

Sensitivity of the $\text{NO}\nu\text{A } \nu_e$ appearance analysis

International school of subnuclear physics – Erice

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Introduction

- ▶ $\text{NO}\nu\text{A}$ and neutrino oscillations
- ▶ Selecting ν_e events
- ▶ Sensitivity
 - ▶ Hierarchy
 - ▶ CP-violation
 - ▶ Octant
- ▶ Conclusion

Neutrino oscillations – theory

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i}^* |\nu_i\rangle$$

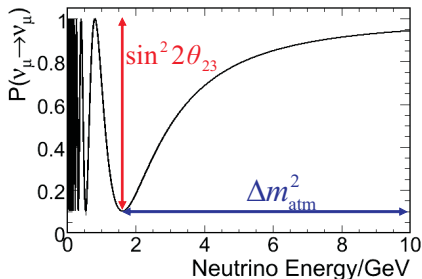
$$i = 1, 2, 3 \quad \alpha = e, \mu, \tau$$

- ▶ PMNS matrix. \sim CKM matrix for neutrinos

$$P_{\alpha\beta} = \left| \sum_i U_{\alpha i}^* e^{-im_i^2 L/2E} U_{\beta i} \right|^2$$

$$U = \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix}$$

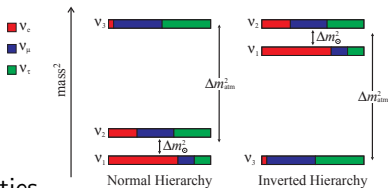
$$P_{\mu\mu} = 1 - \sin^2 2\theta \sin^2 \left(\frac{|\Delta m^2| L}{4E} \right)$$



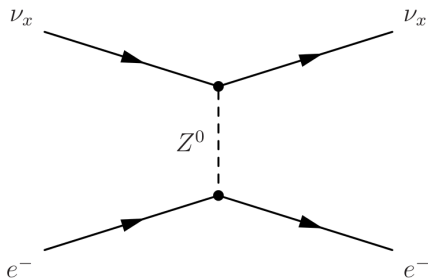
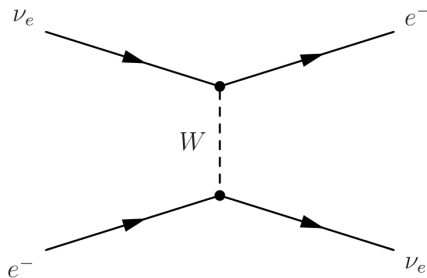
Neutrino oscillations – 3 flavours

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

- ▶ “atmospheric” × “reactor” × “solar”
- ▶ Effect of δ changes sign under CP
- ▶ Need all three angles nonzero for CPV effect
- ▶ δ has no effect on survival probabilities
 - ▶ Only transition (appearance) probabilities
- ▶ Is $\delta \neq 0^\circ, 180^\circ$?



Neutrino oscillations – matter effects



- ▶ Apparent source of CP violation (Earth is made of matter)
- ▶ CC interactions change effective mass of neutrinos
- ▶ Effect depends on hierarchy
 - ▶ Is the most- ν_e state the lightest, or one of the heaviest?

$$\Delta m_M^2 = \sqrt{(\Delta m^2 \cos 2\theta \mp 2\sqrt{2}EG_F N_e)^2 + (\Delta m^2 \sin 2\theta)^2}$$

$$\tan 2\theta_M = \frac{\tan 2\theta}{1 \mp \frac{2\sqrt{2}EG_F N_e}{\Delta m^2 \cos 2\theta}}$$

Neutrino oscillations – θ_{13}

- ▶ Non-zero θ_{13} established by reactor experiments (via $\bar{\nu}_e$ disappearance)

	$\sin^2 2\theta_{13}$
Daya Bay	$0.089 \pm 0.010 \pm 0.005^a$
RENO	$0.113 \pm 0.013 \pm 0.019^b$
Double Chooz	$0.086 \pm 0.041 \pm 0.030^c$

