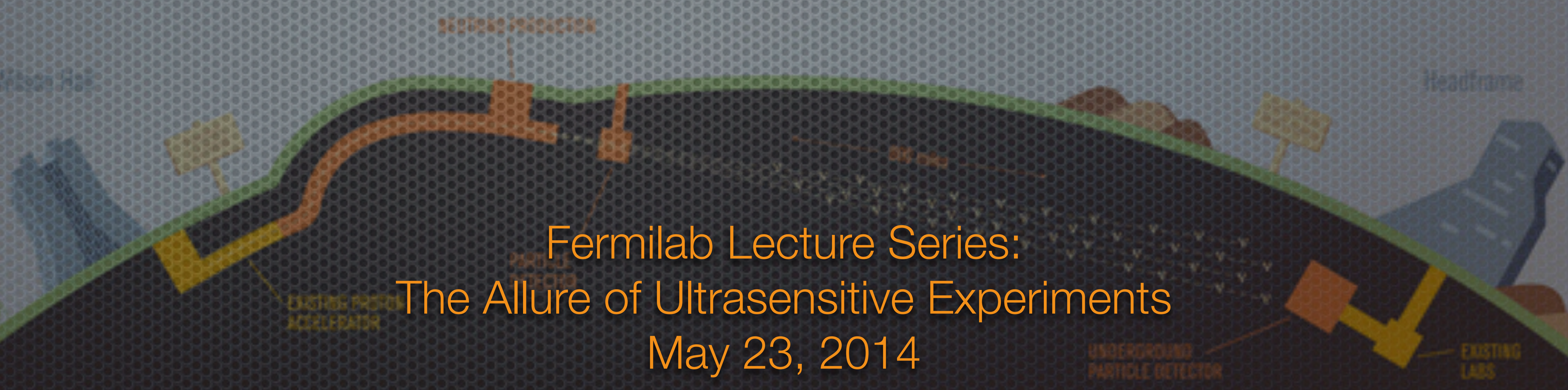
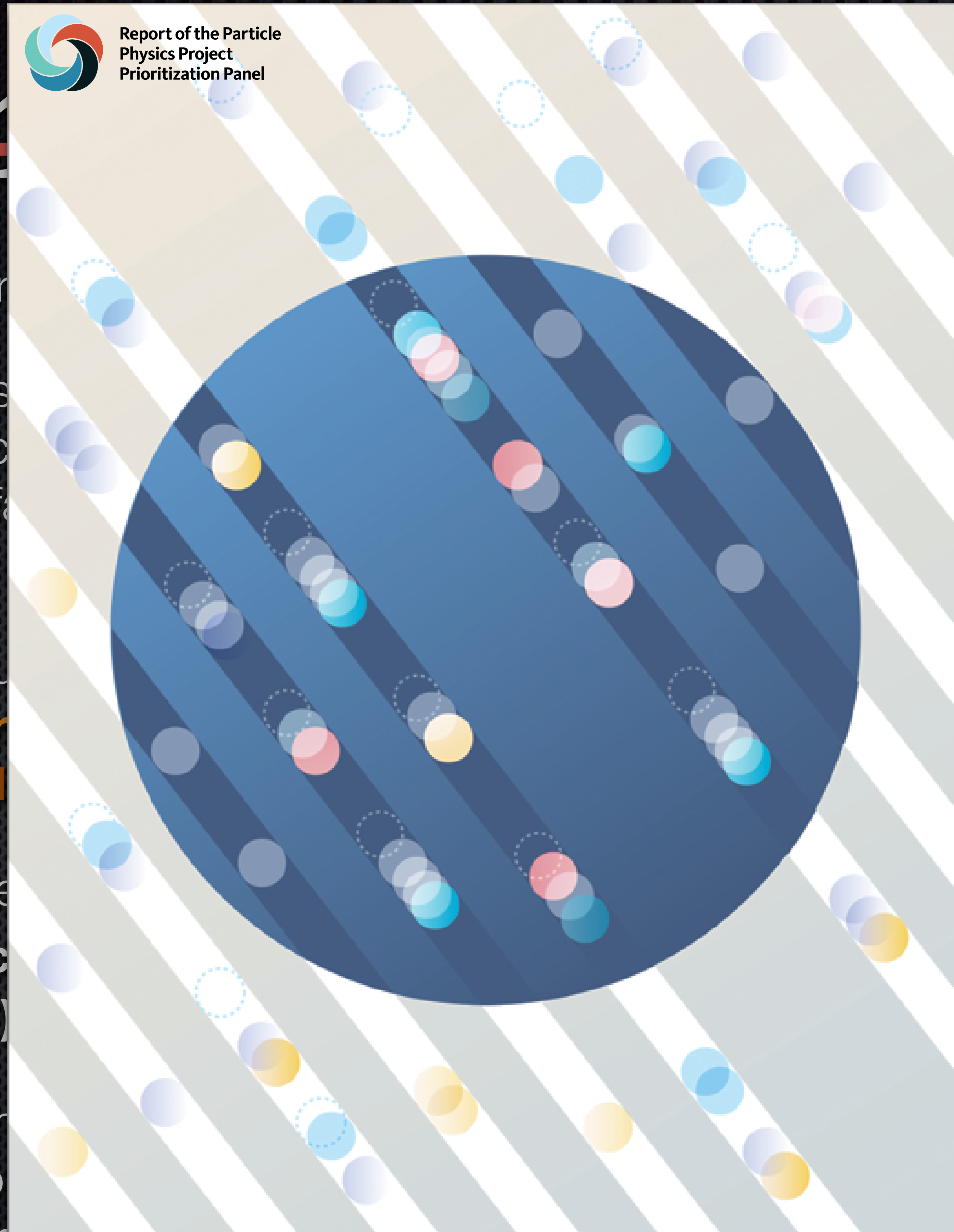
Challenges for Long-Baseline Neutrino Experiments

Mayly Sanchez
Iowa State University



Fermilab Lecture Series:
The Allure of Ultrasensitive Experiments
May 23, 2014

~~The~~ C … oken



- One science dr … utrino Mass
- "Propelled by s … experiments, neutrino physic … decades. (….) Powerful new f … e puzzling and experimentally
- Some of the qu … neutrino **masses order** … **e differently? Are there add**
- "The U.S. is we … ysics program. **Its centerpiec** … **ine neutrino facility (LBNF)**
- "LBNF will com … -baseline, and large-volume p … of the oscillated neutrino spectrum.

Caveats

- Very US centric view of long-baseline experiments. Not all experiments are described in detail.
- Concentrated on MINOS as example to explain the philosophy of the challenges for the long-baseline neutrino experiments.
  - Had to ignore some interesting measurements such as neutrino vs antineutrino oscillation parameters.
  - Using somewhat older MINOS analyses in order to better illustrate some of the choices made.
- No mention of anything that does not involve oscillations in long-baseline experiments (eg no reactor experiments) even if relevant to the parameter set.
- Not describing anything about sterile neutrinos or other exotic phenomena.

Neutrino oscillations basics

- The flavor eigenstates are linear combinations of the mass eigenstates.

$$|\nu_\alpha\rangle = \sum_{k=1}^{n} U_{\alpha k} |\nu_k\rangle \quad (\alpha = e, \mu, \tau)$$

- There is a non-zero probability of detecting a different neutrino flavor than that produced at the source.

$$P(\nu_\mu \to \nu_\tau) = \sin^2(2\theta) \sin^2\left(\frac{1.27 \Delta m_{23}^2 L}{E_\nu}\right)$$

- For the three flavor case we can write a PMNS mixing matrix:

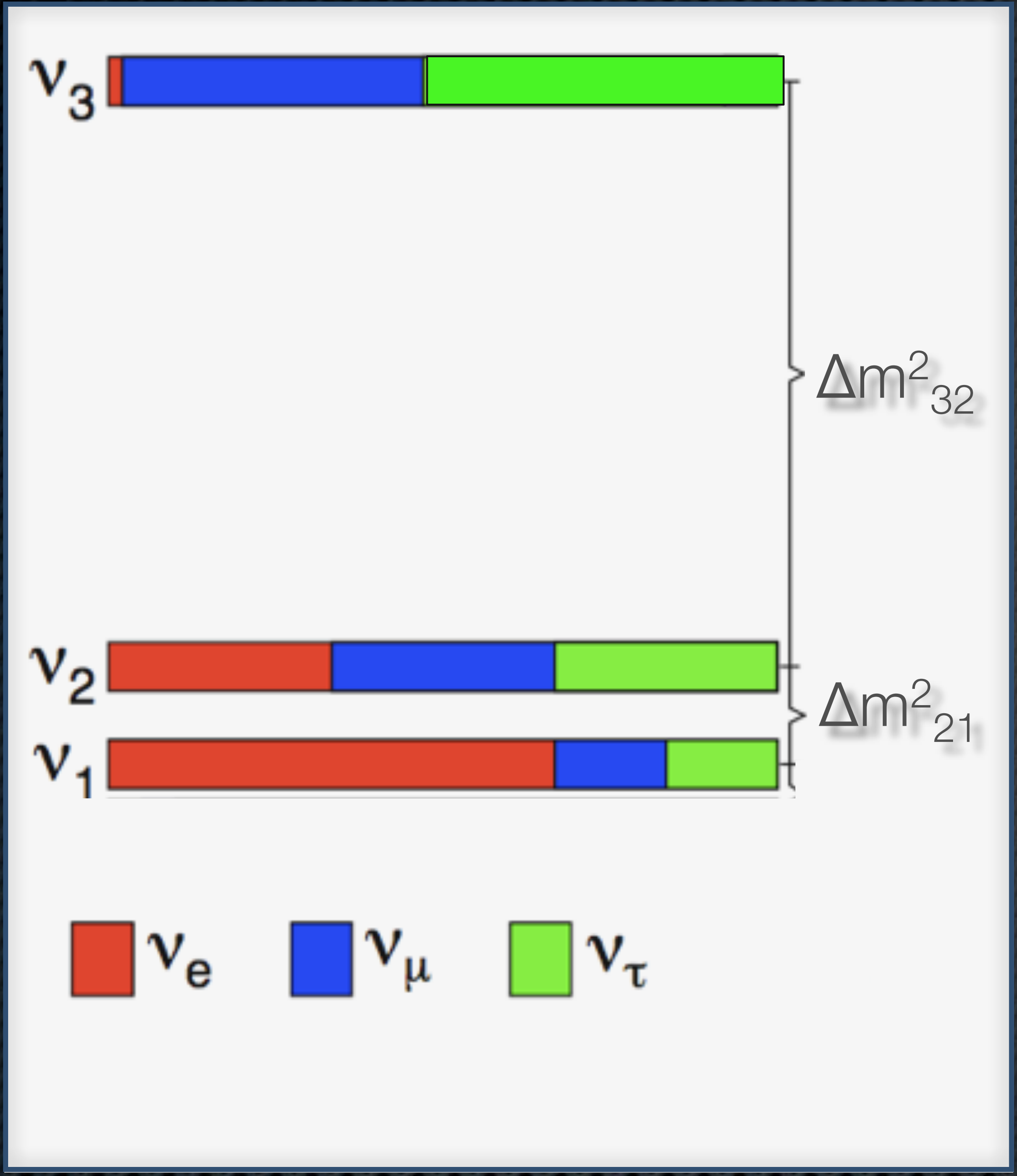
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- The **(23)** and **(12)** sectors are well known. The **(13)** sector only had a limit!
- Since

  matter anti-matter asymmetry of the universe.

