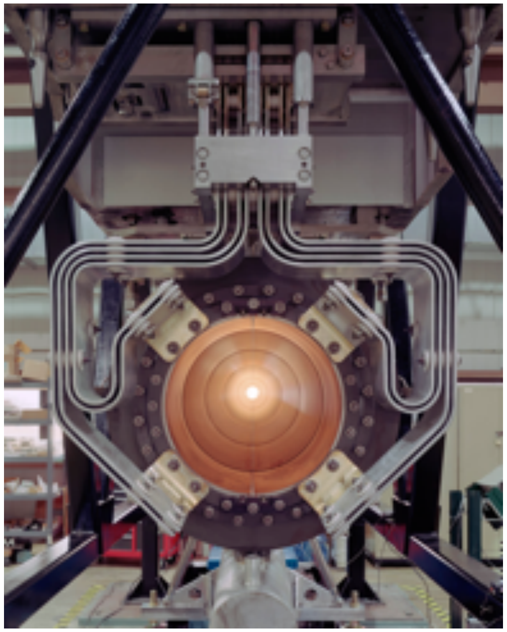
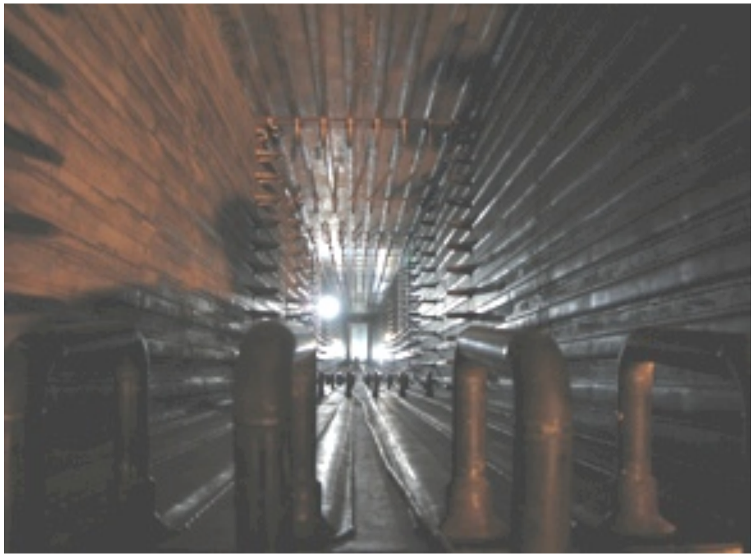
Results from Long-Baseline Neutrino Experiments

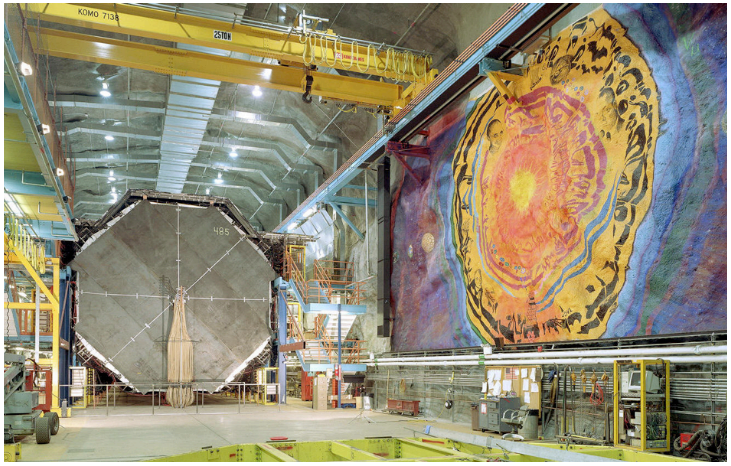


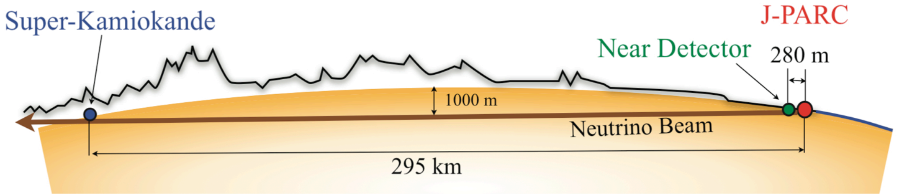


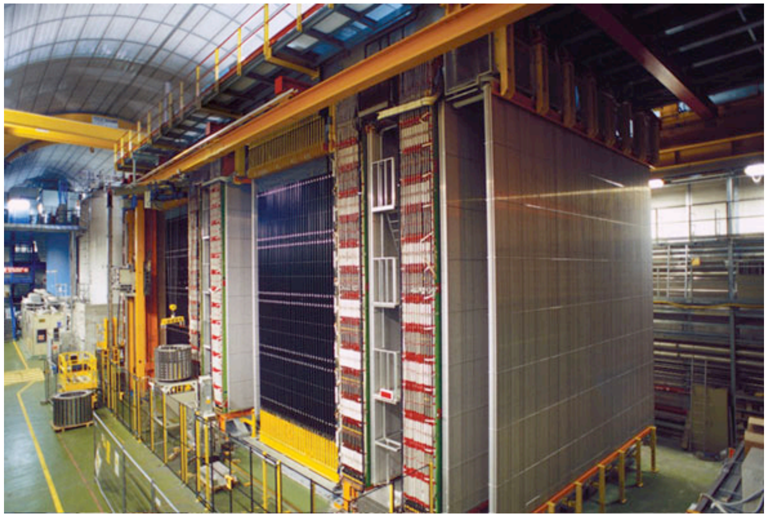
Alysia Marino, University of Colorado at Boulder
PIC, Bloomington, Sept. 17, 2014

Outline

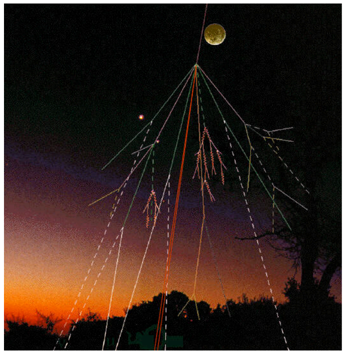
- Neutrino Mixing
- Recent Neutrino Oscillation Results
  - MINOS
  - T2K
  - OPERA
- Results expected in near future
  - MINOS+
  - NOvA



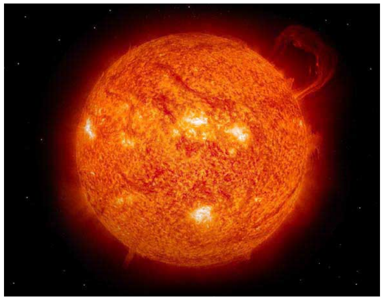




Neutrino Oscillations



- Very **compelling evidence** that neutrinos change flavor
  - Fewer atmospheric muon neutrinos vanish while crossing Earth
  - Confirmed with accelerator neutrino beams.



- Too few electron neutrinos from the solar core are observed. But the total flux of all 3 flavors matches the expected number.
- Confirmed with reactor neutrinos over 100km distances.

- Missing reactor neutrinos at shorter distances
- Electron neutrino appearance in a muon neutrino beam

Neutrino Mixing

- Neutrino flavor states are a mixture of neutrino mass states.
- Interference between the mass and flavor eigenstates causes the observed flavor to oscillate with time.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \left(U \right) \times \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

3x3
mixing matrix

- In general neutrino transition probability to another flavor is given by:

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4 \sum_{i>j} \Re(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2 [\Delta m^2_{ij} L/4E]$$
$$- 2 \sum_{i>j} \Im(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin [\Delta m^2_{ij} L/2E]$$

Matrix Elements

$\Delta m^2_{ij} = m^2_i - m^2_j$

Mixing Matrix

- Unitary matrix relates mixing between flavor and mass states

θ_{23} and Δm^2_{32}
Atmospheric/
Accelerator neutrinos
$\theta_{23} \sim 45^o$

δ, θ_{13} and Δm^2_{31}
reactor anti-neutrinos and
accelerator neutrinos
$\theta_{13} \sim 9^o$

θ_{12} and Δm^2_{21}
Solar neutrinos/
reactor anti-neutrinos
$\theta_{12} \sim 34^o$

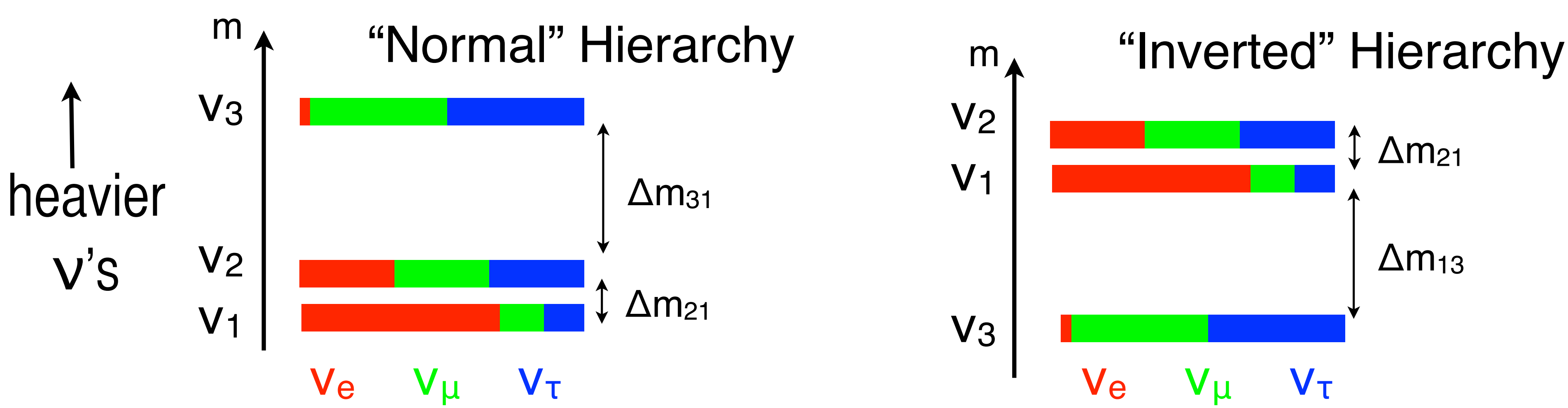
$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \times \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \times \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

where $s_{ij} = sin(\theta_{ij})$ and $c_{ij} = cos(\theta_{ij})$

- Anti-ν depend on U^*

Neutrino Masses

- Two different mass difference scales



- Sign of Δm_{21} is known from solar ν from mass effects, but sign of Δm_{31} isn't, so two possible orderings of masses

Vacuum Oscillation Probability

- L/E scale relevant for recent accelerator beams oscillation effects are dominated by $m_3 \leftrightarrow m_2$ and $m_3 \leftrightarrow m_1$ mixing
- ν_μ Disappearance in a ν_μ Beam (no matter, no CP)

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - \sin^2 2\theta_{23} \cdot \sin^2 (\Delta m^2_{32} L/4E)$$

- ν_e Appearance in a ν_μ Beam (no matter, no CP)

$$P(\nu_\mu \to \nu_e) \simeq \sin^2 2\theta_{13} \cdot \sin^2 \theta_{23} \cdot \sin^2 (\Delta m^2_{31} L/4E)$$

- Can also look for appearance of τ neutrinos
- Increasing need for simultaneous 3 flavor fits

Matter & CP Effects

- In the presence of **matter**, the appearance probability changes to

$$P(\nu_\mu \to \nu_e) \simeq \sin^2 2\theta_{13} \cdot \frac{\sin^2\theta_{23}}{(A-1)^2} \cdot \sin^2\left((A-1)\Delta m^2_{31} L/4E\right)$$

$$\text{where } A = \sqrt{2} G_F N_e \frac{2E}{\Delta m^2_{31}}$$

Depends on hierarchy

- **A** has opposite sign for anti-ν. So even with δ=0, $P(\nu_\mu \to \nu_e)$ increases while $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ decreases for NH, so an apparent CP violation.

- For δ≠0, there are additional terms including

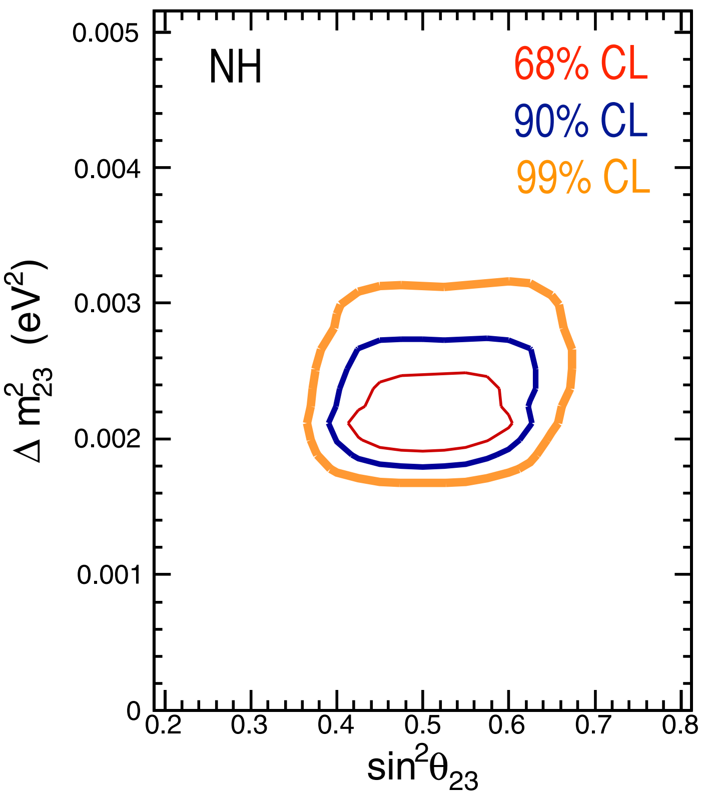
$$-\frac{|\Delta m^2_{21}|}{|\Delta m^2_{31}|} \frac{\sin\delta \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \cos\theta_{13}}{A(1-A)} \sin\Delta \sin(A\Delta) \sin((1-A)\Delta)$$

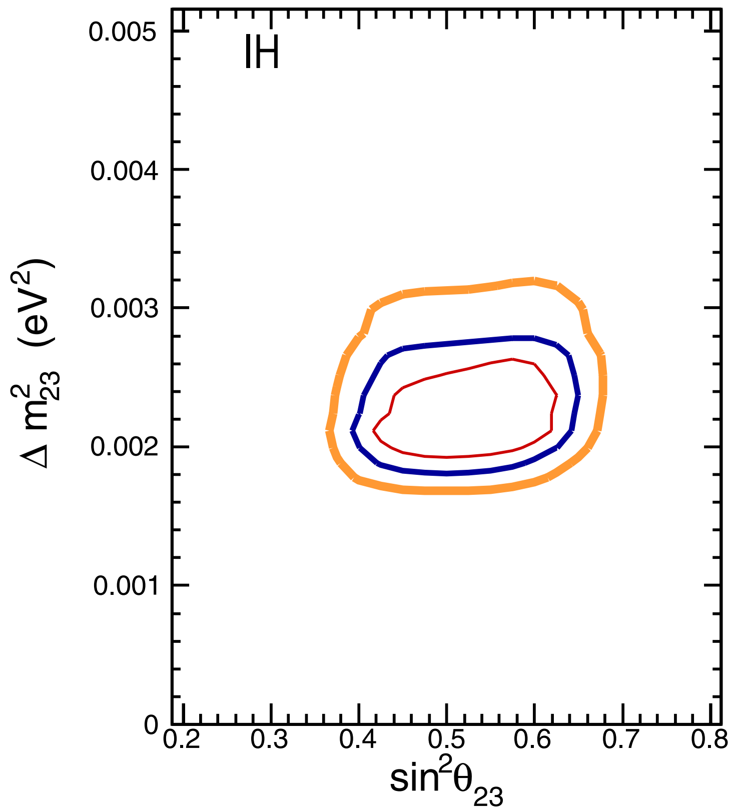
$$\text{where } \Delta = \Delta m^2_{31} L/4E$$

- Changes sign for anti-ν. So positive δ will decrease $P(\nu_\mu \to \nu_e)$ and increase $P(\bar{\nu}_\mu \to \bar{\nu}_e)$.