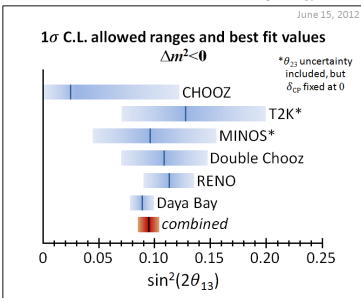
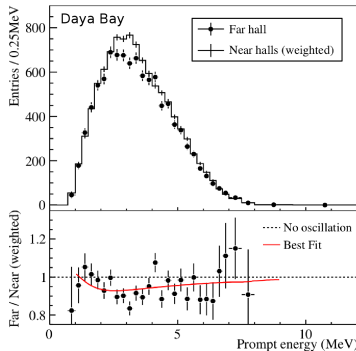
- ▶ $\sin^2 2\theta_{13} \approx 0.1$

- ▶ Long-baseline expts observe $\nu_\mu \rightarrow \nu_e$

^aChin. Phys. C37, 011001 (2013)

^bPhys. Rev. Lett. 108, 191802 (2012)

^cPhys. Rev. Lett. 108, 131801 (2012)

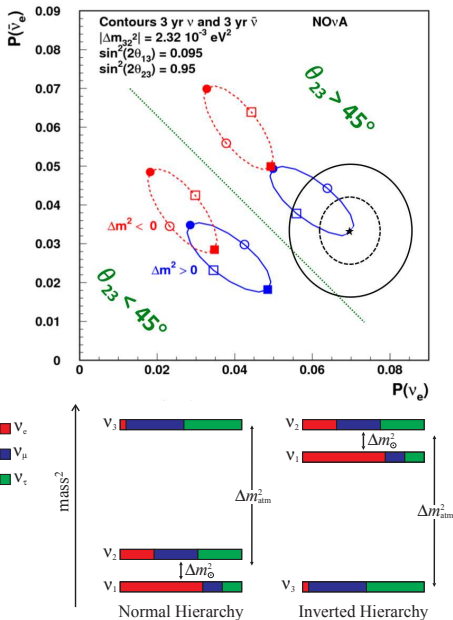


ν_e physics goals

- ▶ To first order, $\text{NO}\nu\text{A}$ measures $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ evaluated at 2GeV

$\nu_\mu \rightarrow \nu_e$

- ▶ Measure θ_{13} via ν_e appearance
- ▶ Determine the θ_{23} octant

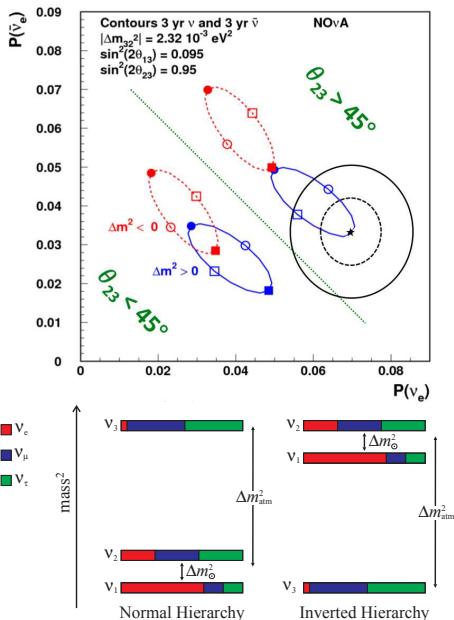


ν_e physics goals

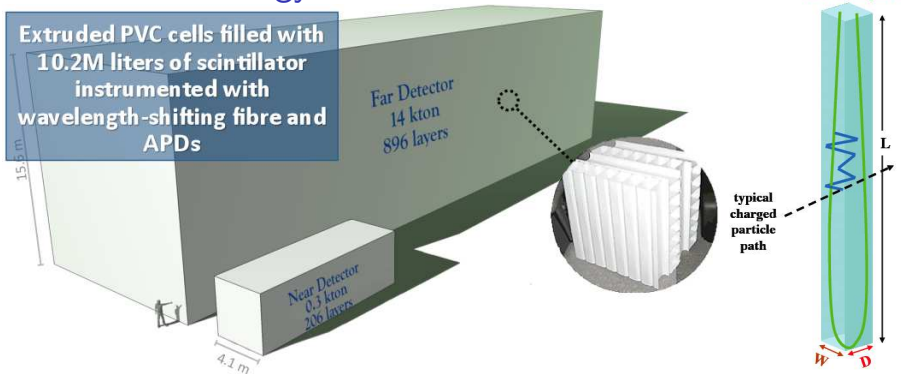
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$\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

