Begins

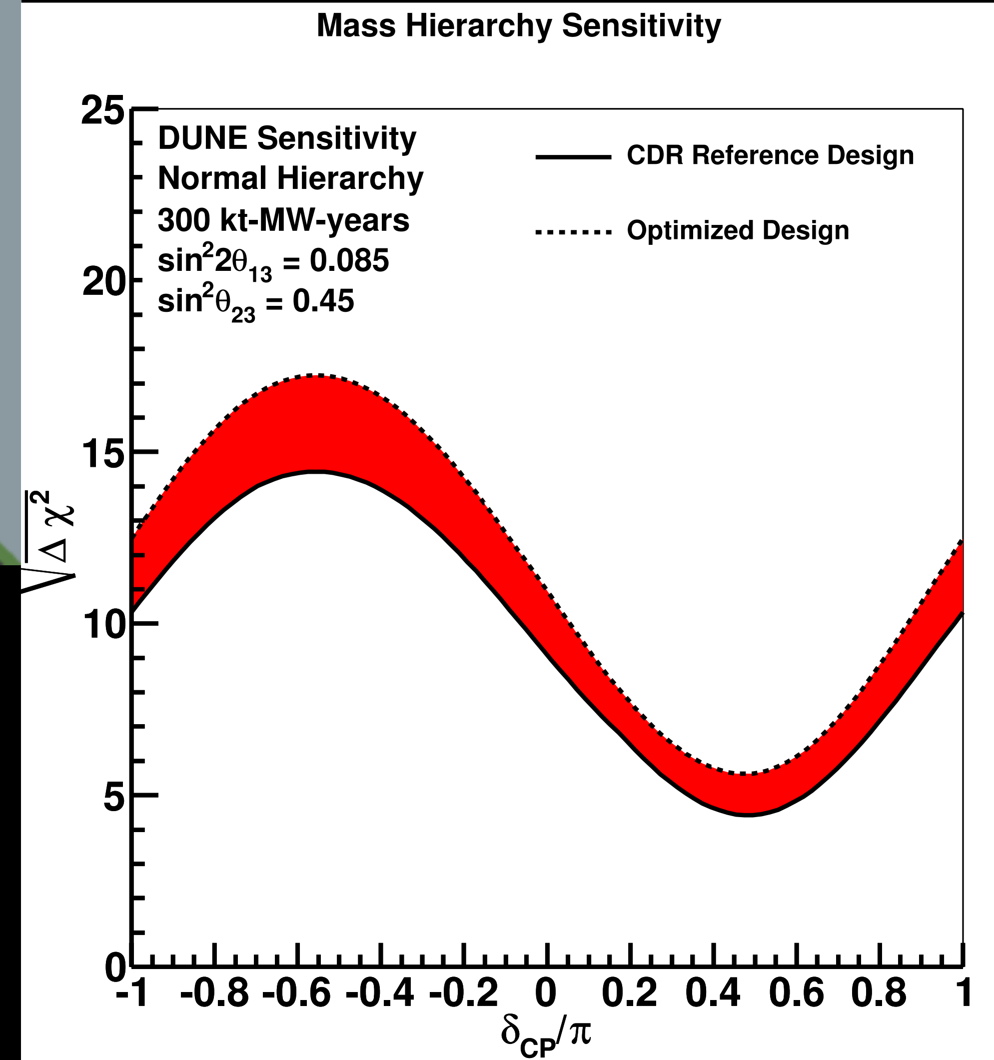
2018: protoDUNEs at CERN

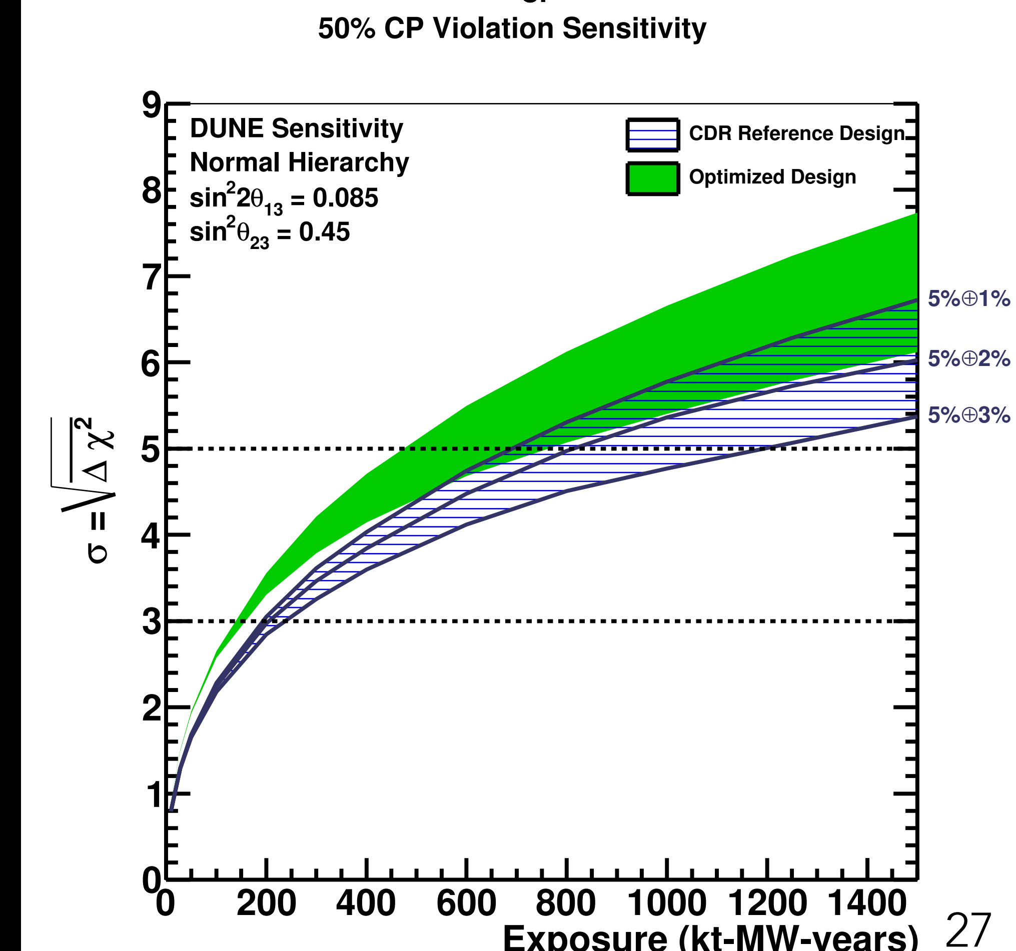
2021: Far Detector Installation Begins

2024: Physics Data Begins (20 kt)

2026: Neutrino Beam Available

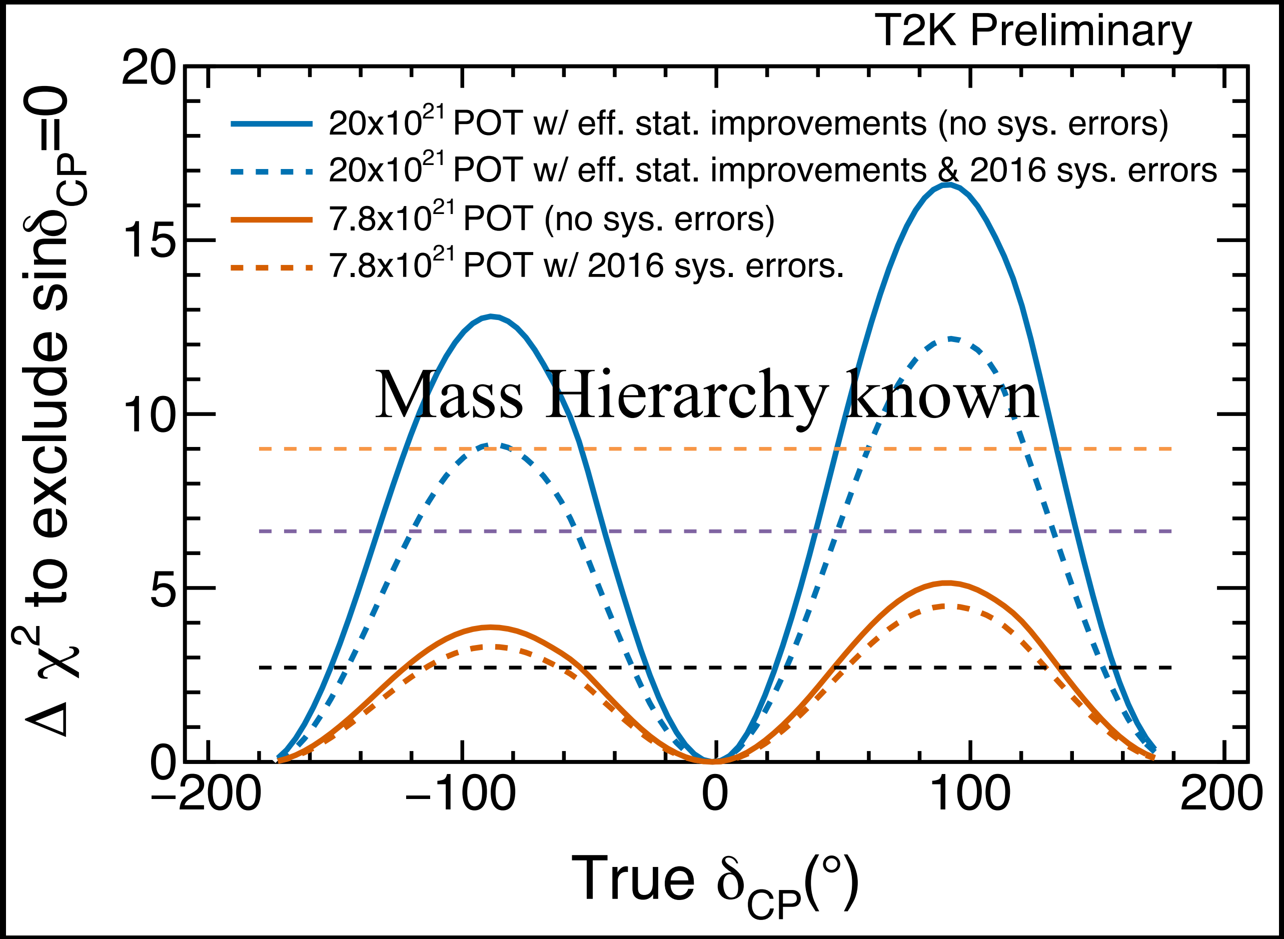
- The US program plans to build:
  - 40 kton liquid argon underground detector in four 10-kton (fiducial) modules. Far Site construction begins next year.
  - A wide-band beam from Fermilab (1300km baseline) at 2.3 MW by 2026.
- The mass hierarchy can be determined above 5$\sigma$ for all values of $\delta_{CP}$.
- CPV at 5$\sigma$ ($\delta$CP = -$\pi$/2 or 3$\pi$/2 ) where the uncertainty in the $\nu_e$ appearance sample normalization has an impact on reach.

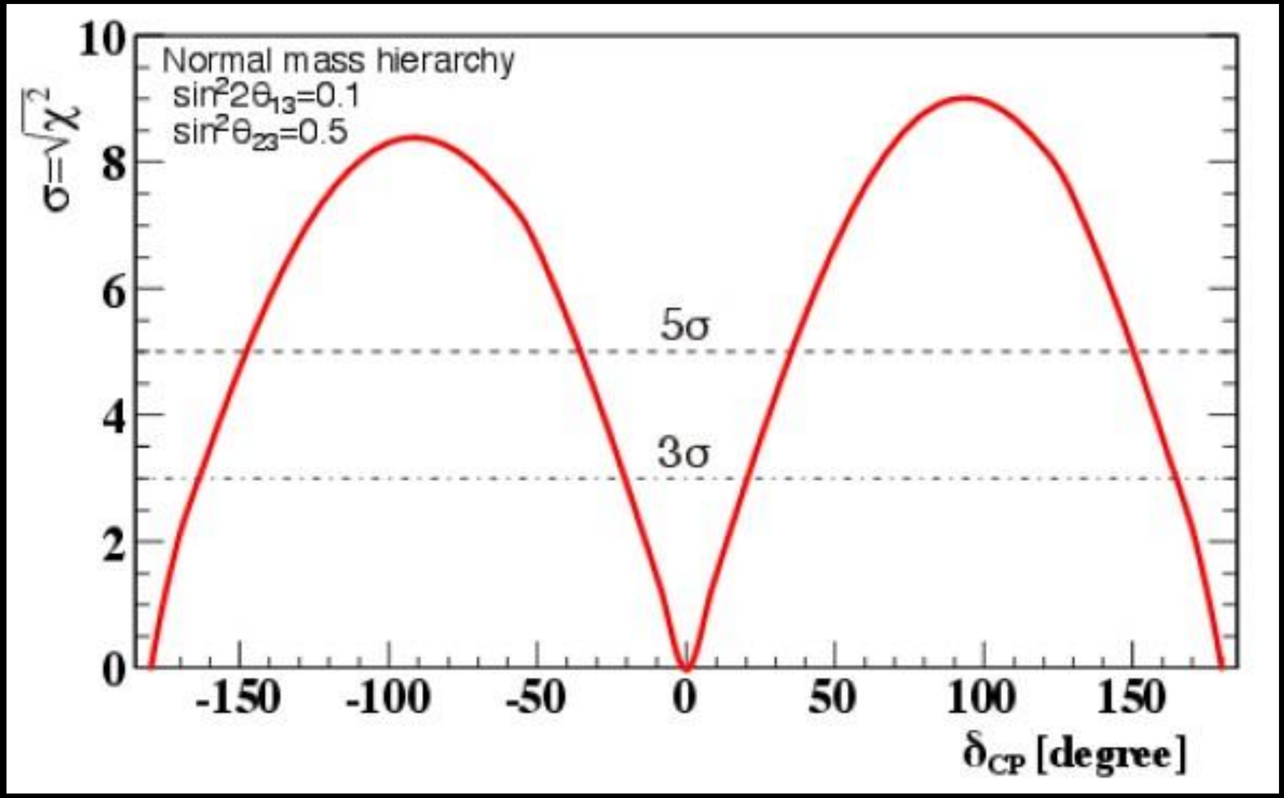


# THE FUTURE: T2HK IN JAPAN

- Current T2K program expects 7.8 x $10^{21}$ Protons on Target (POT) by 2020.
  - Potential extension (T2K-II) would have 20 x $10^{21}$ POT by 2026.
  - ~3$\sigma$ sensitivity to $\boldsymbol{\delta}_{CP}$.
- Requires accelerator and beam-line upgrades to reach 1.3 MW. Currently at 420 kW.
- While T2K-II is running, construction of the next generation detector (Hyper-Kamiokande) begins:
  - By 2026 build 2 large Water Cherenkov of 260 kton each.
  - >5$\sigma$ sensitivity to $\boldsymbol{\delta}_{CP}$.






K. Iwamoto & M. Gonin - ICHEP 2016

# SUMMARY

- Many new results have been released from the accelerator experiments this summer:
  - NOvA observes hints of non maximal mixing.
  - T2K does not find evidence of CPT.
  - T2K excludes CP conservation at 90%.
  - NOvA excludes a CP region of inverted hierarchy for the lower octant.
- The next generation of long-baseline experiments with more mass, more baseline and more detector resolution is being planned.
- Better precision will allow us to test the 3-flavor neutrino oscillation framework.
- Outside of the 3-flavor framework, tests in long-baseline accelerator experiments find no evidence so far for sterile neutrinos beyond LSND and MiniBooNE. A new program using short baseline and decay at rest techniques to study these neutrinos is in progress.

Stay tuned for more data!

