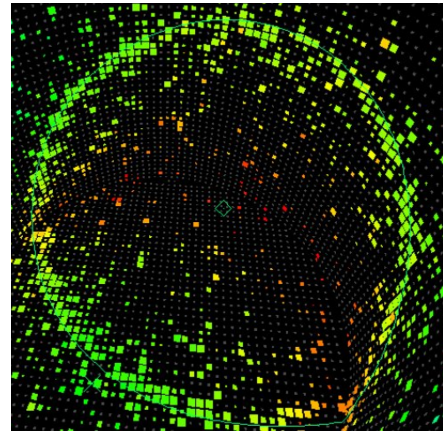
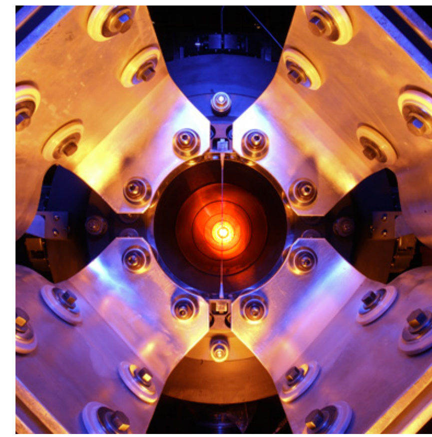
$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$



$$\delta_{CP}$$

$$\nu_\mu \rightarrow \nu_e$$



Long-Baseline Neutrino Physics: Present and Future

Ruth Toner

Harvard University

FPCP 2014

Neutrino Oscillations

- Interact weakly via **flavor eigenstates:** $\nu_e \;\; \nu_\mu \;\; \nu_\tau$
- Propagate as **mass eigenstates:** $\nu_1 \;\; \nu_2 \;\; \nu_3$

Non-zero different masses = neutrino can **slide in and out of phase** as it propagates – **"Oscillation"**

$$P(\nu_\alpha \to \nu_\beta) = |\langle \nu_\beta | \nu_\alpha(L) \rangle|^2$$

$$= \delta_{\alpha\beta} - 4 \sum_{i>j} \Re(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2[1.27 \Delta m^2_{ij} L/E]$$

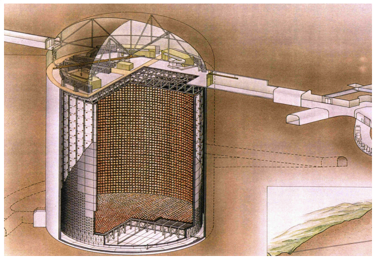
$$+2 \sum_{i>j} \Im(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2[2.54 \Delta m^2_{ij} L/E]$$

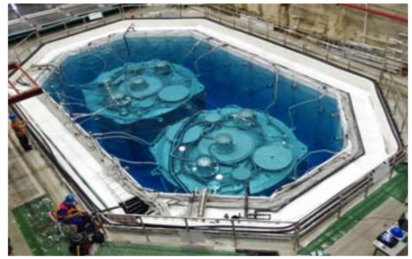
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

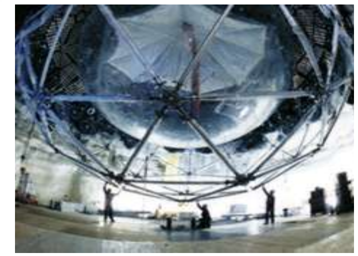
Or, for a two neutrino case:

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2 \left(1.27 \Delta m^2 L/E\right)$$

+ Long-Baseline Neutrino Physics



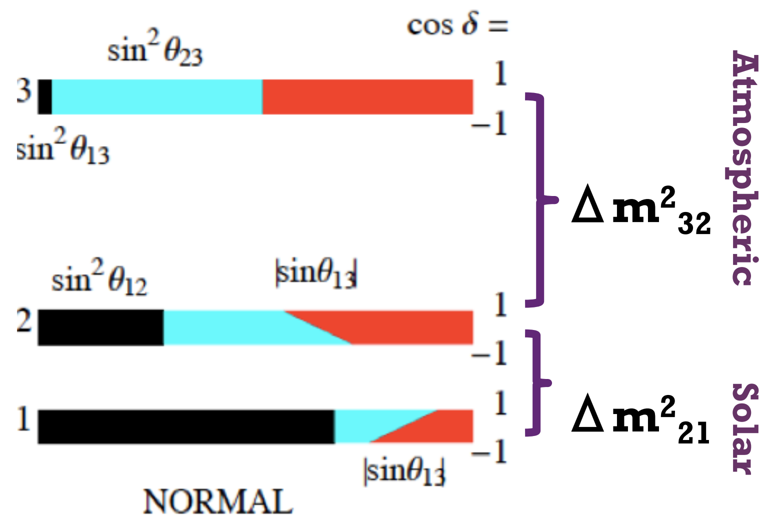




$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

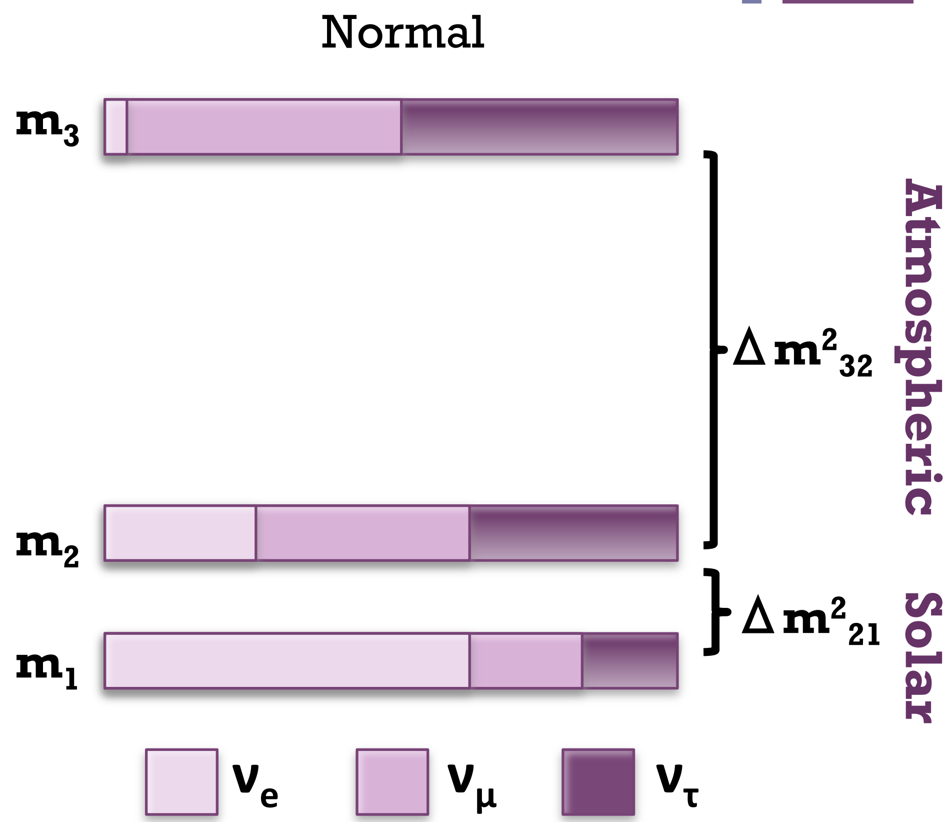
Atmospheric **Reactor** **Solar**

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



Outstanding Questions

- ~~What is the **value of θ_{13}**~~?
  - This is measured with best precision of any mixing angle!
- What is **the sign of Δm^2_{32}?** Is the **mass hierarchy** "Inverted" or "Normal"?
- Do neutrinos exhibit **CP violation**? What the size of phase δ_{CP}?
- Is **θ_{23} exactly 45°** (i.e., what is its "octant"?)
- Do sterile neutrinos exist (mostly short-baseline)?



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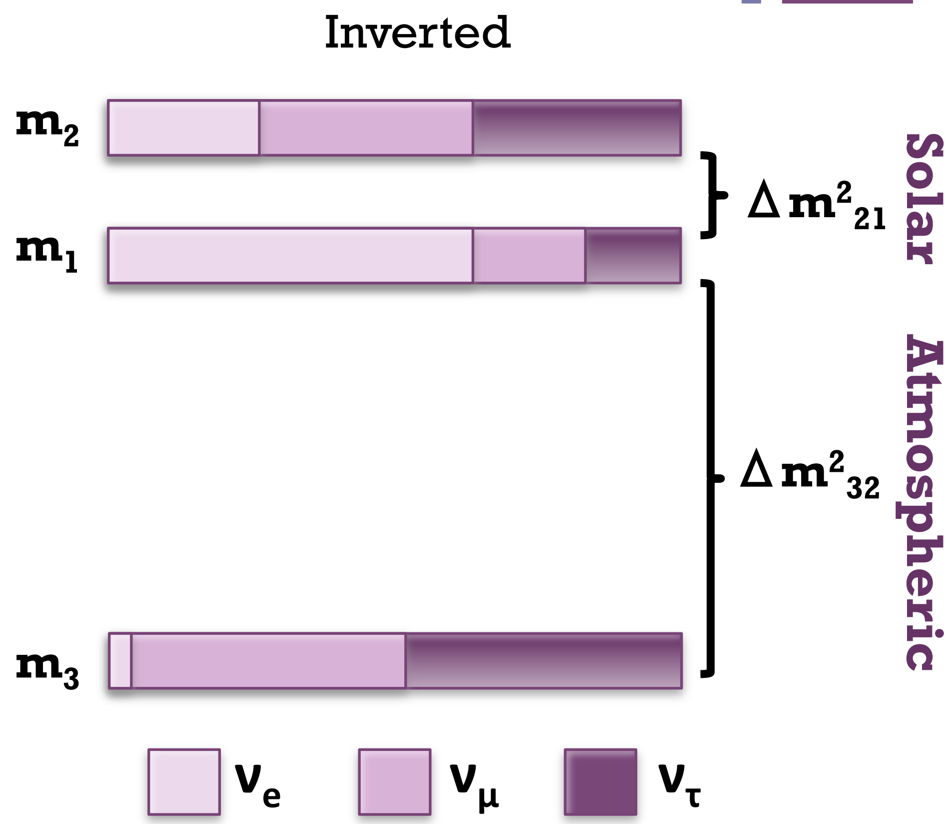

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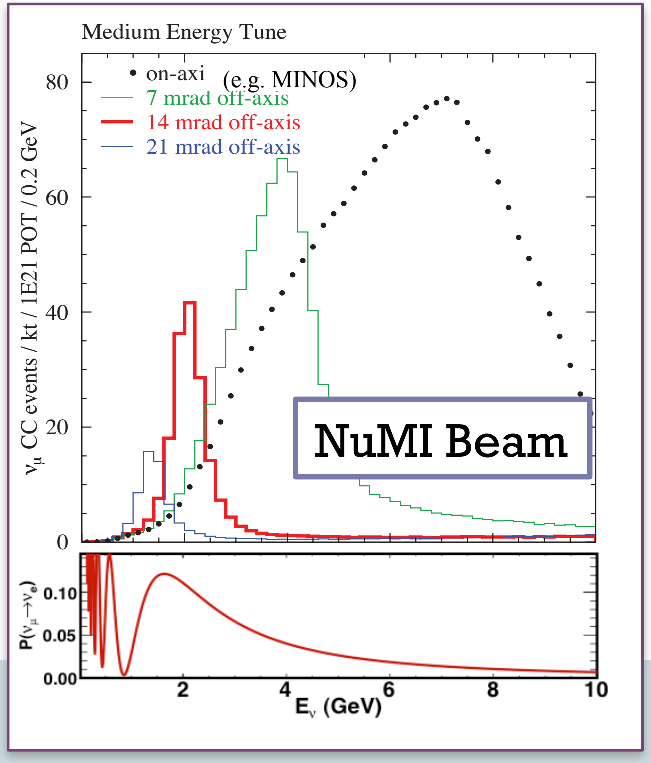
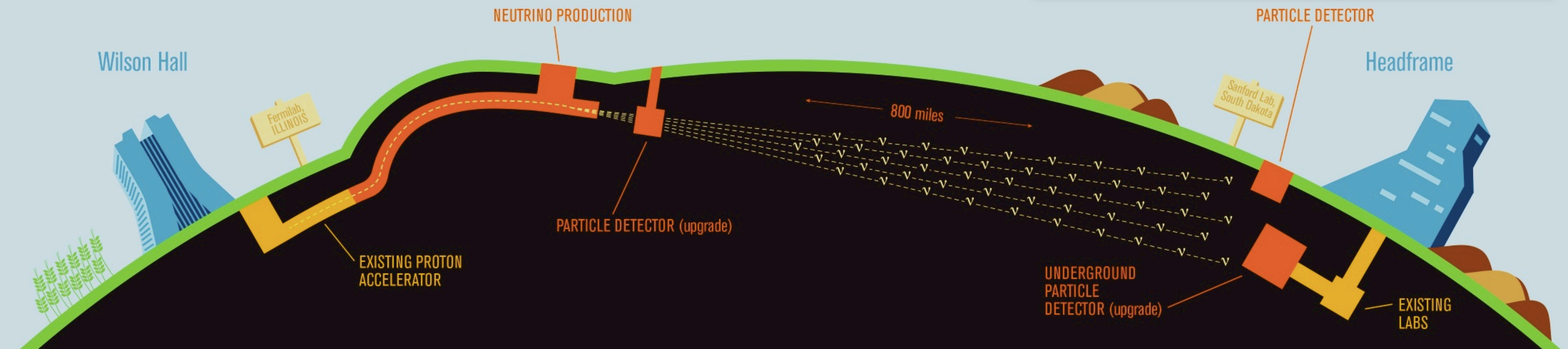
+ Long-Baseline Neutrino Experiments

➢ **Several components in common:**

- **Beam:** Mostly muon neutrinos, produced through decay of particles produced by collision of accelerator protons on stationary target
  - **On-axis beamline**: higher intensity, wide band
  - **Off-axis beamline**: narrow-band beam
- **Detectors:**
  - Look for products of neutrino interaction
  - Choose a Far Detector location at good L/E for observing oscillations, often underground
  - Often use Near Detector to study pre-oscillation neutrinos, reduce systematic uncertainties

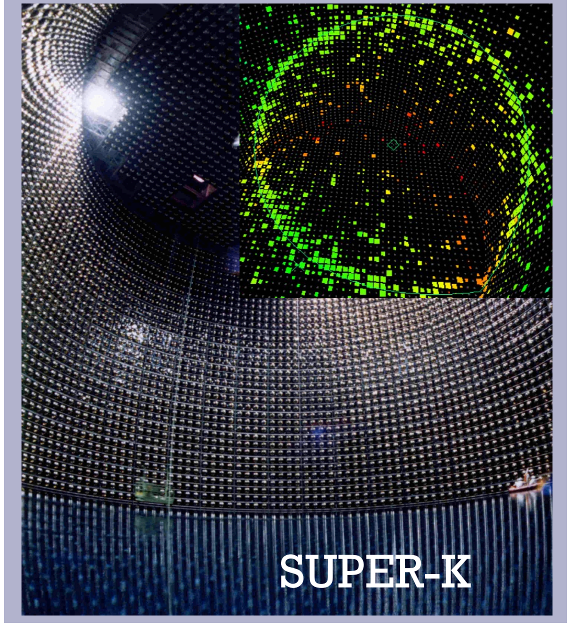


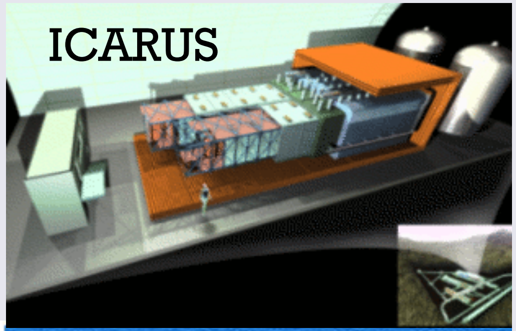
Example: LBNE

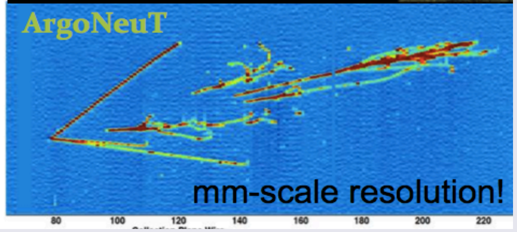


Modern Detector Technologies

Water Cherenkov:
- Surround large volume of water with PMTs
- Charged particles produce ring-like patterns of light
- Can measure energy, distinguish between different lepton types
- Proven, very scalable

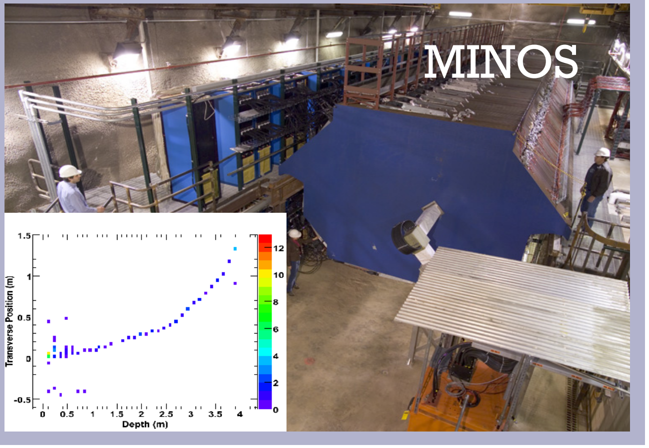






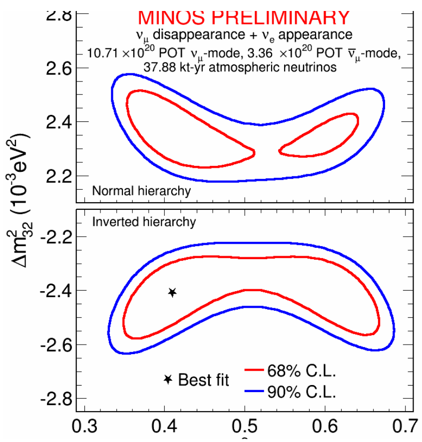
Liquid Argon TPC:
- Charged particle passes through LAr, produces path of ionization e-
- Drift e- with electric field and detect signal on wire frame
- Produces very detailed image of particle interaction with good background rejection