Neutrino masses and mixing

What is the current experimental picture?

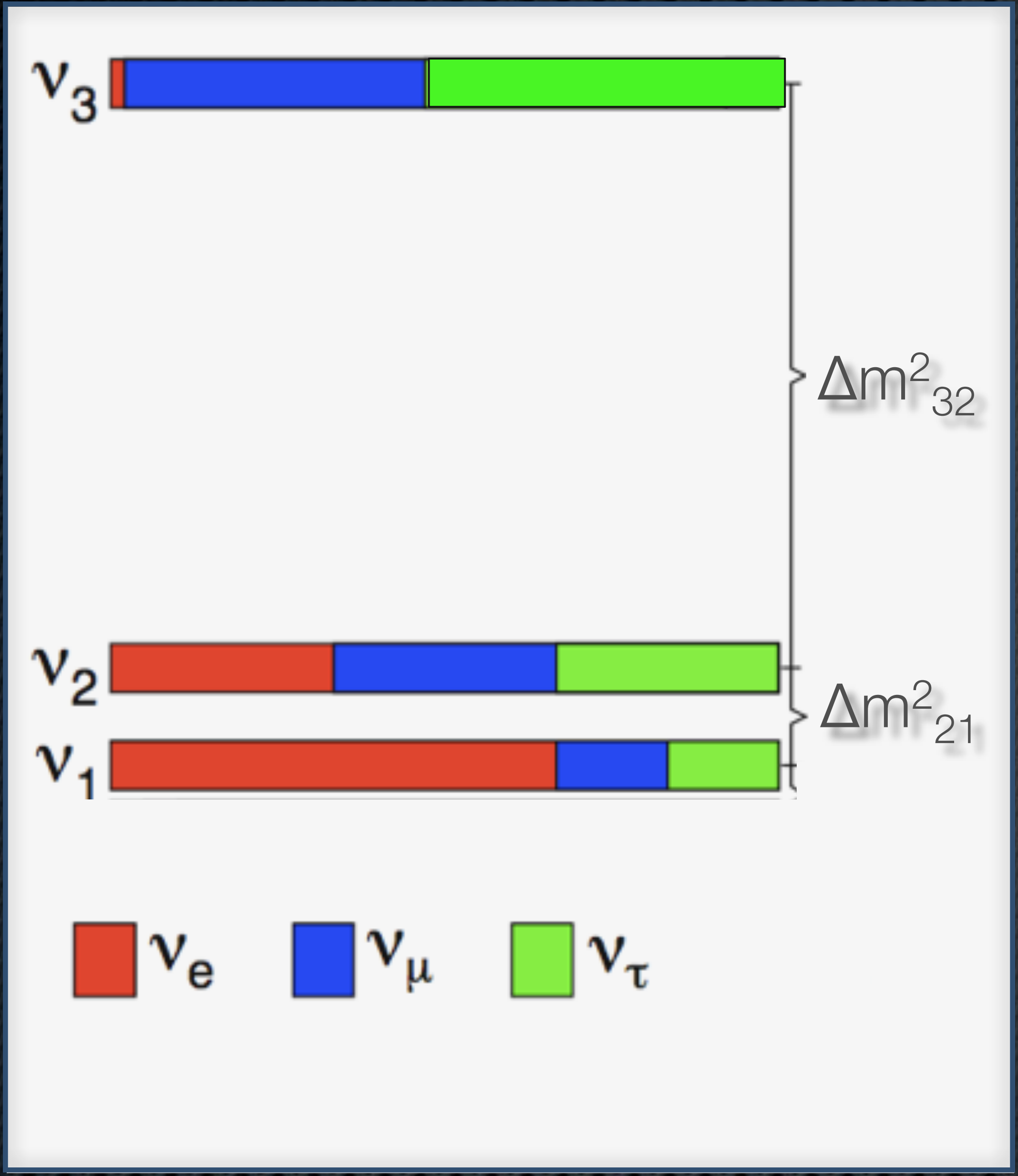


Experimental picture evolves quickly!

- Two mass scales:
  - The "atmospheric" mass scale: Δm^2_{32}
  - The "solar" mass scale: Δm^2_{21}
- Large mixing angle for atmospheric neutrino oscillations.
- Solar neutrino oscillations are subject to matter effects with a non-maximal mixing angle.
- **Third mixing angle is small and has ~~NOT~~ been measured!**
- **Mass ordering is NOT known for atmospheric neutrinos but known for the solar mass scale.**
- **CP violation in the lepton sector has NOT been measured.**

What can we do with...

Long-baseline neutrino experiments!



- The atmospheric mass scale: Δm^2_{32}.
- Large mixing angle for atmospheric neutrino oscillations: θ_{23}.
- Differences between $\Delta m^2_{32}/\Delta \overline{m}^2_{32}$
- **The third mixing angle: θ_{13}.**
- **CP violation: δ_{CP}.**
- **Mass ordering for the atmospheric oscillations: the sign of Δm^2_{32}.**

These are the unanswered questions!

Why Long-baseline?

- “Neutrino oscillation rates depend not only on the fundamental parameters, mass and mixing, but also on **experimental parameters: the baseline, the neutrino energy, and the event rate driven by beam power and detector mass**. The combination of all of these determines the strength of the oscillation signals observed and therefore the sensitivity of the experimental efforts.”

  - P5 report

  Report of the Particle Physics Project Prioritization Panel

- The key point is that **we control the experimental parameters**. By optimizing baseline and neutrino energy and depending on our beam power and detector mass capabilities we can explore the neutrino mass and mixing parameter space.

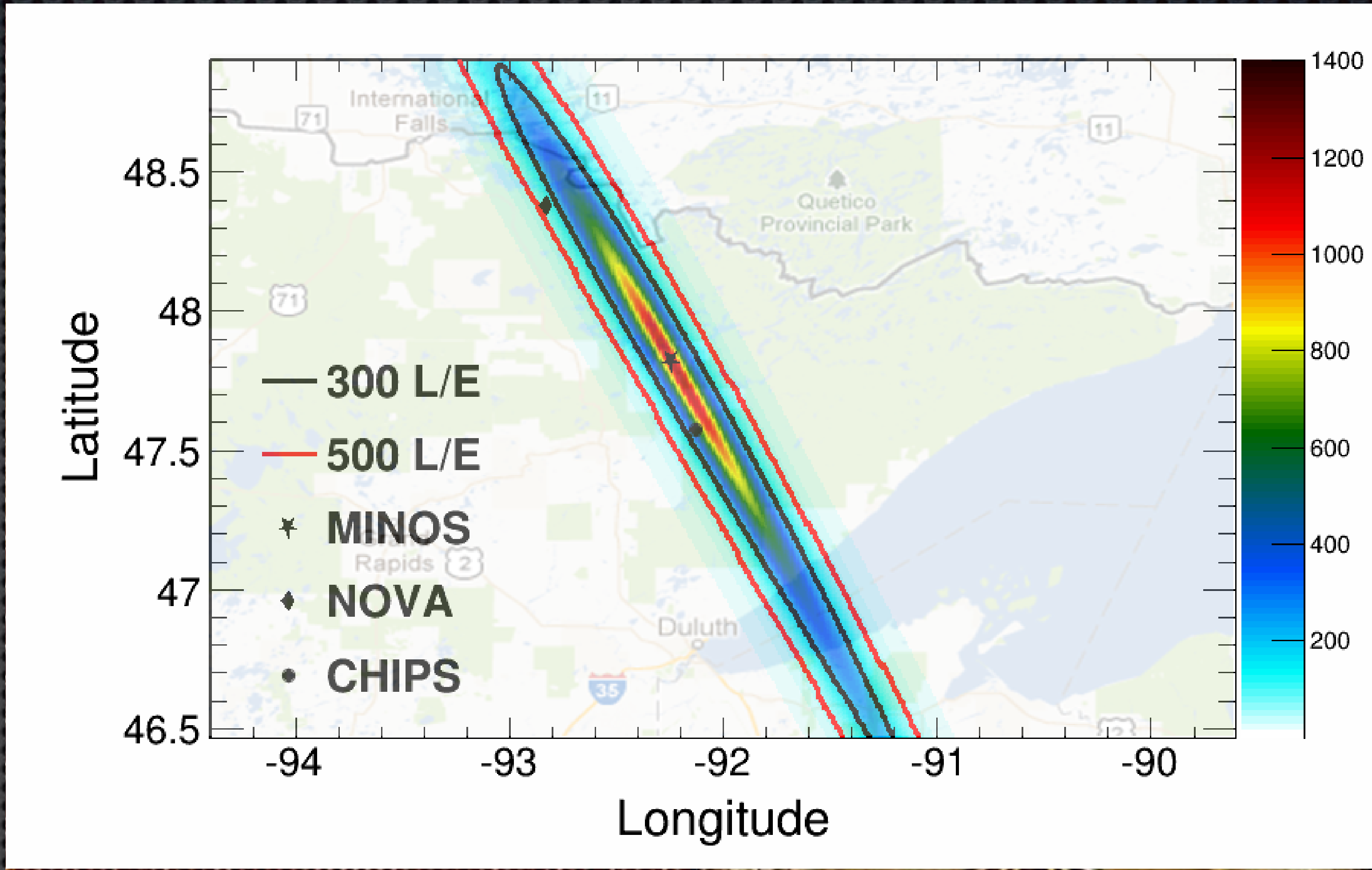
- It so happens that **long-baseline matches the fundamental parameters of mass and mixing of nature with our technological know-how** permitting us to achieve these goals.

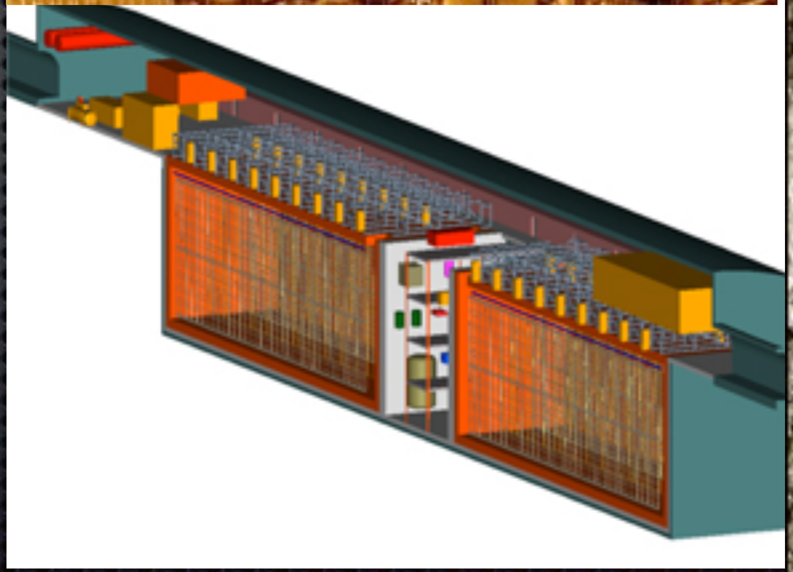
Long-baseline basic challenges

- Baseline / Energy:
  Find a detector location at the right distance from your given beam in order to see oscillation phenomena.