# BACKUP

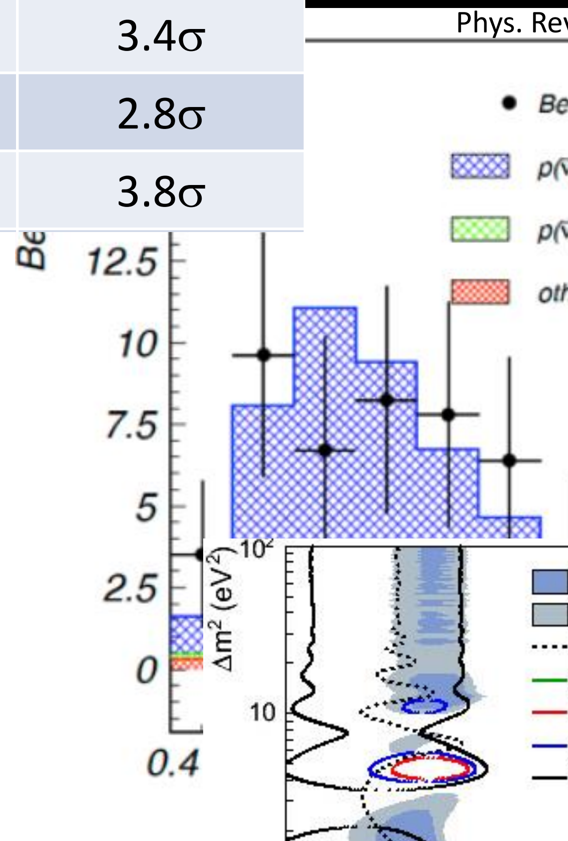
# BEYOND 3 NEUTRINOS

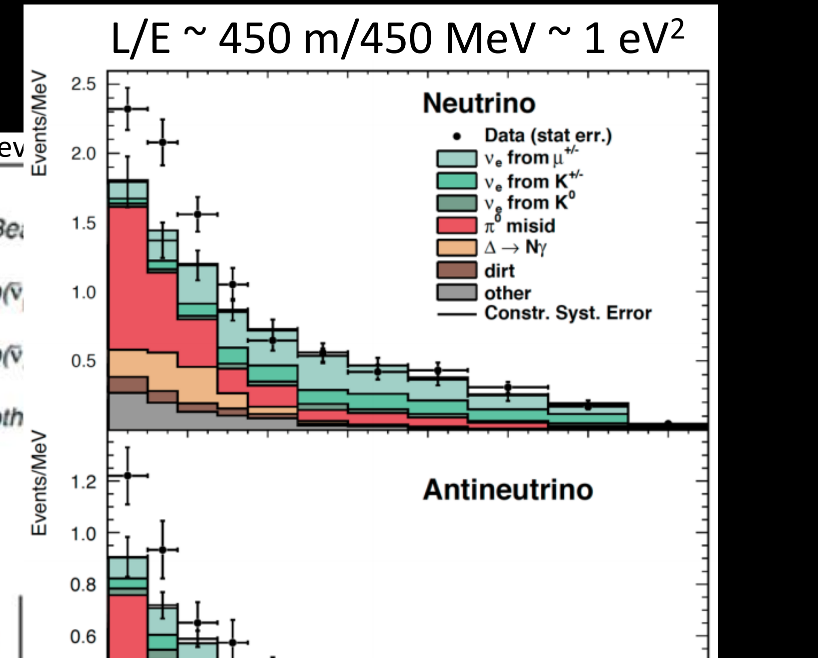
- Some evidence for additional neutrinos, that do not interact via the weak current comes from accelerator experiments: LSND (decay at rest) and MiniBooNE (decay in flight).

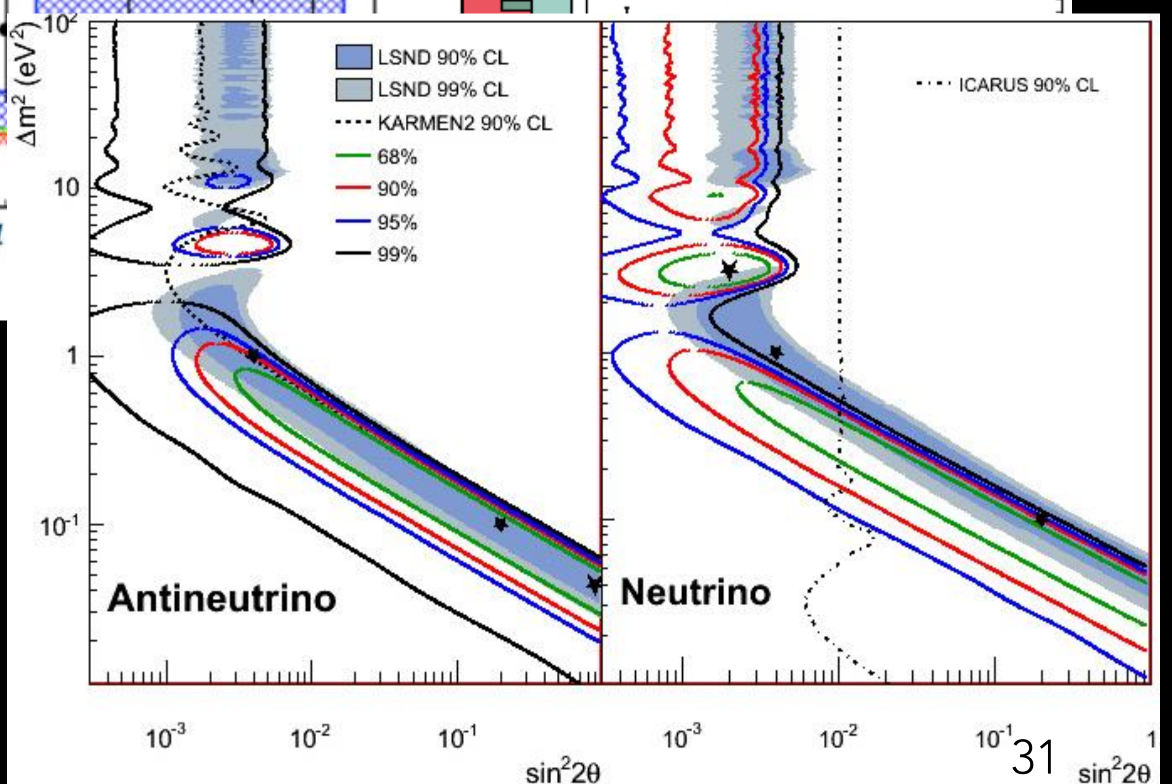
| Experiments | Neutrino source | signal | significance |
|---|---|---|---|
| LSND | $\mu$ Decay-At-Rest | $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ | 3.8$\sigma$ |
| MiniBooNE | $\pi$ Decay-In-Flight | $\nu_\mu \rightarrow \nu_e$ | 3.4$\sigma$ |
| | | $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ | 2.8$\sigma$ |
| | | combined | 3.8$\sigma$ |

- In order to accommodate this evidence within neutrino oscillations, sterile neutrinos have been proposed expanding the the 3x3 mixing matrix.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

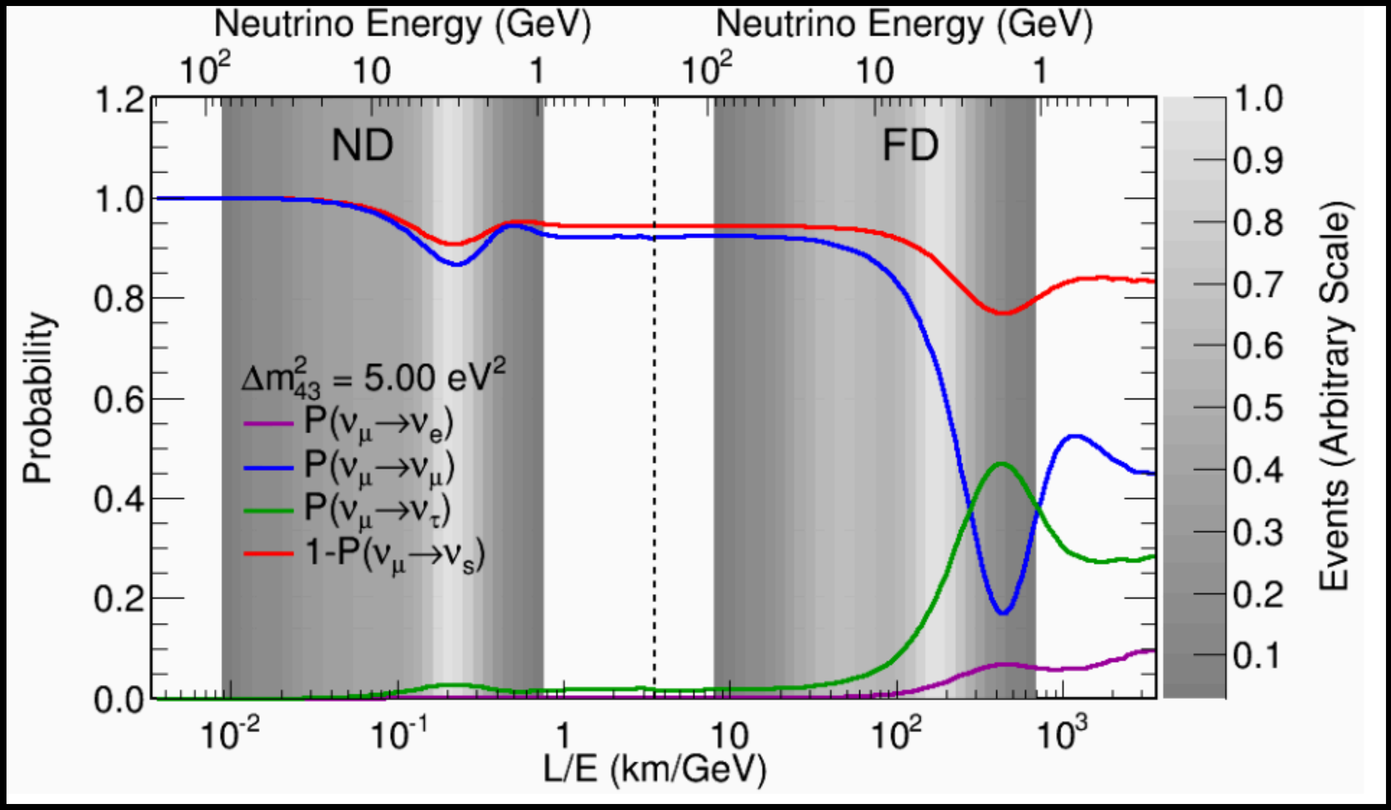


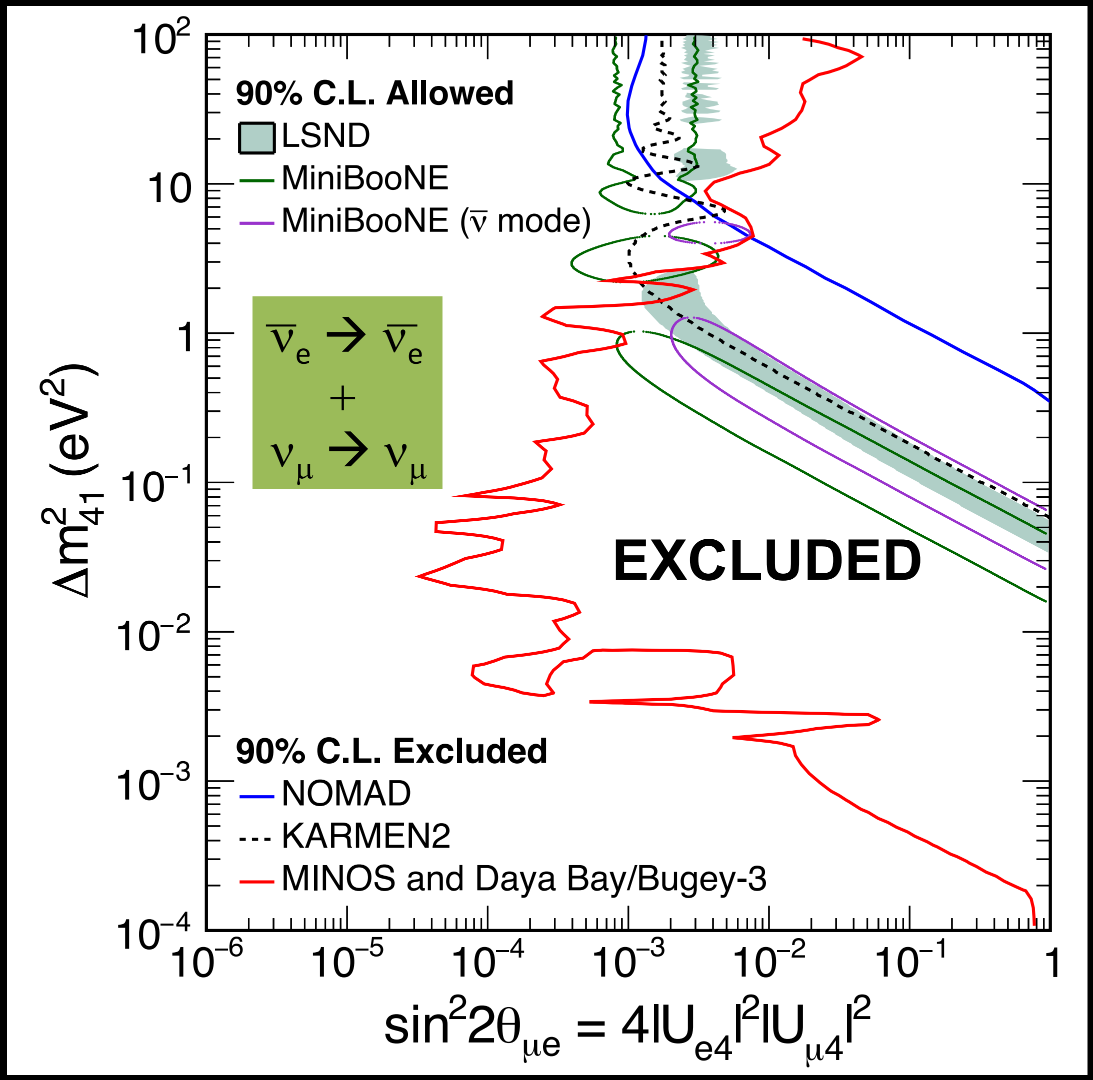



# LOOKING FOR STERILES TODAY

- Sterile neutrinos can be searched for using short as well as long-baseline experiments.
- In long-baseline the observation of neutral current below expectation and energy distortions of the 3-flavor oscillations would be tell tale signs. MINOS and NOvA have done these measurements.
- Other results from non-accelerators: reactors, atmospherics can be combined with these results.