- ▶ Measure θ_{13} via ν_e appearance
- ▶ Determine the θ_{23} octant
- ▶ Determine the mass hierarchy
- ▶ Search for $\delta_{CP} \neq 0, \pi$



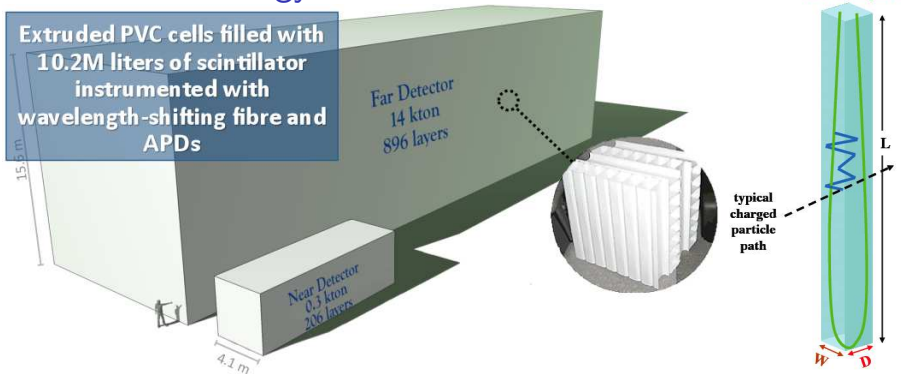
Detector technology



- ▶ Fine-grained low-Z, highly active, tracking calorimeter
- ▶ 64% liquid scintillator by mass
- ▶ WLS fibres looped in 4x6cm cells of PVC extrusion
- ▶ Each to one of 32 pixels of Hamamatsu APD
- ▶ ~85% quantum eff. Gain ~100 \times . Cooled to -15°C



Detector technology



Far Detector

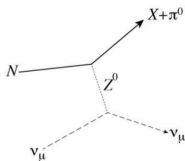
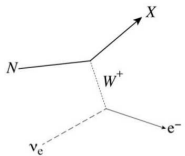
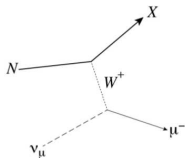
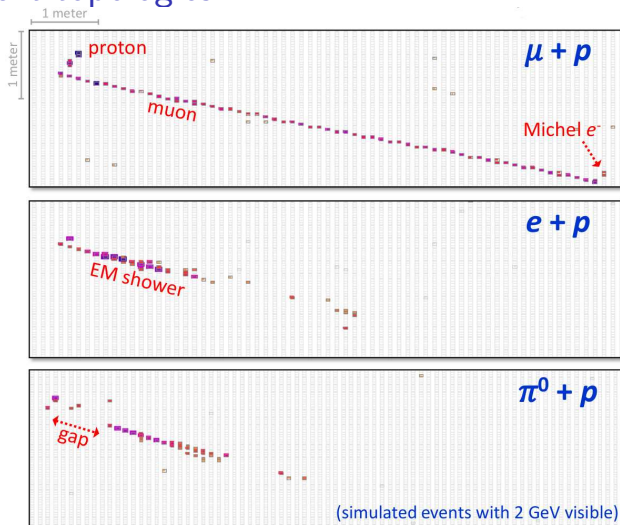
- ▶ 14 kton
- ▶ 344,000 channels

Near Detector

- ▶ 0.3 kton
- ▶ 18,000 channels



Event topologies

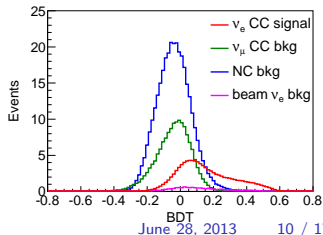
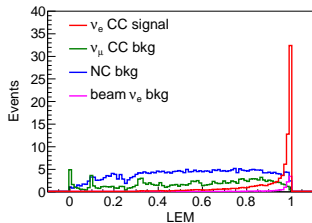
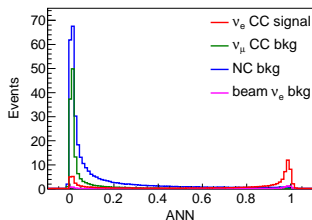