Reminder: Super-K Atmospheric Neutrino Results

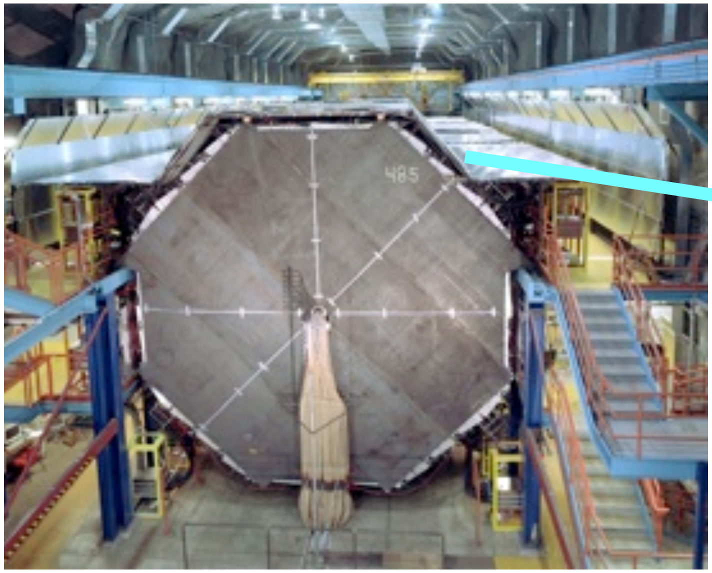
Phys Rev D **81** 092004 (2010)





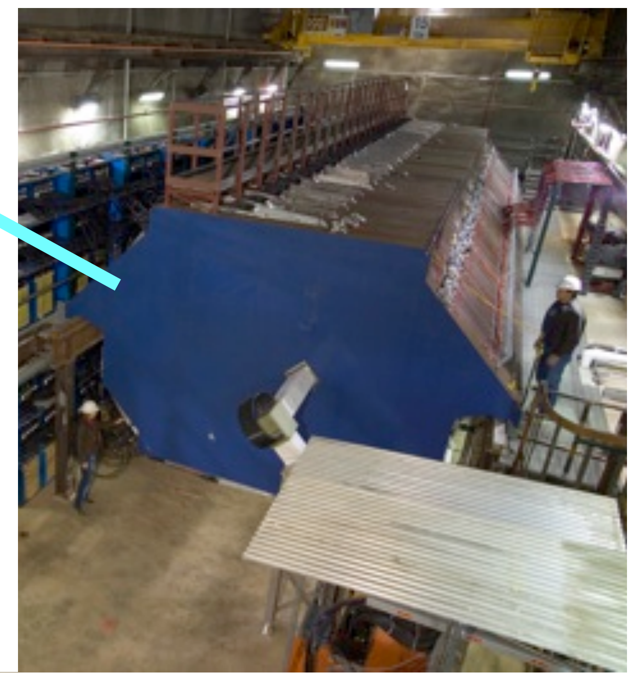
- SK I-III data (1996–2007) analysis for 3 neutrino flavors
- No hierarchy preference; Results consistent with both θ_{13}=0 and non-zero values
- Preliminary results at Neutrino 2014 for SK I-IV (1996-present, 4581 live days) which have a slight preference for NH and weak preference for $\theta_{13} \neq 0$.

MINOS: Main Injector Neutrino Oscillation Search



Near Detector:

- 103 m underground at FNAL
- 1 km from target
- 1 kton mass

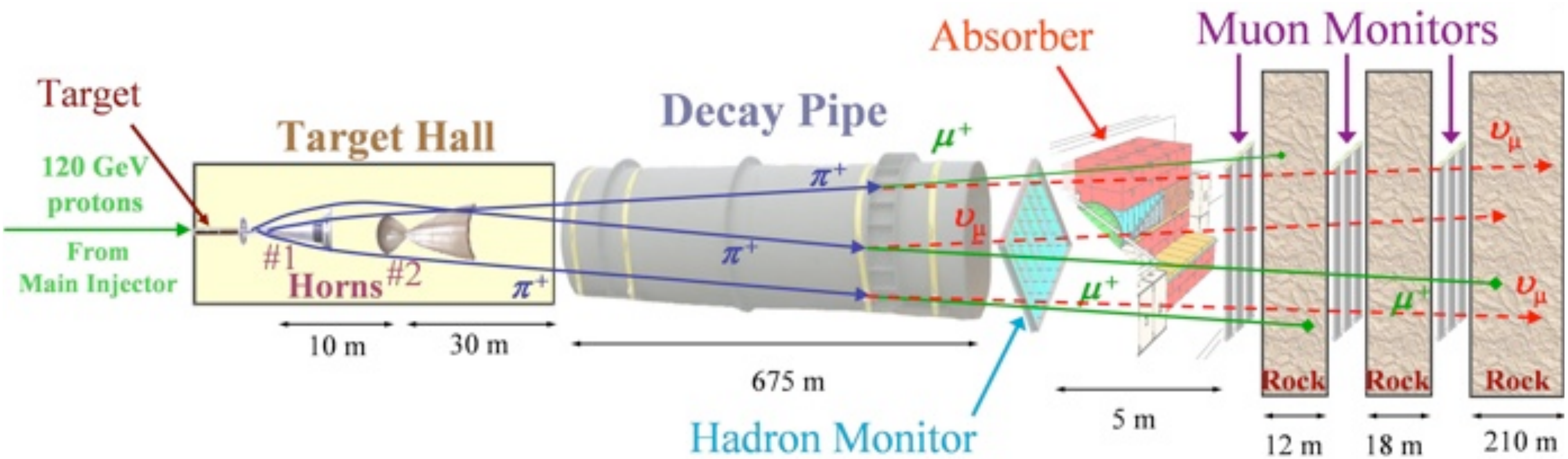


Far Detector:

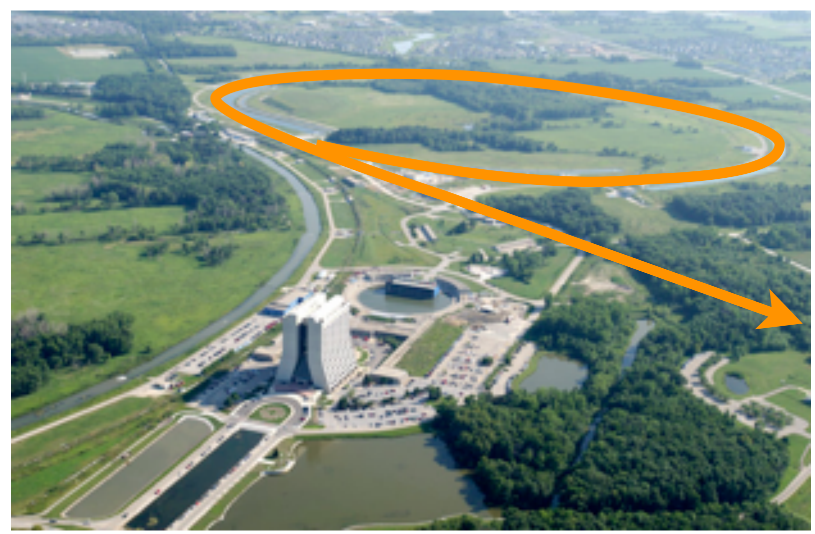
- 735 km from target
- 705 m underground in Soudan, MN
- 5.4 kton mass
- 8 m tall

Magnetized iron/ scintillator sampling calorimeters

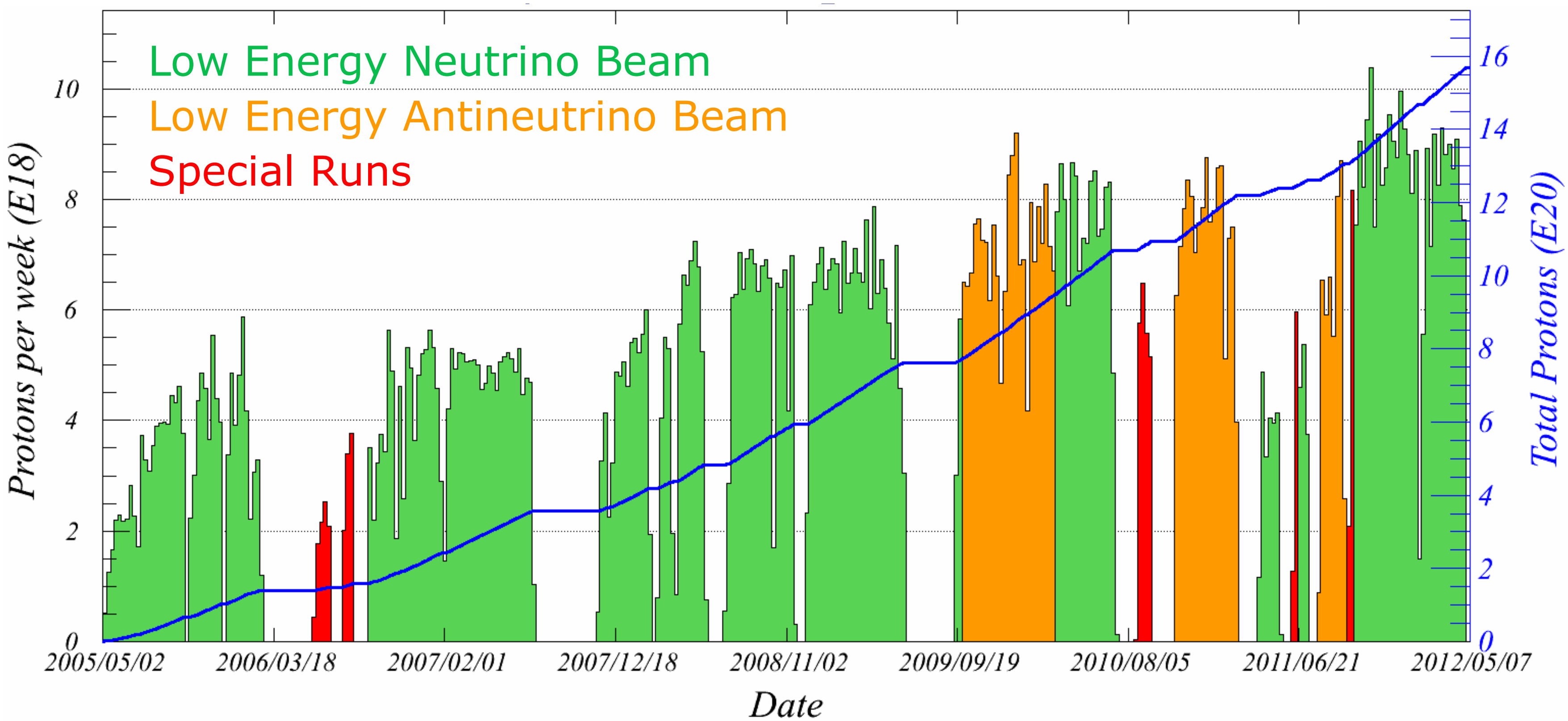
NuMI Beam



- **120 GeV** protons from the Main injector strike a graphite target
- 2 horns focus the pions and kaons, which decay in a 675 m long decay pipe
- 93% ν_μ, 6% $\bar{\nu}_\mu$, 1% ν_e
- 400 kW design power



MINOS Running

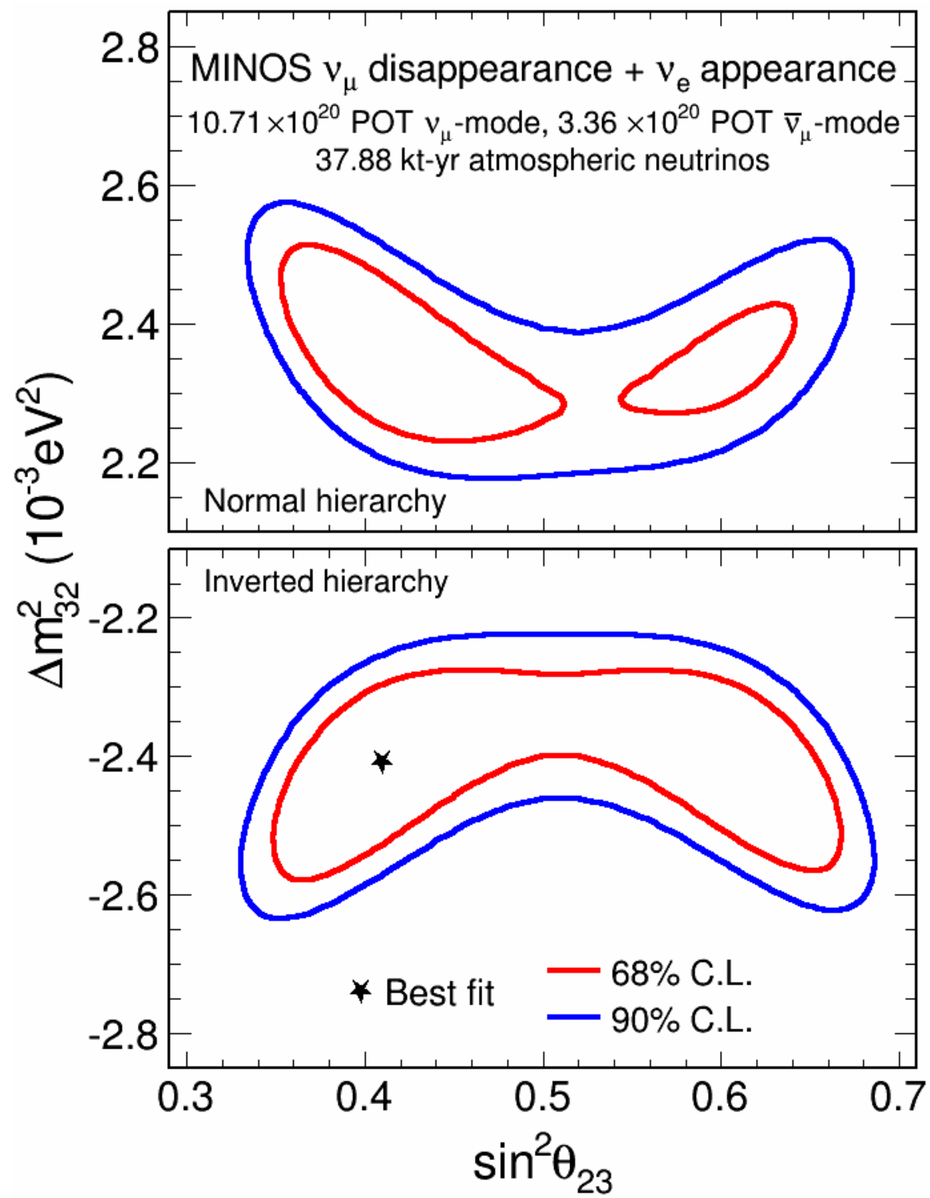


- Neutrino Mode: 10.71×10^{20} protons on target
- Anti-neutrino Mode: 3.61×10^{20} protons on target
- 37.88 kton years of atmospheric neutrinos

Beam + Atmospheric Neutrinos

- Combined fit for ν_μ disappearance and $\nu_\mu \to \nu_e$ appearances using NuMI beam data and atmospheric neutrinos
  - Includes anti-neutrino data
  - 3 flavor fit where Δm^2_{32}, θ_{23}, θ_{13}, δ_{CP} are varied
  - θ_{13} constrained by reactor data

