# BREAKING NUS

## Latest results and future prospects from oscillation experiments

Jonathan M. Paley

Division of Particles and Fields 2017, Fermilab

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# Old News…


The New York Times

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## Mass Found in Elusive Particle; Universe May Never Be the Same

### Discovery on Neutrino Rattles Basic Theory About All Matter

By MALCOLM W. BROWNE

TAKAYAMA, Japan, Friday, June 5 — In what colleagues hailed as a historic landmark, 120 physicists from 23 research institutions in Japan and the United States announced today that they had found the existence of mass in a notoriously elusive subatomic particle called the neutrino.

The neutrino, a particle that carries no electric charge, is so light that it was assumed for many years to have no mass at all. After today's announcement, cosmologists will have to confront the possibility that a significant part of the mass of the universe might be in the form of neutrinos. The discovery will also compel scientists to revise a highly successful theory of the composition of matter, the Standard Model.

Word of the discovery had drawn some 300 physicists here to discuss neutrino research. Among other things, the finding of neutrino mass might affect theories about the formation and evolution of galaxies and the ultimate fate of the universe. If neutrinos have sufficient mass, their presence throughout the universe would increase the overall mass of the universe, possibly slowing its present expansion.

**Detecting Neutrinos**

1 Neutrinos pass through the Earth's surface to a tank filled with 12.5 million gallons of ultra-pure water . . .

2 . . . and collide with other particles . . .

3 . . . producing a cone–shaped flash of light.

4 The light is recorded by 11,200 20–inch light amplifiers that cover the inside of the tank.

LIGHT

LIGHT AMPLIFIER

**And Detecting Their Mass**

By analyzing the cones of light, physicists determine that some neutrinos have changed form on their journey. If they can change form, they must have mass.

Source: University of Hawaii

- Nearly 20 years ago: neutrinos oscillate → they have mass.
- Neutrinos broke the Standard Model.

# Old News…


New Physics!

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{\mathcal{O}_{5D}}{M} + \ldots$$

$$\frac{\lambda_{ij}}{M} H H L_i L_j \qquad m_\nu = \lambda_{ij} \frac{v^2}{M}$$

if $m_\nu \sim 0.1$ eV, $\upsilon \sim 100$ GeV and $\lambda_{ij} \sim 1$,

then M ~ $10^{14}$ GeV (GUT scale)

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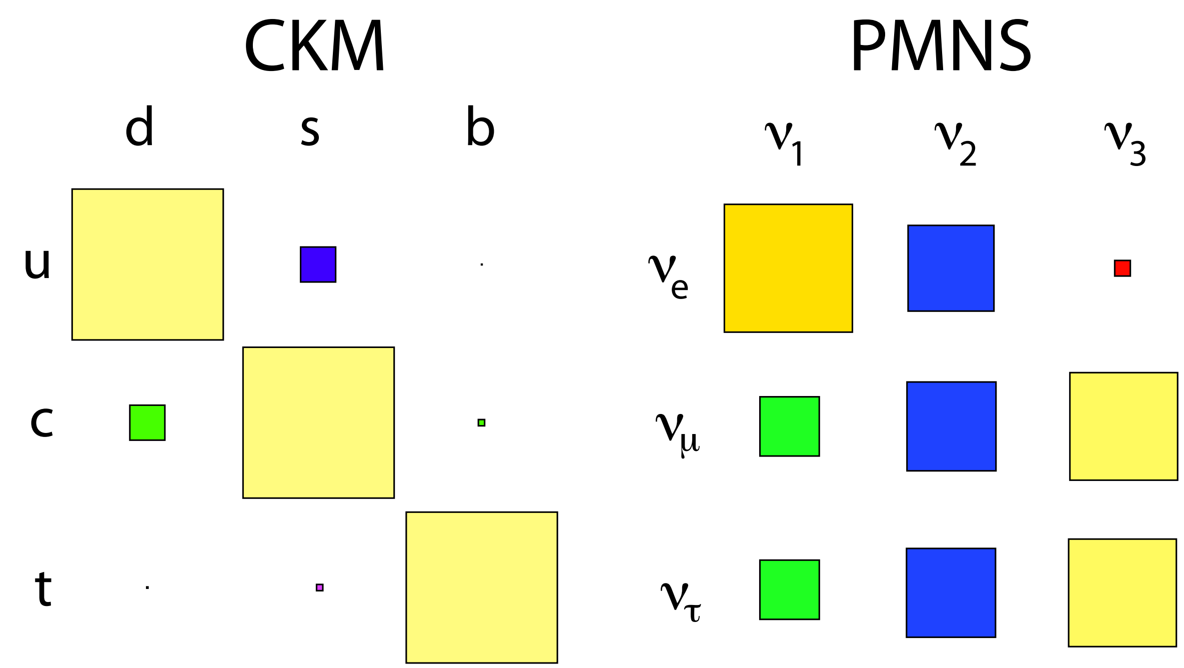
Be careful when you ask Google for an image of “GUT scale”…

# Neutrino Oscillations

S. Stone, ICHEP 2012, arXiv:1212.6374

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}}_{U_{\mathrm{PMNS}}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$|\nu_\alpha > \; = \sum_i U^*_{\alpha i} |\nu_i >$$




- Neutrino oscillations occur because ν flavor states are a quantum superposition of mass eigen states.
- The PMNS matrix is the neutrino analog to the CKM matrix.

$$\underset{\text{in vacuo}}{P(\nu_\alpha \rightarrow \nu_\beta)} = \delta_{\alpha\beta} - 4 \sum_{i>j} \Re(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right)$$

$$+2 \sum_{i>j} \Im(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin\left(\frac{\Delta m^2_{ij} L}{2E}\right)$$

# Neutrino Oscillations

$$U_{\text{PMNS}} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{Atmospheric, Accelerator}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{+i\delta_{\text{CP}}} & 0 & c_{13} \end{pmatrix}}_{\text{Reactor, Accelerator}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar, Reactor}}$$

Atmospheric, Accelerator: $P(\nu_\mu \to \nu_\mu)$

Reactor, Accelerator: $P(\nu_{\mu,e} \to \nu_e)$

Solar, Reactor: $P(\nu_e \to \nu_e)$

- With 3 flavors of neutrinos, there are two independent mass-squared differences:
  - Solar: $\Delta m^2_{21}$
  - Atmospheric: $|\Delta m^2_{32}| \approx |\Delta m^2_{31}|$
- $\sin(1.27\Delta m^2_{ij} L/E)$ oscillation terms →characteristic $L/E$ values:
  - $L/E(\Delta m^2_{sol}) \sim$ 15000 km/GeV
  - $L/E(\Delta m^2_{atm}) \sim$ 500 km/GeV
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**NuFIT 3.0 (2016) Results**

| Parameter | Value | ±1σ | Experiments |
|---|---|---|---|
| $\sin^2\theta_{12}$ | 0.306 | 3.9% | SNO, KamLand, Super-K |
| $\Delta m^2_{21}$ ($eV^2$) | 7.50 x $10^{-5}$ | 2.4% | SNO, KamLand, Super-K |
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| $\|\Delta m^2_{31}\|$ ($eV^2$) | 2.45 x $10^{-3}$ | 1.6% | Super-K, IceCube, MINOS, T2K, NOvA, Daya Bay, RENO, Double Chooz |
| $\sin^2\theta_{13}$ | 2.17 x $10^{-2}$ | 3.5% | Daya Bay, RENO, Double Chooz, T2K, NOvA |
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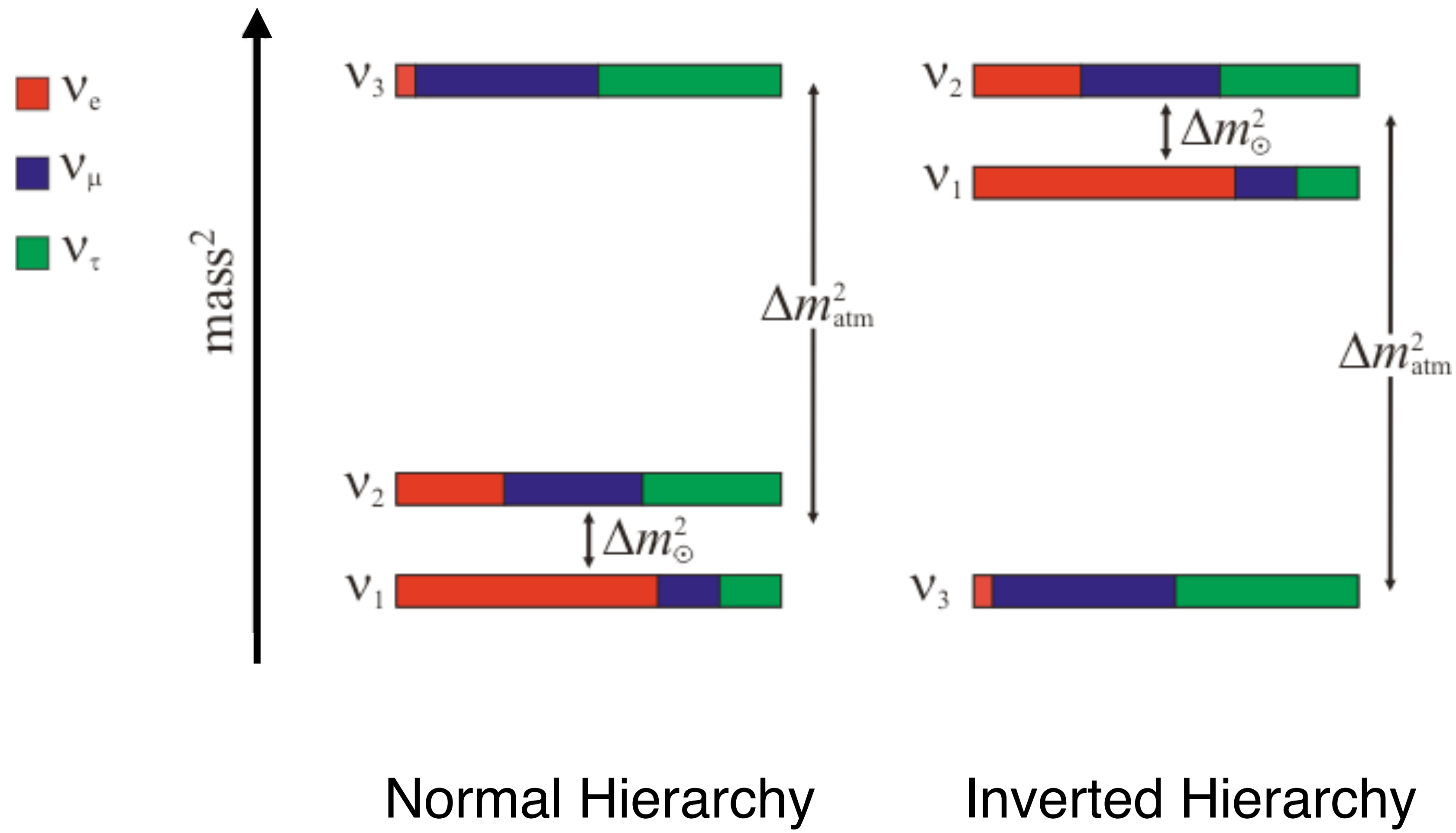

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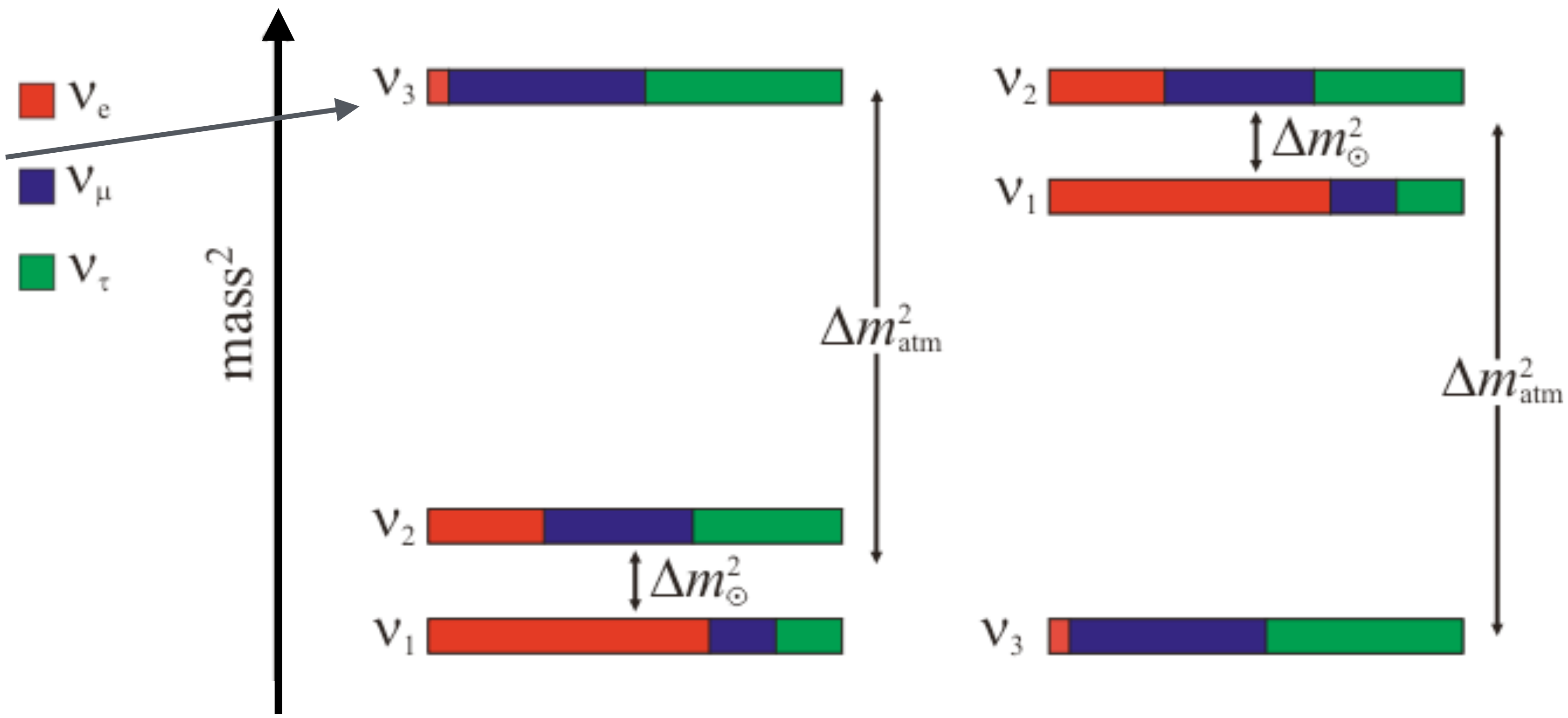


Normal Hierarchy Inverted Hierarchy

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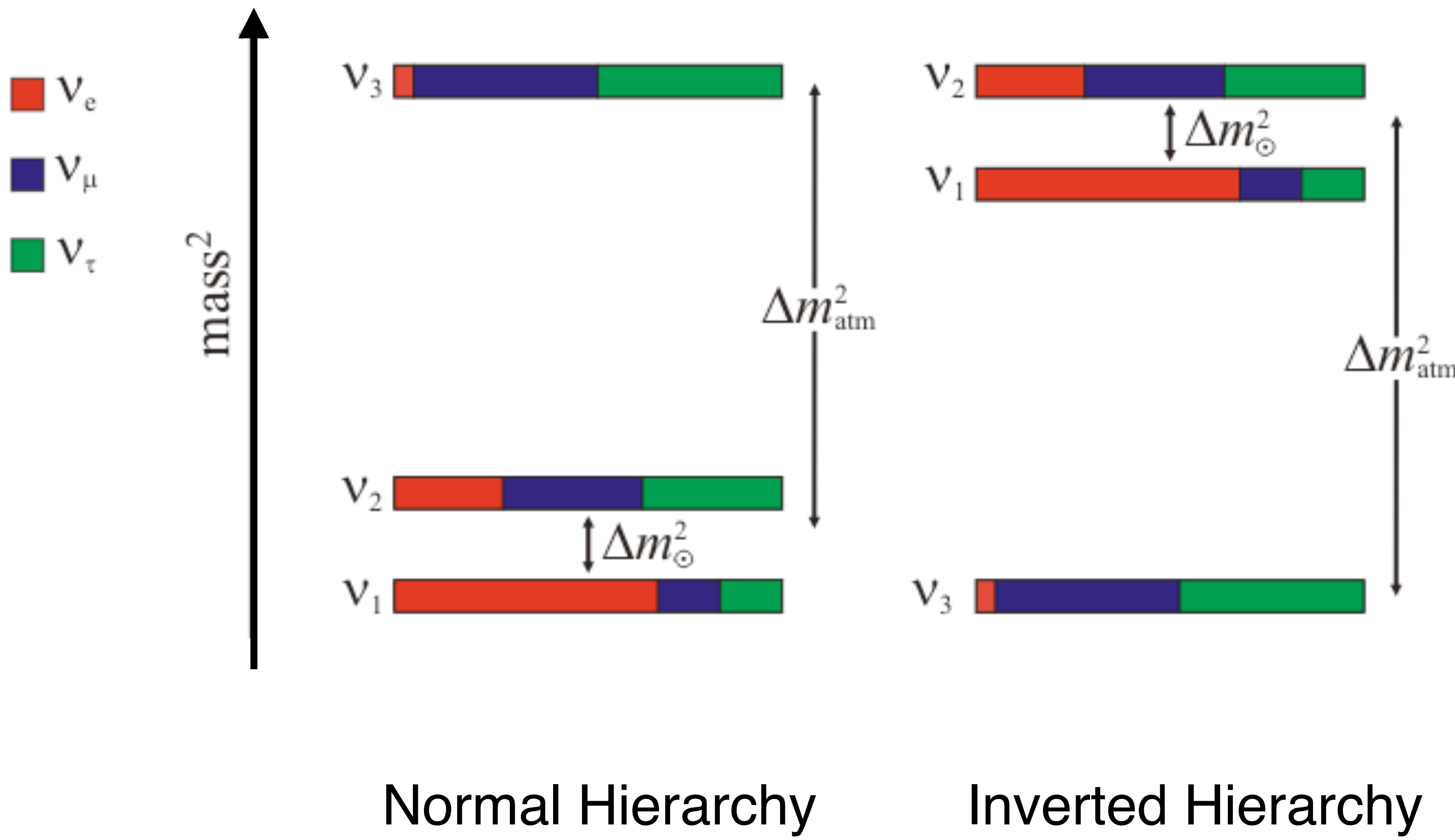


$$P(\nu_\alpha \rightarrow \nu_\beta) \neq P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta)$$

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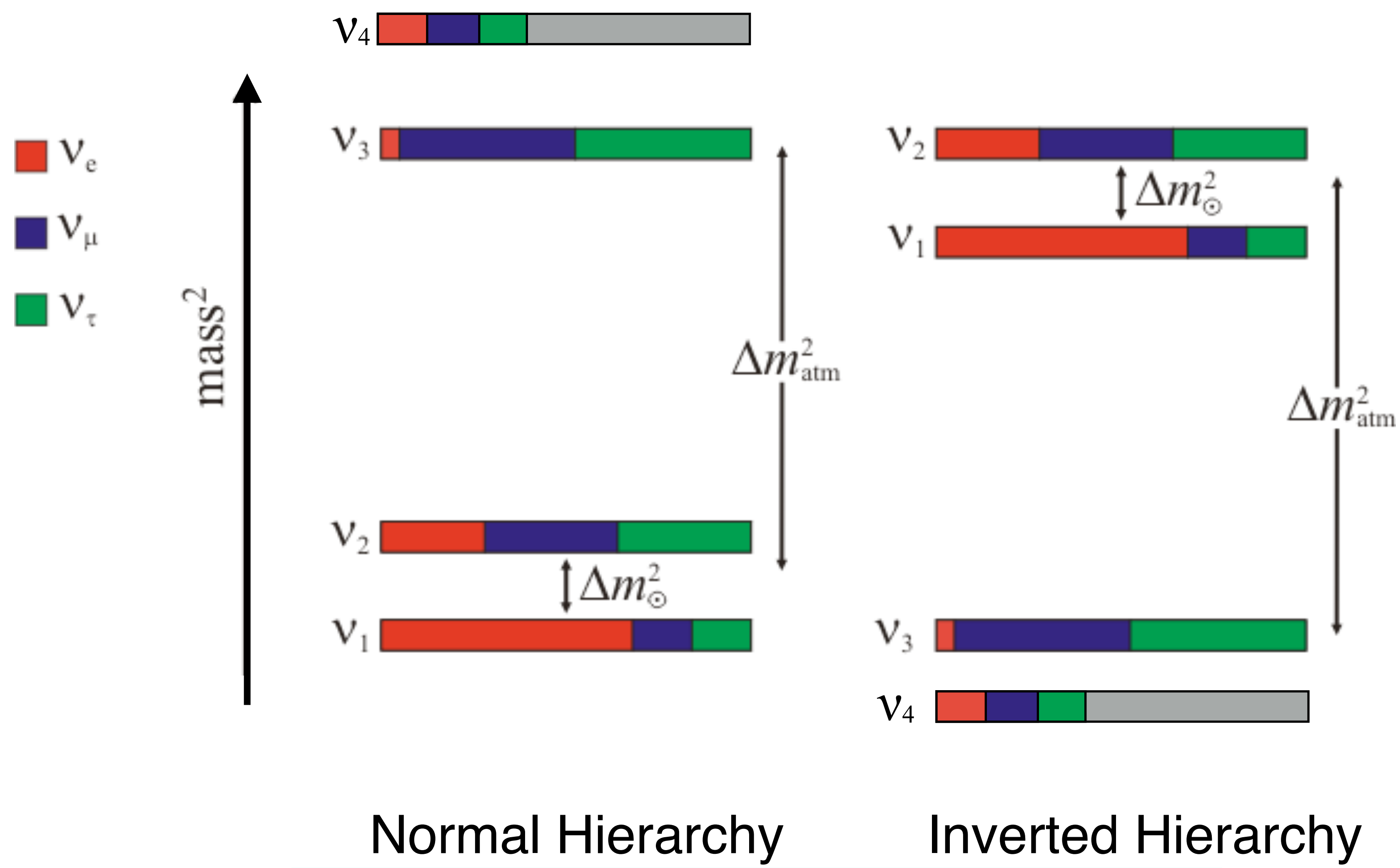


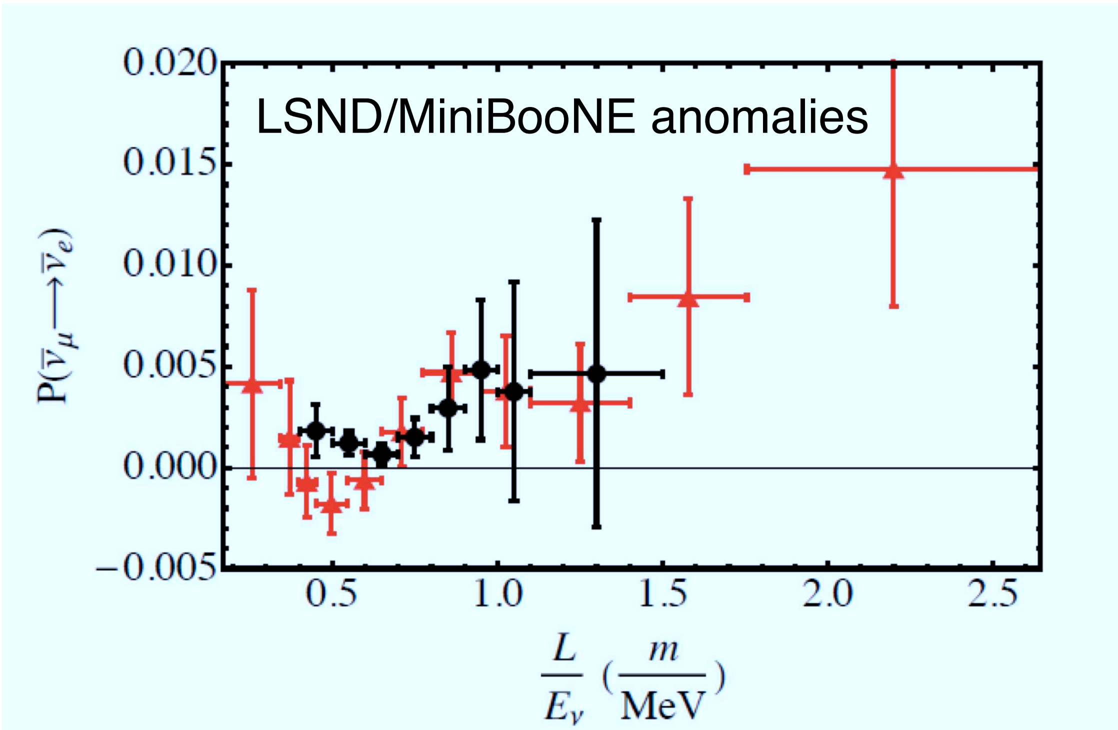

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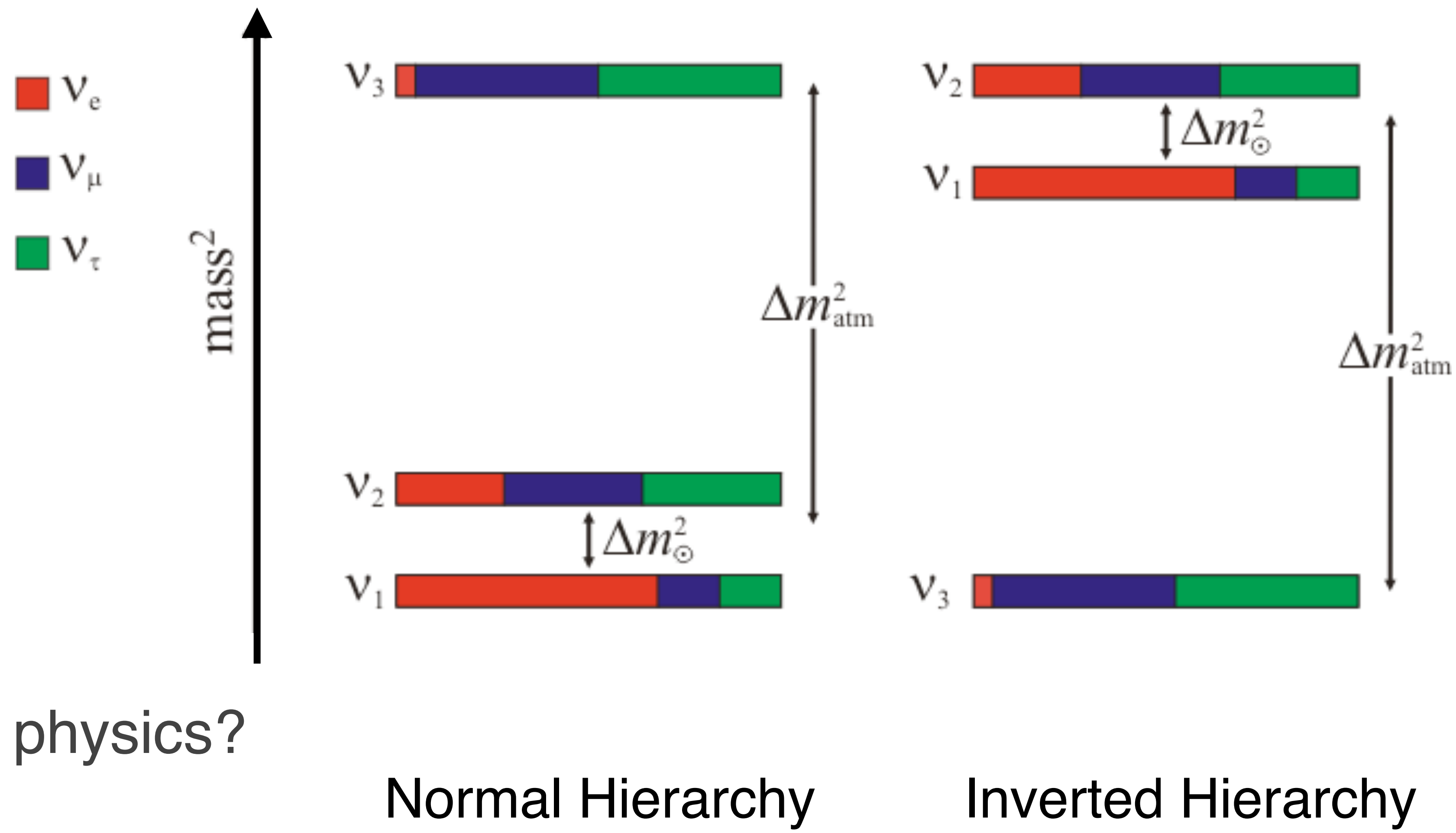


$$V_{ij} = U^{\dagger}_{i\alpha} V_{\alpha\beta} U_{\beta j},$$

$$V_{\alpha\beta} = A \begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix}$$

eg, non-standard neutrino interactions

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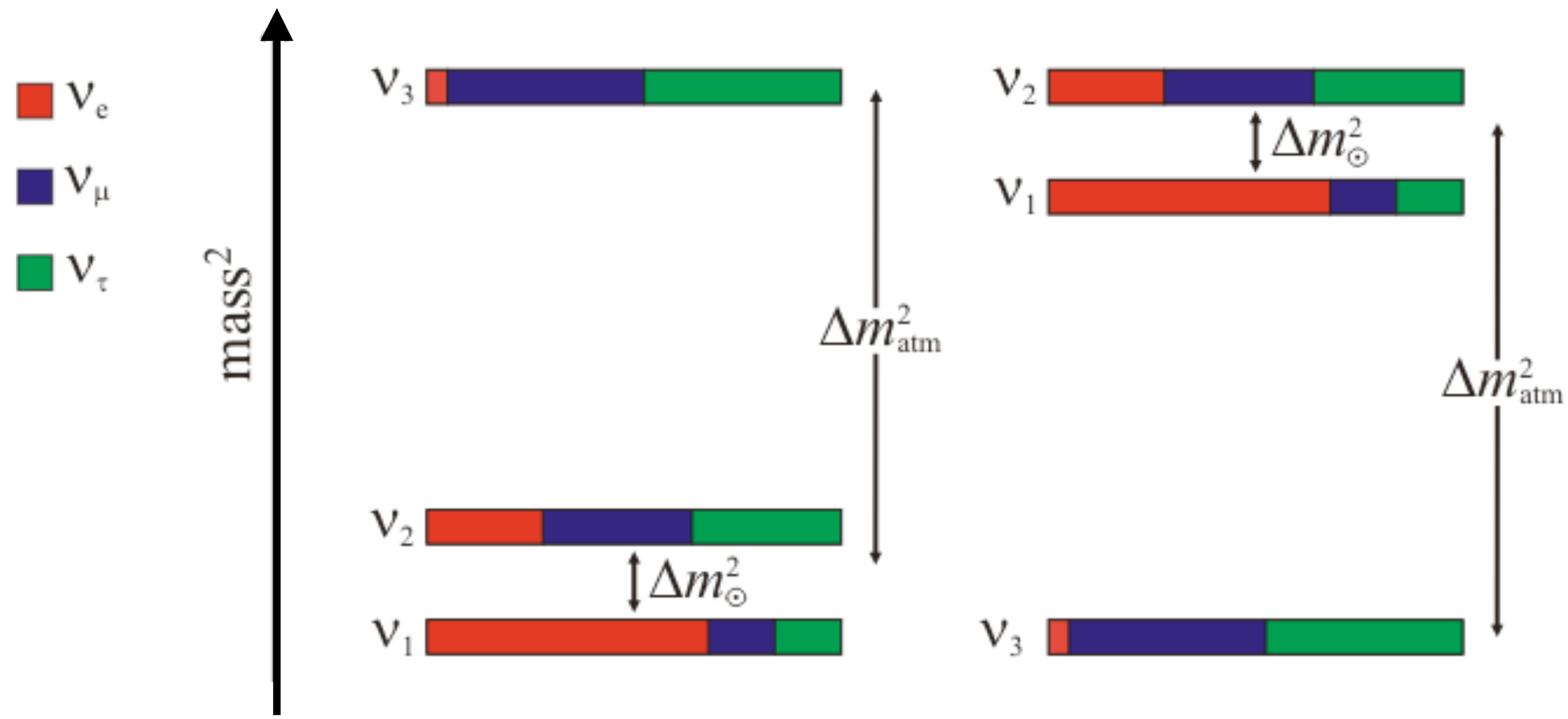