- ▶ Very good granularity, especially considering scale
- ▶ Radiation length 38cm (6 cell depths, 10 cell widths)

PID

- ▶ Several ν_e PIDs under development
 - ANN Likelihood ratios for particle hypotheses
 - LEM Matching to Monte Carlo library events
 - BDT MVA on simple reconstructed quantities
- ▶ Good separation of ν_e signal from backgrounds
- ▶ Approximate expected event counts

18×10^{20} POT	ν	$\bar{\nu}$
Neutral current	19	10
ν_μ charged current	5	<1
Intrinsic ν_e CC	8	5
Total background	32	15
$\nu_\mu \rightarrow \nu_e$ signal	68	32



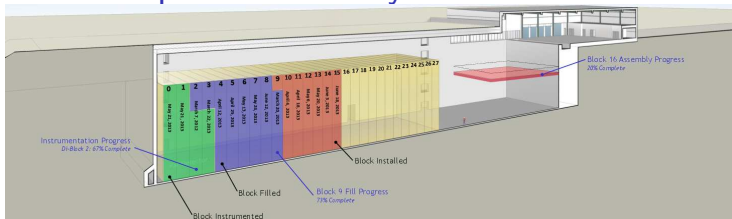
Sensitivities

- ▶ Assuming 3 years ν -mode + 3 years $\bar{\nu}$ -mode @ 6×10^{20} POT/yr
- ▶ Start in neutrino mode
- ▶ Switching to/from antineutrino running is technically easy

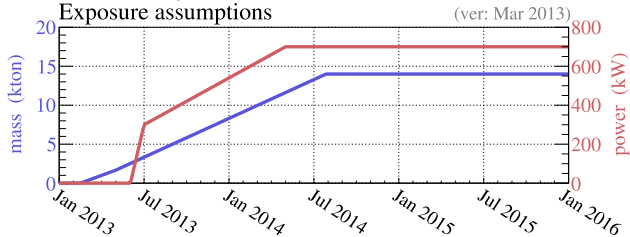
- ▶ $\Delta m_{32}^2 = 2.40 \times 10^{-3} \text{eV}^2$ (MINOS best-fit)
- ▶ $\sin^2 2\theta_{23} = 1.00$ (SK best-fit, except where otherwise stated)
- ▶ $\sin^2 2\theta_{13} = 0.095$ (Reactor average, assumed well-known)

- ▶ Results from full simulation, reconstruction, selection, and analysis framework
 - ▶ FD only. Extrapolation methods from ND in progress

Exposure assumptions and early reach

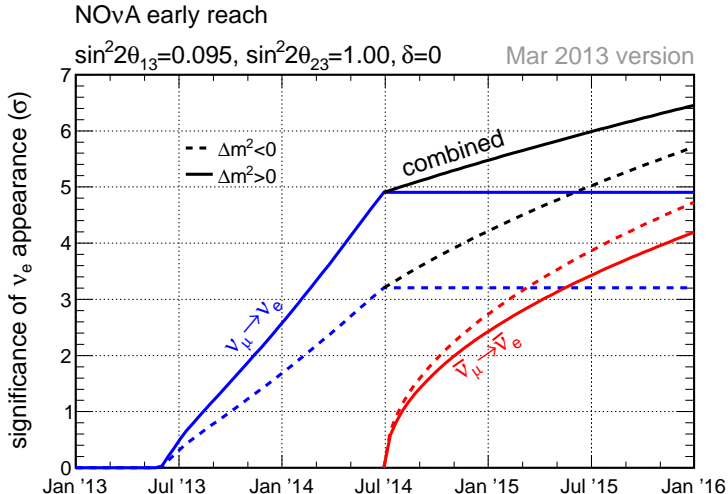


NOVA early reach Exposure assumptions



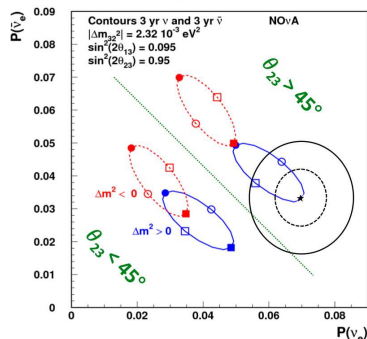
- ▶ 2.5kton when beam returns
- ▶ Ramp up to full 700kW (dependent on Booster improvements)
- ▶ 14kton in Aug 2014