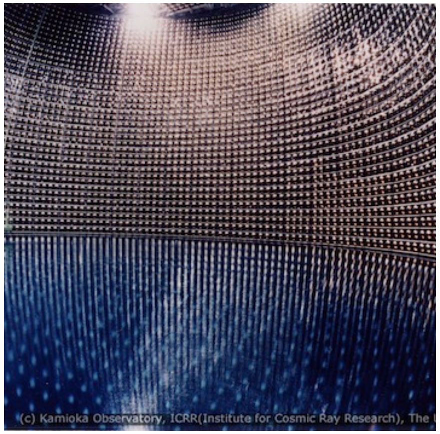
Other tracking technologies:
- Various types of tracking calorimeter can be used for higher-energy neutrinos
- Particles pass through strips of solid scintillator, cells of liquid scintillator, emulsion film, etc. and produce signal
- Use photo-detectors to observe and analyze showers and tracks



Current Experiments And Results

T2K, MINOS(+), OPERA, ICARUS, NOvA



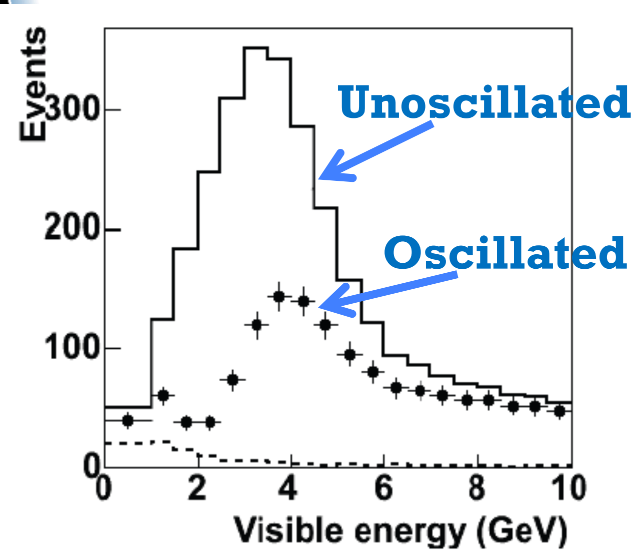


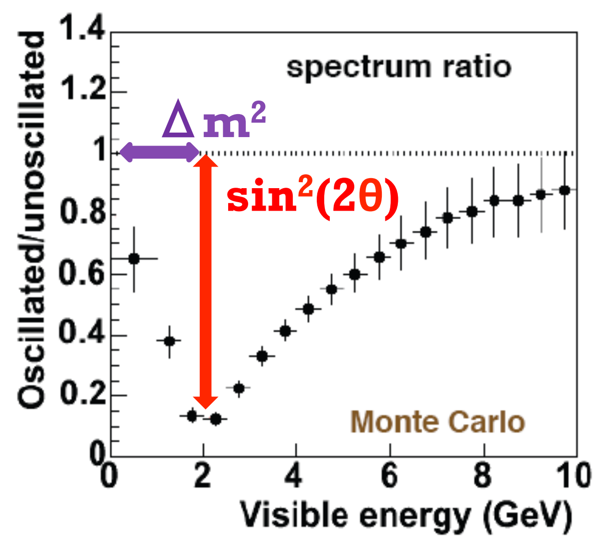
+ ν_μ Disappearance: MINOS

- MINOS consists of two functionally equivalent detectors made of steel and solid scintillator
- **Beam:** NuMI on-axis beam (formerly peaked at 3.3 GeV)
- One Near Detector (0.029 kT fiducial), one Far Detector (4.0 kT fiducial at depth of 700 m) at distance of 735 km
- Primary analysis goal: look for disappearance of muon neutrinos, which is approximately:

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2(2\theta_{23})\sin^2(1.27\Delta m^2_{32}L/E)$$

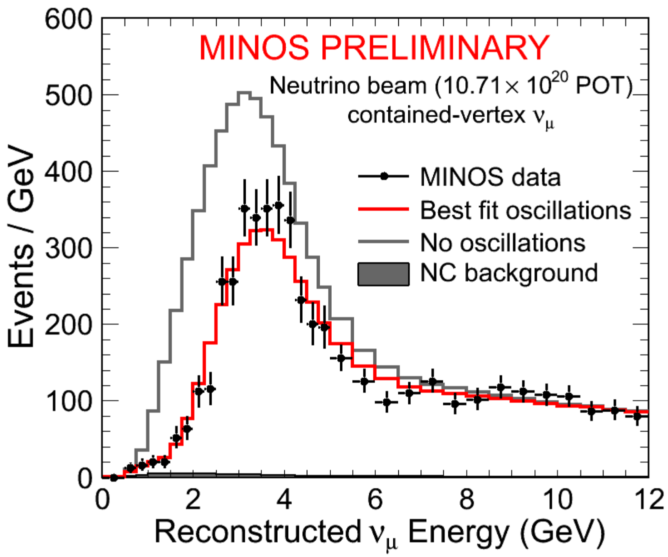
  - This allows for the measurement of $\sin^2(2\theta_{23})$ and Δm^2_{32}

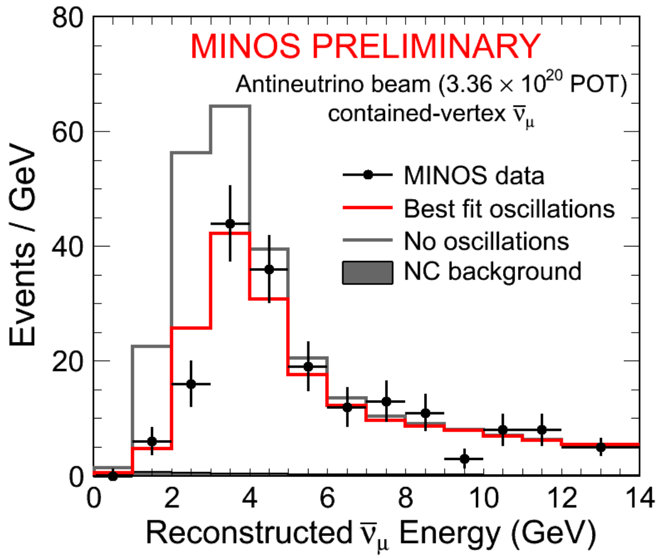




Monte Carlo:(Input parameters: $\sin^2 2\theta = 1.0$, $\Delta m^2 = 3.35\times10^{-3}\ \mathrm{eV}^2$)

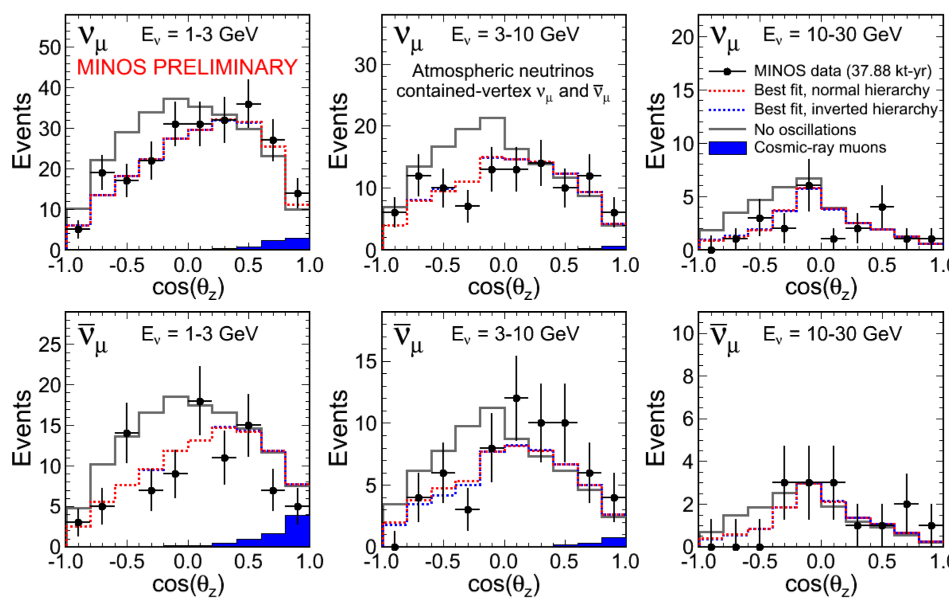
+ ν_μ Disappearance





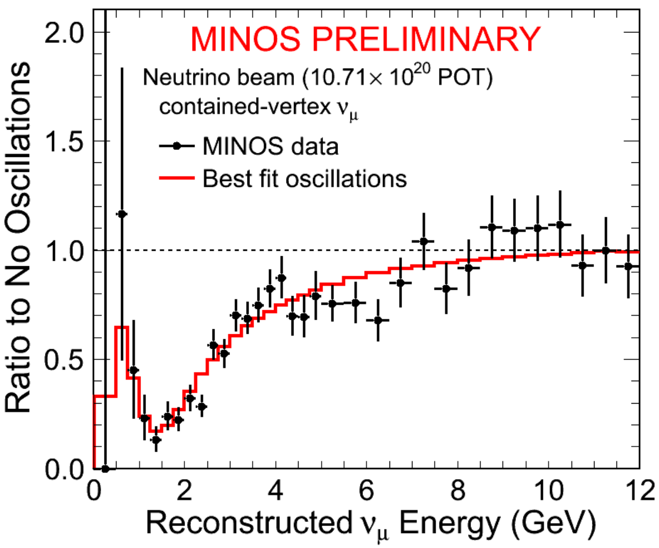
- MINOS previously made measurements using both muon neutrino and anti-neutrino beam
- Recently, have expanded analysis to include information from **atmospheric neutrinos** as well as **electron neutrino appearance** (three-neutrino fit):

	Parameter	Best fit	Confidence limits
Normal hierarchy	$\lvert\Delta m^2_{32}\rvert/10^{-3}\text{eV}^2$	2.37	$2.28 - 2.46$ (68% C.L.)
	$\sin^2\theta_{23}$	0.41	$0.35 - 0.65$ (90% C.L.)
Inverted hierarchy	$\lvert\Delta m^2_{32}\rvert/10^{-3}\text{eV}^2$	2.41	$2.32 - 2.53$ (68% C.L.)
	$\sin^2\theta_{23}$	0.41	$0.34 - 0.67$ (90% C.L.)



Phys. Rev. Lett. 112, 191801 (2014)

+ ν_μ Disappearance



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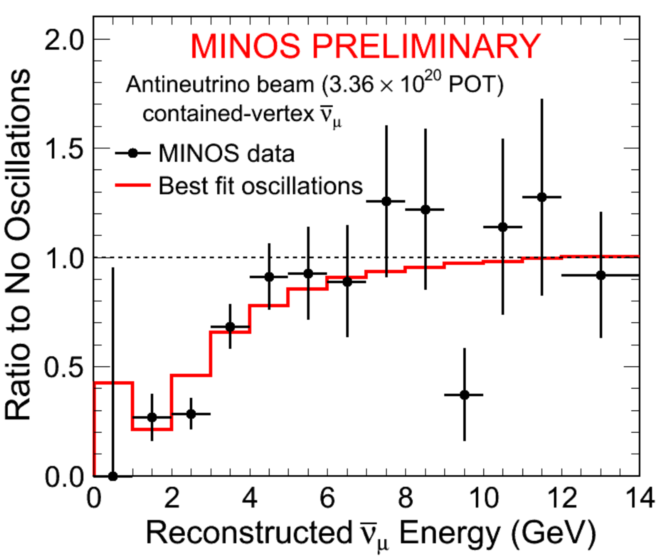
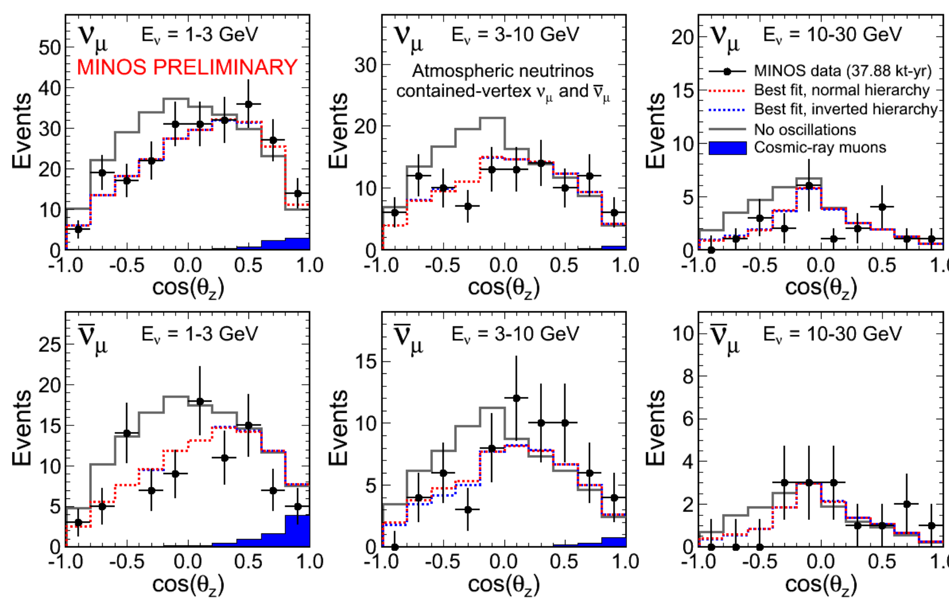
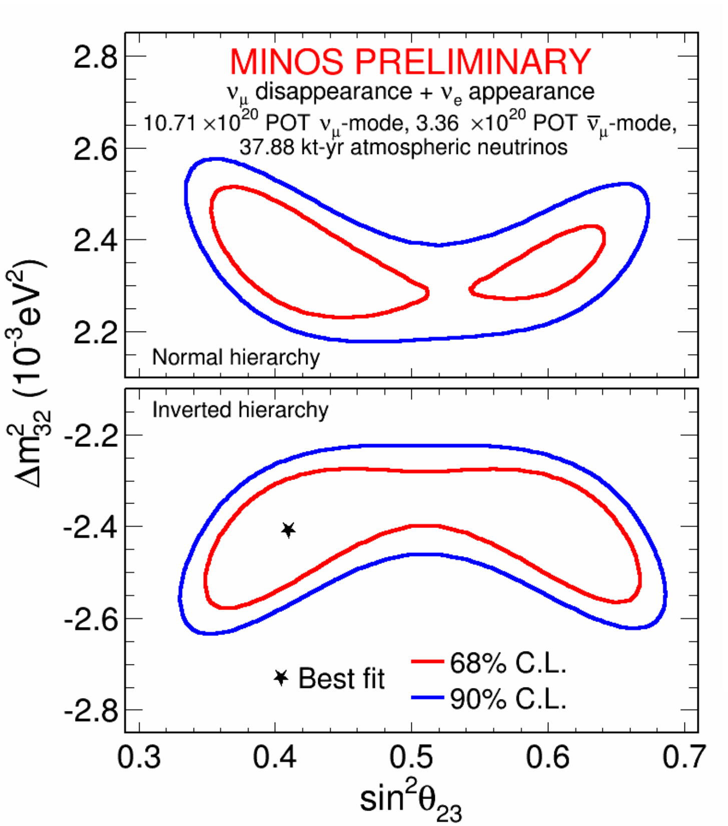


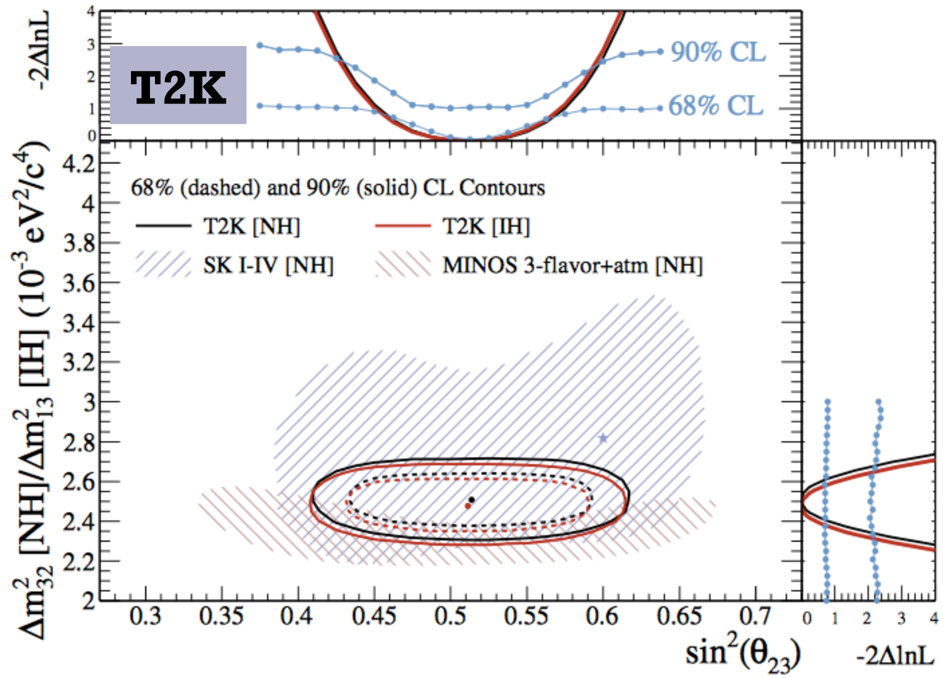


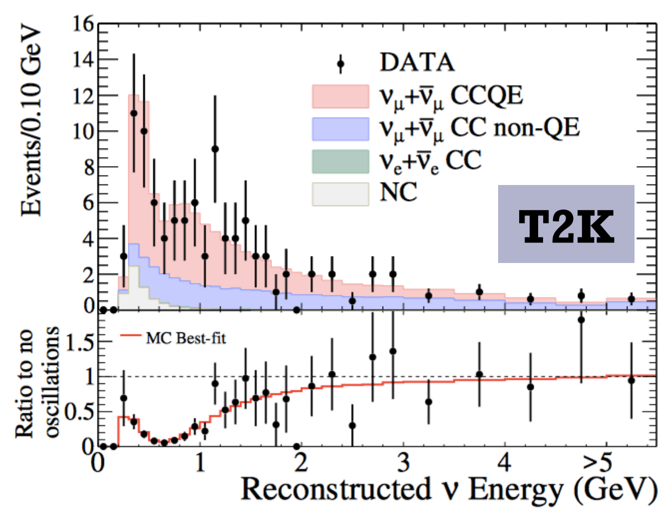
Phys. Rev. Lett. 112, 191801 (2014)

+ θ_{23} Octant?