Phys Rev Lett **112** 191801 (2014)

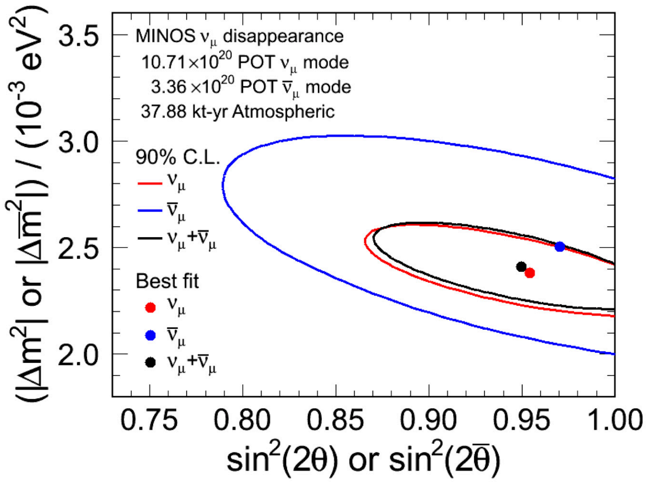


Anti-Neutrino Results

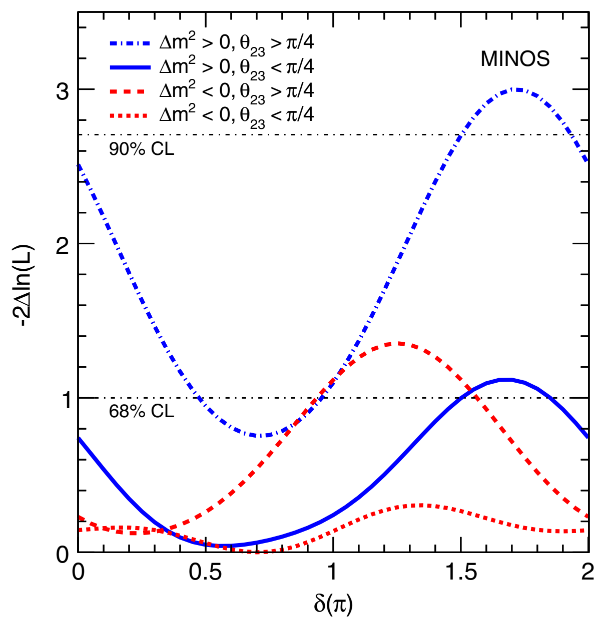
- ν_μ disappearance for ν and anti-ν beam + atmospheric neutrinos
  - anti-ν and ν have similar best fit points and strongly overlapping 90% CL regions

- ν_e appearance for ν and anti-ν beam
  - Data prefer inverted hierarchy, especially for $\theta_{23} > \pi/4$
  - At 68% CL disfavors 31% of the δ/octant/hierarchy phase space, especially normal hierarchy with $\theta_{23} > \pi/4$ and large δ

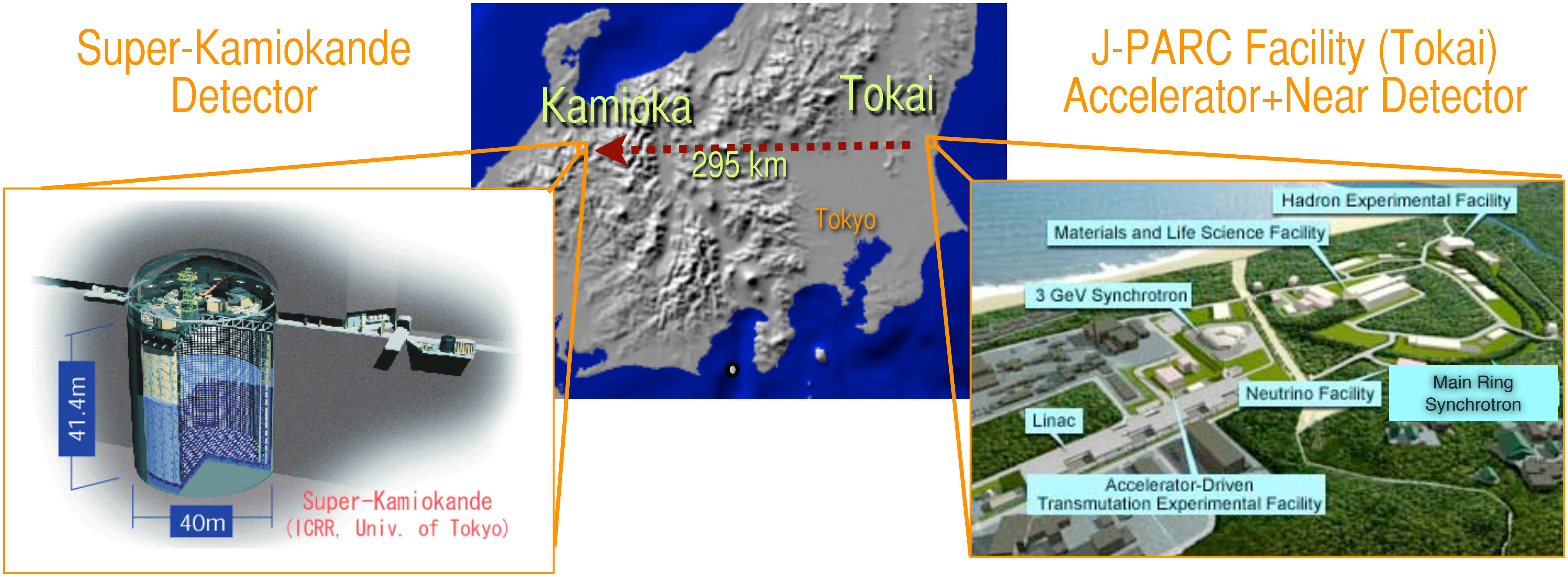
Phys Rev Lett **110** 251801 (2013)



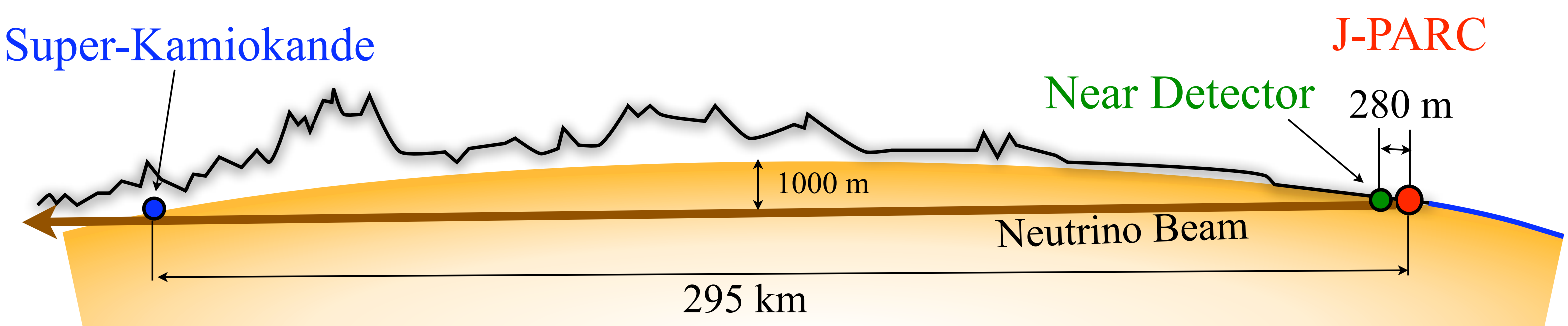
Phys Rev Lett **110** 171801 (2013)



T2K: Tokai-to-Kamioka

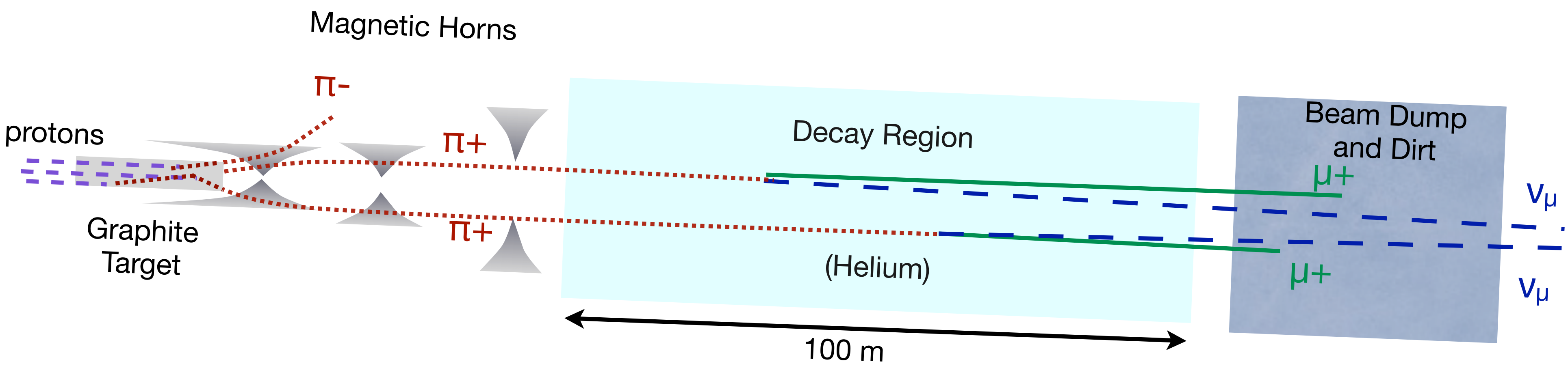


- Long-baseline neutrino experiment in Japan with 295 km baseline



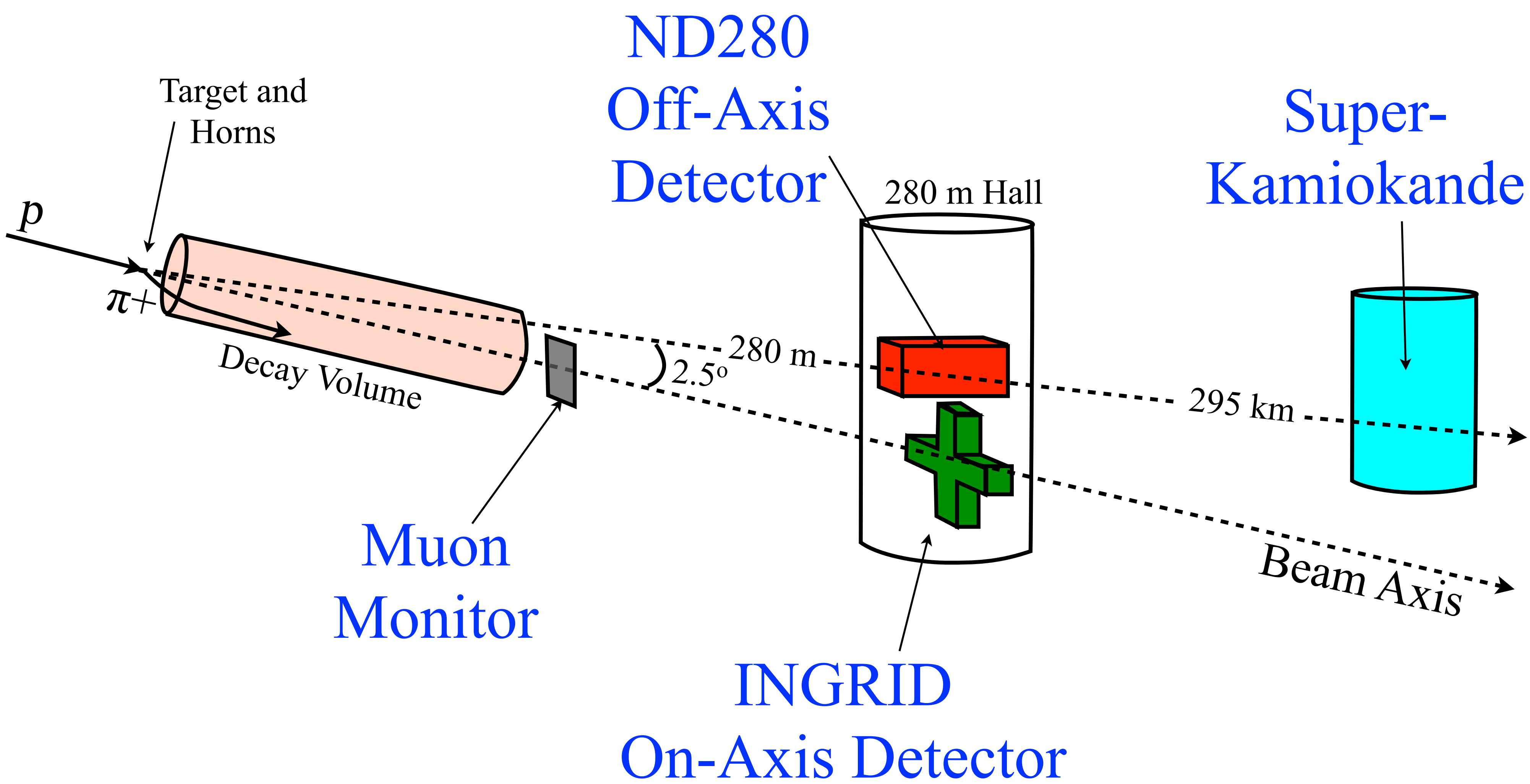
T2K Beam

Side View of T2K Beam (not to scale!)



- 30 GeV protons strike graphite target, producing πs and Ks
- 3 magnetic horns to focus π and K into the desired direction
- Beam is ~95% ν_μ, 4% $\bar{\nu}_\mu$, 1% ν_e
- Designed for 750 kW

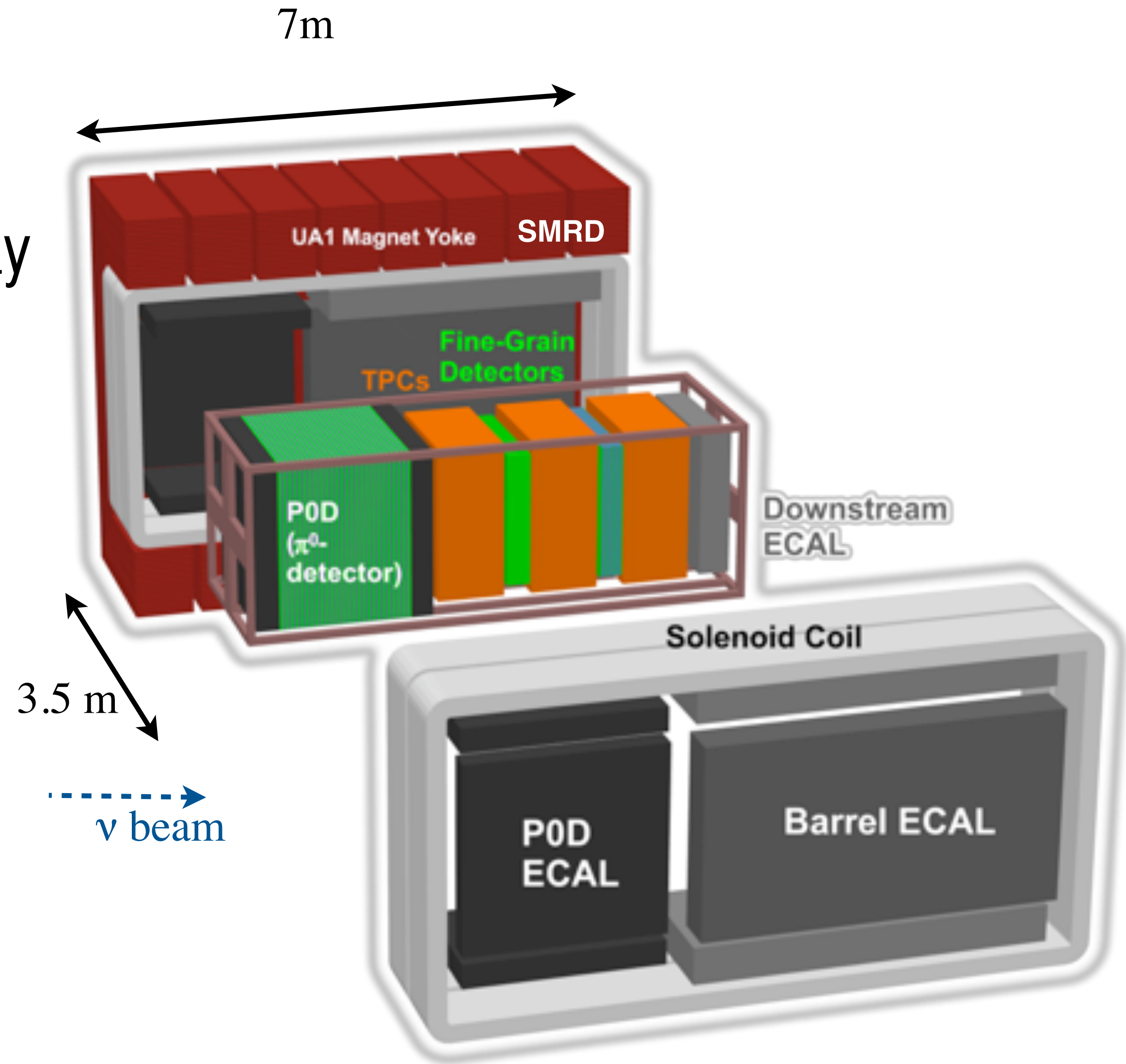
T2K Detectors



Not to scale!

