Results and Prospects from Accelerator Neutrino Experiments

LISHEP: "On a River of Discovery"
Manaus, Amazonas, Brazil
August 9th, 2015

Alex Himmel
Fermilab

Introduction

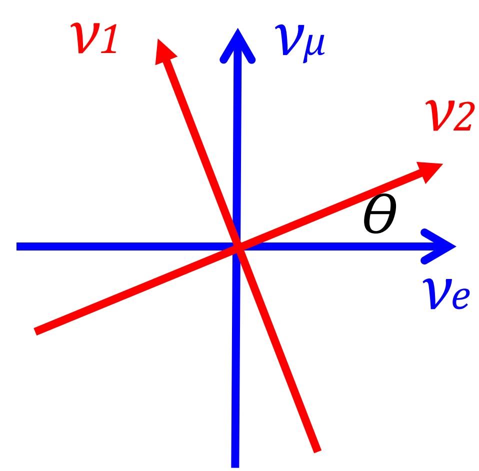
- Brief review of neutrino oscillations
- How to design an accelerator ν experiment
- How to measure oscillations
- Recent results
  - NOνA
  - T2K
  - Opera
- Future experiments
  - DUNE and Hyper-Kamiokande

Neutrino Oscillations

- Create in one flavor (ν_μ), but detect in another (ν_e)

- Each flavor (e, μ) is a superposition of different masses (1, 2)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$



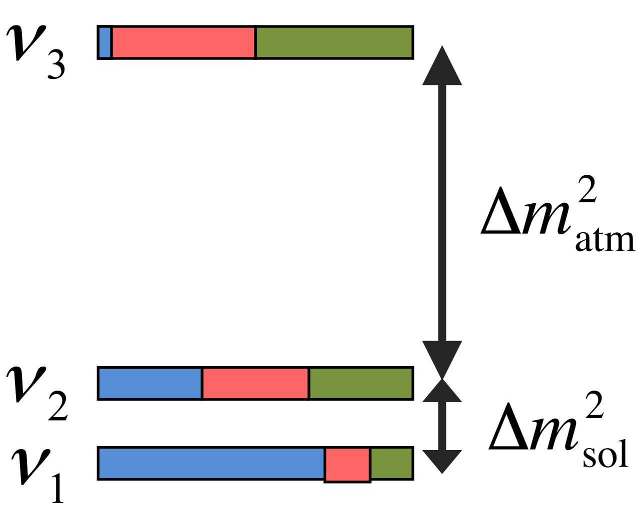
"Mixing Matrix"

The PMNS Mixing Matrix

Flavor

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mass



Pontecorvo

Sov.Phys.JETP 6:429, 1957

Sov.Phys.JETP 26:984-988, 1968

Maki, Nakagawa, Sakata

Prog.Theor.Phys. 28, 870 (1962)

What We Know

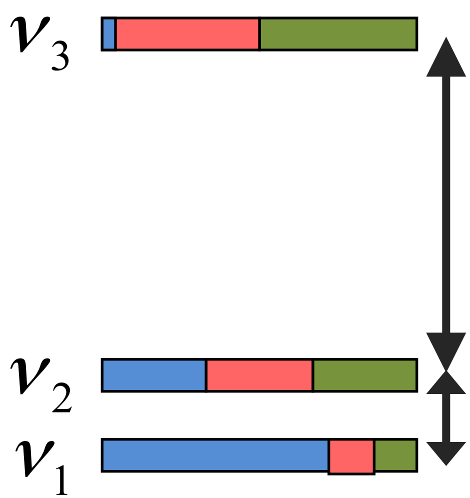
atmospheric accelerator ν_μ	short baseline reactor accelerator ν_e	solar long baseline reactor

Flavor

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mass

$\theta_{23} \approx 45°$ $\theta_{13} \approx 9°$ $\theta_{12} \approx 34°$



$\Delta m^2_{atm} \approx 2 \times 10^{-3}$ eV^2

$\Delta m^2_{sol} \approx 8 \times 10^{-5}$ eV^2

What We Don't Know

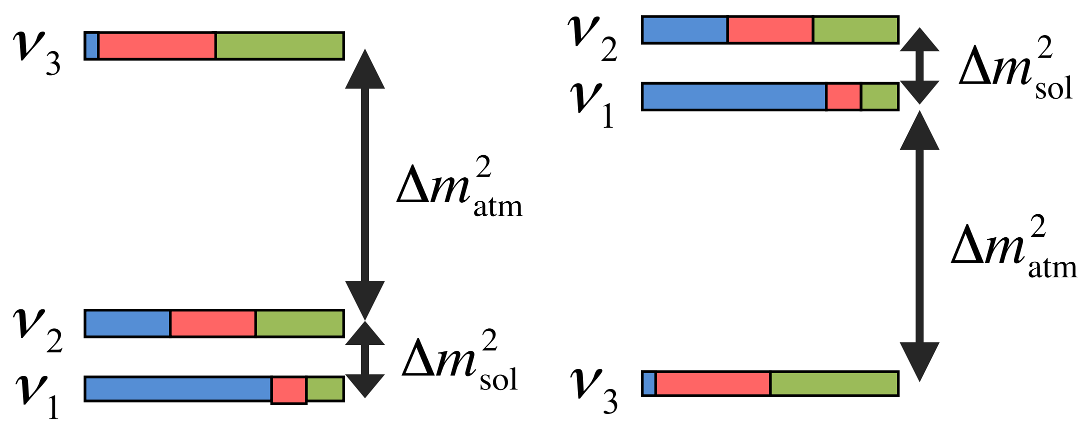
atmospheric — accelerator ν_μ | short baseline reactor — accelerator ν_e | solar — long baseline reactor

Flavor

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mass

Phase δ_{CP}, and potentially CP violation



The "mass hierarchy," the sign of the atmospheric Δm^2

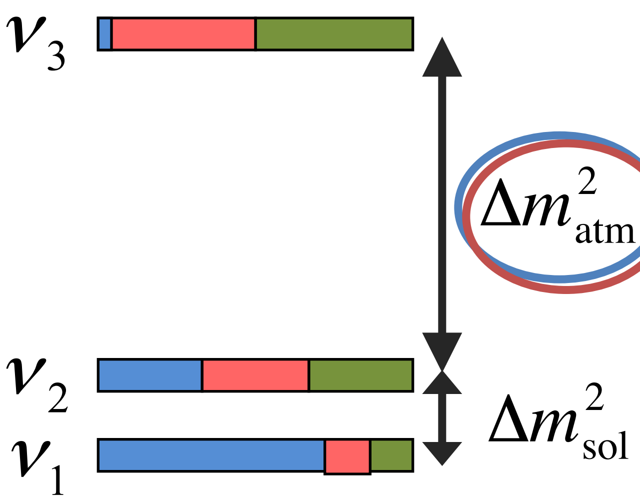
Oscillation Physics with Accelerator ν's

atmospheric / accelerator ν_μ — short baseline reactor / accelerator ν_e — solar / long baseline reactor

Flavor

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mass



ν_μ Disappearance: θ_{23}, $|\Delta m^2{}_{\text{atm}}|$

$\nu_\mu \rightarrow \nu_e$ Appearance: θ_{13}, δ_{CP}

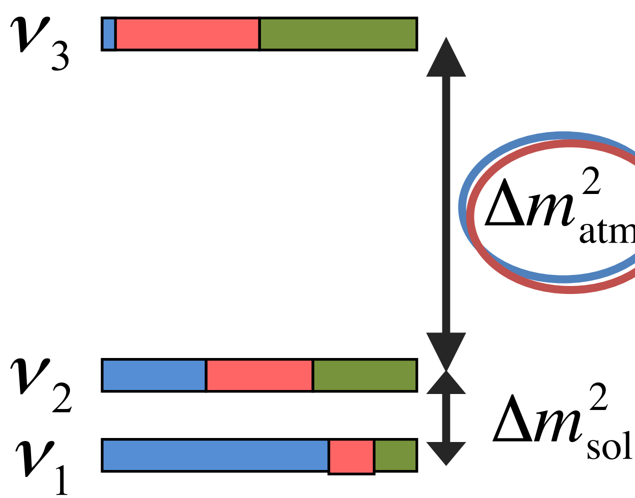
Oscillation Physics with Accelerator ν's

atmospheric / accelerator ν_μ — short baseline reactor / accelerator ν_e — solar / long baseline reactor