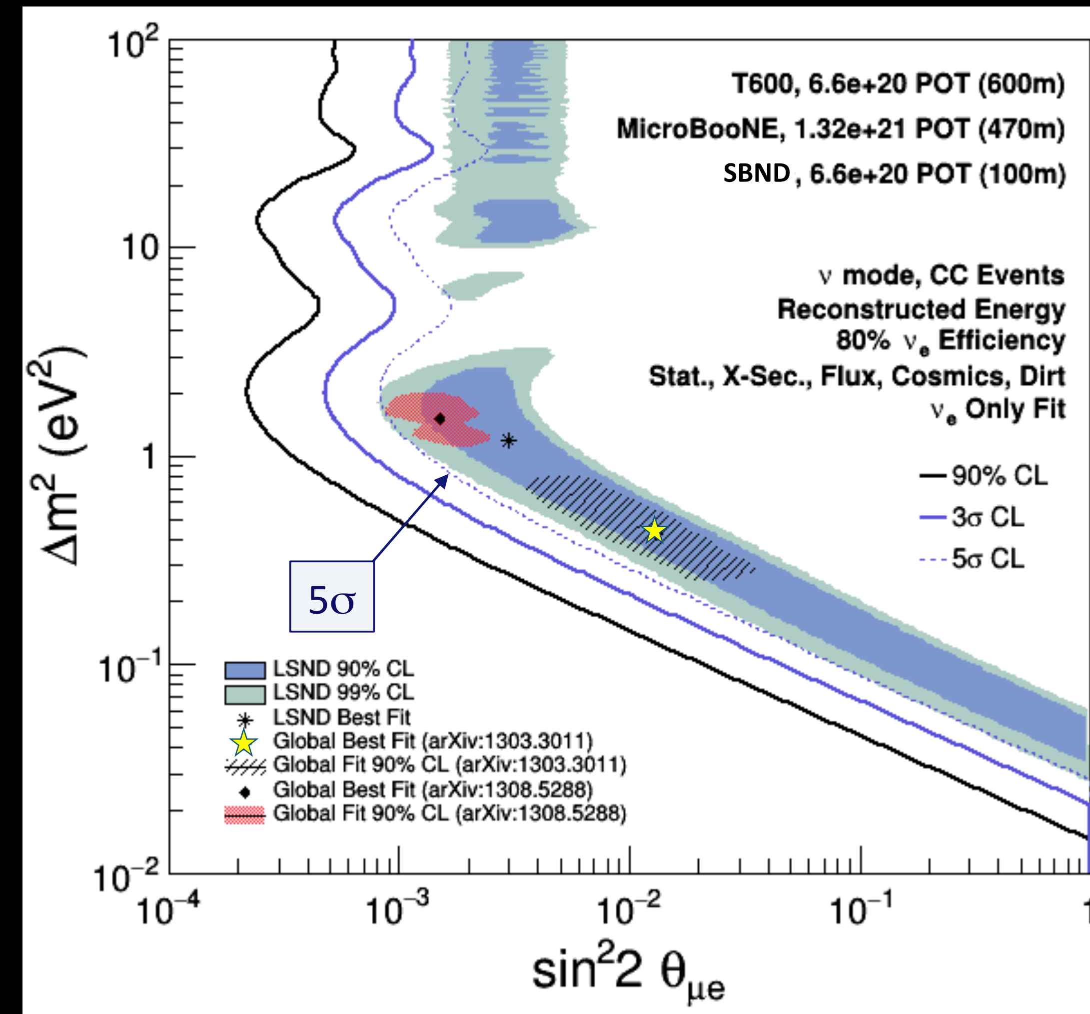



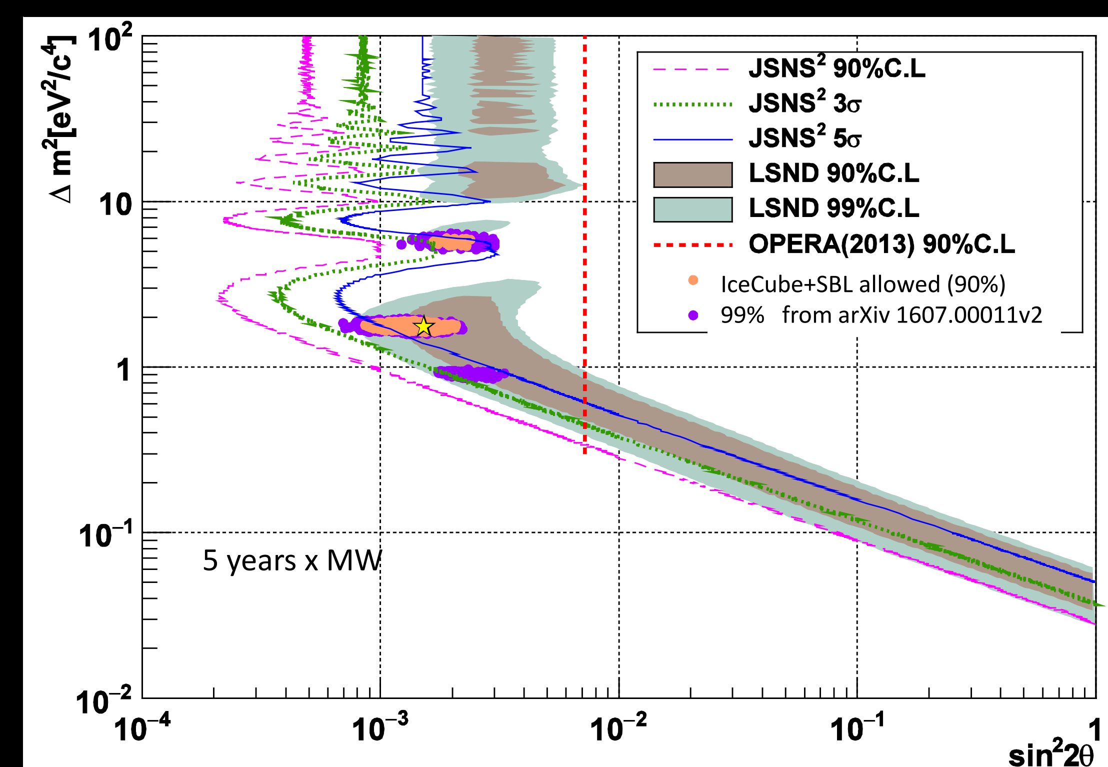

J. Evans - Neutrino 2016

# FUTURE STERILE SEARCHES

- A short-baseline program (SBN) has begun construction at Fermilab using the booster beam.
- A 3-detector system (SBND, MicroBooNE and ICARUS - all liquid argon-based) will explore the anomalous hints of new physics in the neutrino sector with coverage of the LSND allowed oscillation parameters in neutrinos at >5σ.
- In Japan, $JSNS^2$ will seek to use a decay at rest beam to reproduce LSND results directly. Expecting exclusion at 3σ of the allowed LSND region.

D. Schmitz - Neutrino 2016

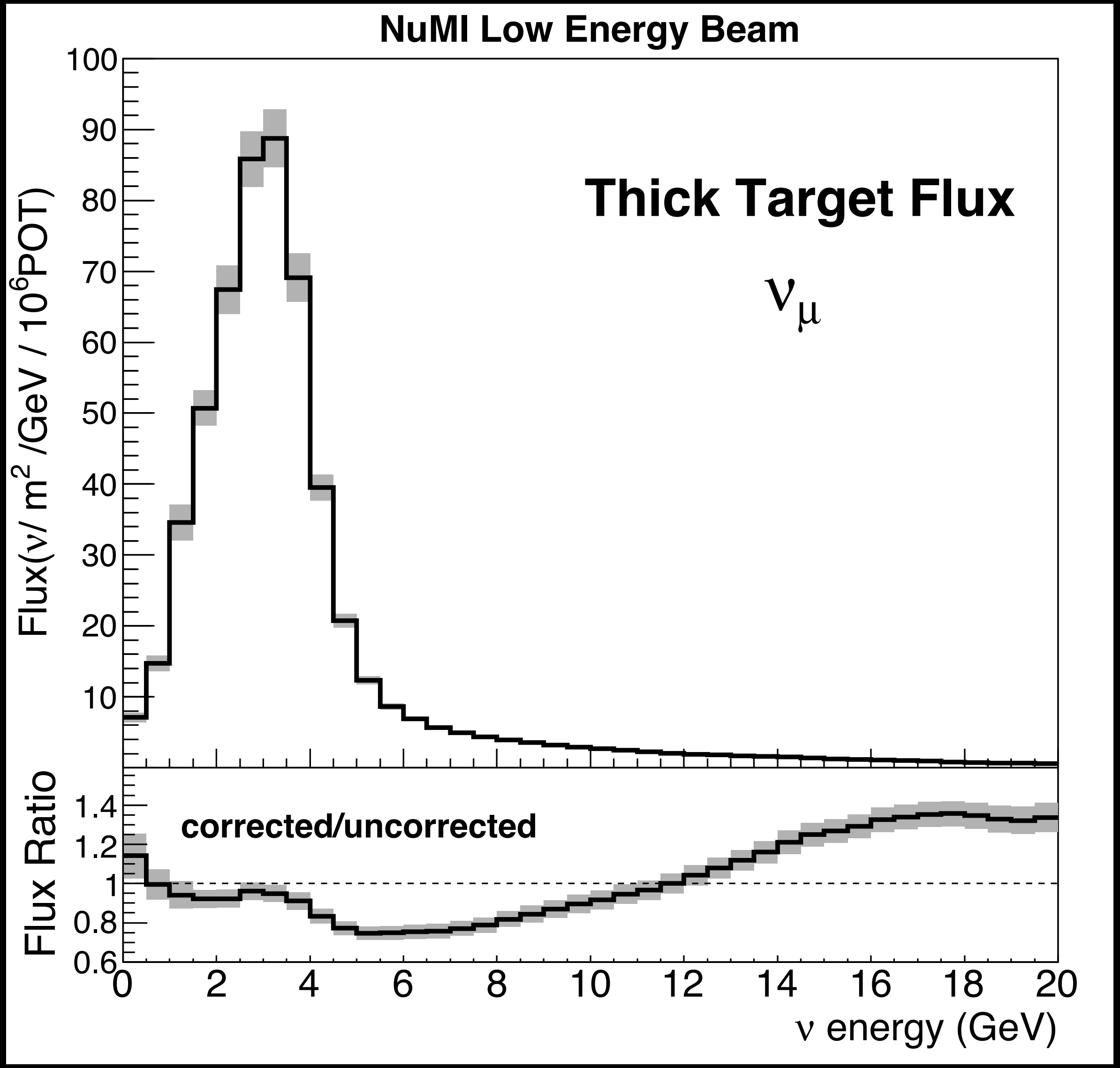


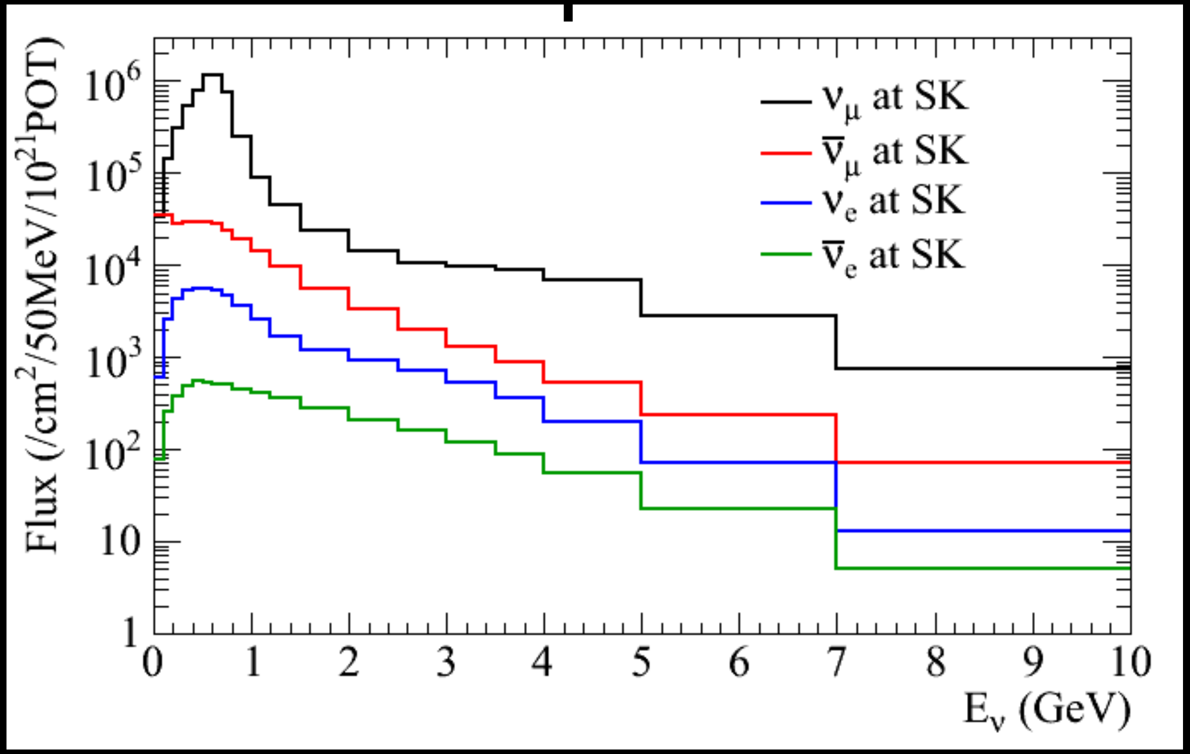




T. Maruyama - ICHEP 2016

# IMPROVING OUR UNDERSTANDING OF THE BEAM

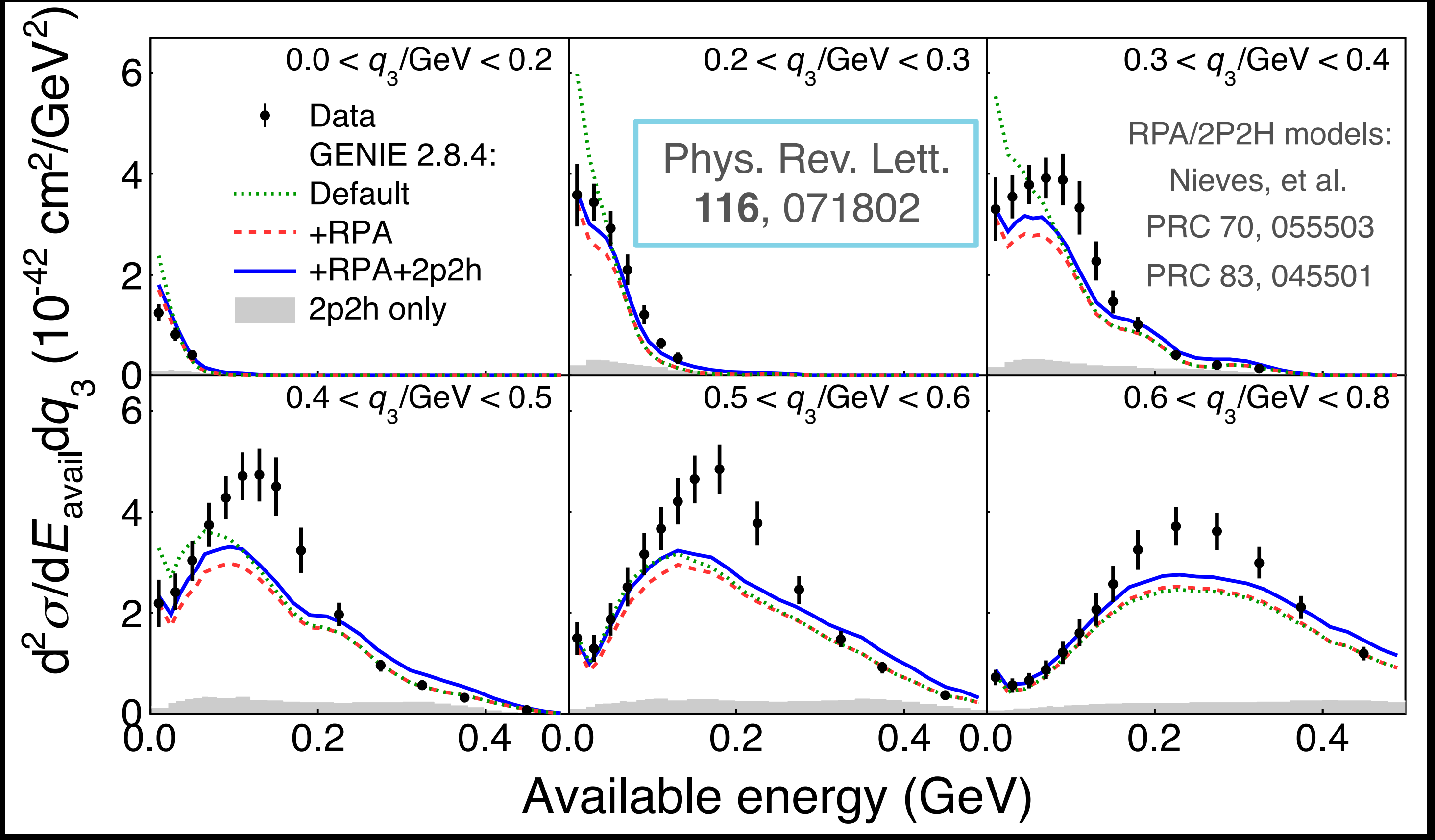
- While most of the uncertainties cancel for functionally identical Near/Far detectors, experiments must be able to measure cross sections and this requires knowledge of the flux.
  - A new method to constraint the NUMI flux to 5.4% overall errors and ~7% at the peak for numi (arXiv:1607.00704)
- For non-identical detector like T2K a program that disentangles beam flux and cross sections is even more essential.
  - T2K has been able to reduce errors from 12-15% to 5-8%.
  - Next generation needs few % uncertainties.

