Sensitivity of the NOνA ν_e appearance analysis

APS April Meeting – Denver
April 14, 2013

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for the NOνA Collaboration

Introduction

- NOνA and neutrino oscillations
- Selecting ν_e events
- Updated sensitivity
  - Hierarchy
  - CP-violation
  - Octant
- Conclusion

Neutrino oscillations – θ_{13}

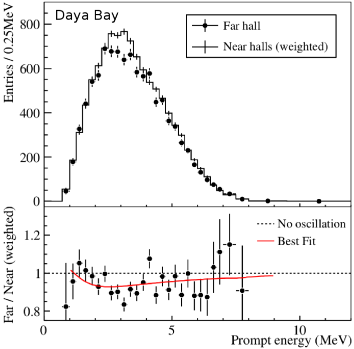
- Non-zero θ_{13} established by reactor experiments (via $\bar{\nu}_e$ disappearance)

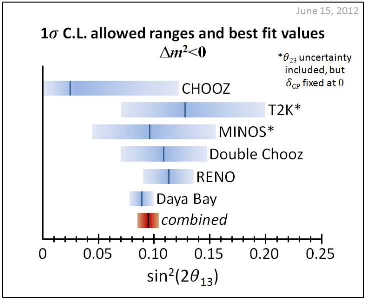
	$\sin^2 2\theta_{13}$
Daya Bay	$0.089 \pm 0.010 \pm 0.005$ [a]
RENO	$0.113 \pm 0.013 \pm 0.019$ [b]
Double Chooz	$0.086 \pm 0.041 \pm 0.030$ [c]

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

- Long-baseline expts observe $\nu_\mu \to \nu_e$

[a] Chin. Phys. C37, 011001 (2013)
[b] Phys. Rev. Lett. 108, 191802 (2012)
[c] Phys. Rev. Lett. 108, 131801 (2012)



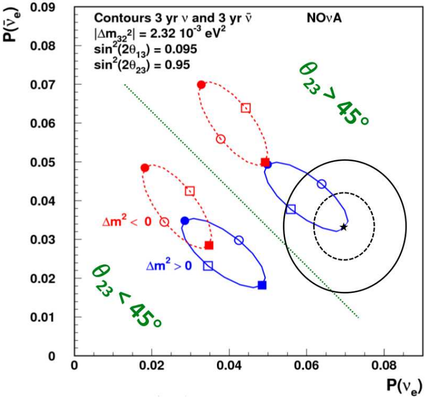


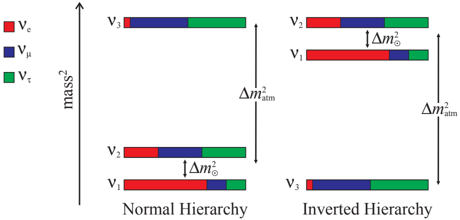
ν_e physics goals

- To first order, NOνA measures $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ evaluated at 2GeV

$\nu_\mu \longrightarrow \nu_e$

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





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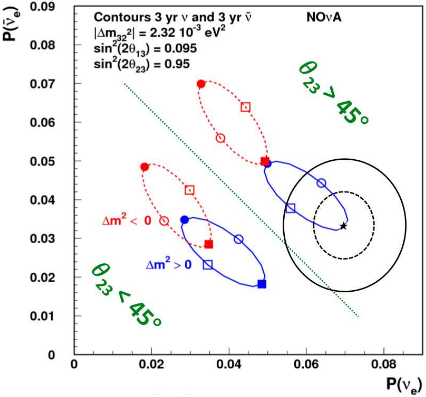
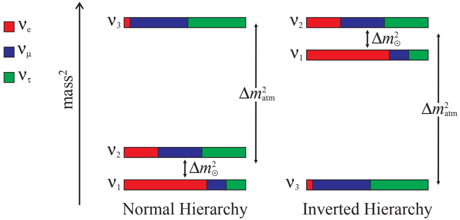
- To first order, NOνA measures $P(\nu_\mu \to \nu_e)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ evaluated at 2GeV