ND280: Off-Axis Near Detector

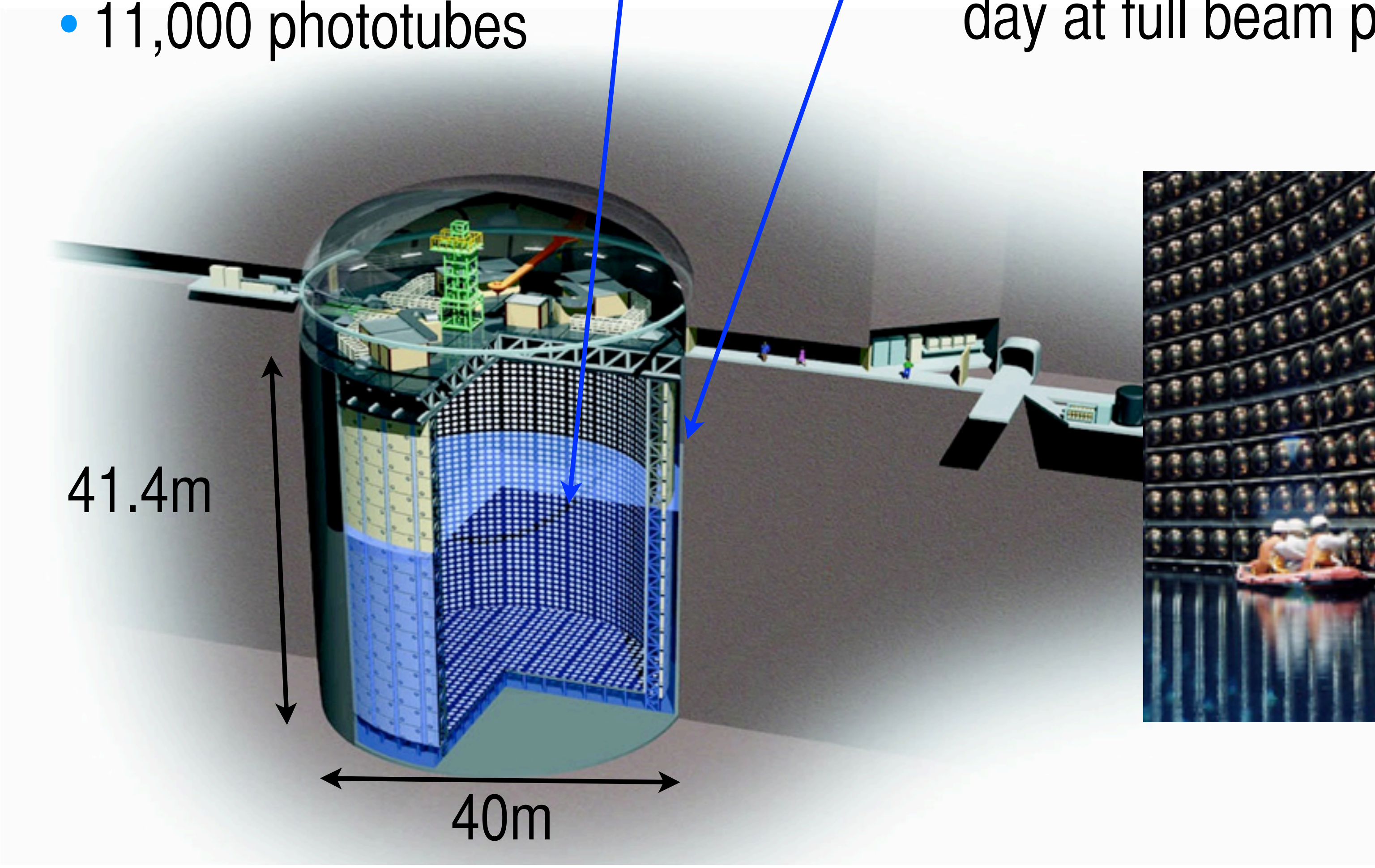
- Inside the 0.2 T UA-1 magnet
- ~ 10,000 ν interactions per day
- Tracker
  - Fine-grained scintillator tracker + 3 TPCs (and water targets)
- Pi-Zero Detector
  - Brass/Lead/plastic scintillator calorimeter (and water targets)
- ECAL
  - Lead/plastic scintillator calorimeter
- Side Muon Range Detector
  - Plastic scintillator paddles interspersed between magnet yoke layers

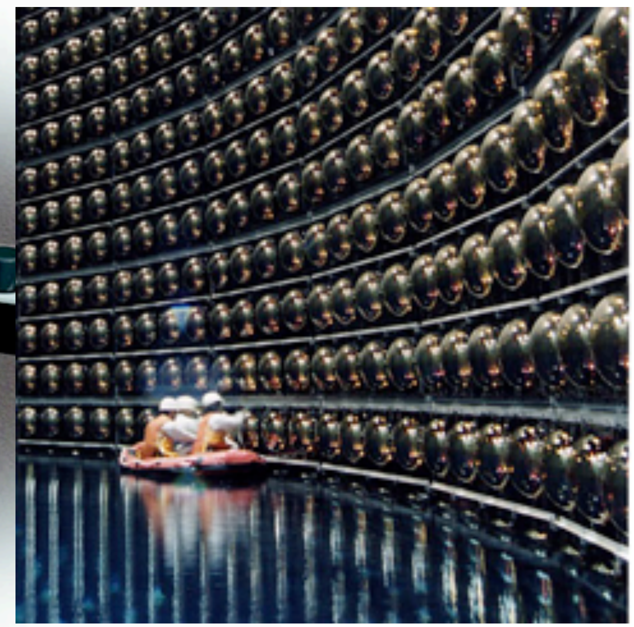


Super-Kamiokande: Far Detector

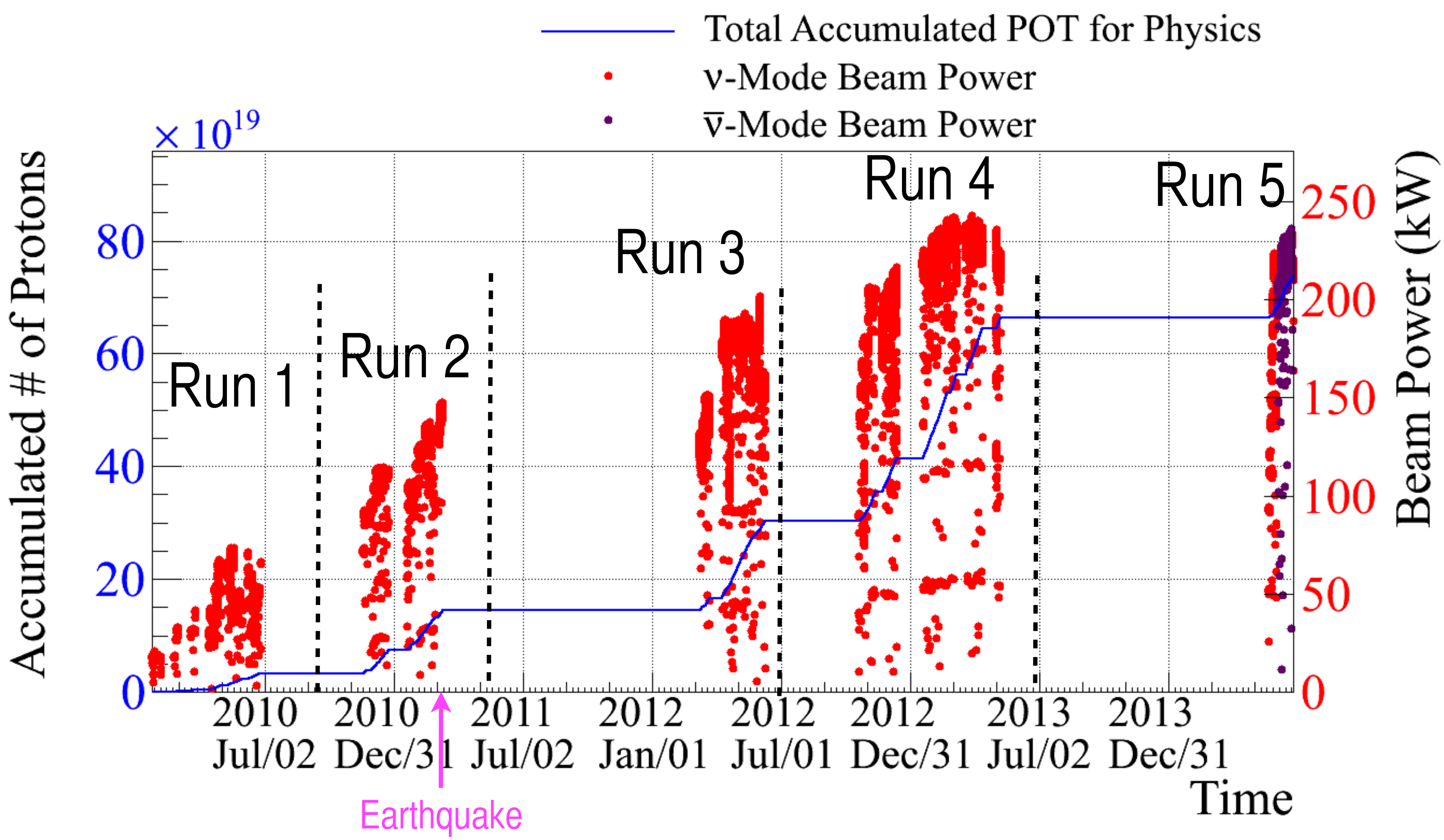
- Large volume water Cherenkov detector
- 50 kton of pure H_2O (22.5 kton fiducial volume)
- 11,000 phototubes

- Outer layer with 1885 phototubes to reject external events
- Expect a handful of events per day at full beam power.





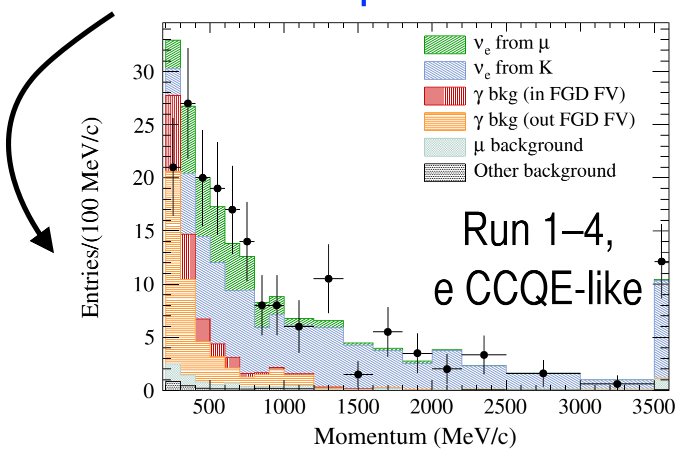
T2K Beam Running



- Total ν physics running 6.88 x10^{20} protons on target
- Total anti-ν physics running 0.51 x10^{20} protons on target
- Only 10% of expected protons

Measurements Using Only Near Detectors

- Papers from **On-Axis Near Detector**
  - Inclusive ν_μ CC cross section on Fe and C, arXiv:1407.4256, accepted by Phys Rev D
- Papers from **Off-Axis Near Detector Data**
  - Inclusive ν_μ CC cross section on C, Phys Rev D **87** 092003 (2013)
  - Inclusive ν_e CC cross section on C, arXiv: 407.7389
  - Measurement of ν_e component of the Beam, Phys Rev D **89** 092003 (2014)



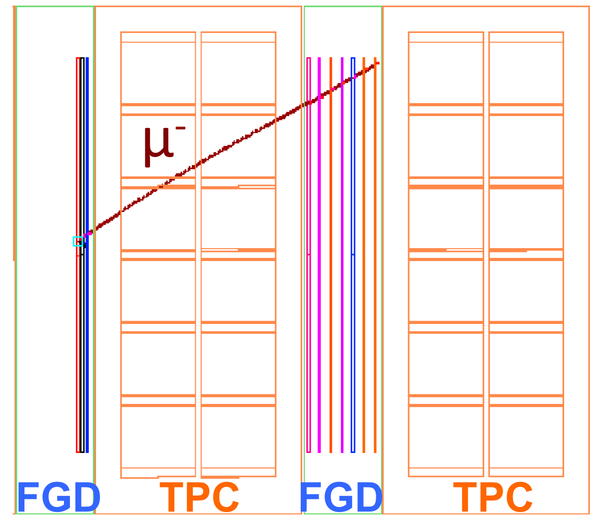
Measured/Predicted = 1.01±0.1

- Preliminary cross sections results have been also presented on a number of topics including ν_μ CC quasi-elastic cross section on C, NC elastic scattering cross section, and CC coherent pion production

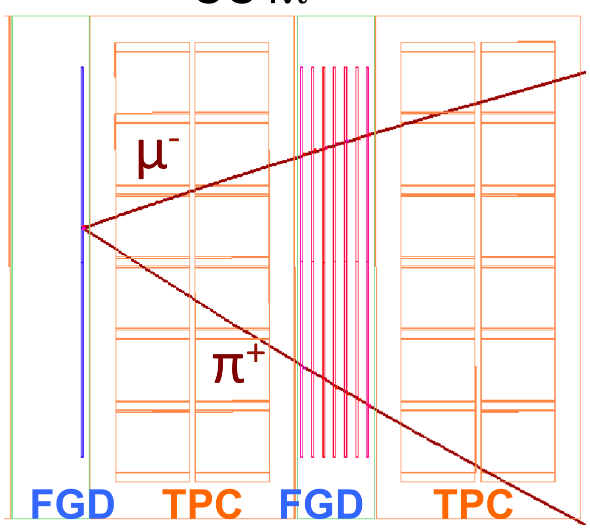
Near Detector Samples

- 3 ND samples used as constraints for oscillation analyses
  - $CC0\pi$
  - $CC1\pi+$
  - CC Other