Flavor

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mass



Why? L and E

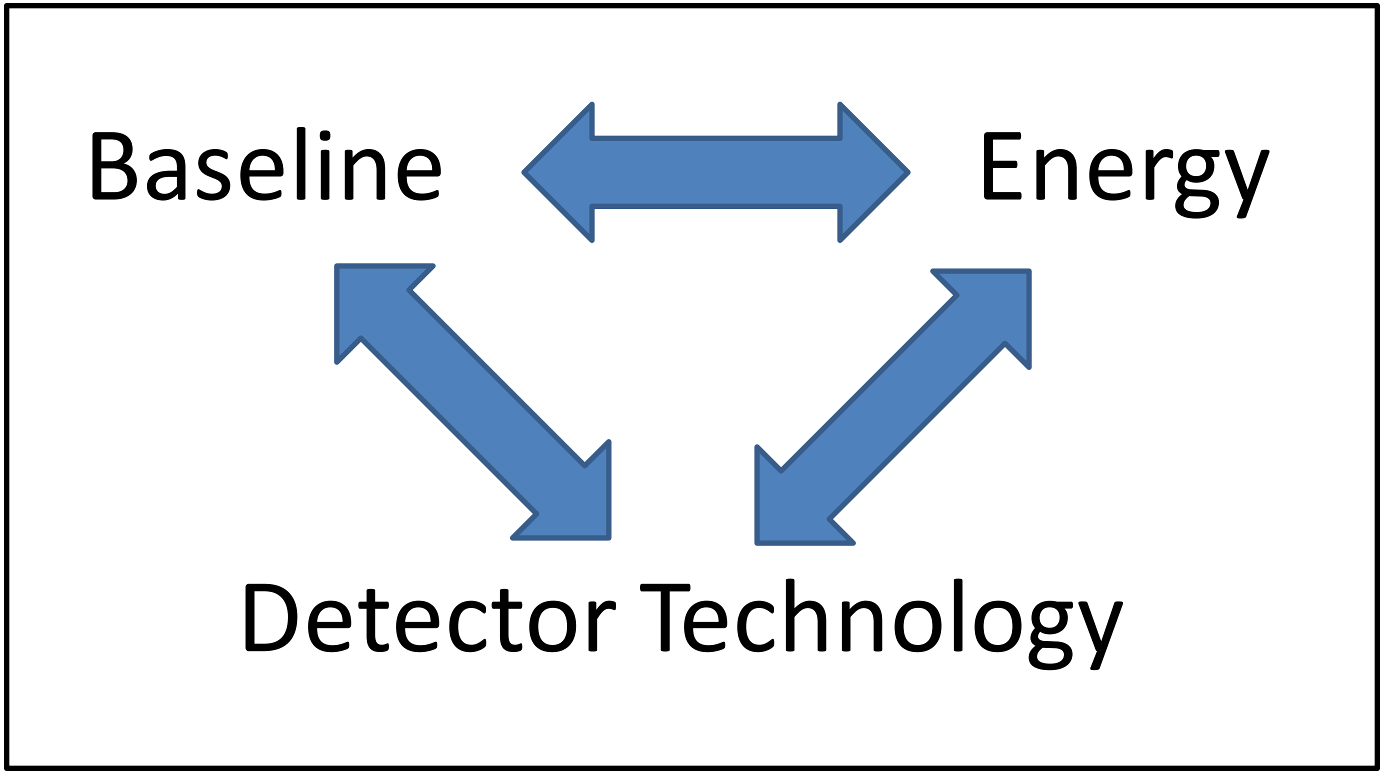
Accelerators produce $E_\nu \sim 1$ GeV

$$L_{\text{osc}} = 2\pi E / \Delta m^2$$

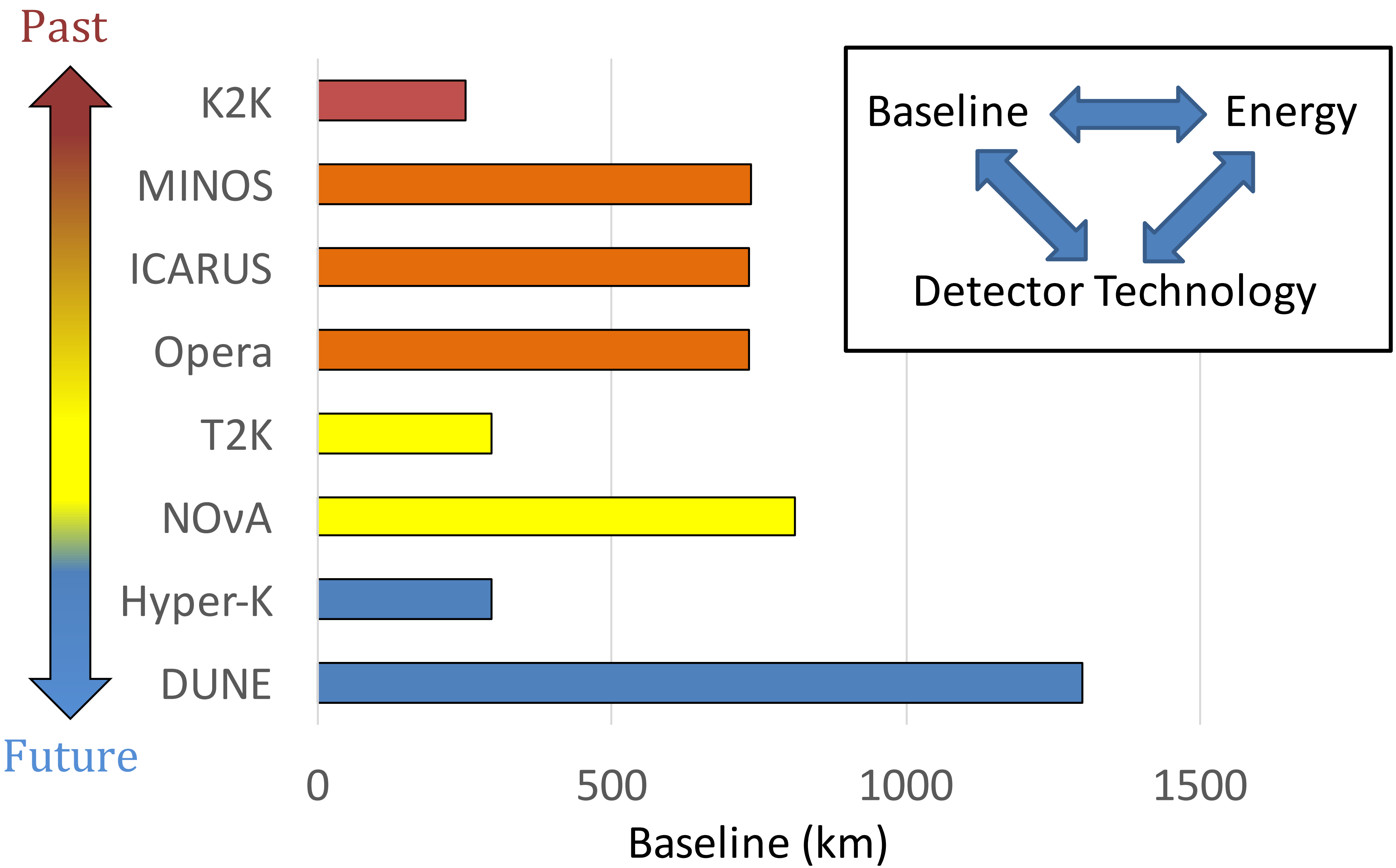
Atm. Oscillations: $L \sim 500$ km

Sol. Oscillations: $L \sim 16{,}000$ km

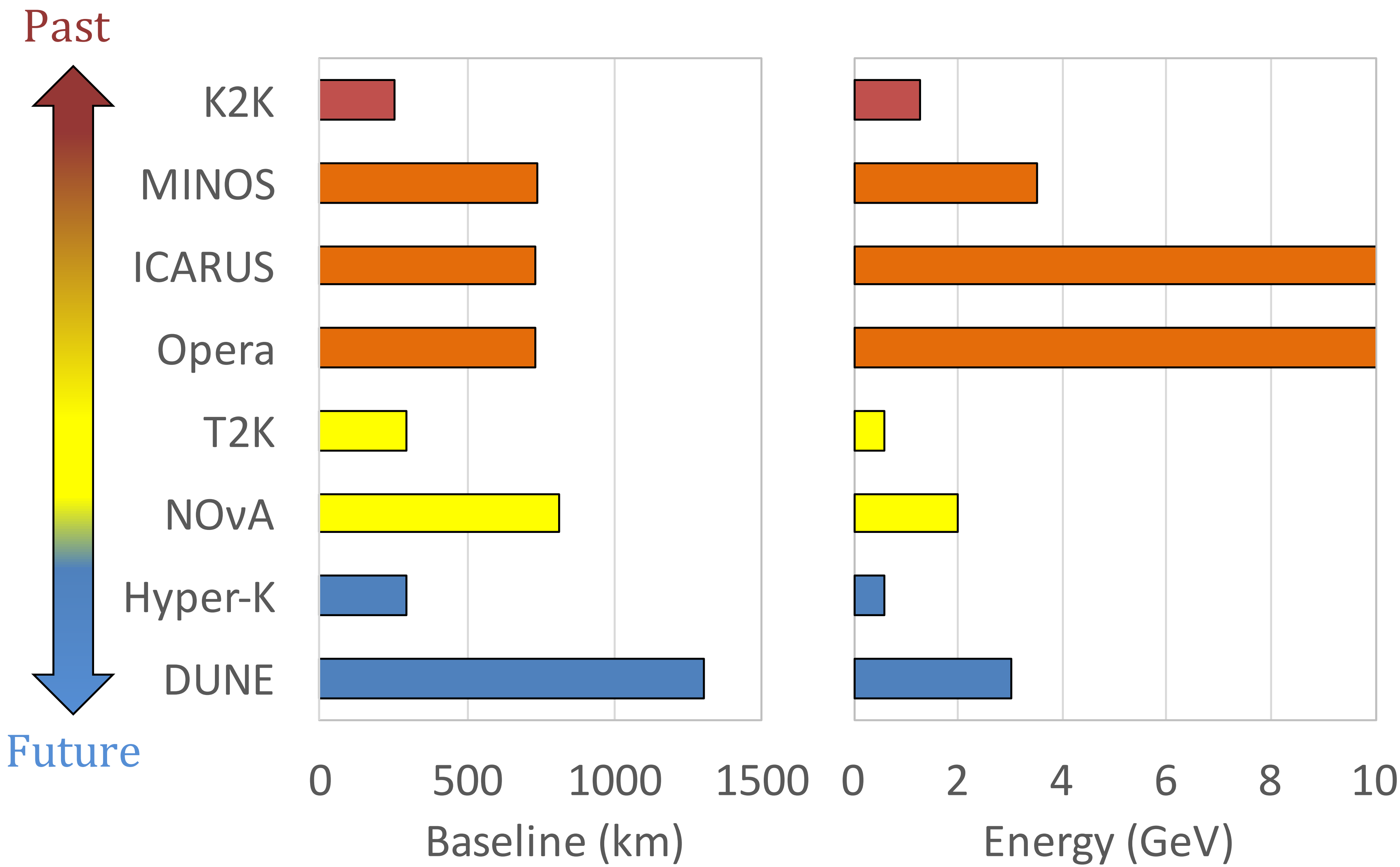
Designing an Accelerator ν Experiment



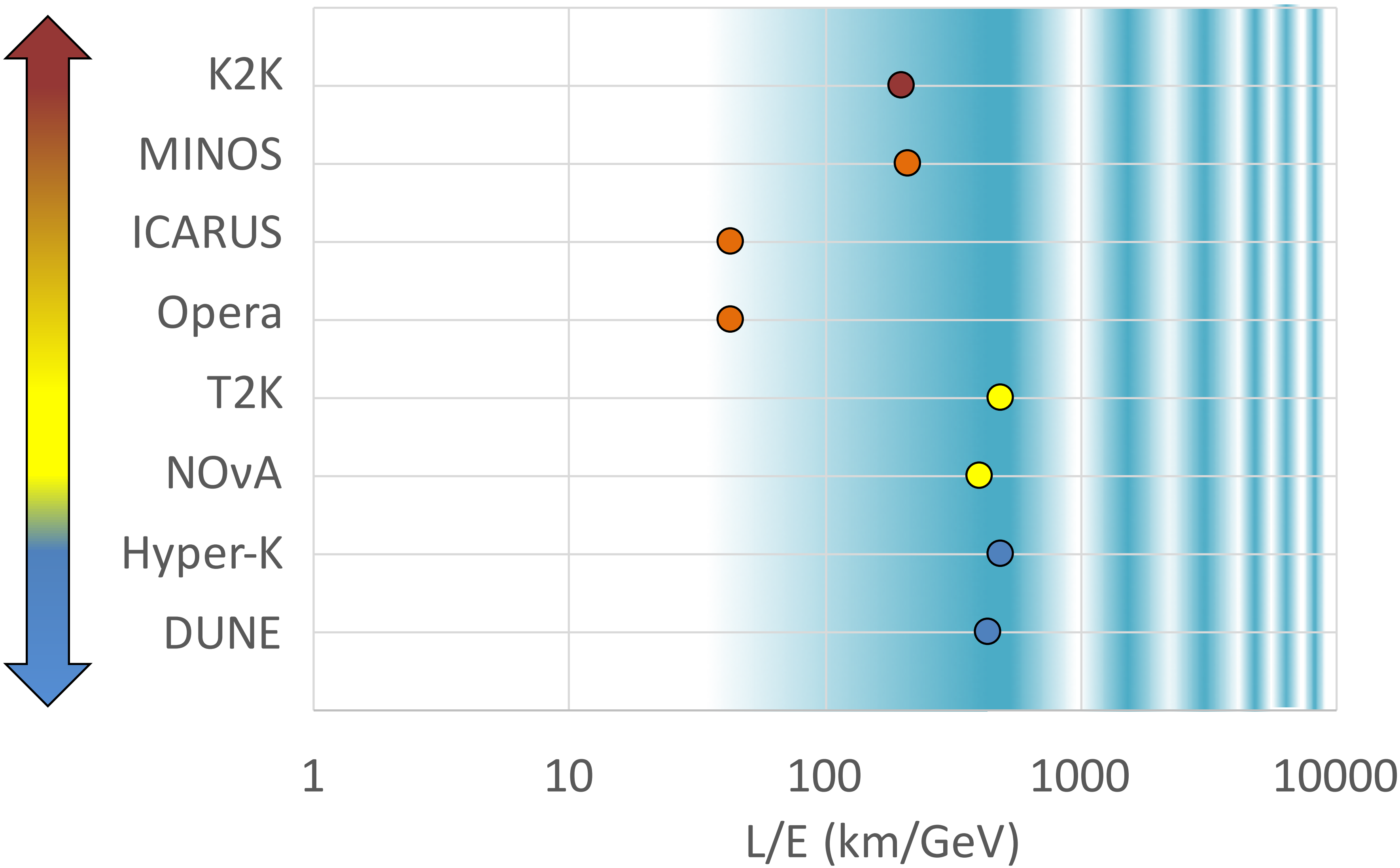
Designing an Accelerator ν Experiment



Designing an Accelerator ν Experiment



Designing an Accelerator ν Experiment



Designing an Accelerator ν Experiment

T2K

NOνA

J-PARC

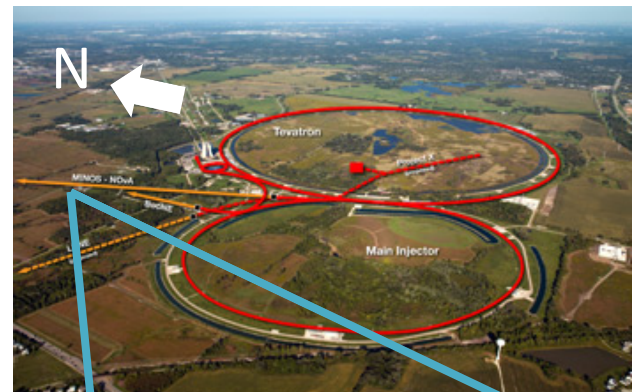
Fermilab

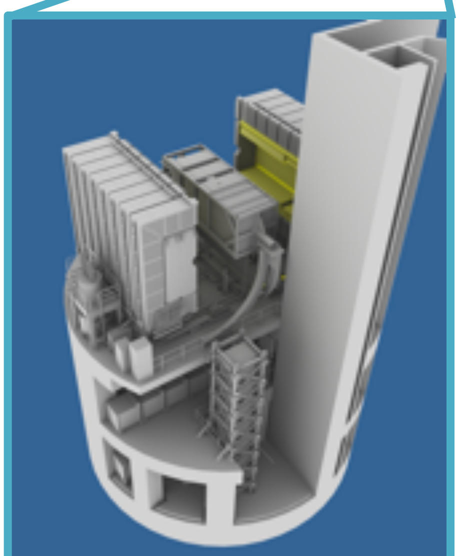
A neutrino beam from a proton accelerator

Designing an Accelerator ν Experiment

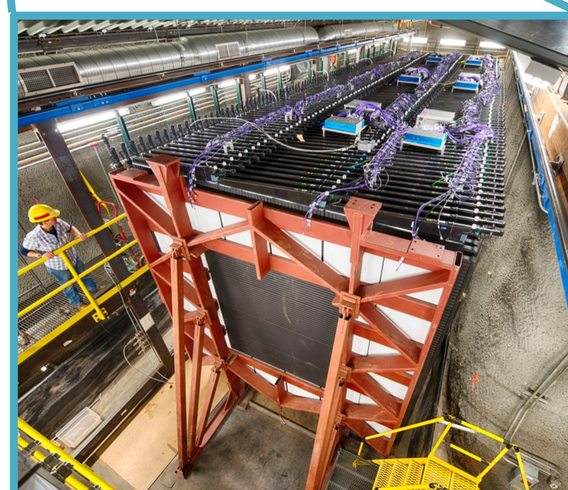
T2K

NOνA





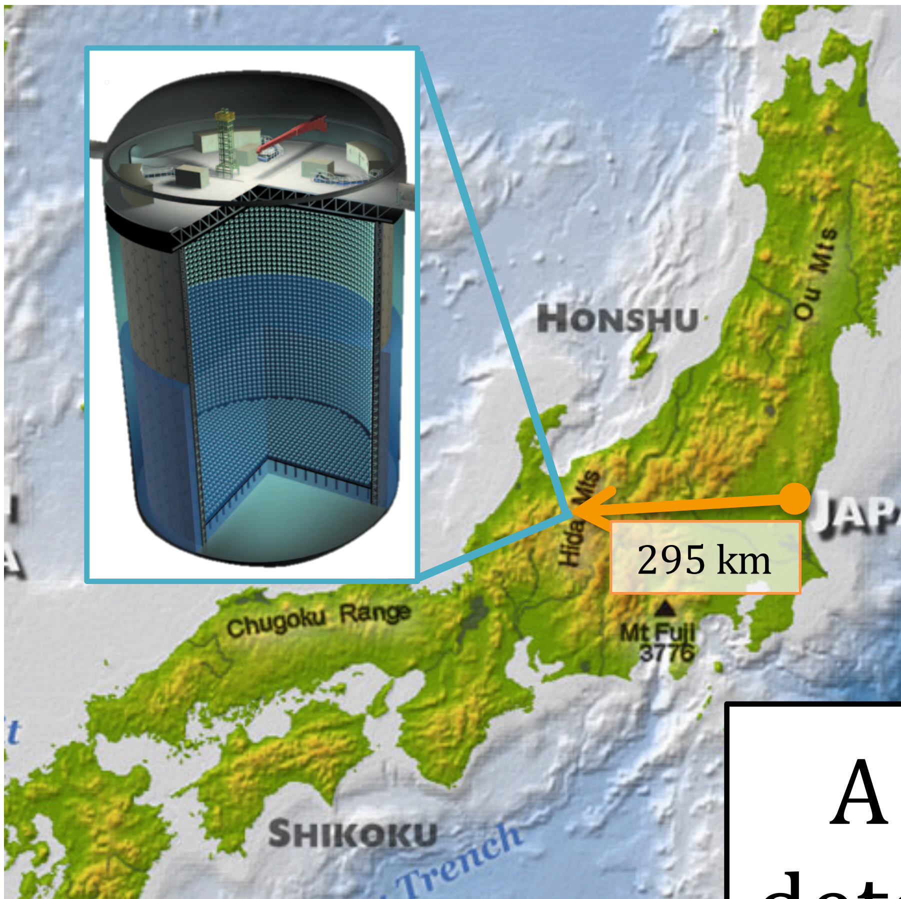
A near detector

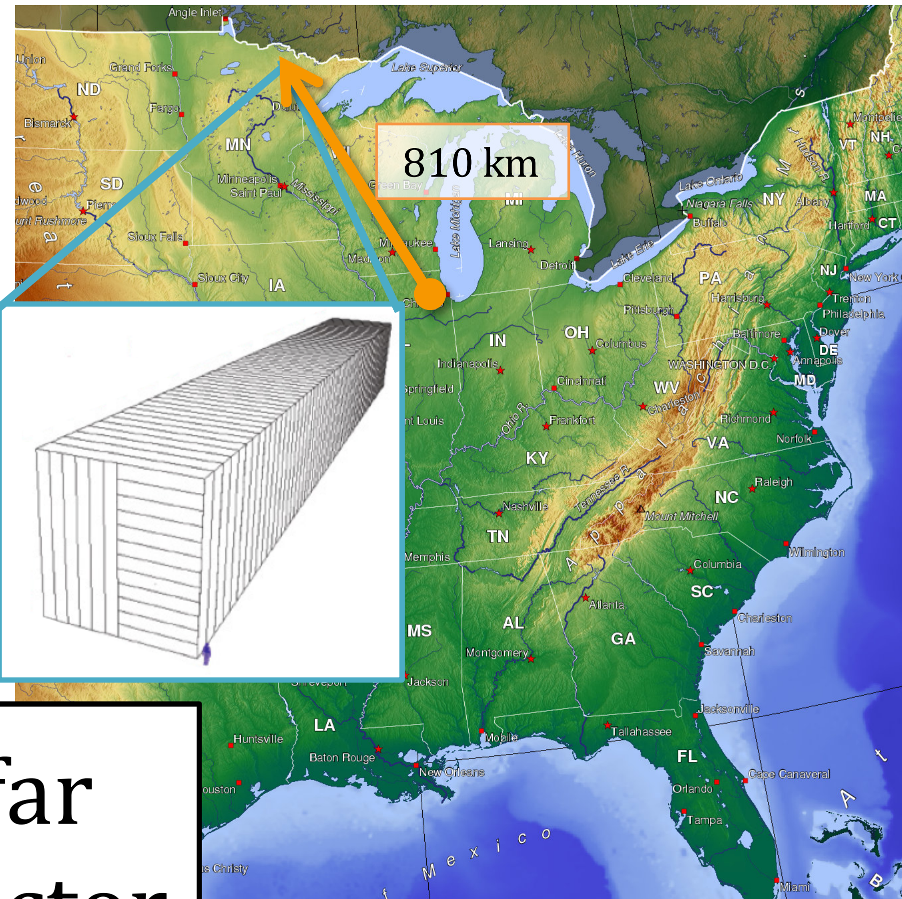


Designing an Accelerator ν Experiment

T2K

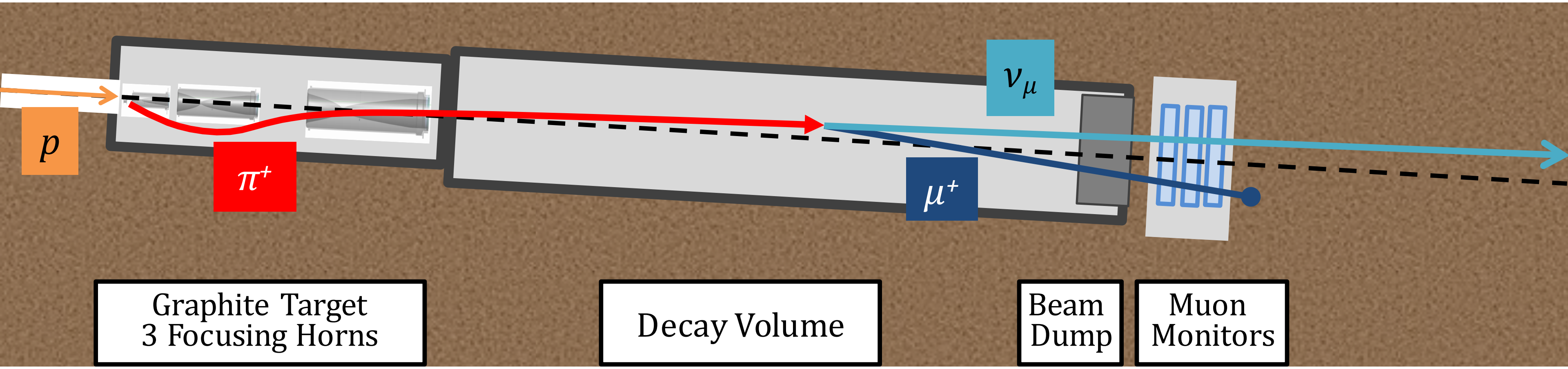
NOνA



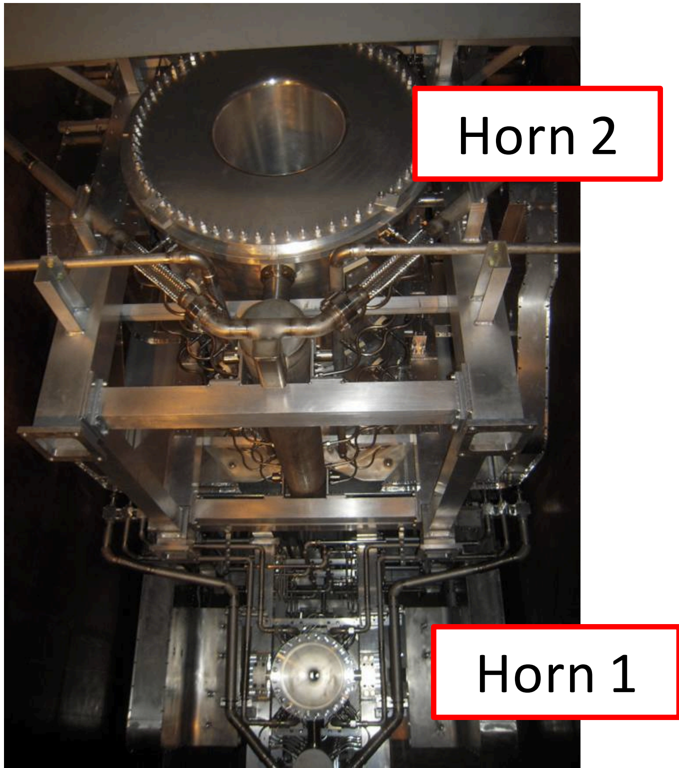


A far detector

Making a Neutrino Beam

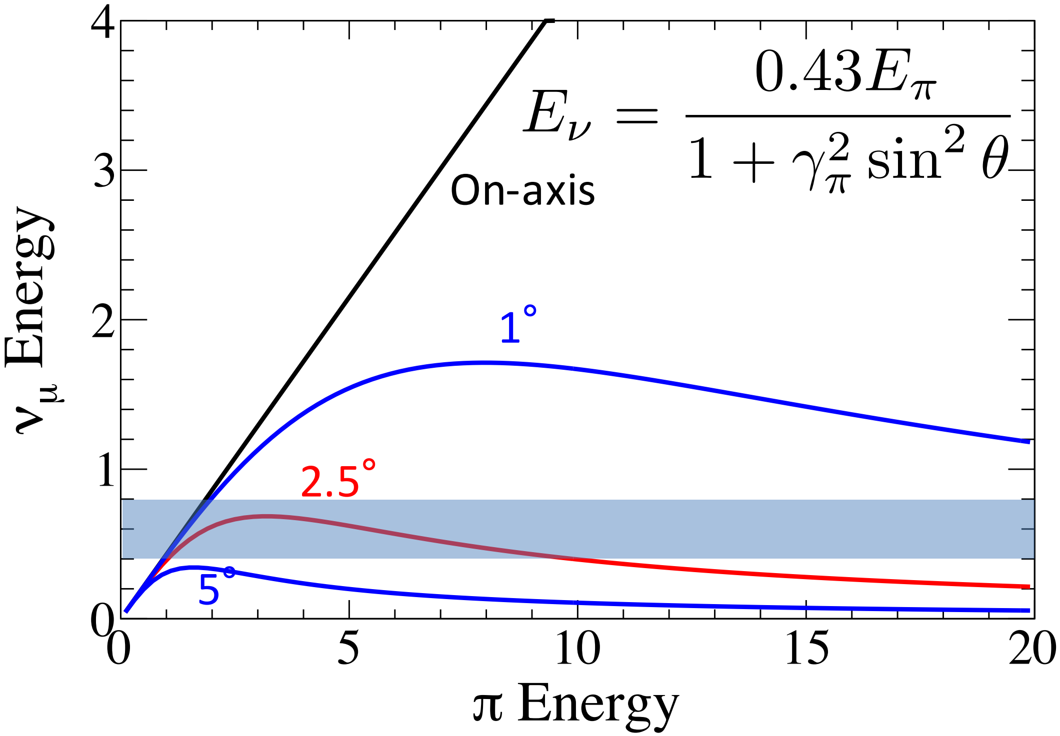


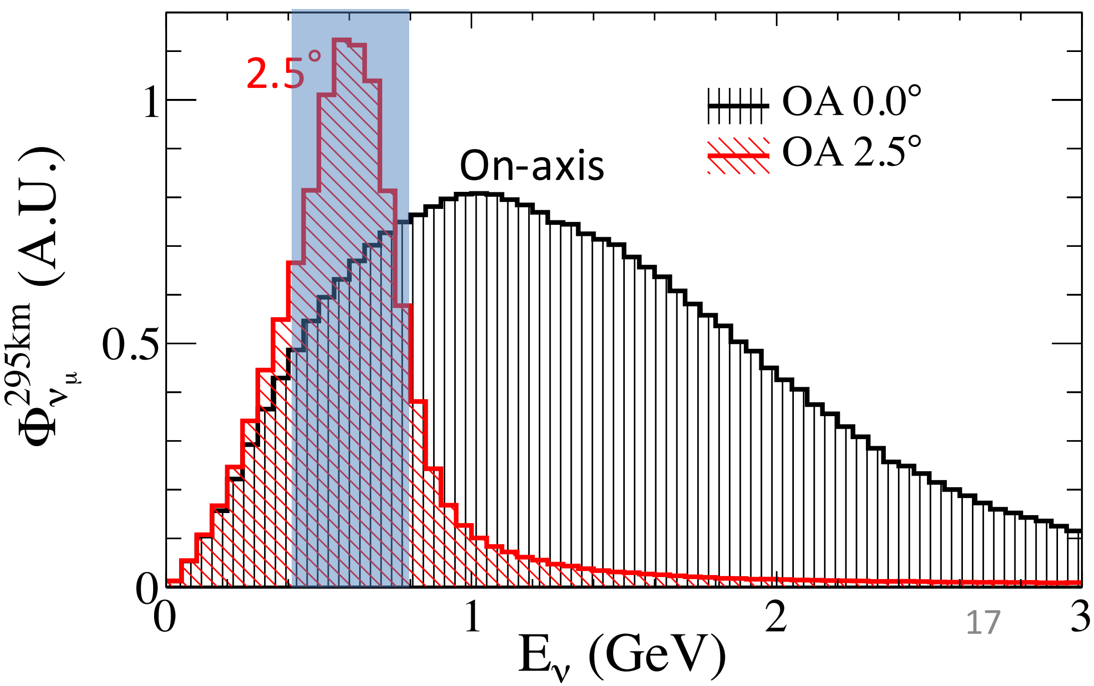
- *p* beam on graphite target to produce $\pi^\pm$, $K^\pm$
- Focus charged mesons
  - 3 Large electromagnetic "horns" act like lenses
  - 250,000 amps every ~2 seconds
- Mesons decay to produce a beam of neutrinos