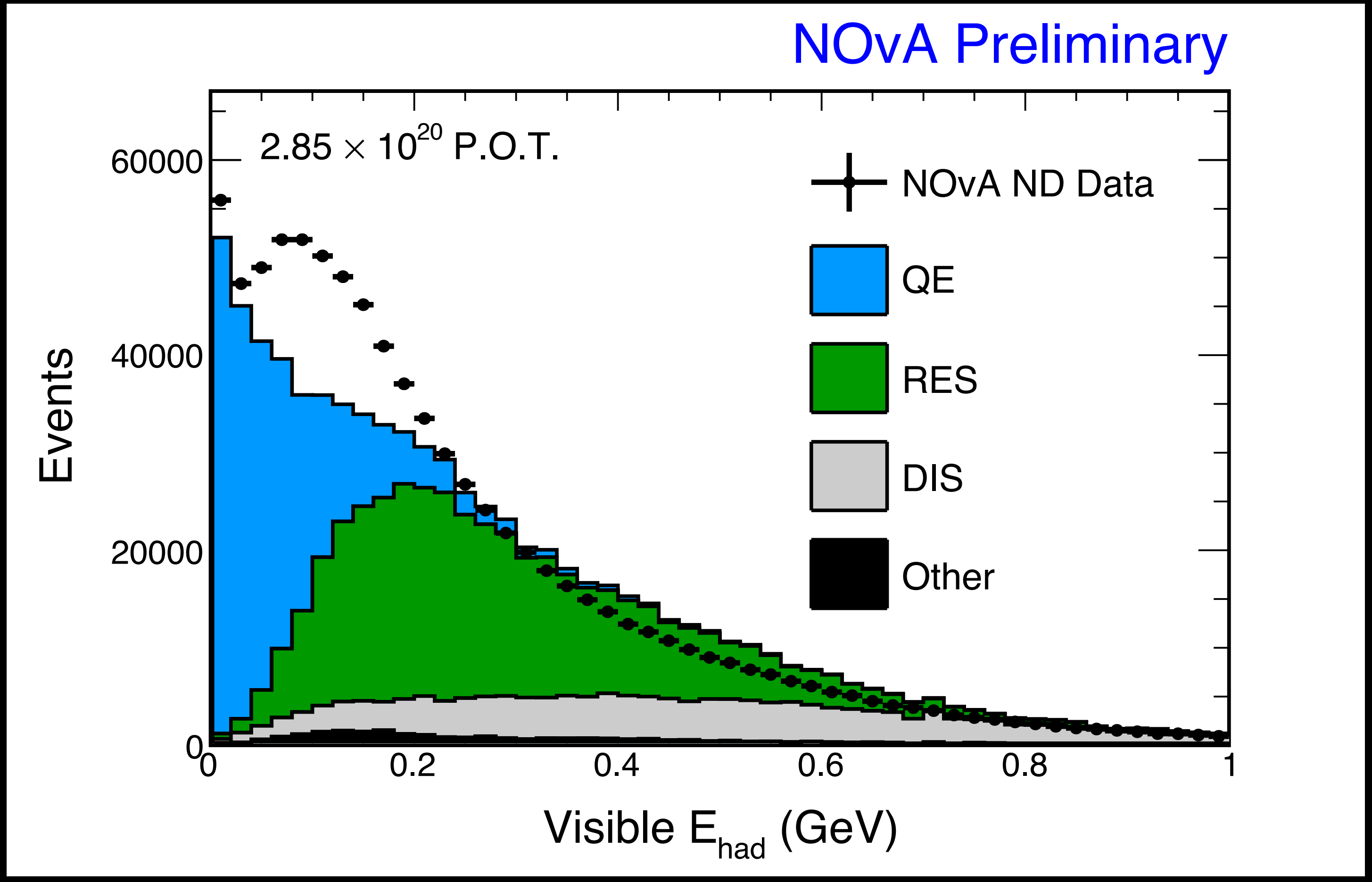


# IMPROVING OUR UNDERSTANDING OF NEUTRINO INTERACTIONS

- The MINERvA experiment runs on the NUMI beam studying neutrino interactions.
- High statistic samples puts in evidence the need for better modeling/data.
- MINERvA has found disagreement in muon neutrino charged selected events as a function of momentum transfer.
  - NOvA has observed a similar effect.
- A part of this observed disagreement is explained by the absence of meson exchange currents or 2p2h processes in the simulation.



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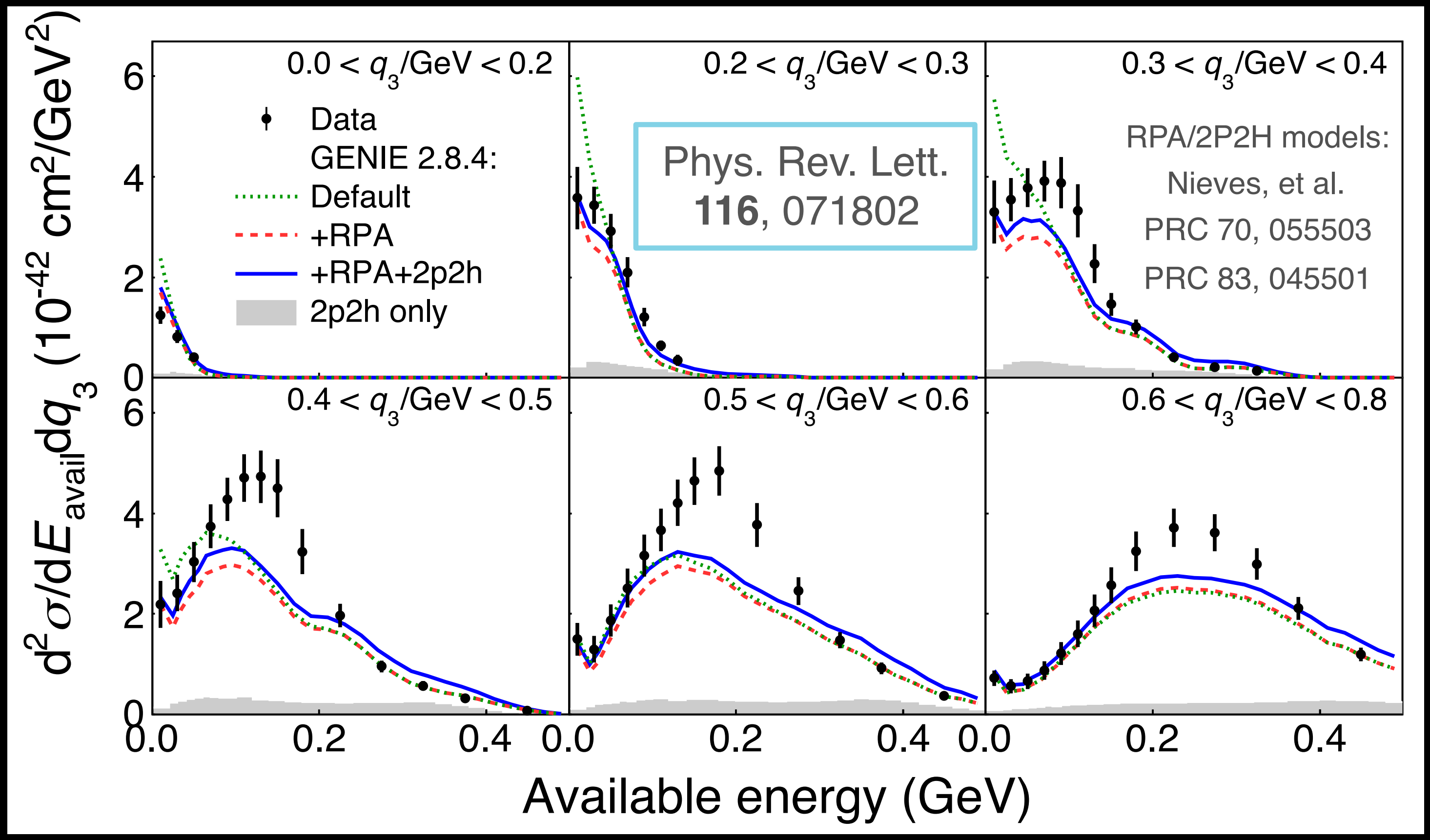
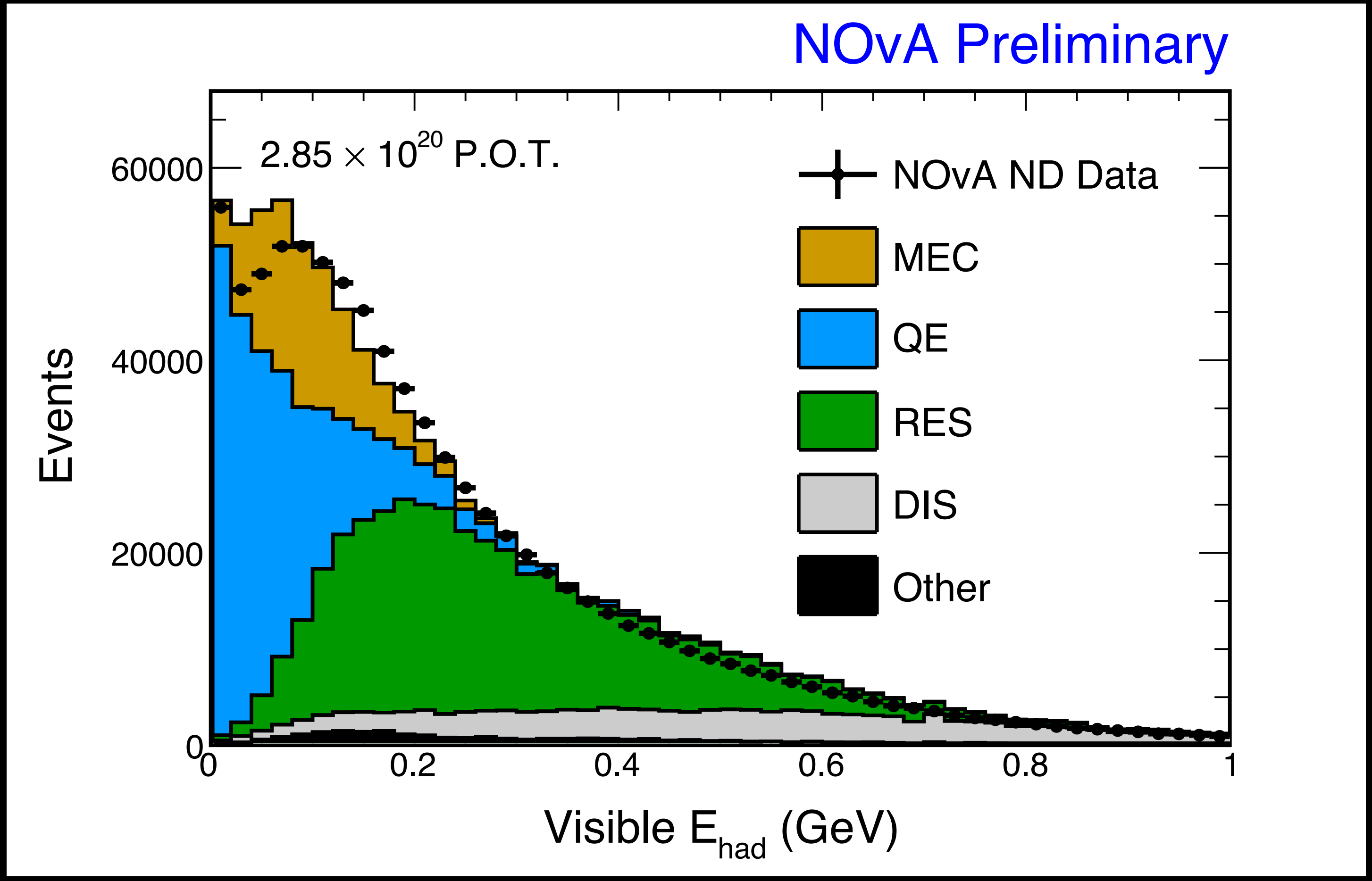
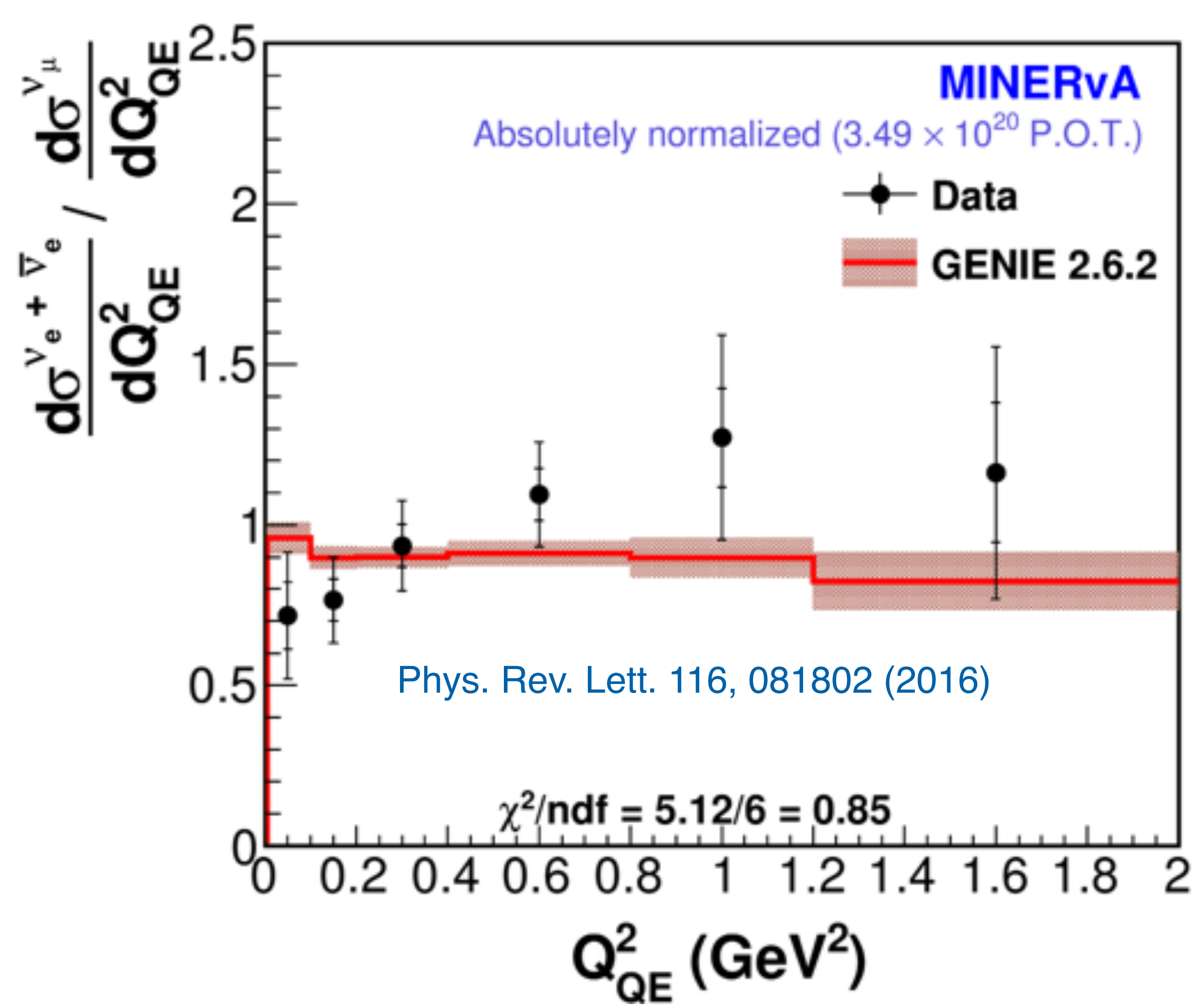
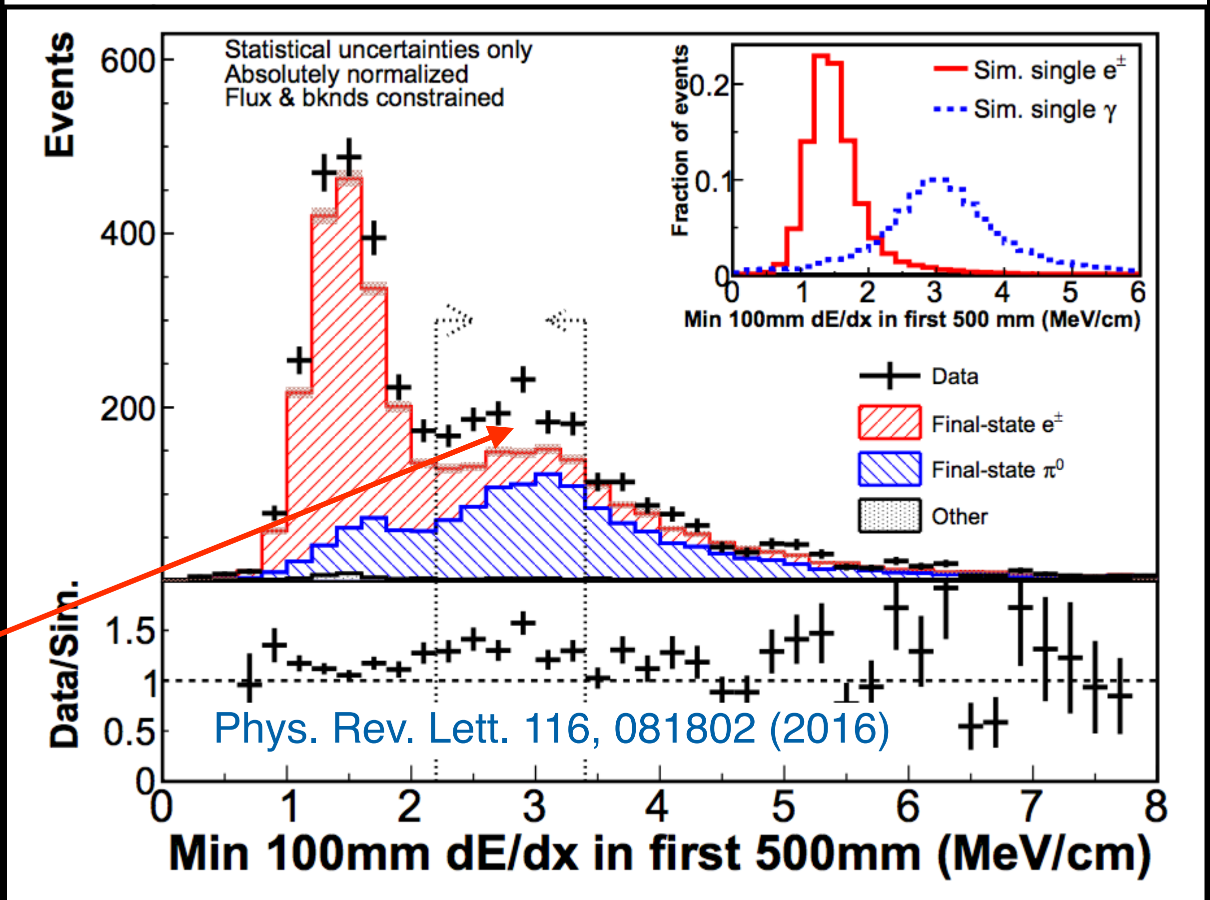