Phys. Rev. Lett. 112, 191801 (2014)



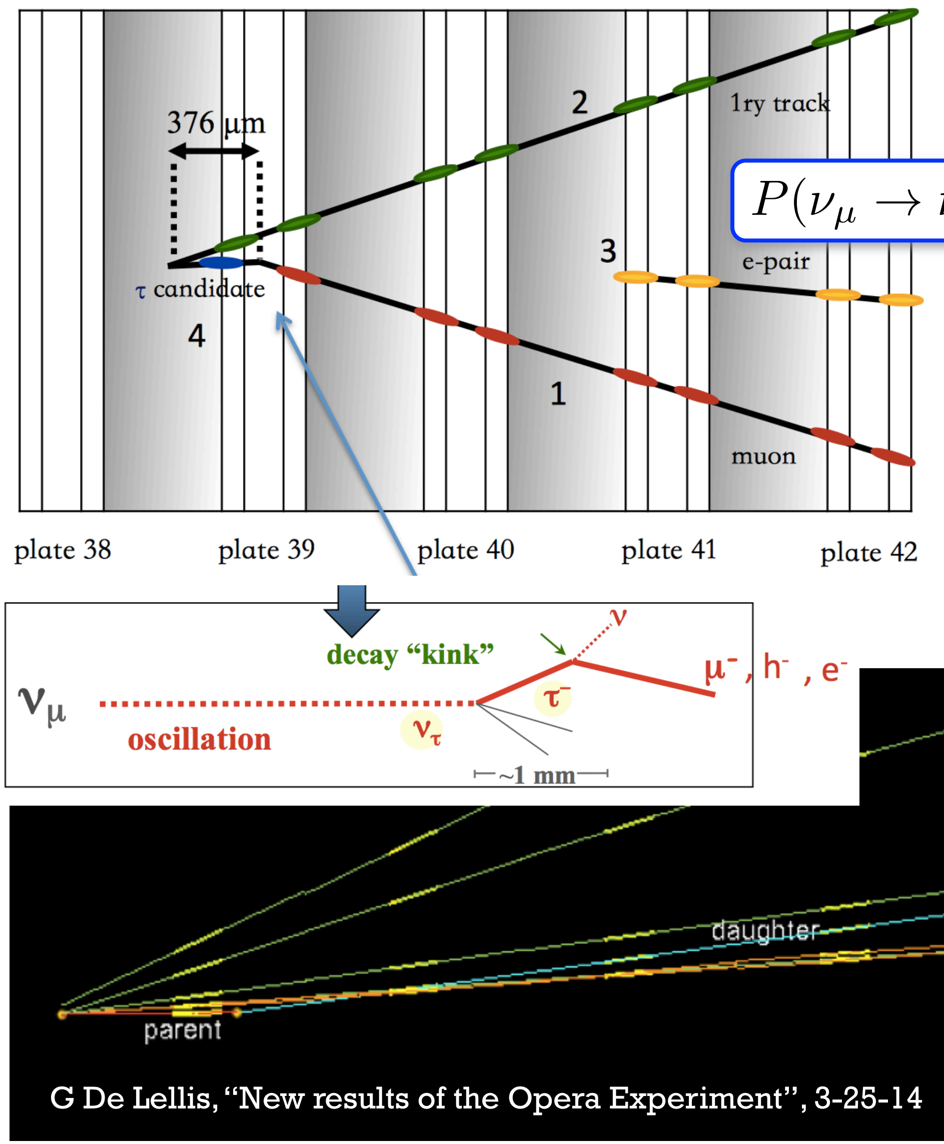




Phys. Rev. Lett. 112, 181801 (2014)

- MINOS and T2K have made initial attempt to measure the θ_{23} octant
- If θ_{23} is precisely 45°, might indicate some previously unknown symmetry
- Precise knowledge of θ_{23} = less uncertainty in studies of ν_e appearance

+ OPERA: $\nu_\mu \rightarrow \nu_\tau$ Appearance



G De Lellis, "New results of the Opera Experiment", 3-25-14

- "Disappearing" muon neutrinos in MINOS and T2K should be mostly oscillating to tau neutrinos:

$$P(\nu_\mu \rightarrow \nu_\tau) \sim \sin^2 2\theta_{23} \cos^4 \theta_{13} \sin^2(1.27\Delta m^2_{32} L/E)$$

- OPERA experiment designed to observe this oscillation, using 17 GeV muon neutrino CNGS beam
- **Detector:** magnetized, constructed from bricks of nuclear emulsion film
  - Located at LNGS (730 km)
- Have now observed **4 tau appearance events**, on top of background expectation of 0.22 evts
  - Probability of being explained by background = 1.1×10^{-5}
  - Corresponds to **$4.2\,\sigma$ significance**

+ $\nu_\mu \rightarrow \nu_e$ Appearance

$$P(\nu_\mu \rightarrow \nu_e) \cong T_1 \sin^2 2\theta_{13} - T_2 \alpha \sin 2\theta_{13} + T_3 \alpha \sin 2\theta_{13} + T_4 \alpha^2$$

$$\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}}$$

atmospheric $$T_1 = \sin^2 \theta_{23} \frac{\sin^2[(1-x)\Delta)]}{(1-x)^2}$$

interference $$T_2 = \sin \delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \sin \Delta \frac{\sin(x\Delta)}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}$$

$$T_3 = \cos \delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \cos \Delta \frac{\sin(x\Delta)}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}$$

solar $$T_4 = \cos^2 \theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(x\Delta)}{x^2}$$

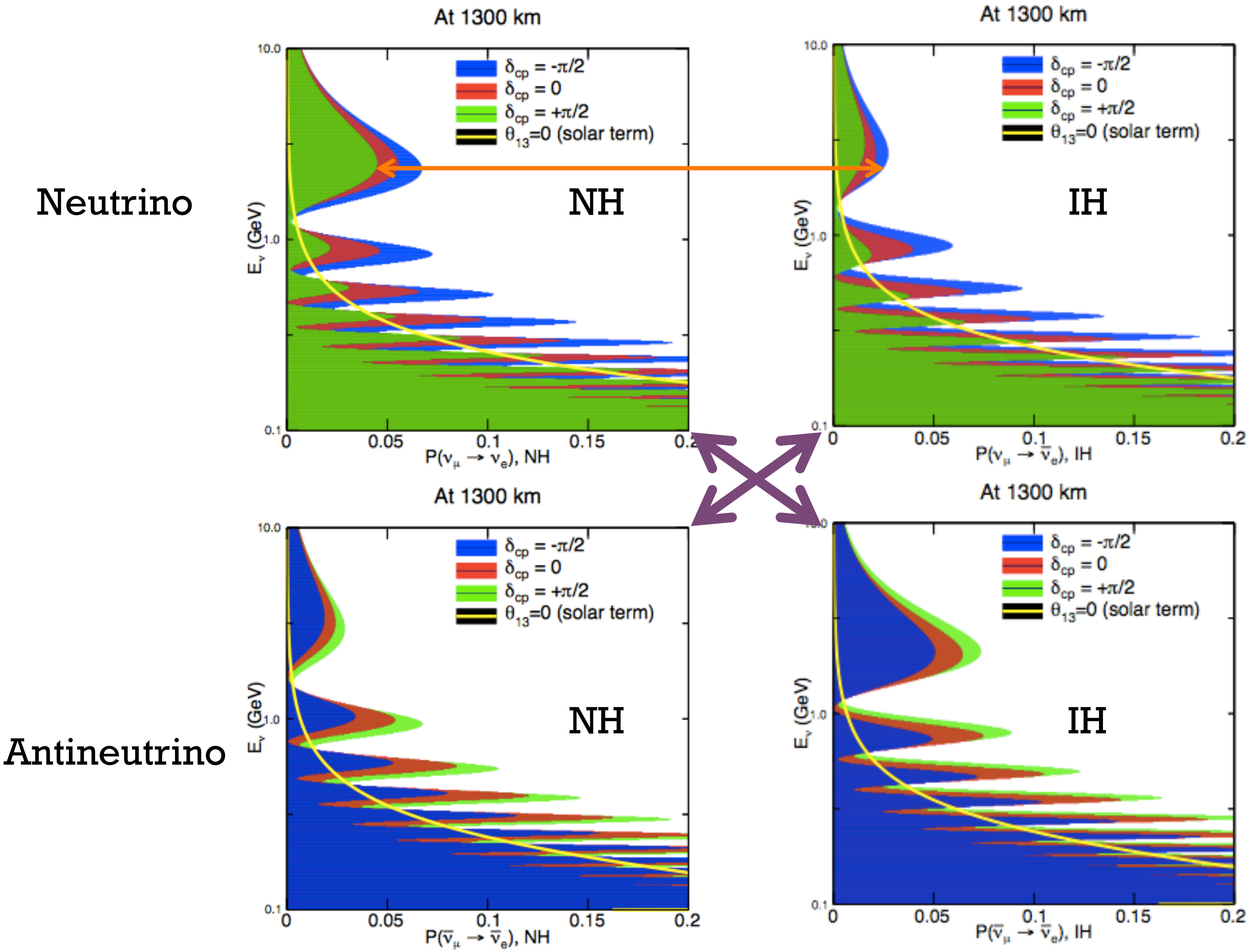
$\Delta m^2_{32} \approx \Delta m^2_{31}$

$$\Delta = \Delta m^2_{31} L/4E \qquad x = 2\sqrt{2} G_F N_e E/\Delta m^2_{31} \cong E/12 \text{ GeV}$$

- $\nu_\mu \rightarrow \nu_e$ **appearance** = connected to numerous neutrino mixing parameters:
  - **Value of θ_{13}**: now known to be non-zero, meaning other parameters can be measured
  - **Sign of Δm^2_{32}**: becomes relevant via **matter effects** which occur when beam passes through earth; sign of effect changes for anti-neutrinos
  - **Precise value and octant of θ_{23}**
  - **CP violation phase δ_{CP}**: sign of effect different for neutrinos and antineutrinos

From: Ed Kearns, ICFA January 2014

+ Degeneracies…



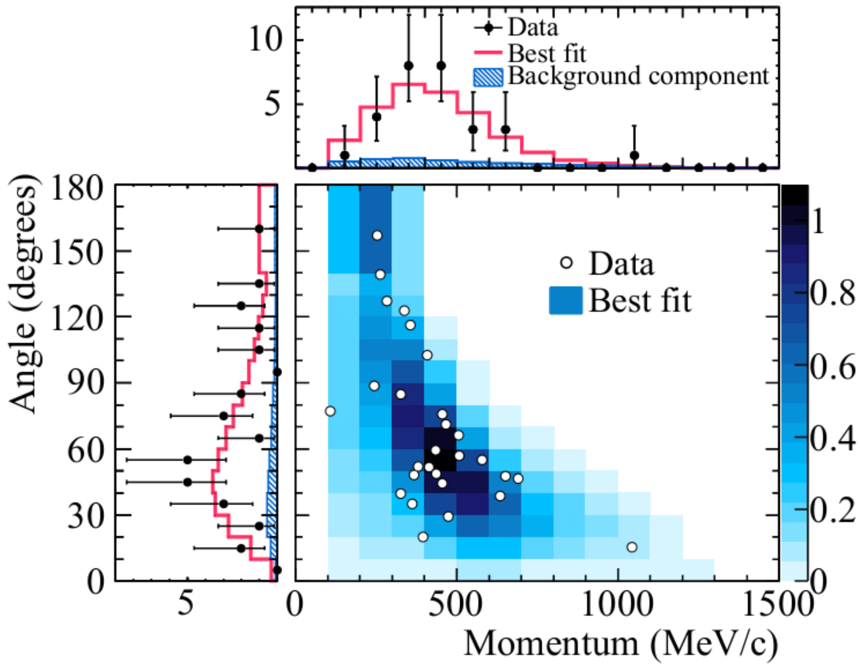
"The Long Baseline Neutrino Experiment: Exploring Basic Symmetries of the Universe" (2014)

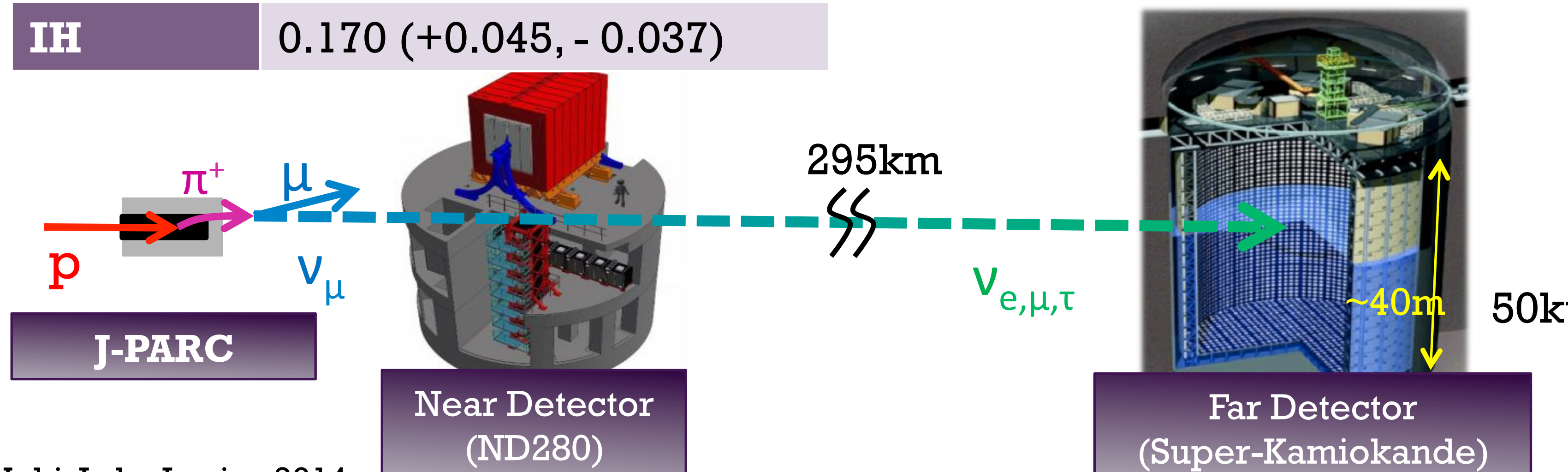
+ ν_e Appearance and θ_{13}

- **T2K (Tokai to Kamioka):**
  - Beam = off-axis muon neutrino beam produced at J-PARC, peaked at < 1 GeV, 295 km baseline
  - **Near Detector:** ND280
  - **Far Detector:** Super-Kamiokande

- 2014 best fits (±68%) for $\sin^2(2\theta_{13})$, rejecting null hypothesis at 7.3σ:

NH	0.140 (+0.036, –0.032)
IH	0.170 (+0.045, - 0.037)



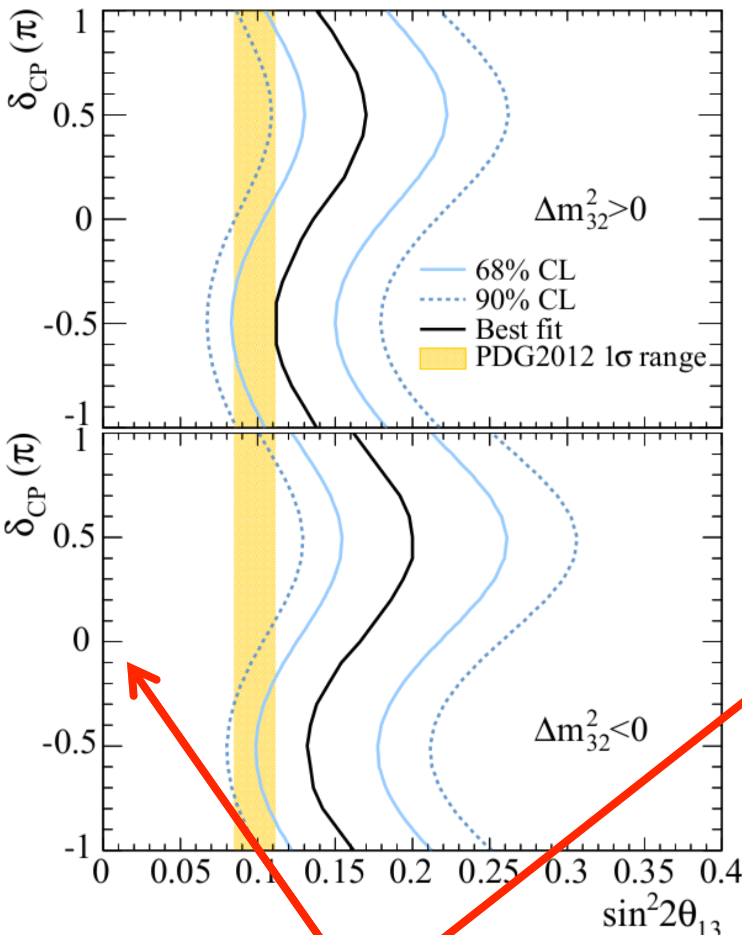


PRL 112, 061802 (2014)

K. Ieki, Lake Louise 2014

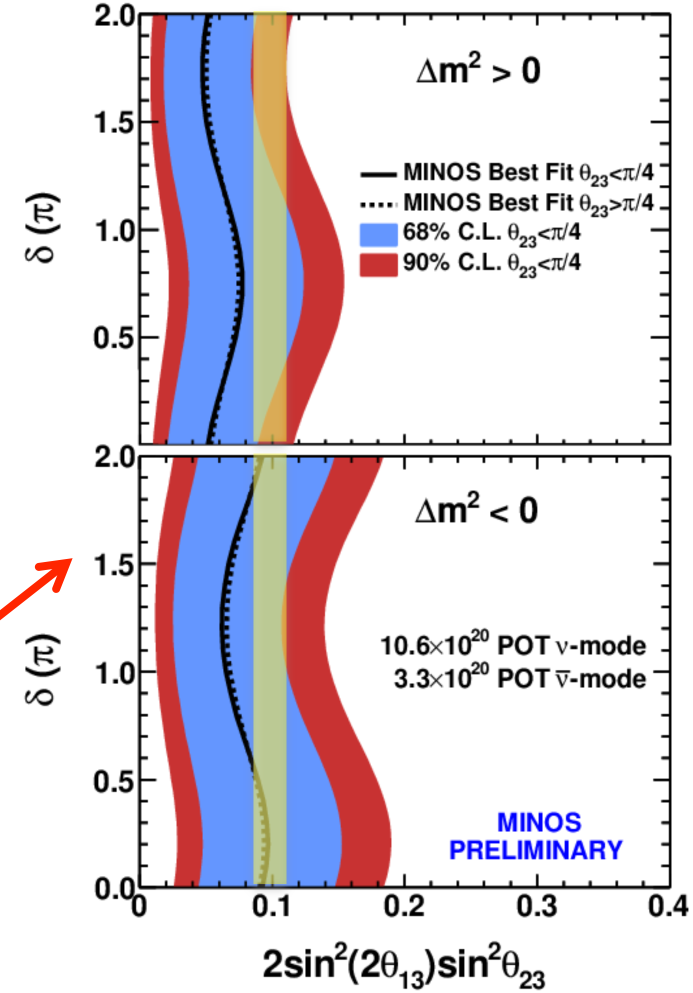
+ ν_e Appearance and θ_{13}

T2K:



PRL 112, 061802 (2014)

MINOS:

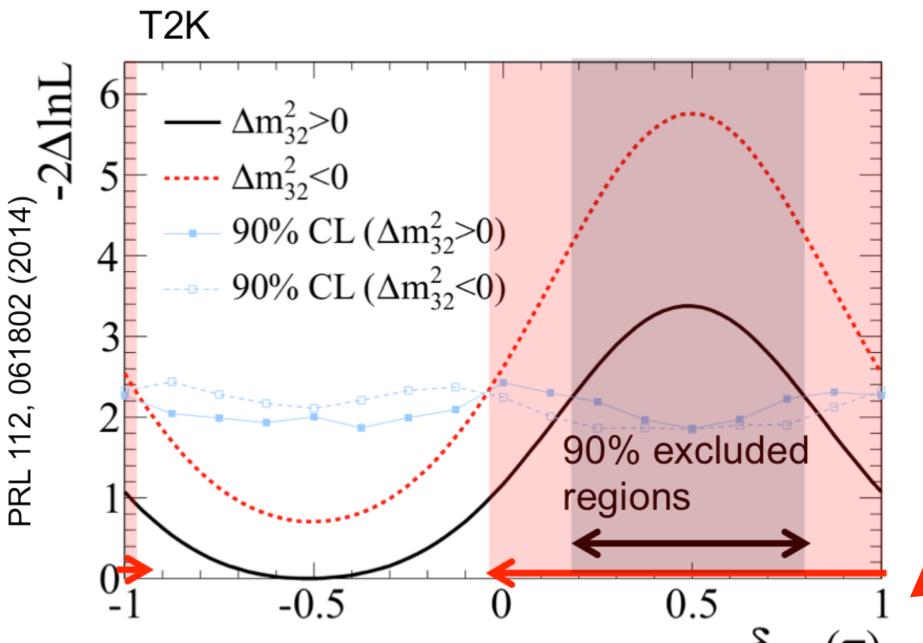


Phys. Rev. Lett. 112, 191801 (2014)

NOTE DIFFERENT Y AXIS for δ!