- Detector mass:
  Depending on your event rate, build a sufficiently large detector.

- Beam intensity:
  Depending on your technological capabilities maximize the intensity.





MINOS as an example

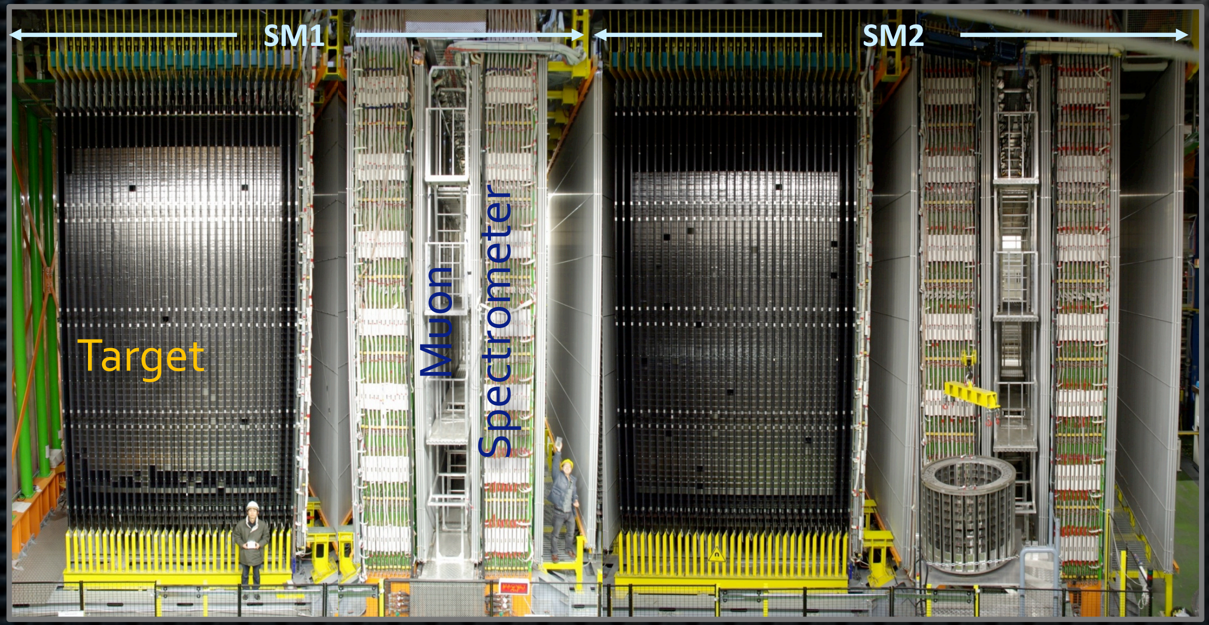
- Produce a high intensity beam of muon neutrinos at Fermilab.
- Measure these neutrinos at the **Near Detector** and use it to predict the **Far Detector** spectrum.
- If neutrinos oscillate we will observe a distortion in the data at the Far Detector in Soudan.

←long baseline→
735 km

Main **I**njector **N**eutrino **O**scillation **S**earch

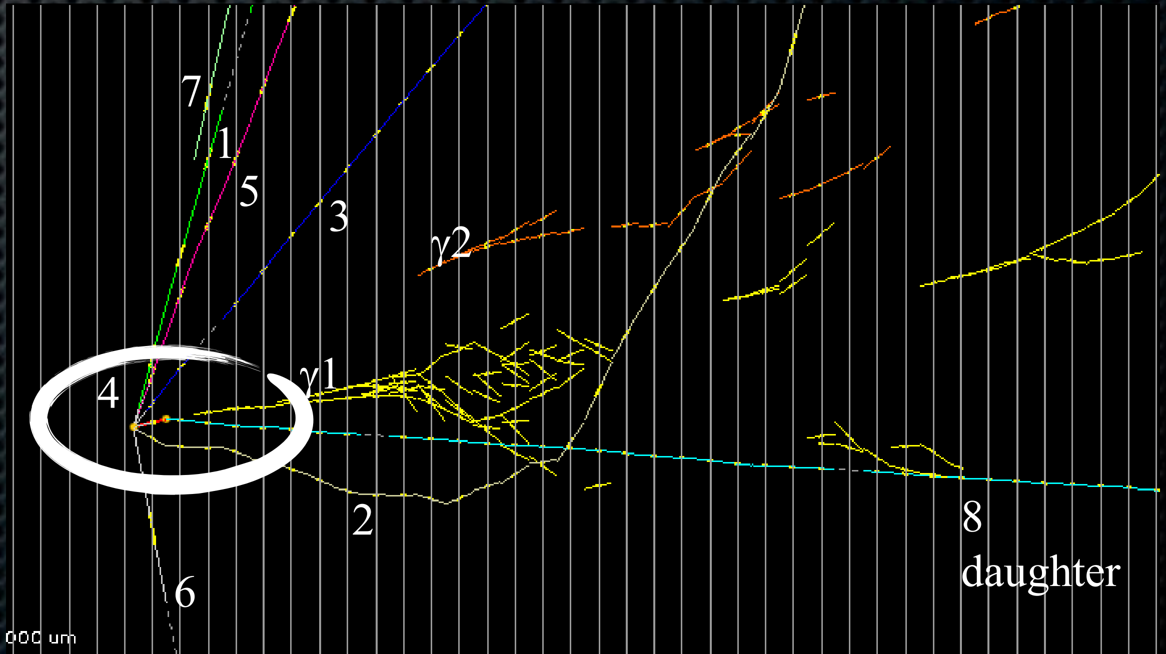
Taking data since 2005!

Opera as another example



Taking data since 2008!

- Produce a high intensity beam of muon neutrinos at CERN. Distance similar to Fermilab - Soudan.
- If muon neutrinos oscillate, directly **observe resulting tau neutrinos** from the dominant oscillation mode.
- Far detector divided in two supermodules. Target composed of lead/emulsion bricks.



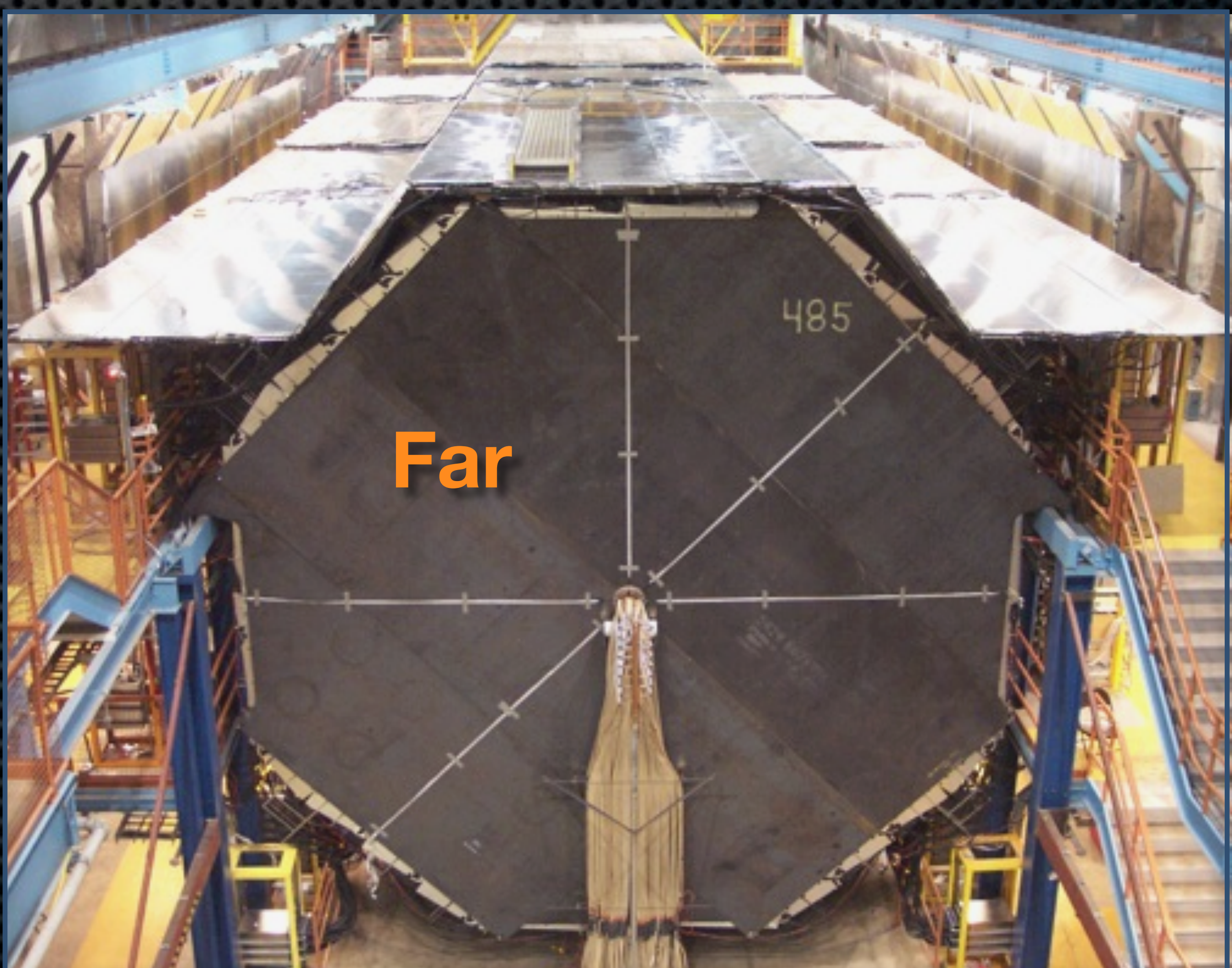
Seeking precision in long-baseline neutrino experiments

- MINOS and Opera are a good examples of long-baseline neutrino experiments. However, they are seeking different goals.
  - Opera expected to observe a handful of tau neutrino events over their running time. Once tau neutrinos have been observed the dominant oscillation mode for neutrinos has been proven and there is no need to remeasure the oscillation parameters.
  - MINOS expected to measure neutrino oscillation parameters with higher precision than it had been achieved by atmospheric experiments. Significantly higher number of muon neutrinos were expected, better control of systematic uncertainties needed.