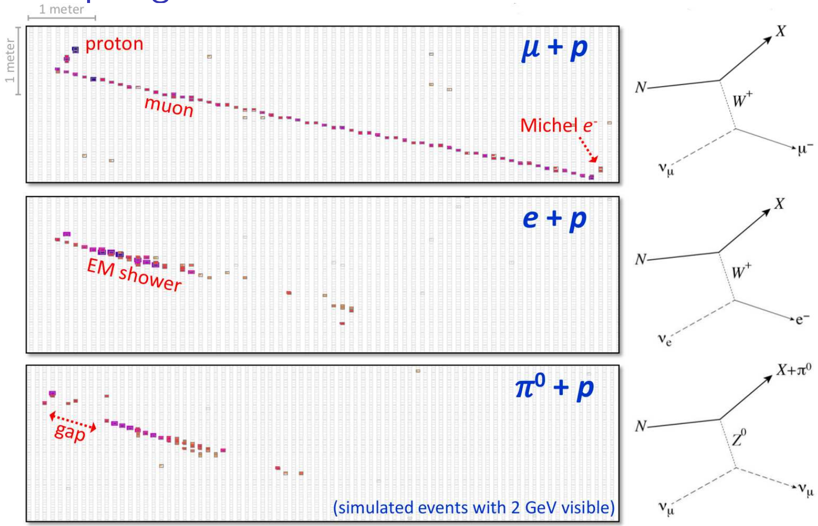


$\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$

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



Event topologies



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

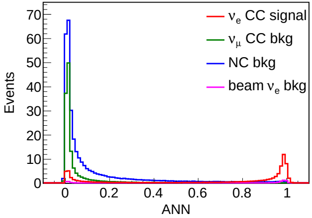
PID

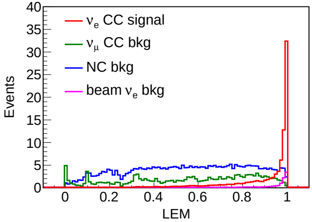
- Several ν_e PIDs under development

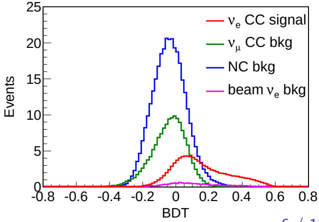
ANN	Likelihood ratios for particle hypotheses
LEM	Matching to Monte Carlo library events
BDT	MVA on simple reconstructed quantities

- Good separation of ν_e signal from backgrounds
- See poster by Himansu Sahoo (session K2)
- 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
$\nu_\mu \to \nu_e$ signal	68	32







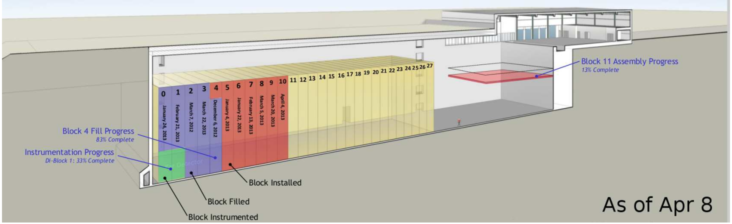
Sensitivities

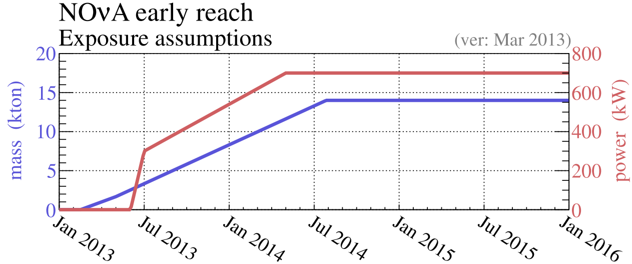
- Assuming 3 years ν-mode + 3 years $\bar{\nu}$-mode @ 6×10^{20} POT/yr
- Start in neutrino mode
- Switching to/from antineutrino running is technically easy

- $\Delta m^2_{32} = 2.40 \times 10^{-3}\mathrm{eV}^2$ (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

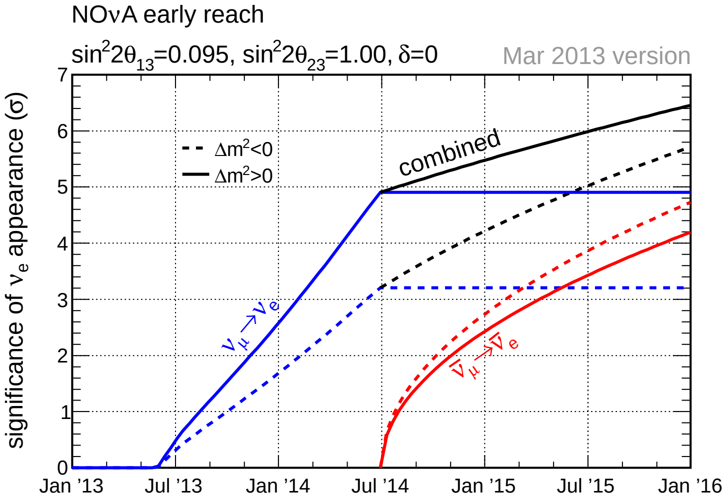
Exposure assumptions and early reach





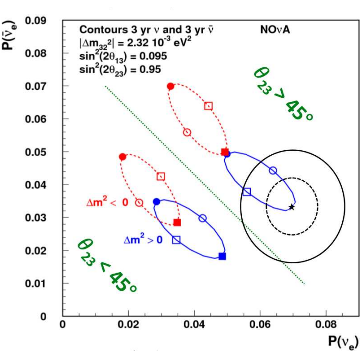
- 2.5kton when beam returns
- Ramp up to full 700kW (dependent on Booster improvements)
- 14kton in Aug 2014