= 2013 PDG range for θ_{13}

+ CP and Hierarchy?



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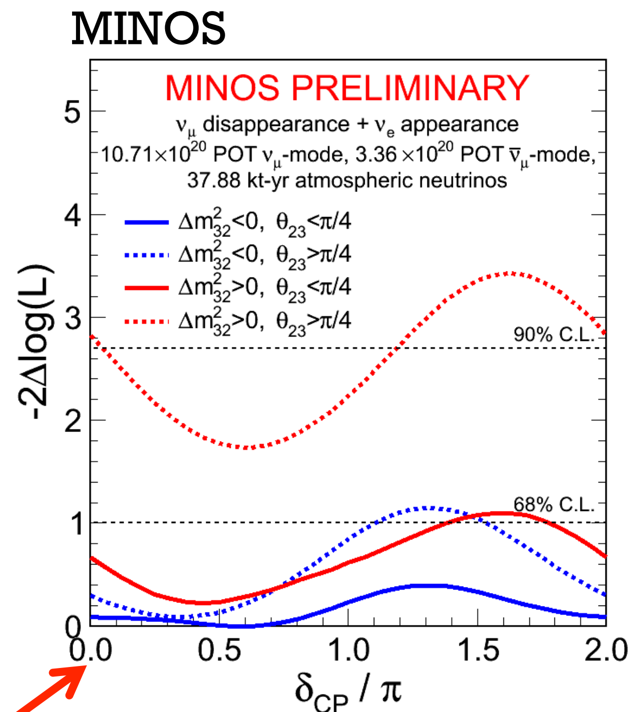
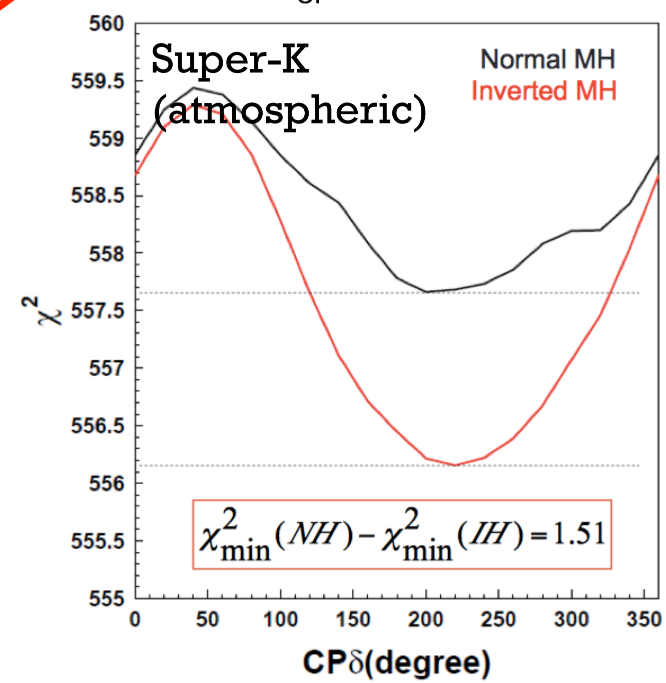


Phys. Rev. Lett. 112, 191801 (2014)



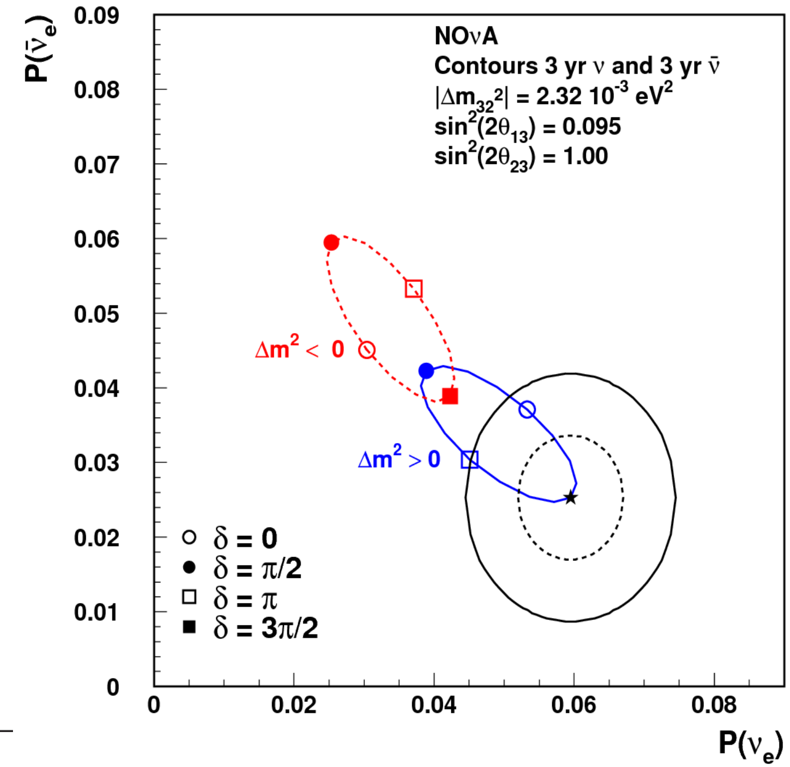
Raaf, NNN 13

- Combining ν_e appearance results with current reactor results can put limits on possible values of $\boldsymbol{\delta_{CP}}$
- MINOS results have larger impact from matter effects (hierarchy and octant)
- Contradictory! But not very strong limits
  - Need more sensitive experiments…

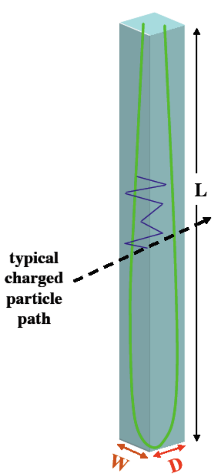
+ NOvA

- Neutrino experiment using the NuMI beam
  - Off-axis, with a 2 GeV beam peak; can be run in both neutrino and anti-neutrino mode
  - Designed to look for ν_e appearance
- **Near Detector** (0.3 kT) at FNAL, and **Far Detector** (13 kT) at Ash River (MN), 810 km away
  - For best EM shower resolution, "fully active" detector built from low-Z materials
  - Blocks of extruded PVC cells filled with liquid scintillator
  - Light collected by wavelength shifting fiber and read out by APDs

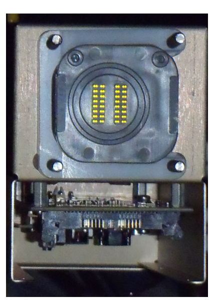
1 and 2 σ Contours for Starred Point



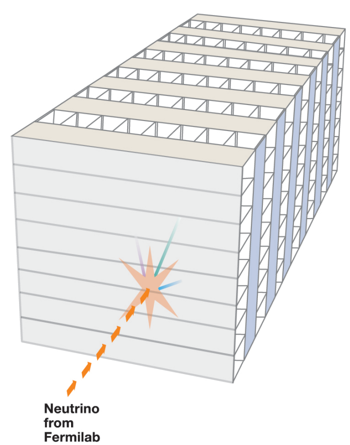
1 Channel

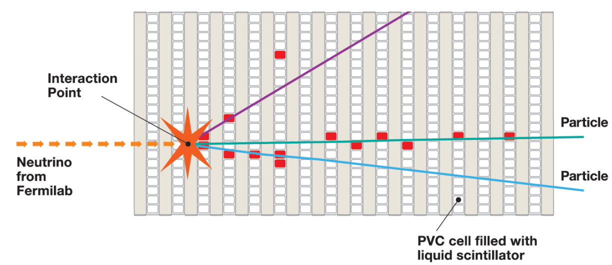


APD
32 Channels

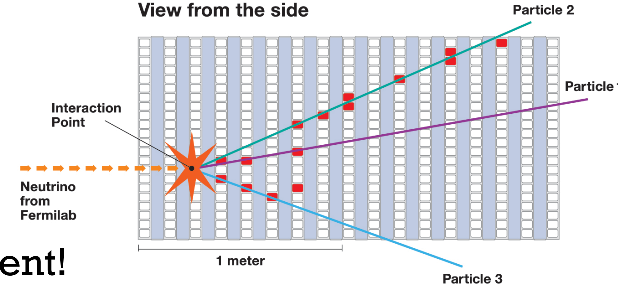


3D schematic of NOvA particle detector





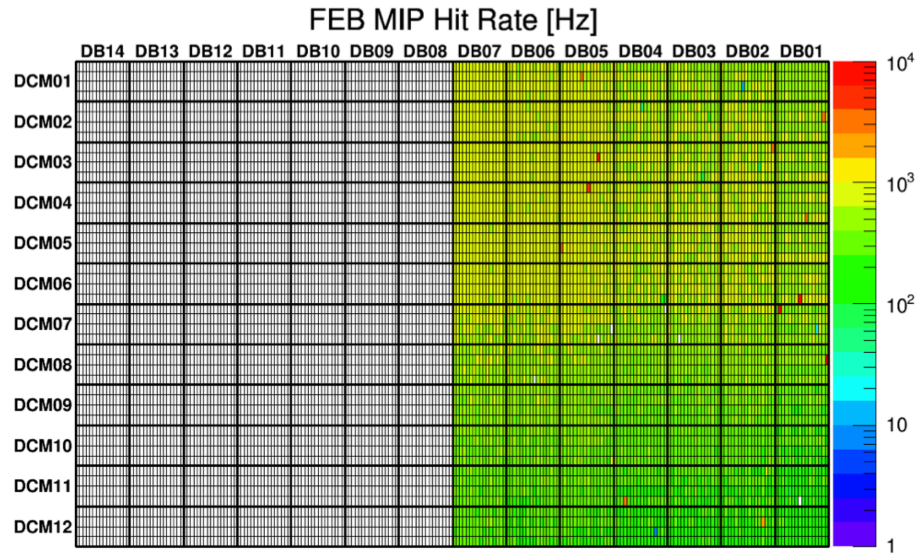
View from the side

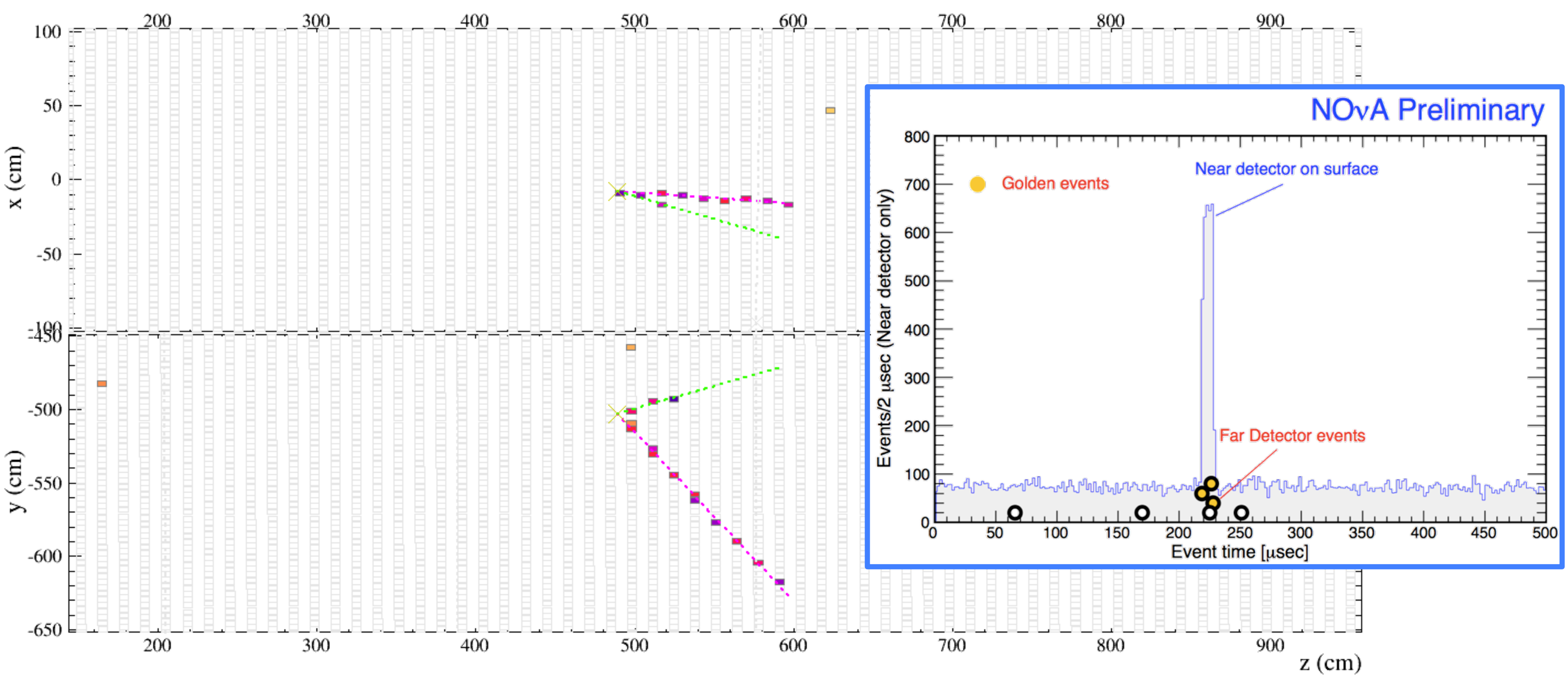


Cartoon of First Event!

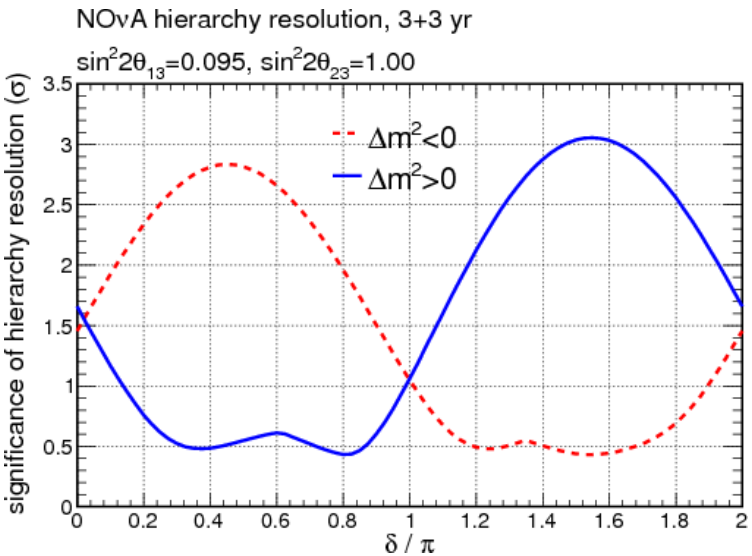
+ NOvA Status

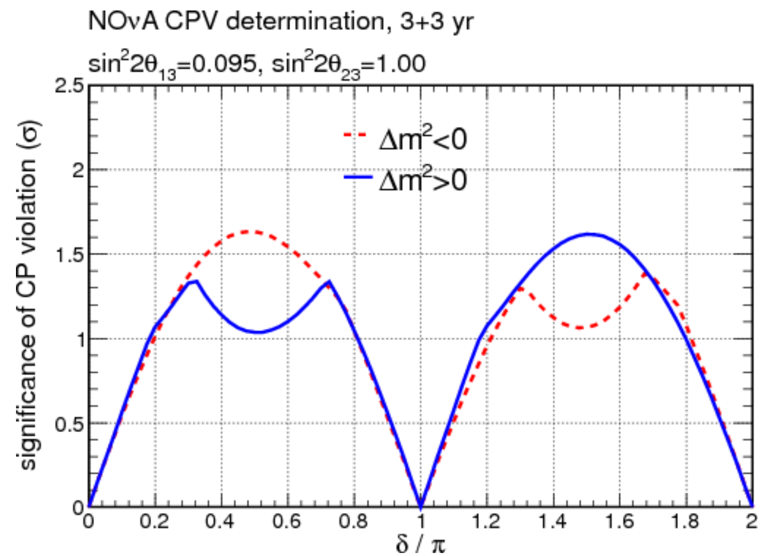
- **Far Detector:** final detector block was placed in February 2014
  - All filled, currently being instrumented (completing this summer)
  - Data is being collected, and have observed beam peak!
- **Near Detector:** all blocks placed and filled, currently being instrumented as well