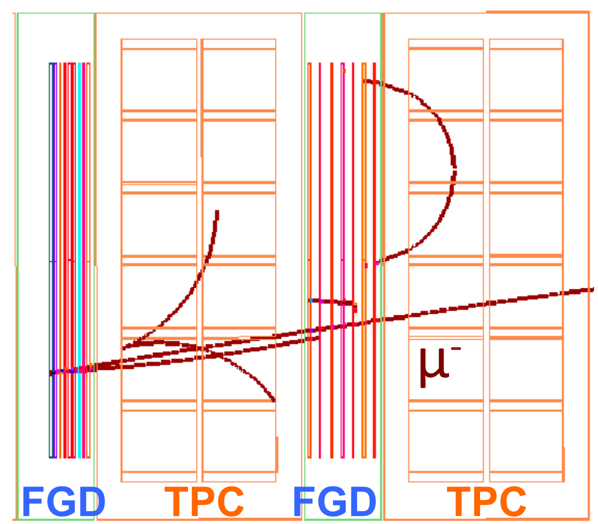
CC0π



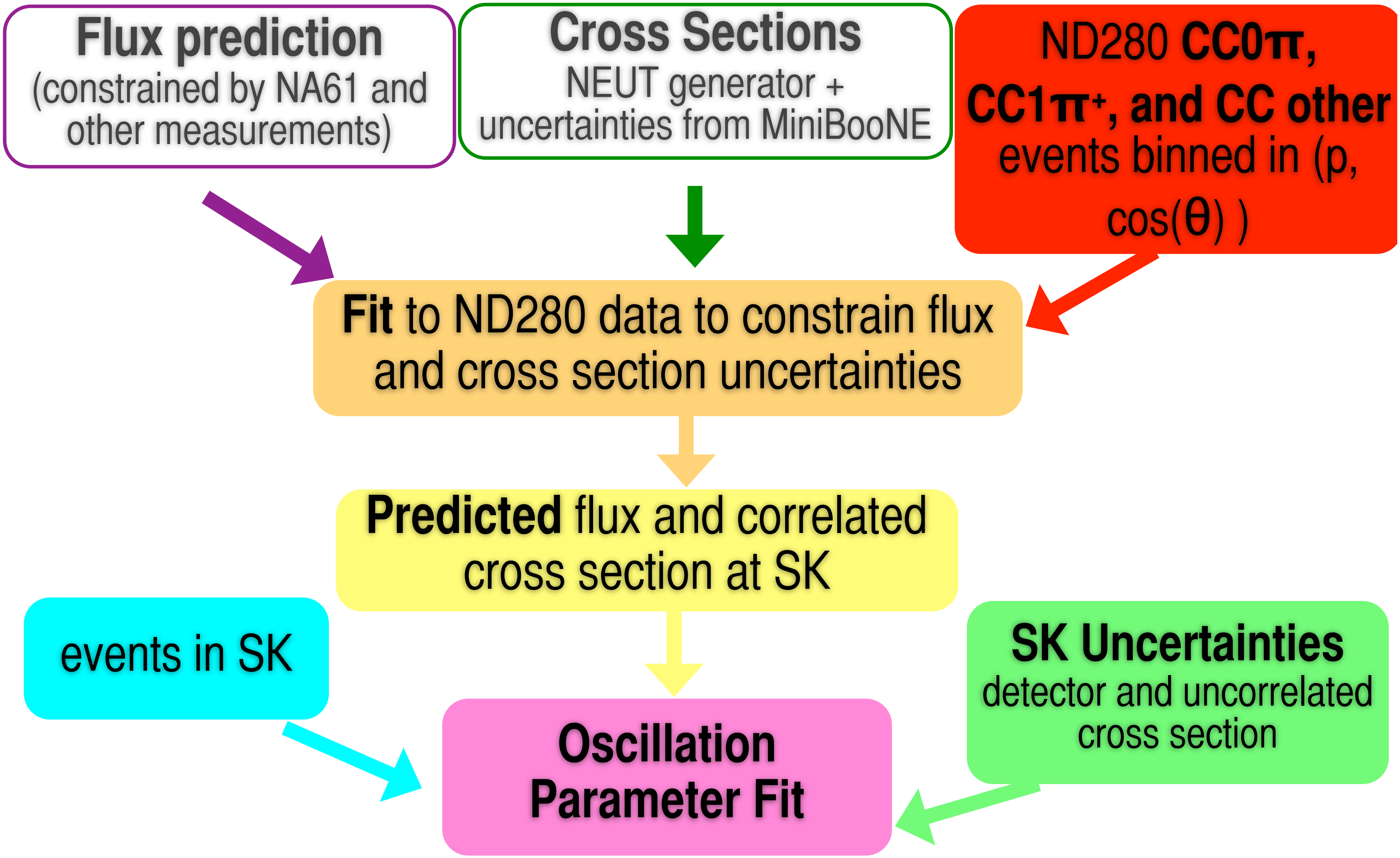
CC1π+



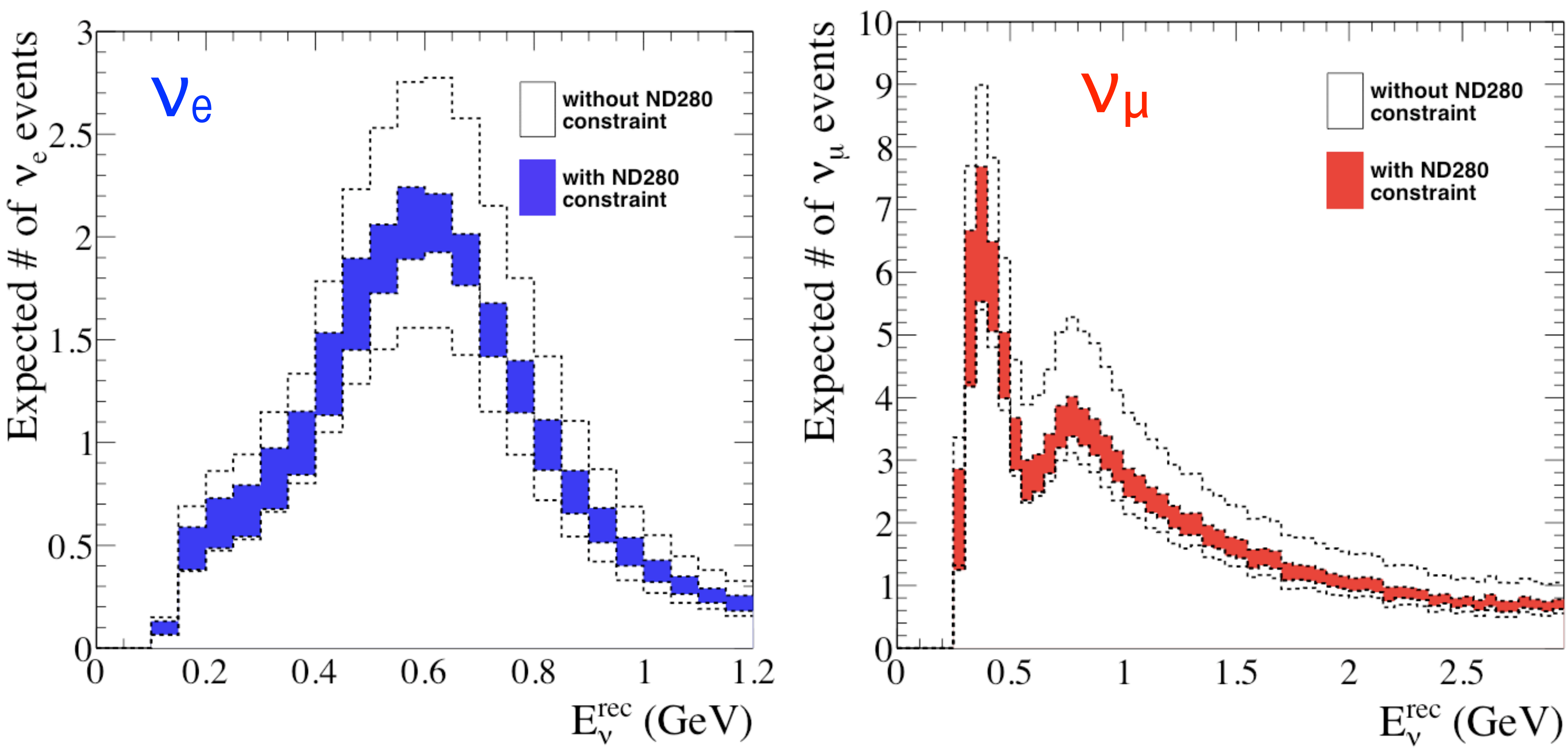
CCOther



Constraints for Oscillation Analysis



Constraints and Uncertainties

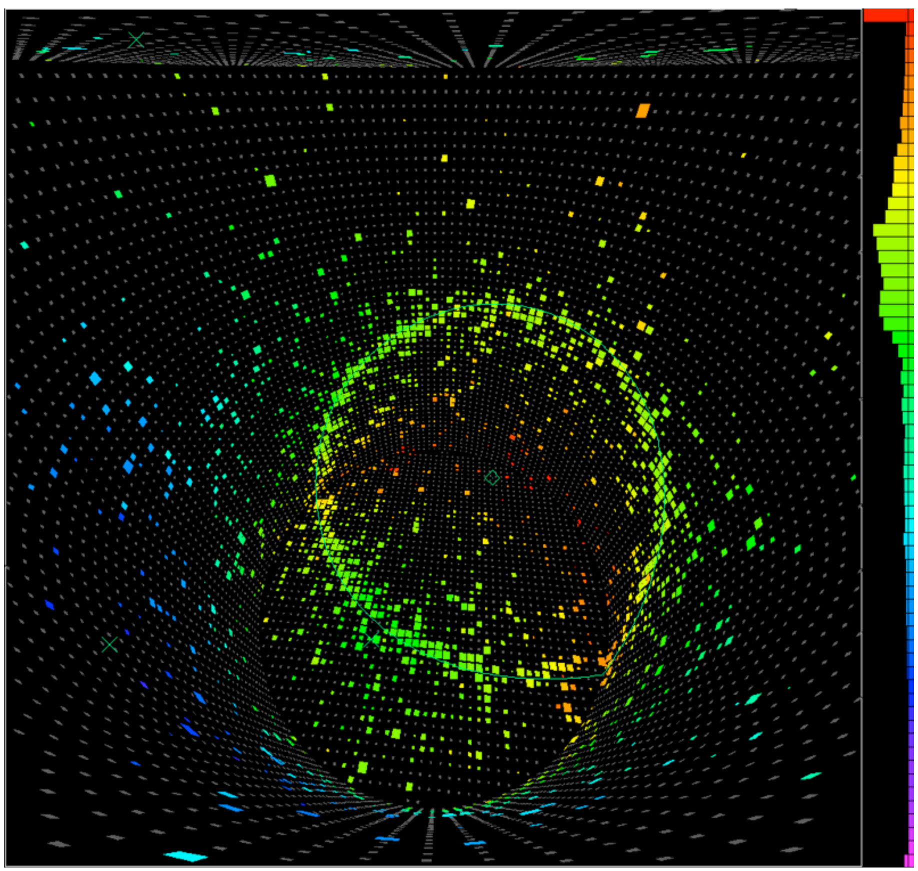


- Fractional error on # ν_e events: 6.8% ; on # ν_μ events: 7.7%
- After constraint, largest sys uncertainty due to difference in nuclear targets

Event Selection in Super-K

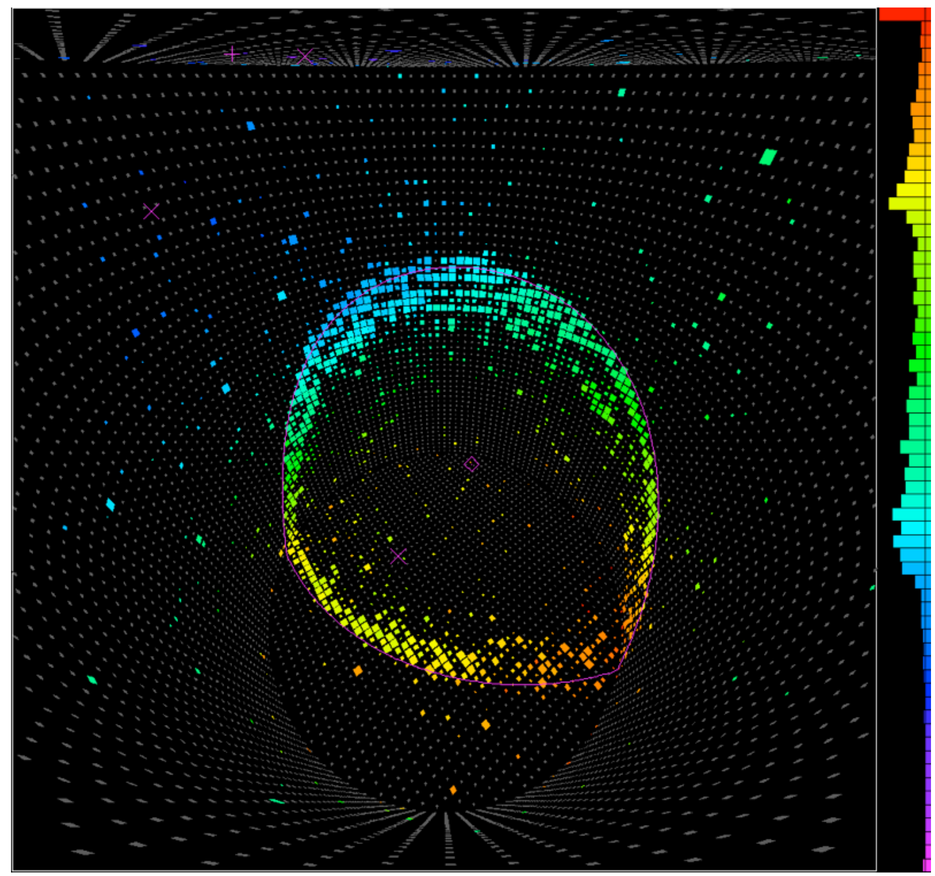
ν_e sample

Fully-contained event with single electron-like ring, E<1250 MeV



ν_μ sample

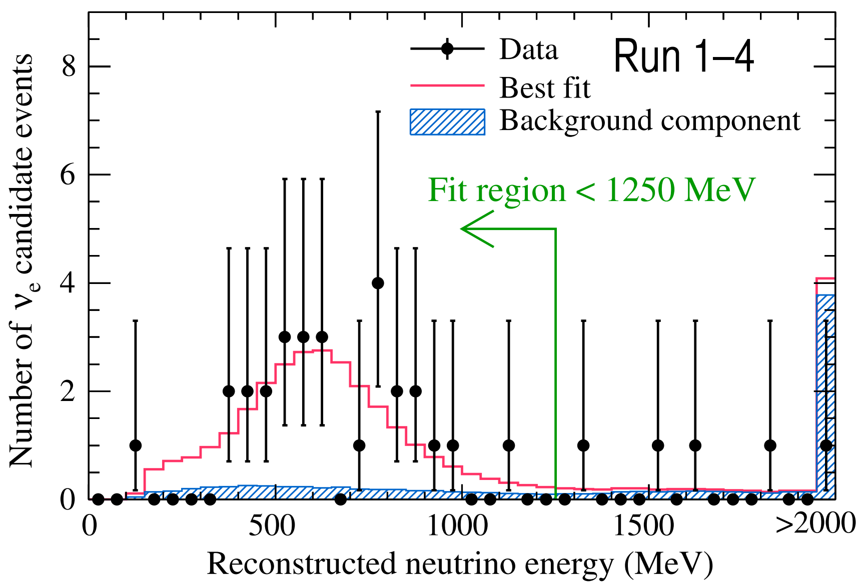
Fully-contained event with single muon-like ring