Let's go back to MINOS

The MINOS detectors

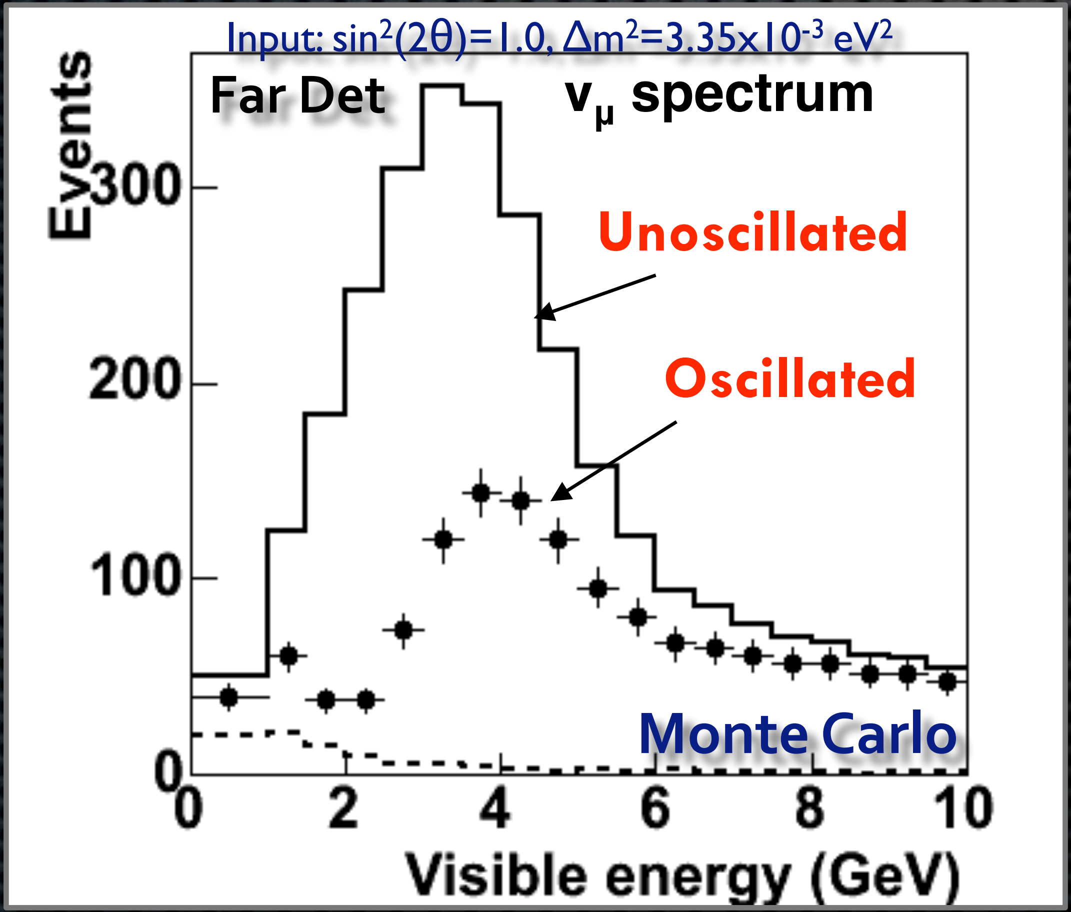
- Functionally identical: **Near and Far detectors**
- Octogonal steel planes (2.54cm thick ~1.44X_0). **Magnetized detector.**
- Alternating with planes of scintillator strips (4.12cm wide, Moliere rad ~3.7cm).
  - **Near (ND)**: ~ 1kton, 282 steel squashed octagons. Partially instrumented.
  - **Far (FD)**: 5.4 kton, 486 (8m/octagon) fully instrumented planes.

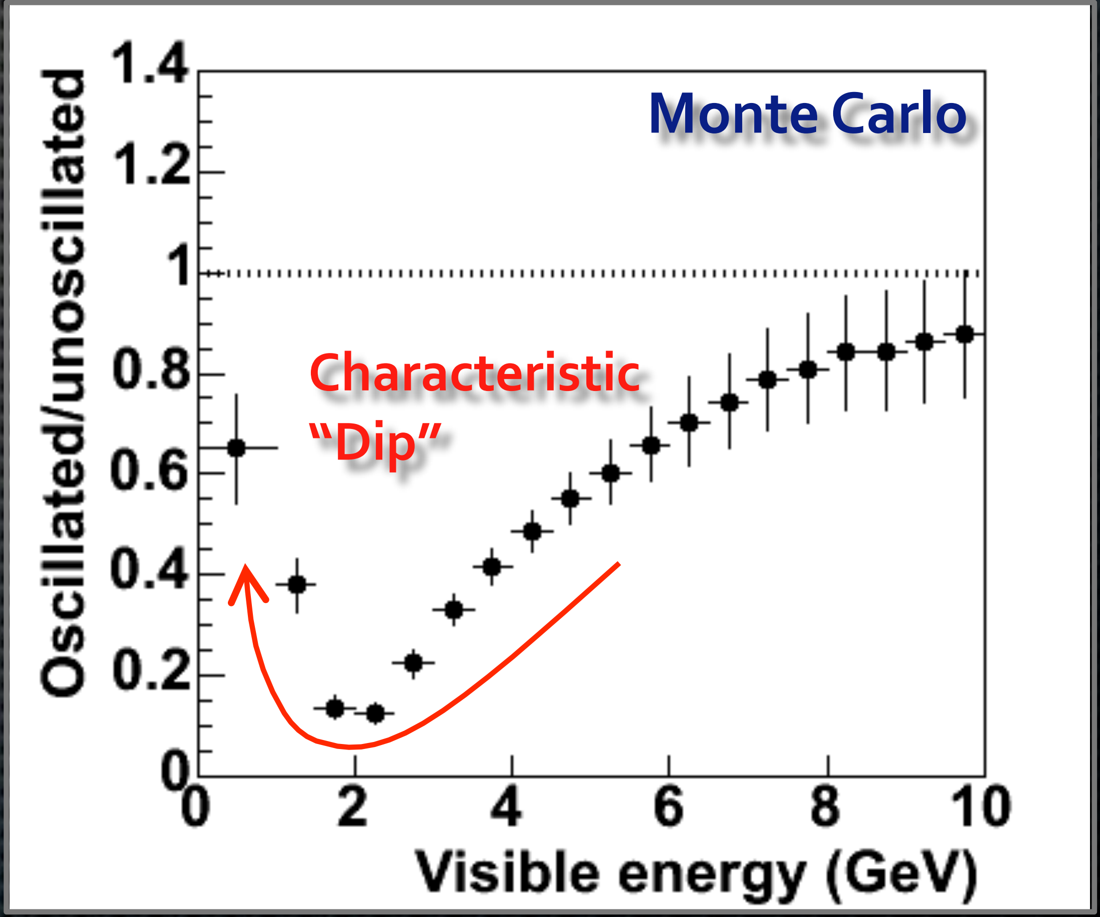


Searching for ν_μ disappearance

- In long-baseline experiments, we compare a prediction obtained from Near Detector data with a Far Detector measurement.
  - Neutrino oscillations deplete rate and distort the energy spectrum.

$$P(\nu_\mu \rightarrow \nu_\mu) \simeq 1 - \sin^2(2\theta_{23}) \sin^2\left(1.267\Delta m^2_{32}\frac{L}{E}\right)$$