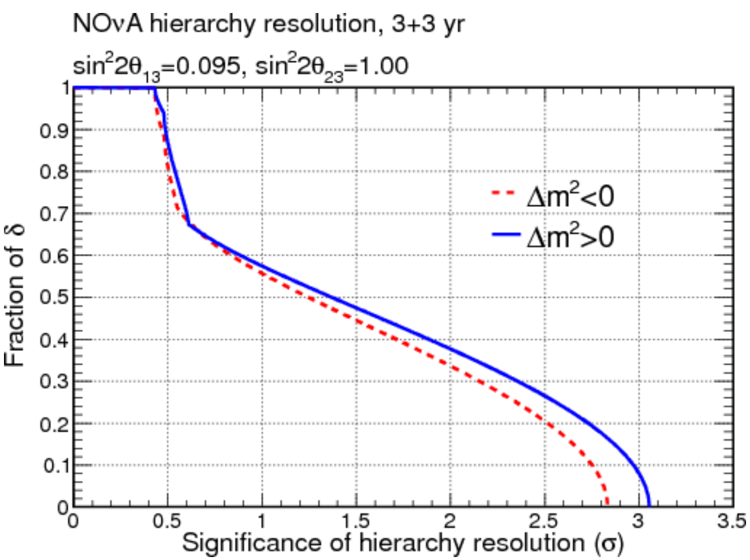


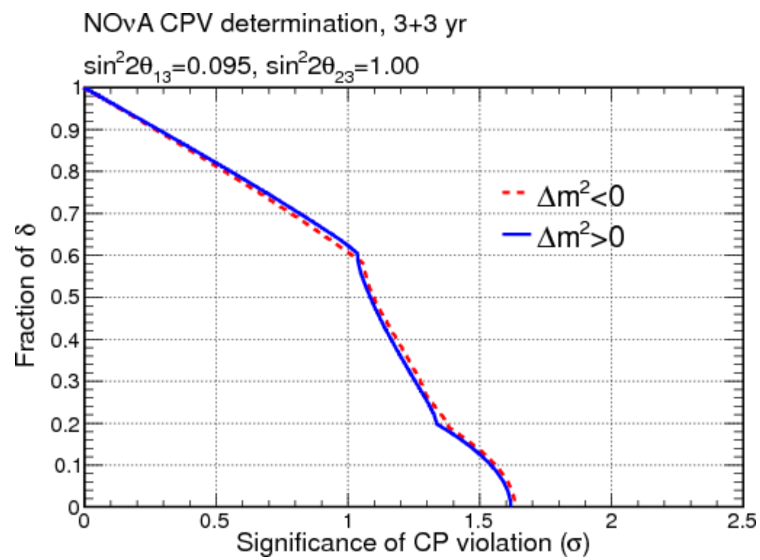


+ NOvA

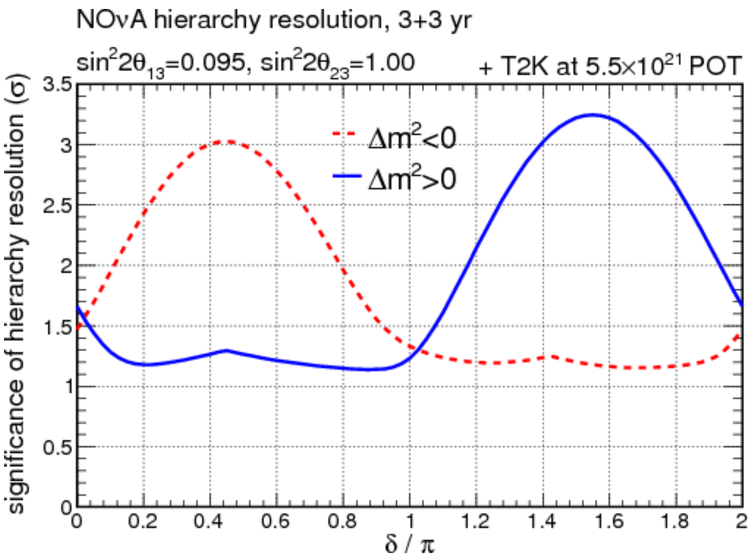

NOνA hierarchy resolution, 3+3 yr
sin²2θ13=0.095, sin²2θ23=1.00
Δm²<0
Δm²>0
significance of hierarchy resolution (σ)
δ / π
0
0.5
1
1.5
2
2.5
3
3.5
0.2
0.4
0.6
0.8
1.2
1.4
1.6
1.8

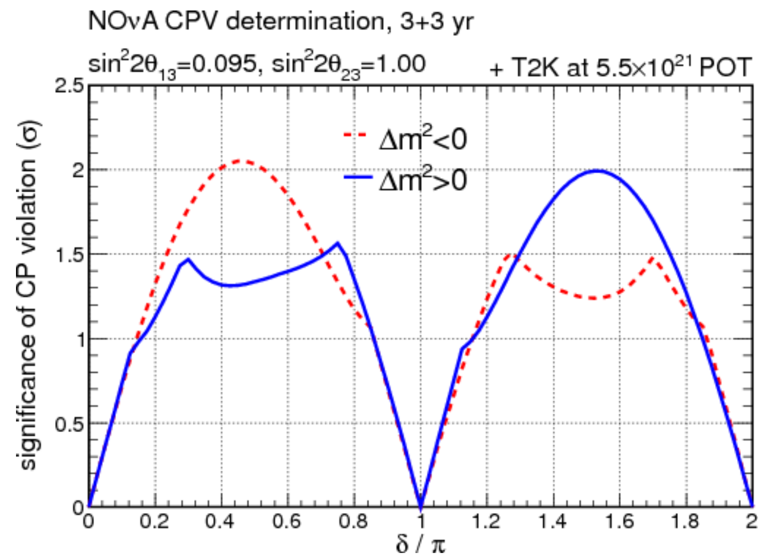

NOνA CPV determination, 3+3 yr
sin²2θ13=0.095, sin²2θ23=1.00
Δm²<0
Δm²>0
significance of CP violation (σ)
δ / π
0
0.5
1
1.5
2
2.5
0.2
0.4
0.6
0.8
1.2
1.4
1.6
1.8

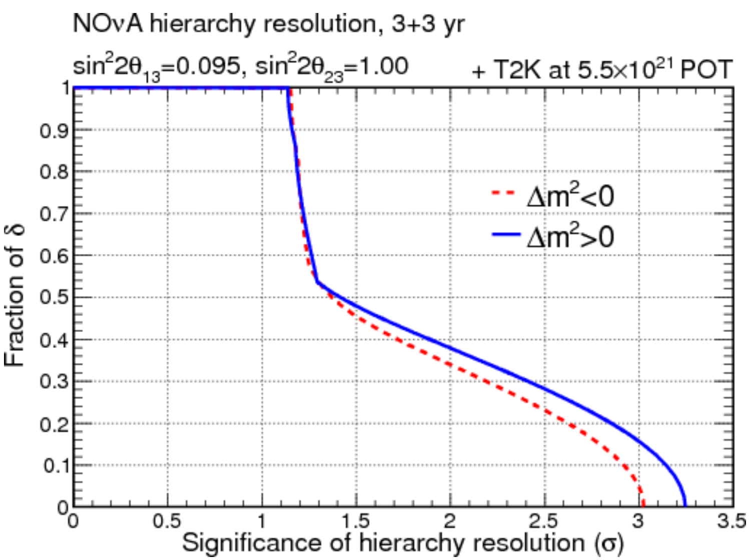

NOνA hierarchy resolution, 3+3 yr
sin²2θ13=0.095, sin²2θ23=1.00
Δm²<0
Δm²>0
Fraction of δ
Significance of hierarchy resolution (σ)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.5
2
2.5
3
3.5


NOνA CPV determination, 3+3 yr
sin²2θ13=0.095, sin²2θ23=1.00
Δm²<0
Δm²>0
Fraction of δ
Significance of CP violation (σ)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.5
2
2.5

+ NOvA + T2K


NOvA hierarchy resolution, 3+3 yr
sin²2θ13=0.095, sin²2θ23=1.00
+ T2K at 5.5×10²¹ POT
Δm²<0
Δm²>0
significance of hierarchy resolution (σ)
δ / π


NOvA CPV determination, 3+3 yr
sin²2θ13=0.095, sin²2θ23=1.00
+ T2K at 5.5×10²¹ POT
Δm²<0
Δm²>0
significance of CP violation (σ)
δ / π


NOvA hierarchy resolution, 3+3 yr
sin²2θ13=0.095, sin²2θ23=1.00
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Δm²<0
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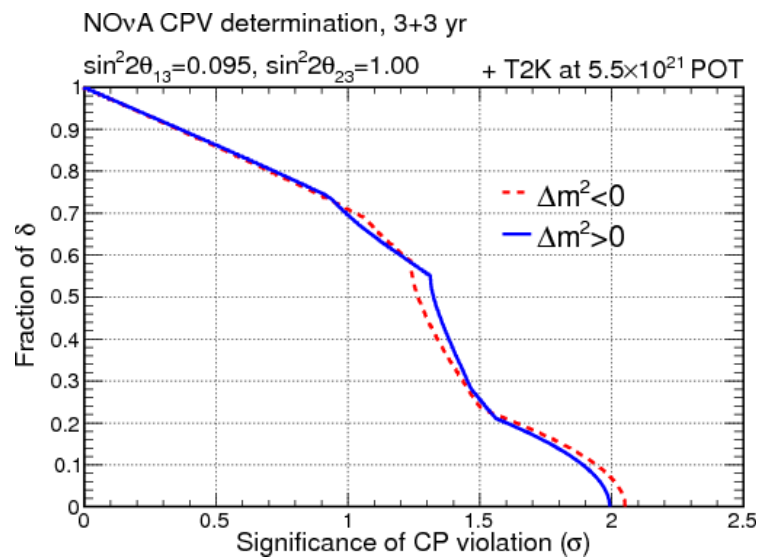
Fraction of δ
Significance of hierarchy resolution (σ)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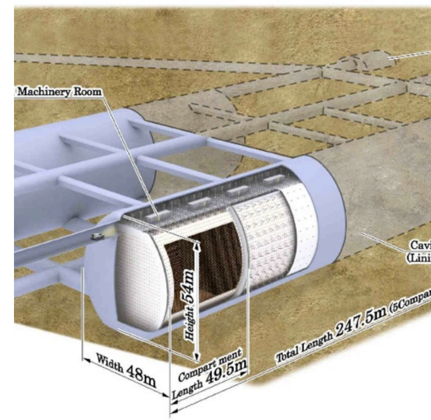
+ T2K at 5.5×10²¹ POT
Δm²<0
Δm²>0
Fraction of δ
Significance of CP violation (σ)

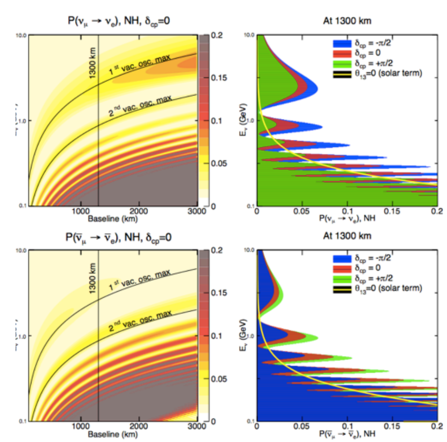
+

- Need more powerful generation of experiments to resolve degeneracy between mass hierarchy and δ_{CP}…

Future Experiments and the Search for CP Violation

LBNE, Hyper-K, LBNO, new neutrino sources

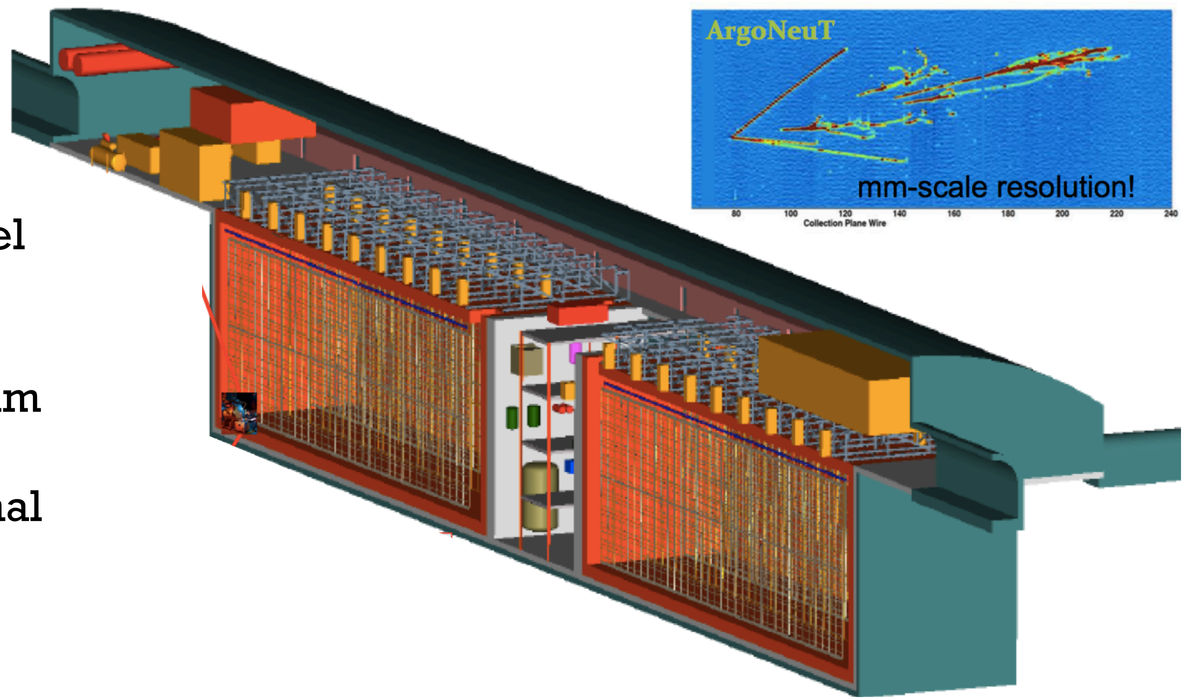


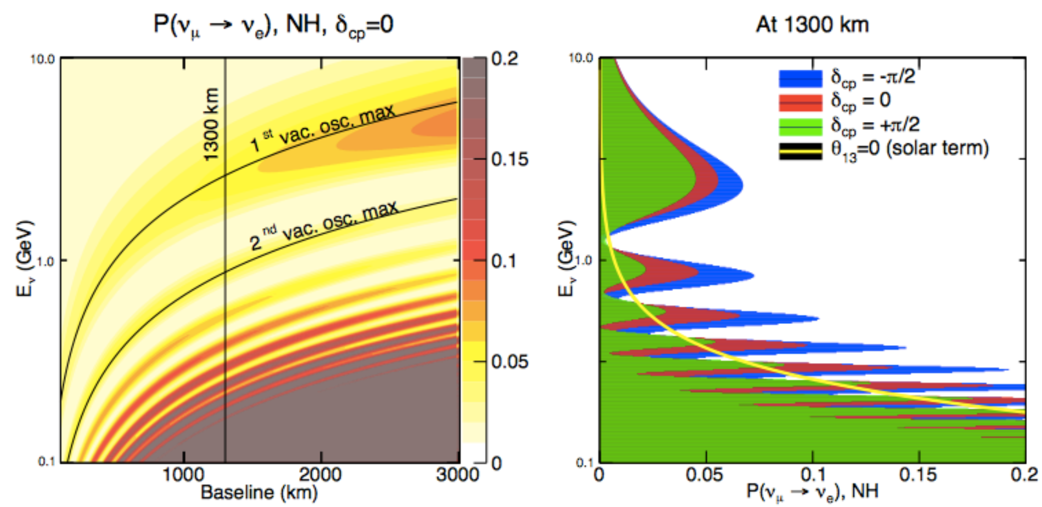


+ ~~LBNE~~ LBNF

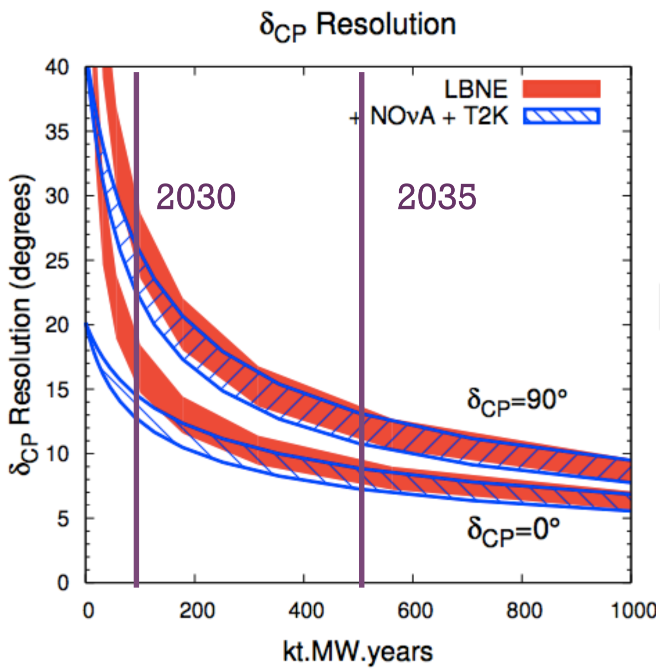
P5 Draft available at:
http://science.energy.gov/hep/hepap/meetings/

- **Long Baseline Neutrino ~~Experiment~~ Facility**
- **Far Detector:** Liquid Argon TPC, goal is 35 kt fiducial volume, at Sanford 4850 ft level
- **Near Detector:** Fine grained, high-resolution (at FNAL)
- **Beam:** intense wideband beam from FNAL, >1 MW (PIP-II)
  - 1300 km beamline, optimal for oscillation studies
- **Longer baseline** = larger influence from matter effects
  - Larger enhancement/ suppression of ν_e appearance due to sign of mass hierarchy
  - At LBNE baseline, this asymmetry exceeds the impact from CP violation and reduces MH/CP ambiguity