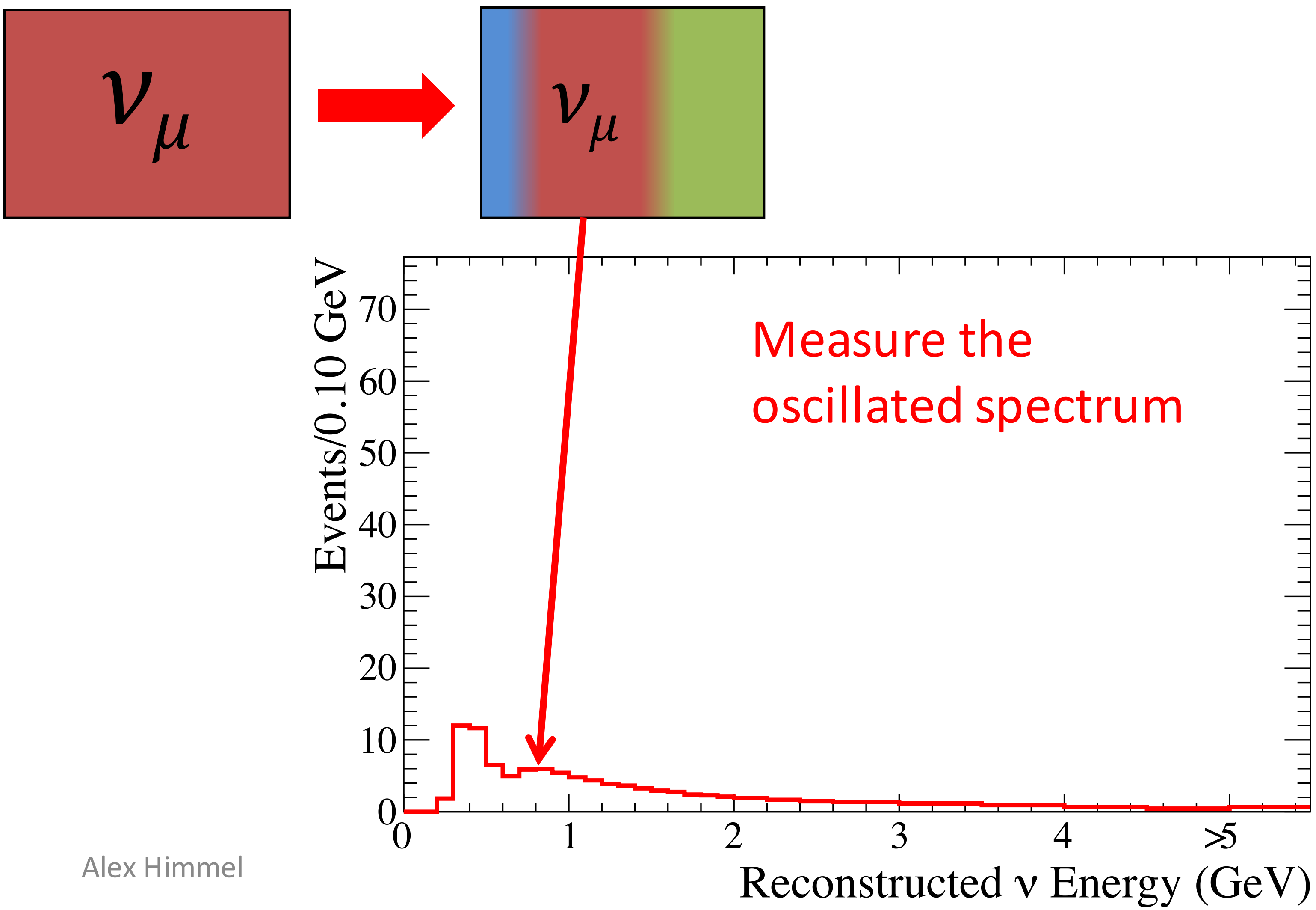
On- vs. Off-axis

- 2.5° off-axis angle
  - 2-body π decay gives narrow range of ν energies
- Tune peak energy for oscillations
  - More events at max oscillations
  - Fewer backgrounds from high energy

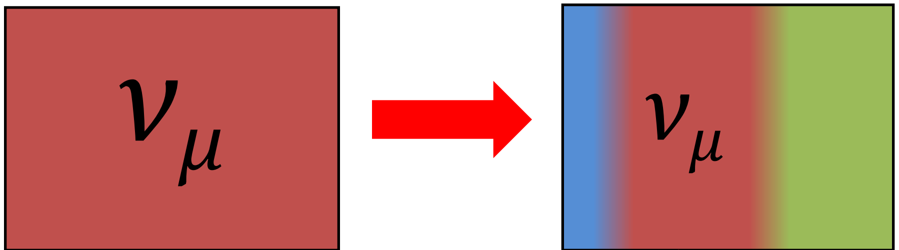




How We Measure Oscillations: Disappearance

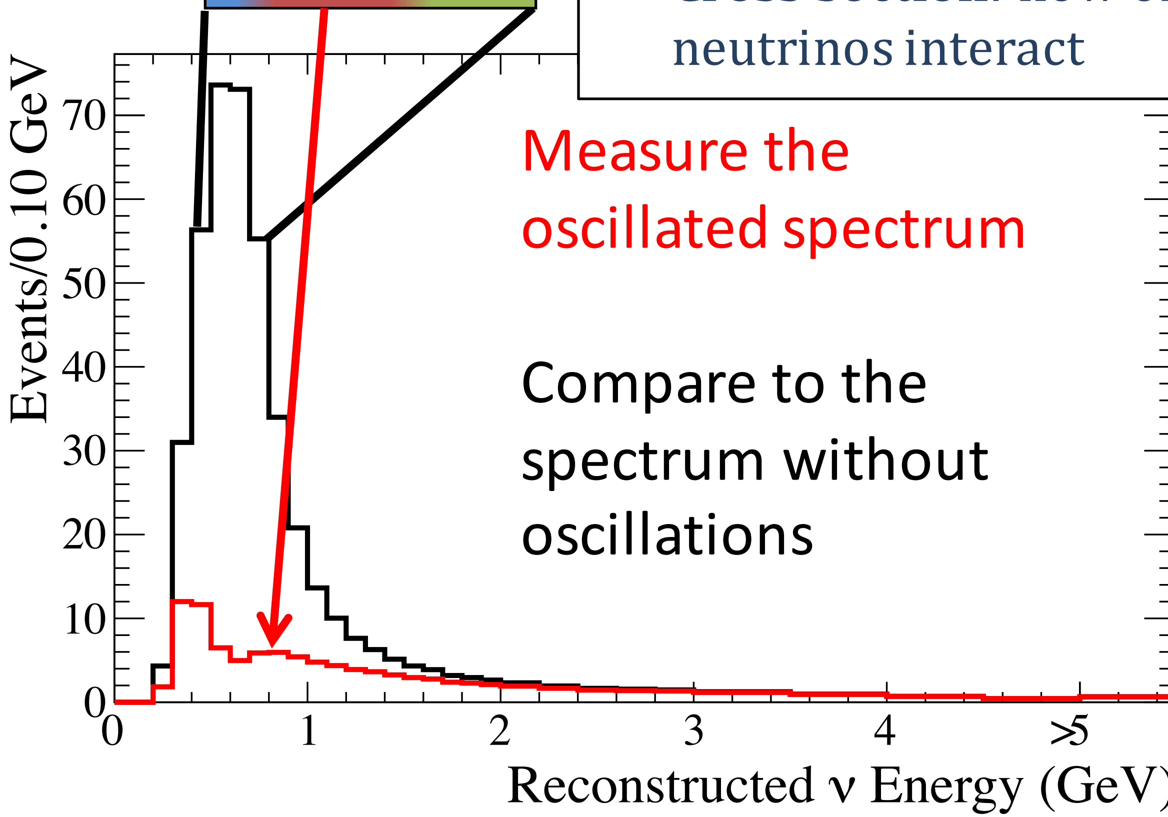


How We Measure Oscillations: Disappearance



Significant uncertainties in the prediction

- **Flux**: number of neutrinos produced
- **Cross section**: how often the neutrinos interact



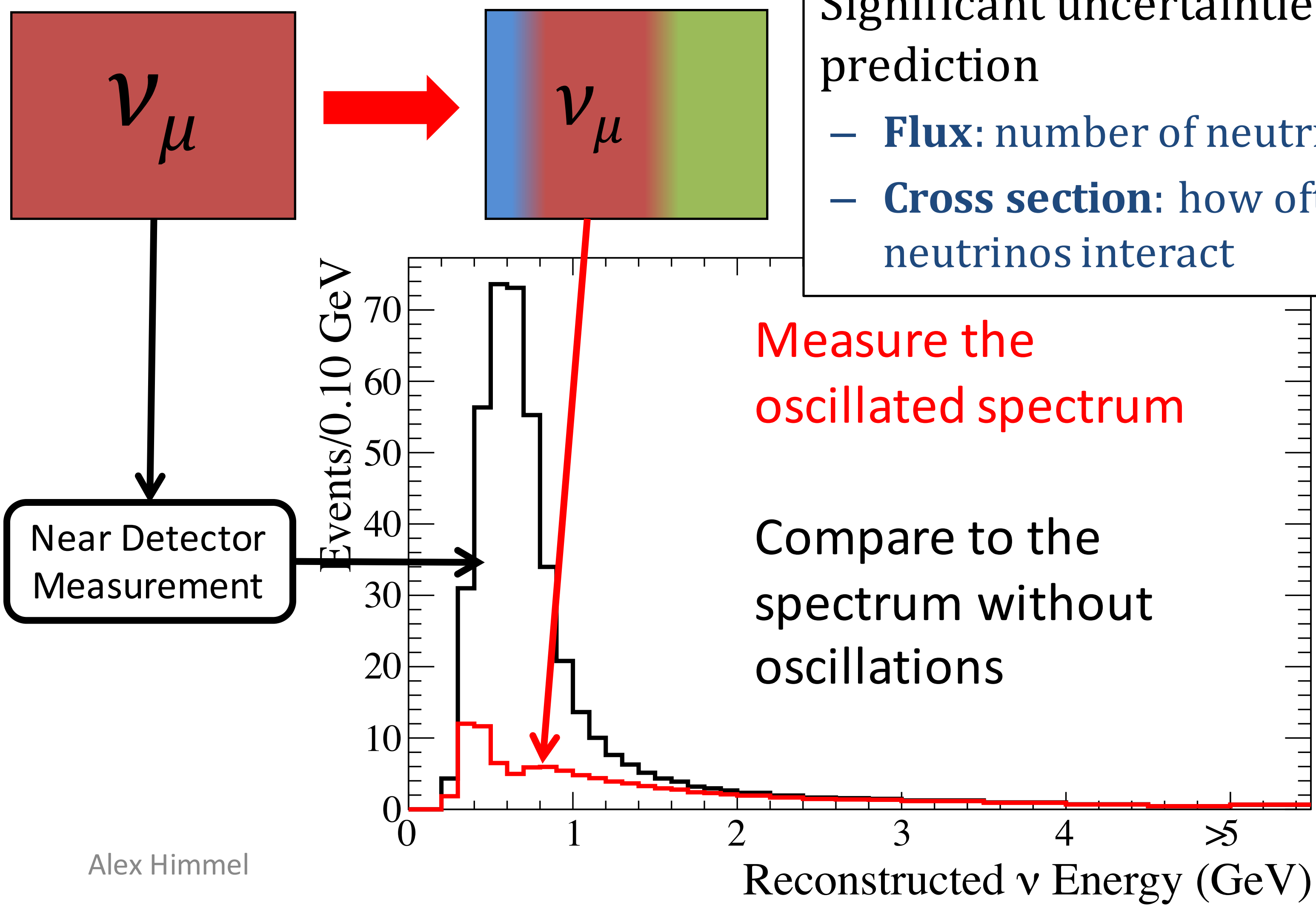
Measure the oscillated spectrum

Compare to the spectrum without oscillations

How We Measure Oscillations: Disappearance

Significant uncertainties in the prediction

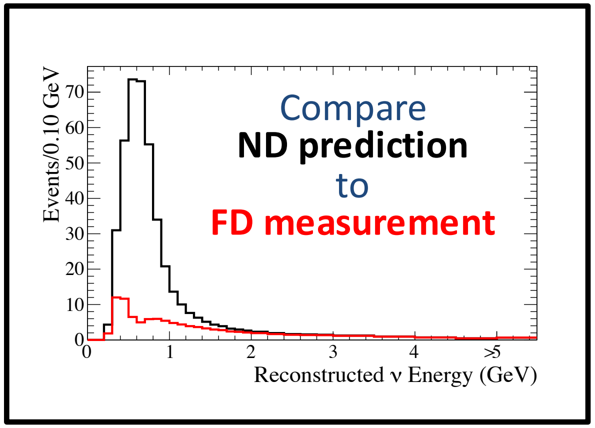
- **Flux**: number of neutrinos produced
- **Cross section**: how often the neutrinos interact

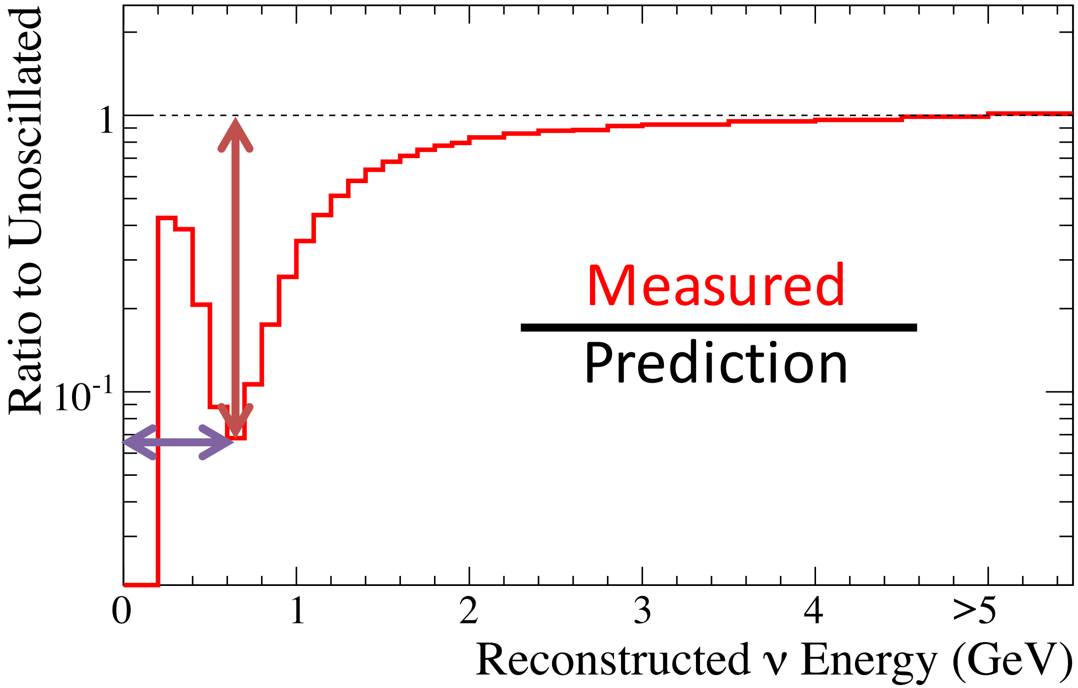


How We Measure Oscillations: Disappearance

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \left(\cos^4\theta_{13} \sin^2 2\theta_{23} + \sin^2\theta_{23} \sin^2 2\theta_{13} \right) \sin^2\left(\frac{\Delta m^2 L}{4E_\nu} \right)$$