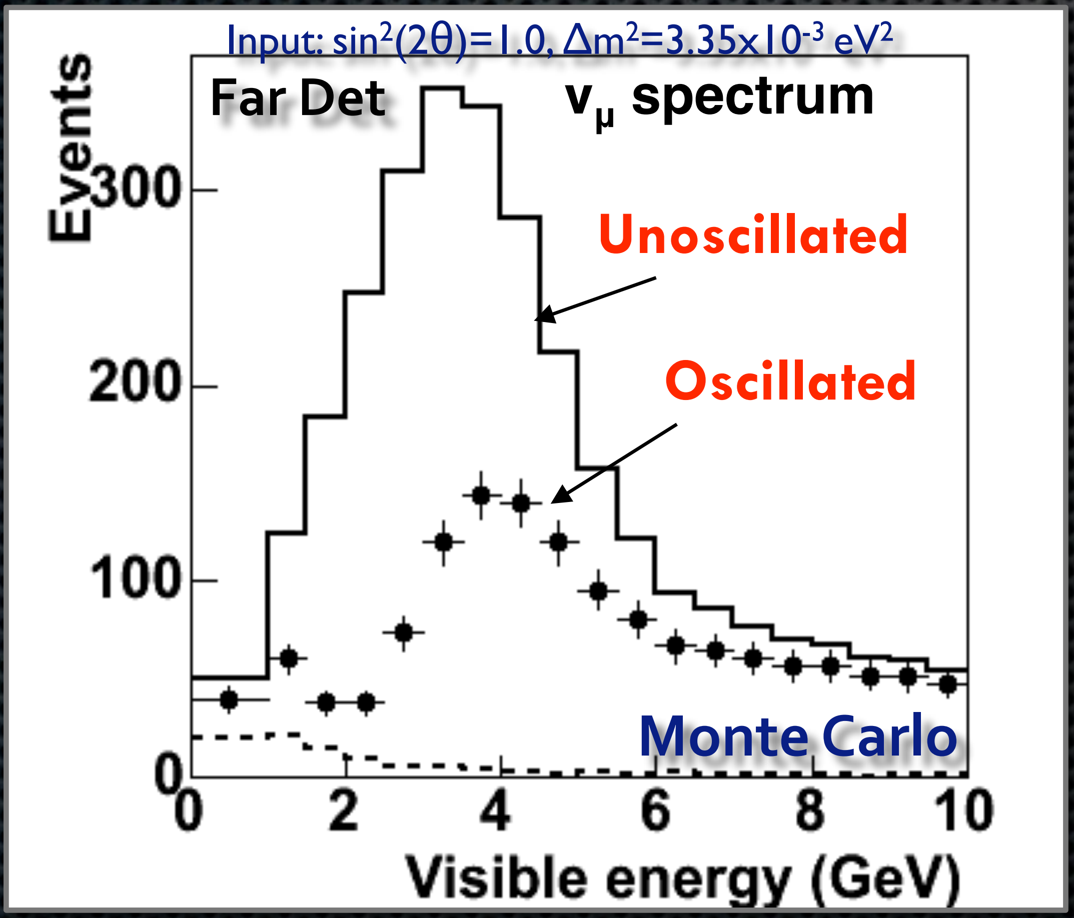


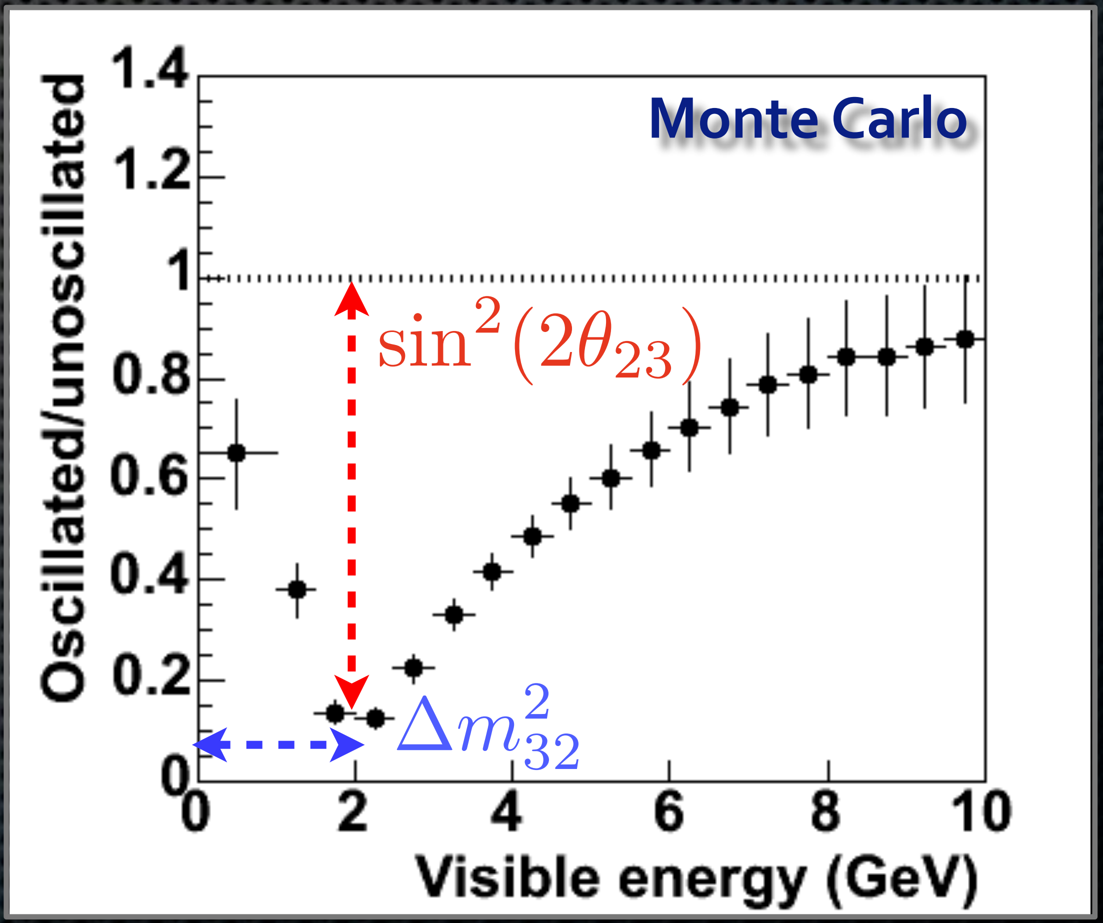


Searching for ν_μ disappearance

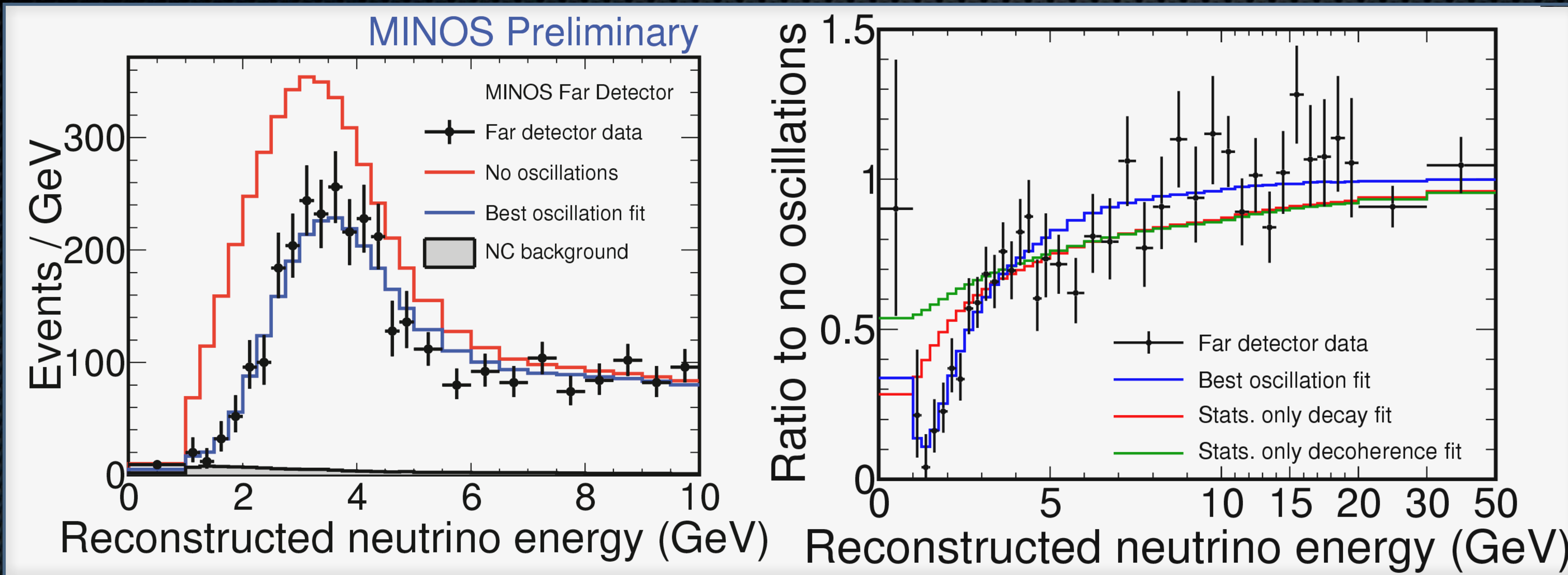
- In long-baseline experiments, we compare a prediction obtained from Near Detector data with a Far Detector measurement.
  - Neutrino oscillations deplete rate and distort the energy spectrum.

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - \sin^2(2\theta_{23}) \sin^2\left(1.267\Delta m^2_{32}\frac{L}{E}\right)$$





MINOS ν_μ disappearance

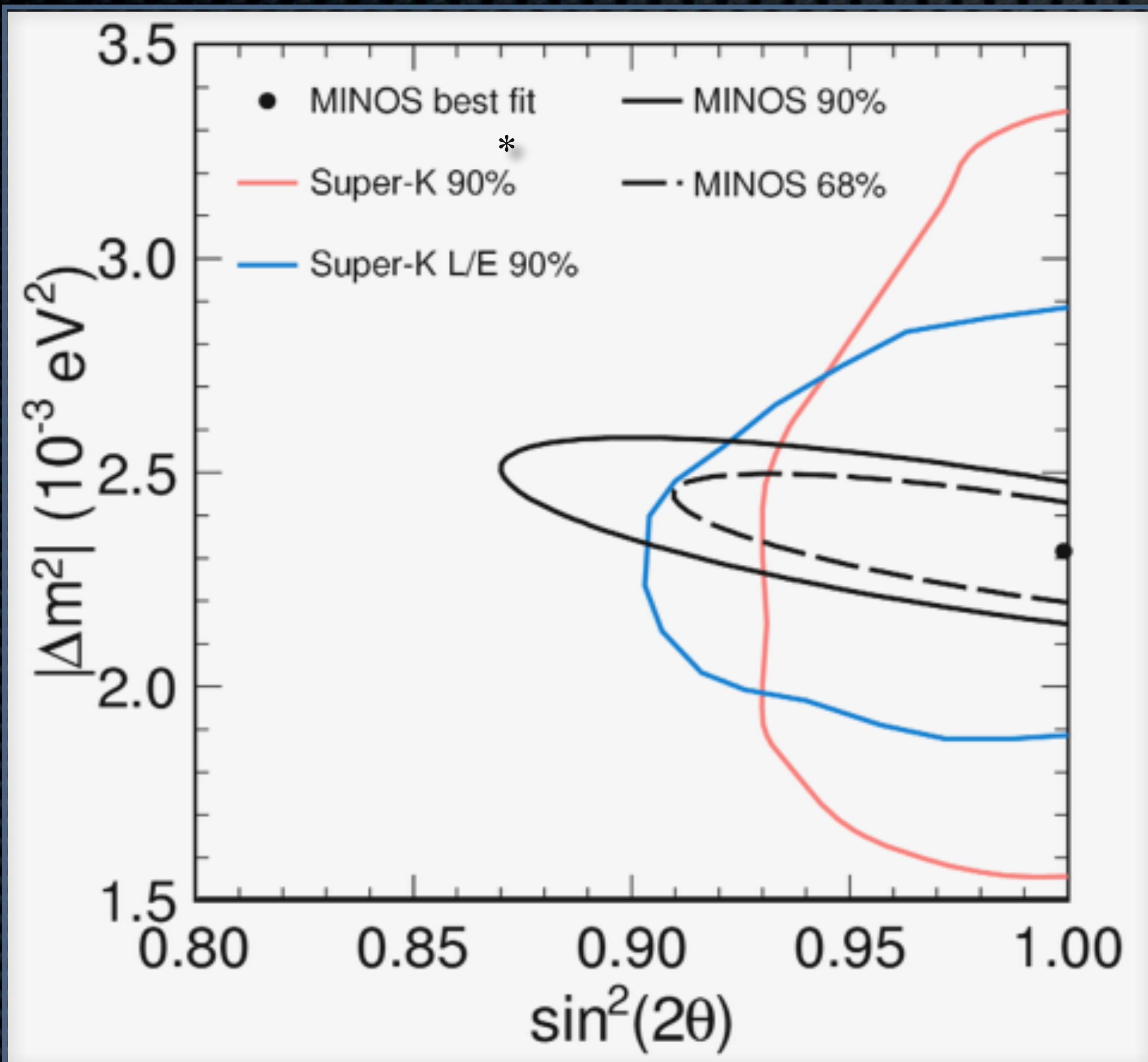


Contained: Expect **2451**. Observe **1986.**

- Oscillations fit well. More recent analyses by MINOS consider full 3 flavor oscillation fits and have even better precision.
- Pure decoherence disfavored at 8 σ.
- Pure decay disfavored at 6 σ.