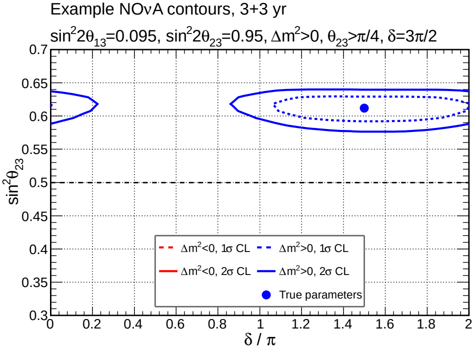
Exposure assumptions and early reach



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

Sensitivity contours

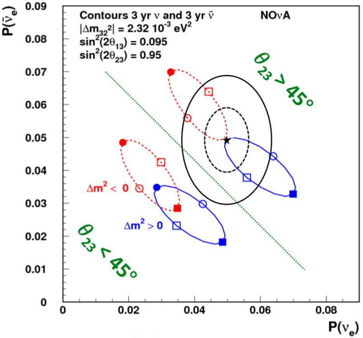


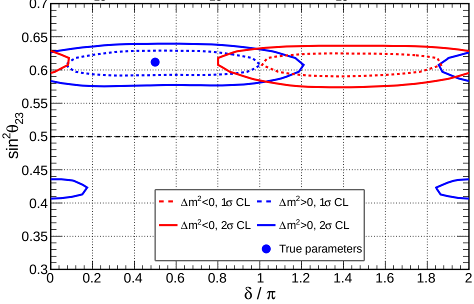


- Assuming tight measurement of θ_{13} from reactors
- Combine with NOνA ν_μ analysis for θ_{23} constraints

- In this favourable case we distinguish hierarchy and octant at $> 2\sigma$
- Rule out half of δ_{CP} space (2σ)

Sensitivity contours

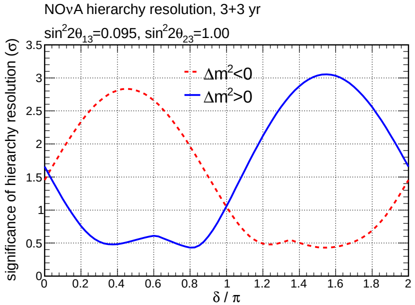


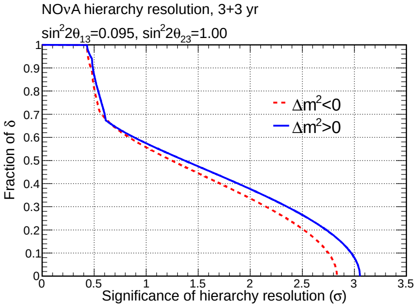


- Assuming tight measurement of θ_{13} from reactors
- Combine with NOνA ν_μ analysis for θ_{23} constraints

- In a degenerate case hierarchy and δ information are coupled
- Octant information mostly independent

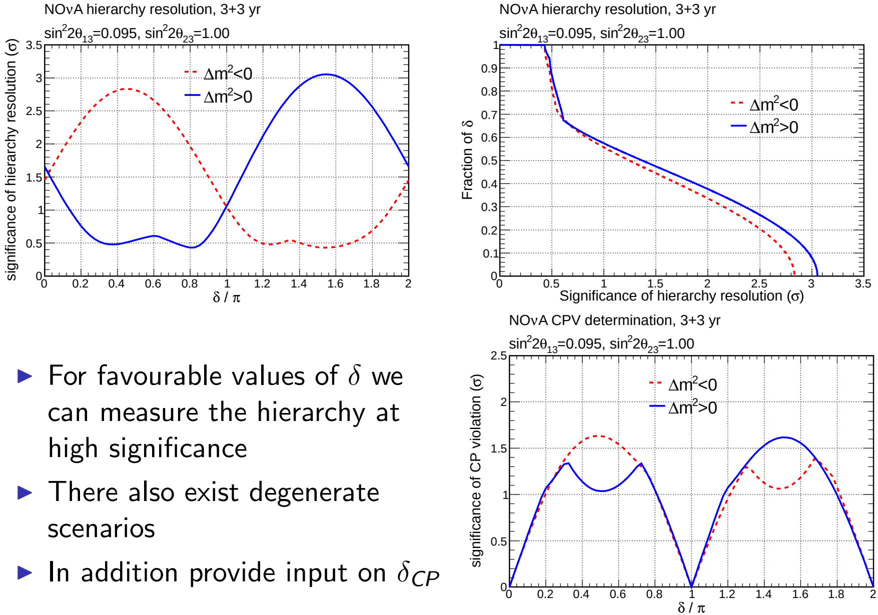
Significance to resolve hierarchy/discover CPV