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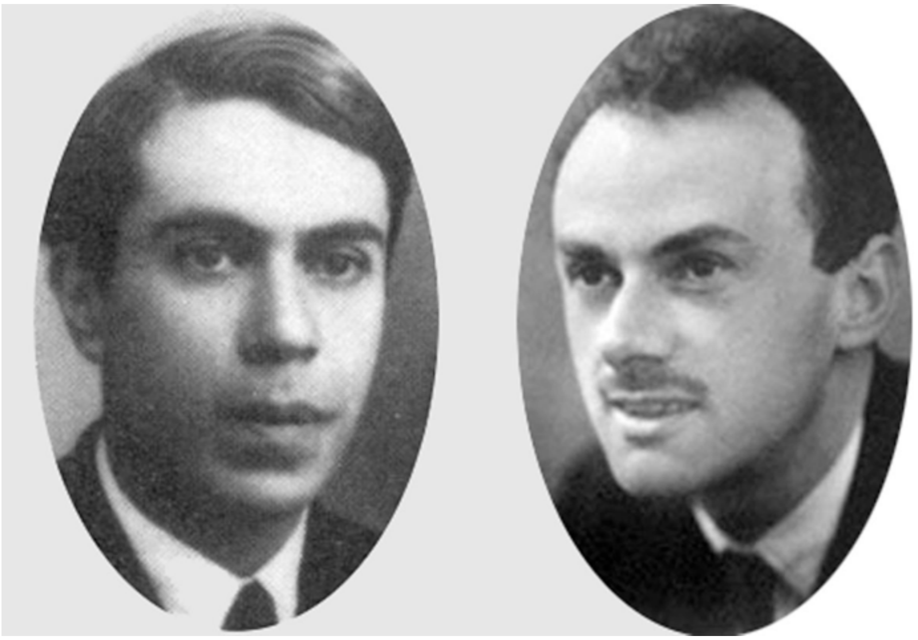

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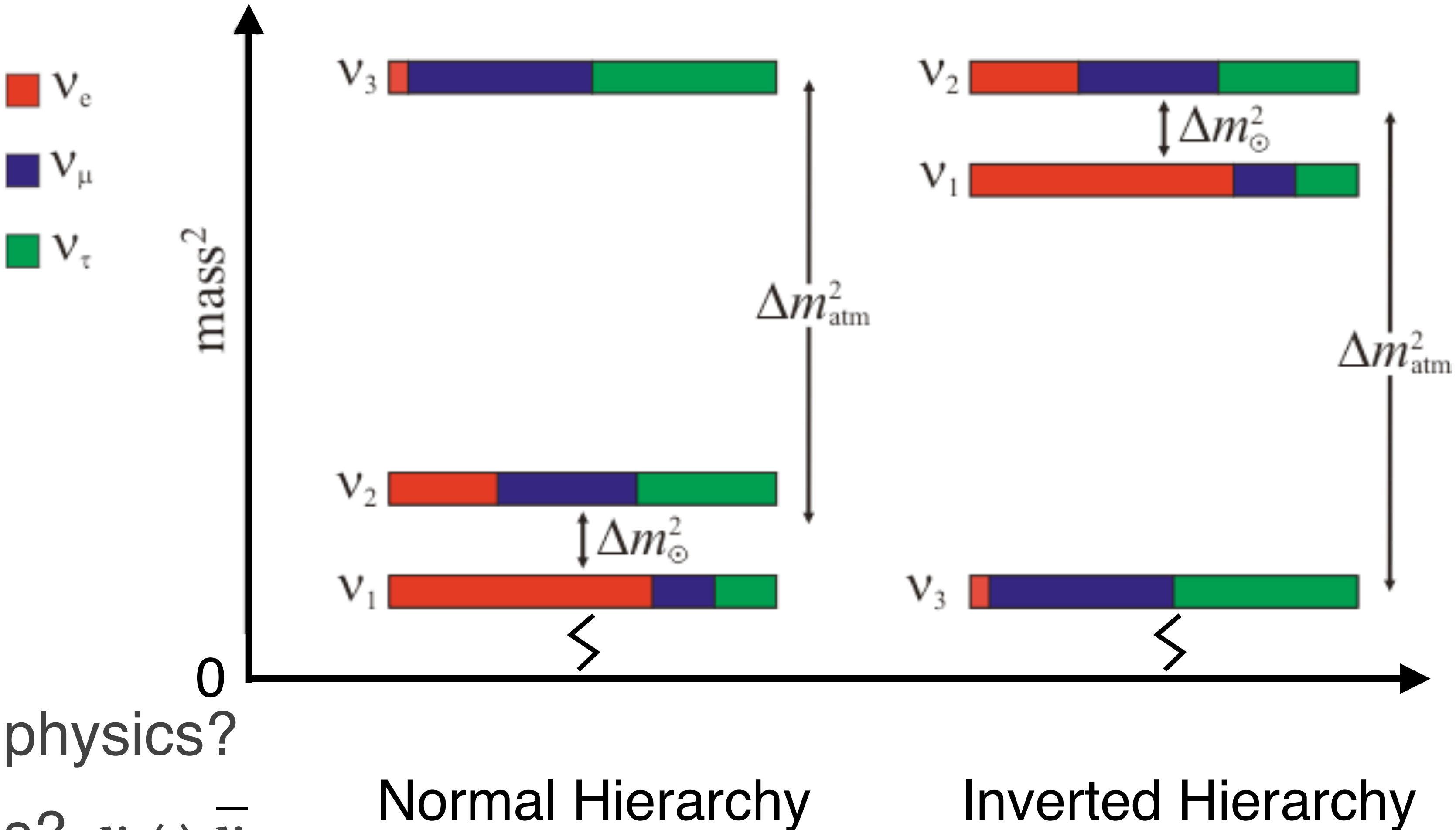

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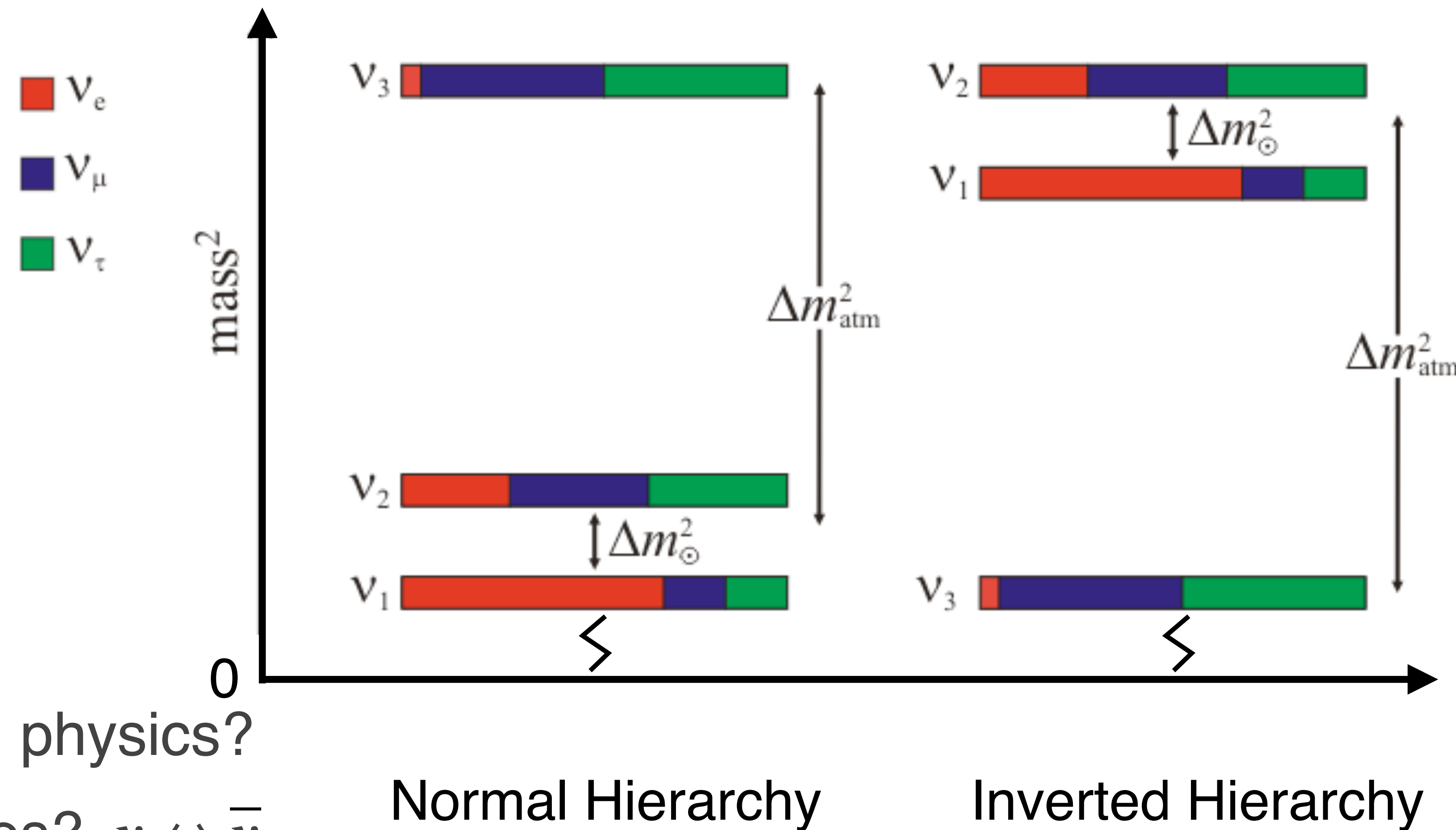
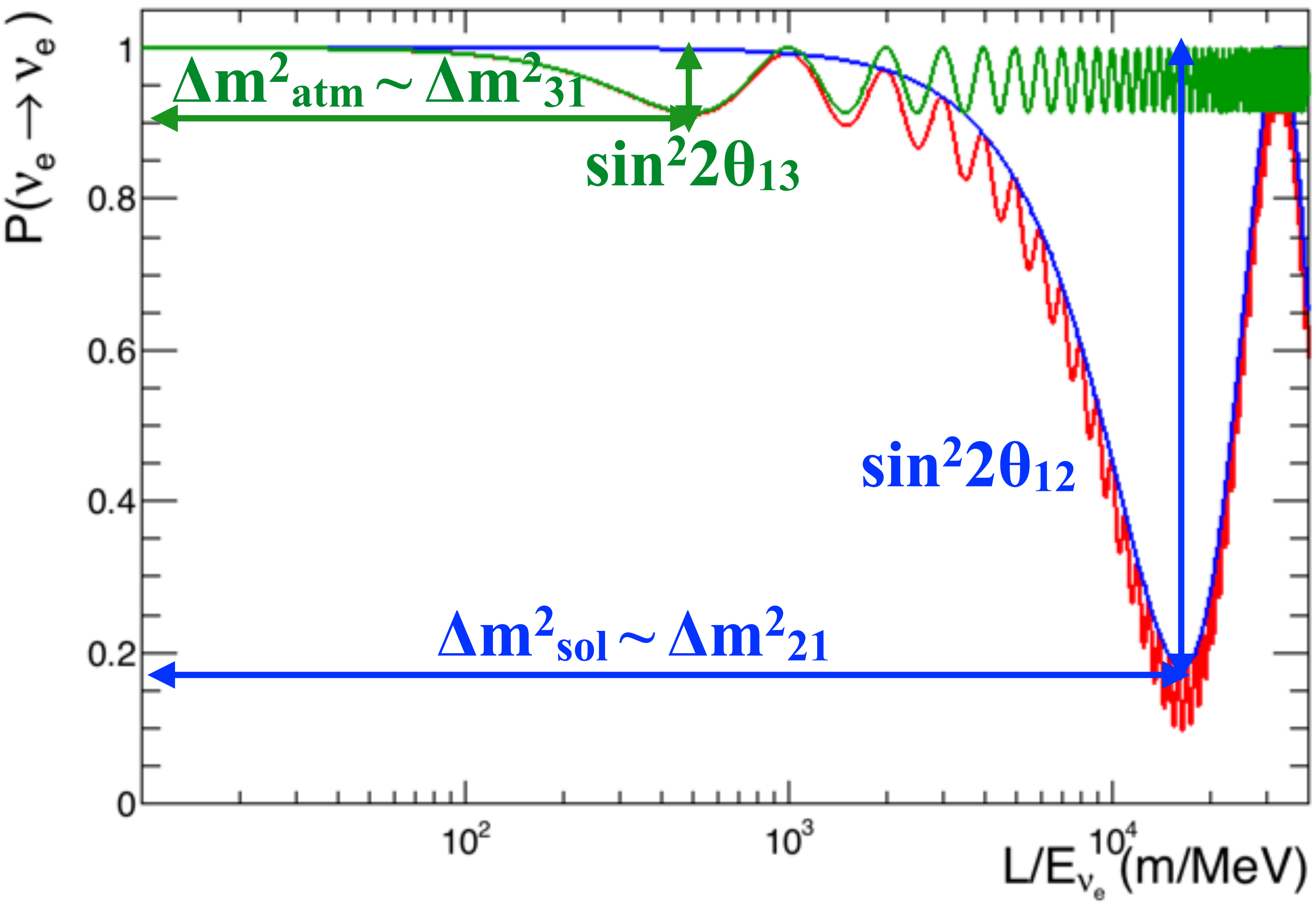



- Are they coupled to other BSM physics?
- Are neutrinos Majorana particles? $\nu \Leftrightarrow \bar{\nu}$
- What are the absolute masses of the neutrinos?
- Three approaches allow us to experimentally address these questions: neutrino oscillation measurements, direct mass measurements and searches for neutrinoless double-beta decay.
- Today I will present “breaking news” from the oscillation experiments.

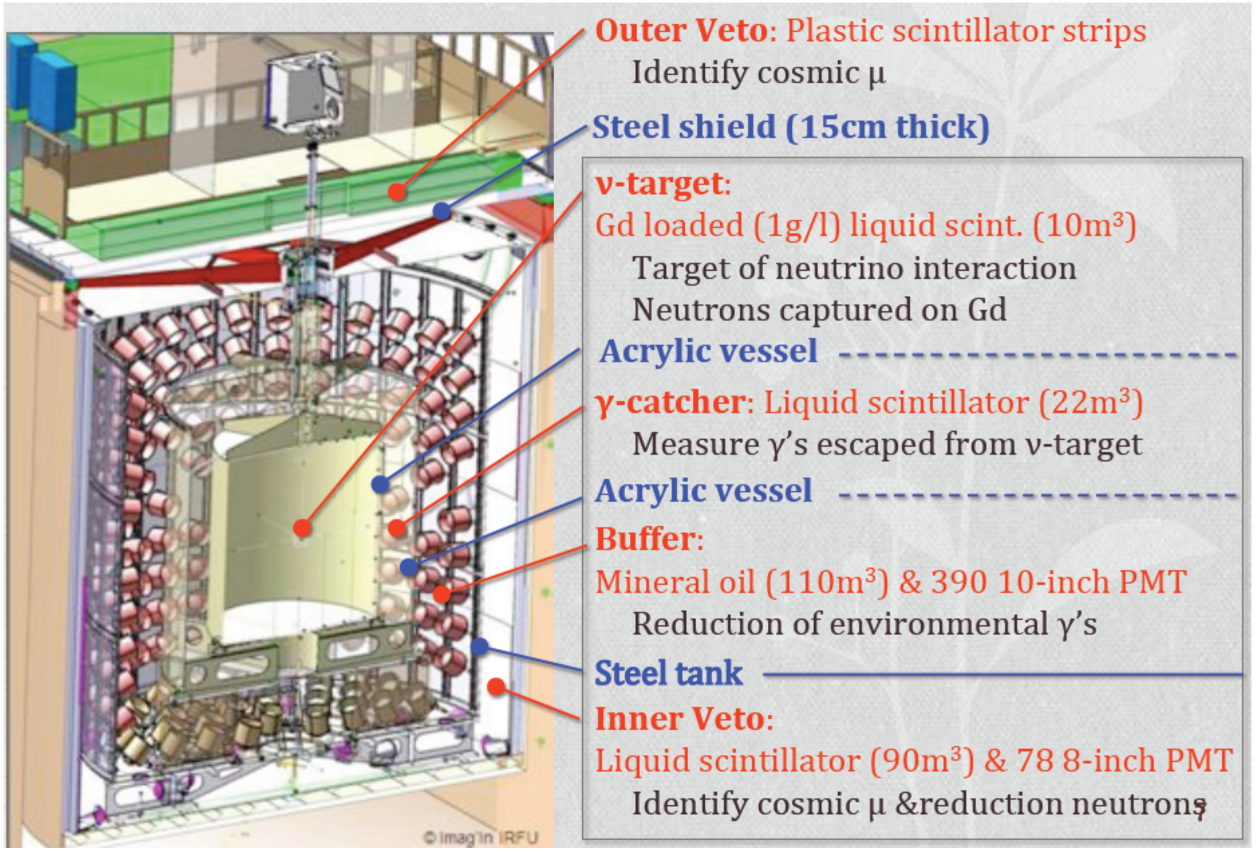
# Electron Neutrino Disappearance

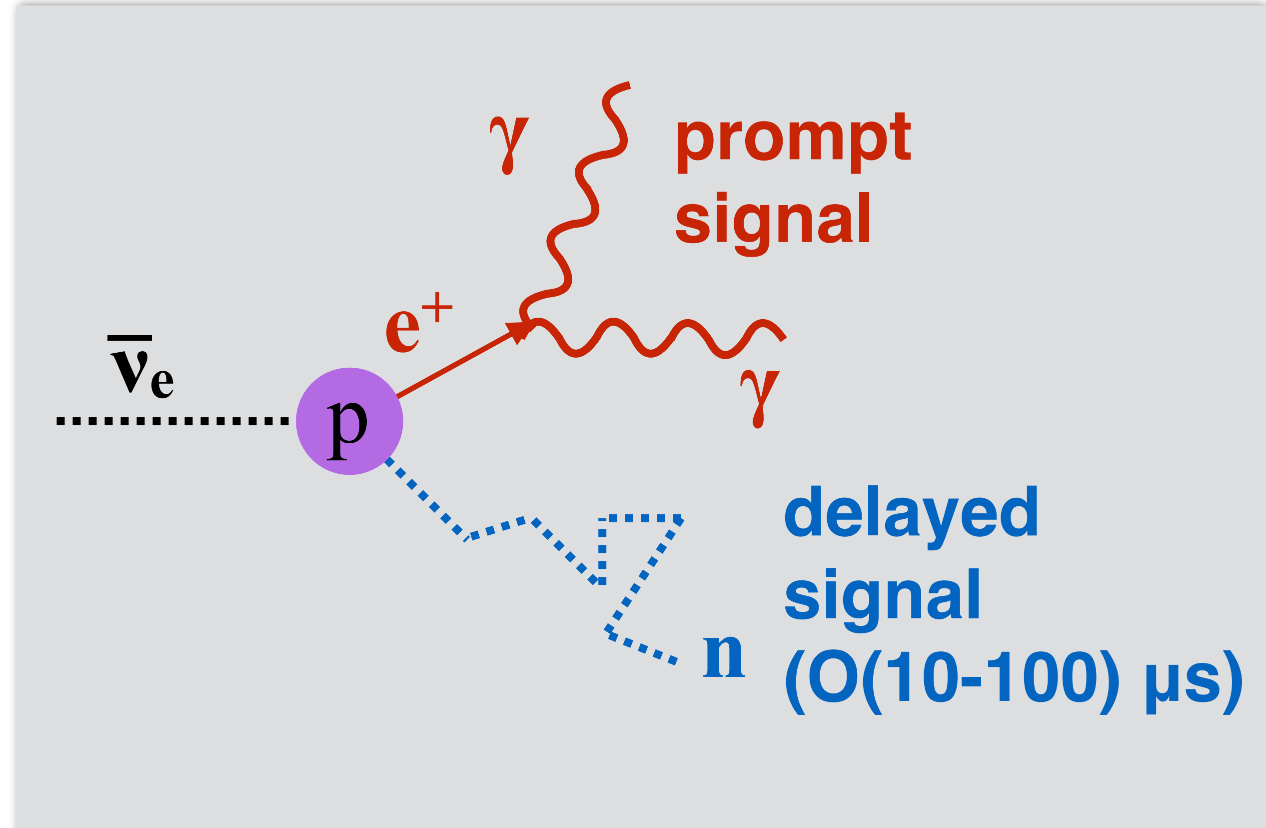
$$P(\nu_e \to \nu_e) = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32})$$




- The solar term enables measurements of the $\theta_{12}$ and $\Delta m^2_{21}$ parameters.
- **The atmospheric term enables measurements of $\theta_{13}$ and $\Delta m^2_{atm}$.**
- Note, CPT symmetry means there is no dependence on $\delta_{CP}$.