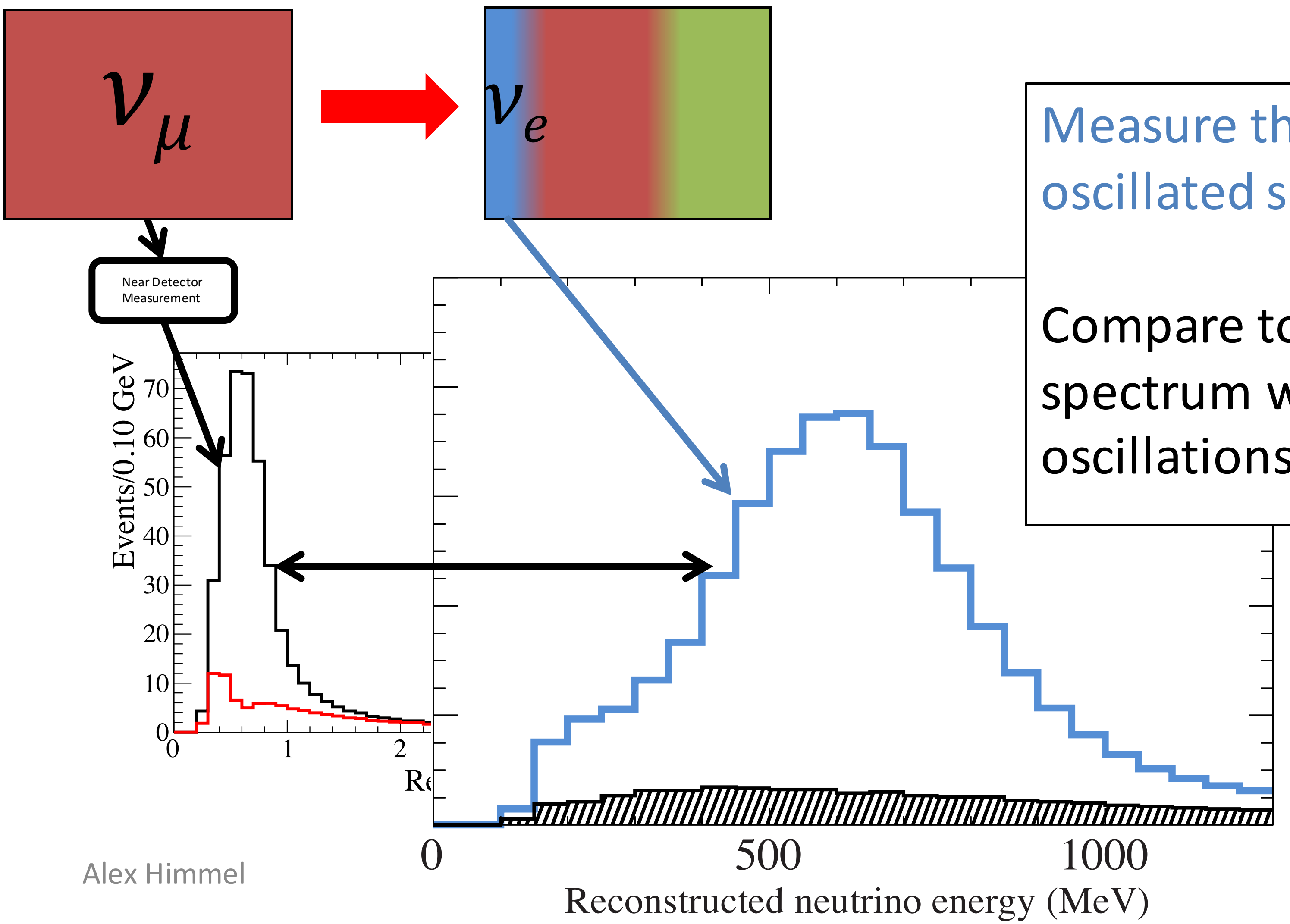
PDG 2013





Alex Himmel

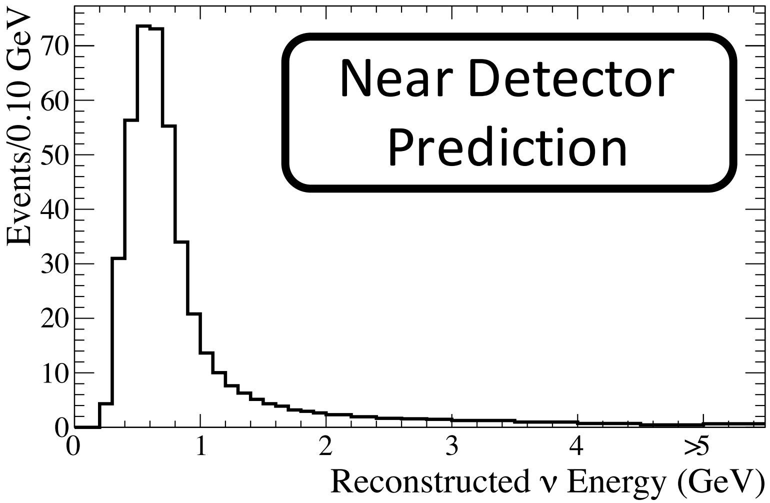
How We Measure Oscillations: Appearance



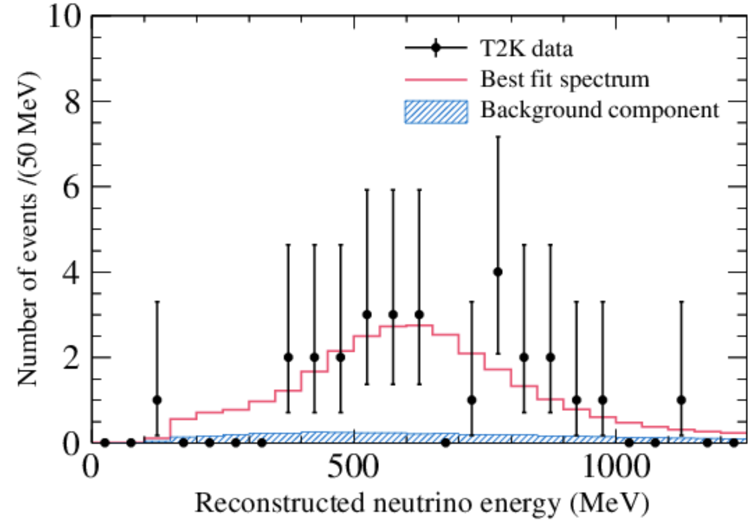
Measure the oscillated spectrum

Compare to the spectrum without oscillations

How We Measure Oscillations: Appearance



+



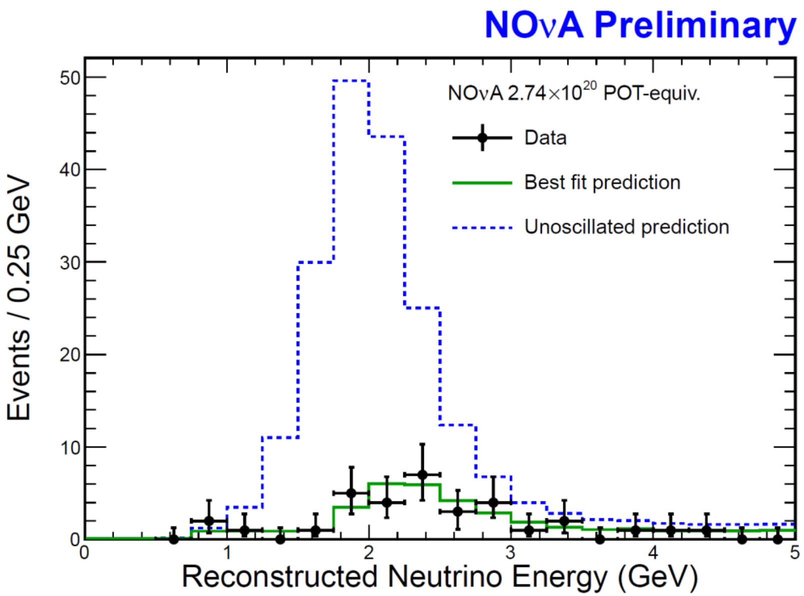
Combine ***ν_e* appearance sample** with near detector **unoscillated prediction** to extract oscillation parameters.

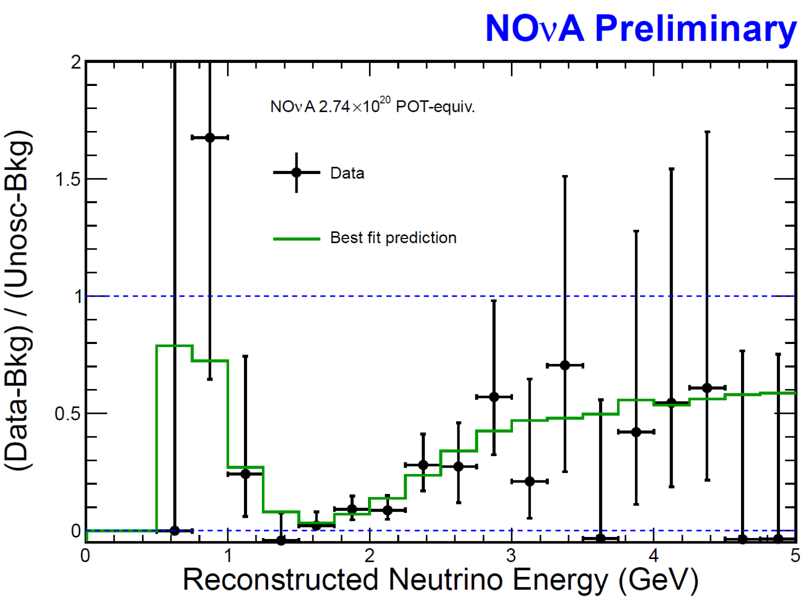
$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{32}L}{4E_\nu}\right)\left(1 + \frac{4\sqrt{2}G_F n_e E}{\Delta m^2_{31}}(1 - 2\sin^2\theta_{13})\right)$$

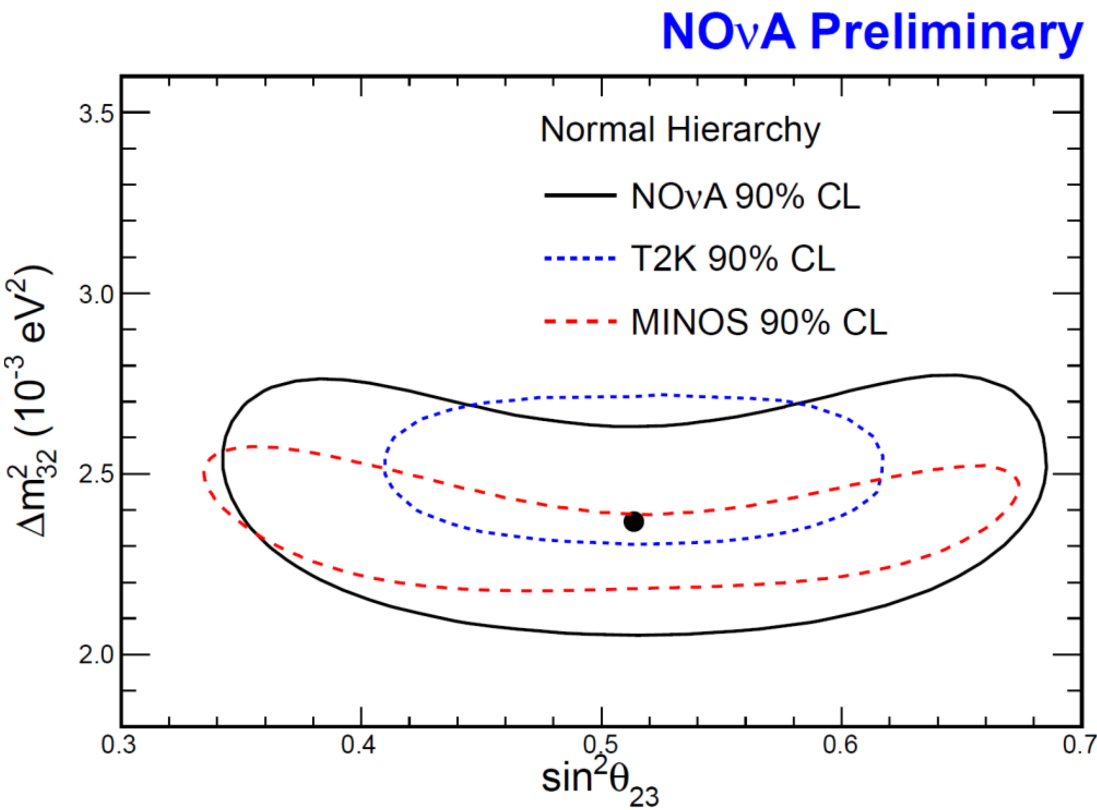
$$- \sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}\cos\theta_{13}\sin\delta\sin^2\left(\frac{\Delta m^2_{32}L}{4E_\nu}\right)\sin^2\left(\frac{\Delta m^2_{21}L}{4E_\nu}\right)$$

CP violation   Mass Hierarchy

NOvA ν_μ Disappearance





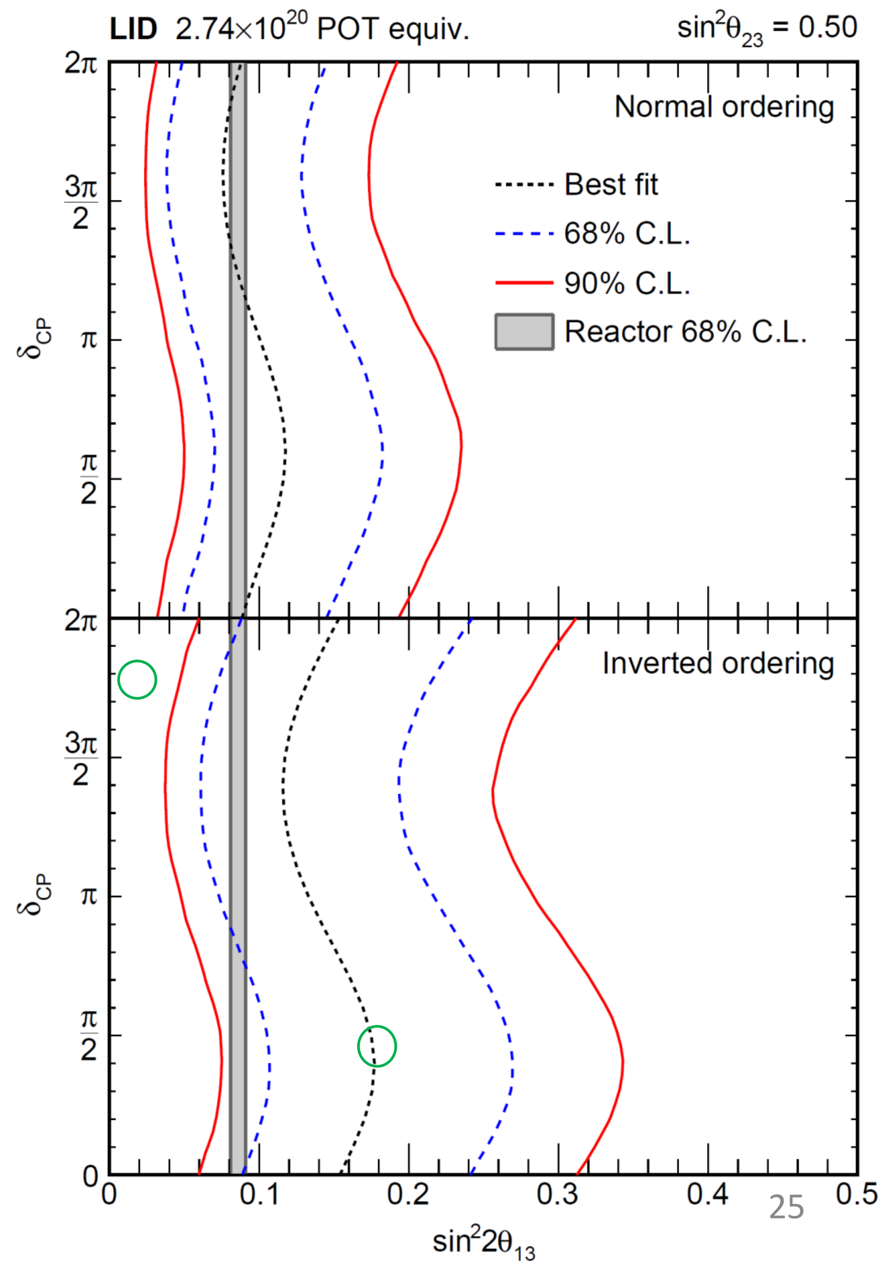


- Consistent with previous measurements.
- Interesting with only <8% of planned exposure.

NOvA ν_e Appearance

Data		6
Background-only		0.9
IH	$\delta = +\pi/2$	3.1
NH	$\delta = -\pi/2$	6.5

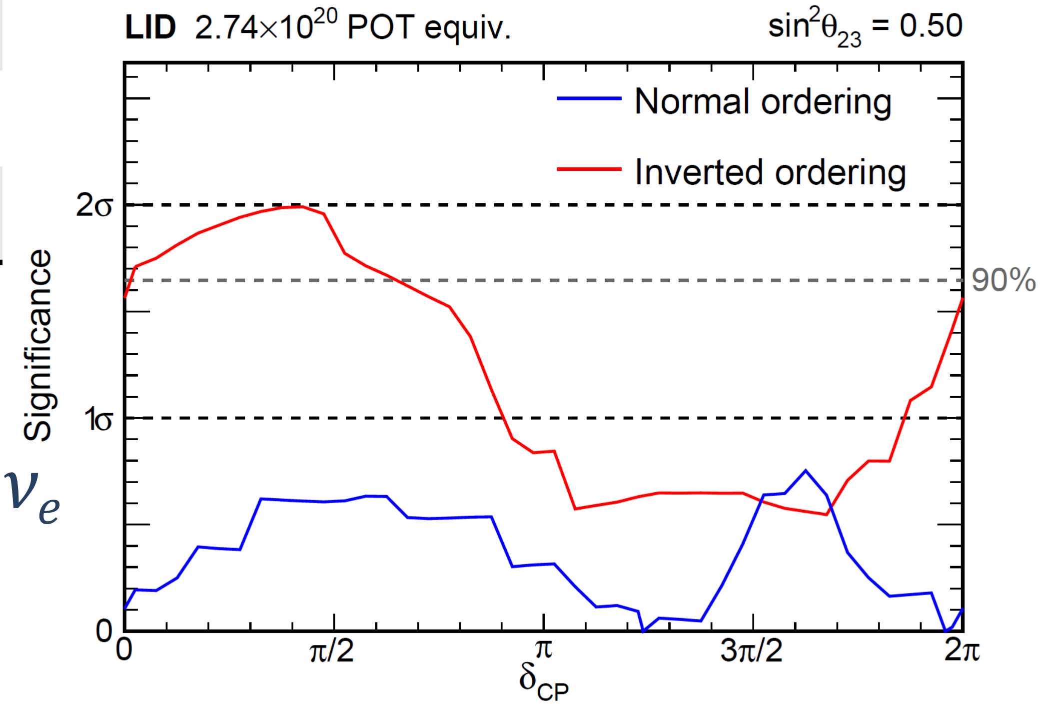
- 6 events observed
  - 3.3σ significance for ν_e appearance.
- Limited sensitivity to δ and MH so far



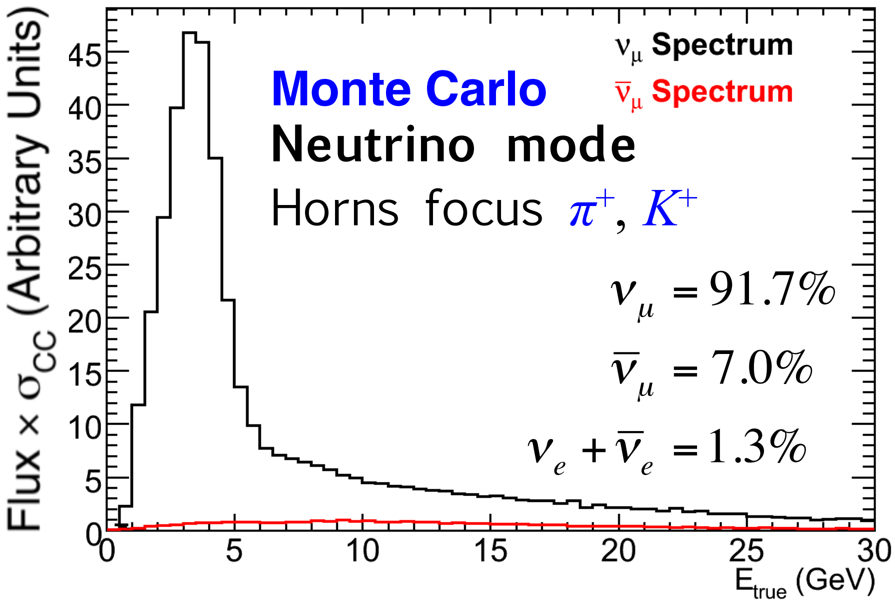
NOvA ν_e Appearance

Data		6
Background-only		0.9
IH	δ = +π/2	3.1
NH	δ = -π/2	6.5

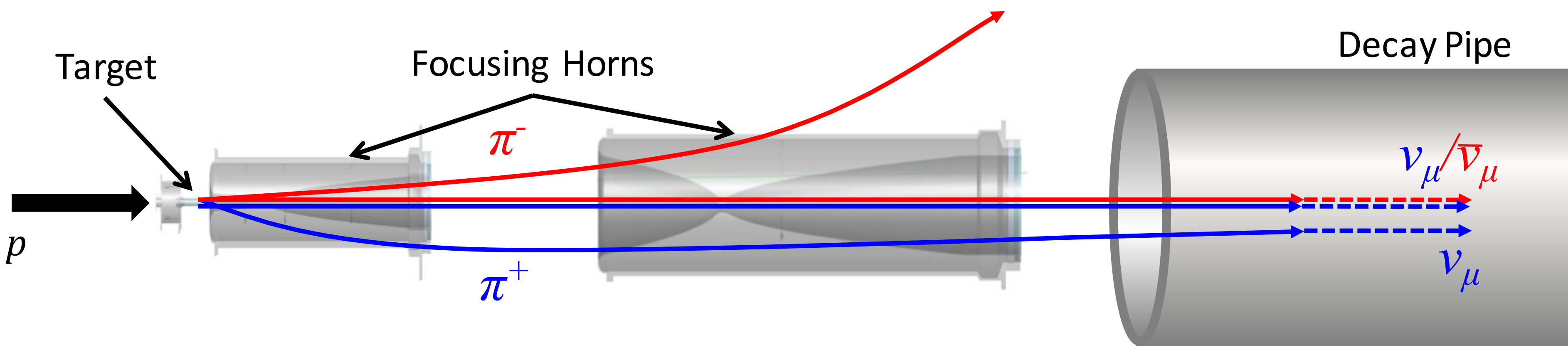
- 6 events observed
  - 3.3σ significance for ν_e appearance.
- Limited sensitivity to δ and MH so far