# IMPROVING THE SIGNAL PREDICTION

- Large statistics for the appearance signal implies that we need to keep the systematic uncertainties at the few percent level.
- In long-baseline appearance experiments, signal at FD is $\nu_e$ (for a $\nu_\mu$ beam), so cross-section uncertainties do not cancel out between ND and FD.
- MINERvA, T2K and NOvA have presented results.
  - MINERvA recently encountered additional background from neutral current diffractive pion production.

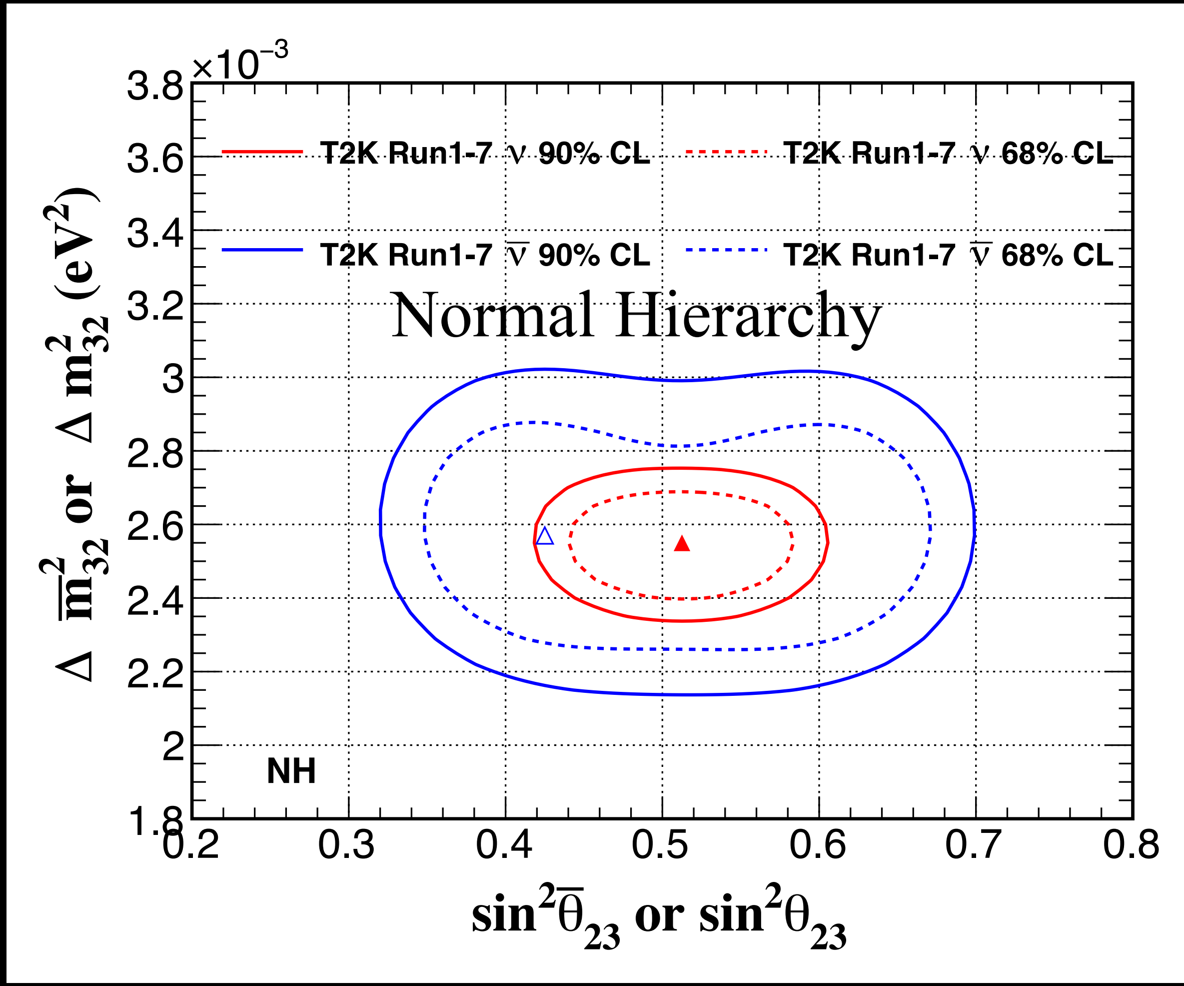


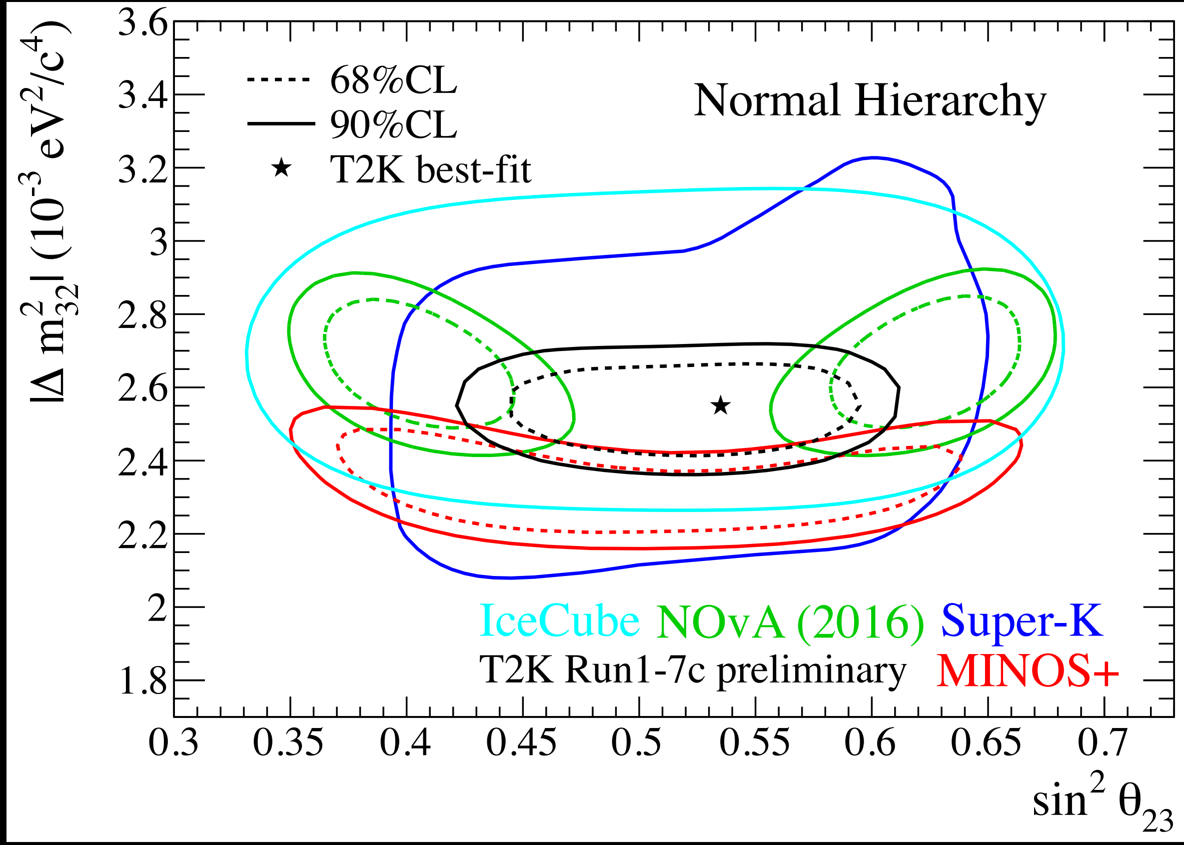



# T2K MUON NEUTRINO AND ANTINEUTRINO DISAPPEARANCE RESULTS

- T2K results are consistent with maximal mixing for both neutrinos and antineutrinos.
  - No hint of CPT within errors.
  - The best fit for antineutrinos is slightly non-maximal.
- This result agrees with previous MINOS results.
- Small amount of tension between T2K's maximal and NOvA's non-maximal result. More data should resolve this.

| | NH | IH |
|---|---|---|
| $\sin^2\theta_{23}$ | $0.532^{+0.046}_{-0.068}$ | $0.534^{+0.043}_{-0.066}$ |
| $\|\Delta m^2_{32}\|[10^{-3}\mathrm{eV}^2]$ | $2.545^{+0.081}_{-0.084}$ | $2.510^{+0.081}_{-0.083}$ |



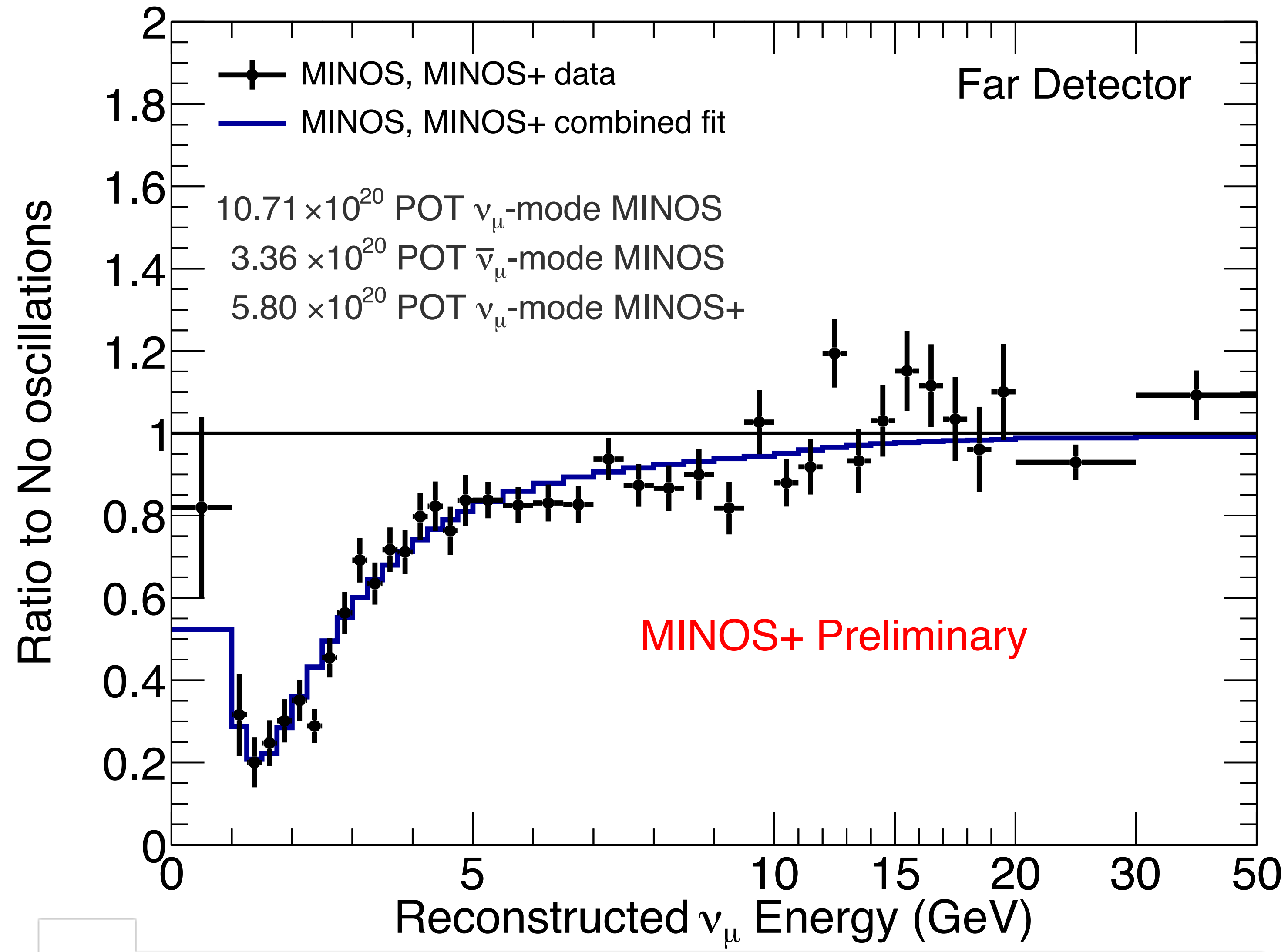



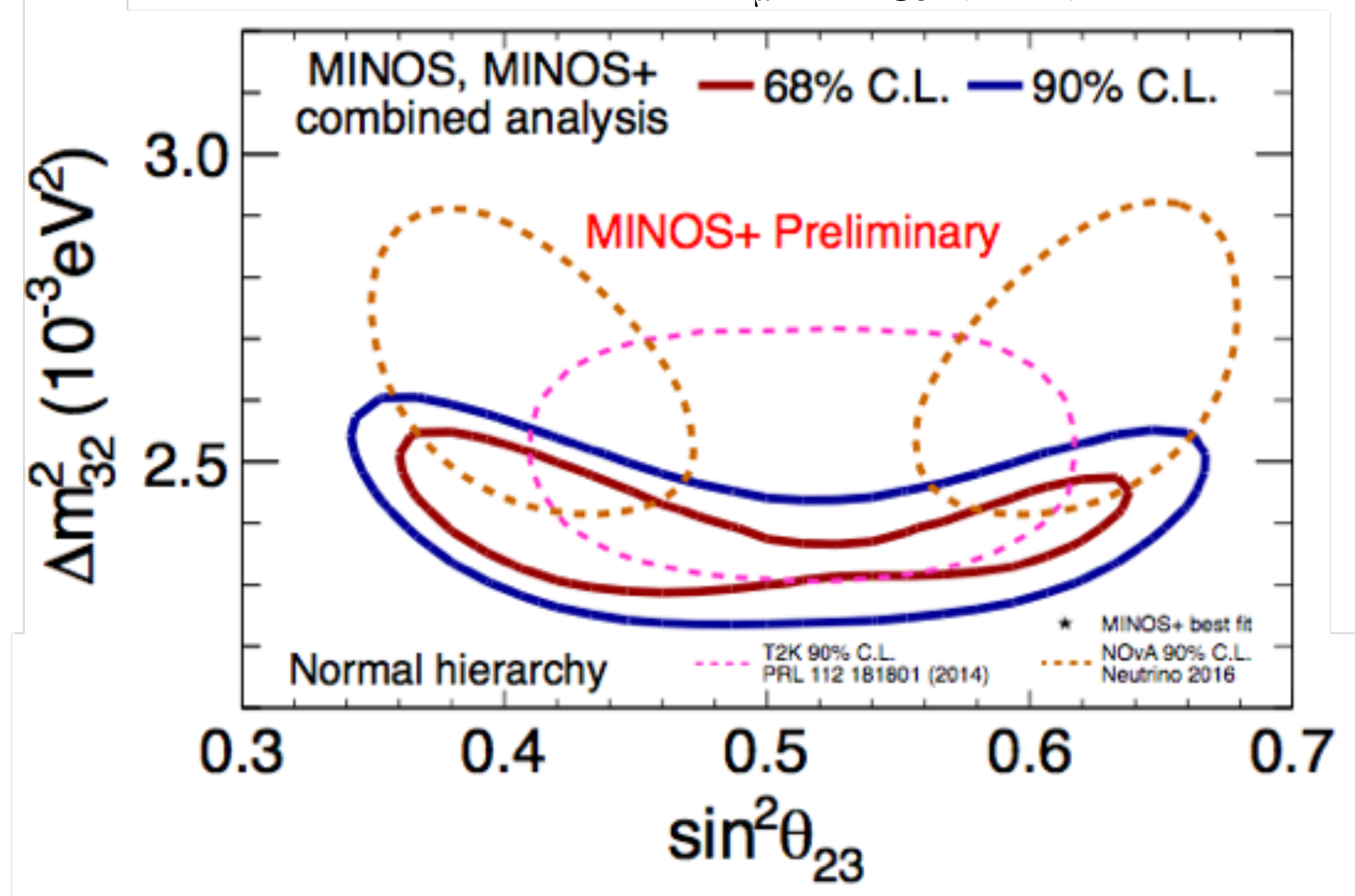
# MINOS: AN ON-AXIS EXPERIMENT ON THE NUMI BEAM

- MINOS and MINOS+ combines data from low energy and high energy beam running to fill-in the spectrum observed by the iron-calorimeter.
- Using additional atmospheric and electron neutrino appearance data, they observe a slight octant preference.
  - Best fit is in the lower octant (IH).