# Detecting Solar/Reactor Neutrinos




- Two general approaches:
  - inverse beta-decay

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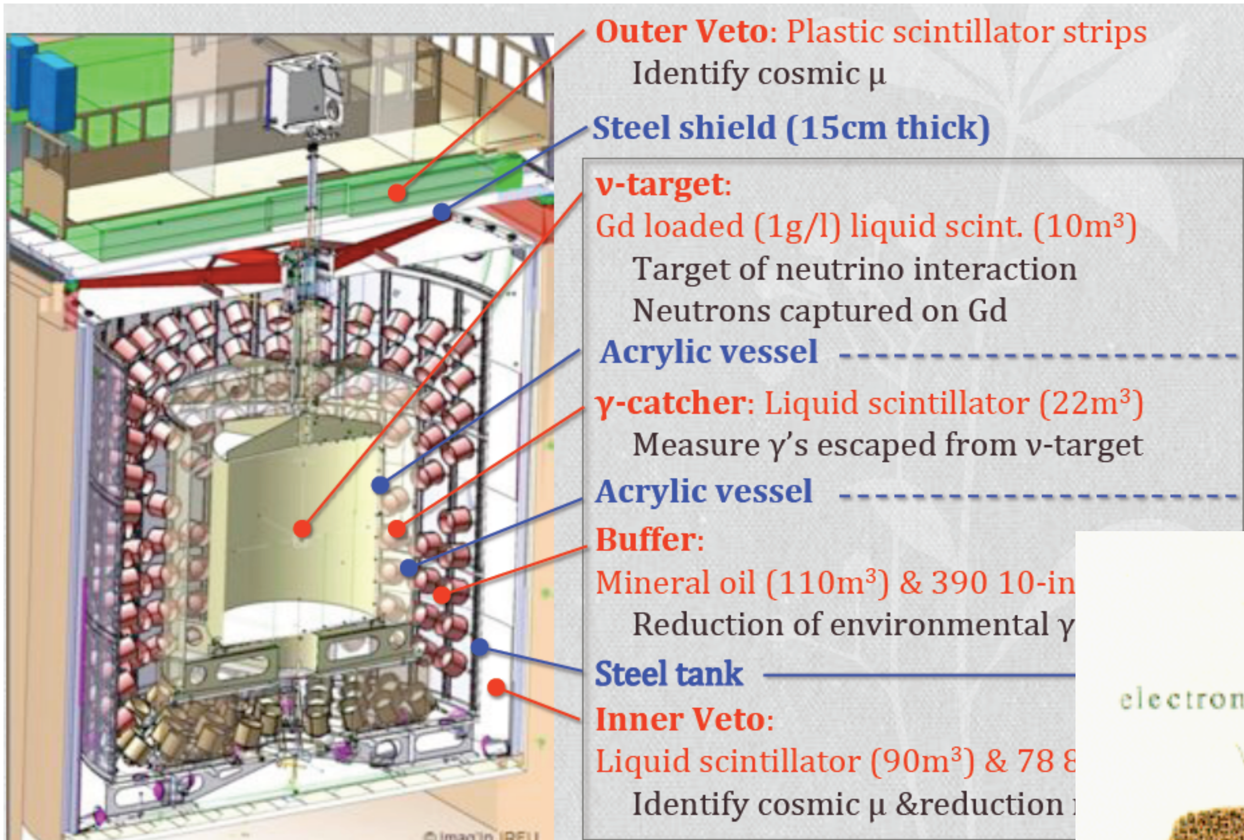
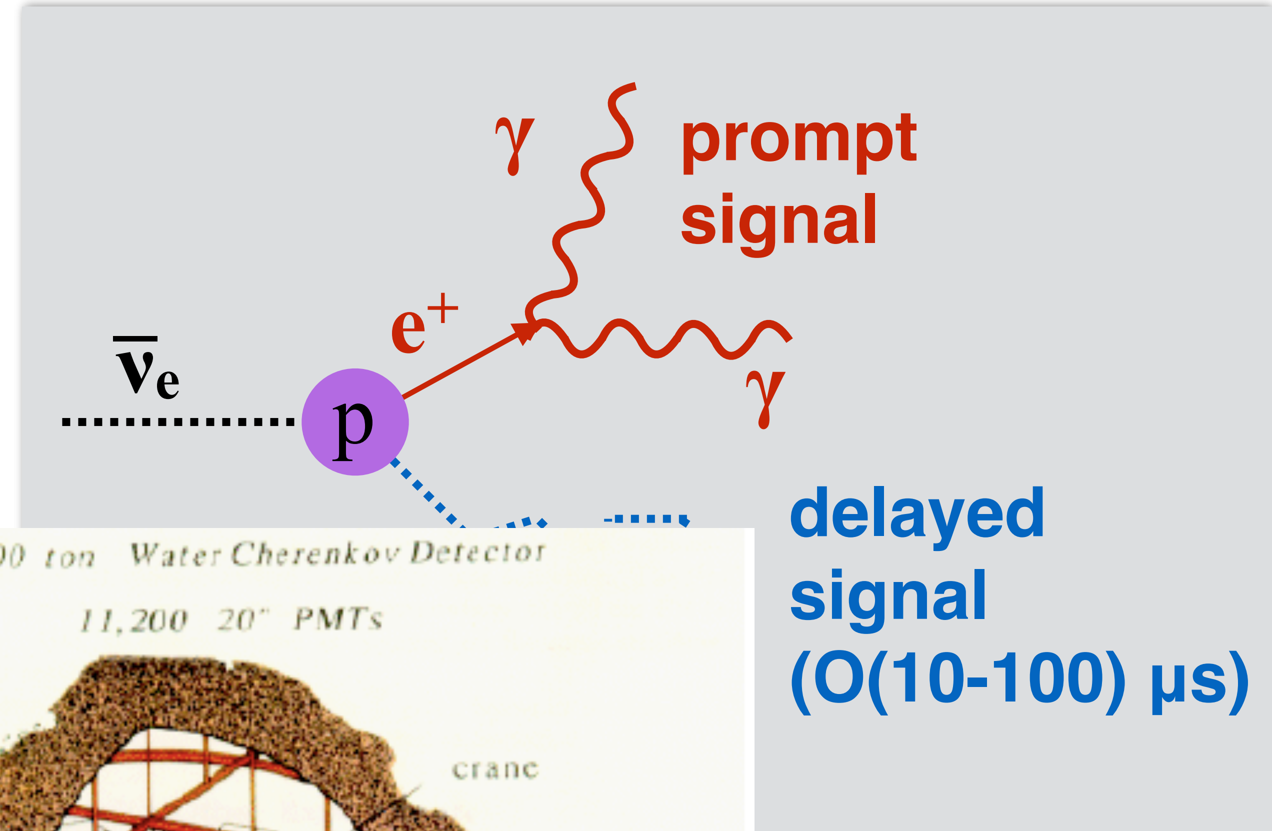
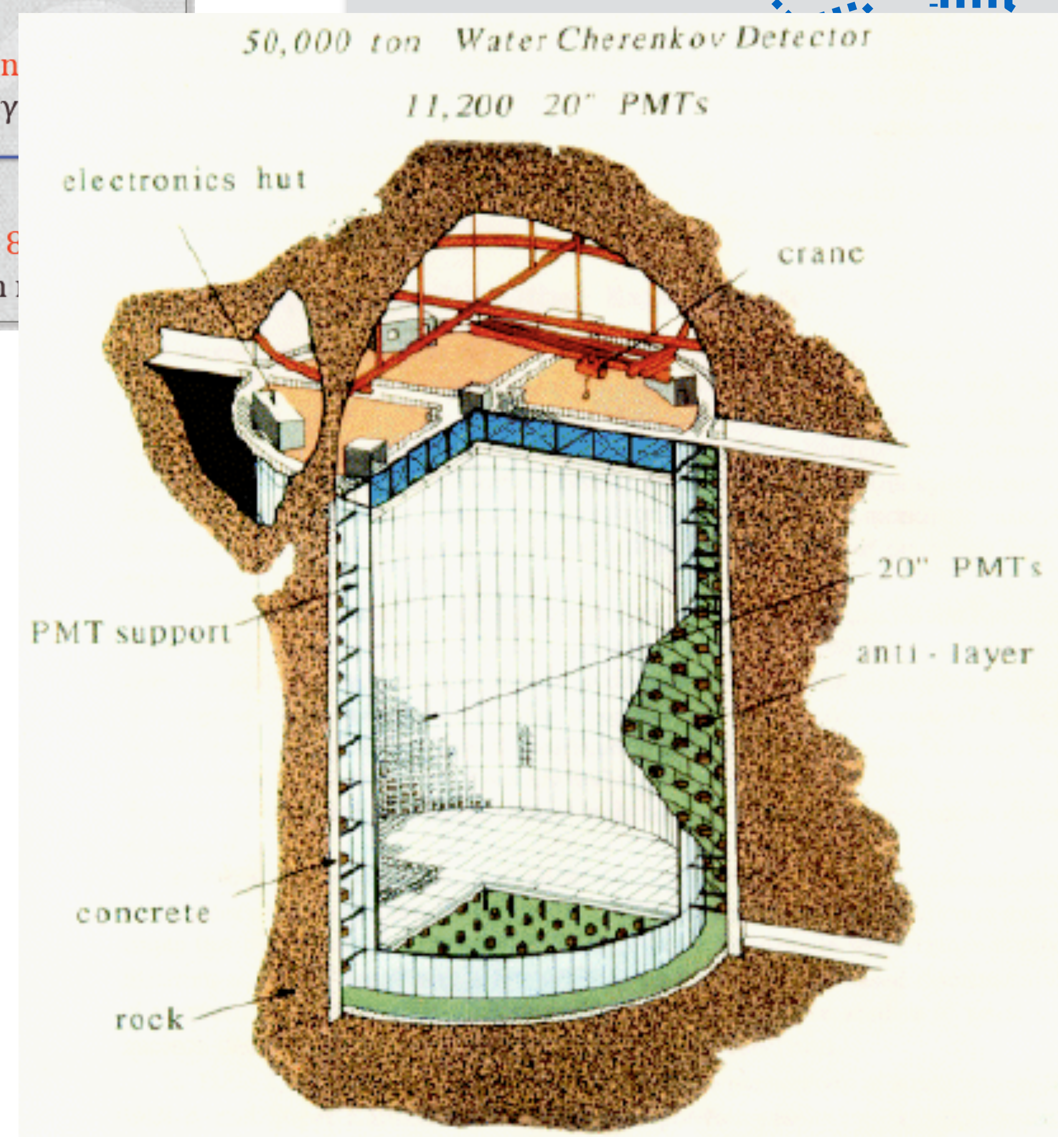
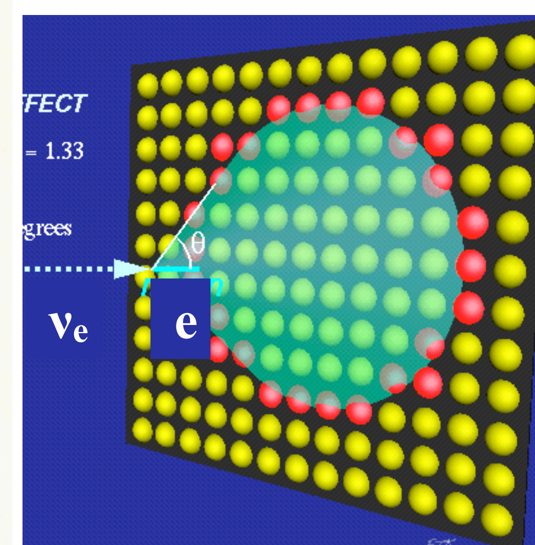


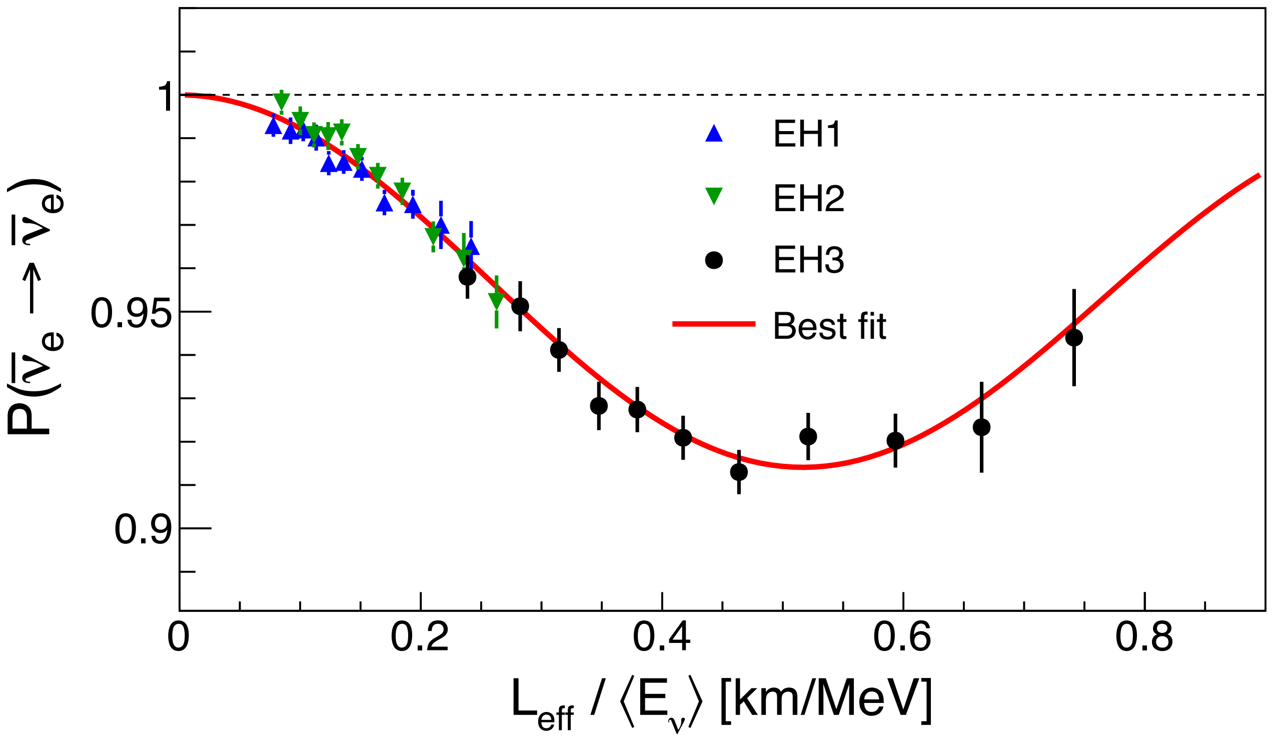



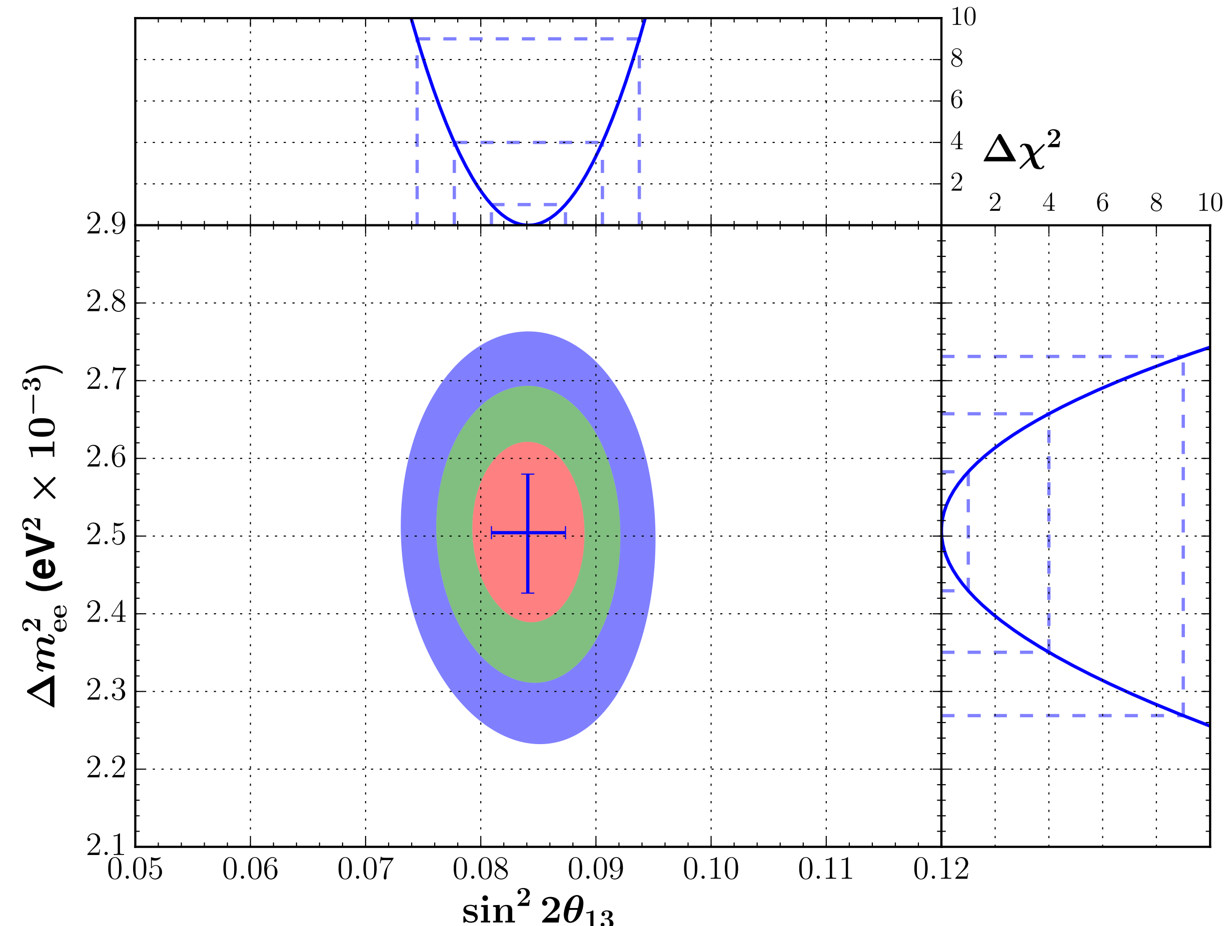




- Two general approaches:
  - inverse beta-decay
  - Cherenkov light
- Threshold: ~MeV

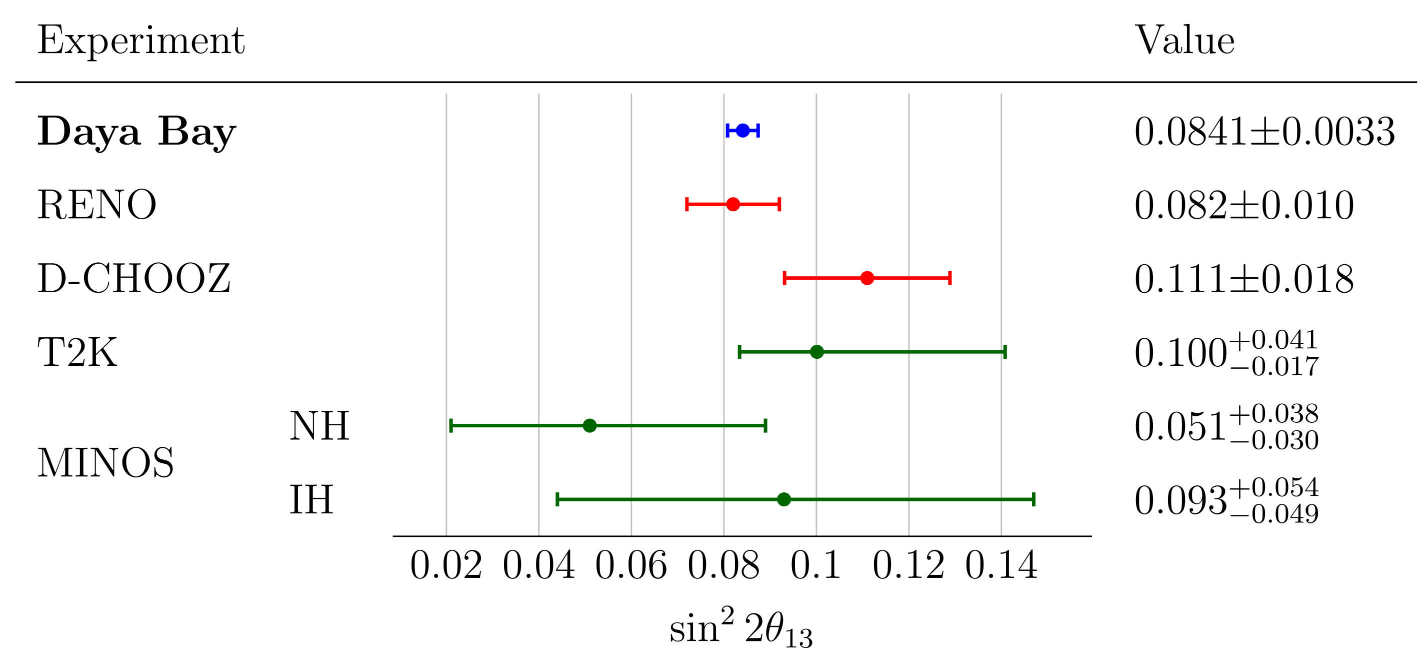
# Latest Results from Daya Bay (China)




Phys. Rev. D 95, 072006 (2017)

- 11% (2012) → 4% (2016), close to their 3% goal.
- Spectral analysis also provides measurement of $\Delta m^2_{ee}$ (~ $\Delta m^2_{31}$), consistent with MINOS results (and comparable precision)



# Muon Neutrino Oscillations in Long-Baseline Experiments

- Long-baseline $\nu_\mu \rightarrow \nu_e$ experiments have the potential to simultaneously measure $\theta_{13}$, $\delta_{CP}$, sign($\Delta m_{31}^2$), sign($\theta_{23}$-45°):

$$\Delta = \Delta m_{31}^2 L/(4E_\nu)$$

$$A = 2\sqrt{2} G_F n_e E_\nu / \Delta m_{31}^2$$

$$\alpha = \Delta m_{12}^2 / \Delta m_{31}^2$$

$$P(\nu_\mu \rightarrow \nu_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2((A-1)\Delta)}{(A-1)^2} +$$

in matter

Leading term

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

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Sensitive to octant.

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

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

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Interference terms: Jarlskog invariant up to $10^3$ larger than in quark mixing

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$$P(\nu_\mu \rightarrow \nu_e) \simeq \sin^2\theta_{23} \sin^2 2\theta_{13} \frac{\sin^2((A-1)\Delta)}{(A-1)^2} +$$

in matter

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

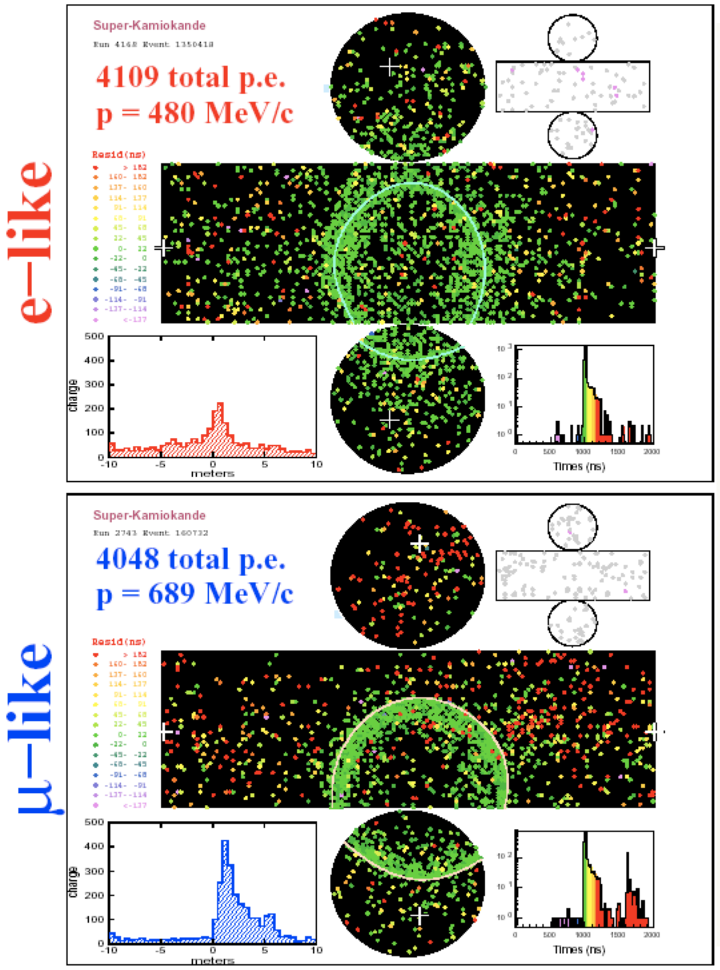
$$\alpha \cos\delta \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \cos\Delta \sin(A\Delta) \frac{\sin((1-A)\Delta)}{A(1-A)} + \mathcal{O}(\alpha^2)$$

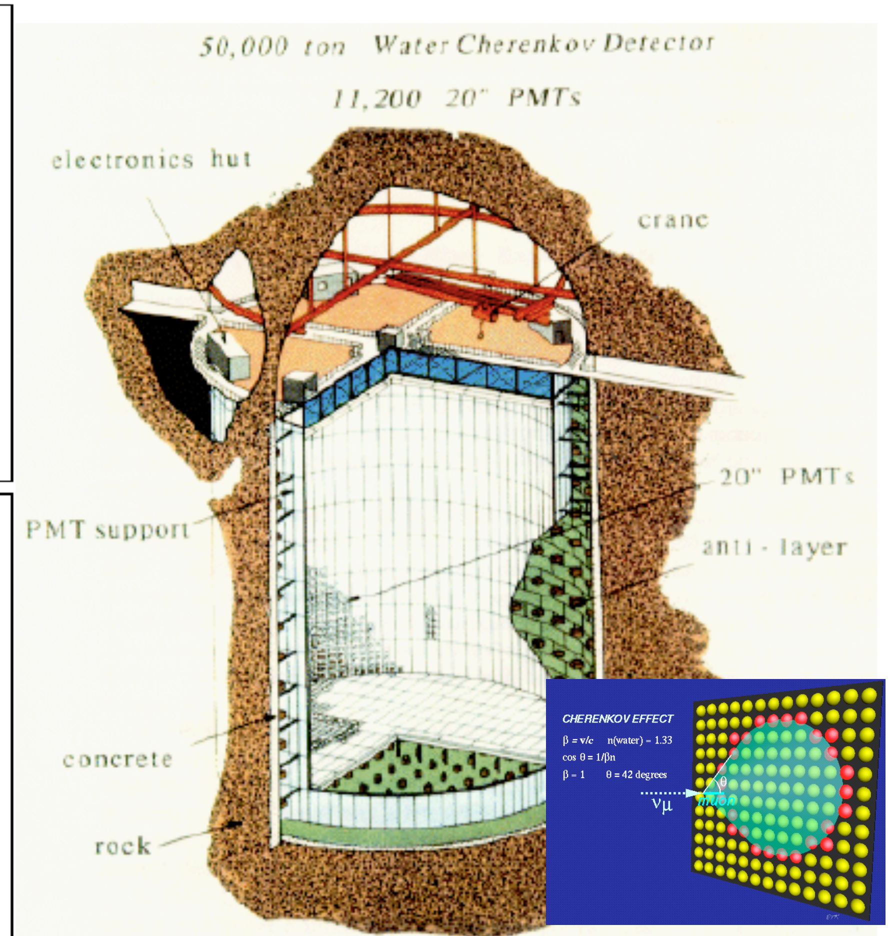
**M. Freund, Phys. Rev. D64 (2001) 053003**

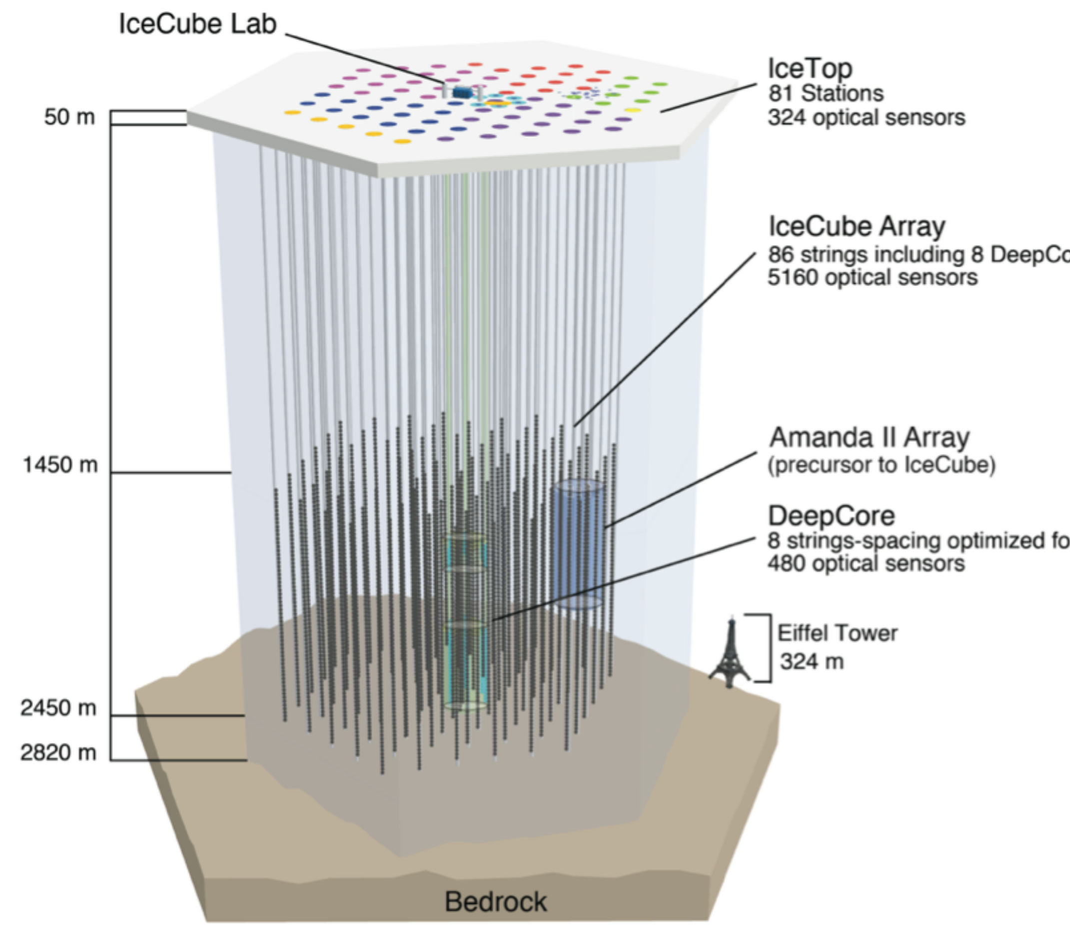
- Separate measurement of $\nu_\mu \rightarrow \nu_\mu$ gives access to $\sin^2(2\theta_{23})$ and $\Delta m^2_{32}$:

$$P(\nu_\mu \rightarrow \nu_\mu) \simeq 1 - \sin^2(2\theta_{23}) \sin^2\left(1.27 \Delta m^2_{32} \frac{L}{E}\right)$$