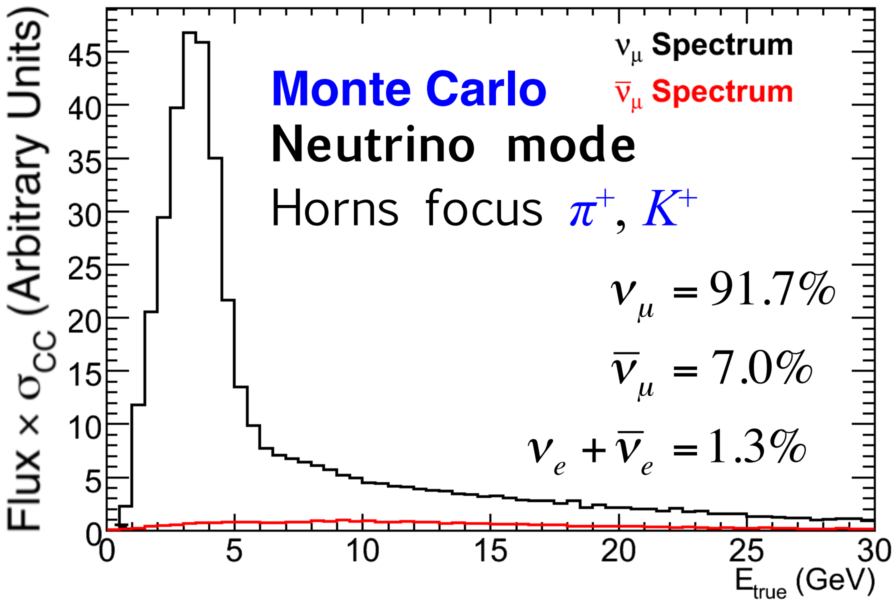
Neutrinos and Antineutrinos

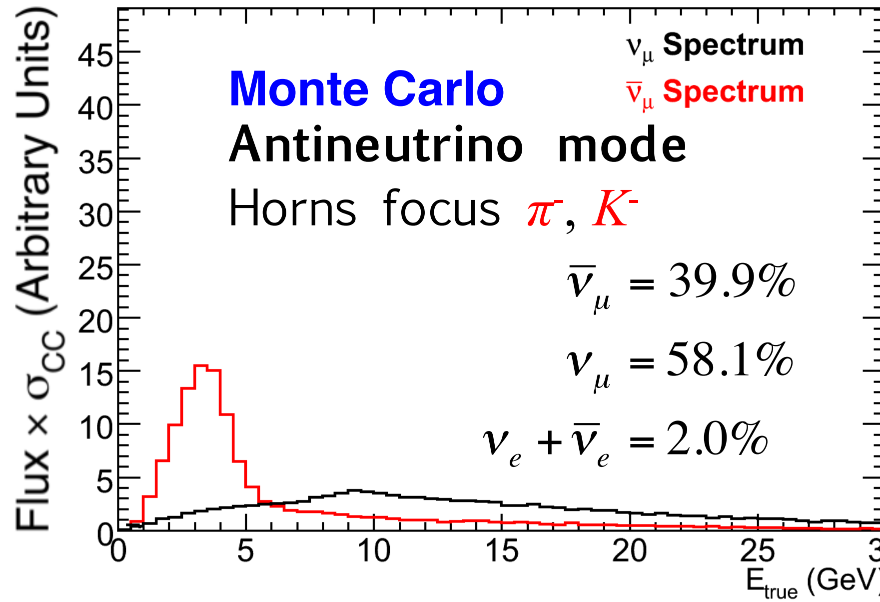


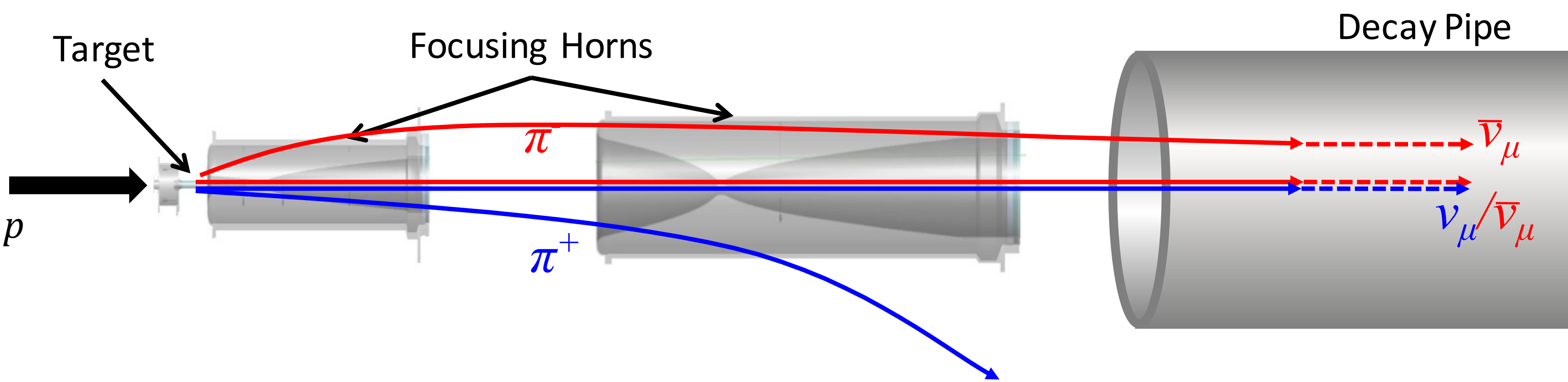
- Example from MINOS
  - On-axis Numi beam



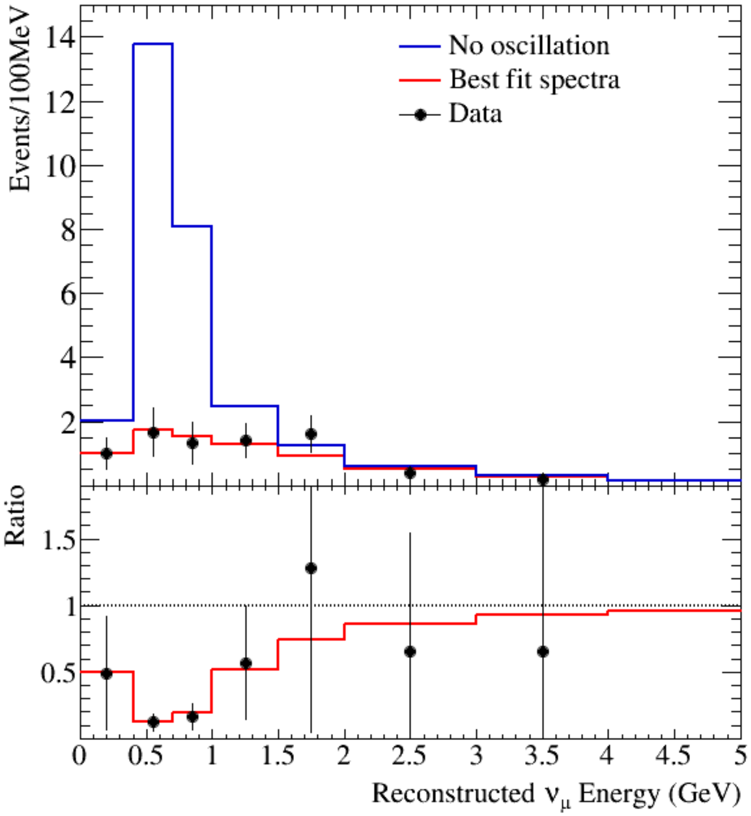
Neutrinos and Antineutrinos

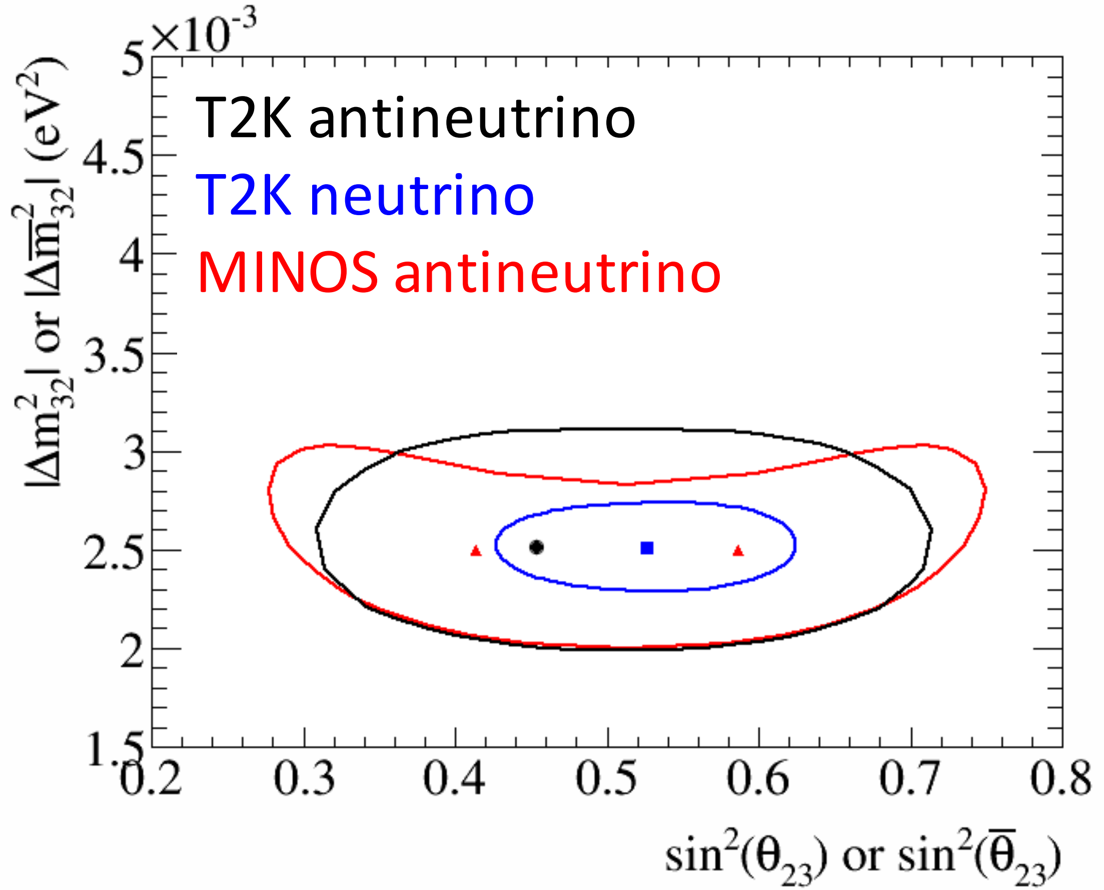






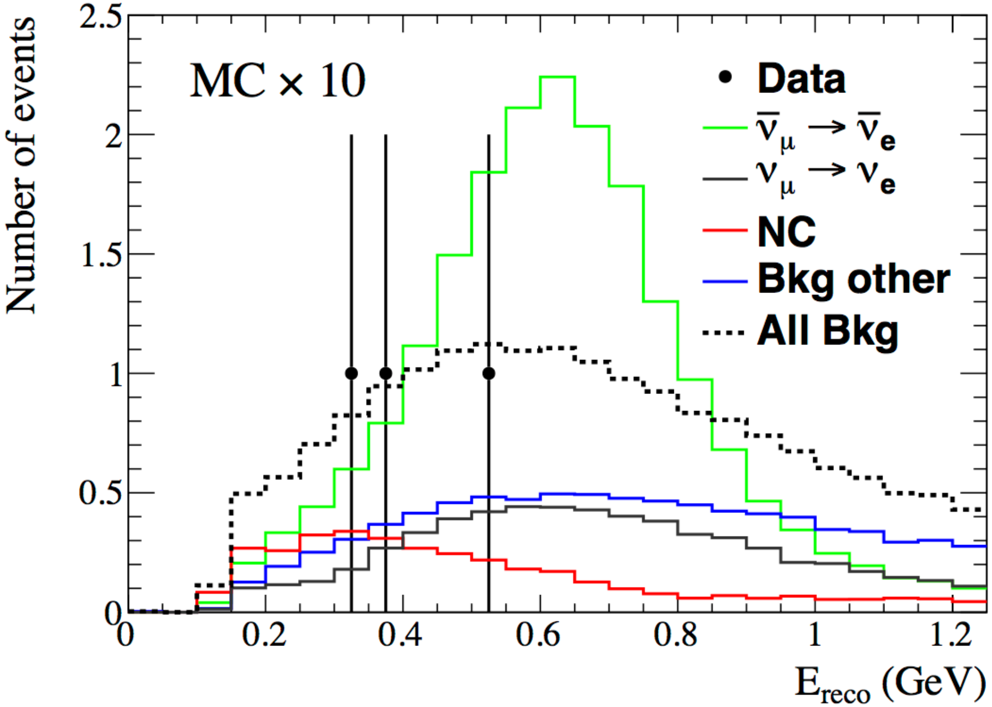
T2K anti-ν_μ Disappearance





- Consistent with T2K neutrino disappearance and MINOS antineutrino disappearance.

T2K anti-ν_e Appearance



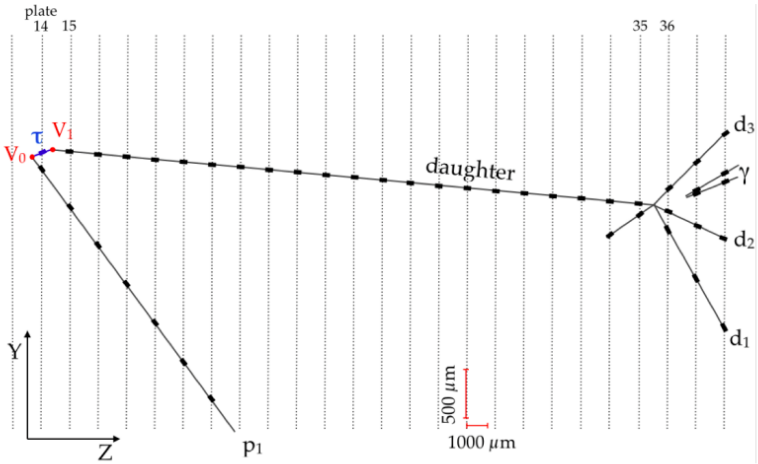
Data		3
Background-only		1.6
IH	δ = +π/2	5.5
NH	δ = -π/2	3.7

- 3 events has ~equal probability of being from anti-ν_e appearance or background fluctuation

OPERA ν_τ Appearance

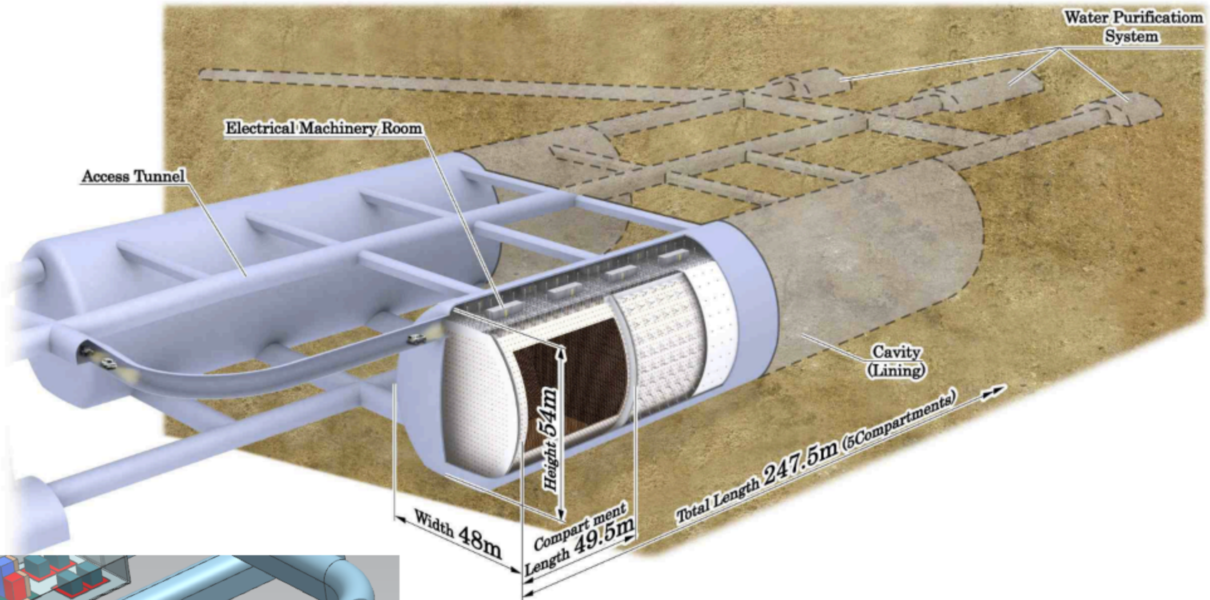
- Operated in the CNGS beam from CERN to Gran Sasso
  - Running finished, but data analysis continues.