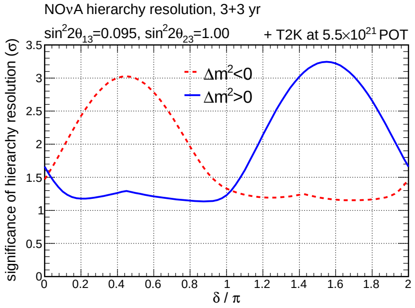
- For favourable values of δ we can measure the hierarchy at high significance
- There also exist degenerate scenarios

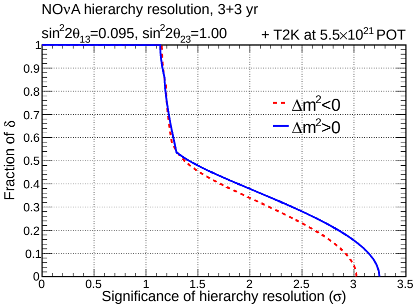
Significance to resolve hierarchy/discover CPV

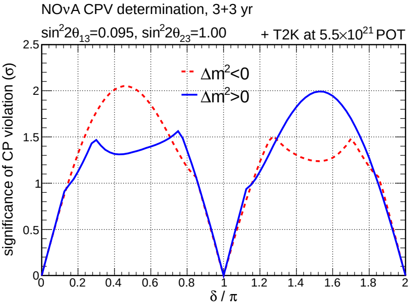


- For favourable values of δ we can measure the hierarchy at high significance
- There also exist degenerate scenarios
- In addition provide input on δ_{CP}

Significance to resolve hierarchy/discover CPV

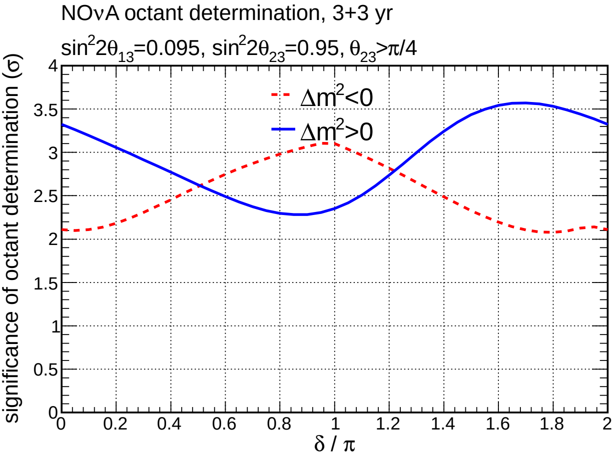






- Matter effects have a much smaller impact on T2K
- Help to break hierarchy degeneracies but not CPV
- Small improvement in best-case scenarios

Octant sensitivity



- 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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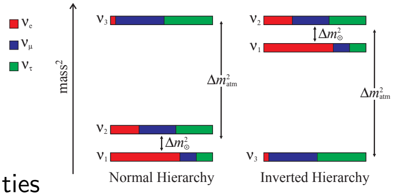
Backup

Neutrino oscillations – 3 flavours

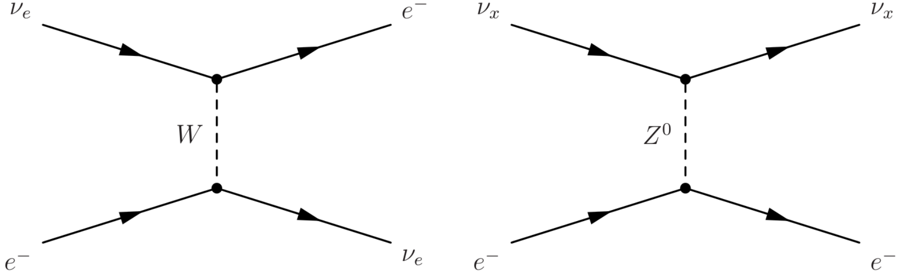
$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

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

- "atmospheric" $\times$ "reactor" $\times$ "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?

$$\Delta m^2_M = \sqrt{(\Delta m^2 \cos 2\theta \mp 2\sqrt{2} E G_F N_e)^2 + (\Delta m^2 \sin 2\theta)^2}$$

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