P. Adamson *et al.*, Phys.Rev.Lett. 106 181801 (2011)

MINOS ν_μ disappearance



- Study ν_μ disappearance as a function of energy.
- Precision measurements of Δm^2_{32} and $\sin^2(2\theta_{23})$.

$$\left|\Delta m^2\right| = 2.32^{+0.12}_{-0.08} \times 10^{-3}\,\mathrm{eV}^2$$

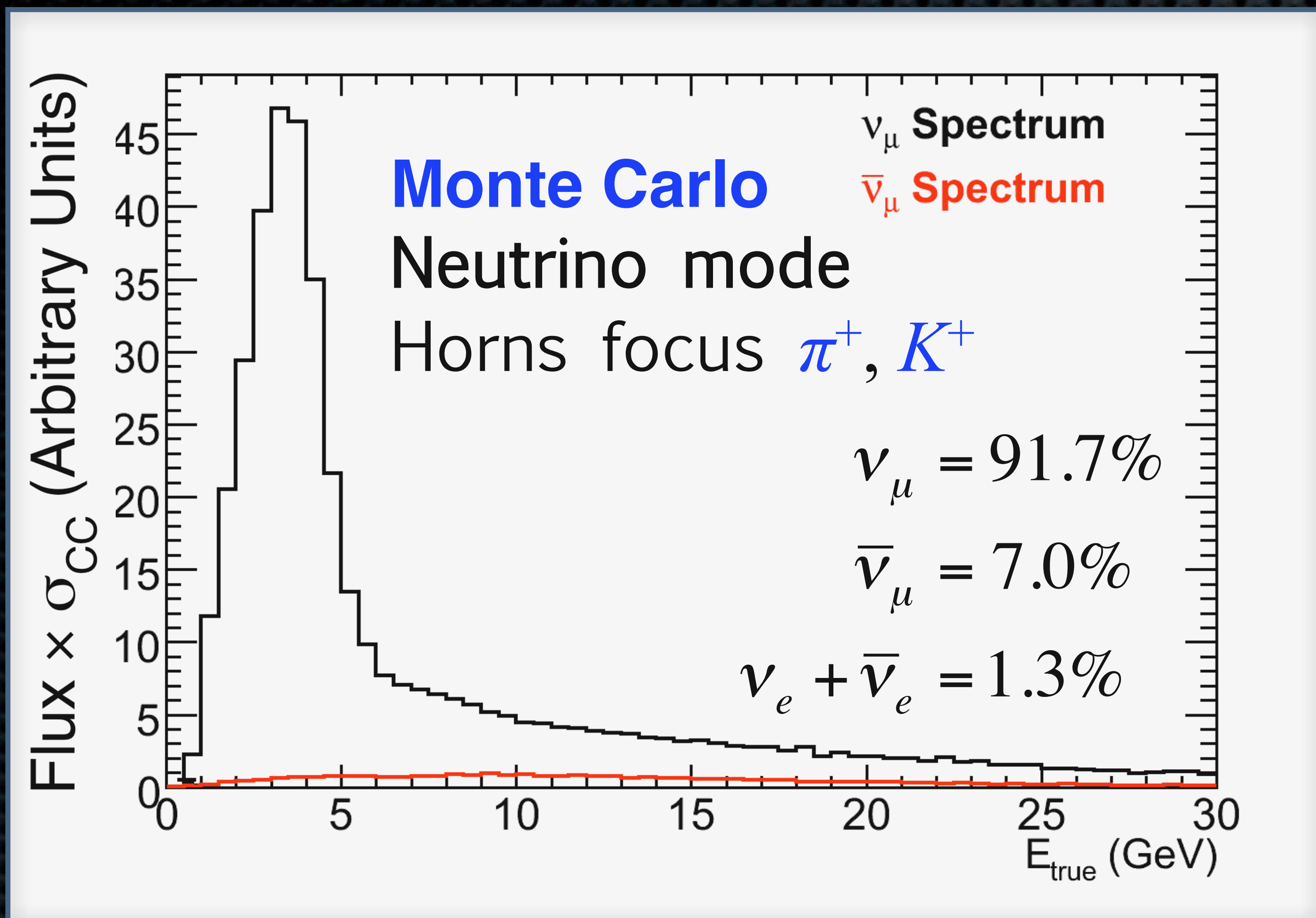
$$\sin^2(2\theta) > 0.90 \ (90\%\ \mathrm{C.L.})$$

- World's best measurement: ~ 5% in Δm^2_{32}.

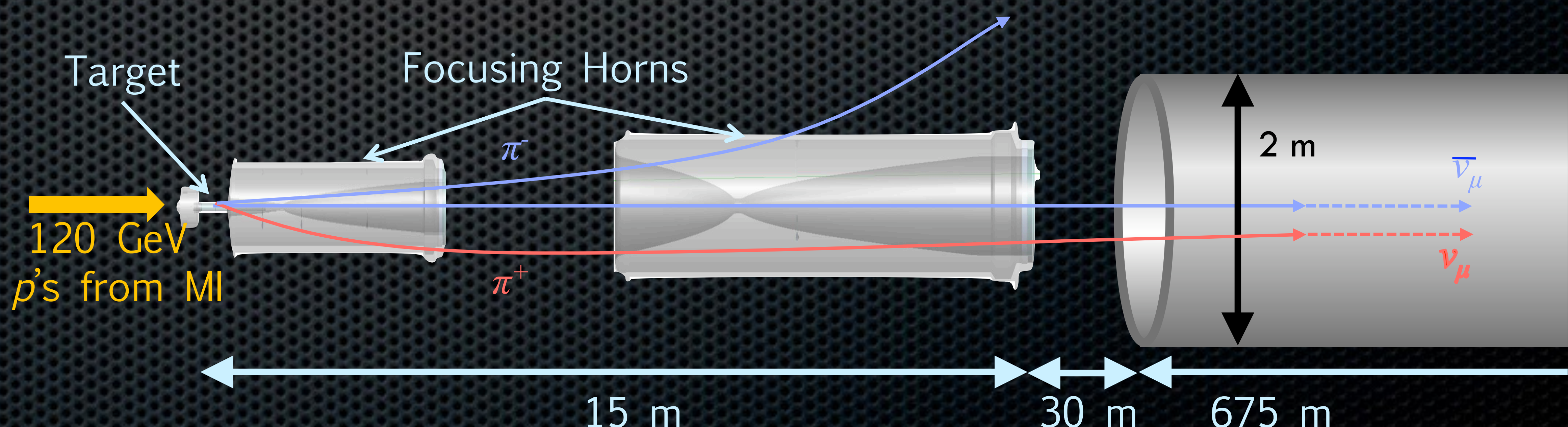
- How does MINOS achieve this level of precision?