Exposure assumptions and early reach



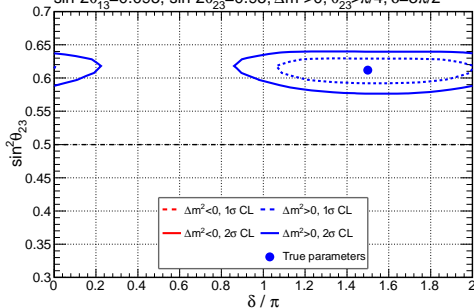
- ▶ 5σ observation of ν_e appearance within first year (for NH, $\delta = 0$)
- ▶ With detector still under construction and beam commissioning

Sensitivity contours



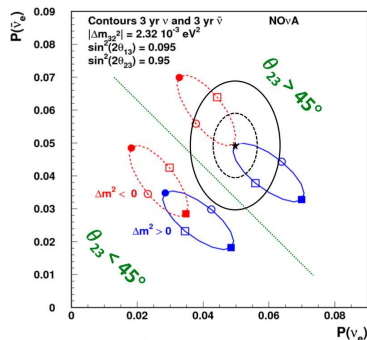
Example NOvA contours, 3+3 yr

$\sin^2 2\theta_{13} = 0.095$, $\sin^2 2\theta_{23} = 0.95$, $\Delta m^2 > 0$, $\theta_{23} > \pi/4$, $\delta = 3\pi/2$



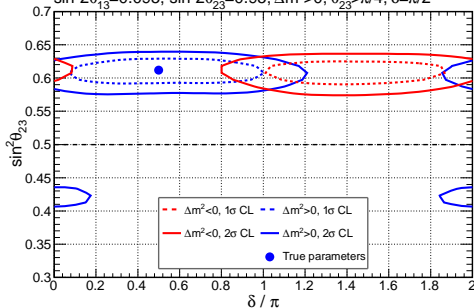
- ▶ Assuming tight measurement of θ_{13} from reactors
- ▶ Combine with NO ν A ν_μ analysis for θ_{23} constraints
- ▶ In this favourable case we distinguish hierarchy and octant at $> 2\sigma$
- ▶ Rule out half of δ_{CP} space (2σ)

Sensitivity contours



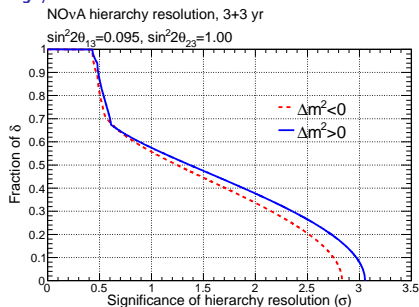
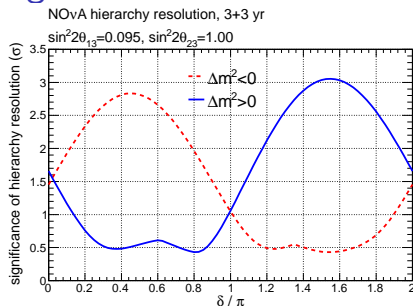
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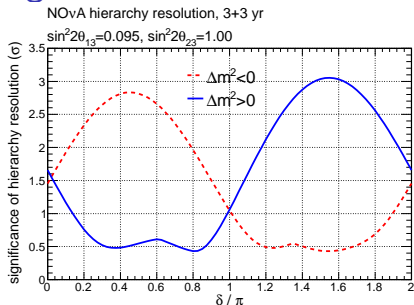
- ▶ Assuming tight measurement of θ_{13} from reactors
- ▶ Combine with NO ν A ν_μ analysis for θ_{23} constraints
- ▶ In a degenerate case hierarchy and δ information are coupled
- ▶ Octant information mostly independent