# Detecting High Energy Neutrinos



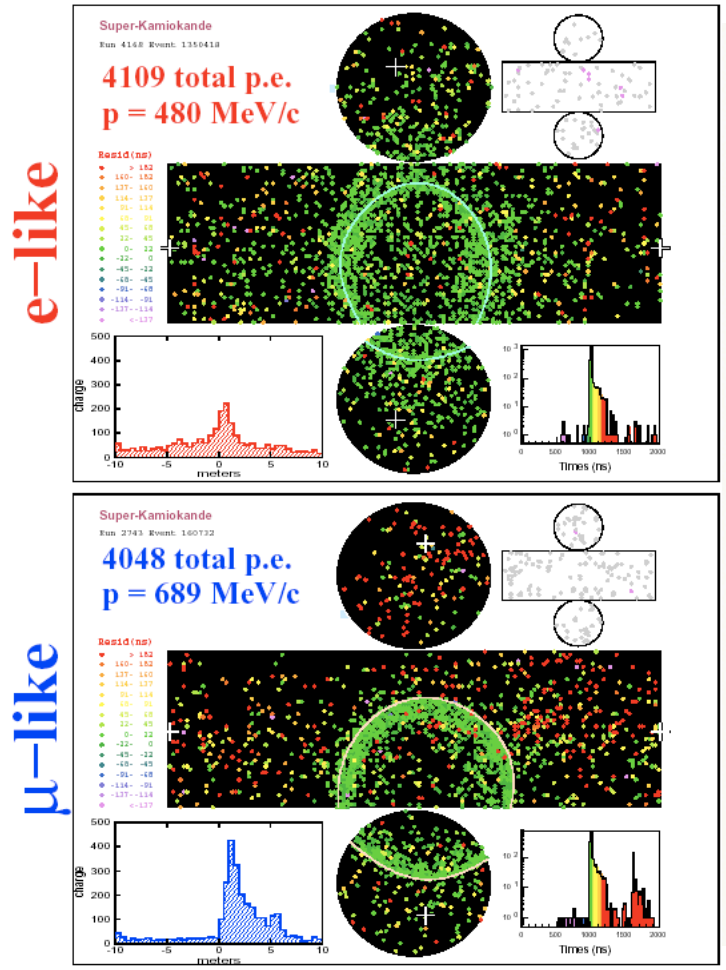



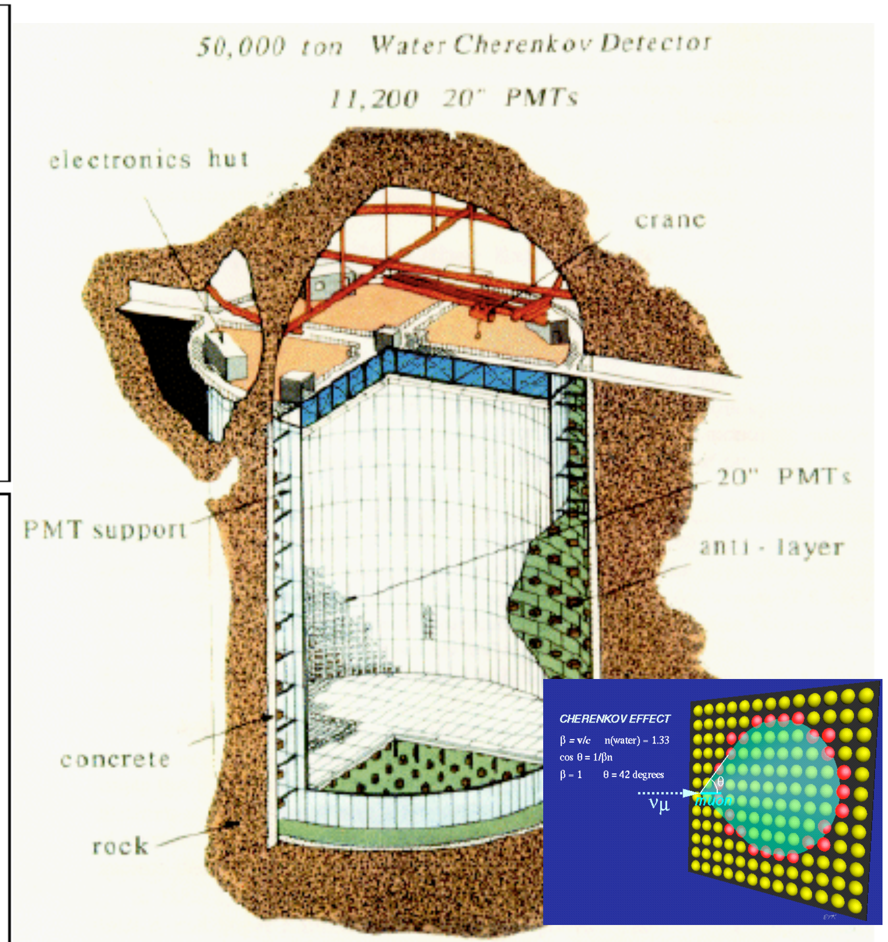



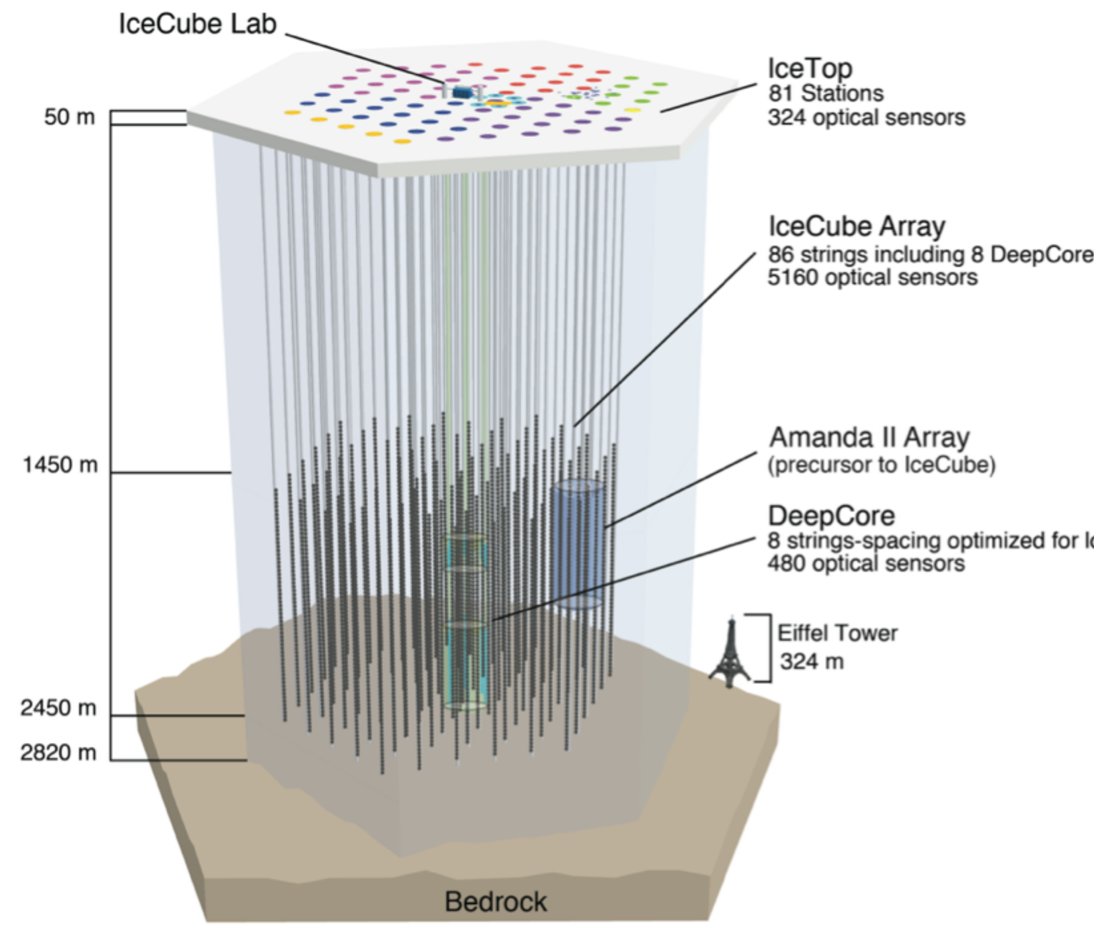

Two general approaches:

- Water/Ice Cherenkov (energy threshold: 100s of MeV to several GeV)

# Detecting High Energy Neutrinos

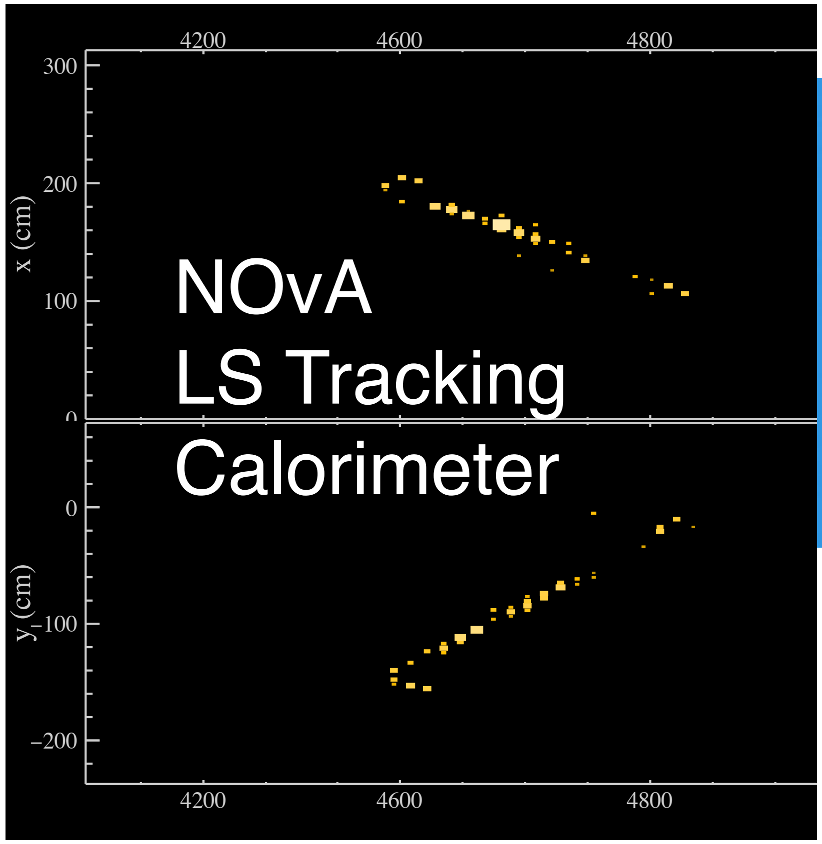


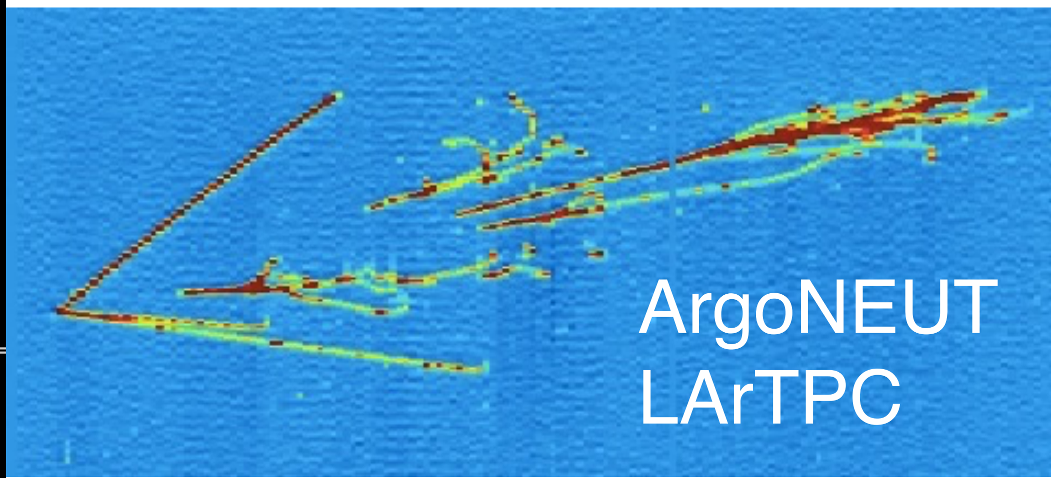




Two general approaches:

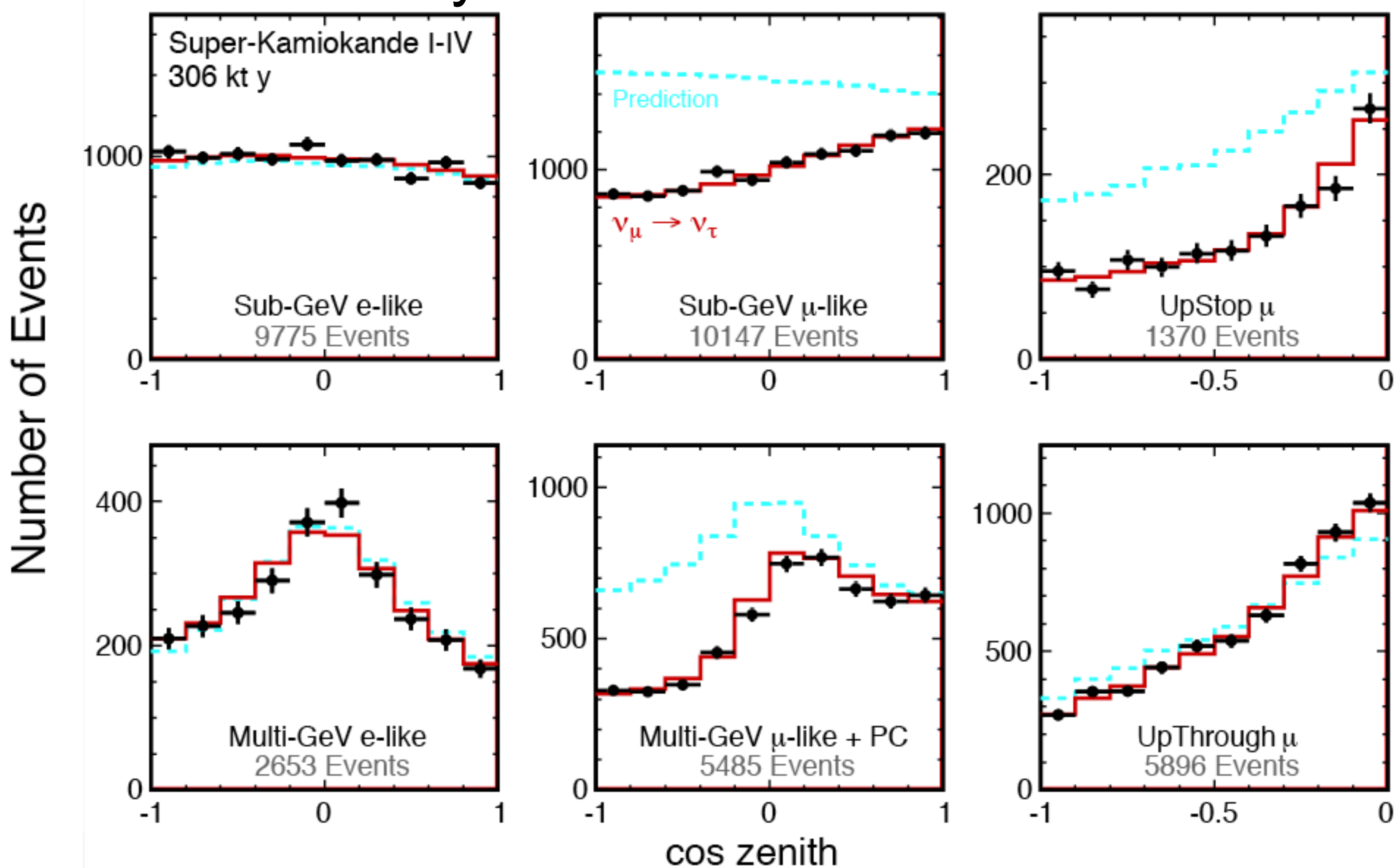
- Water/Ice Cherenkov (energy threshold: 100s of MeV to several GeV)
- Tracking calorimeter (energy threshold: few MeV)



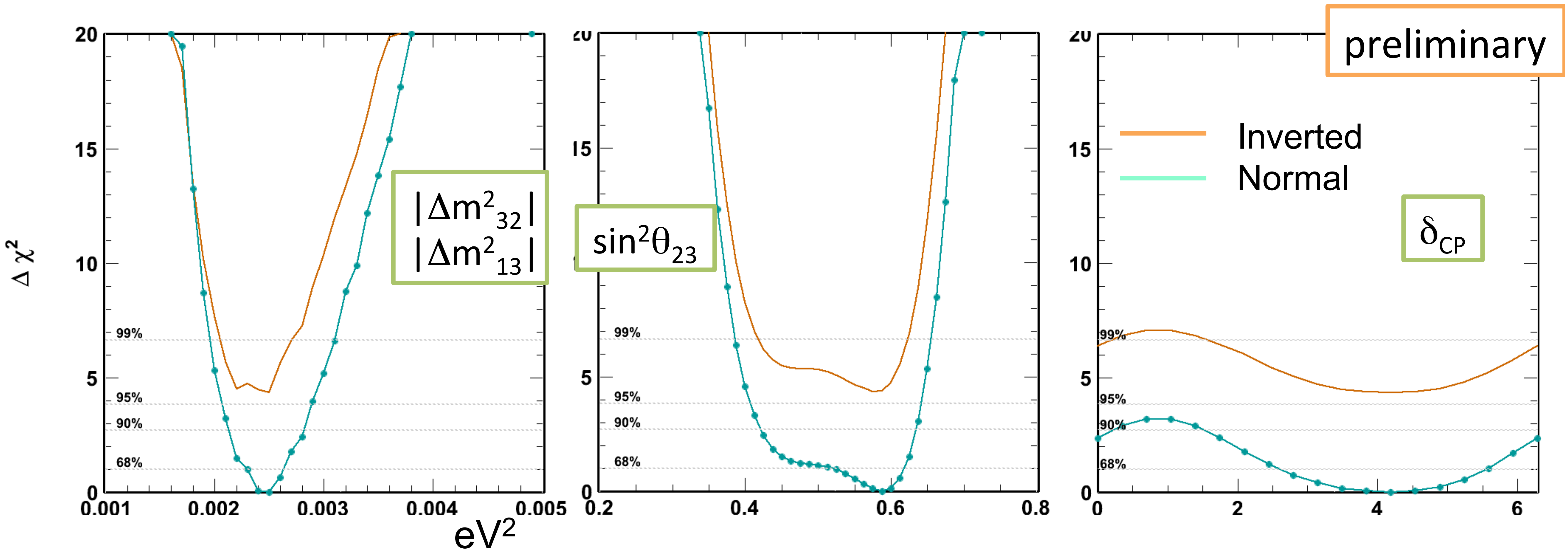
# Atmospheric Neutrino Measurements from Super-Kamiokande (Japan)

~ 20 years of data accumulation




**Y. Suzuki, NeuTel 2017**

# Latest Atmospheric Oscillation Results from Super-K

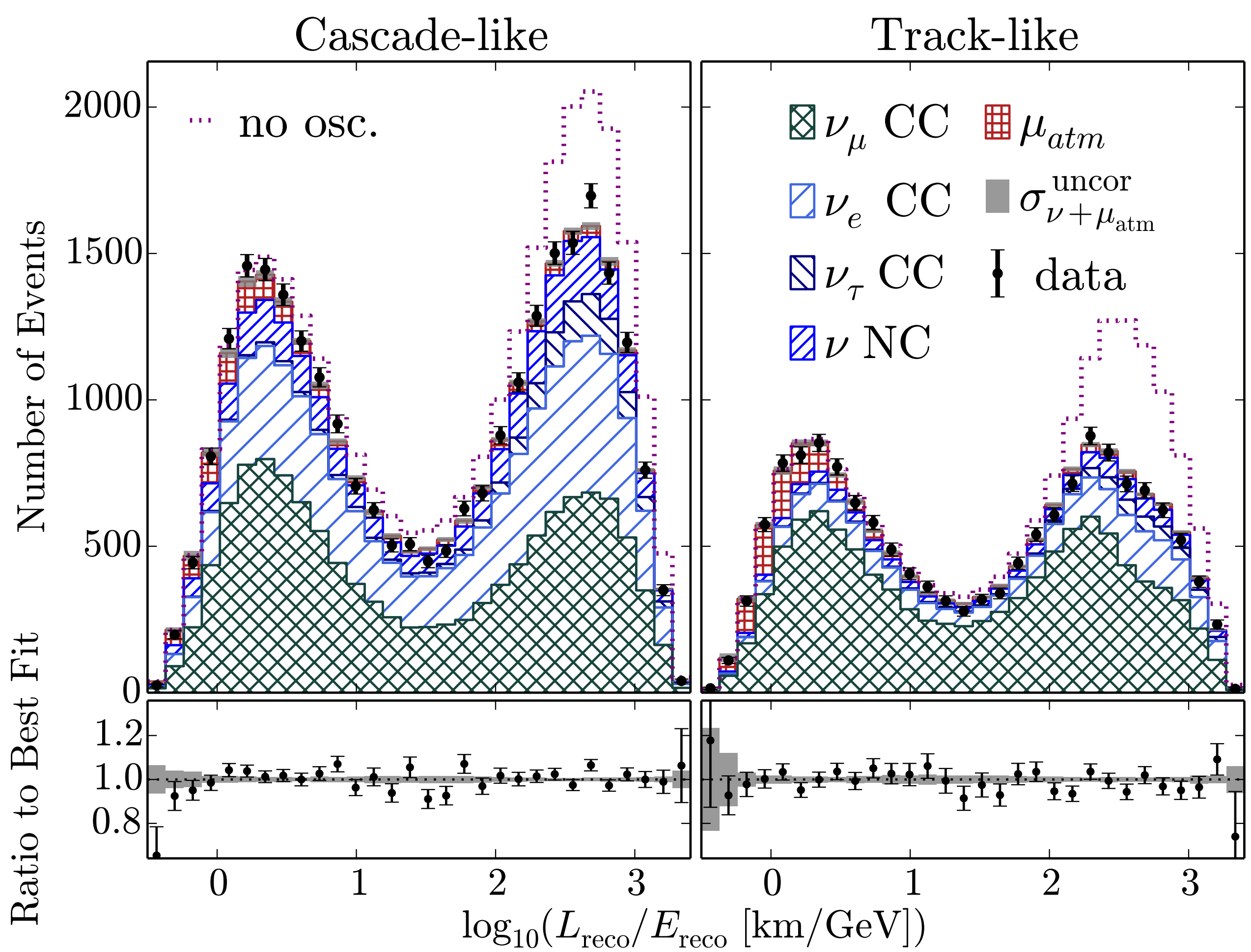


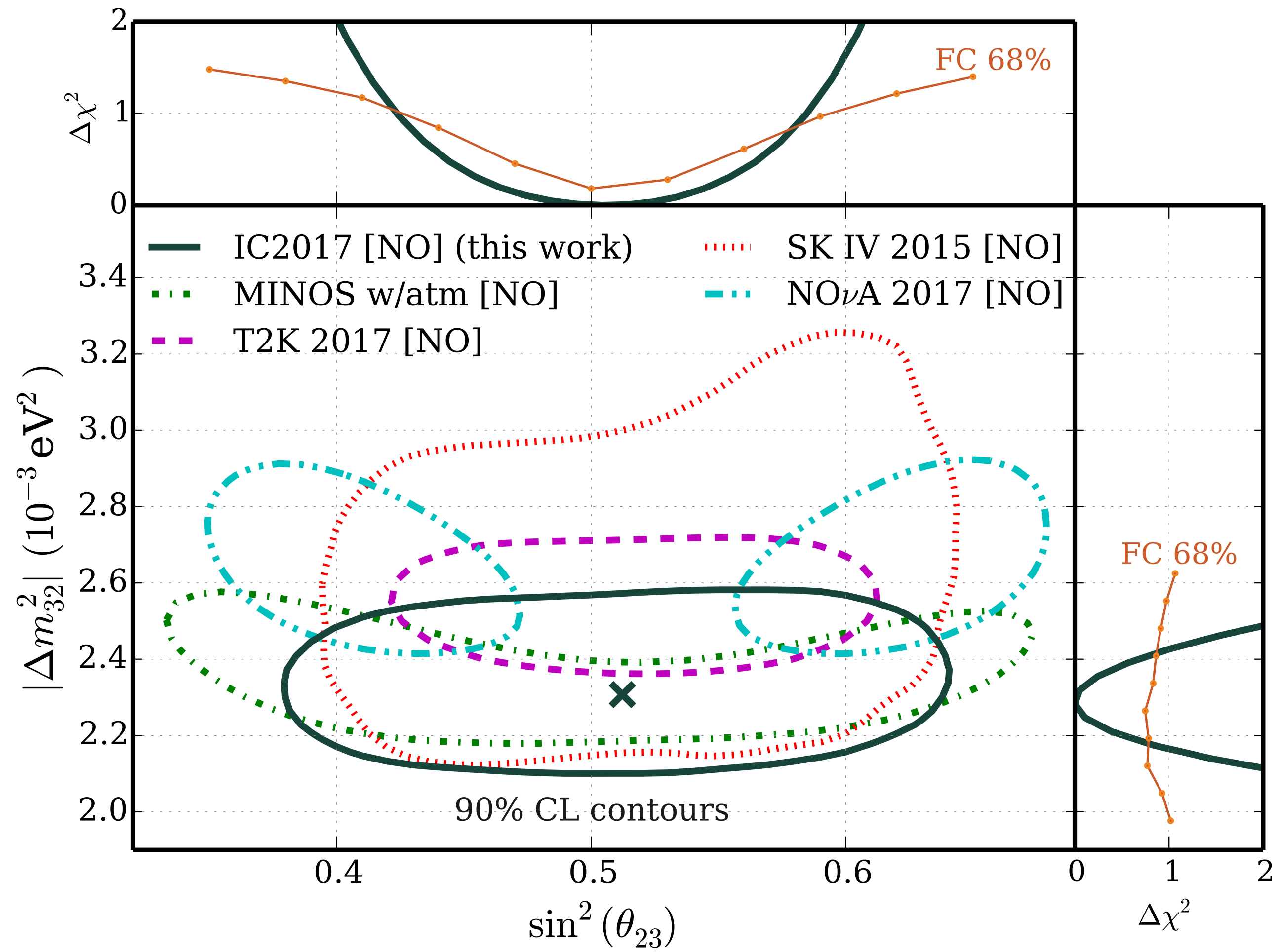

| Fit (517 dof) | $\chi^2$ | $\sin^2\theta_{13}$ | $\delta_{CP}$ | $\sin^2\theta_{23}$ | $\|\Delta m^2_{32}\|$ eV$^2$ |
|---|---|---|---|---|---|
| SK (IH) | 576.08 | 0.0219 (fix) | 4.189 | 0.575 | $2.5\times10^{-3}$ |
| SK (NH) | 571.74 | 0.0219 (fix) | 4.189 | 0.587 | $2.5\times10^{-3}$ |