P. Adamson *et al.*, Phys.Rev.Lett. 106 181801 (2011)

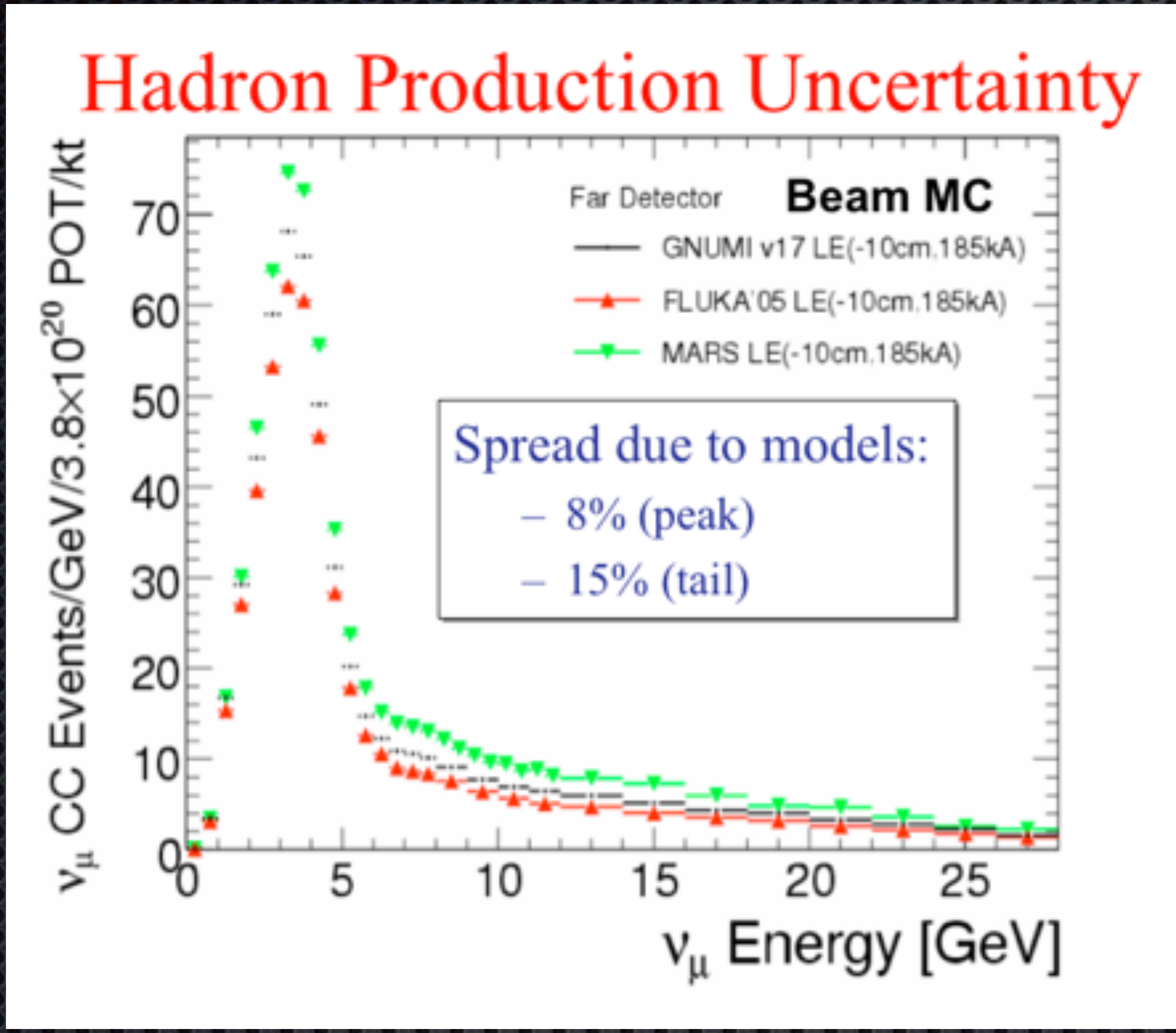
Producing Neutrinos with NuMI

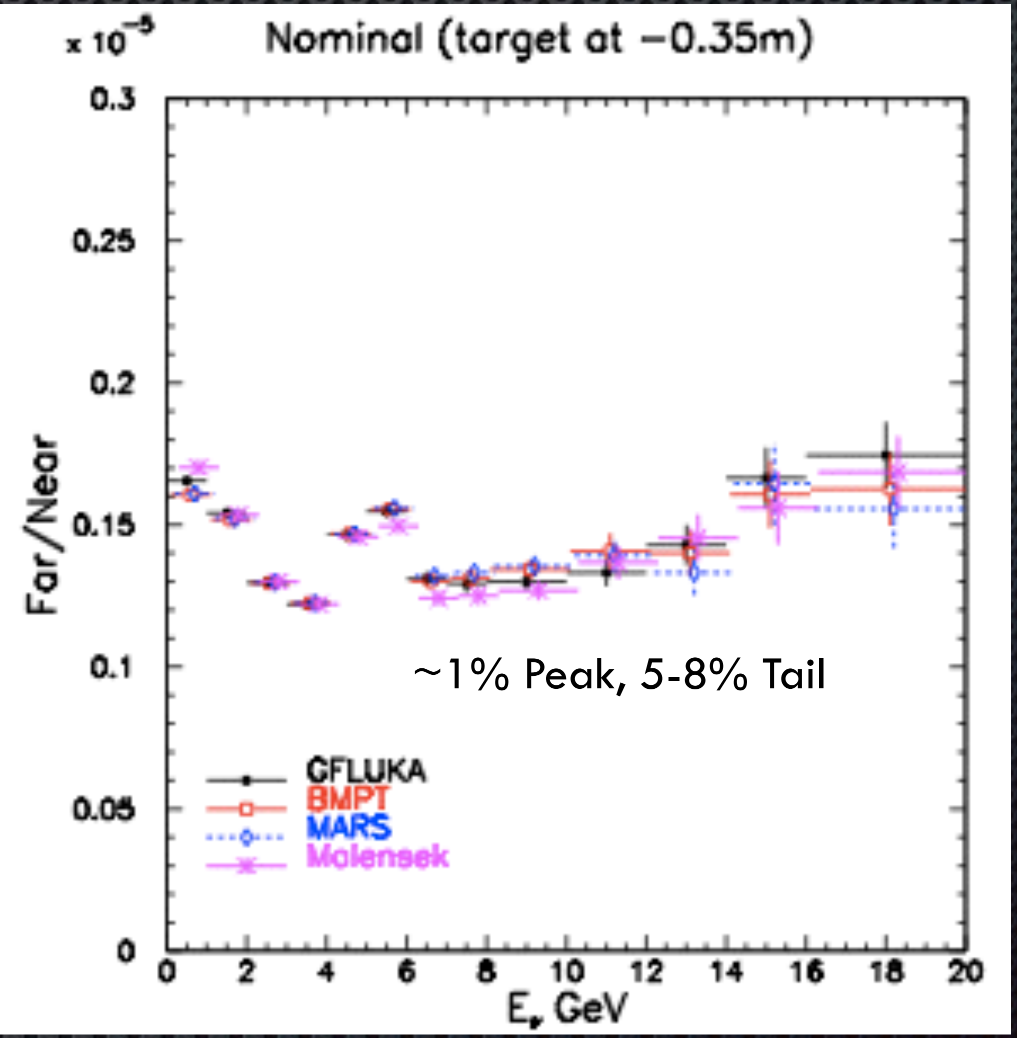


- Horns are positive pions and kaons which decay into neutrinos.
- Higher energy anti-neutrinos from very forward negative pions.
- Most of MINOS data is taken in this configuration.



Beam flux: Hadron production uncertainties





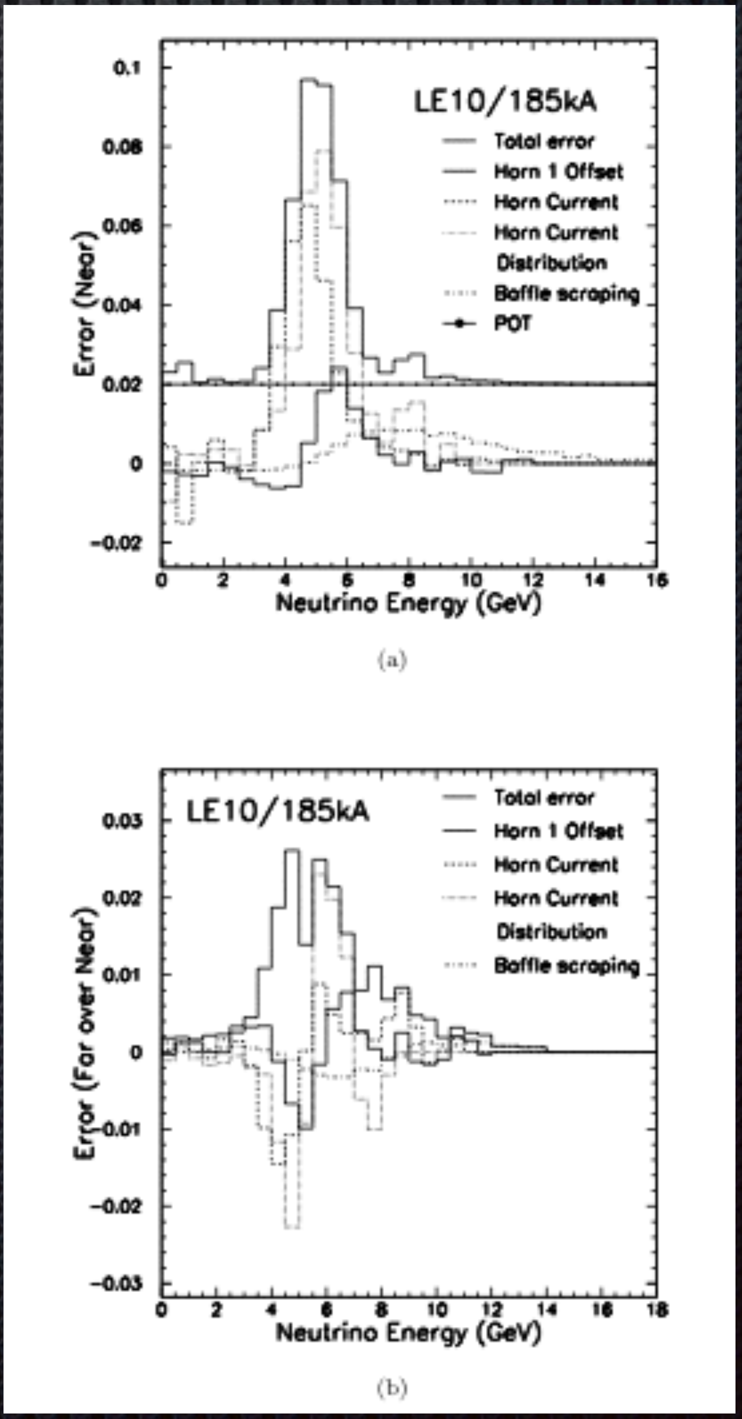
- Uncertainties in the neutrino flux cause large uncertainties in the ND simulated spectrum, but the errors largely cancel in the Far to Near Comparison

P. Vahle SBL talk 2012

Beam flux: systematics

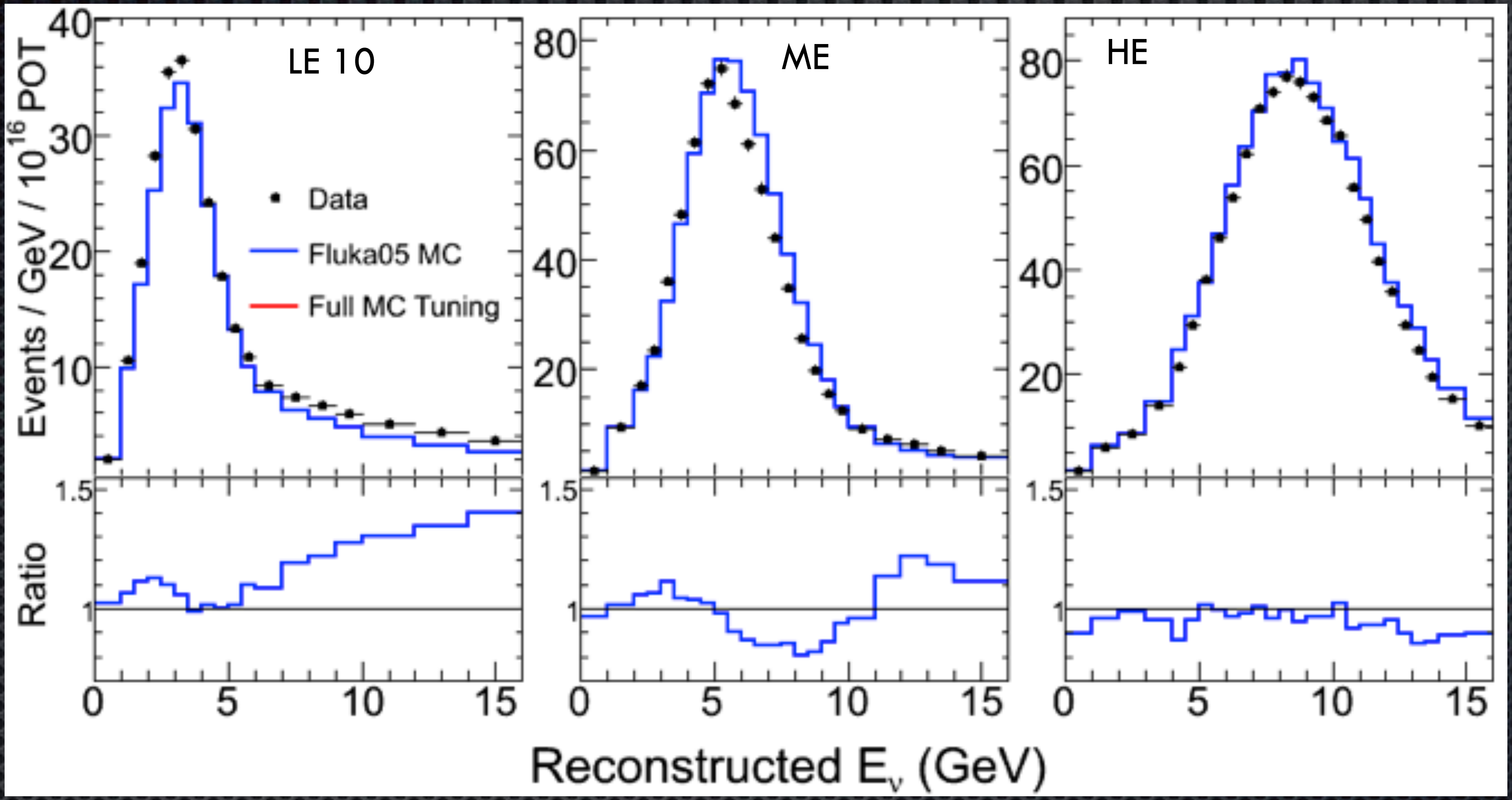
- Additional flux uncertainties arise from focusing and alignment uncertainties
- Errors in flux estimated using comparisons between nominal (pbeam) simulation and systematically offset simulation sets
- Offsets determined from beam survey measurements, target scans, hadron/muon monitoring, etc. (Documented in R. Zwaska thesis, UT Austin, 2005)

(Horn angles, horn 2 offset errors also evaluated, small, not shown on plots)