$$\Delta m^2_{32} = \begin{cases} 2.42 \pm 0.09 \times 10^{-3}\,\mathrm{eV}^2 & \text{Normal} \\ -2.48^{+0.09}_{-0.11} \times 10^{-3}\,\mathrm{eV}^2 & \text{Inverted} \end{cases}$$

$$\sin^2(\theta_{23}) = \begin{cases} 0.35\text{–}0.65\,(90\%\ \text{C.L.}) & \text{Normal} \\ 0.35\text{–}0.66\,(90\%\ \text{C.L.}) & \text{Inverted} \end{cases}$$



# ELECTRON NEUTRINO APPEARANCE

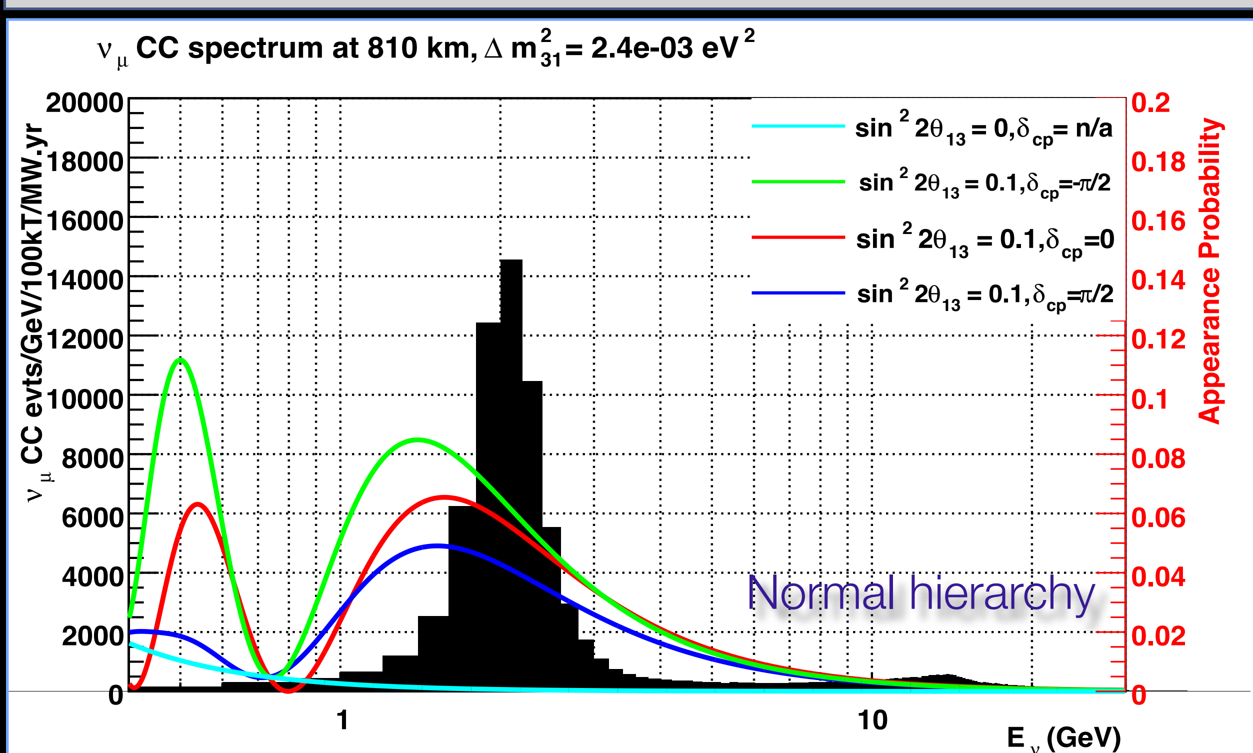
- The probability of $\nu_e$ appearance in a $\nu_\mu$ beam:

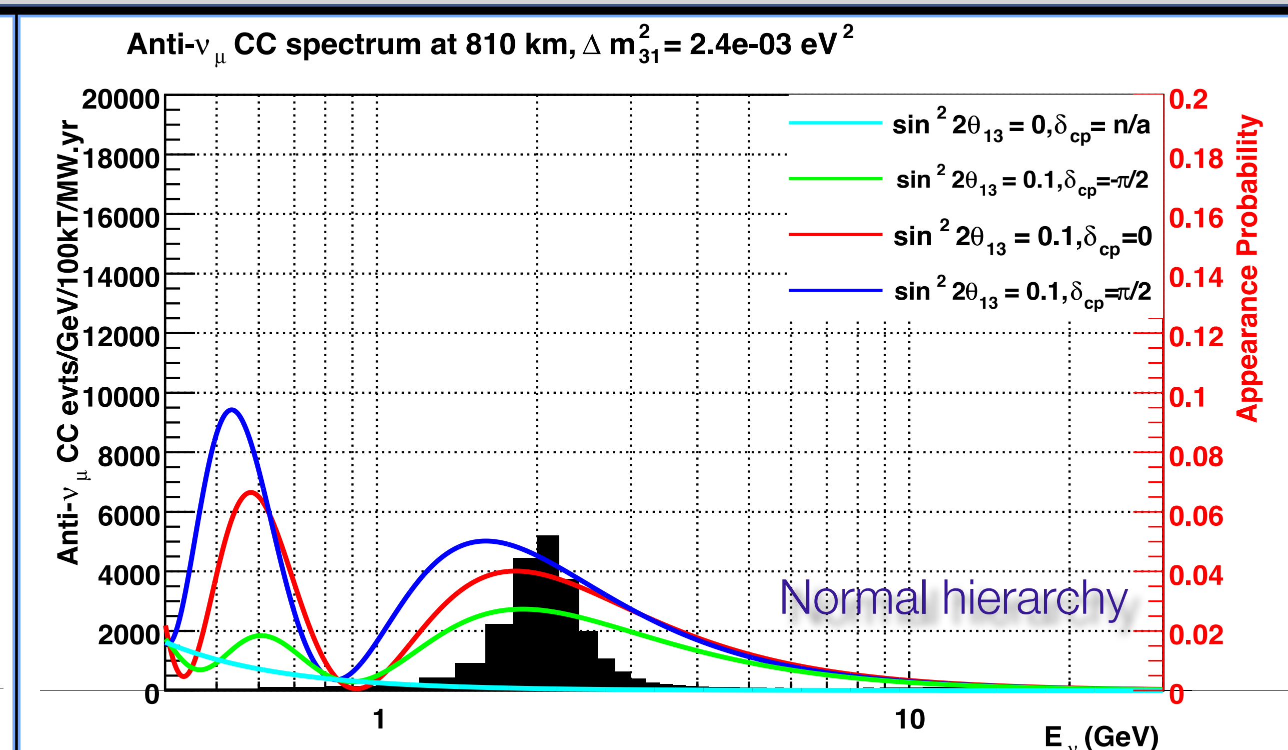
$$A \equiv \frac{G_f n_e L}{\sqrt{2}\Delta} \approx \frac{E}{11\ \mathrm{GeV}}$$

$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2(A-1)\Delta}{(A-1)^2} \qquad \Delta \equiv \frac{\Delta m^2_{31} L}{4E}$$

$$+2\alpha \sin\theta_{13}\cos\delta \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \cos\Delta$$

$$-2\alpha \sin\theta_{13}\sin\delta \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \sin\Delta$$



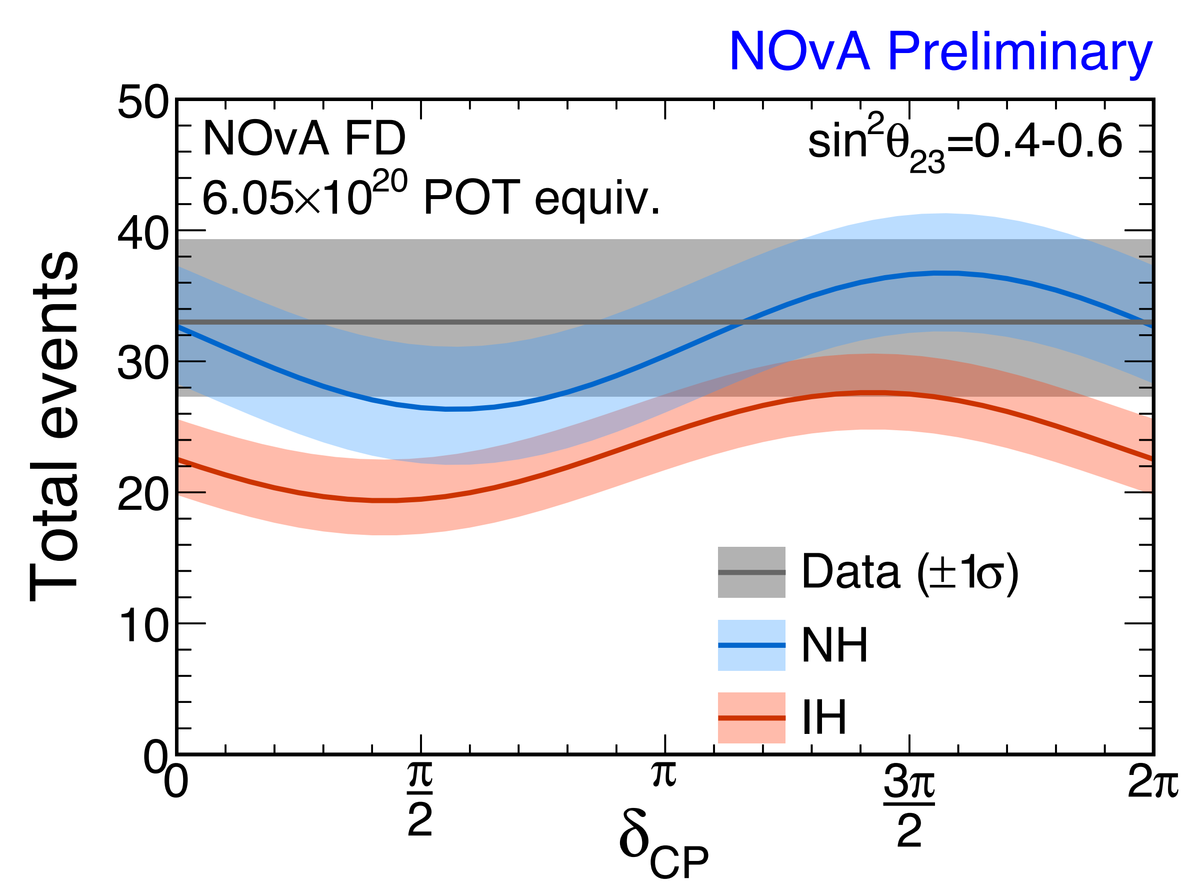
# NOVA ELECTRON NEUTRINO APPEARANCE RESULTS

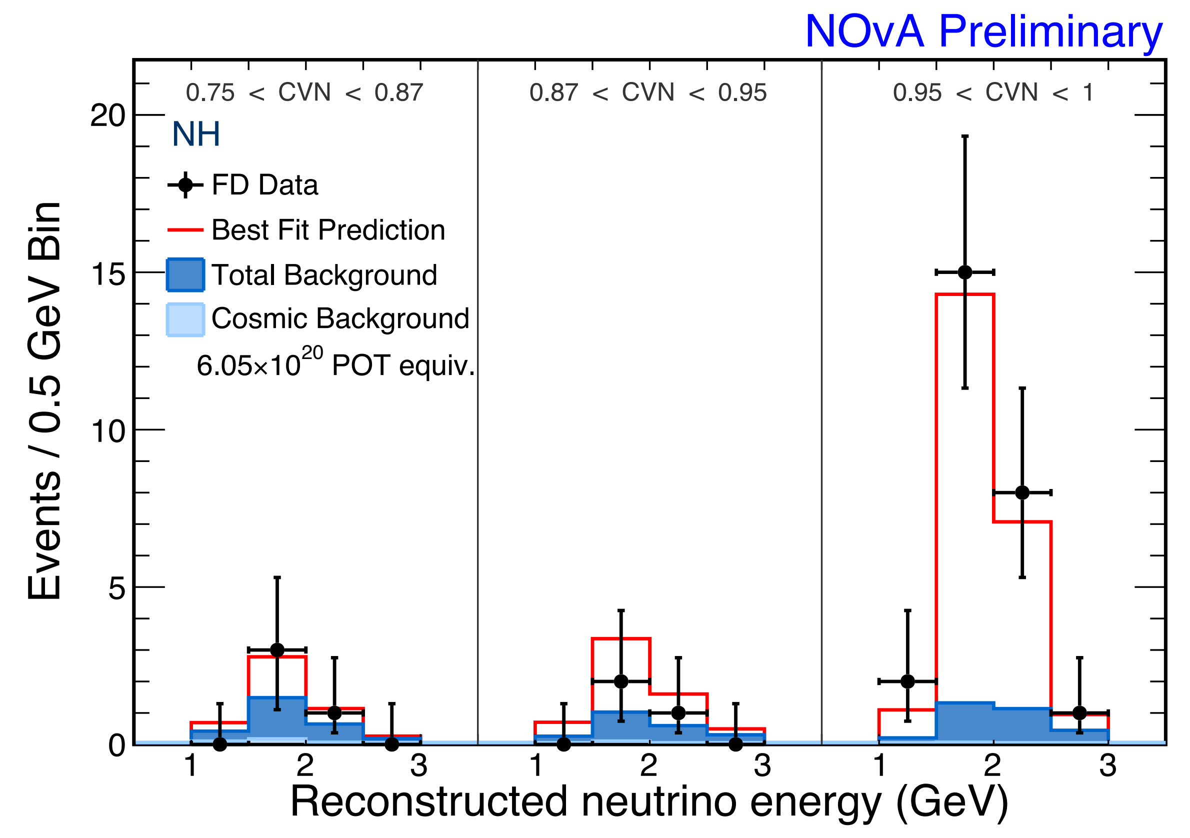
- **Range of expectation (for maximal mixing):**

| NH, $3\pi/2$, | IH, $\pi/2$, |
|---|---|
| 36 | 19 |

- **Observe 33 events for 8.2 expected background events.**

- Electron neutrino appearance observed at > 8 σ.