**$\Delta\chi^2$ = -4.3**

**Moriyama, Neutrino 2016**

# Latest Results from the IceCube/DeepCore Experiment

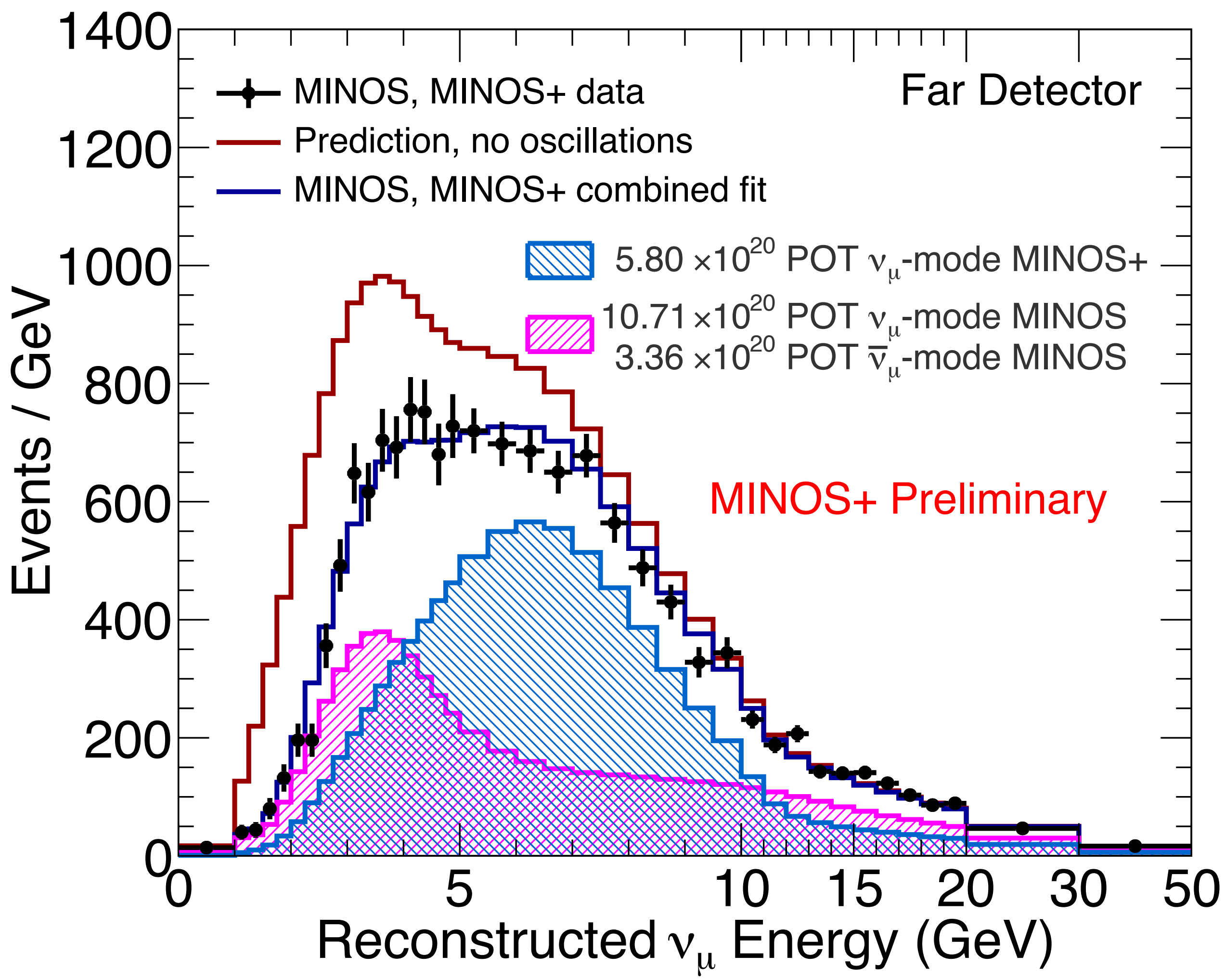


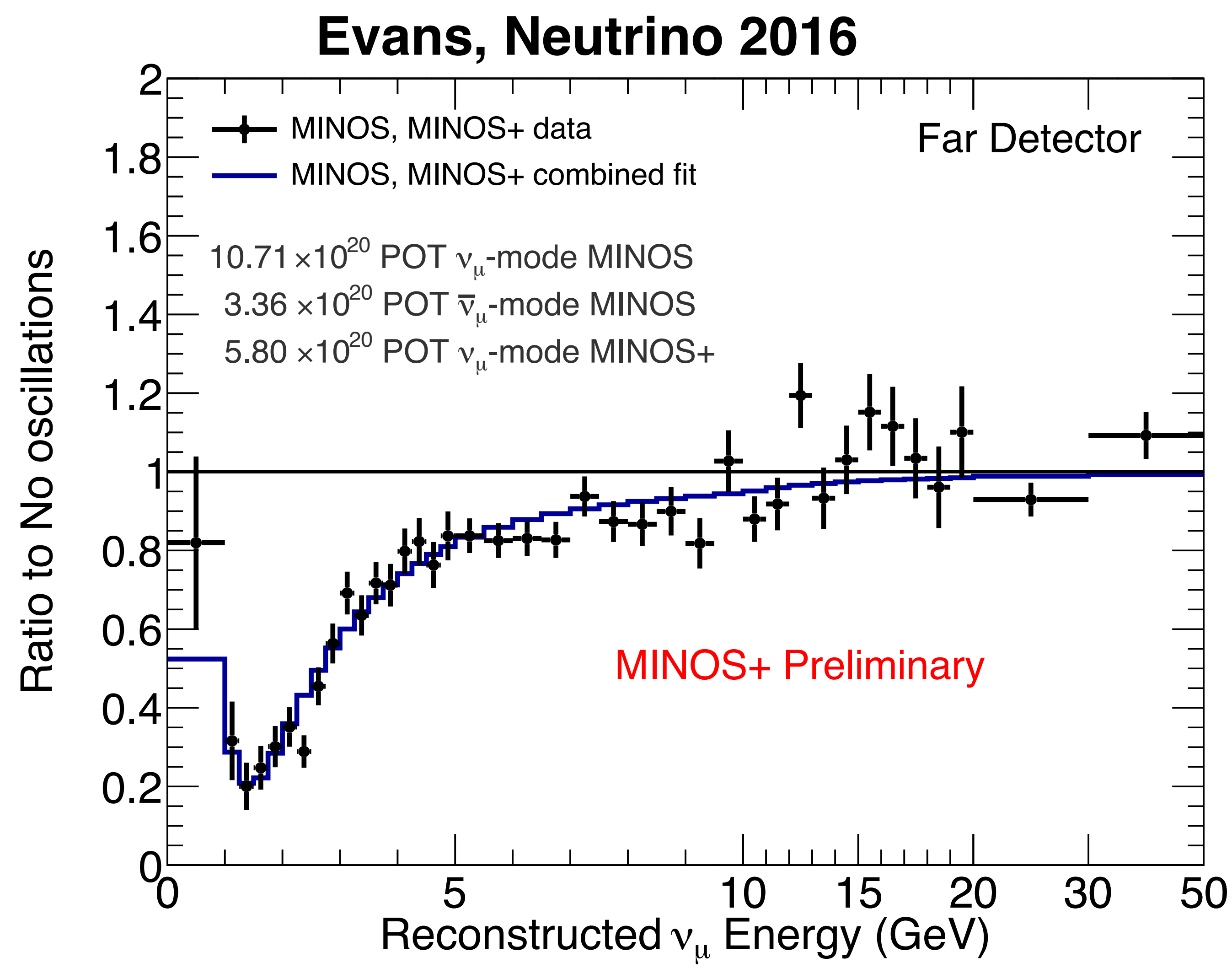




arXiv:1707.07081

- New results on arXiv (July 22).
- Makes use of events with reconstructed energies between 5.6 and 56 GeV.
- Improvements in reconstruction → x10 increase in event selection.
- Statistics-limited result, consistent with results from experiments that use lower energy neutrinos.

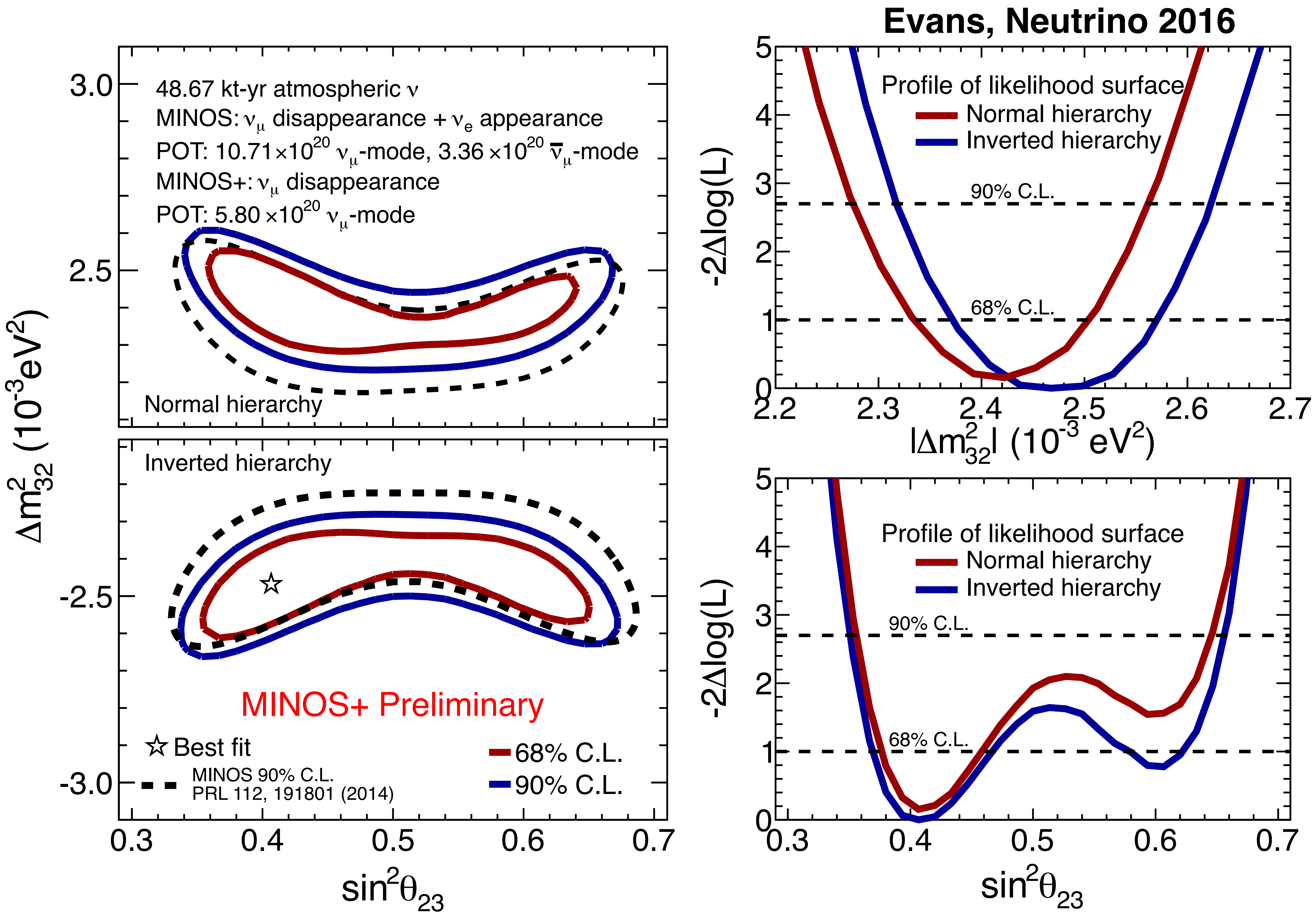
# Latest Results from the MINOS(+) Experiment




- Includes all data collected since 2005.
- The far detector has now been decommissioned and removed from the Soudan Lab after a decade of excellent performance.

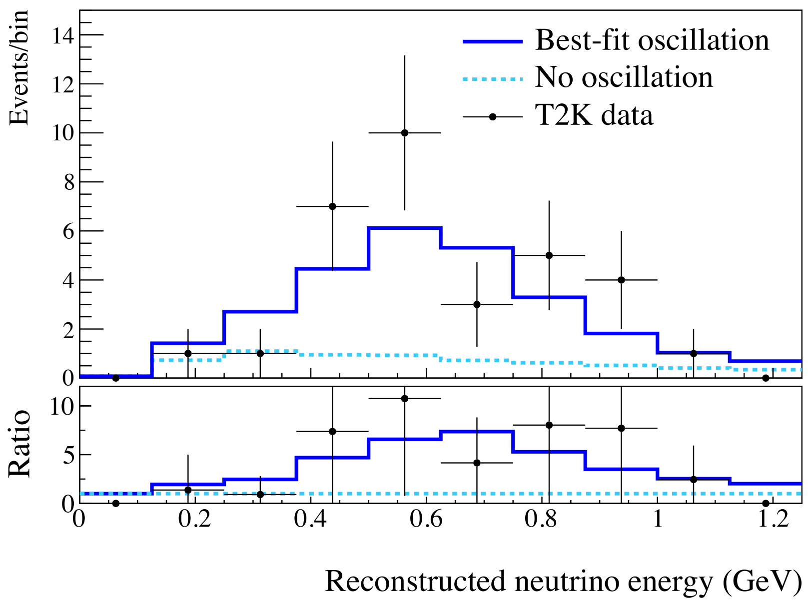
# Latest Results from the MINOS(+) Experiment



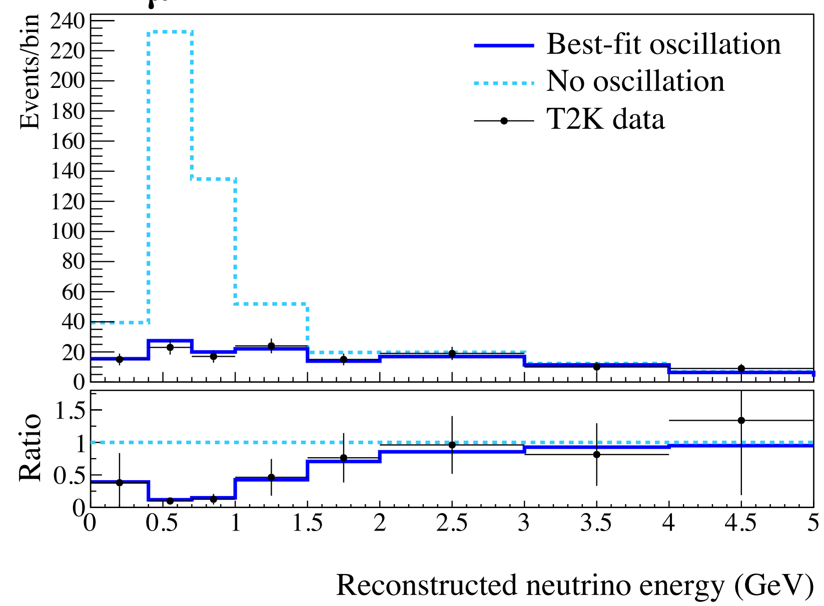

Joint fit of beam & atmospheric $\nu_\mu$, $\nu_e$ data.