ν_e Appearance and ν_μ Disappearance

ν_e Appearance

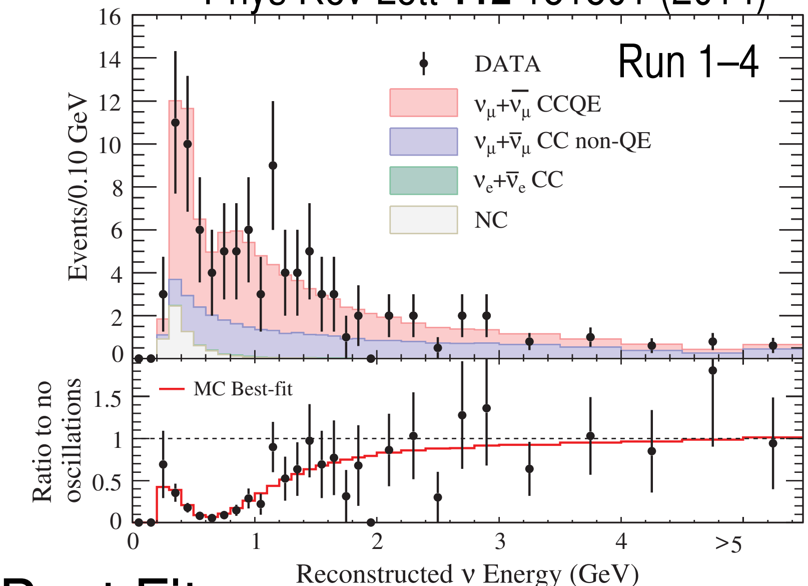
Phys Rev Lett **112** 061802 (2014)



- Best Fits at $\delta_{cp}=0$, $\Delta m^2_{32}=2.51\times10^{-3}$ eV^2, $\sin^2\theta_{23}=0.5$
  - NH: $\sin^2 2\theta_{13}=0.140\pm^{0.038}_{0.032}$
  - IH: $\sin^2 2\theta_{13}=0.170\pm^{0.045}_{0.037}$
- 7.3σ significance compared to bkg

ν_μ Disappearance

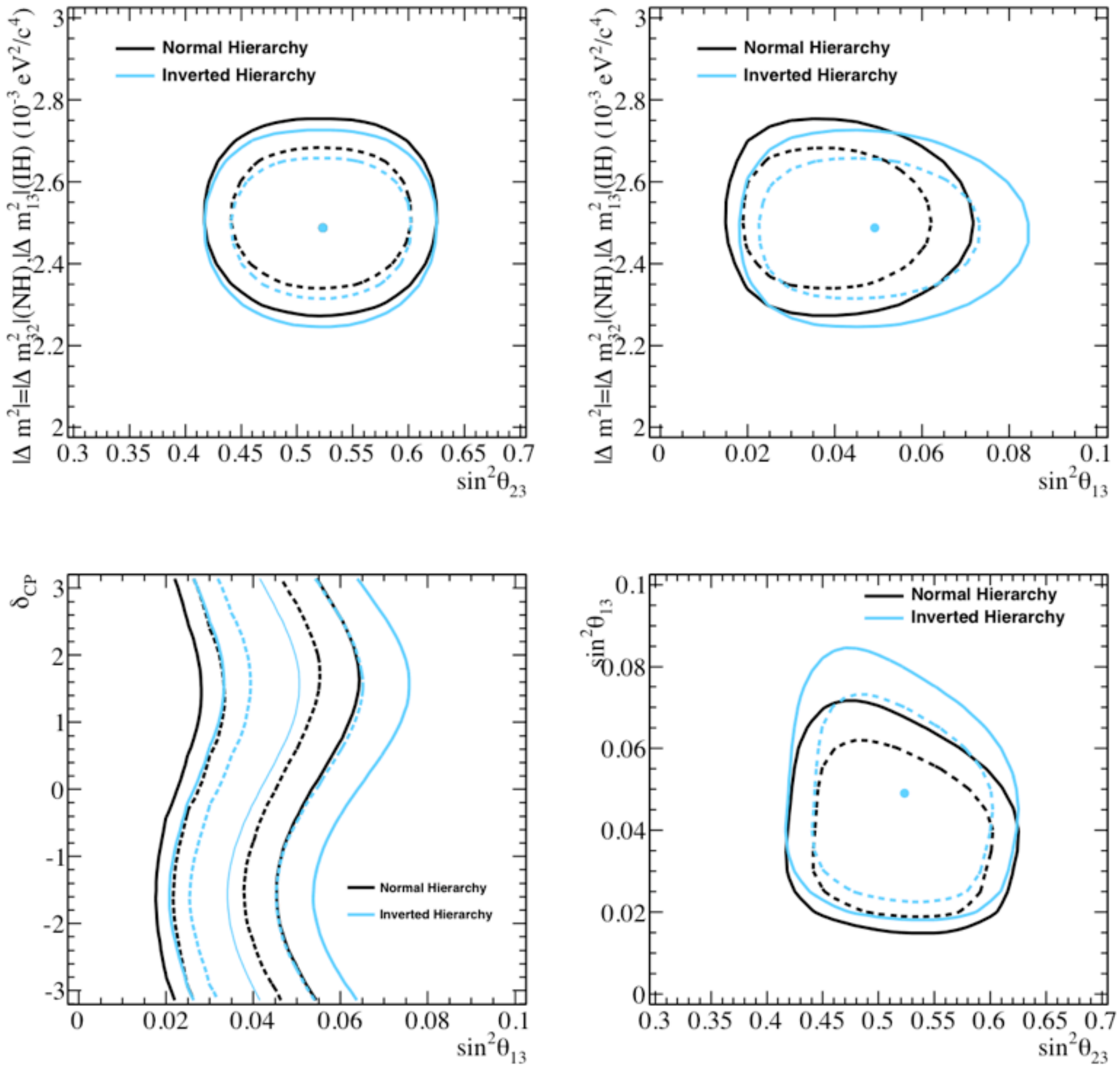
Phys Rev Lett **112** 181801 (2014)



- Best Fit
  - NH: $\Delta m^2_{32}=(2.51\pm0.10)\times10^{-3}$ eV^2, $\sin^2\theta_{23}=0.514\pm^{0.055}_{0.056}$
  - IH: $\Delta m^2_{32}=(2.48\pm0.10)\times10^{-3}$ ev^2, $\sin^2\theta_{23}=0.511\pm0.055$
- Most precise measurement of θ_{23}

T2K Combined 3-flavor Fit

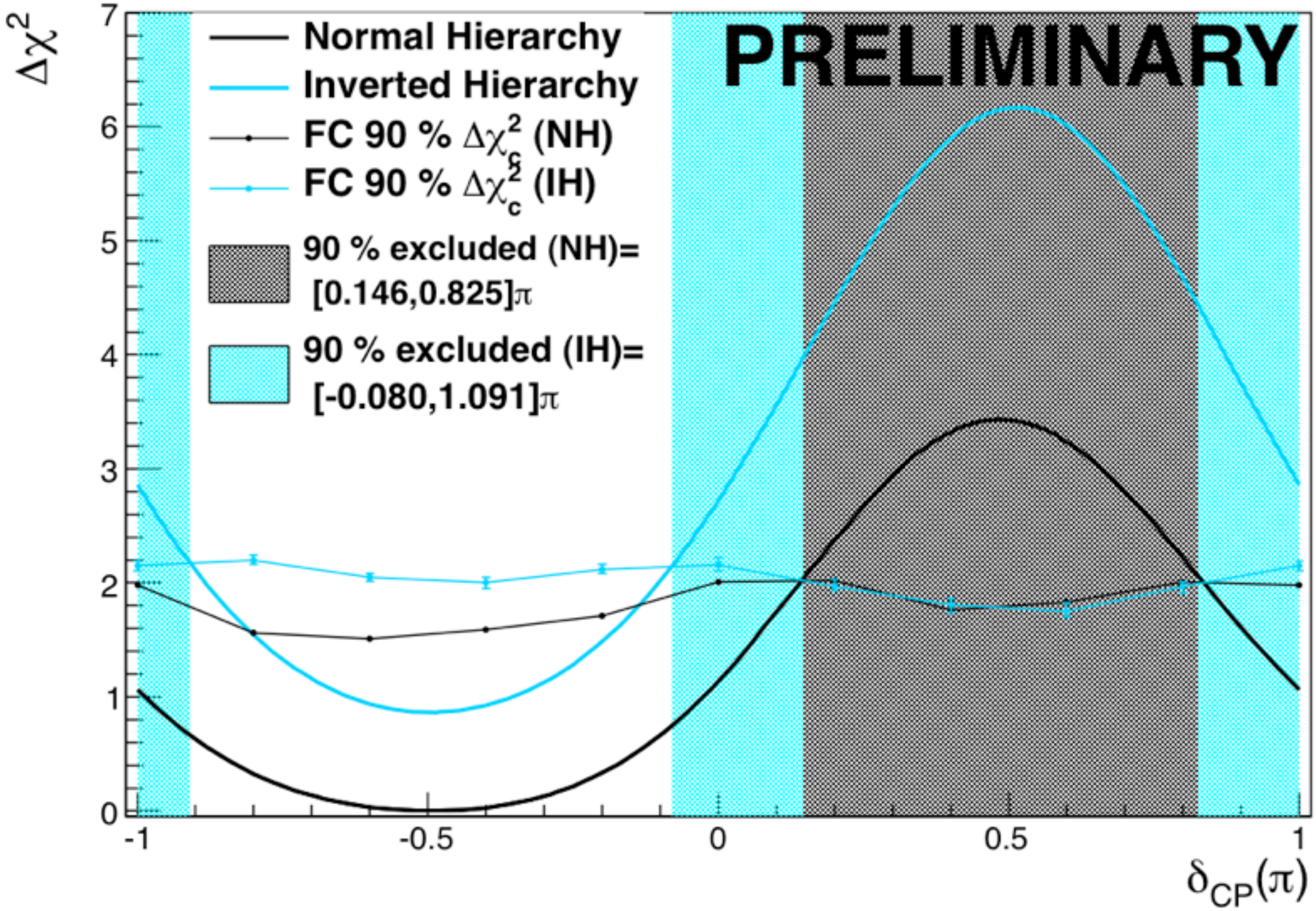
T2K Preliminary



- Combined 3-flavor fit for T2K ν_μ disappearance and ν_e appearance data

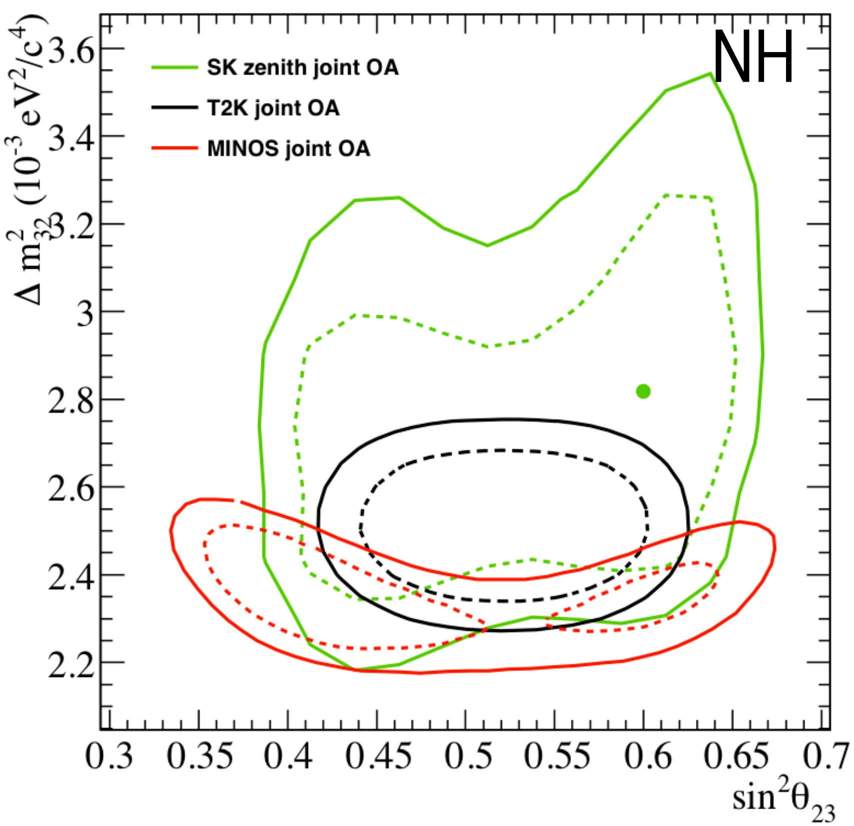
Hierarchy and δ_{CP}

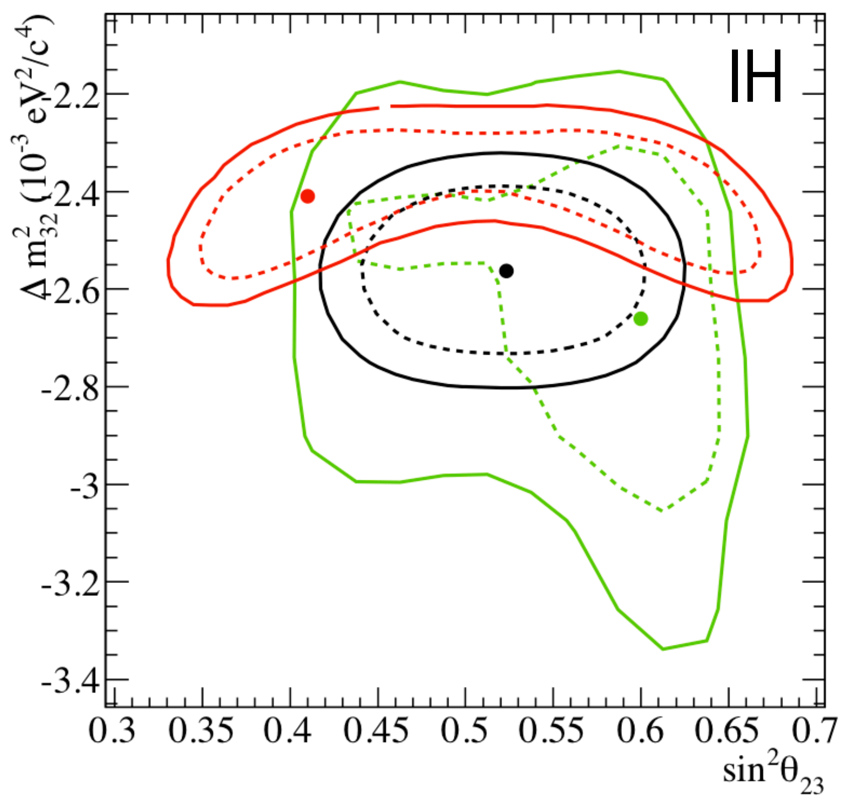
- Includes reactor constraint on θ_{13}
- Preference for negative δ