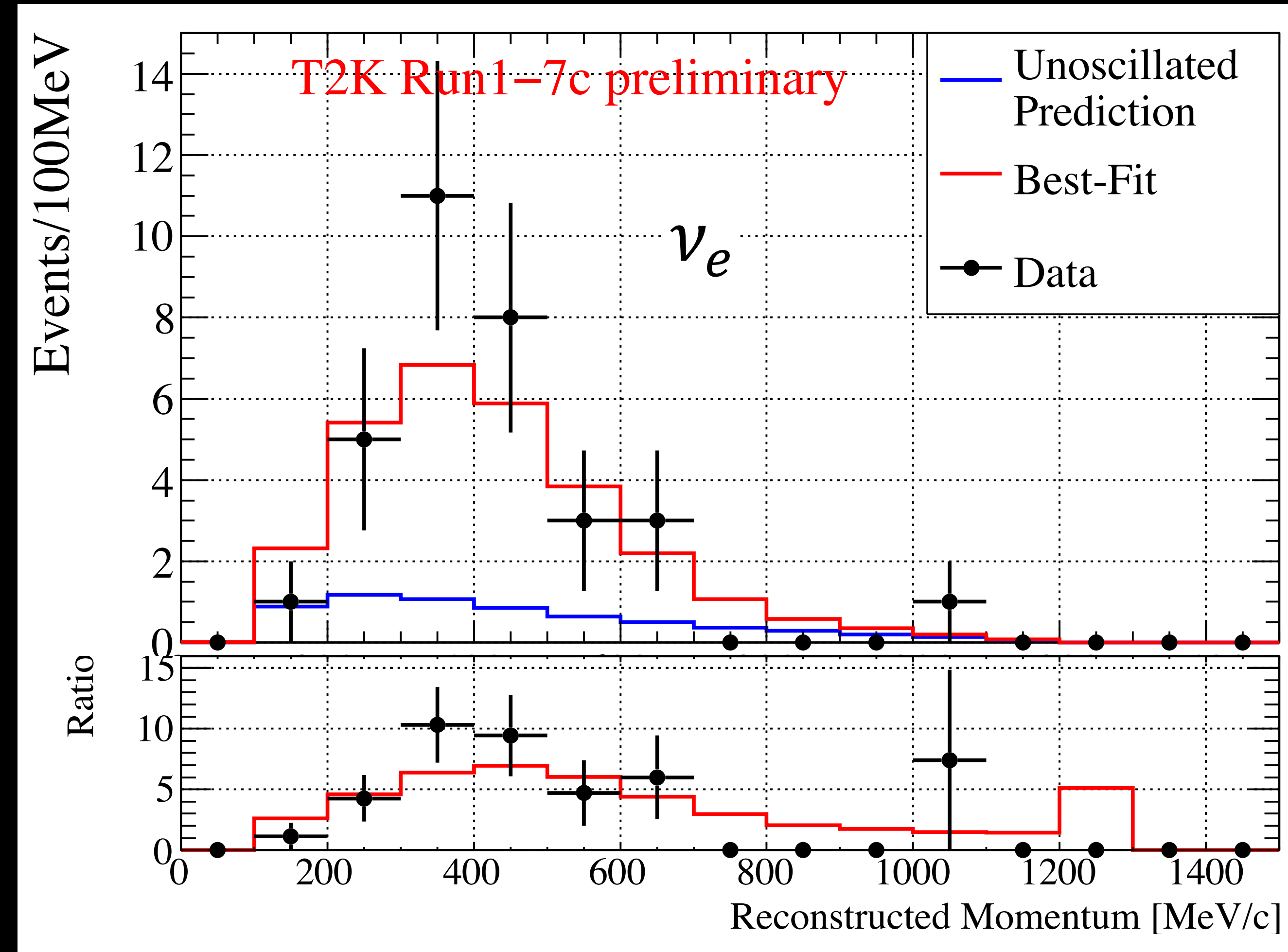


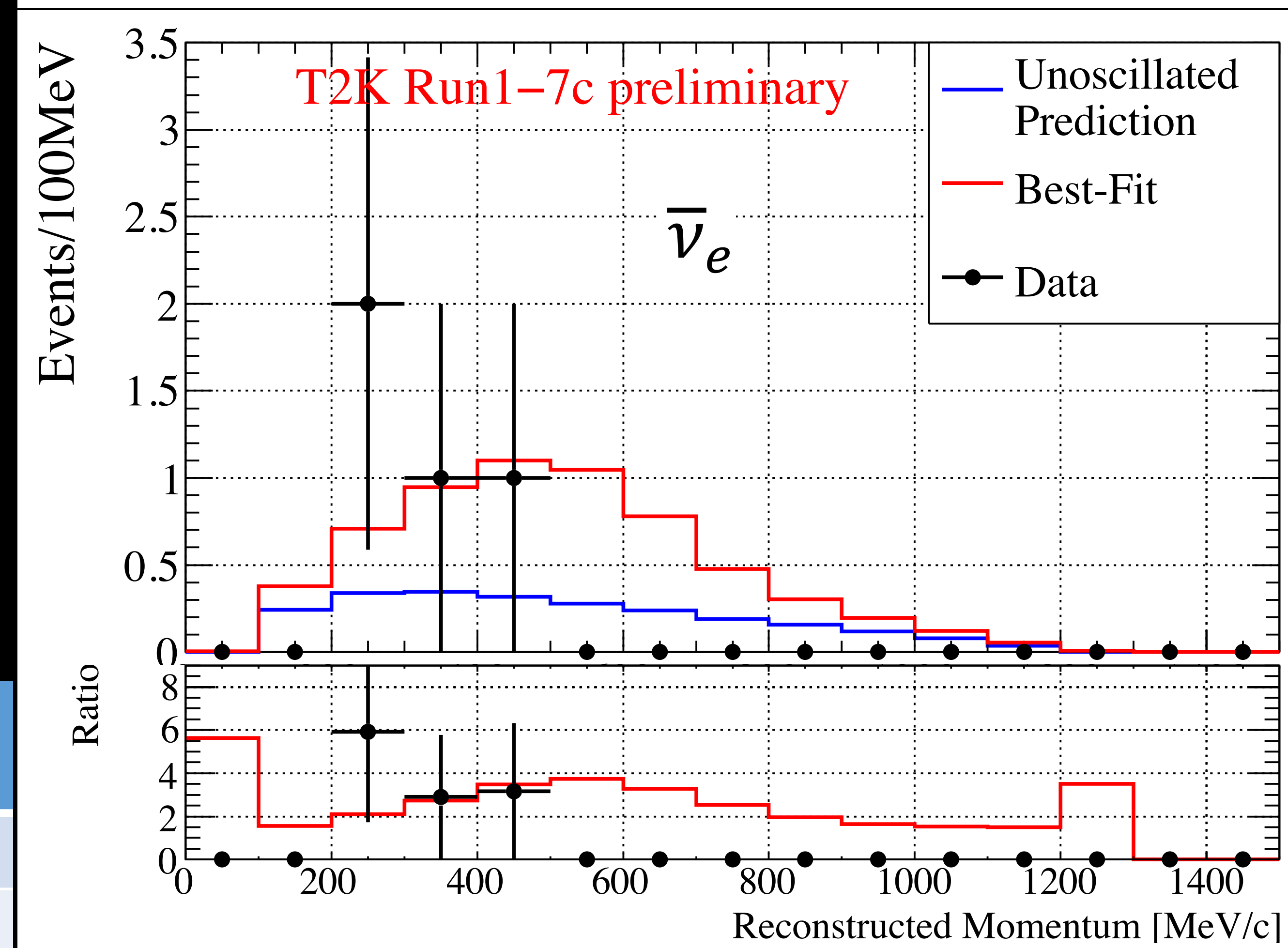



# T2K ELECTRON NEUTRINO APPEARANCE RESULTS

- T2K has observed 32 neutrinos and 4 antineutrinos.
- There are 29 and 6 expected at NH, $\boldsymbol{\delta}_{CP}$ = -π/2 (or 3π/2) which is the largest asymmetry.
- More $\nu_e$ candidates than predicted and fewer $\bar{\nu}_e$ candidates than predicted.

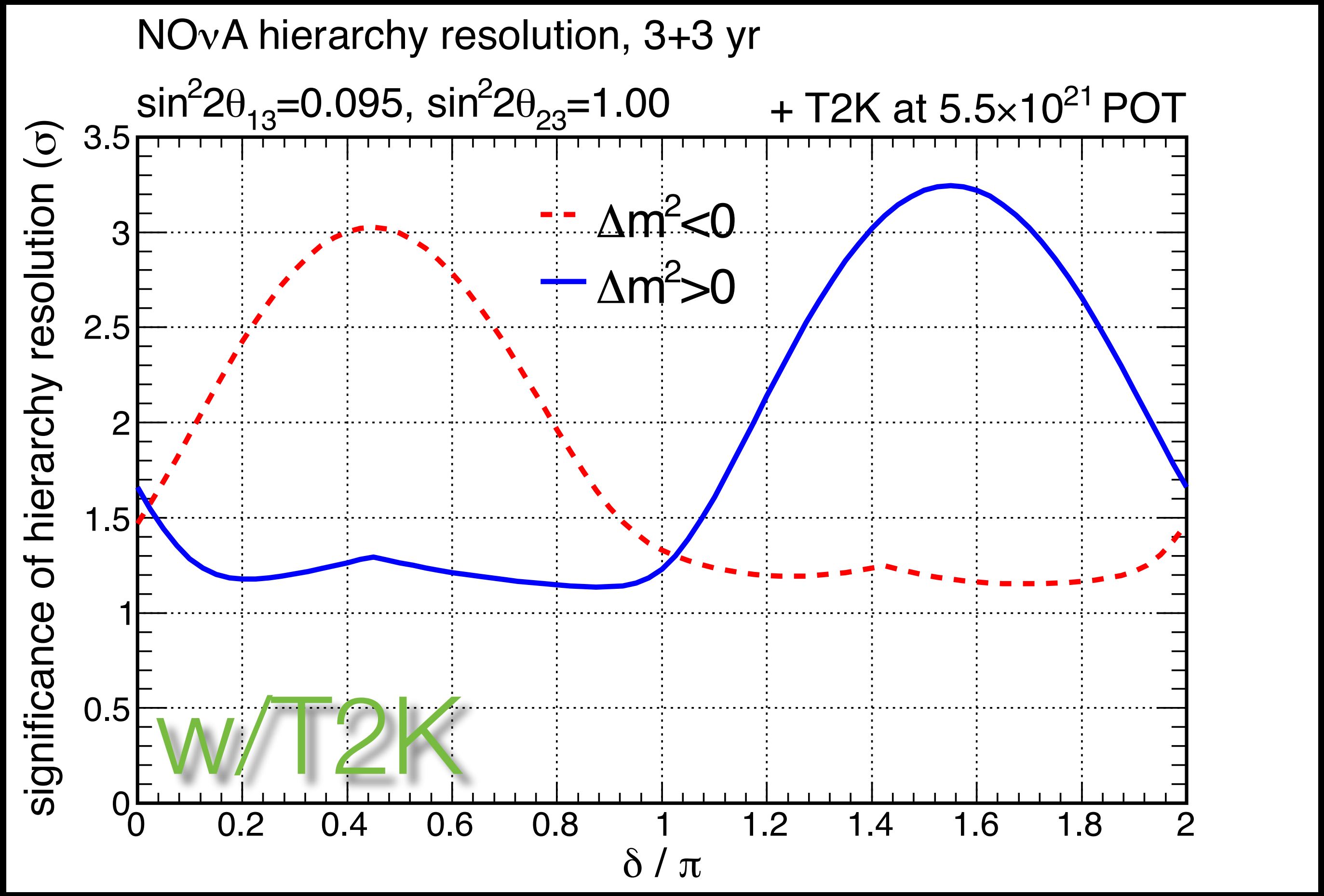
| | $\delta_{cp} = -\pi/2$ (NH) | $\delta_{cp} = 0$ (NH) | $\delta_{cp} = +\pi/2$ (NH) | $\delta_{cp} = \pi$ (NH) | Observed |
|---|---|---|---|---|---|
| $\nu_e$ | 28.7 | 24.2 | 19.6 | 24.1 | 32 |
| $\bar{\nu}_e$ | 6.0 | 6.9 | 7.7 | 6.8 | 4 |

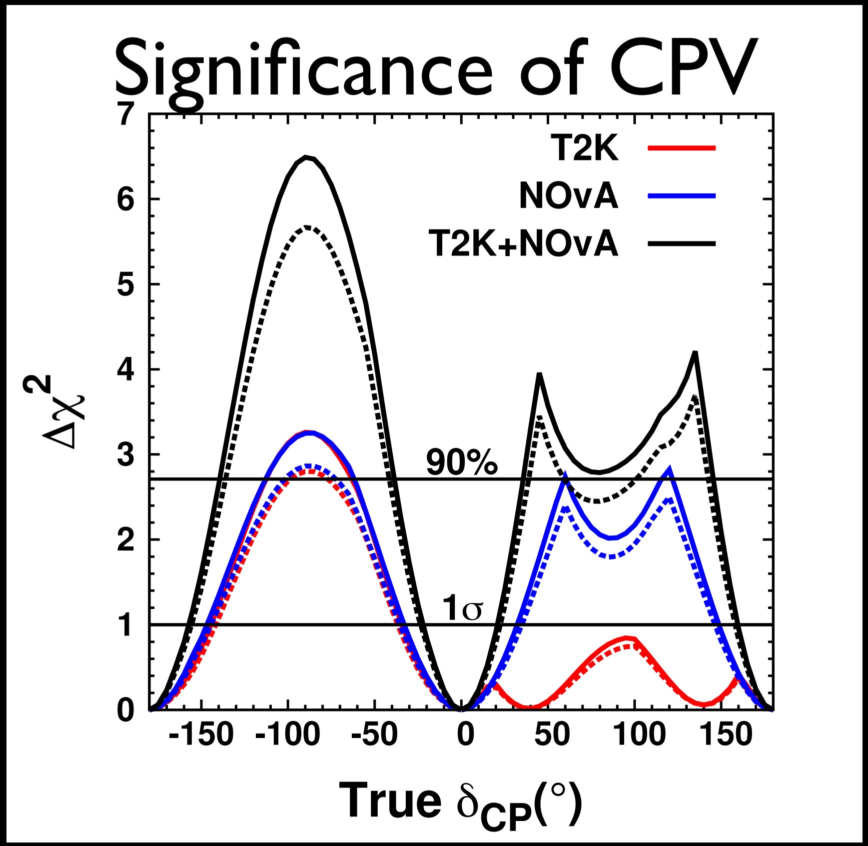


# OFF-AXIS BEAM NEUTRINOS: T2K AND NOVA

- Combining results from T2K and NOvA we have the potential for improved sensitivities.

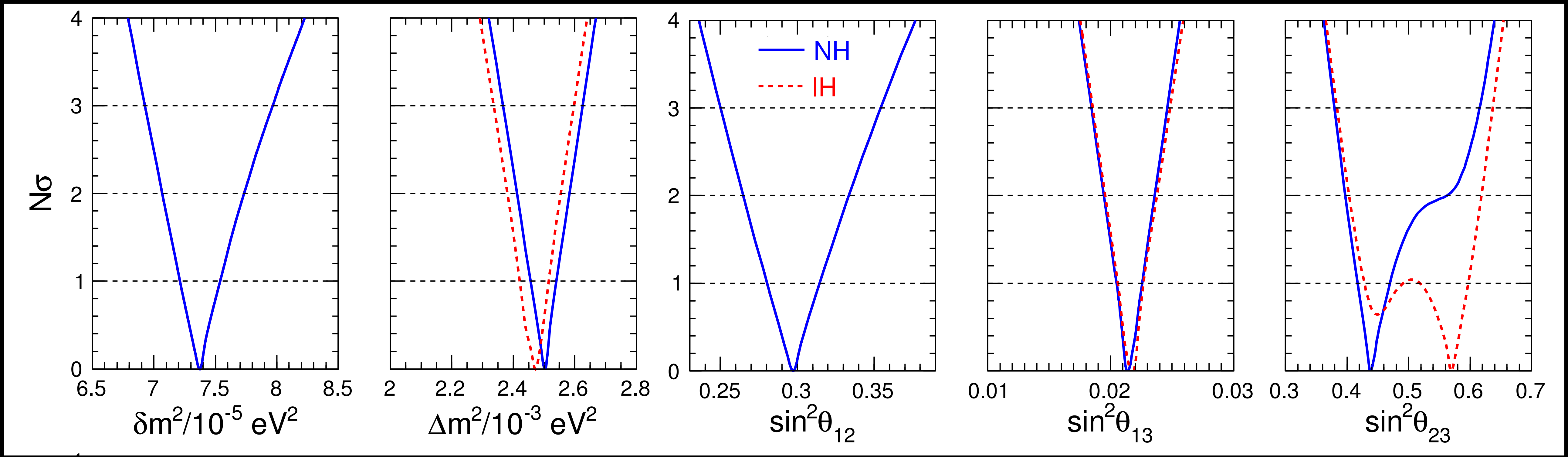



- The combined sensitivities can achieve 2.5-3 sigma for some values of the CP phase.