# Latest Results from the T2K Experiment

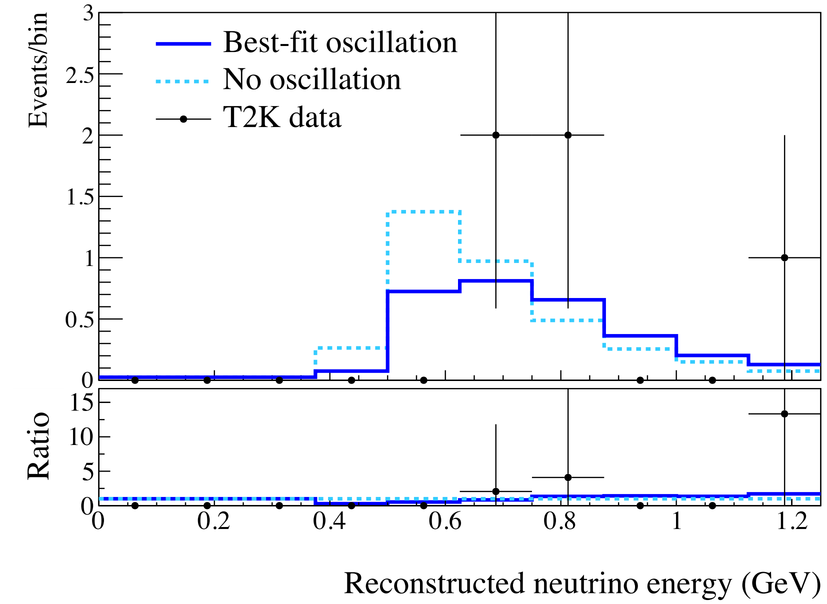
$\nu_e$ CC candidate events



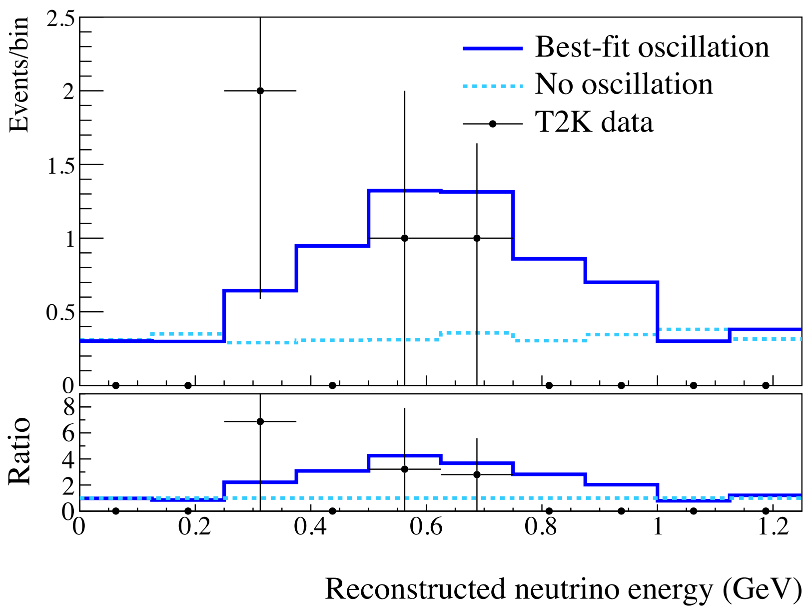

$\nu_\mu$ CC candidate events



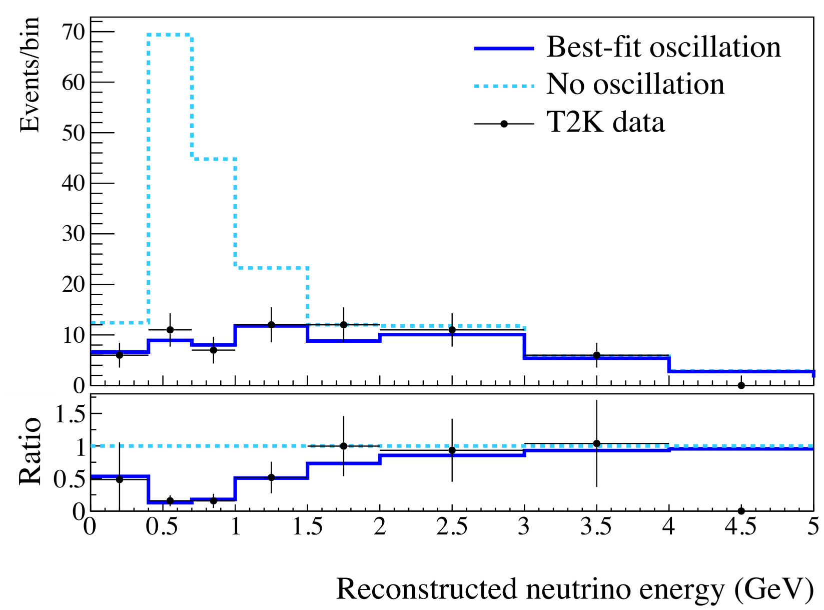

$\nu_e\ \pi^+$ CC candidate events




$\overline{\nu}_e$ CC candidate events




$\overline{\nu}_\mu$ CC candidate events

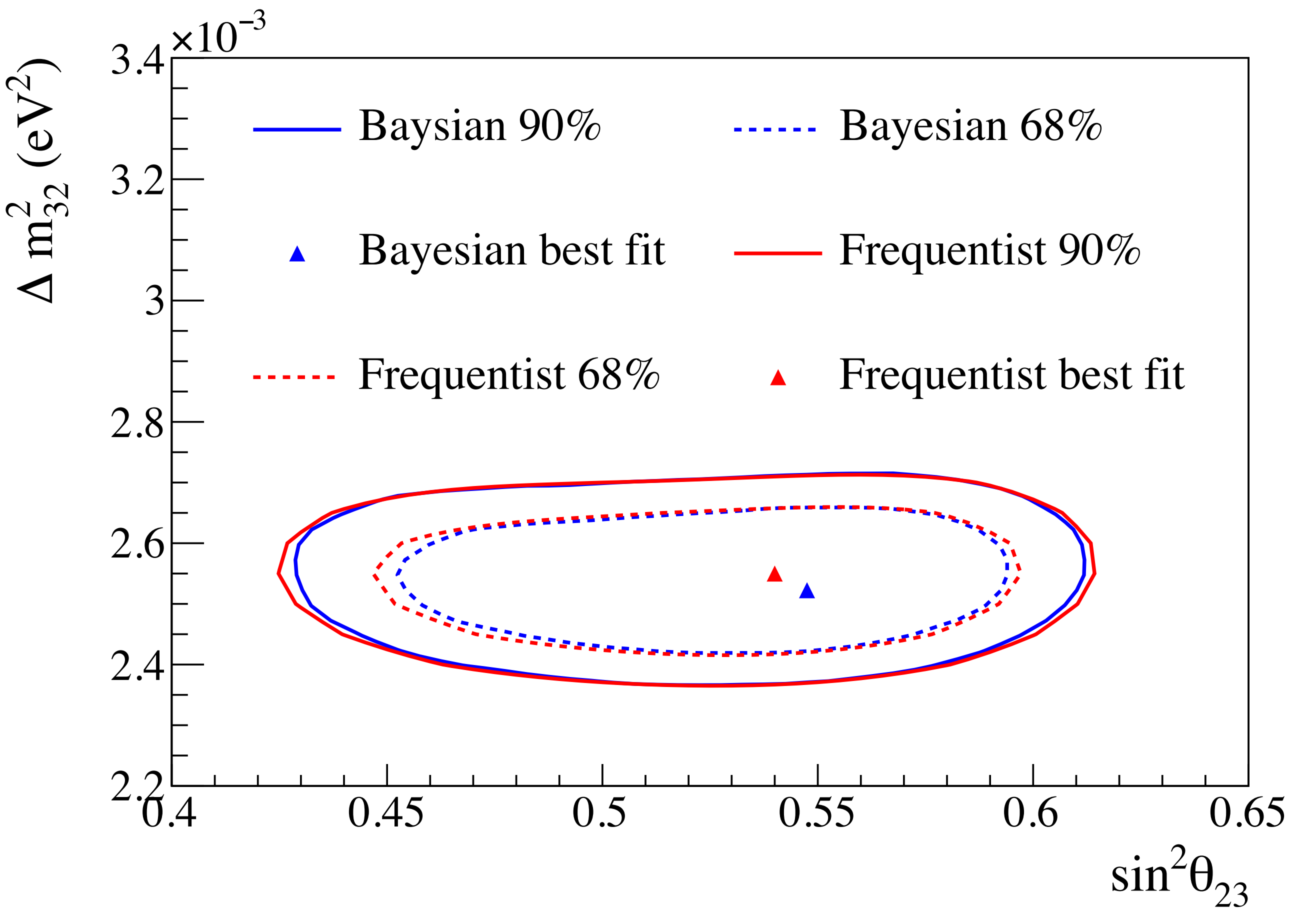


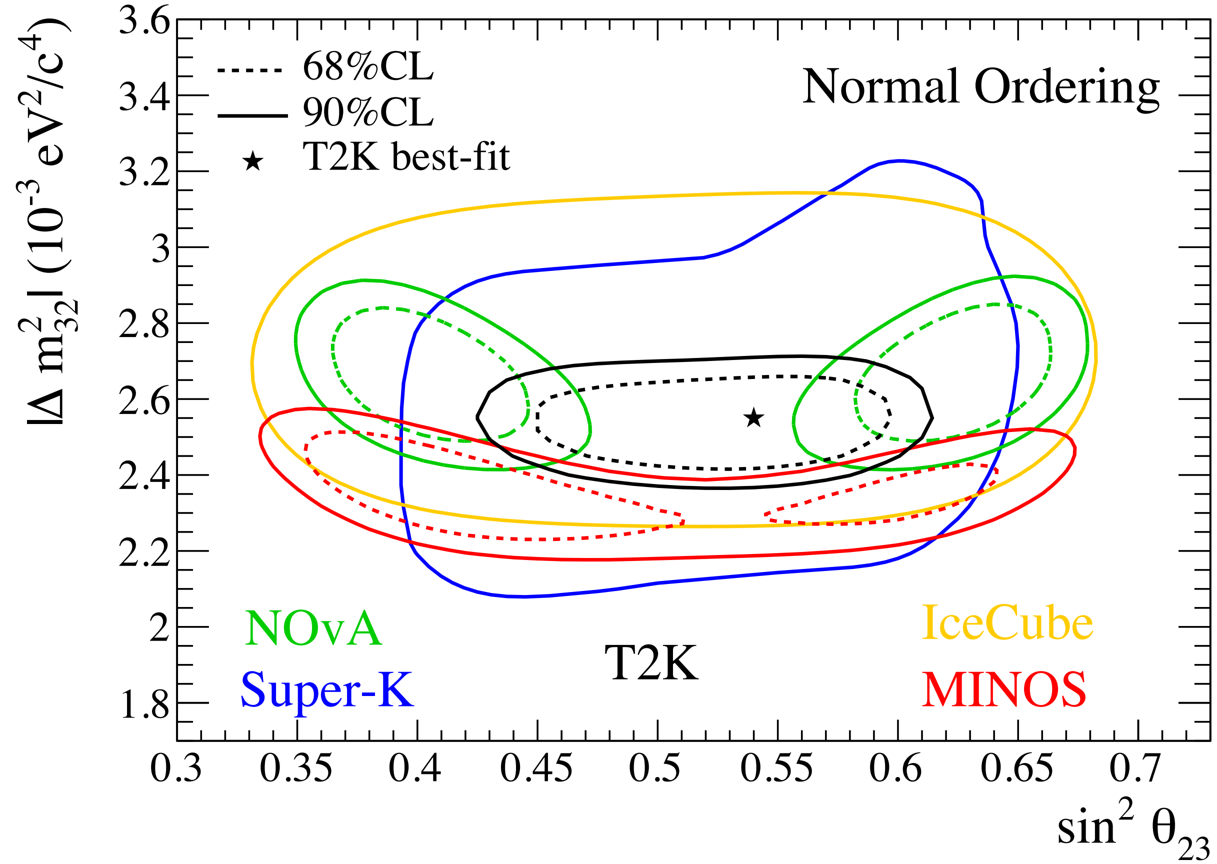

**Results based on equal POT for neutrino and anti-neutrino modes.**

**Joint 3-flavor fit performed on all data sets.**

# Latest Results from the T2K Experiment

arXiv:1707.01048



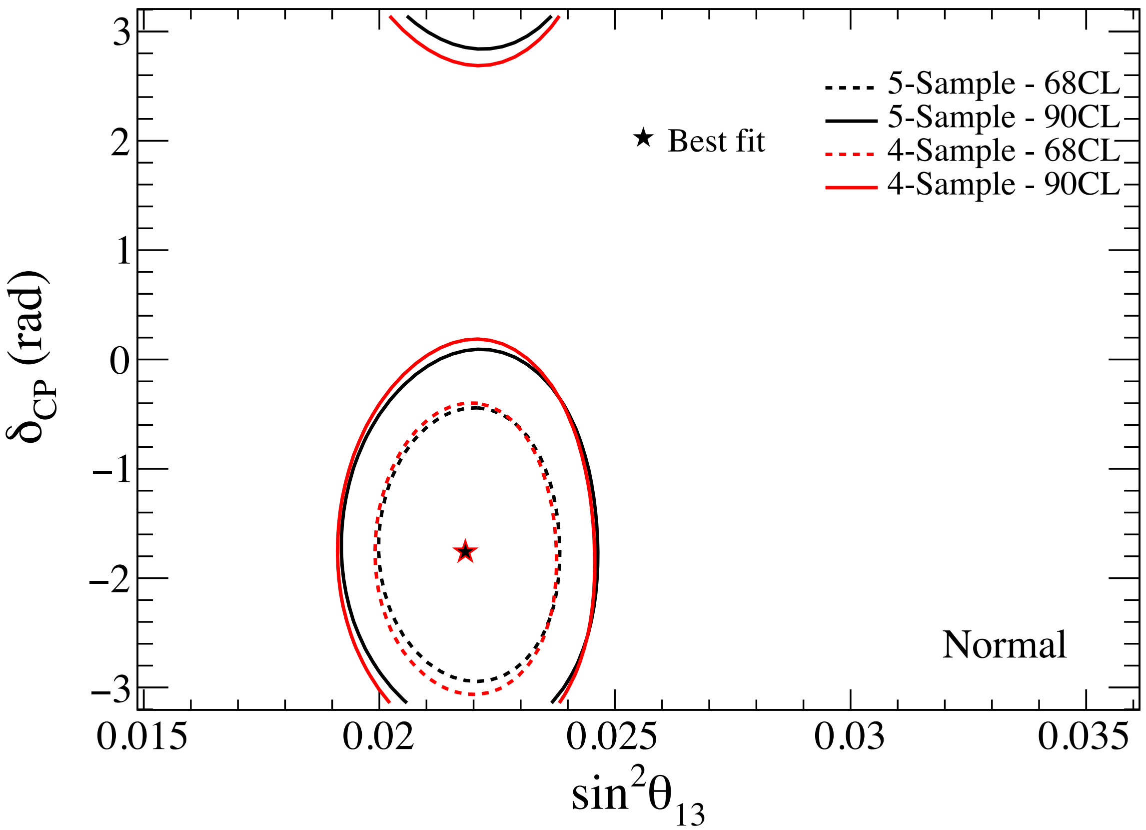




$$\sin^2 2\theta_{23} = 0.550^{+0.051}_{-0.085}$$

$$\Delta m^2_{32} = 2.54^{+0.080}_{-0.081} \times 10^{-3}\mathrm{eV}^2$$

# Latest Results from the T2K Experiment

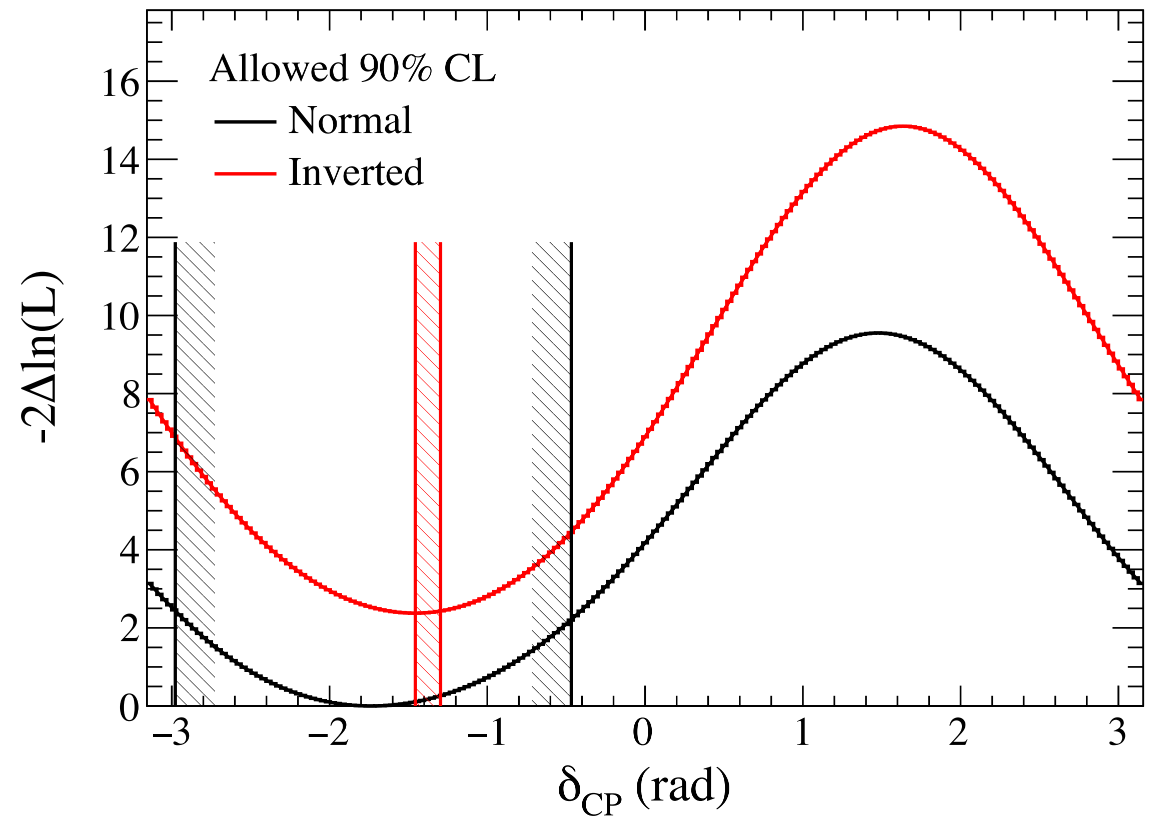
arXiv:1707.01048

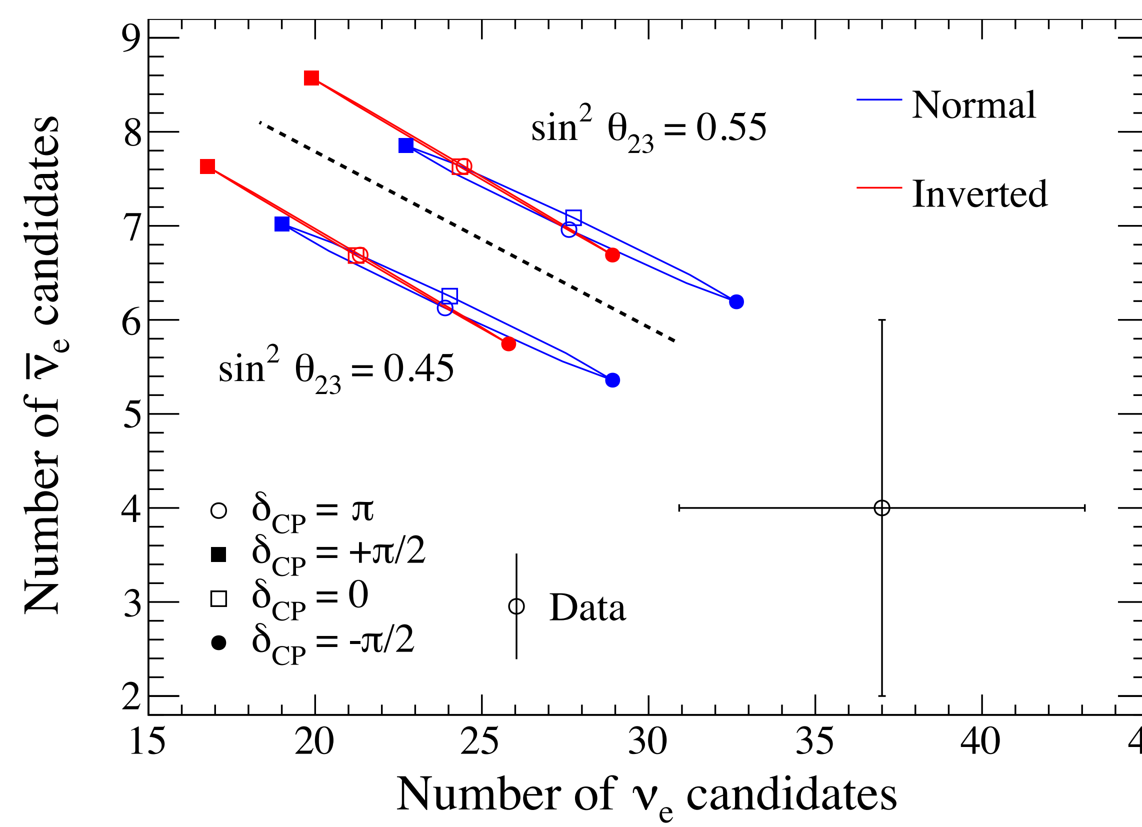



**using constraint of**

**$\sin^2 2\theta_{13} = 0.085 \pm 0.005$**

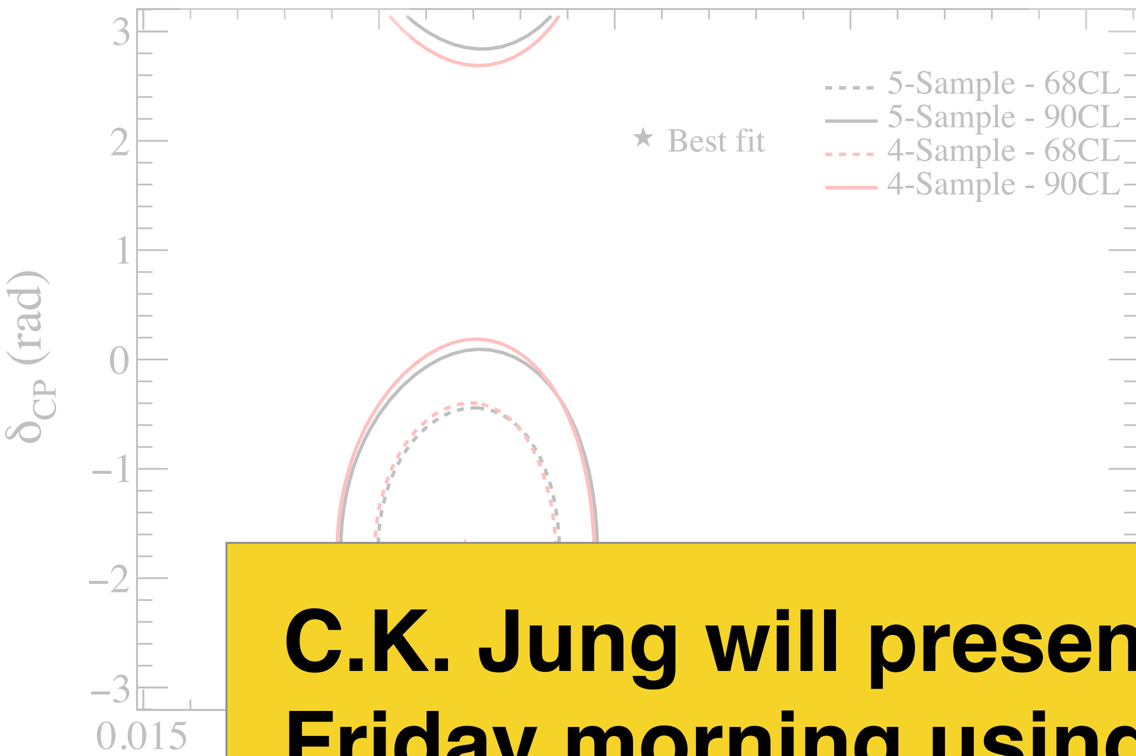
- CP conservation excluded at the 90% CL
- Measurement is outside of physical bounds.

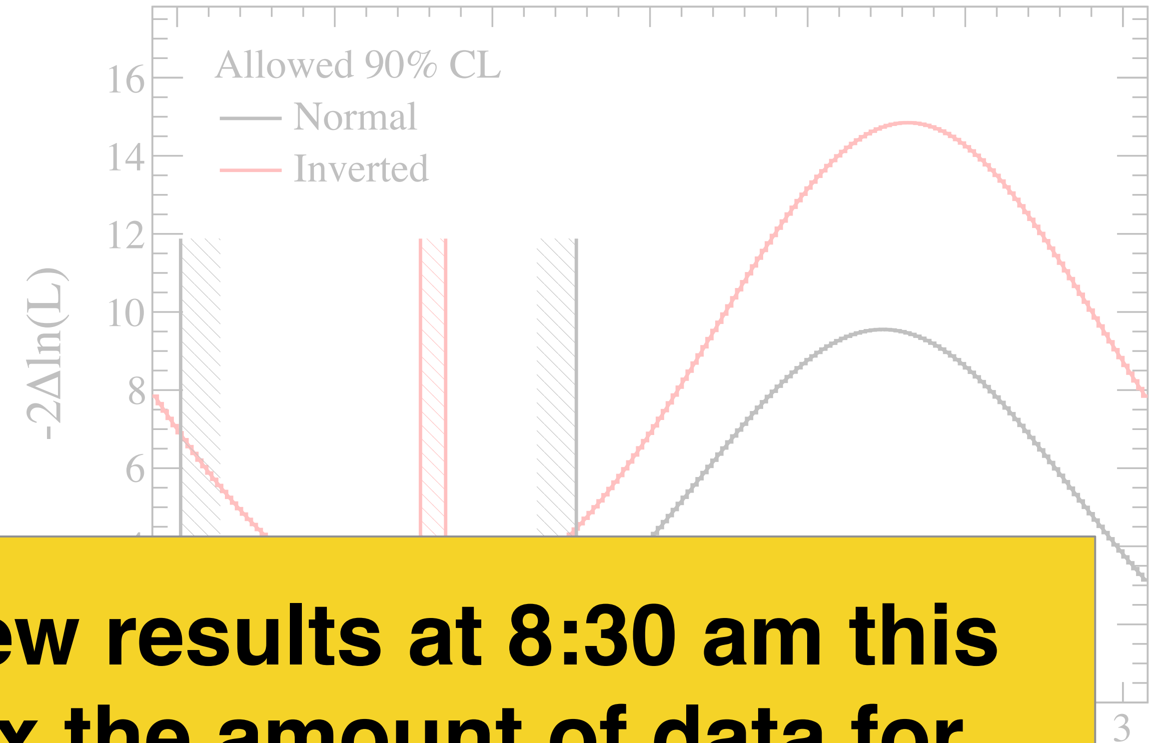


# Latest Results from the T2K Experiment

arXiv:1707.01048

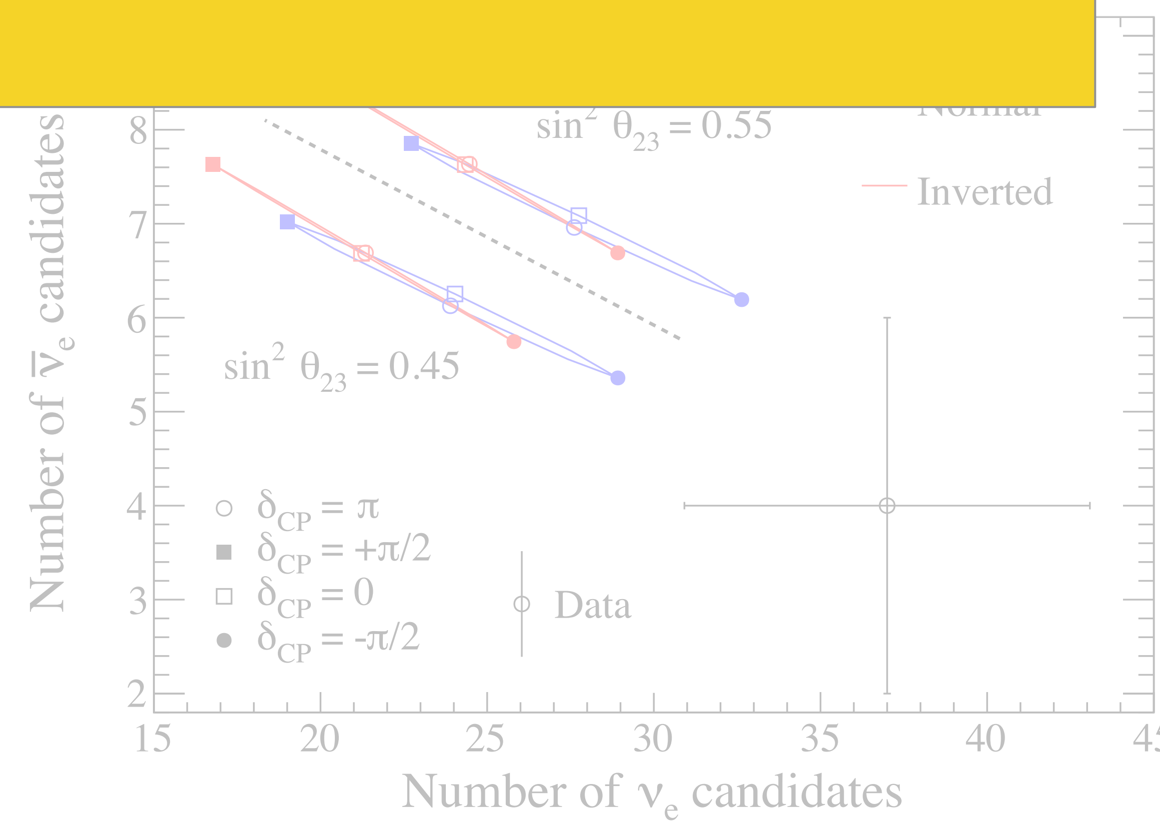



**C.K. Jung will present new results at 8:30 am this Friday morning using ~2x the amount of data for neutrino-mode.**

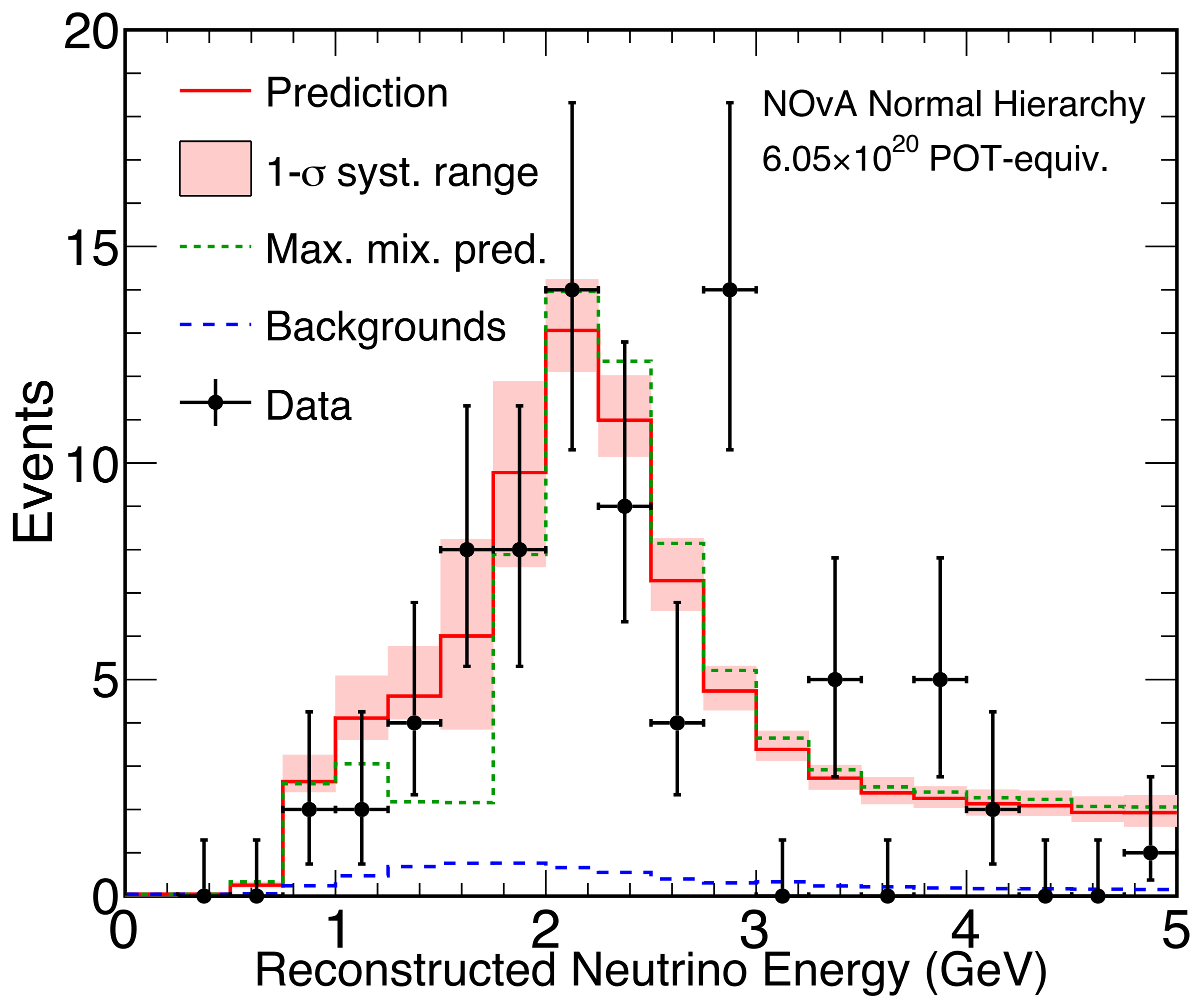
usi

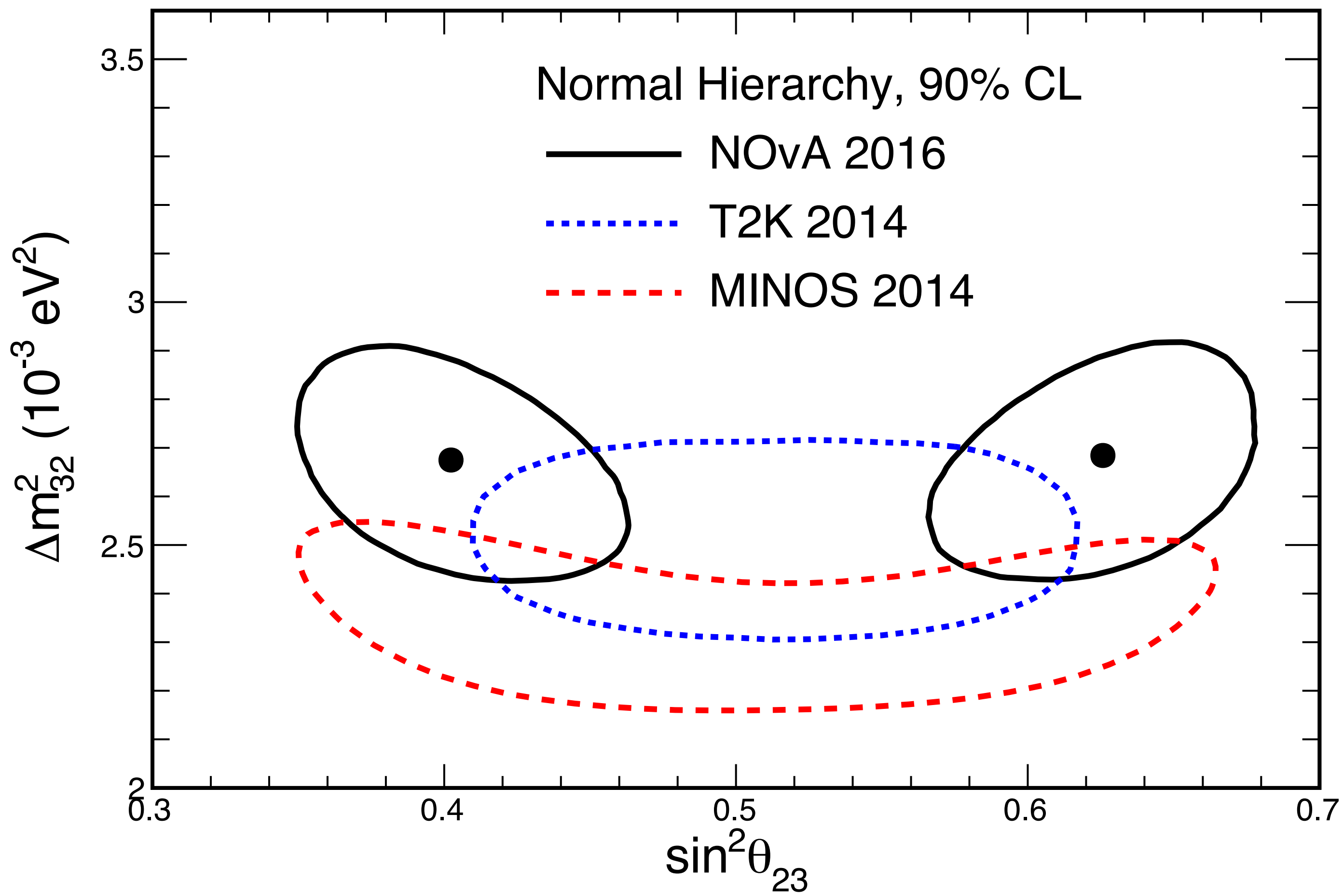
sin




- CP conservation excluded at the 90% CL
- Measurement is outside of physical bounds.

# Latest Results from the NOvA Experiment



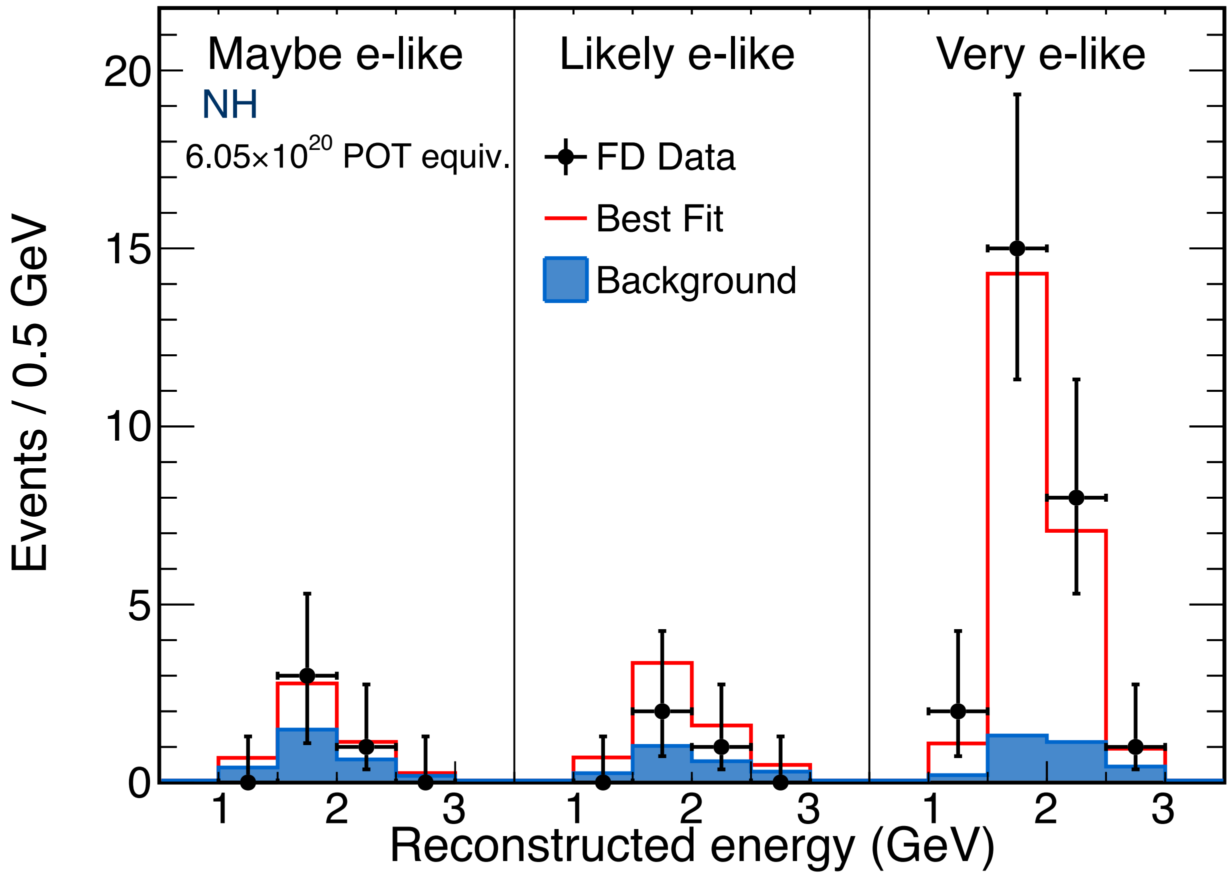

**Phys. Rev. Lett. 118, 151802 (2017)**

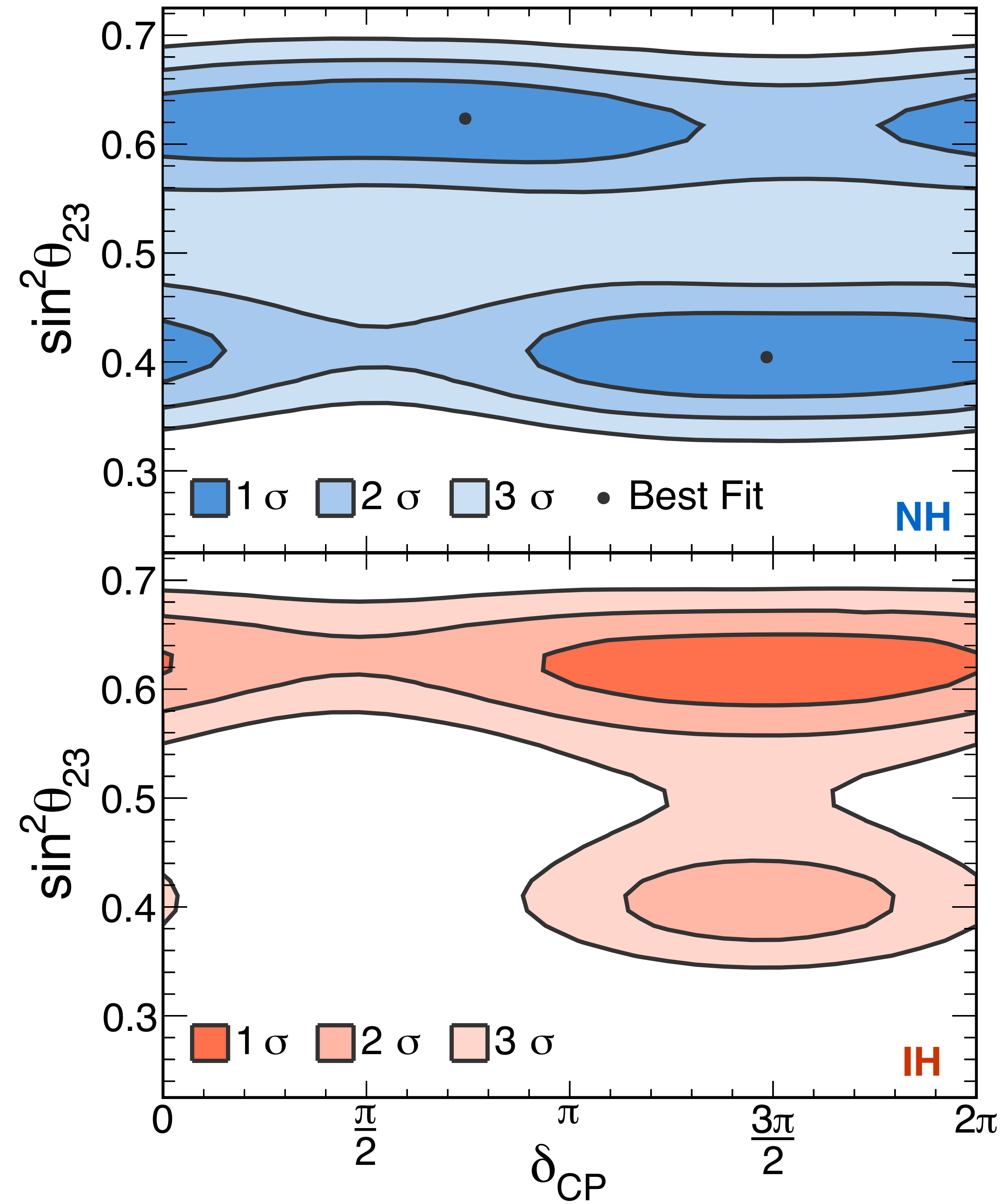
$$\sin^2\theta_{23} = \begin{cases} 0.404^{+0.030}_{-0.022} \\ 0.624^{+0.022}_{-0.030} \end{cases}$$

$$|\Delta m^2_{32}| = 2.67 \pm 0.11 \times 10^{-3}\mathrm{eV}^2$$

**Maximal mixing excluded at 2.6 σ**

# Latest Results from the NOvA Experiment



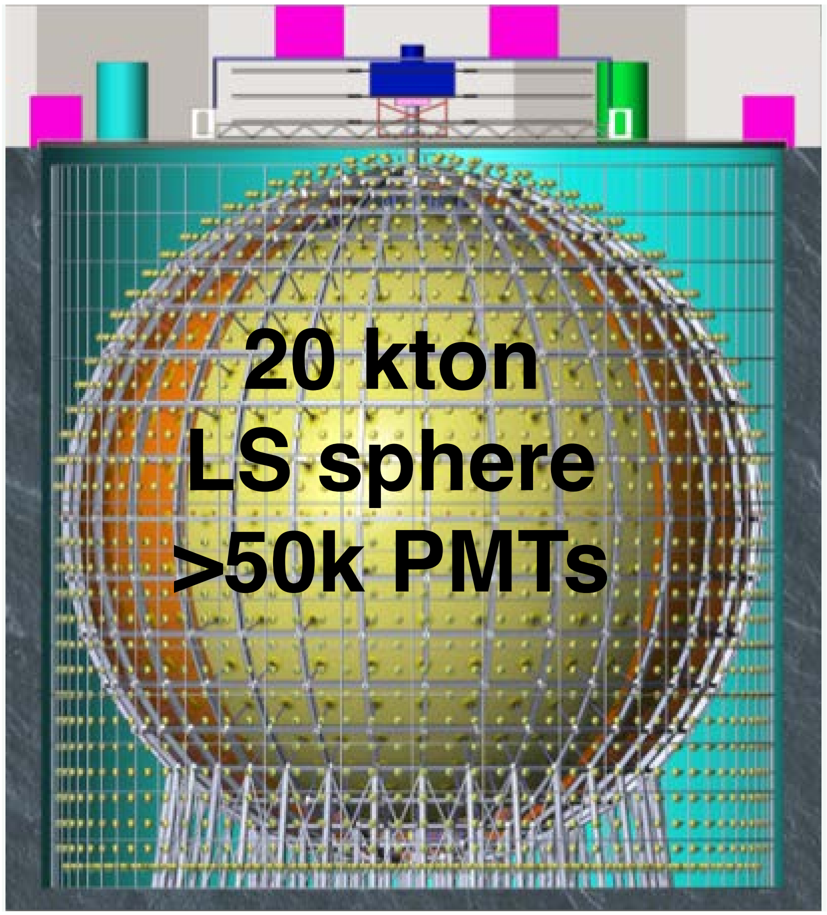




Phys. Rev. Lett. 118, 231801 (2017)