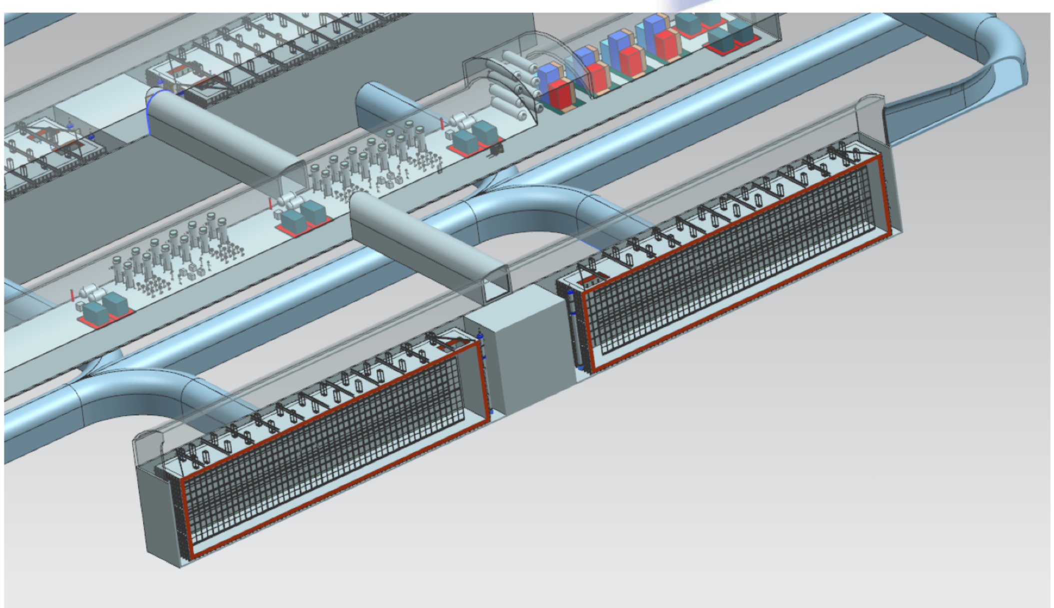
- They have now observed 5 ν_τ candidates appearing in a ν_μ beam
  - Observation of ν_τ appearance significance of 5.1σ



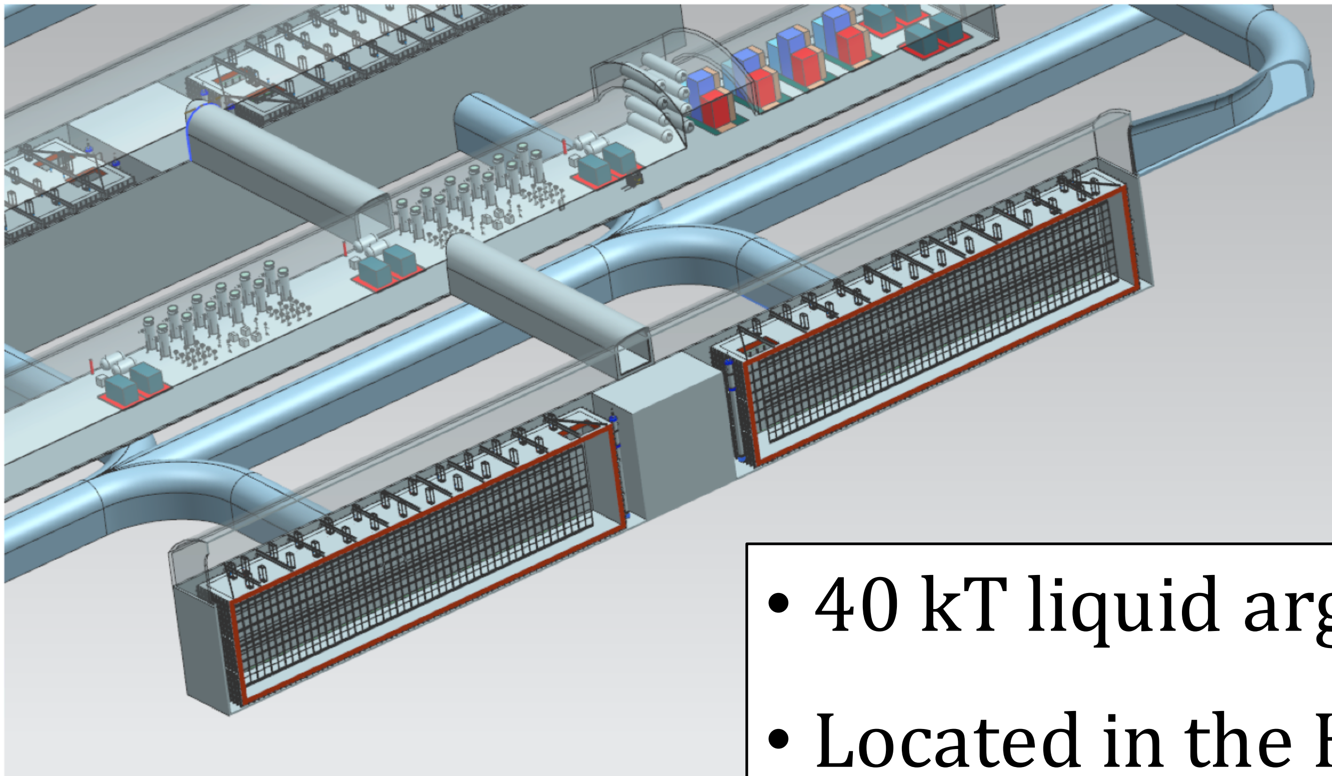
arXiv:1507.01417 [hep-ex]

The Future:
DUNE and Hyper-Kamiokande



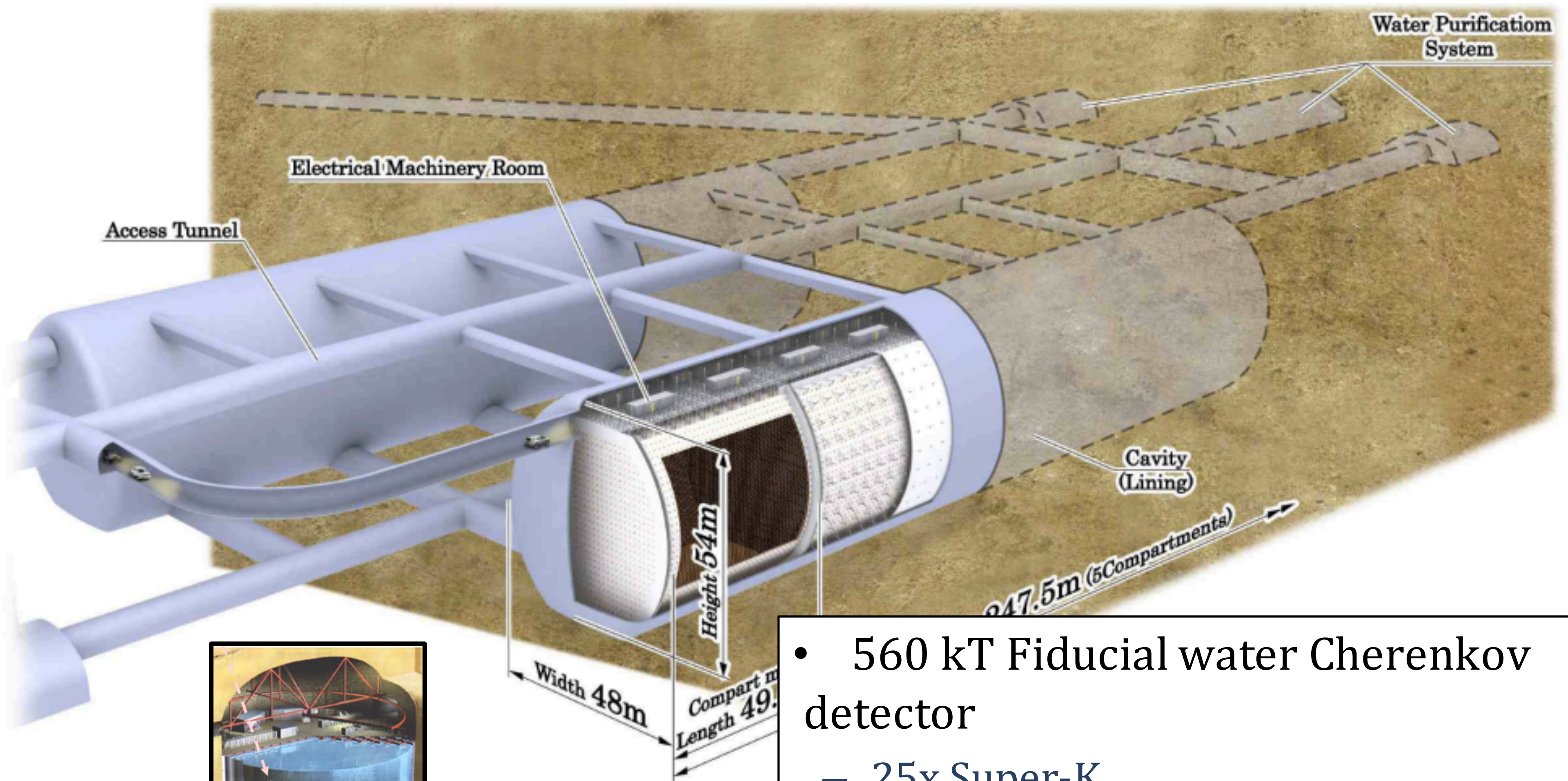


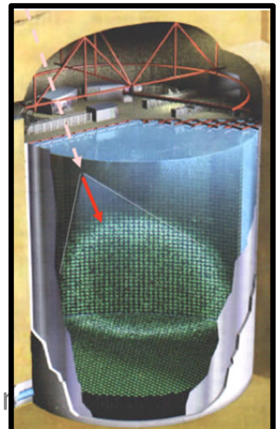
DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT



- 40 kT liquid argon TPC
- Located in the Homestake mine in South Dakota with a beam at Fermilab
  - 1300 km baseline, on-axis

Hyper-Kamiokande

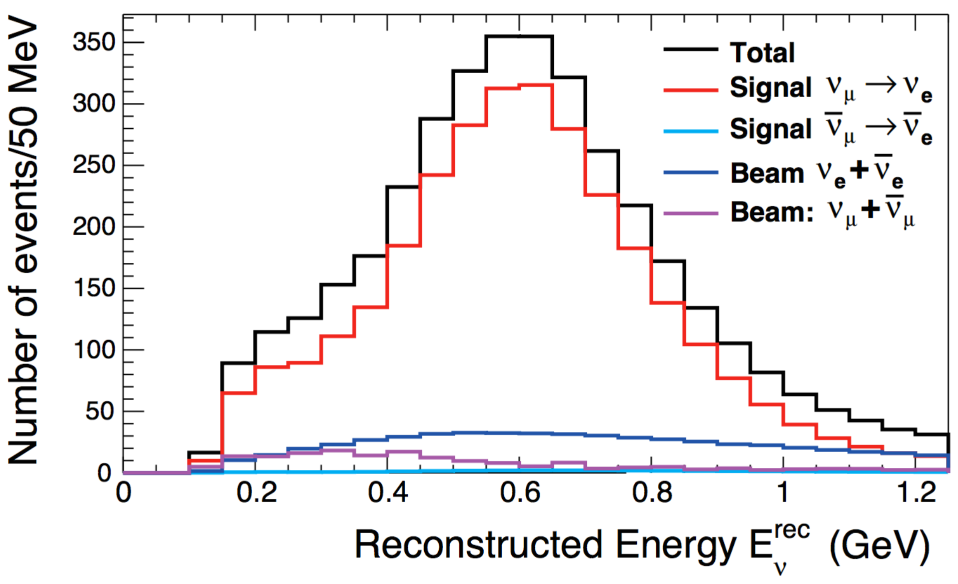




- 560 kT Fiducial water Cherenkov detector
  - 25x Super-K
- J-PARC beam
  - 295 km, off-axis

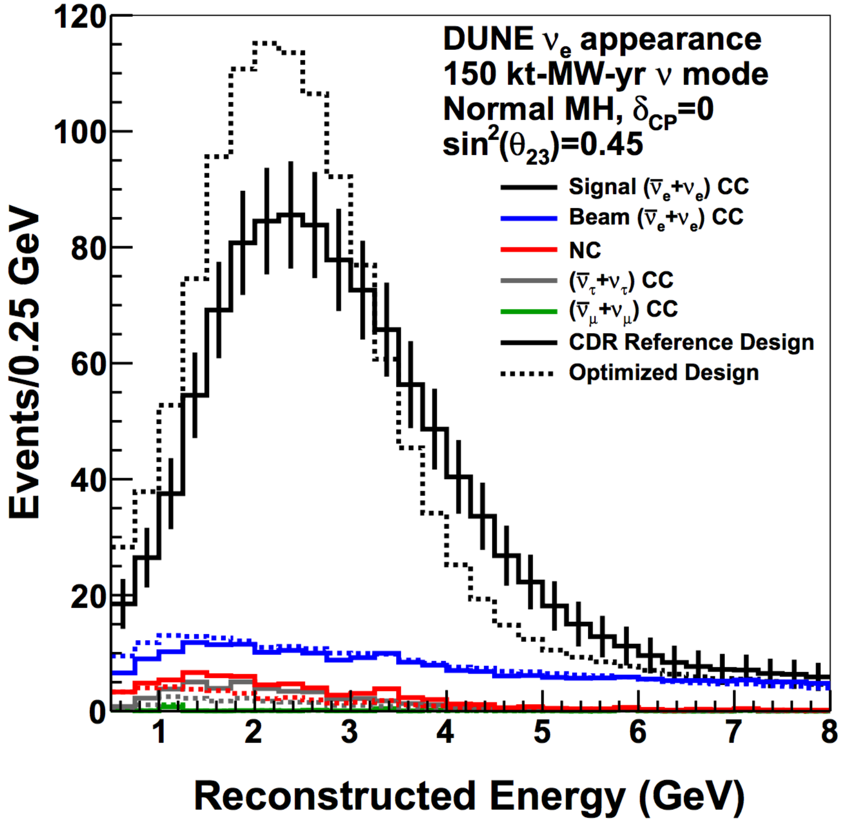
Data Rate

Hyper-K



Prog. Theor. Exp. Phys. (2015) 053C02

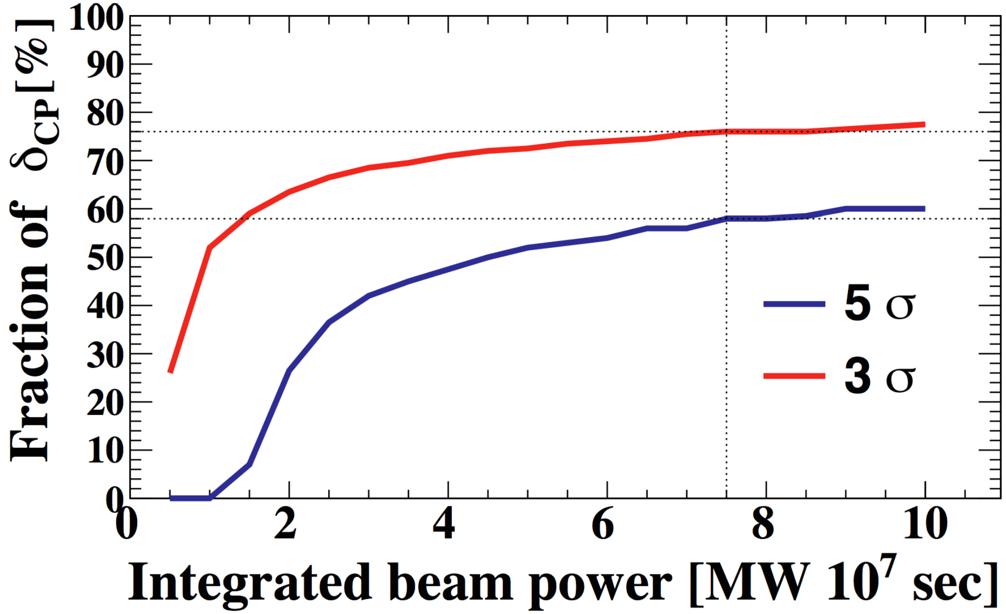
DUNE

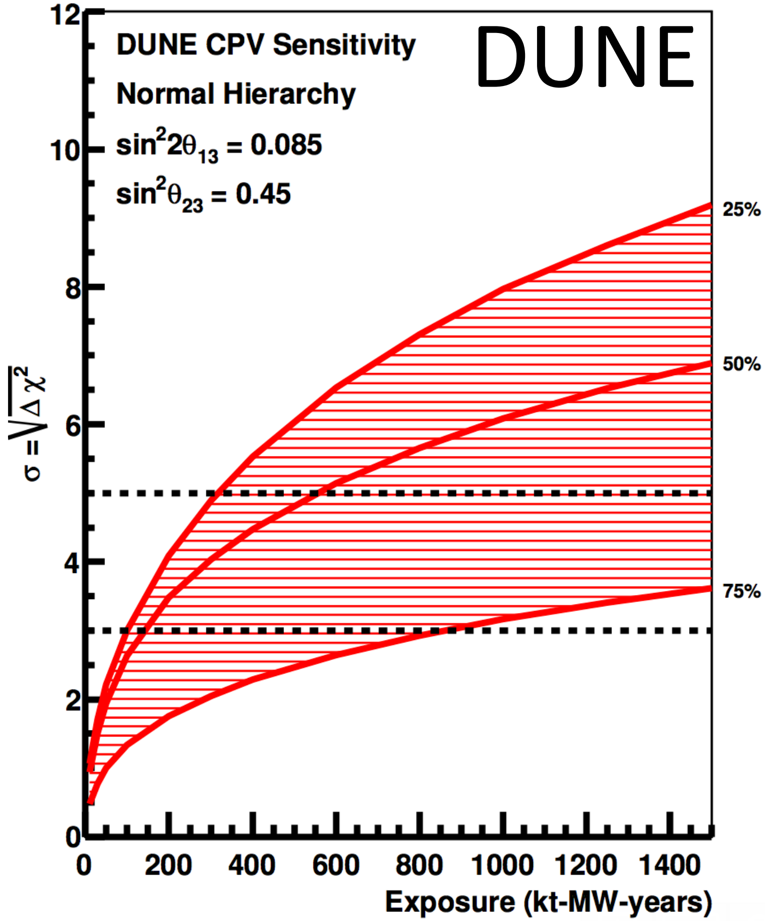


DUNE CDR

CP Violation Sensitivity

Hyper-K





Prog. Theor. Exp. Phys. (2015) 053C02

DUNE CDR

Both experiments, when fully realized, are capable of excluding $\delta_{cp} = 0$ across a wide range of values

Conclusions

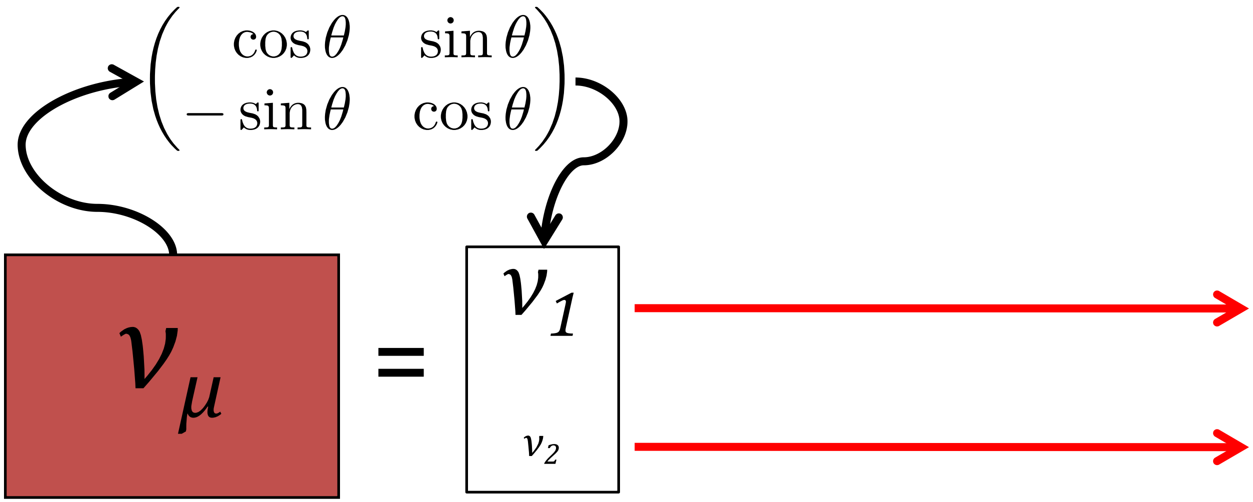
- Accelerator neutrinos are an effective tool for studying many neutrino oscillation parameters.

- Current experiments are…
  - Improving our measurements of θ_{23} and $\Delta m^2{}_{\mathrm{atm.}}$
  - Probing for differences between neutrino and antineutrino oscillations.
  - Confirming the appearance of ν_τ's via oscillations.

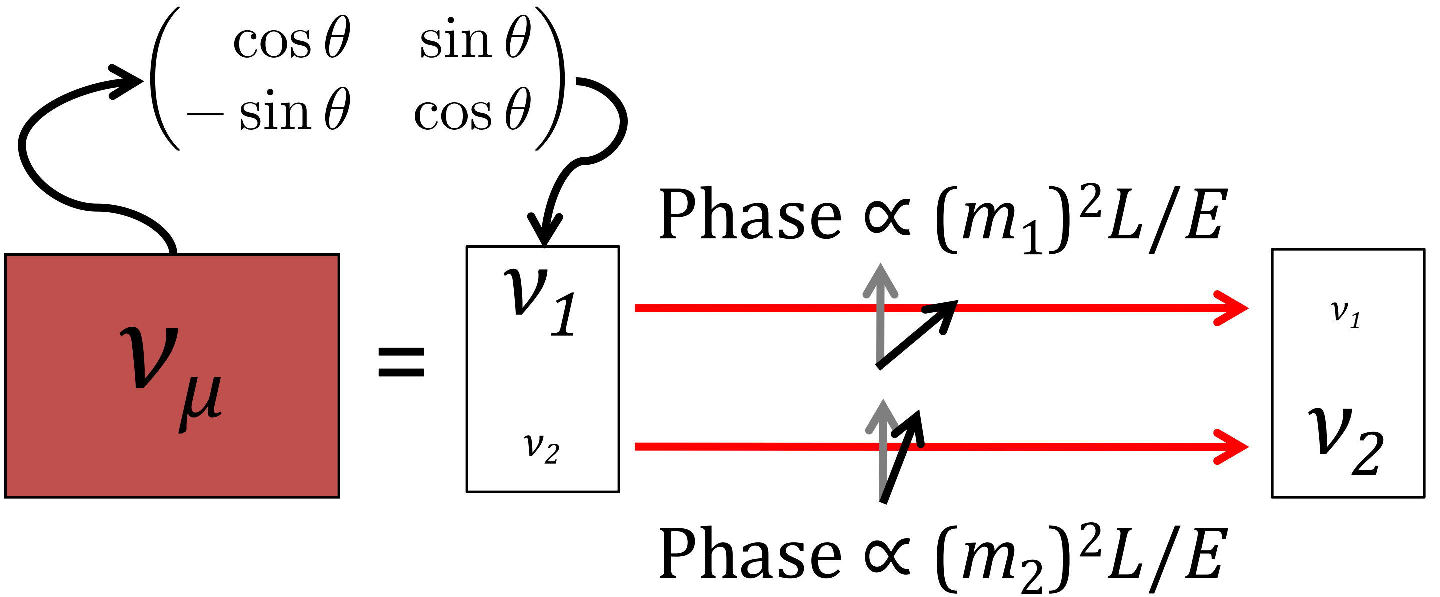
- In the future, accelerator neutrino experiments are…
  - Our best hope for measuring neutrino CP violation.
  - One of the best options for resolving the neutrino mass hierarchy.