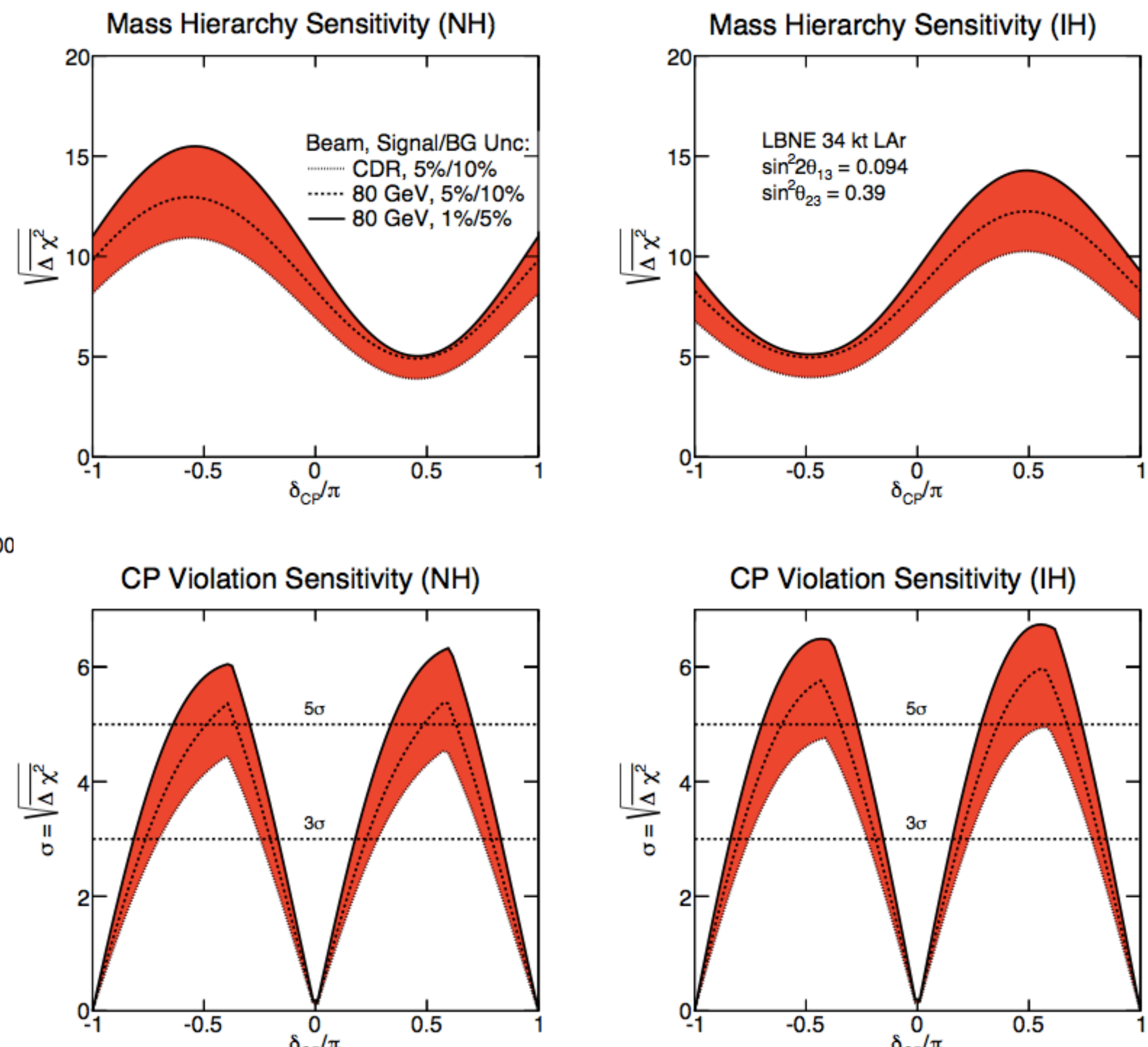




+ LBNE Reach Studies



3yr nu + 3yr anti-nu:



- After several years' running, can accomplish minimum **5σ** measurement of mass hierarchy
- **σ≈5** for ~50% of δ_{CP}
- **P5 Report, May 2014:** recommends forming new international experiment to accomplish **5σ** for 75% of δ_{CP}

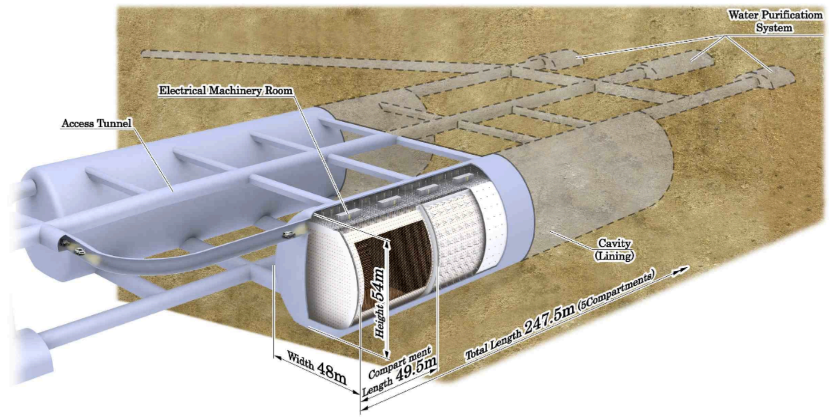
"The Long Baseline Neutrino Experiment: Exploring Basic Symmetries of the Universe" (2014)

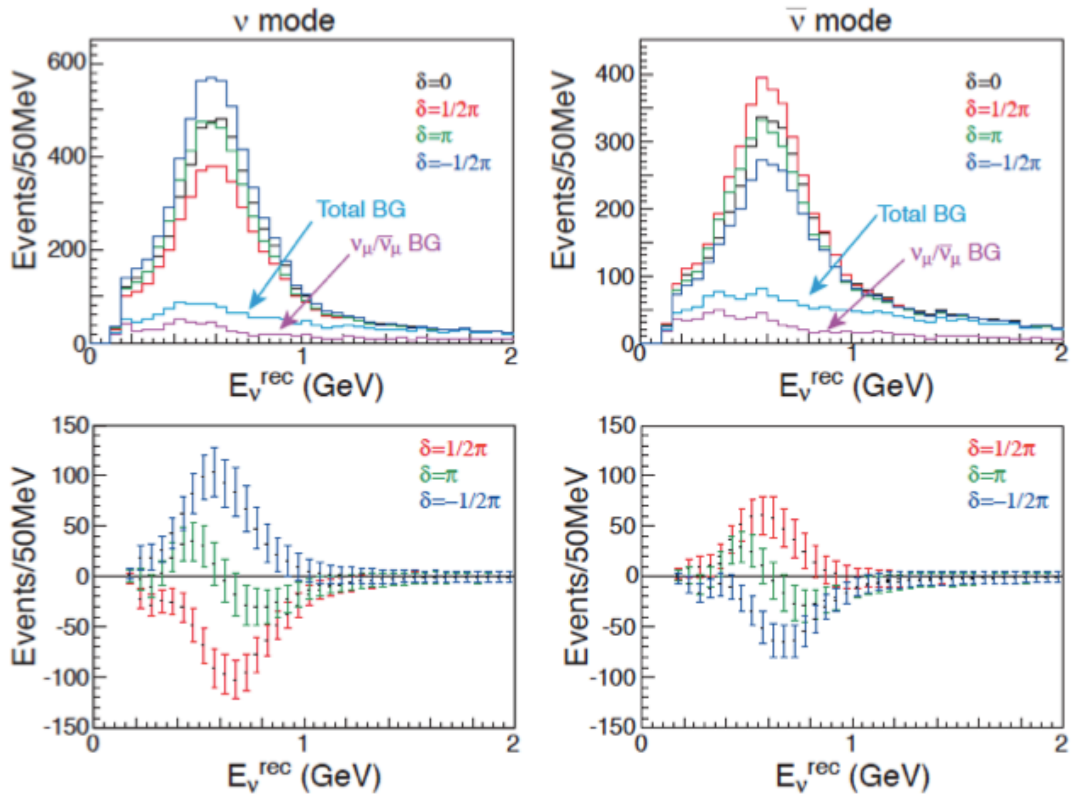
+ Hyper-K

- **Proposed detector:** 0.99 MT (0.56 MT fiducial) water separated into two tanks
  - 99K 20" PMTs (inner det) + 25K 8" PMTs (outer det)
  - **25x the size of Super-Kamiokande**

- **Beam:** Off-axis ~MW beam from J-PARC at baseline of 295km, peaked at ~0.6 GeV
- Aim for high statistics, excellent signal/bkgd separation at <1 GeV, better than 5% syst error

- Upgrade ND280 for better flux and cross-section measurements
- New WC Near Detector at 2-3 km?



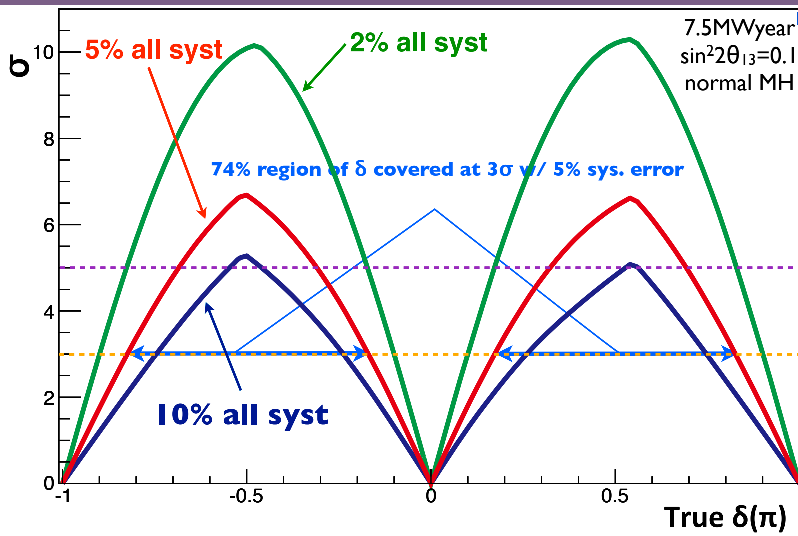


F. Di Lodovico, ICFA Neutrino European Meeting, Jan 2014

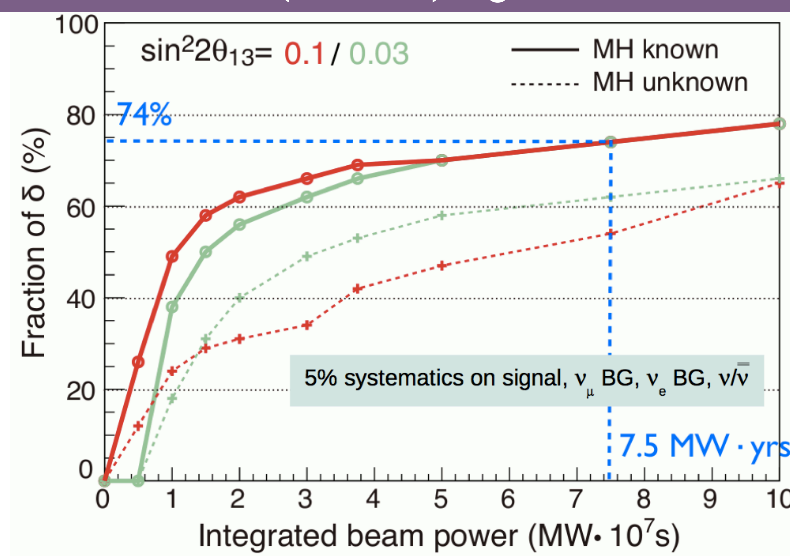
+ Hyper-K

F. Di Lodovico, ICFA Neutrino European Meeting, Jan 2014

CP Discovery Sensitivity (w/ MH Known)

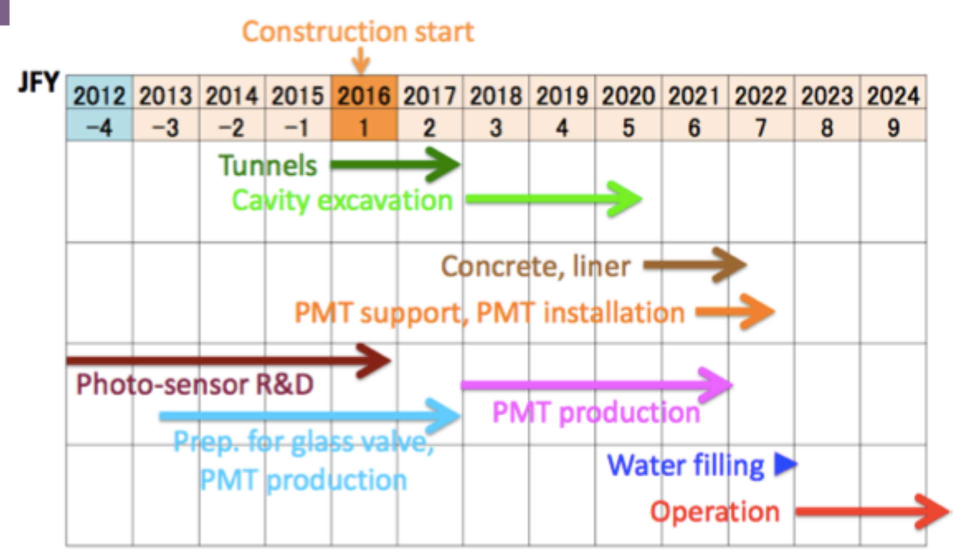


% of δ w/ CPV (sin δ ≠0) significance > 3 σ



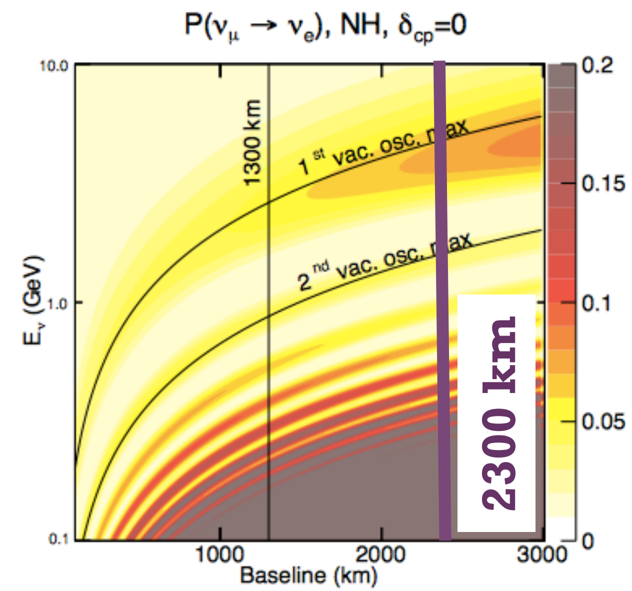
- With 7.5 MW•yr (1.5 MW x 5yrs), can cover CPV > 3σ (5σ) for 74%(55%) of delta range
- 3σ mass hierarchy determination for $\sin 2\theta_{23}$ > 0.42 (0.43) for normal (inverted) hierarchy for 10 yrs' data

- Aim to begin construction of 1kt WC prototype in 2016
  - Overall construction = 7 years, assuming funding available 2016

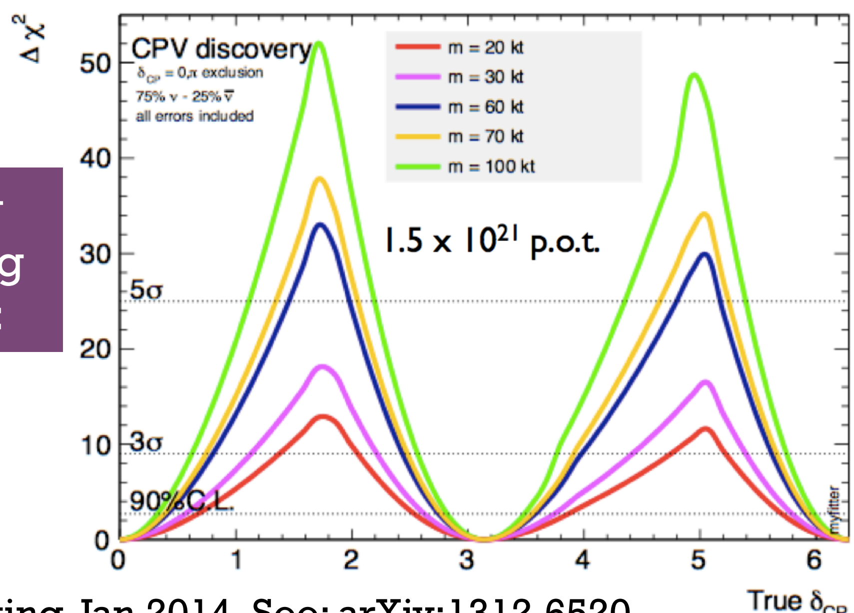


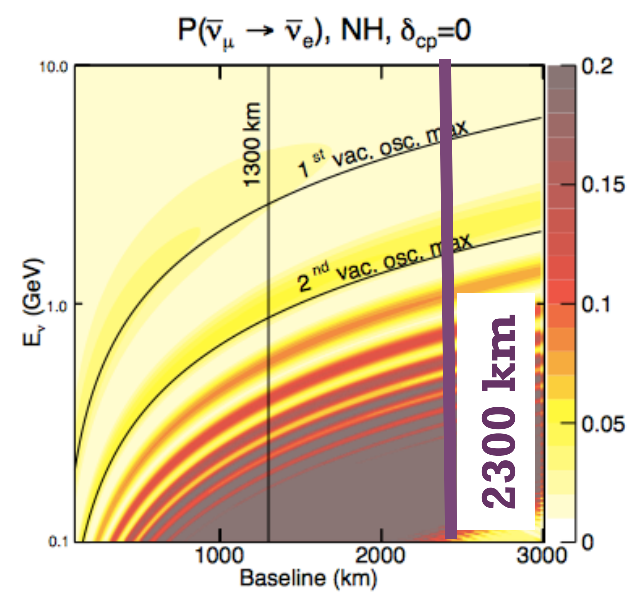
+ LBNO/LAGUNA

- **LAGUNA/LBNO:**
  - Beam from CERN to far detector at proposed baseline of 2300km
  - Can begin to see 2nd oscillation peak , where there is event greater sensitivity to $\boldsymbol{\delta_{CP}}$
- **Phase I:** 20kt LAr / 750kW conventional beam
  - Guaranteed 5σ sensitivity for MH in 5 years
- **Phase II:** 70kt detector, 2 MW beam
  - Can reach 5σ CPV coverage



5 years running after determining mass hierarchy:





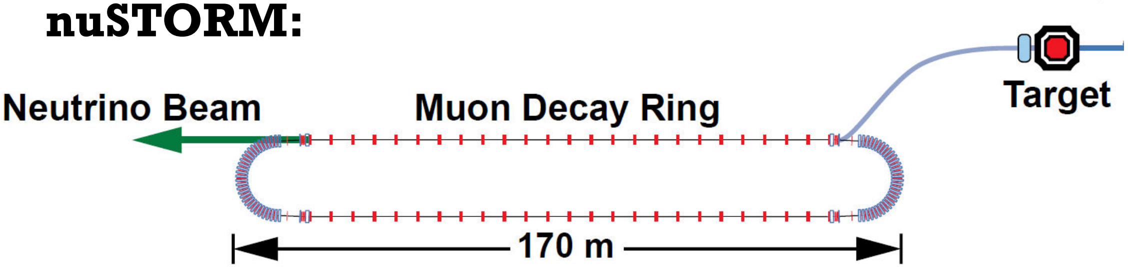
T. Patzak, ICFA Meeting, Jan 2014 See: arXiv:1312.6520