- Observed 33 events, with an expected background of 8.2 ± 0.8 events.
- Right: $\Delta m^2$ and $\theta_{23}$ are constrained from NOvA disappearance fits.
- Best fit: Normal Hierarchy, $\delta_{CP}$=1.5π, $\sin^2(\theta_{23})$ = 0.40.
- 93% CL exclusion of IH in the lower octant

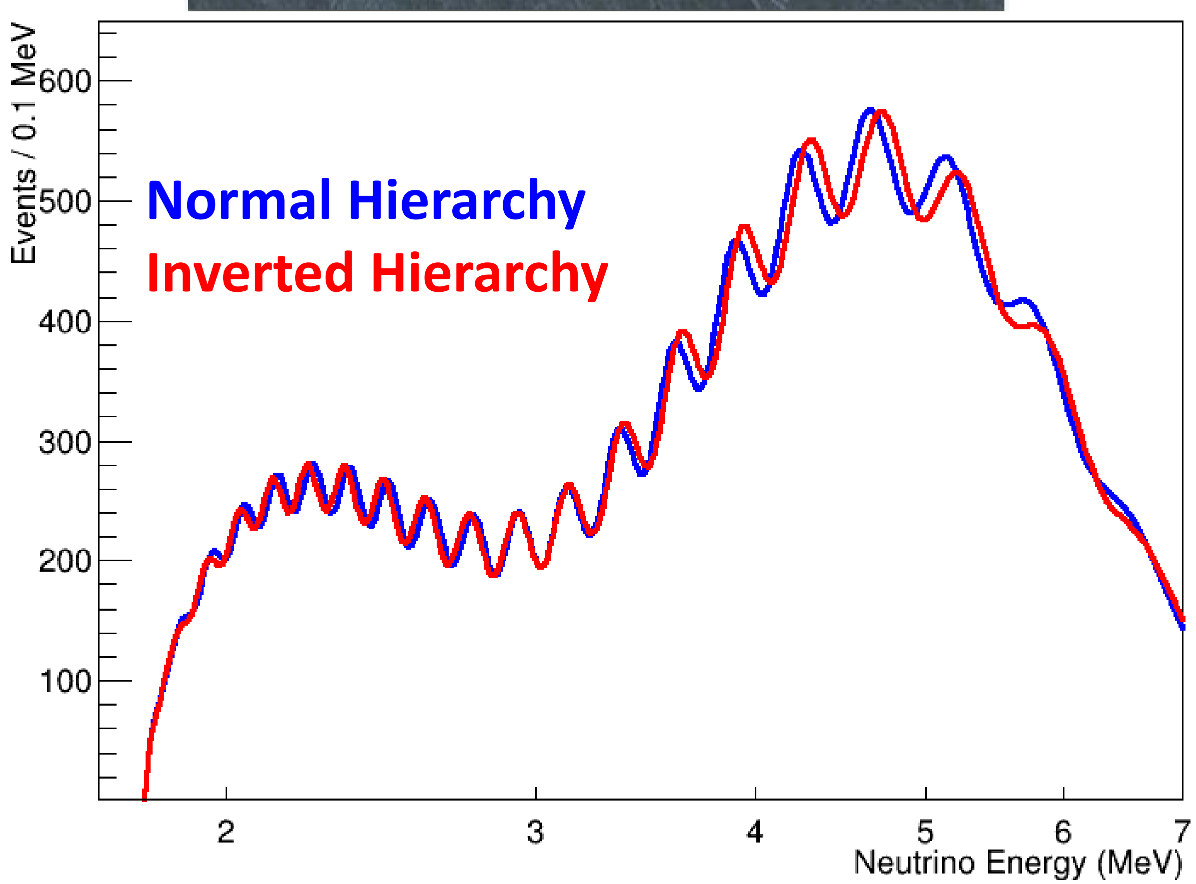
# Looking to the Not-too-Distant Future...

# Jiangmen Underground Neutrino Observatory (JUNO, China)



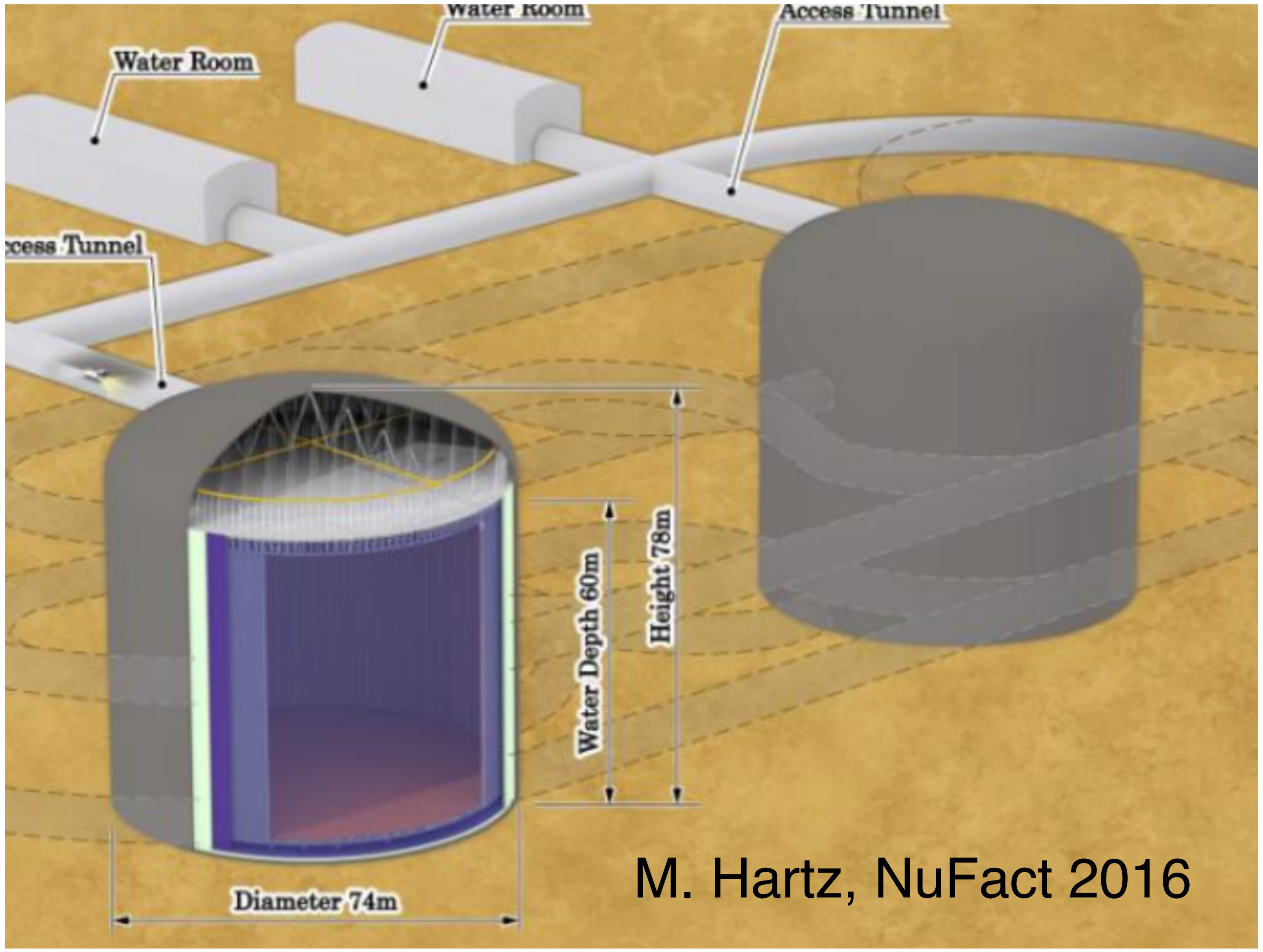


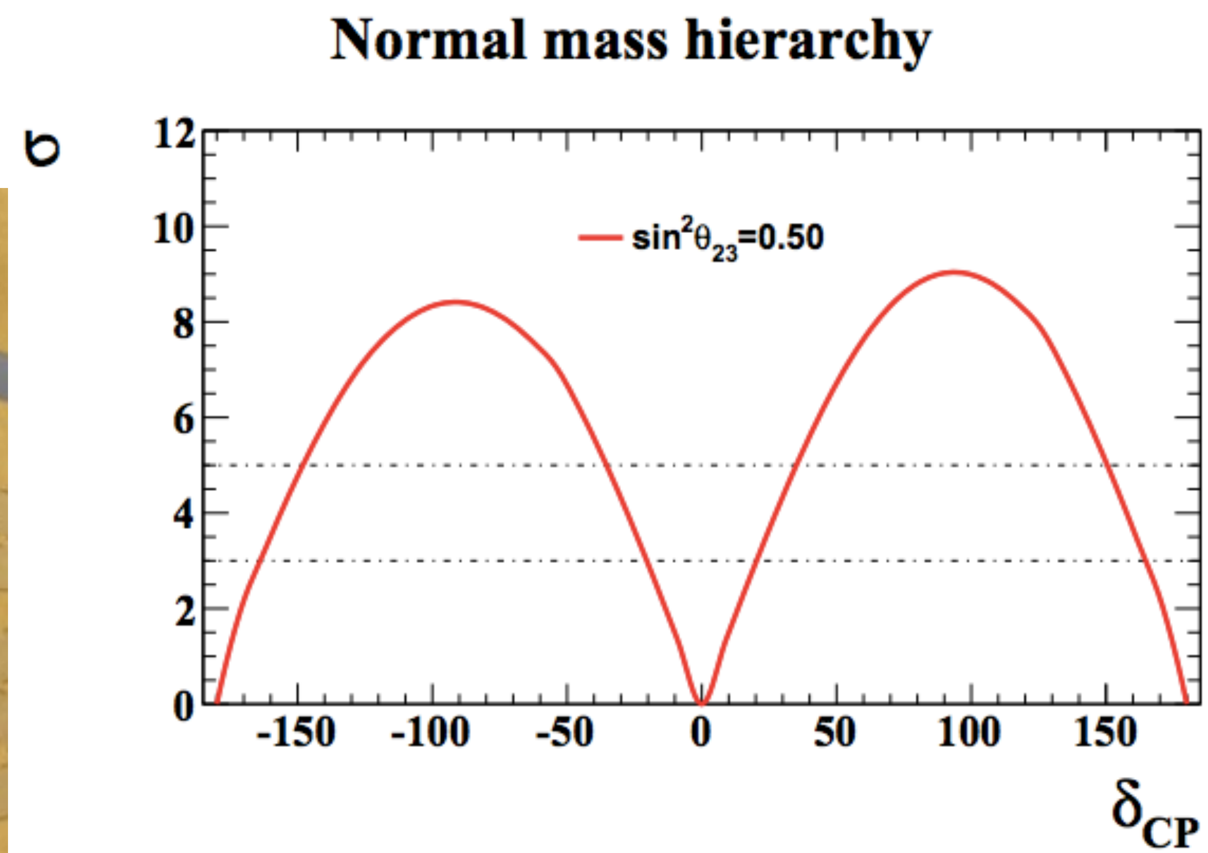
| Cores | YJ-C1 | YJ-C2 | YJ-C3 | YJ-C4 | YJ-C5 | YJ-C6 |
|---|---|---|---|---|---|---|
| Power (GW) | 2.9 | 2.9 | 2.9 | 2.9 | 2.9 | 2.9 |
| Baseline (km) | 52.75 | 52.84 | 52.42 | 52.51 | 52.12 | 52.21 |
| Cores | TS-C1 | TS-C2 | TS-C3 | TS-C4 | DYB | HZ |
| Power (GW) | 4.6 | 4.6 | 4.6 | 4.6 | 17.4 | 17.4 |
| Baseline (km) | 52.76 | 52.63 | 52.32 | 52.20 | 215 | 265 |

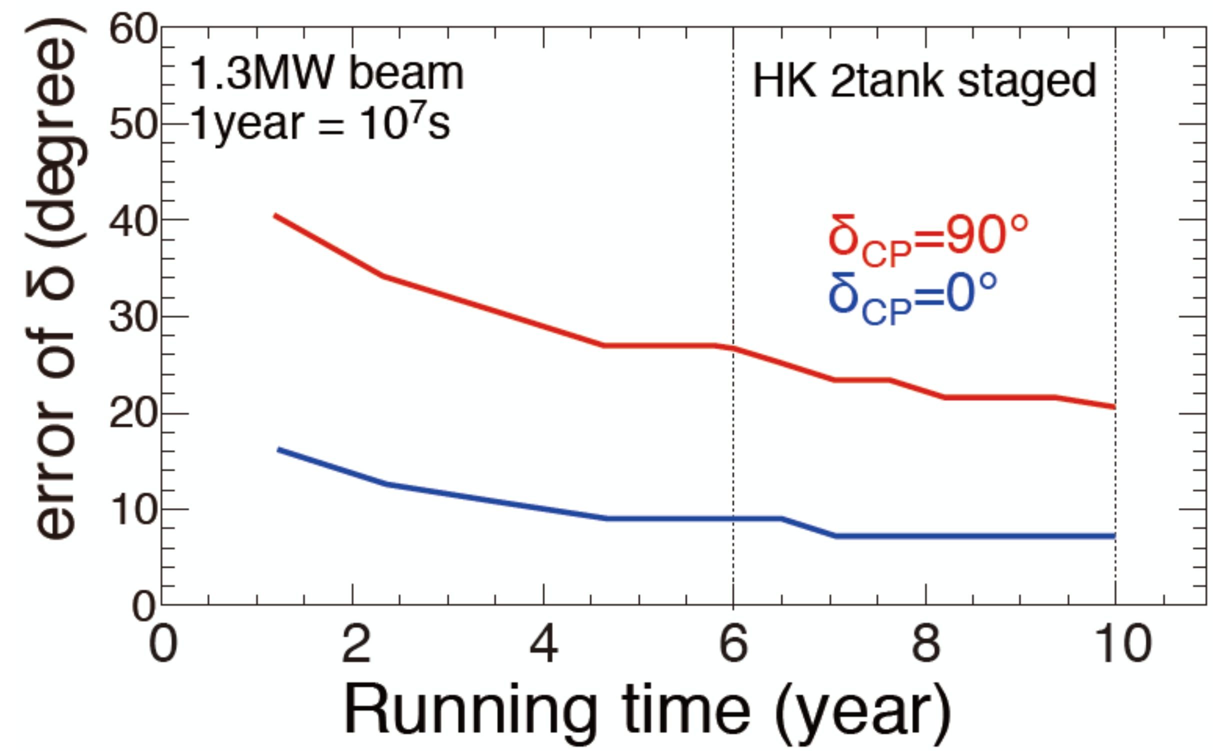



- 700 m overburden, aims to determine mass hierarchy via precise measurement of energy spectrum.
- Requires 3%/√E energy resolution and energy scale uncertainty < 1%
- Also: other precise measurements, supernovae neutrinos, sterile neutrino searches, etc.
- Civil construction of the underground facility to be completed this year; data-taking by 2020.

# Hyper-Kamiokande (Japan)

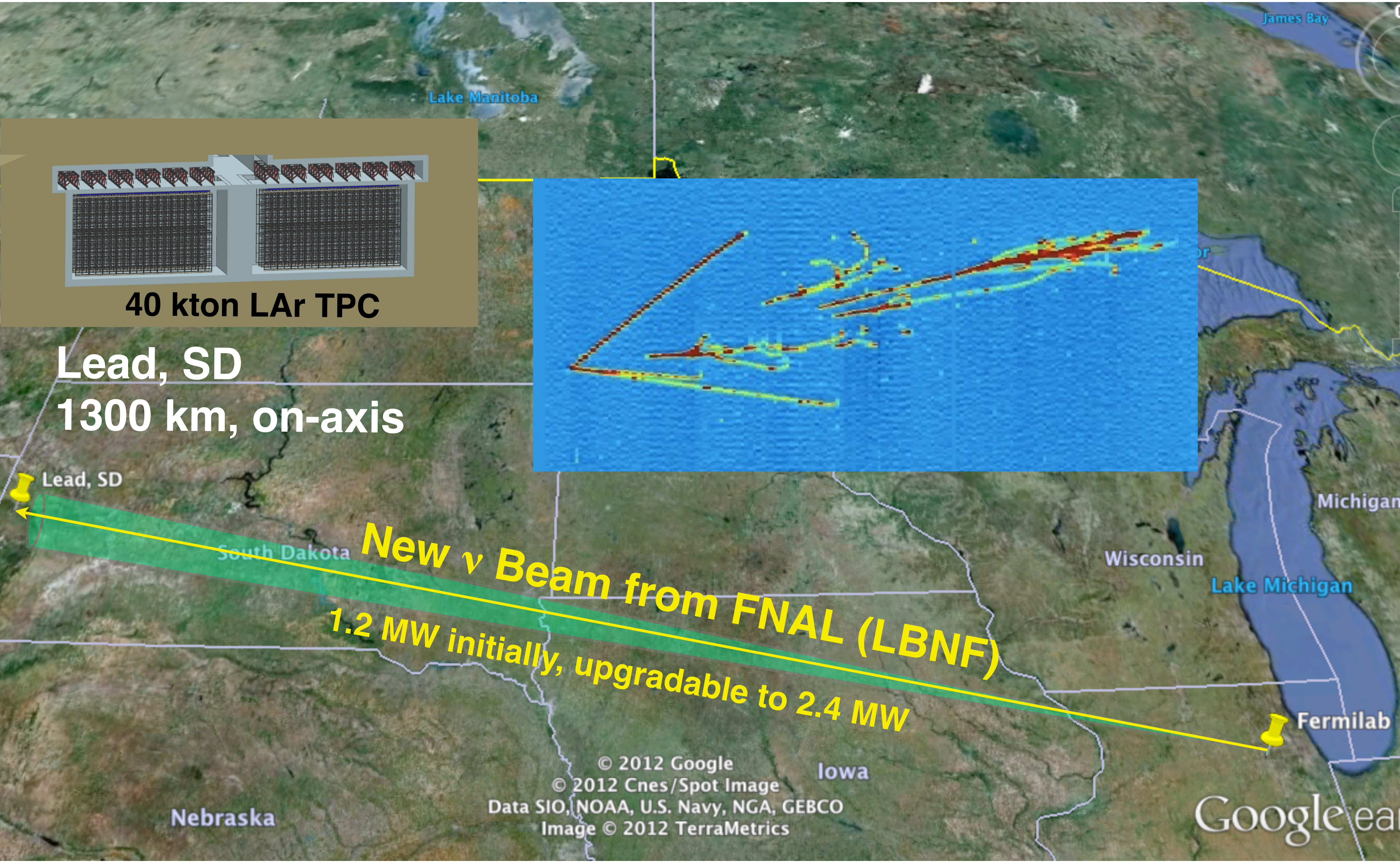



- 520 kton water Cherenkov detector + upgrade of J-PARC neutrino beam to 1.3 MW
- 295 km baseline
- Main goal is discovery of CPV, but can do much more including 10x improvement on $p \rightarrow e^+ + \pi^0$

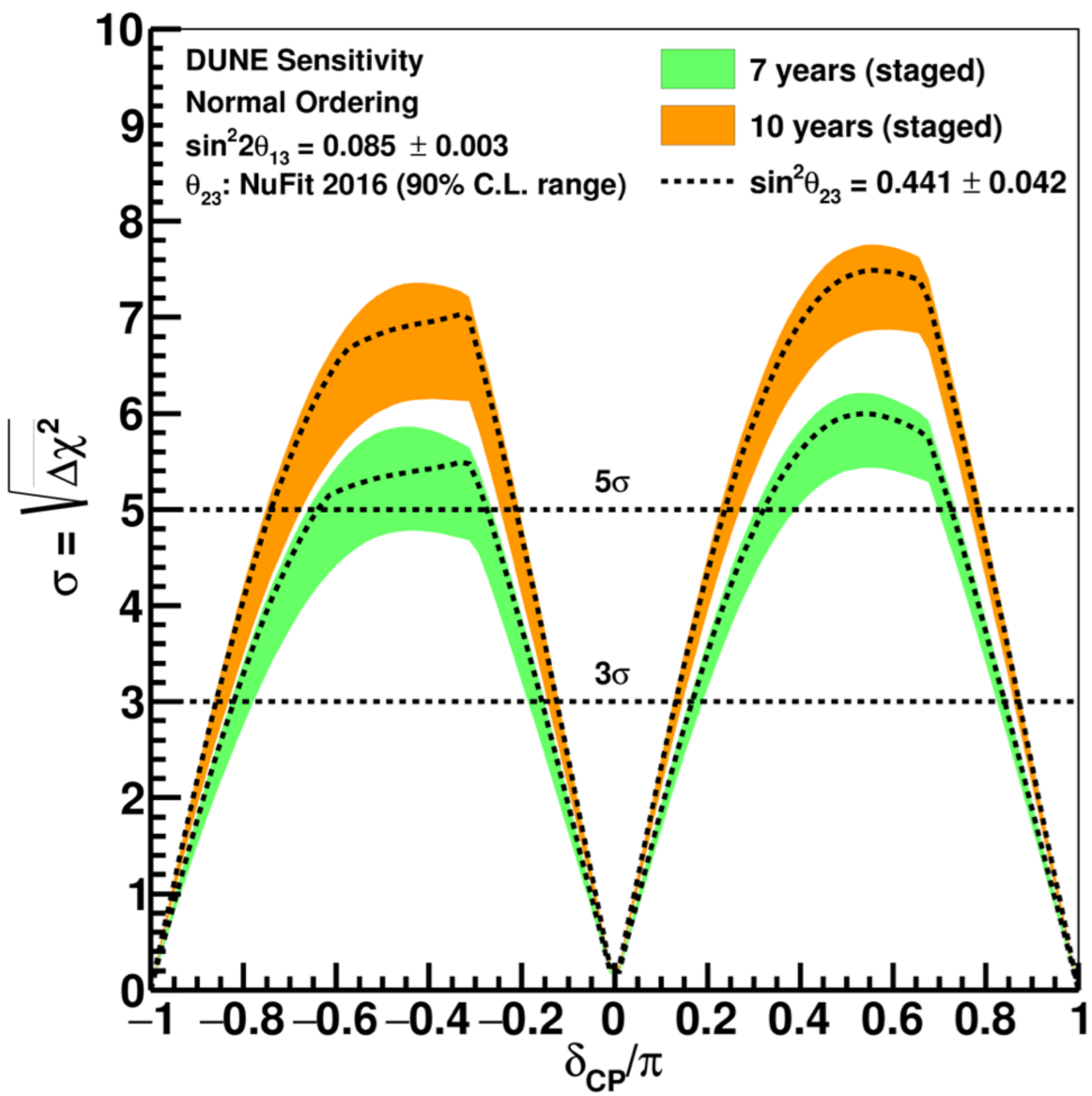
# The Deep Underground Neutrino Experiment (DUNE, USA)



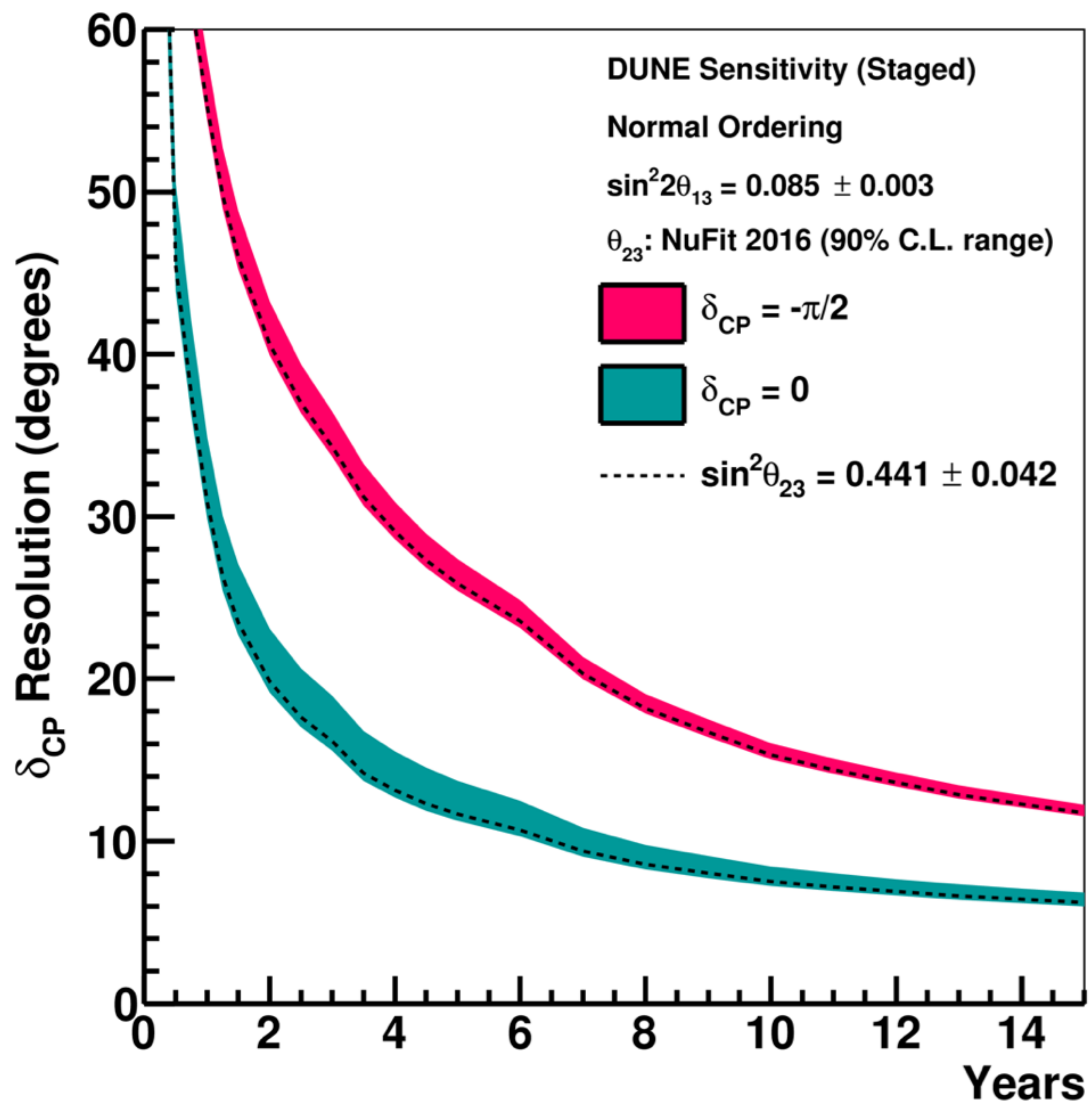
# The Deep Underground Neutrino Experiment (DUNE, USA)