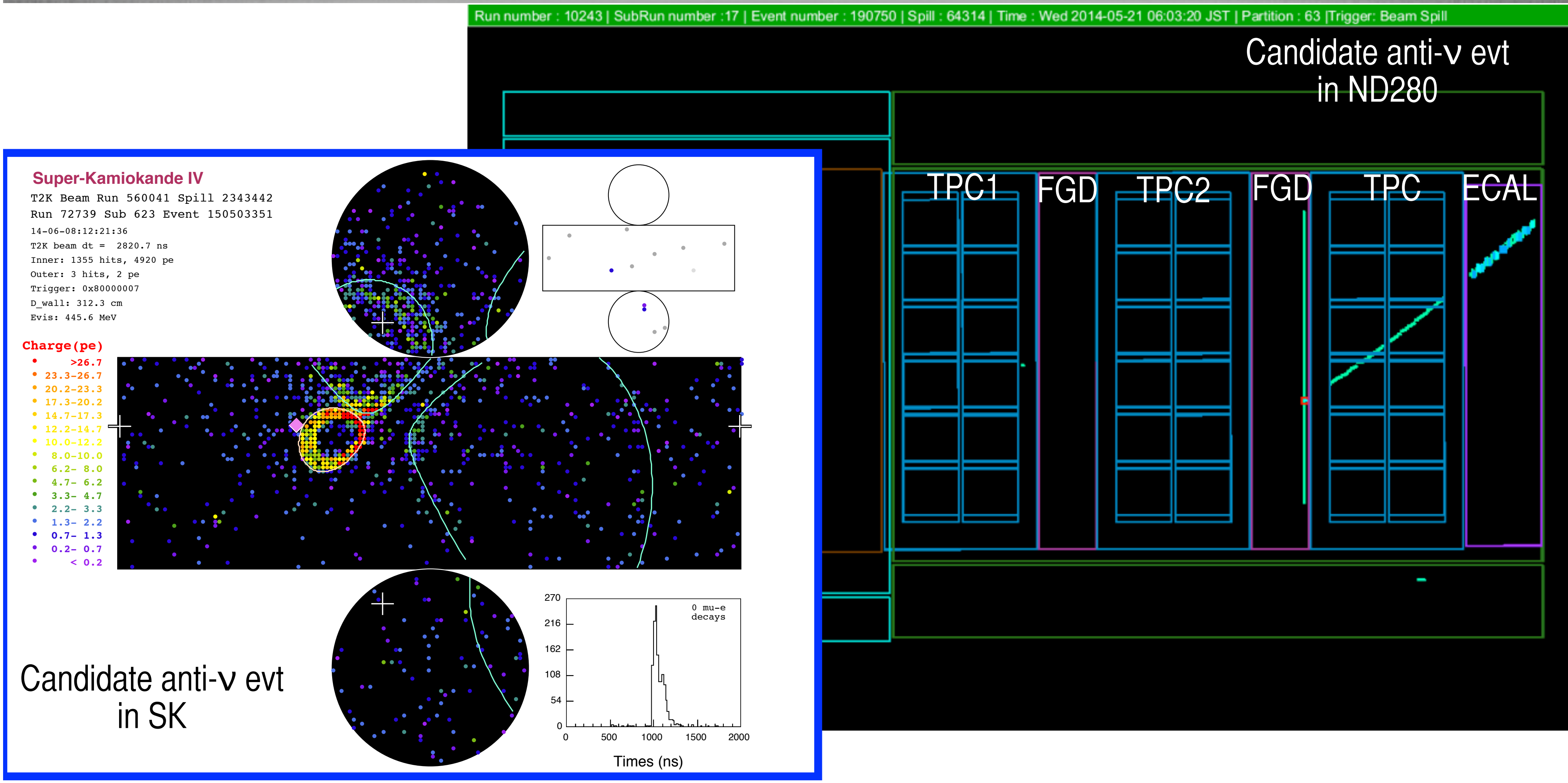
Comparison of Masses and Angles

- Simultaneous appearance/disappearance 3-flavor fits for each experiment
- Allowed regions for mixing angles and mass splitting overlap very well





Anti-Neutrinos in T2K

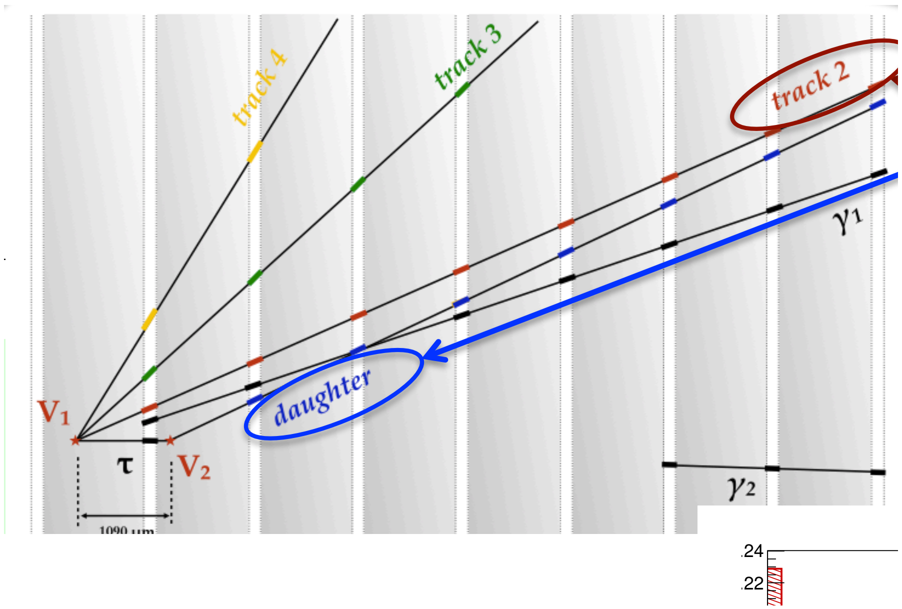


- In June 2014 began data taking with anti-ν beam
- In future will take similar amounts of anti-ν and ν data

Tau Appearance

- **OPERA** 2008–2012 data in Phys Rev D **89** 051102 (2014)
- A 4th τ appearance event discovered in more recent data, no oscillation now excluded at the 4.2σ CL

4th candidate, S. Dusini, Neutrino 2014

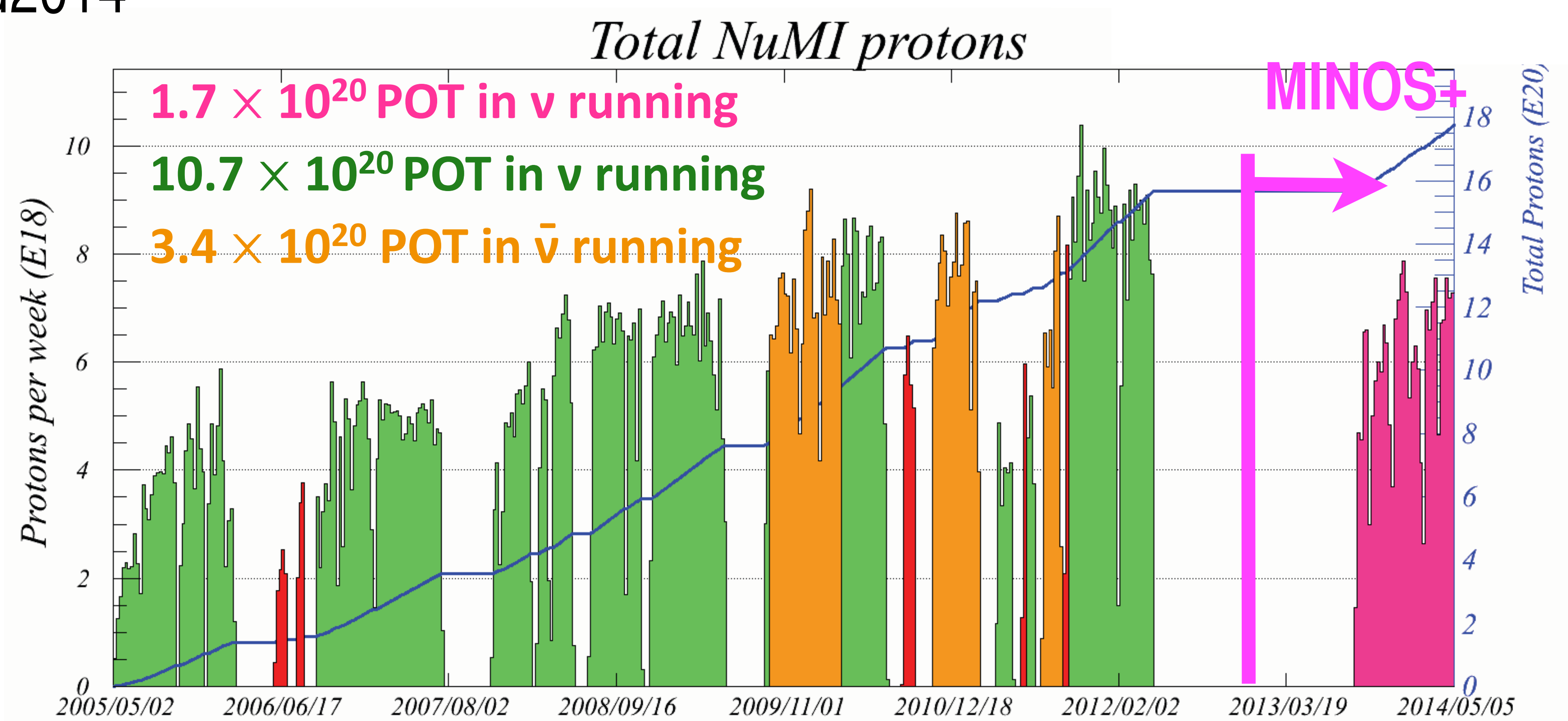


- Super-K in Phys Rev Lett **110** 181802 (2013) also reported 3.8σ CL evidence for tau appearance in events resulting from hadronic tau decays.

Near Future Accelerator-Based Neutrino Experiments

MINOS+

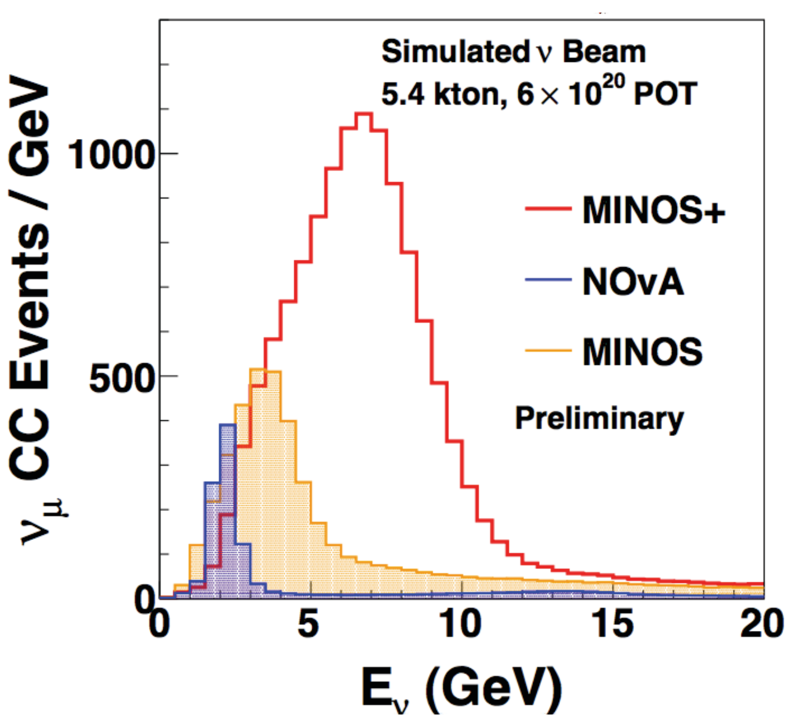
A. Souza, Nu2014



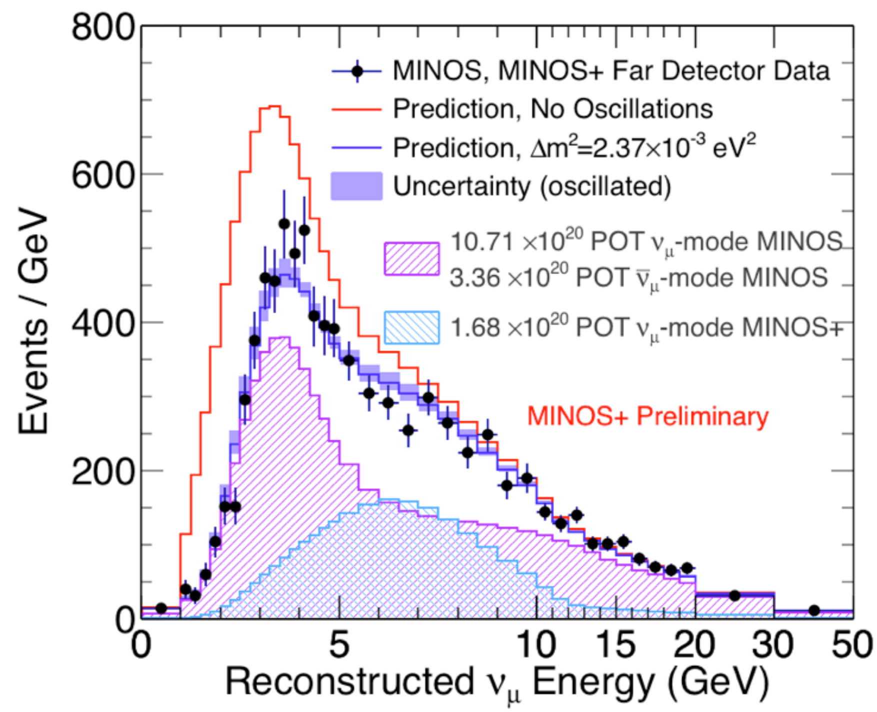
- MINOS+ : Operate MINOS detectors in NOvA-era NuMI beam

MINOS+ Physics

- Beam is higher in energy and has a greater flux per POT
- Goals include precision 3-flavor mixing tests, sterile neutrinos, non-standard interactions, neutrino cross section measurements