Backup Slides

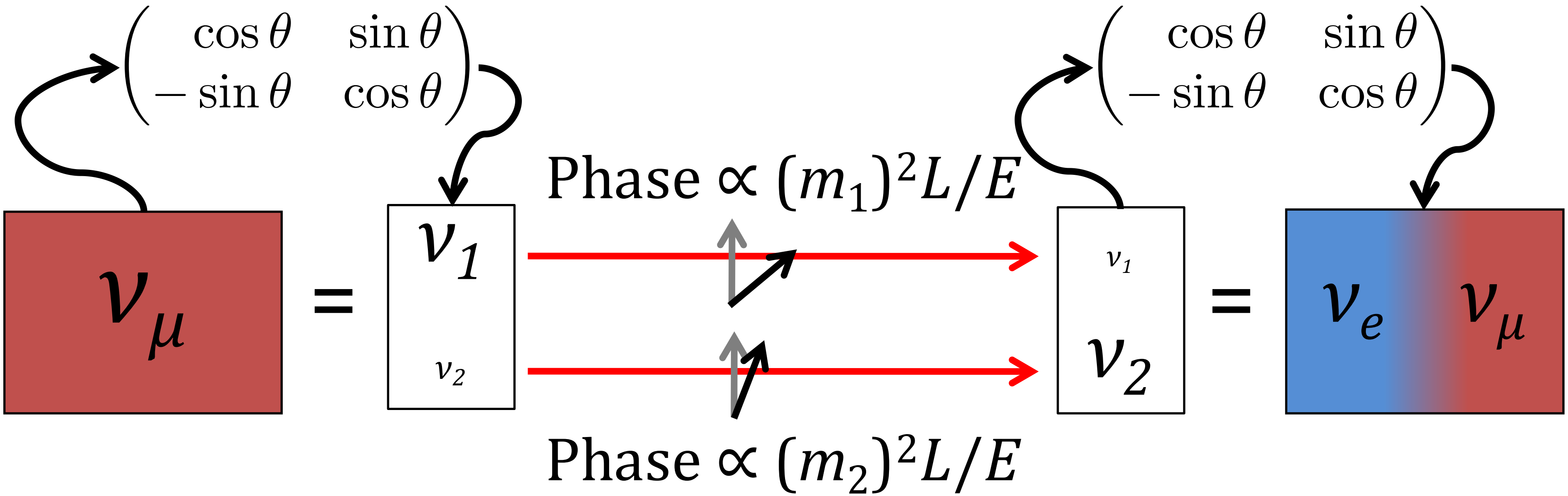
Neutrino Oscillations



Neutrino Oscillations

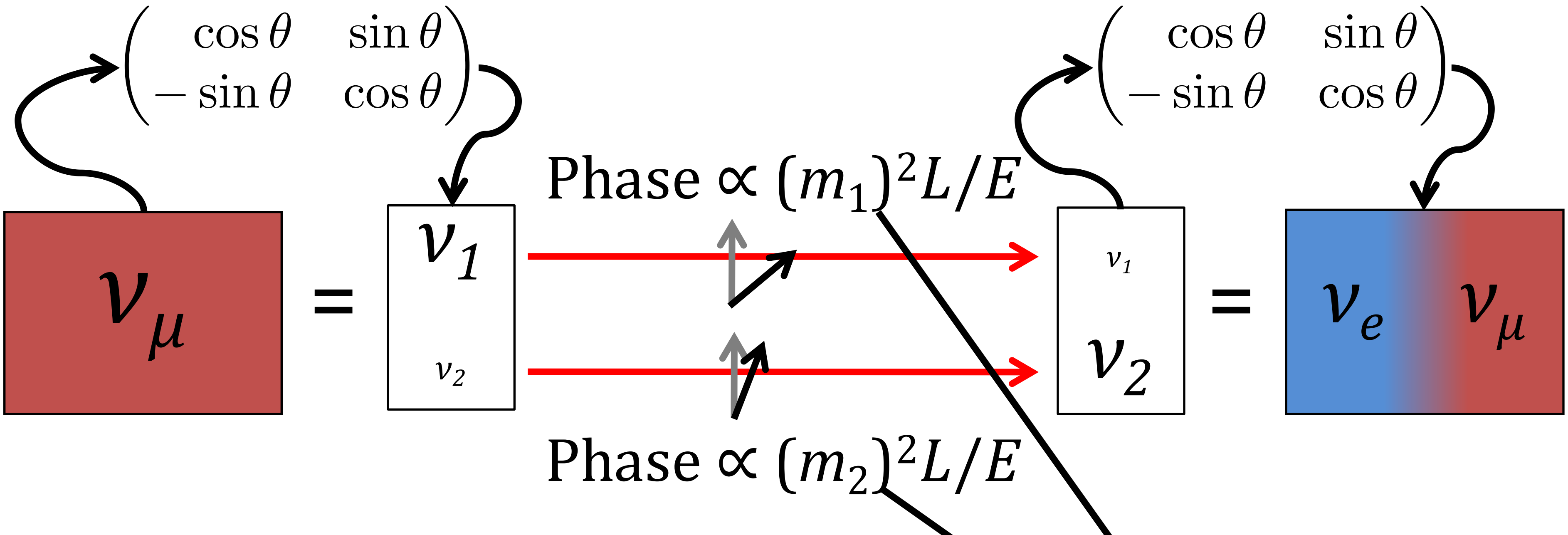


Neutrino Oscillations



Neutrino oscillations require that neutrinos have mass!

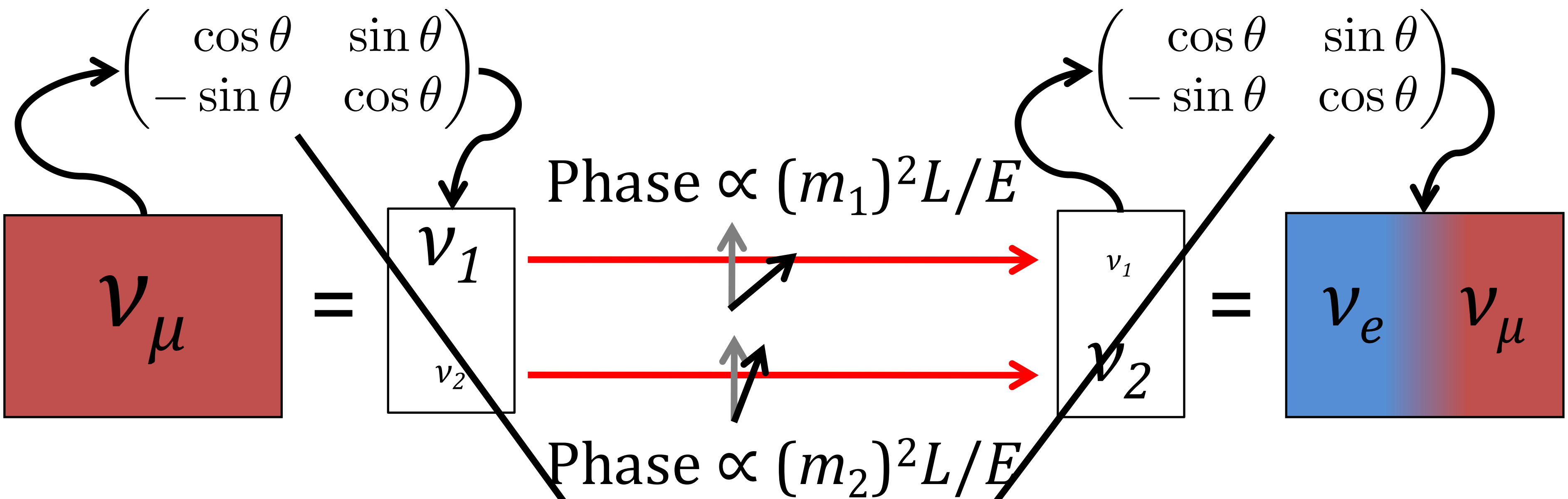
Neutrino Oscillations



Muon Neutrino Survival Probability

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta)\,\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Neutrino Oscillations



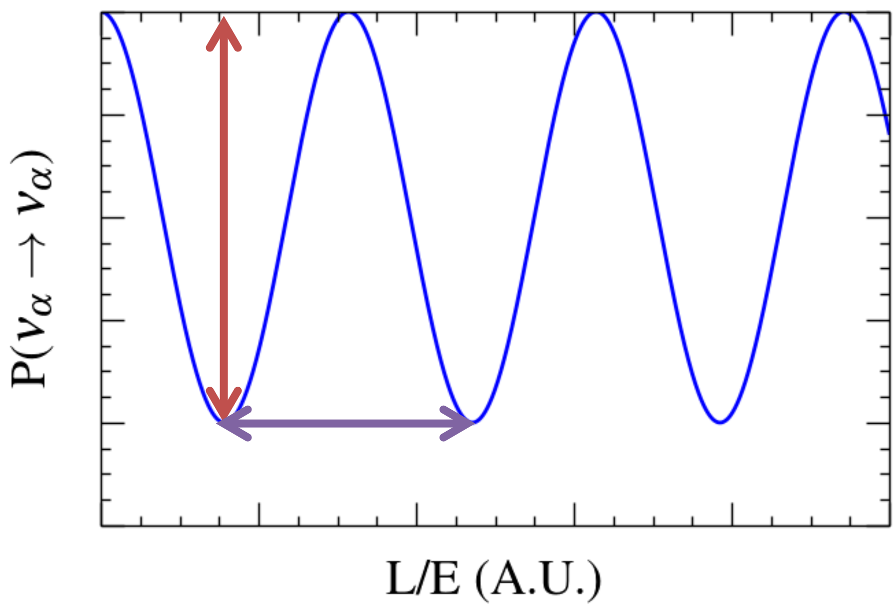
Muon Neutrino Survival Probability

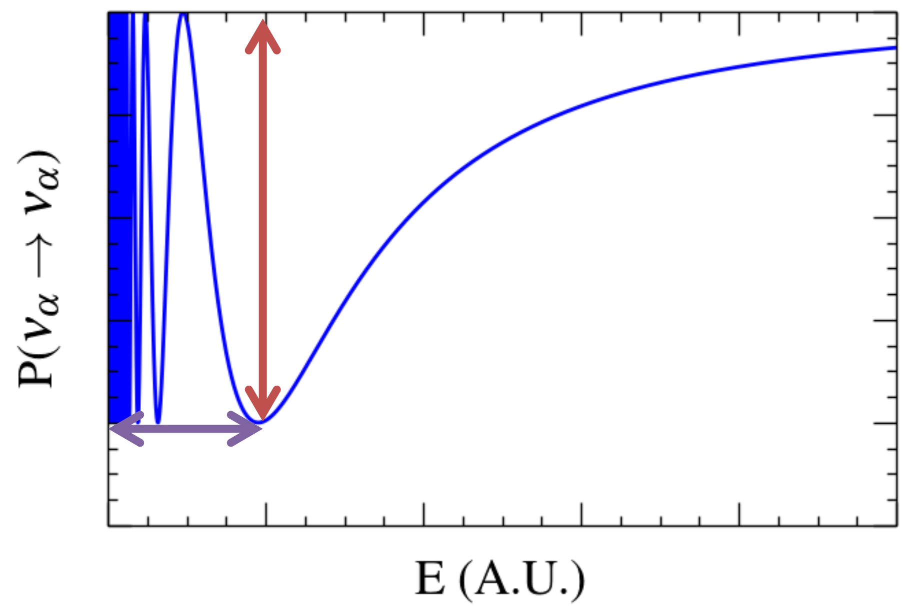
$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Neutrino Oscillations

- With only 2 neutrinos, the oscillation formula is simple:

$$P(\nu_\alpha \rightarrow \nu_\alpha) = 1 - \sin^2(2\theta) \sin^2 \left(\Delta m^2 \frac{L}{4E} \right)$$





Studying Oscillations: Short Baseline

- Can search for sterile neutrinos (oscillations at different L/E)
- List experiments, no time to cover
- LSND, MiniBooNE, MicroBooNE, SBN, OscSNS

“Identical” Near Detector?

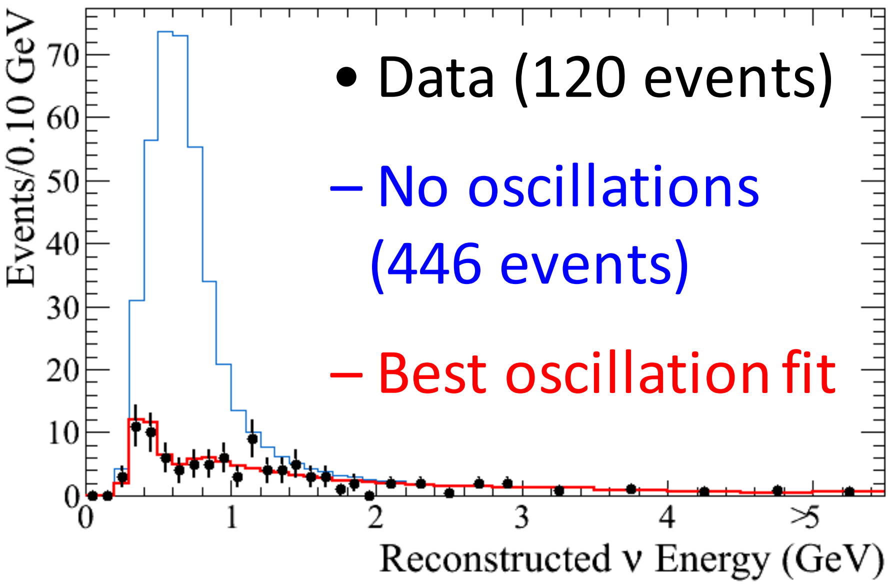
T2K

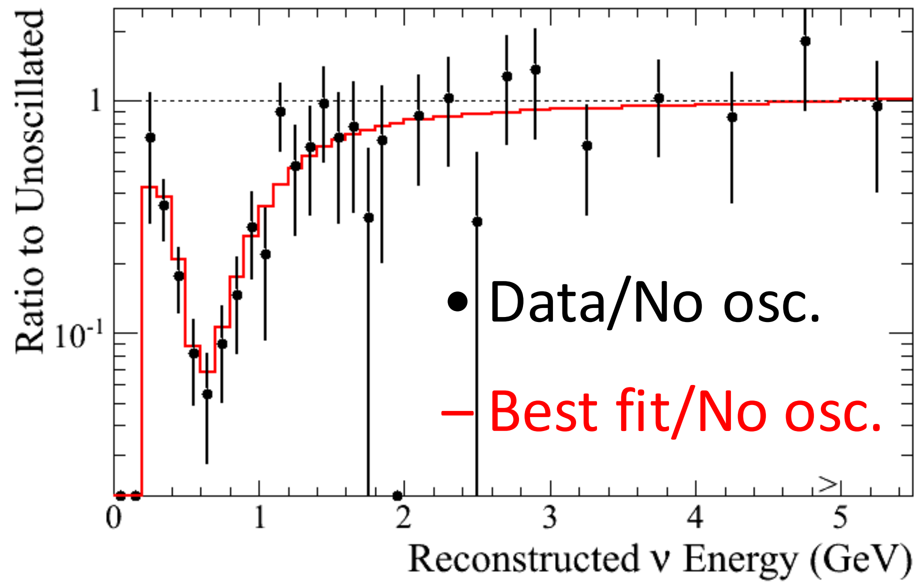
- Multi-component near detector measures μ kinematics in various CC ν_μ and anti-ν_μ CC samples
  - QE-like, resonant π-like, etc.
- Fit for flux and cross-section parameters used in the simulation
- Use these as priors in the fit for oscillations with the far detector data

NOvA

- Functionally identical near detector measures CC ν_μ inclusive sample
- Use the simulation to correct for selection efficiency and energy resolution
- Extrapolate the ND spectrum to the FD to serve as the unoscillated template in the fit

T2K ν_μ Disappearance

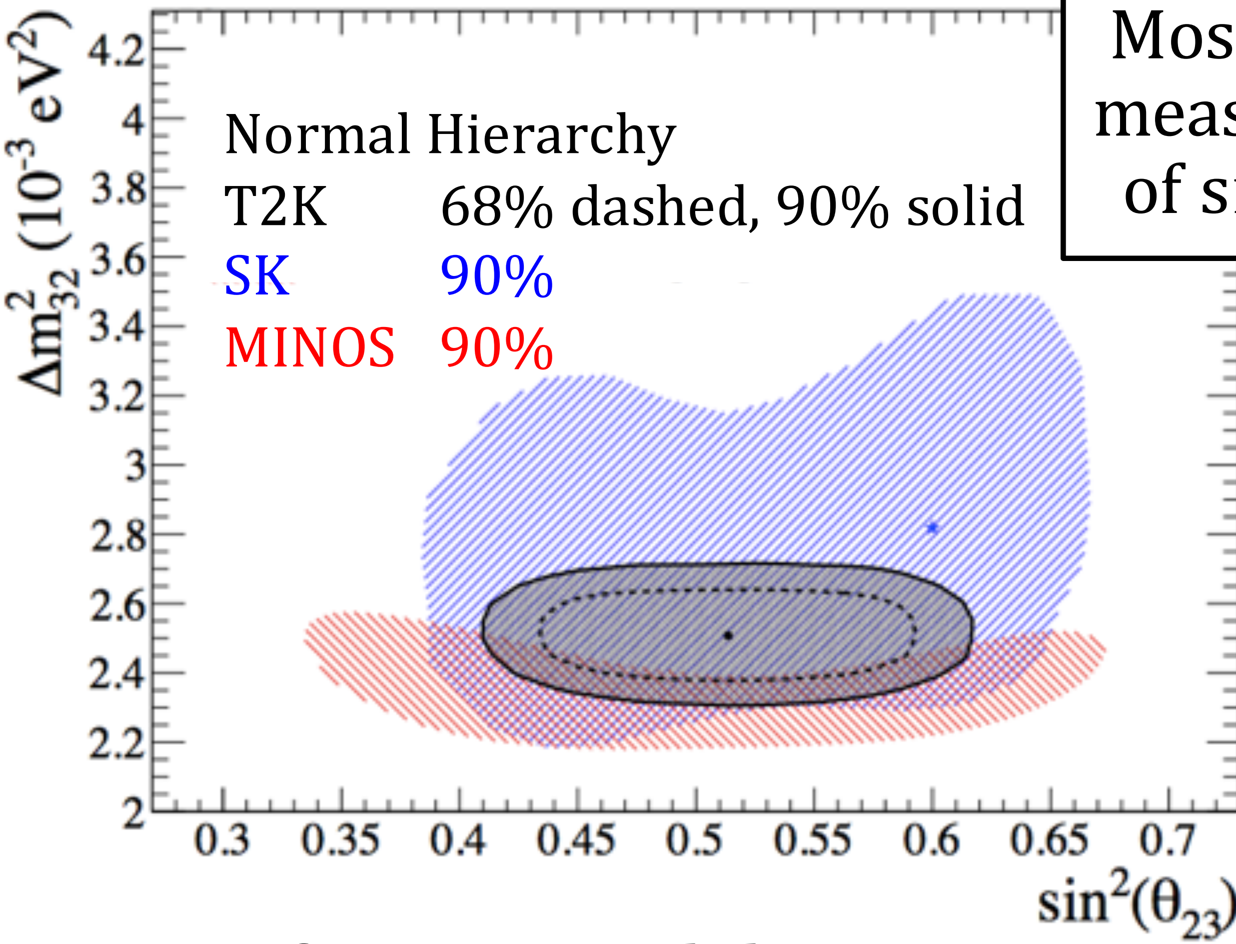




Normal Hierarchy	Inverted Hierarchy
$\sin^2\theta_{23} = 0.514^{+0.055}_{-0.056}$	$\sin^2\theta_{23} = 0.511 \pm 0.055$
$\Delta m^2_{32} = (2.51 \pm 0.10) \times 10^{-3}\,\mathrm{eV}^2$	$\Delta m^2_{13} = (2.48 \pm 0.10) \times 10^{-3}\,\mathrm{eV}^2$

PRL 112 (2014) 181801

T2K ν_μ Disappearance



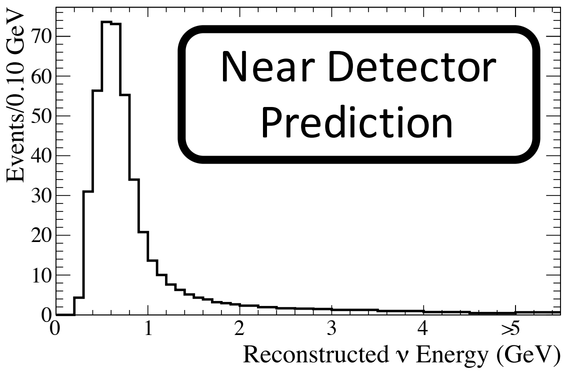
Most precise measurement of $\sin^2(\theta_{23})$!