Significance to resolve hierarchy/discover CPV

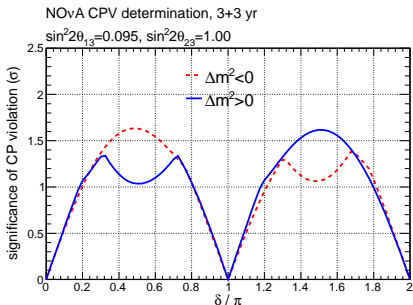
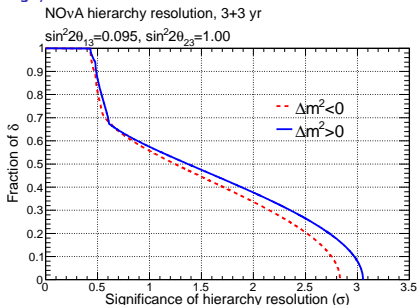


- ▶ For favourable values of δ we can measure the hierarchy at high significance
- ▶ There also exist degenerate scenarios

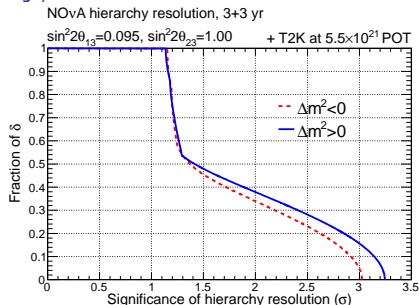
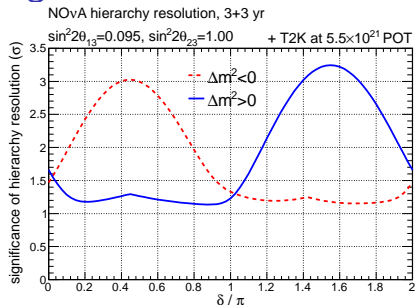
Significance to resolve hierarchy/discover CPV



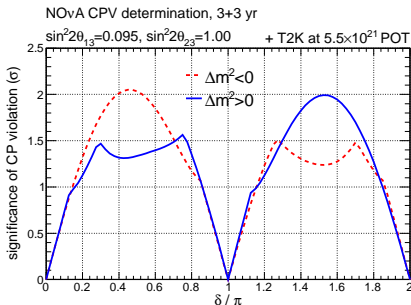
- ▶ For favourable values of δ we can measure the hierarchy at high significance
- ▶ There also exist degenerate scenarios
- ▶ In addition provide input on δ_{CPV}



Significance to resolve hierarchy/discover CPV



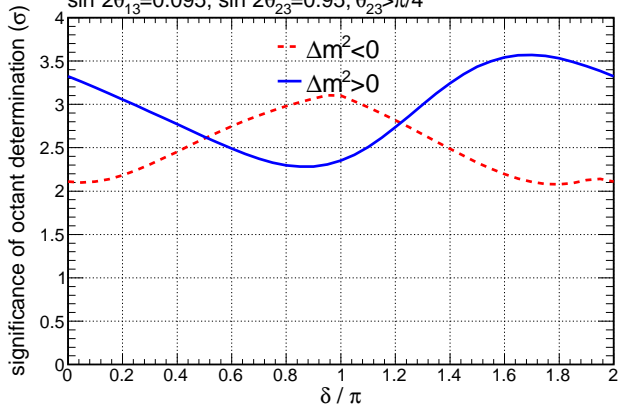
- ▶ Matter effects have a much smaller impact on T2K
- ▶ Help to break hierarchy degeneracies but not CPV
- ▶ Small improvement in best-case scenarios



Octant sensitivity

NO ν A octant determination, 3+3 yr

$\sin^2 2\theta_{13}=0.095$, $\sin^2 2\theta_{23}=0.95$, $\theta_{23} > \pi/4$



- ▶ Octant sensitivity less dependent on δ and hierarchy
- ▶ In this case ($\sin^2 2\theta_{23} = 0.95$, $\theta_{23} > \pi/4$) determine octant at better than 2σ for any δ and hierarchy

Conclusion

- ▶ First Far Detector beam data coming soon
- ▶ Substantial analysis components already in place
- ▶ Longest baseline of any current accelerator experiment
- ▶ Will be first to have significant mass hierarchy sensitivity
- ▶ Will run in both neutrino and antineutrino modes
- ▶ Provide first information on CP-violation
- ▶ Can determine θ_{23} octant in combination with ν_{μ} analysis

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