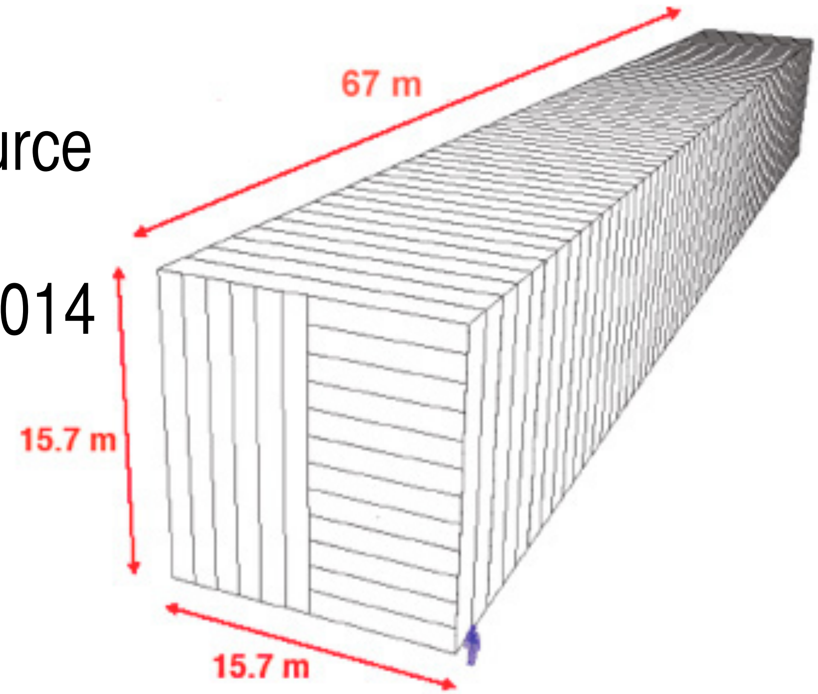


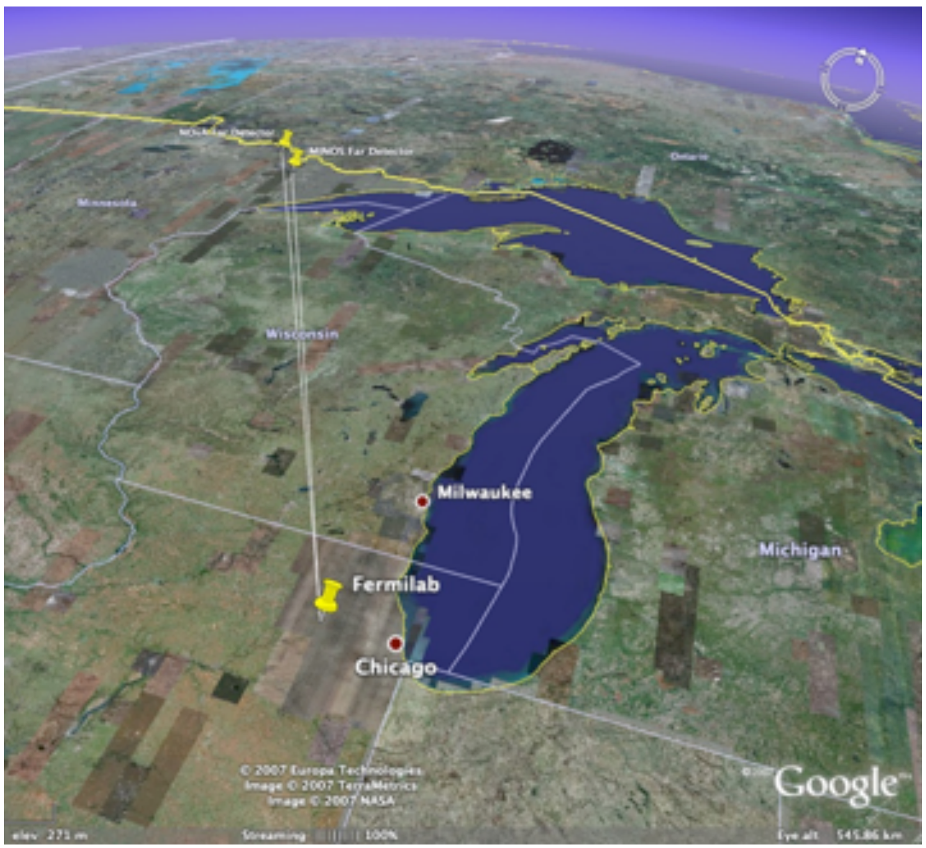
Preliminary Far CC spectrum



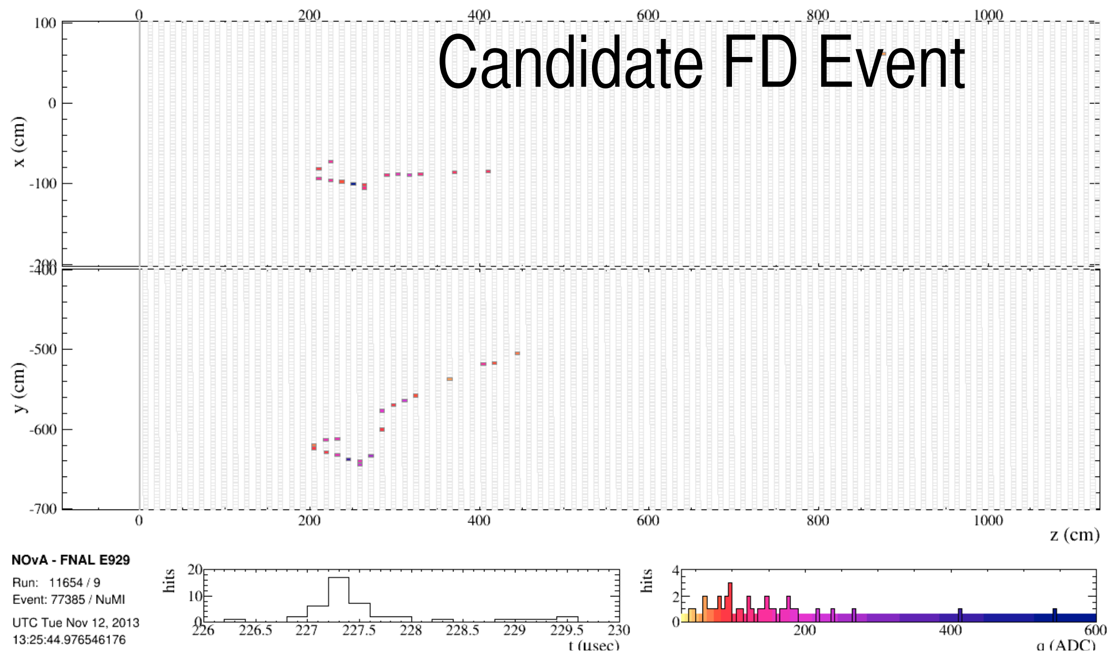
NOνA

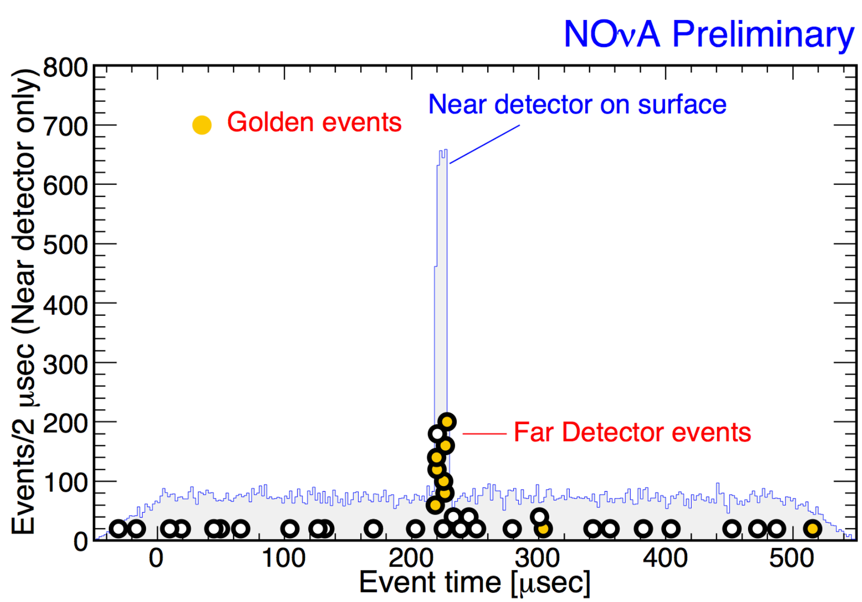
- active scintillator detectors, 14 kton far det
- Off-axis from NuMI beam, 810 km from source
- First beam April 2013
- Near and Far Detectors complete in April 2014





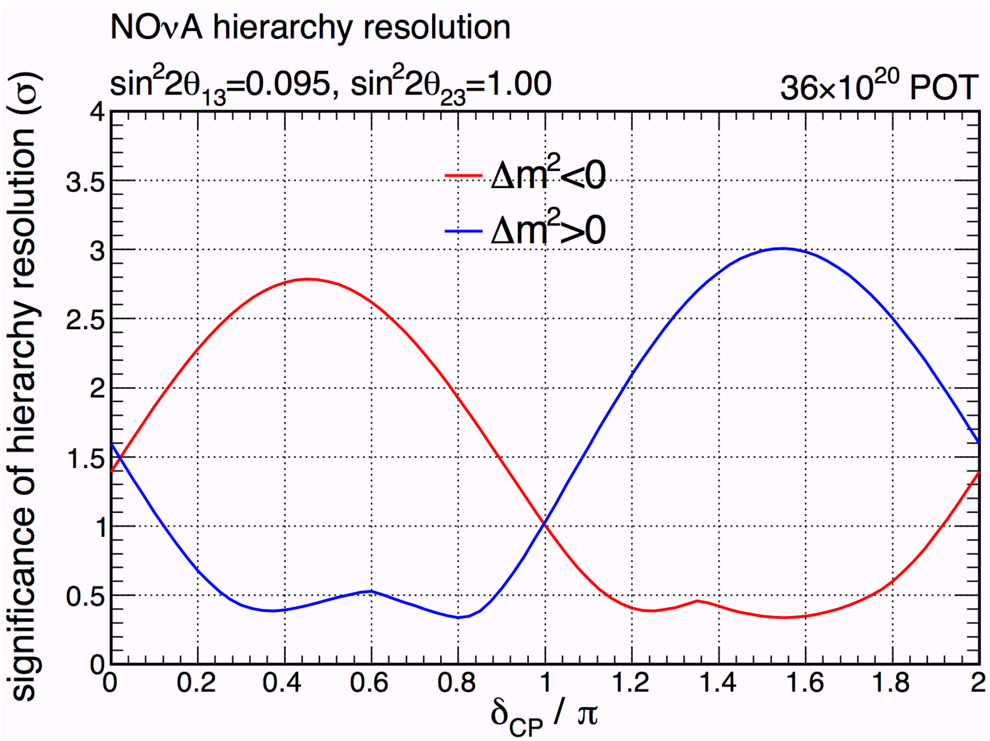
NOvA Candidate Events



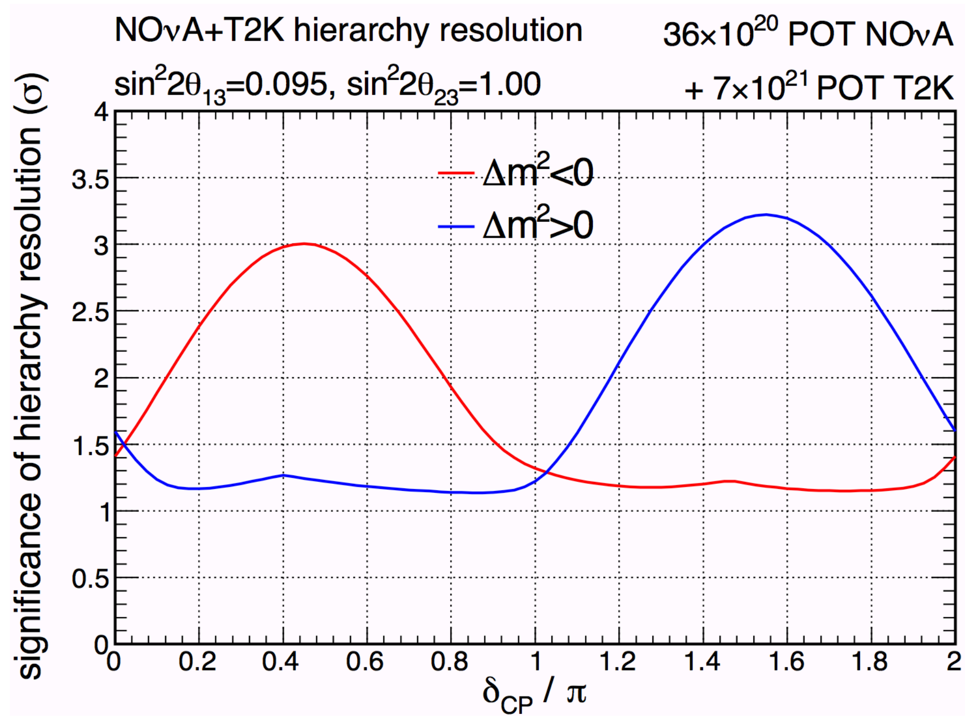


Hierarchy Sensitivity

NOvA



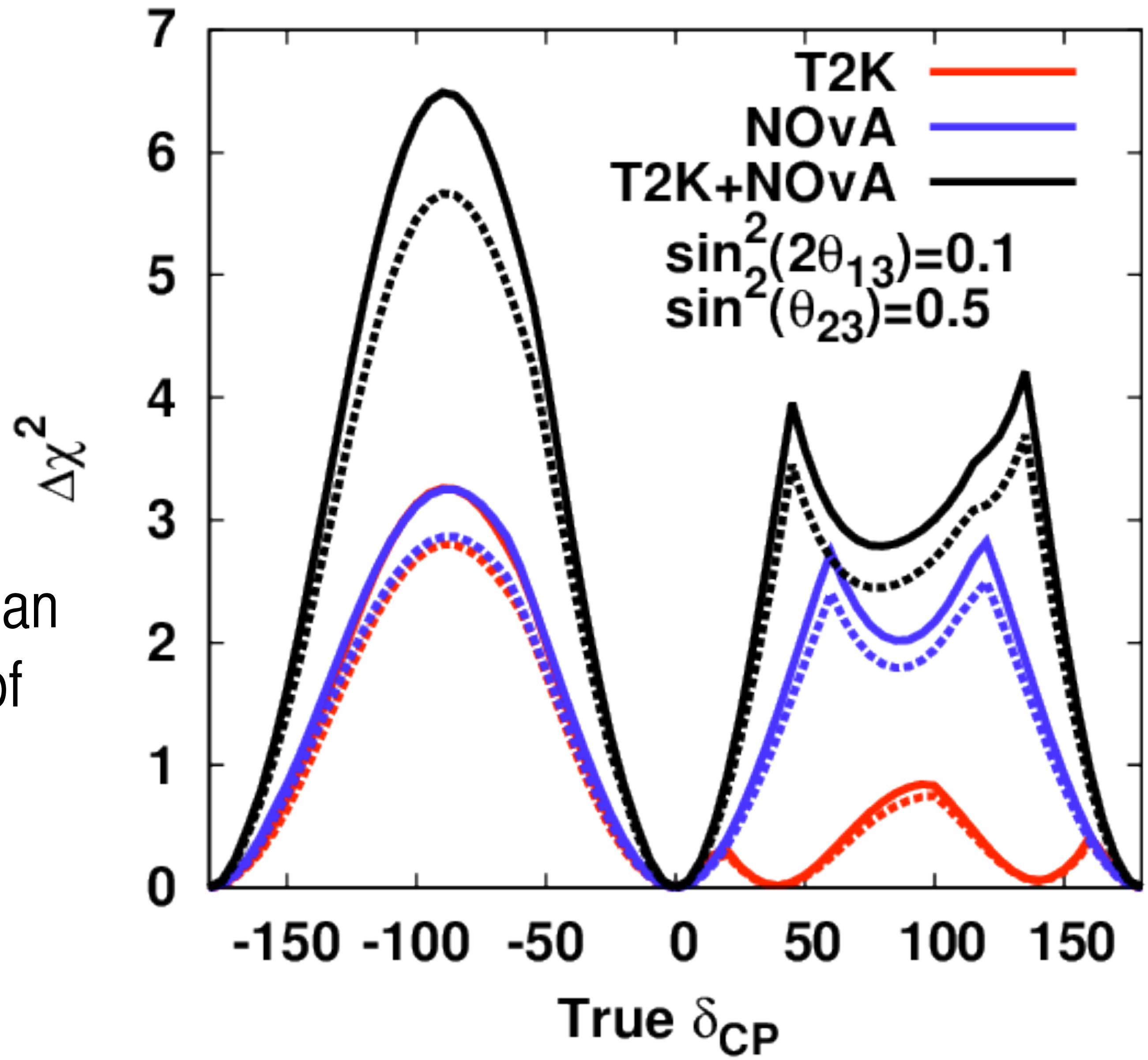
NOvA+T2K



- NOvA has 2σ resolution of hierarchy over 1/3rd of δ space
- NOvA+T2K have better than 1σ resolution over all space

δ_{CP} Sensitivity

- Assumes hierarchy is unknown
- Dashed lines include systematics
- T2K+NOvA have more than 1σ sensitivity over 75% of the δ_{CP} range



Summary

- We are moving into an era of precision measurements of neutrino oscillation parameters in the 1–3 and 2–3 sector with accelerator-based neutrino experiments.
- MINOS and T2K have observed the disappearance of ν_μ and the appearance of ν_e
- MINOS operations have concluded, joint 3-flavor analysis performed of beam (ν+anti-ν) + cosmics
- T2K began taking anti-ν data in 2014

- MINOS+ and NOvA have started data collection and will present physics result in the near future