Best fit at maximal disappearance

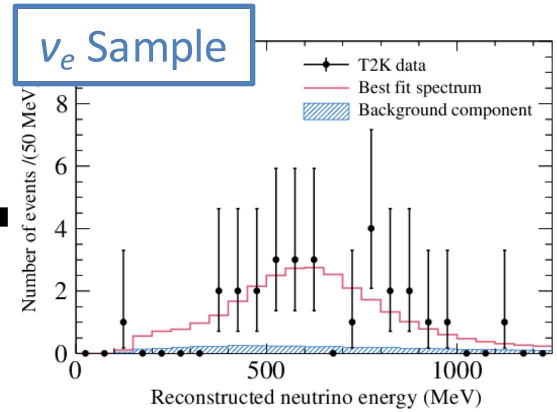
- Result narrower than sensitivity by 0.04 in $\sin^2(\theta_{23})$

PRL 112 (2014) 181801

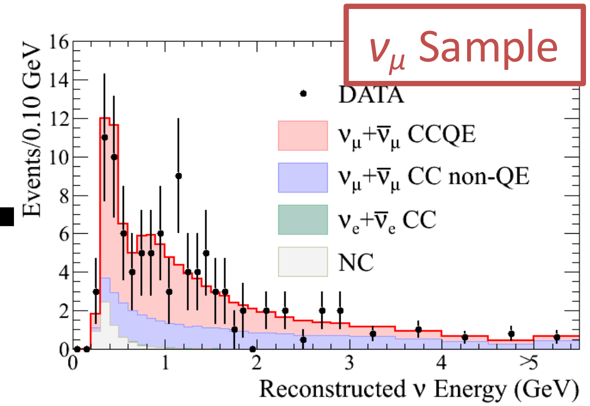
T2K Fits to $\nu_\mu + \nu_e$



+

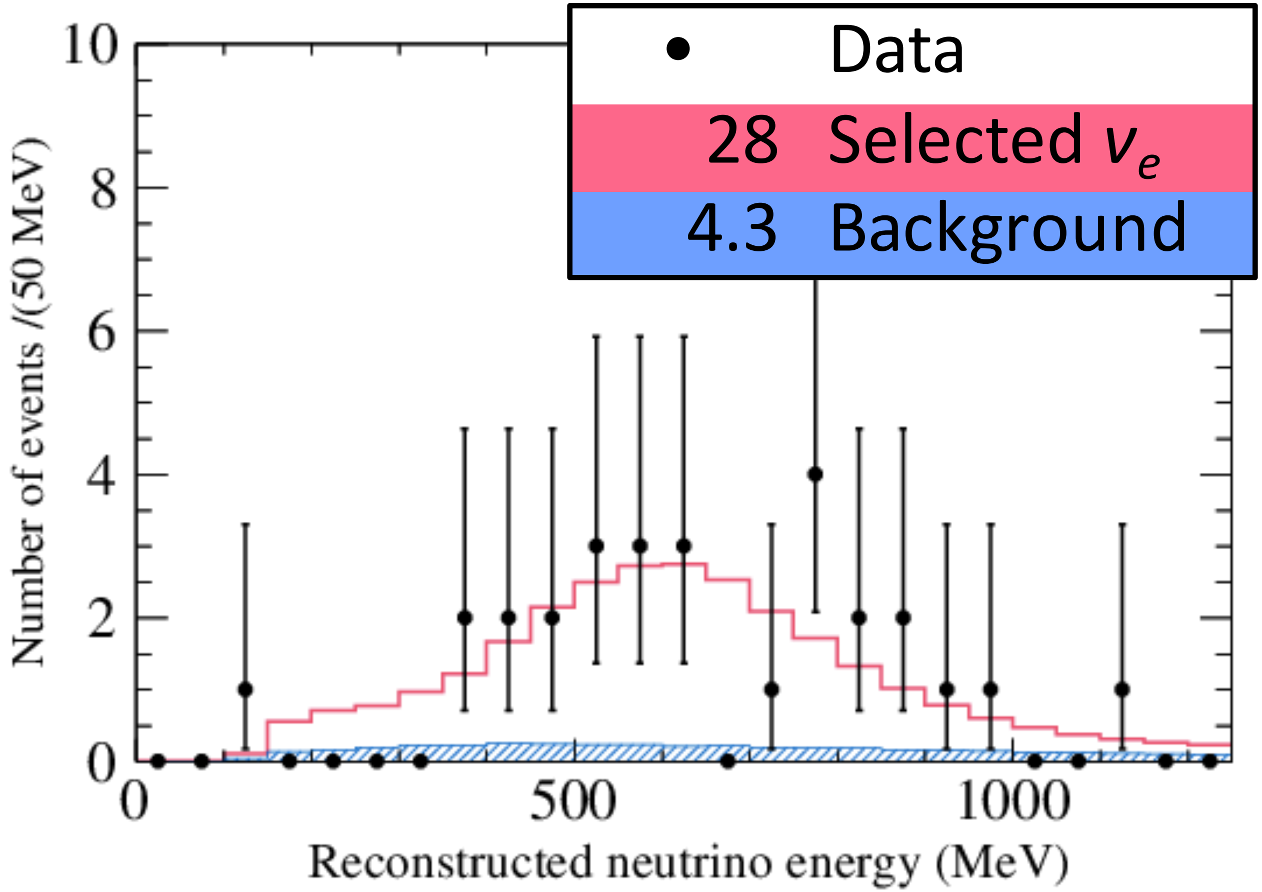


+



- Likelihood ratio fit of ν_μ and ν_e samples
- Both Frequentist and Bayesian analyses performed
- Simultaneous fit for: $\boxed{\delta_{cp},\ \theta_{13},\ \theta_{23},\ \Delta m^2_{32}}$

T2K ν_e Appearance



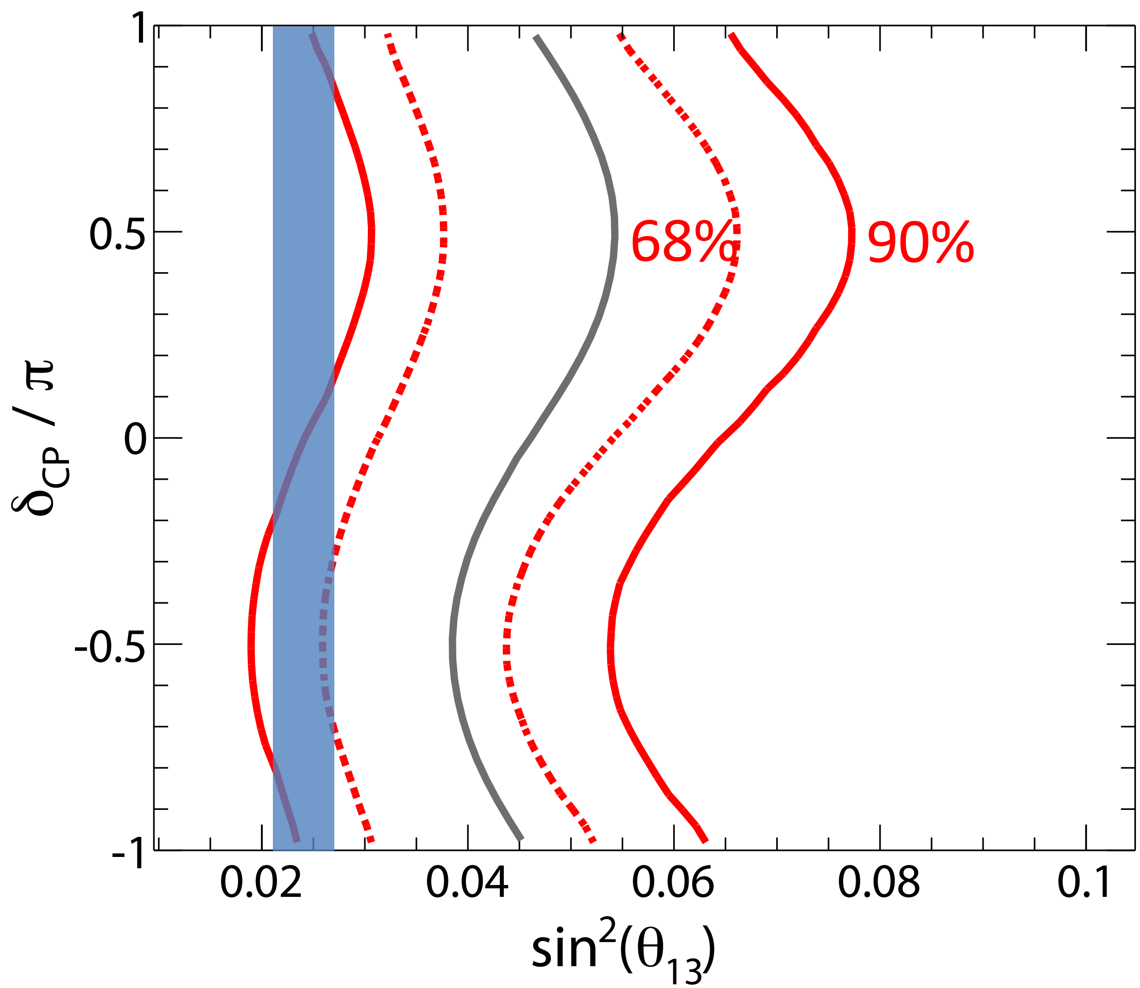
28 Events

66% efficiency

Background-only excluded at > 7σ

Contours using T2K Data Only

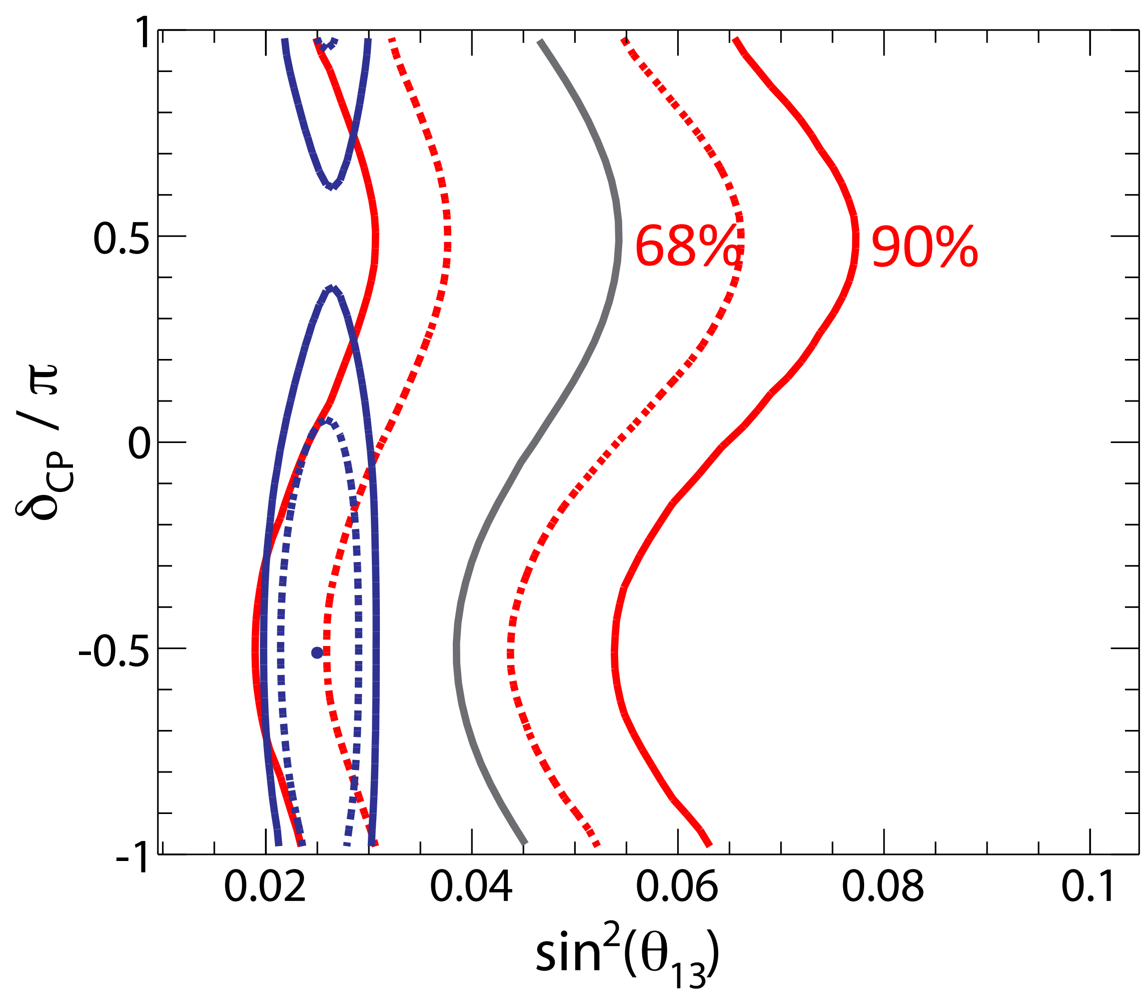
- $\sin^2(\theta_{23})$ shifts up to 0.52 in response to large appearance signal
- Our appearance signal is large relative to reactor measurements
  - 2013 Weighted average
    - Daya Bay
    - RENO
    - Double Chooz
  - $\sin^2(2\theta_{13}) = 0.095 \pm 0.010$



PRD 91 (2015) 072010

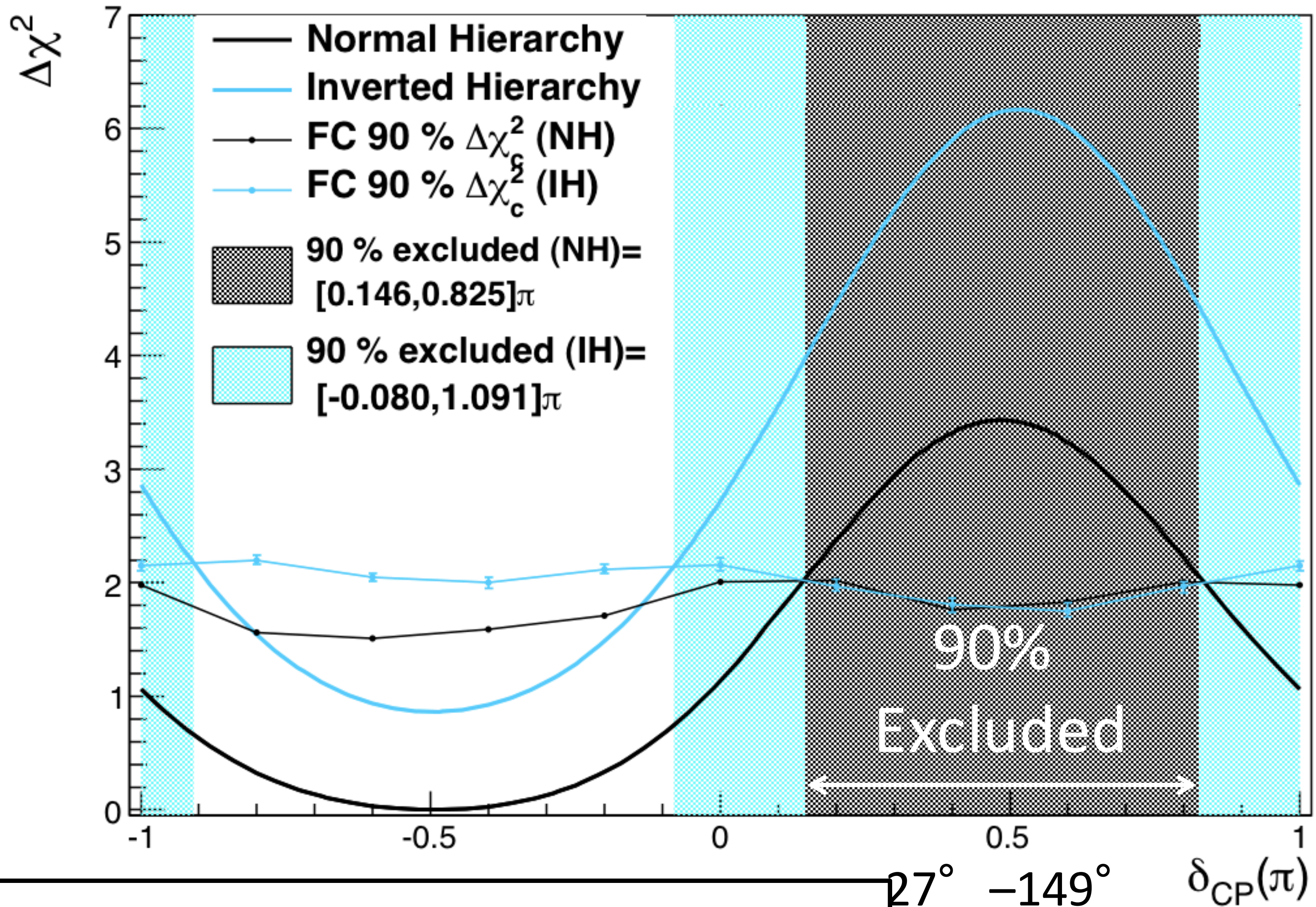
Contours with Reactor Constraint

- $\sin^2(\theta_{23})$ shifts up to 0.52 in response to large appearance signal
- Our appearance signal is large relative to reactor measurements
  - 2013 Weighted average
    - Daya Bay
    - RENO
    - Double Chooz
  - $\sin^2(2\theta_{13})$ = 0.095±0.010



PRD 91 (2015) 072010

Constraint on δ_{CP}



First exclusion of a region of δ_{CP}!

PRD 91 (2015) 072010