# DUNE Sensitivities

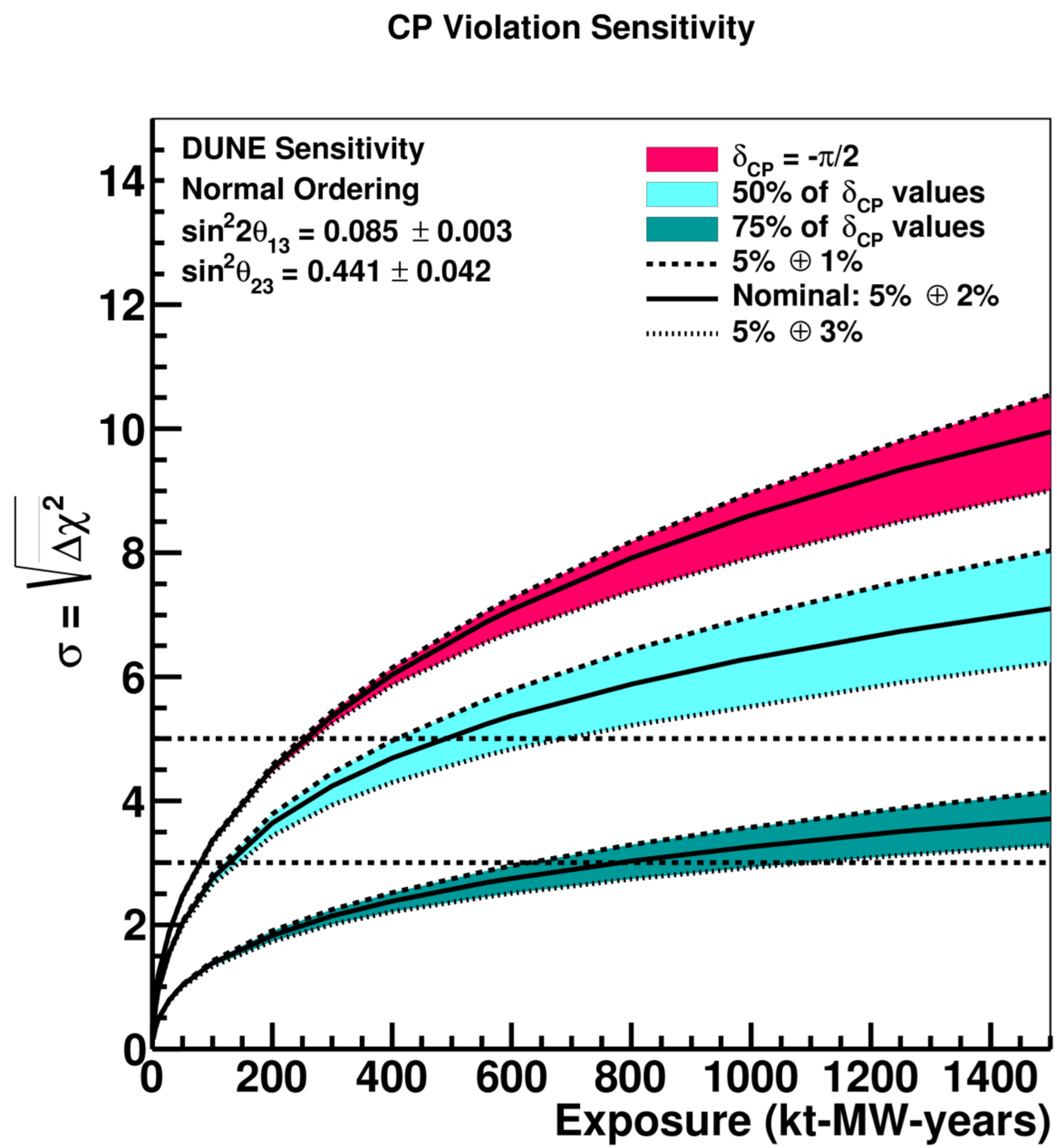
CP Violation Sensitivity



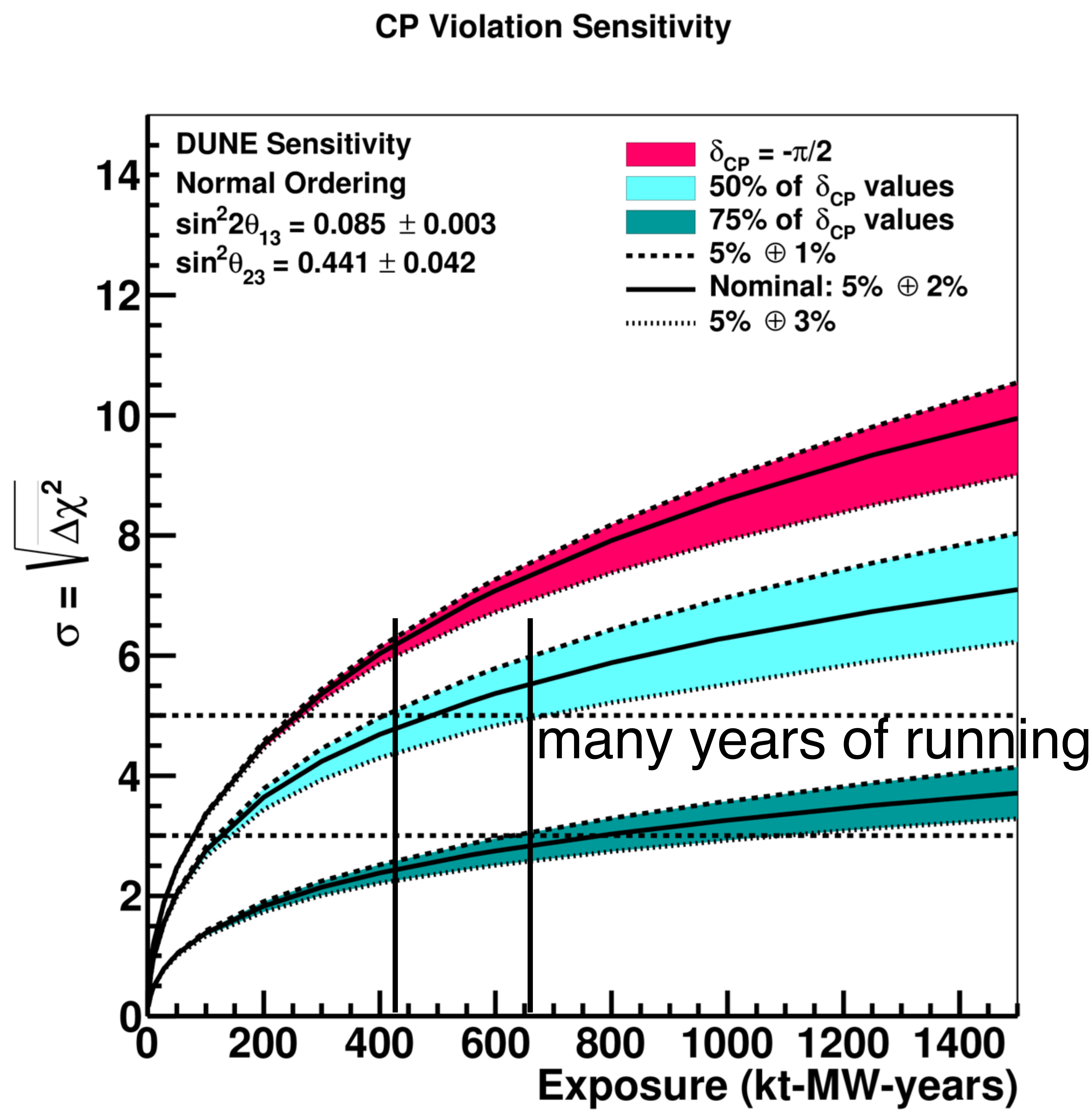

δCP Resolution



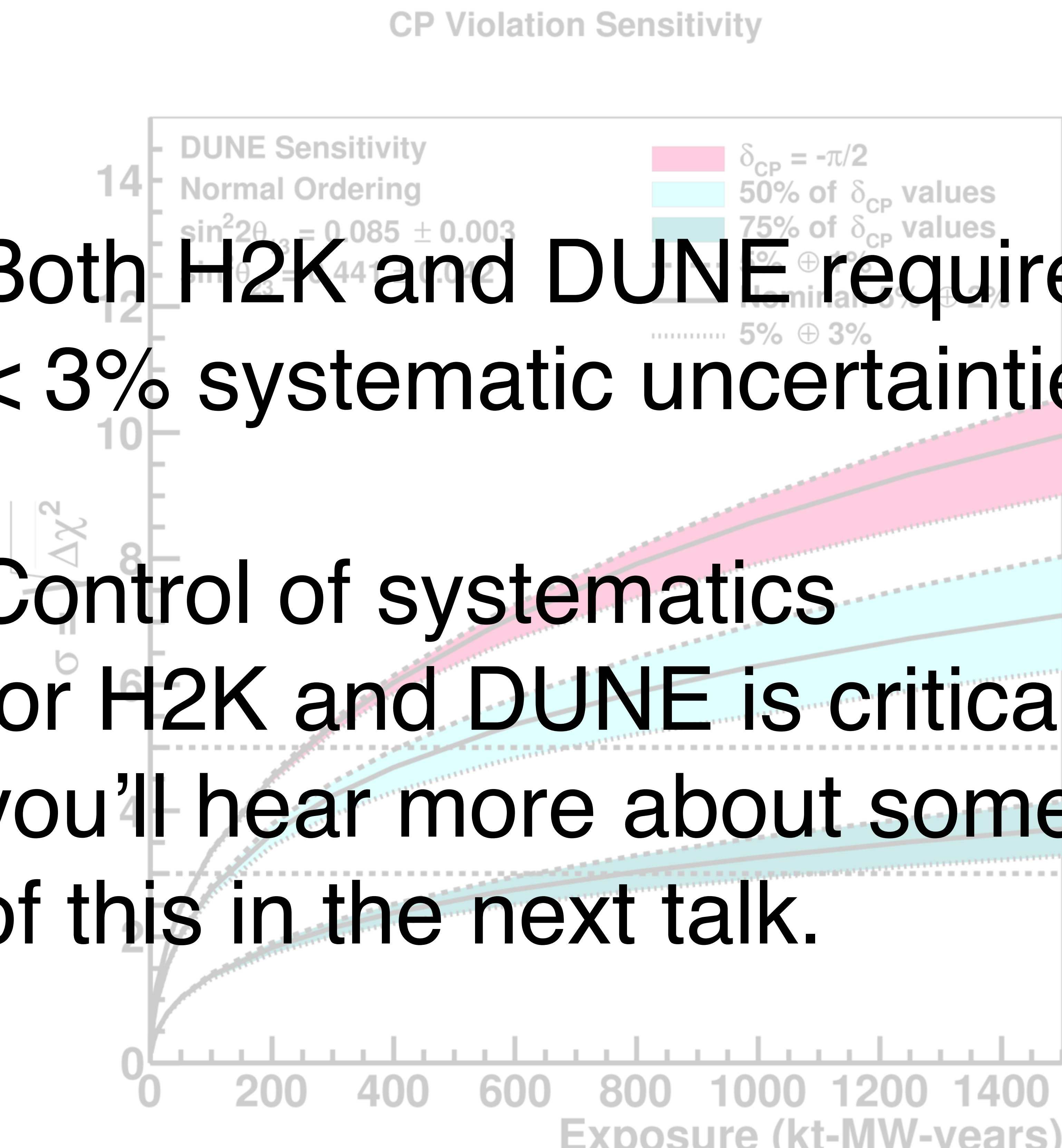
# Systematics in Future Precision Experiments



# Systematics in Future Precision Experiments



# Systematics in Future Precision Experiments

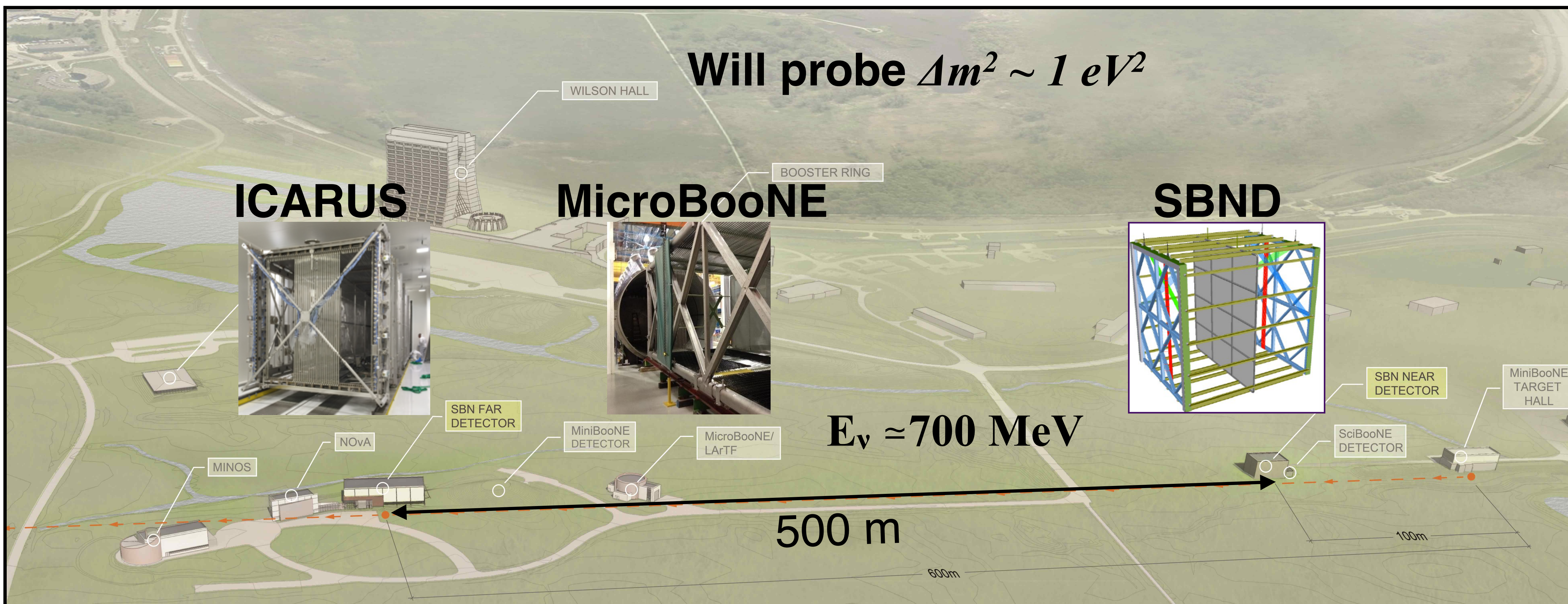



Both H2K and DUNE require < 3% systematic uncertainties.

Control of systematics for H2K and DUNE is critical, you'll hear more about some of this in the next talk.

# Short-Baseline Neutrino Program

- A short-baseline neutrino oscillation program featuring three LAr TPC detectors is underway at Fermilab that will:
  - improve our understanding of $\nu$-Ar interactions
  - accelerate the improvement of LArTPC simulations and reconstruction
  - address the LSND and MiniBooNE anomalies



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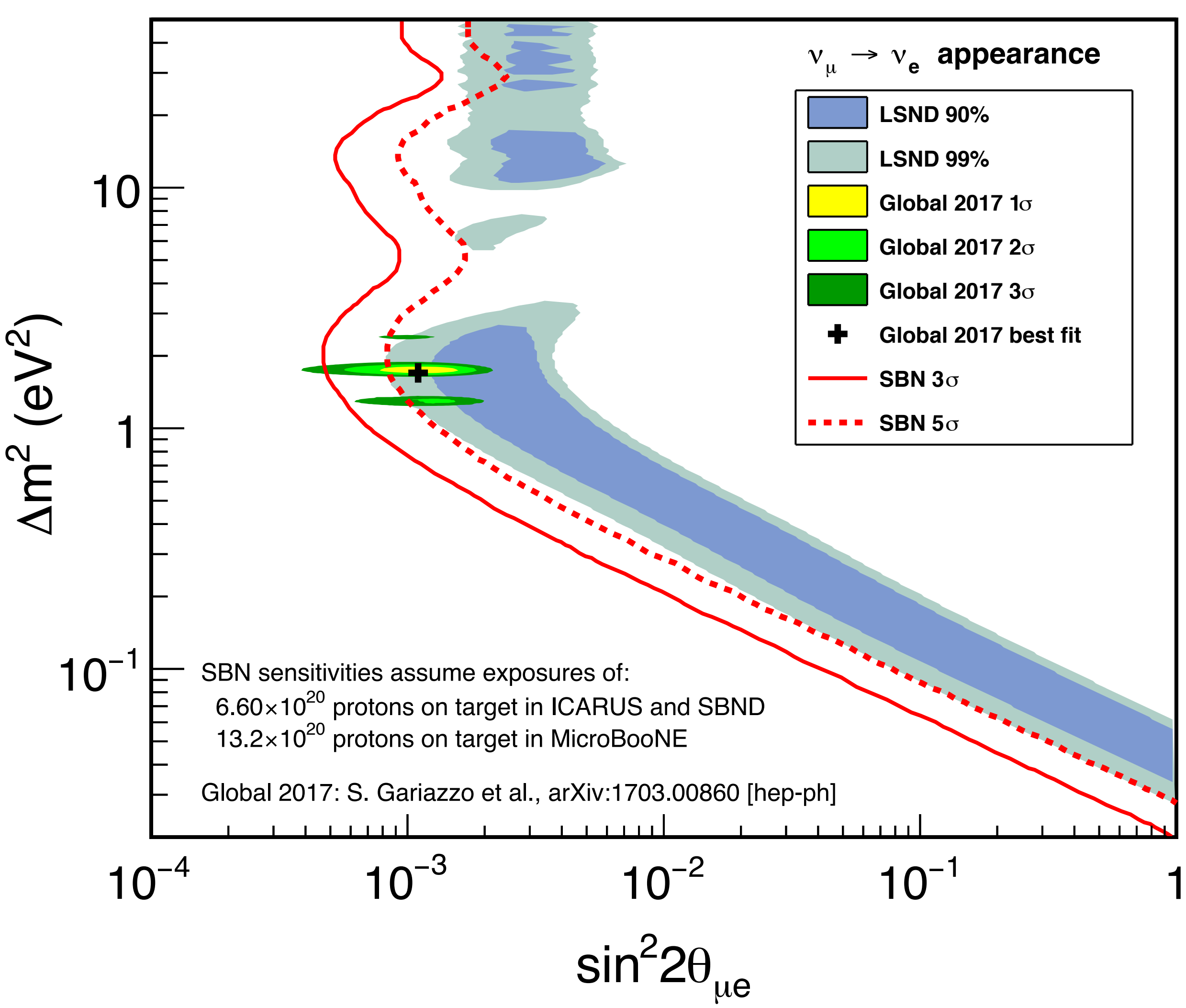


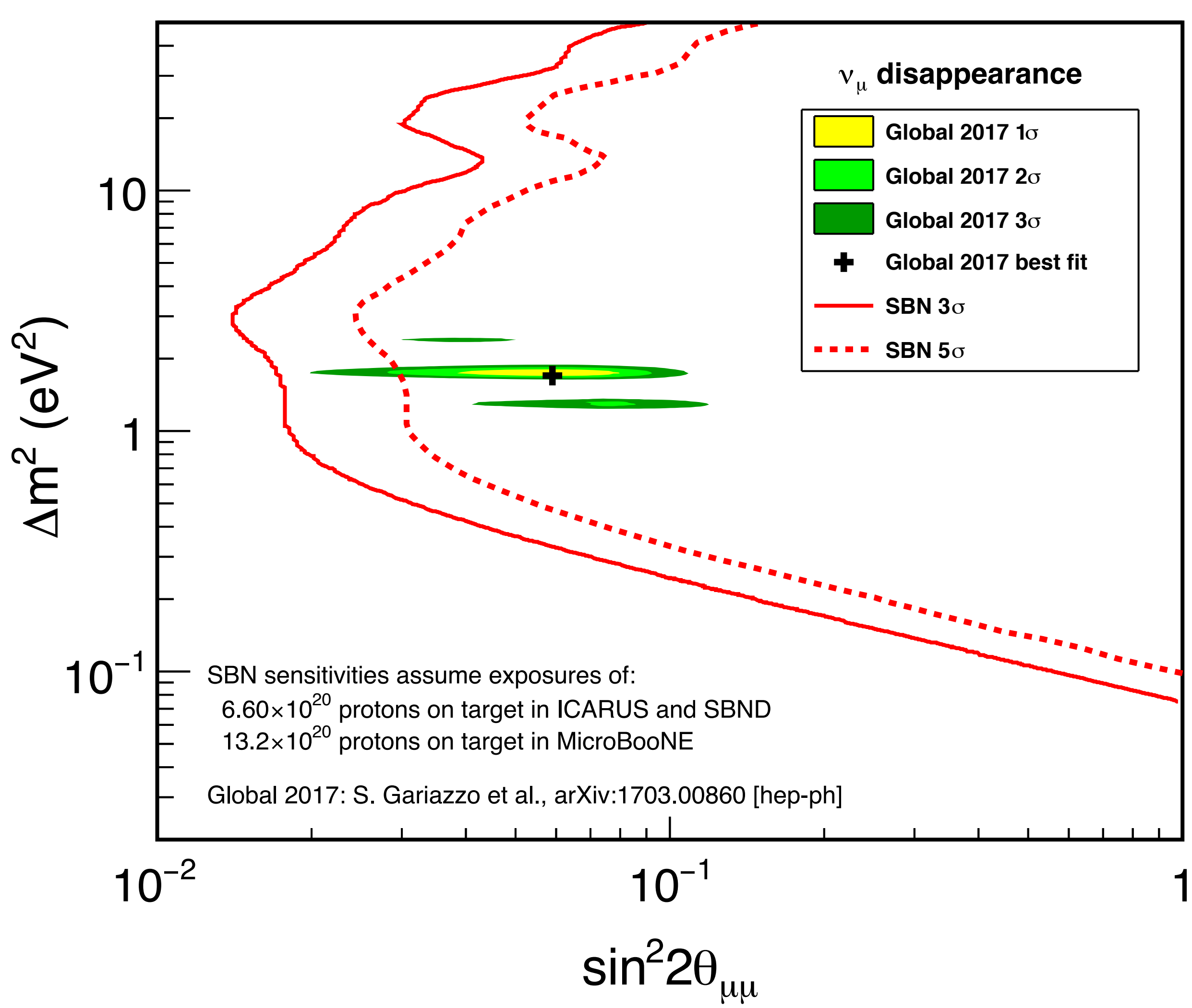

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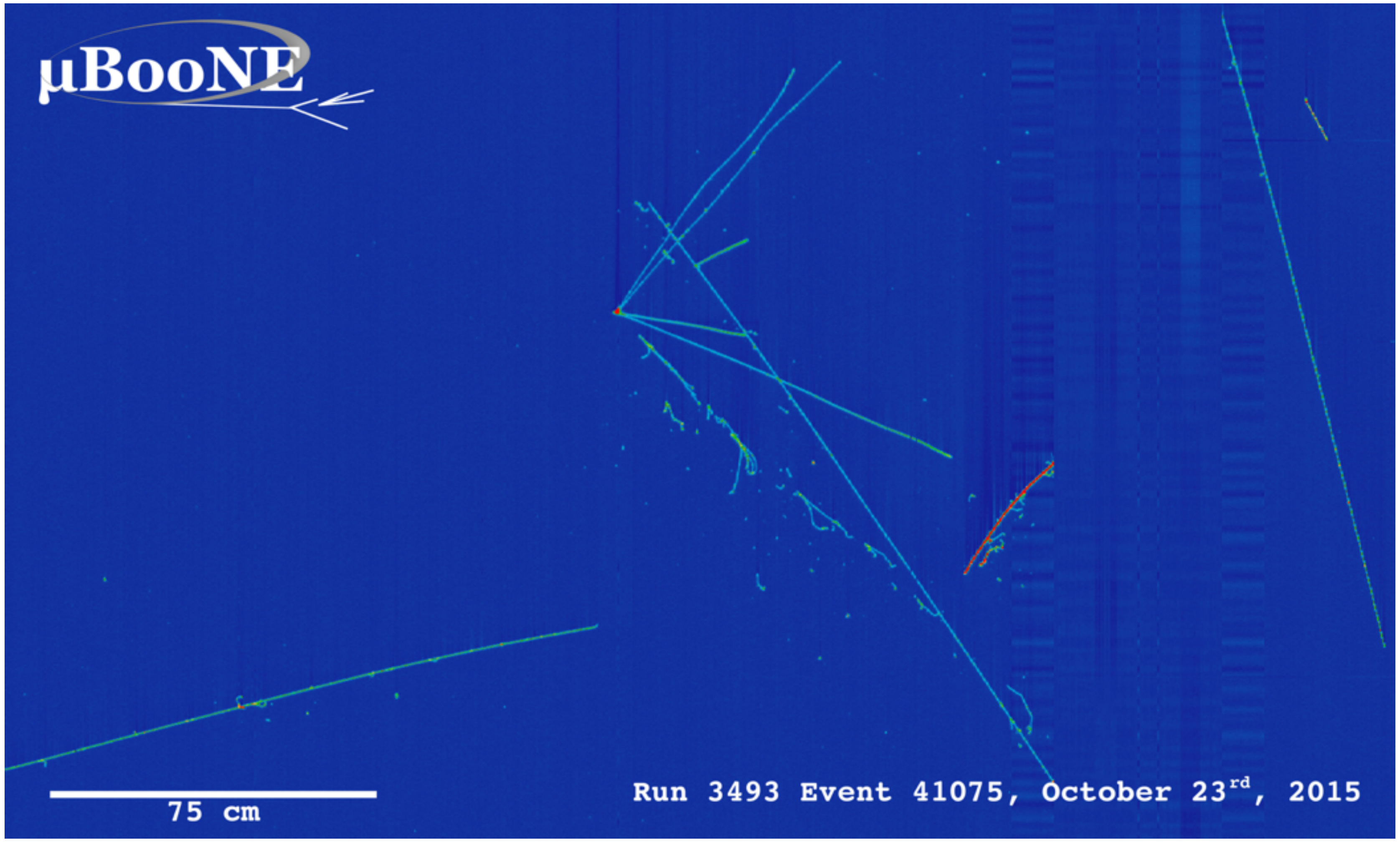
- **MicroBooNE is up and running,**



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  - improve our understanding of $\nu$-Ar interactions
  - accelerate the improvement of LArTPC simulations and reconstruction
  - address the LSND and MiniBooNE anomalies
- **MicroBooNE is up and running, and ICARUS will be installed later this year.**

# Summary

- Although we have learned much in the last 20 years, there is much we still do not know.
- This is a very active field: @ this meeting: 55 parallel session talks, 35/70 posters are neutrino-related.
- The latest results from SK, T2K and NOvA all have slight preferences for the normal hierarchy of the neutrino masses, as well as values of $\delta_{CP}$ around $3\pi/2$. Both NOvA and T2K are exploring ways to increase their exposure in the coming years.
- Both current and future oscillation experiments are well-positioned to determine many of the other "unknowns".
- Data and results will continue to flow for the next decade; look for many more "breaking nus" in the future!