# NEUTRINOS MASSES AND MIXING

## How well are these known?



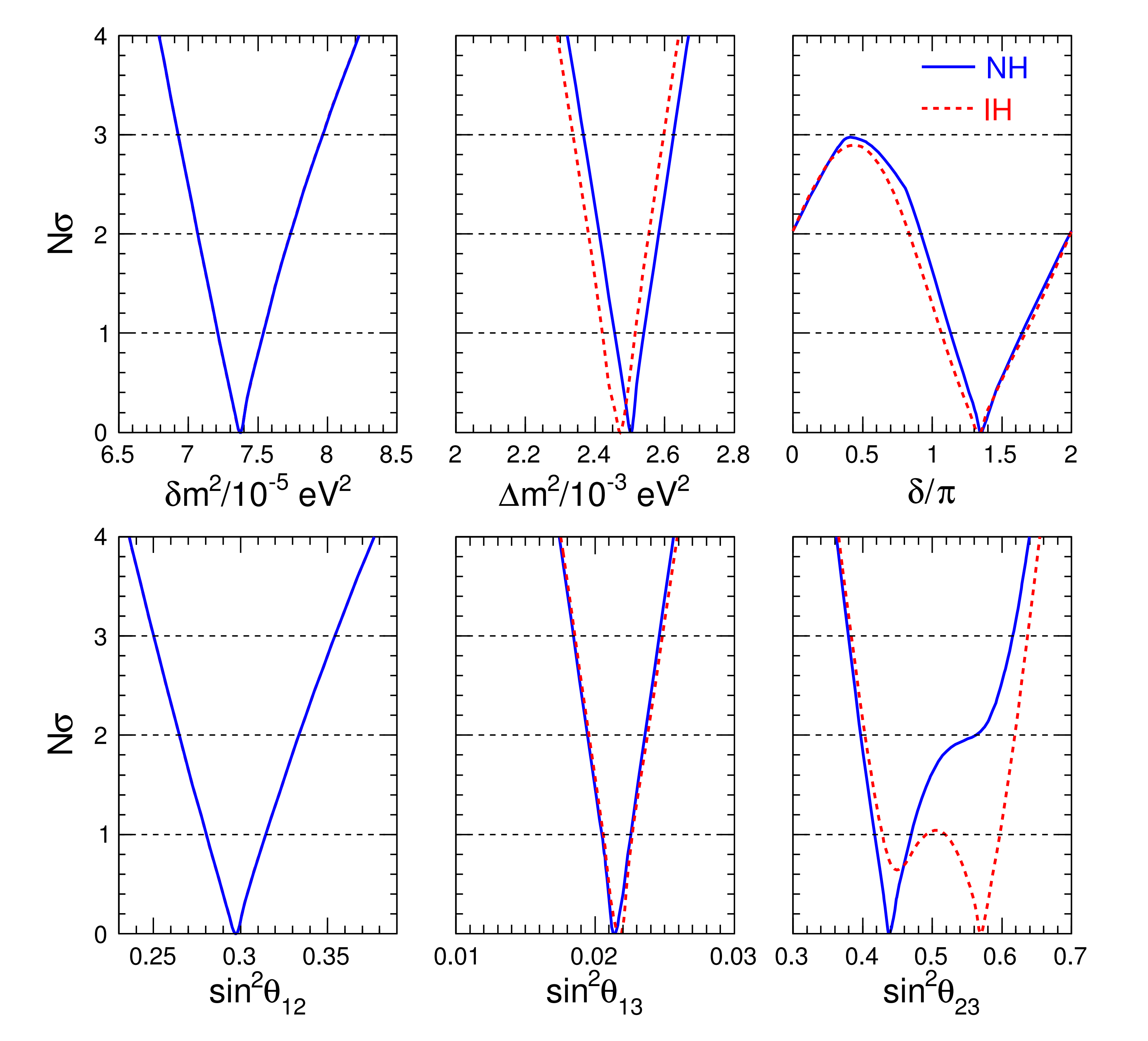

| | | |
|---|---|---|
| SOLAR | $\delta m^2$ | $2.4\%$ |
| ATMOSP. | $\Delta m^2$ | $1.8\%$ |
| SOLAR | $\sin^2\theta_{12}$ | $5.8\%$ |
| REACT. | $\sin^2\theta_{13}$ | $4.7\%$ |
| ATMOSP. | $\sin^2\theta_{23}$ | $\sim 9\%$ |

- Global analysis presented by A. Marrone at Neutrino 2016 (before new results).
- This fit combines the World's data from solar, reactor, atmospheric and long baseline neutrinos.

**EXPERIMENTAL PICTURE EVOLVING QUICKLY!**

# GLOBAL ANALYSIS FOR CP VIOLATION

A. MARRONE (NEUTRINO 2016)

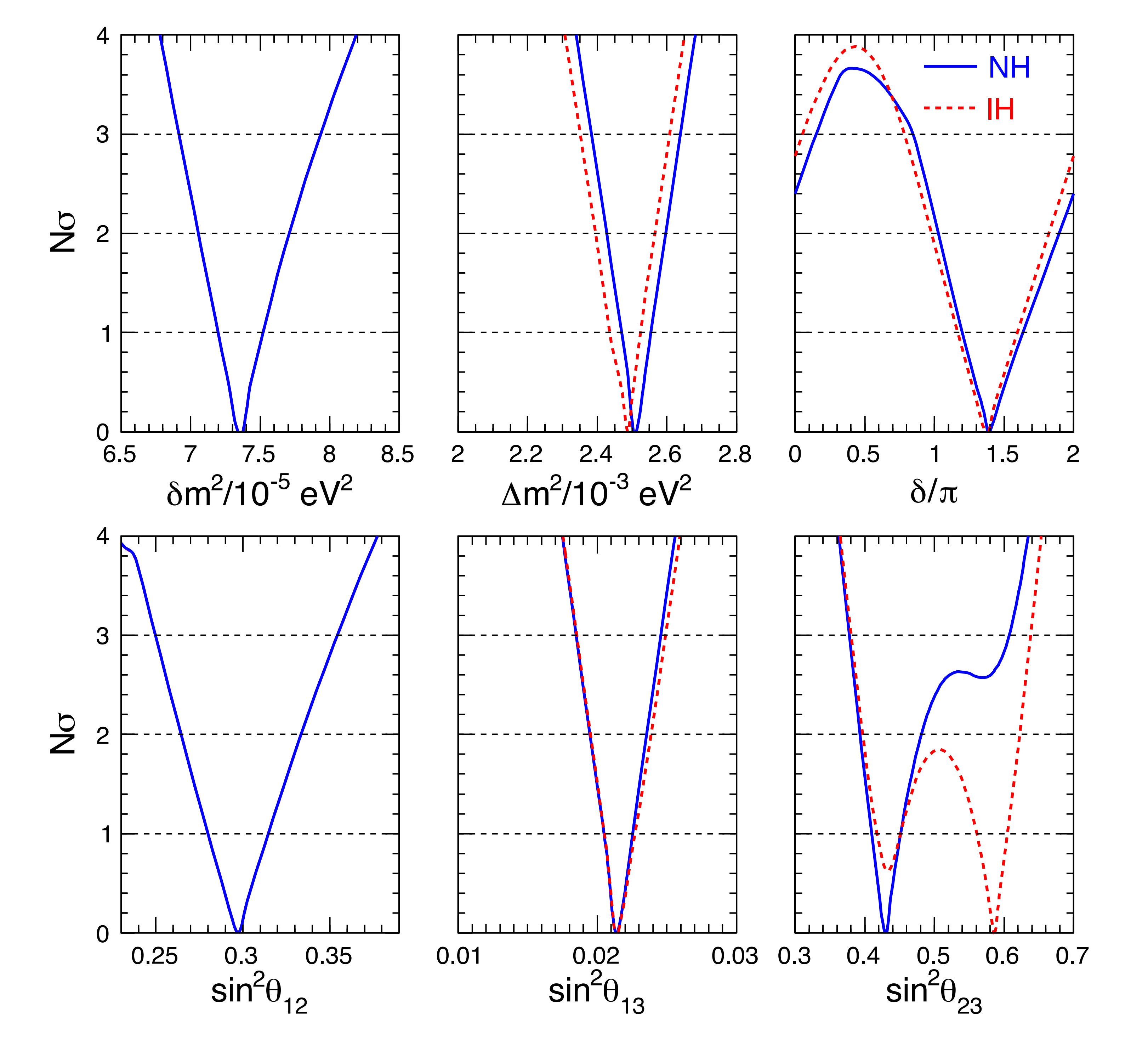



- Combining all the World's data mass squared differences and the 12 and 13 mixing angles are well defined.

# GLOBAL ANALYSIS FOR CP VIOLATION

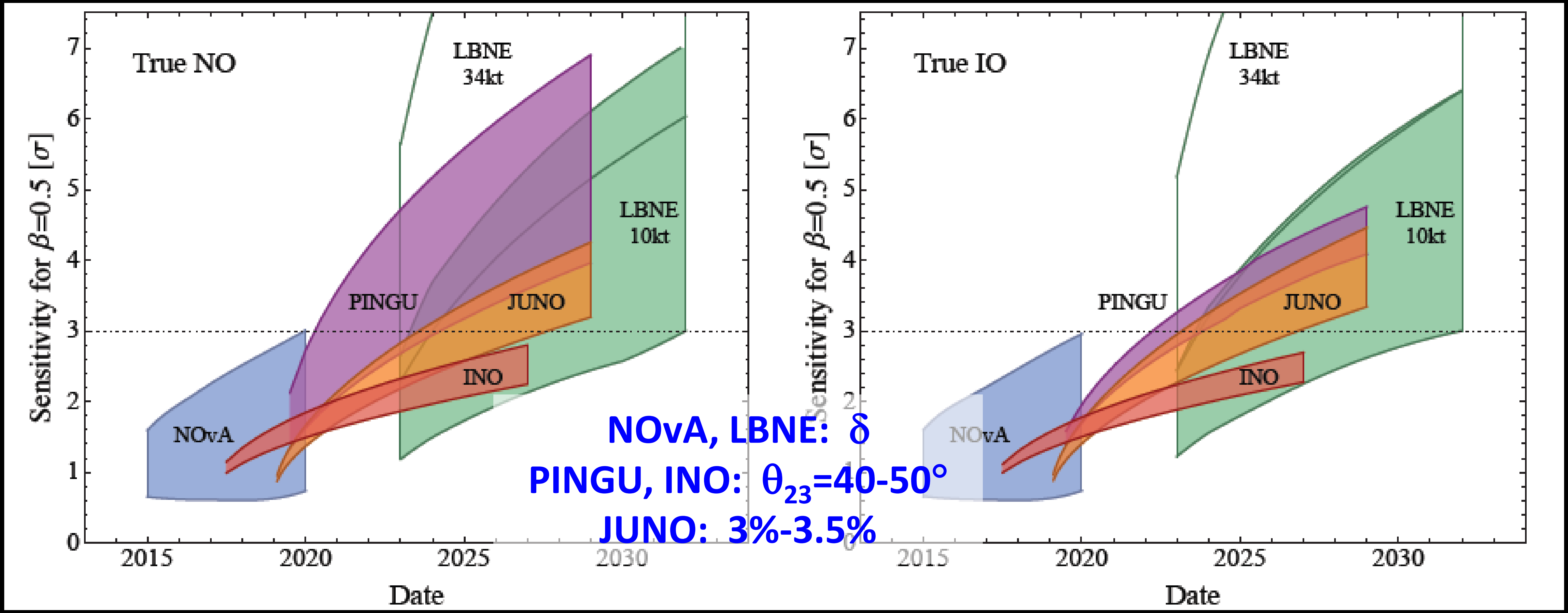
INCLUDES NEW RESULTS

A. MARRONE (NEUTRINO 2016)




- Combining all the World's data mass squared differences and the 12 and 13 mixing angles are well defined.
- Delta CP conserving cases are disfavored about 2 sigma and some regions [0, Pi] are disfavored at more than 3 sigma.
- Slight preference for a non maximal 23 angle goes from 1 to 2 sigma.
- Slight preference as well for Normal Hierarchy (less than 2 sigma).

# THE RACE TO THE MASS HIERARCHY




- An independent mass hierarchy measurement is required to take the bite off the CP violation measurement (in the wrong half of the phase space).
- Experiments like PINGU (an IceCube upgrade), JUNO (a second generation Daya Bay), INO (an atmospheric neutrino experiment) could provide this measurement.

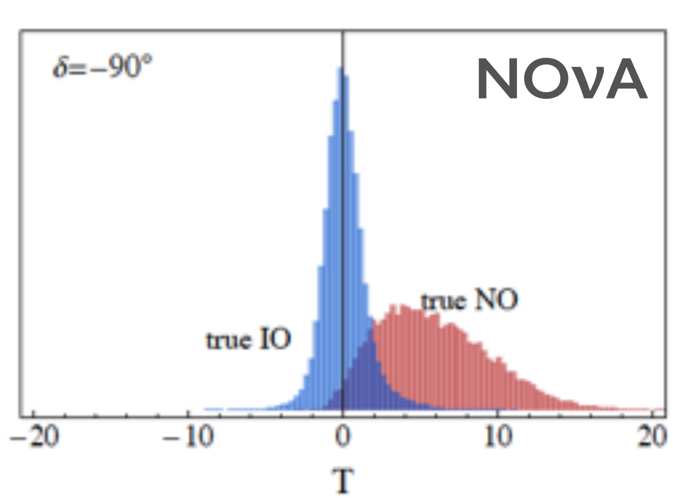
# A NOTE ABOUT THE SENSITIVITY TO THE MASS HIERARCHY

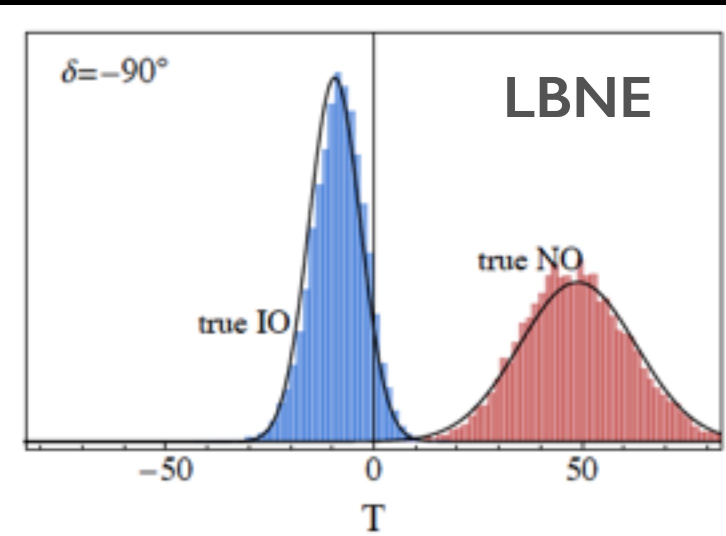
- In the mass hierarchy determination, only two discrete results are considered, as the true mass hierarchy: either normal (NH) or inverted (IH).

- The $T = \Delta\chi^2(\theta)$ test metric we typically use does not follow a $\chi^2$ distribution for mass ordering (i.e. Wilks' theorem not valid)

- Instead, T is approximately gaussian, with mean $T_0$ and width $2(T_0)^{½}$, where $T_0$ is the value for the data set without statistical fluctuations

- Need to check gaussianity using MC for each experiment. Quote median sensitivity instead of $(T_0)^{½}$.




| $T_0$ | std. sens. | | median sens. | |
|---|---|---|---|---|
| 9 | 99.73% | (3.0σ) | 99.87% | (3.2σ) |
| 16 | 99.9937% | (4.0σ) | 99.9968% | (4.2σ) |
| 25 | 99.999943% | (5.0σ) | 99.999971% | (5.1σ) |

From arxiv:1311.1822