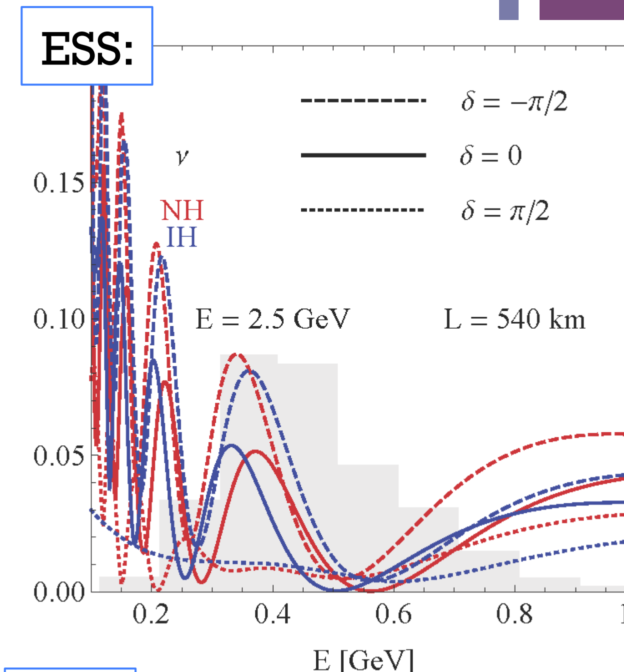
+ New Neutrino Sources

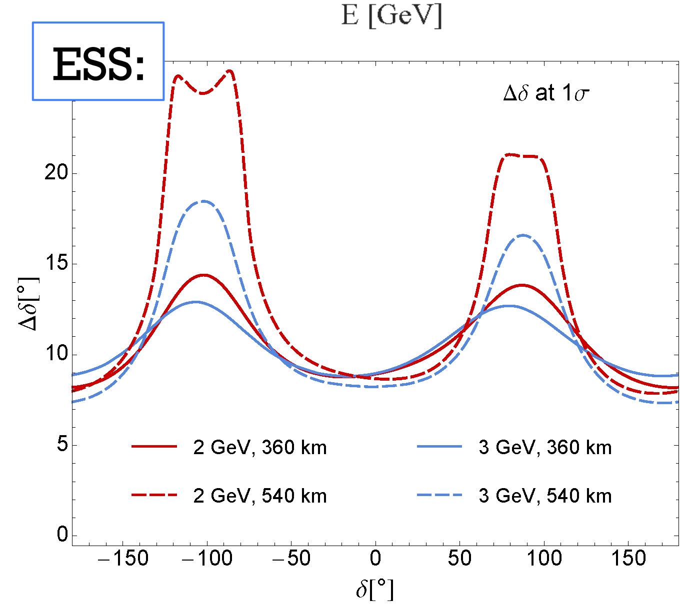
- **European Spallation Source:** currently being built in Lund, Sweden
  - Will have ~2 GeV 5 MW super-conduction LINAC
  - At least two times higher intensity than any other planned proton driver for a neutrino beam
    - First beam 2019, full power by 2022
  - Very high statistics; lower energy beam (<1 GeV); can put detector at 2nd oscillation max w/ relatively short baseline (~500-1000km)

- **New neutrino sources from stored muons:**
  - nuSTORM (funding?), Neutrino Factory, etc.
  - Reduced systematics from beam, good understanding of flux

nuSTORM:

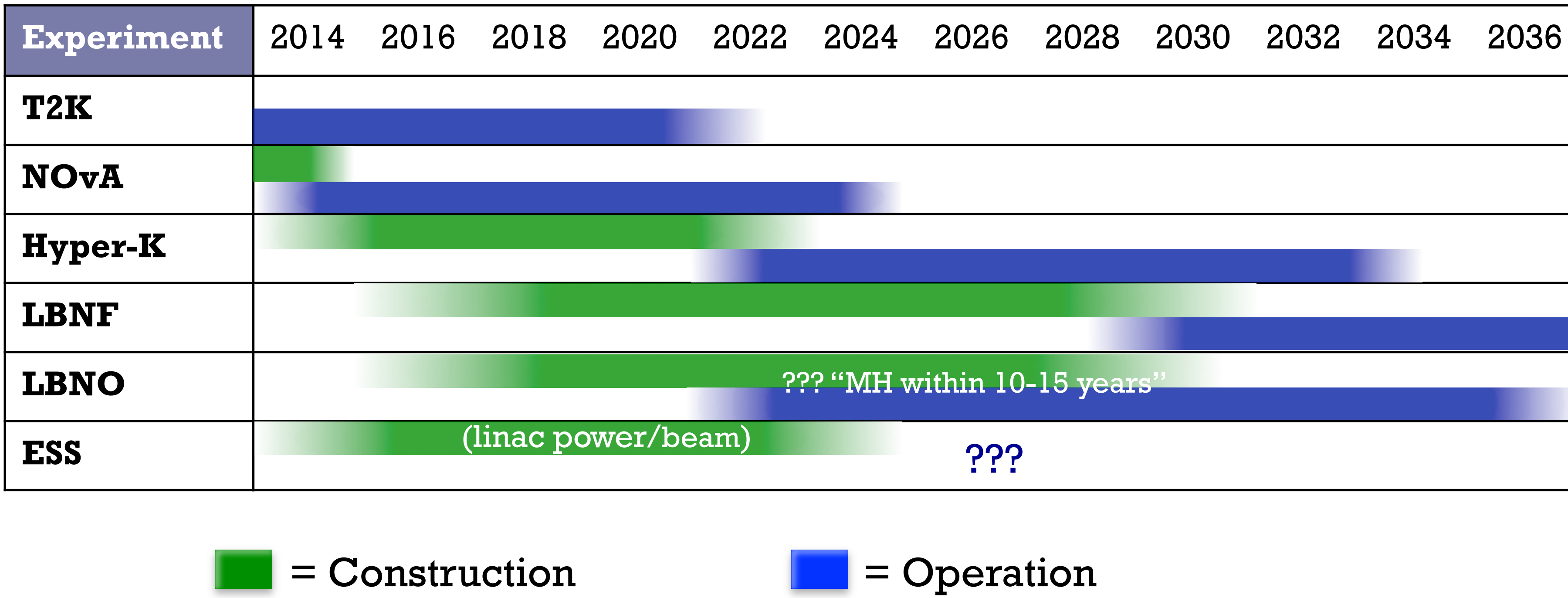






T. Ekelof, ICFA Jan 2014 (arXiv:1309.7022)

+ A (Very Rough) Timeline



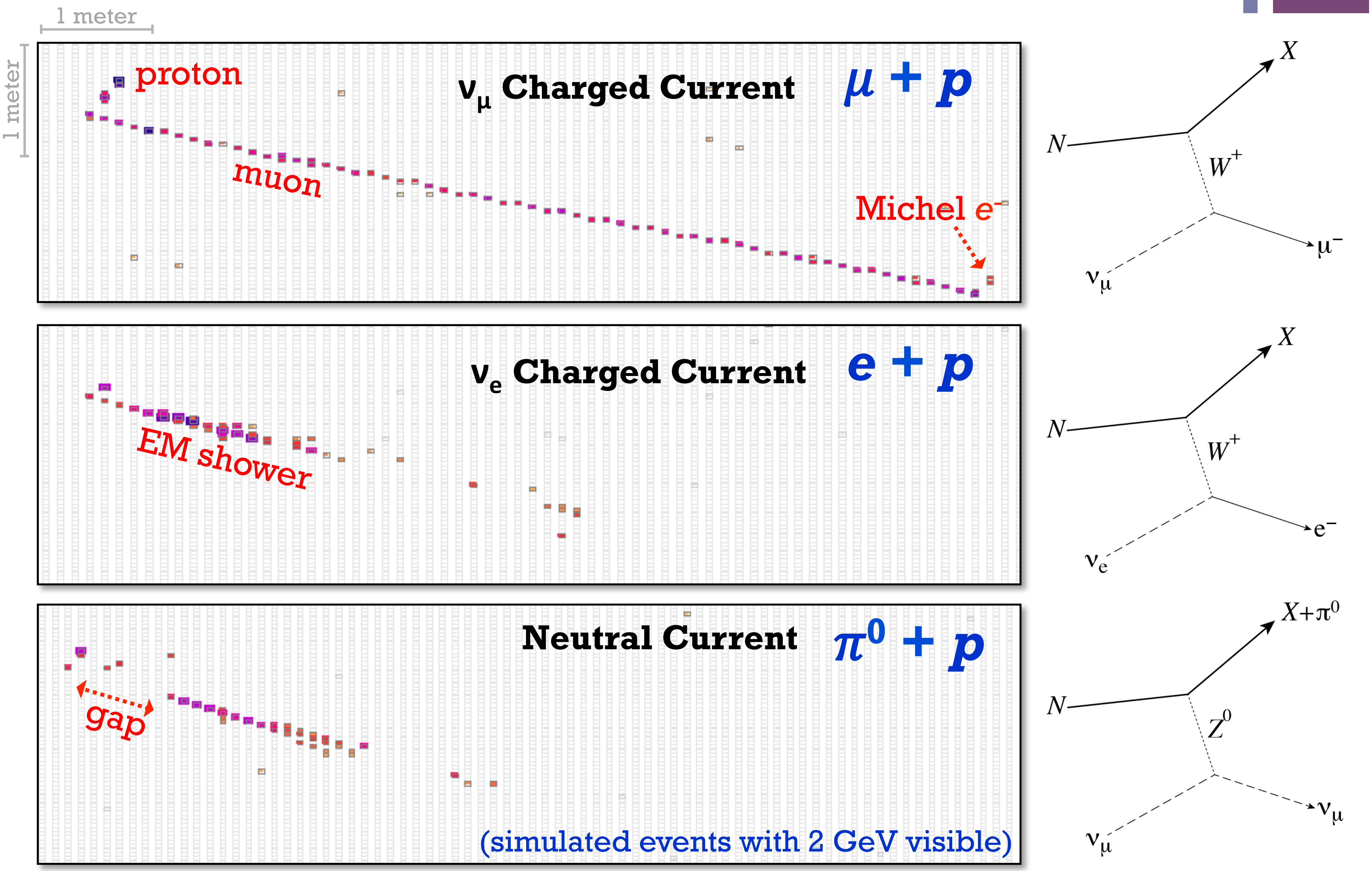
- Above estimates = based on January ICFA talks, funding reports, etc.
- **This is highly approximate and subject to change**
  - All end dates are extremely rough estimates
  - Heavily dependent on future funding decisions
  - Will probably hear more updates **next week**, at Neutrino 2014 in Boston

Conclusions

- We now have measurements of most of the major parameters involved in neutrino oscillations (mixing angles, mass differences)
- Long baseline experiments provide key measurements and independent verifications
- Using current and next-gen experiments, can now begin to answer some very interesting questions
  - **Especially: can we see CP Violation in the lepton sector?**

+ Backup Slides

+ Neutrino Events (NOvA Example)



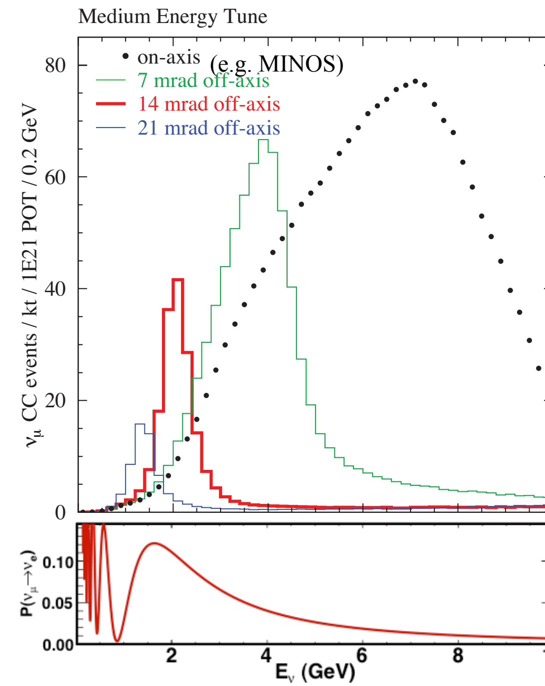
Source: Ryan Patterson, Caltech, Neutrino 2012 NOvA Talk

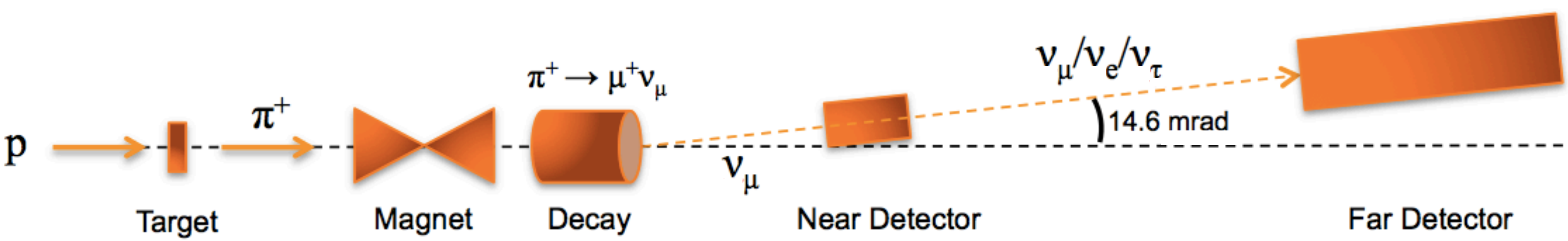
+ Beamline Example: NuMI

- **Production:** 120 GeV p+ from Main Injector collides with graphite target to produce hadrons (mostly pions and kaons)
- **Focusing:** Two magnetic focusing horns focus hadrons
  - Focus pi+/K+ for neutrino beam
  - Focus pi-/K- for antineutrino beam
- **Decay:** Hadrons decay in 675 m long decay pipe
  - End = on-axis wide-band muon neutrino beam
- **Off-axis beam:** take advantage of angular dependence of final neutrino energy from two-body hadron decay:

$$E_\nu = \frac{\left(1 - \frac{m_\mu}{M^2}\right) E}{1 + \gamma^2 \tan^2 \theta_\nu}$$

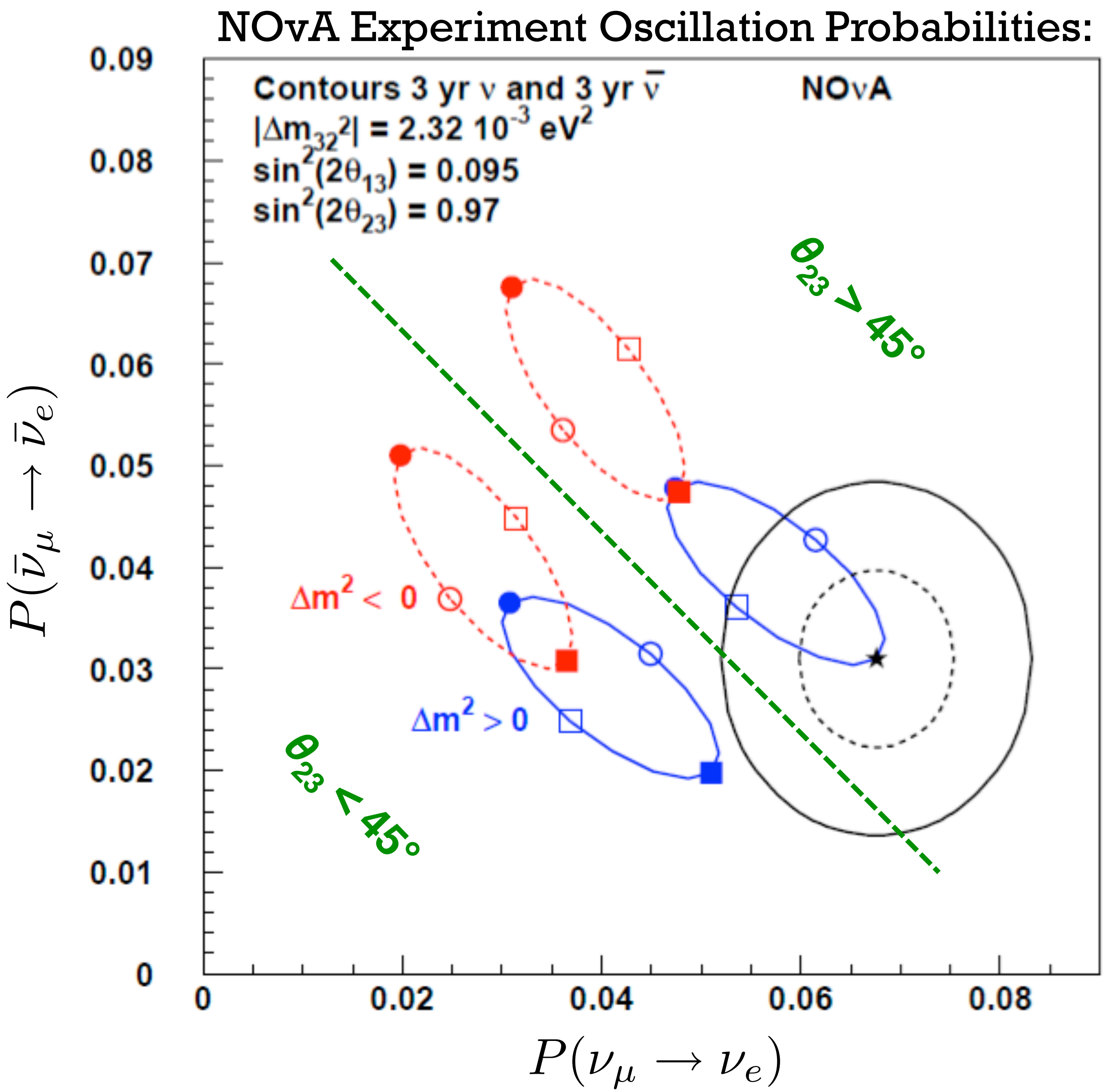
  - Lower intensity, but narrower energy profile (can design so this is at L/E oscillation peak!)





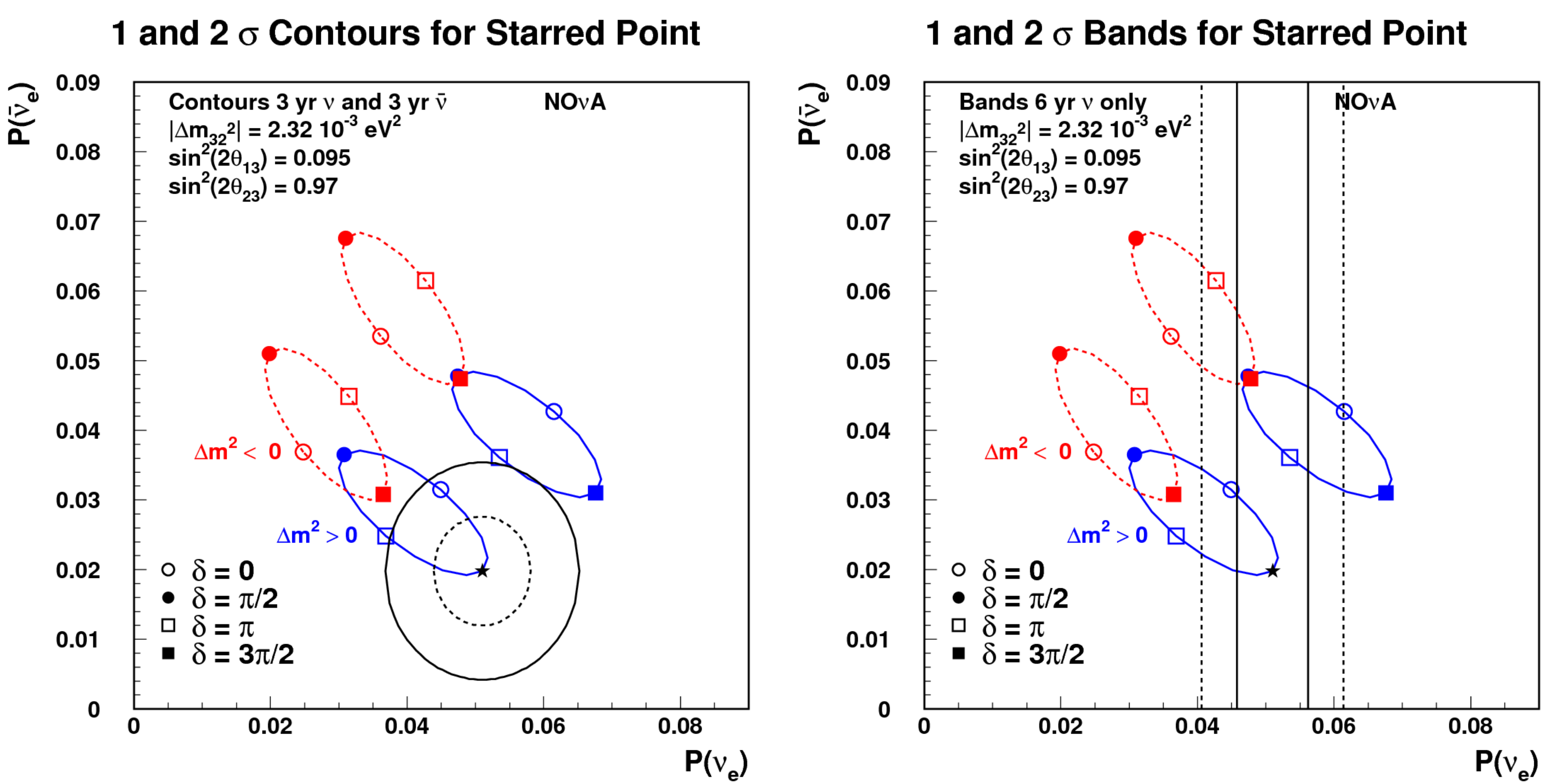
Source: M. Frank, NuInt 2014

Effect of Octant on $\nu_\mu \rightarrow \nu_e$

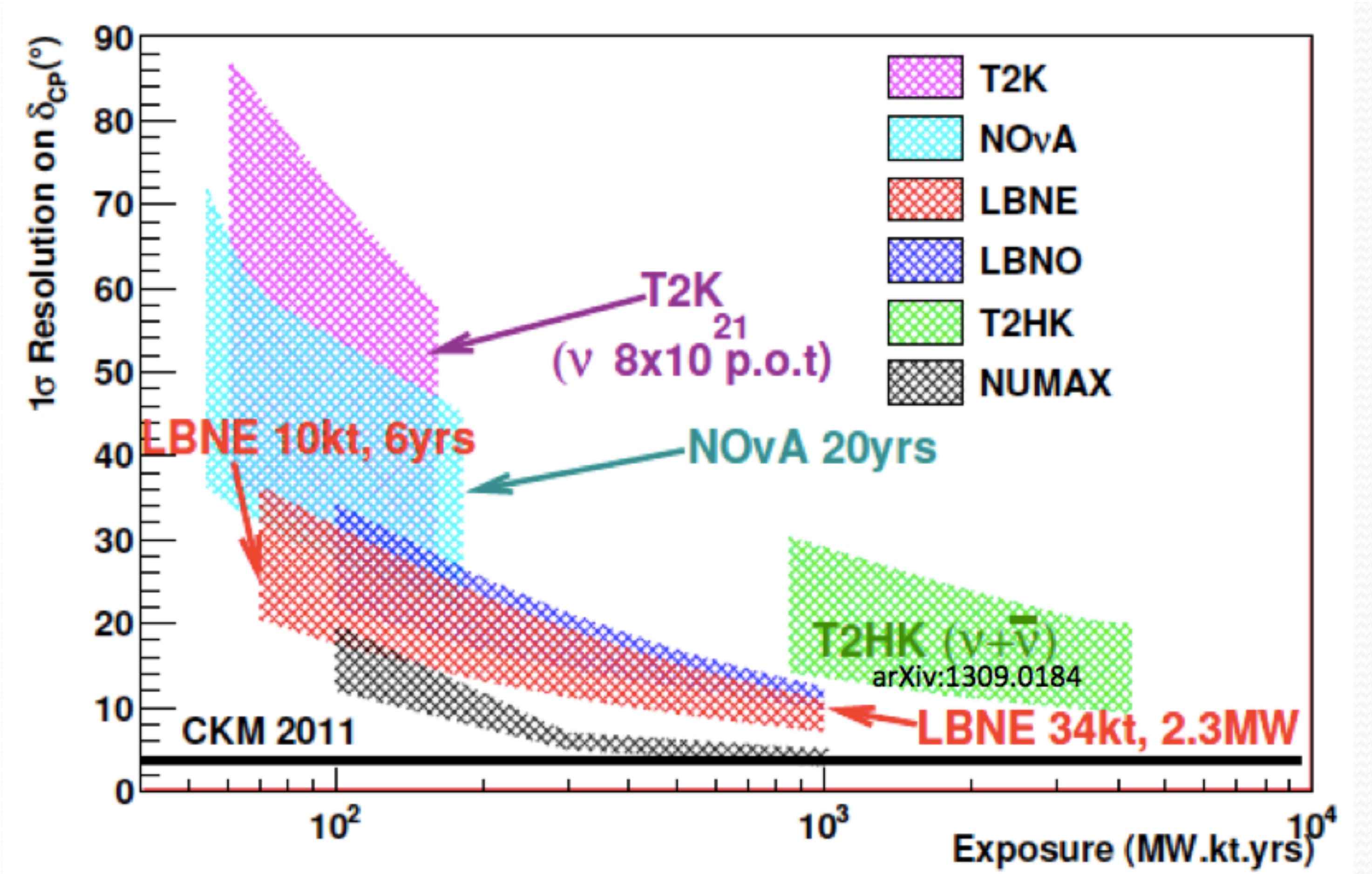


- Measurements of $\sin^2(2\theta_{23})$ show it is close to unity
- Is it in fact unity, or does it fall into one of two "octants"?:
  - $\theta_{23} > 45°$
  - $\theta_{23} < 45°$
- The value of θ_{23} will have an effect on appearance probability for both neutrinos and anti-neutrinos.

NOvA Octant Plots

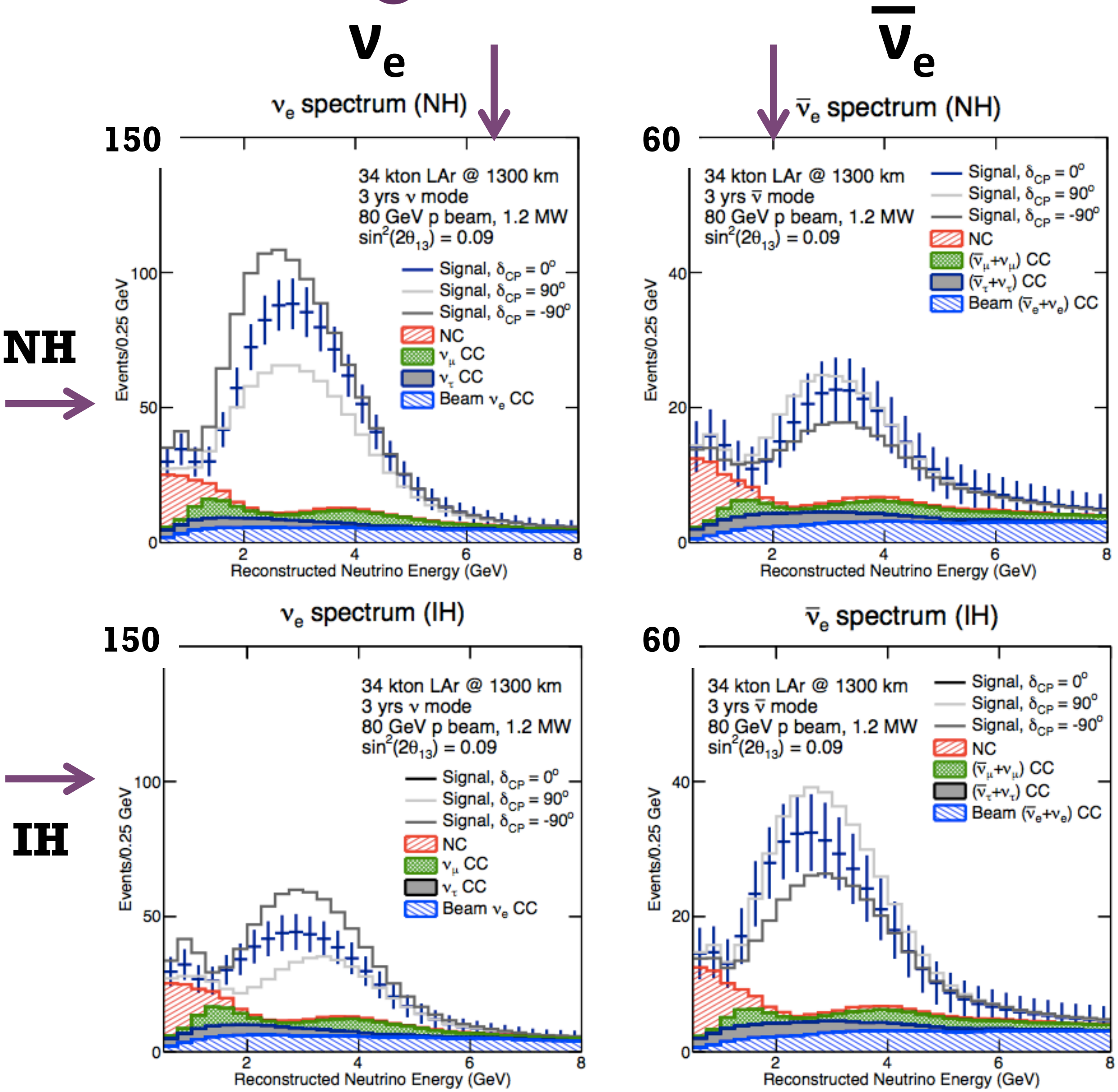


+ Coverage (one version…)



Source: Robert Wilson, ICFA Neutrino Panel Mini-Workshop, Jan 2014

+ Existing LBNE Studies



- Longer baseline = larger influence from matter effects
- Enhancement/ suppression of ν_e appearance is linked to sign of mass hierarchy
- At LBNE baseline, this asymmetry exceeds the impact from CP violation and reduces MH/ CP ambiguity

"The Long Baseline Neutrino Experiment: Exploring Basic Symmetries of the Universe" (2014)

+ Neutrino Mass and Leptogenesis

- Standard **Dirac mass** term allowed: $\mathcal{L}_D = -m_D \left(\bar{\nu}_L \nu_R + \bar{\nu}_R \nu_L\right)$
- Can also write additional **Majorana mass** term, if ignore lepton number conservation:

$$\mathcal{L}_M = -\frac{1}{2} m_R \left(\nu_R^T \nu_R + \bar{\nu}_R \bar{\nu}_R^T\right)$$

- Neutrinos have no electric charge; also, this means neutrinos = anti-neutrinos
- Rewrite this as a mass matrix:

$$\mathcal{L} = -\frac{1}{2} \left(\bar{\nu}_L, \nu_R^T\right) \begin{pmatrix} 0 & m_D \\ m_D & m_R \end{pmatrix} \begin{pmatrix} \bar{\nu}_L^T \\ \nu_R \end{pmatrix} + \text{h.c.}$$

- Diagonalize this to get the following:

$$m_1 \sim \frac{m_D^2}{m_R} \qquad m_2 \sim m_R$$

- One choice = m_D near electroweak (~100 GeV) scale, m_R near GUT (~10^{14} GeV) scale
- This gives a neutrino mass which resembles reality: m_1 ~ 0.1eV
- Heavy neutrinos (m_2) existed in early universe and they decayed?
- **Leptogenesis:** if $v_R \to l^+ + h^- \neq v_R \to l^- + h^+$, could explain matter/antimatter asymmetry of the early universe
  - Makes lepton-sector CP Violation a very important topic of study

+ PMNS vs CKM

"The Long Baseline Neutrino Experiment: Exploring Basic Symmetries of the Universe" (2014)

Approximate forms:

$$|U_{\text{PMNS}}| \sim \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.5 & 0.6 & 0.6 \\ 0.2 & 0.6 & 0.8 \end{pmatrix} \qquad |V_{\text{CKM}}| \sim \begin{pmatrix} 1 & 0.2 & 0.004 \\ 0.2 & 1 & 0.04 \\ 0.008 & 0.04 & 1 \end{pmatrix}$$

- Precision measurements of neutrino oscillation necessary for understanding why PMNS matrix has the form that it does, and how it relates to quark CP violation (which seems very different)
    - Would like to achieve same degree of precision as CKM
    - E.g., precision can help determine if predictions from Quark-Lepton Universality are true:

$$U^{\text{CKM}} = 1 + \epsilon_{\text{Cabbibo}}$$

$$U^{\text{PMNS}} = T + \epsilon_{\text{Cabbibo}}$$

$$\theta_{23} \sim \pi/4 + \Delta\theta$$

$$\theta_{13} \sim \theta_C/\sqrt{2}$$

Of order θ_C

$$\theta_C = \theta_{12}^{CKM}$$

Determined by Majorana Physics

Important to determine octant!

+ $\nu_\mu \rightarrow \nu_e$ Appearance

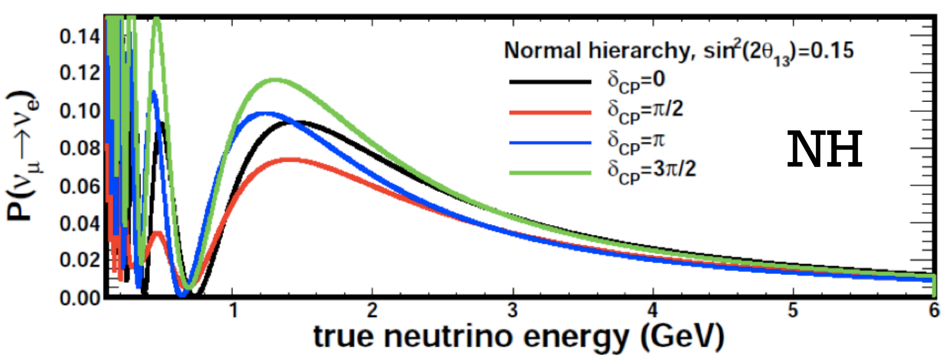
$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2(2\theta_{13})\sin^2(\theta_{23})\sin^2\left(1.27\Delta m^2_{31}\frac{L}{E}\right) +$$
$$\sin^2(2\theta_{12})\cos^2(\theta_{23})\sin^2\left(1.27\Delta m^2_{21}\frac{L}{E}\right) +$$
$$\sin(2\theta_{13})\sin(2\theta_{23})\sin(2\theta_{12})\sin\left(1.27\Delta m^2_{31}\frac{L}{E}\right)\sin\left(1.27\Delta m^2_{21}\frac{L}{E}\right)\cos\left(1.27\Delta m^2_{32}\frac{L}{E}\pm\delta_{CP}\right)$$

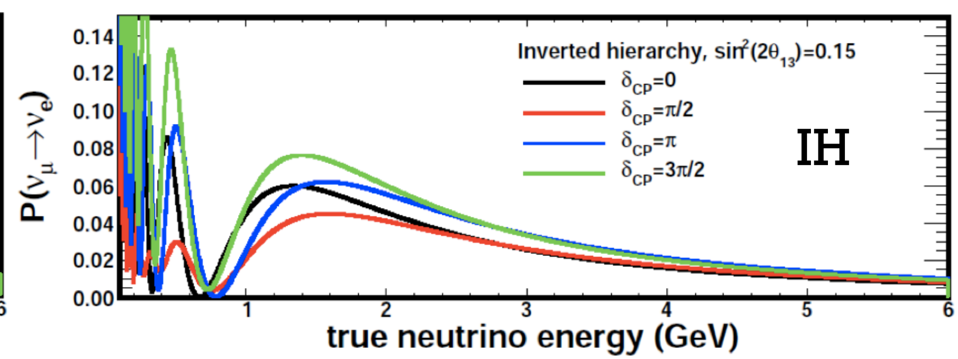
$\Delta m^2_{32} \approx \Delta m^2_{31}$

Small solar contribution

CP phase

- **$\nu_\mu \rightarrow \nu_e$ appearance** = connected to numerous neutrino mixing parameters:
  - **Value of θ_{13}**: now known to be non-zero, meaning other parameters can be measured
  - **Sign of Δm^2_{32}**: relevant via **matter effects** when beam passes through earth
  - **Precise value and octant of θ_{23}**
  - **CP violation phase δ_{CP}**: sign of effect different for neutrinos and antineutrinos





MINOS Beamline (735 km)