P. Vahle SBL talk 2012

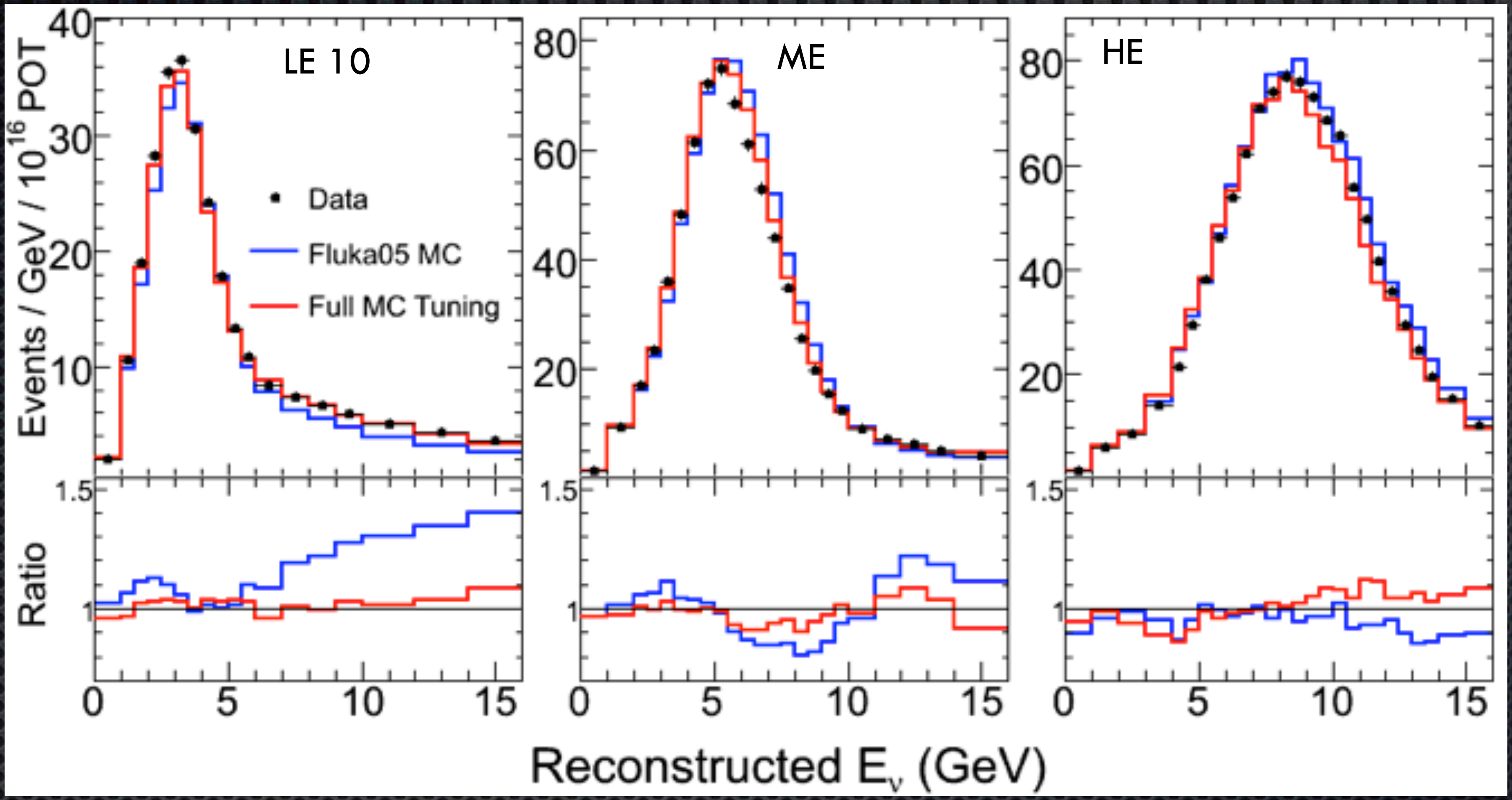
Initial ND data



- State of the simulation with respect to the data for 3 different beam energy configurations before any fits in early MINOS data.

(Refs: Z. Pavlovich, UT Austin, 2008, Phys. Rev. D76 (2007) 072005)

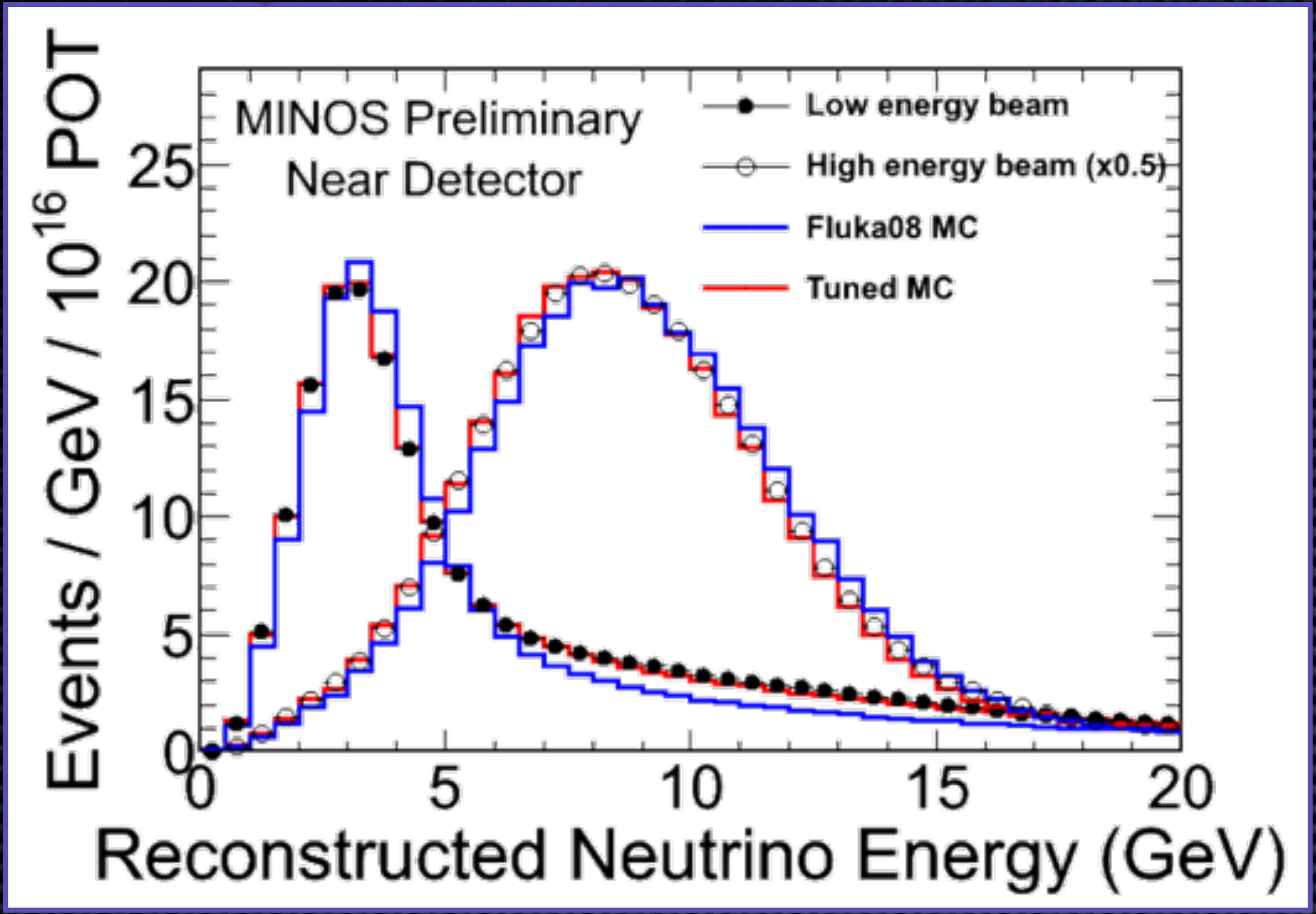
Initial ND data



- Remaining data/MC discrepancies ~5-10% level
- Fit errors provide a better estimate of systematic error than (correlated) model spread

(Refs: Z. Pavlovich, UT Austin, 2008, Phys. Rev. D76 (2007) 072005)

ν_μ CC events in the Near Detector

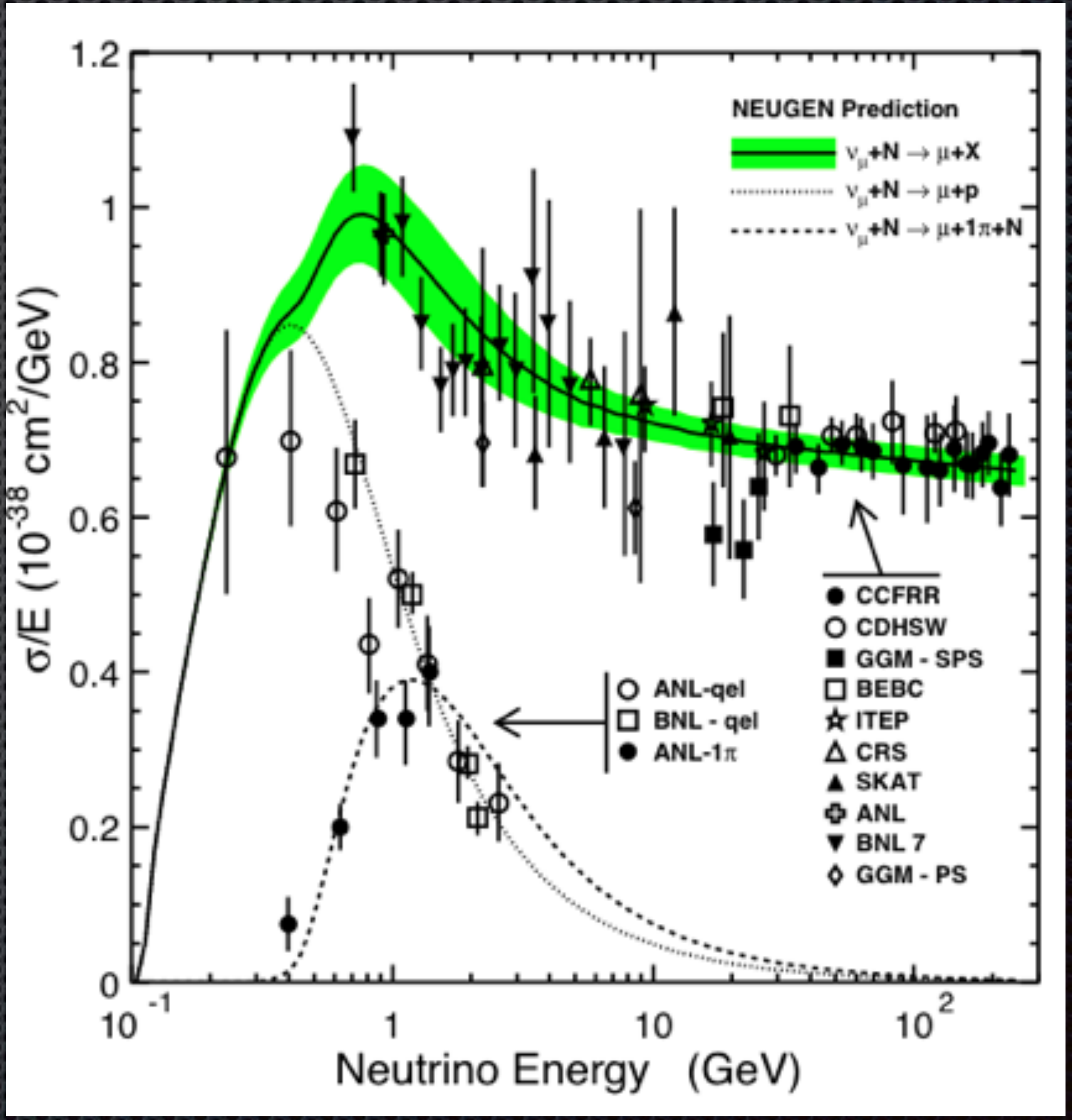


- Majority of data is from the low energy beam.
- High energy beam improves statistics in energy above the oscillation dip.
- Additional exposure in other beam configurations for commissioning and systematic studies.

- The beam spectrum can be tuned by varying relative positions of target and magnetic horns.
- MINOS uses ν_μ CC events in ND to constrain flux using 7 beam configurations.
- NA49 data used to constrain π^+/π^- and π/K ratios in fits.

Cross Sections Uncertainties

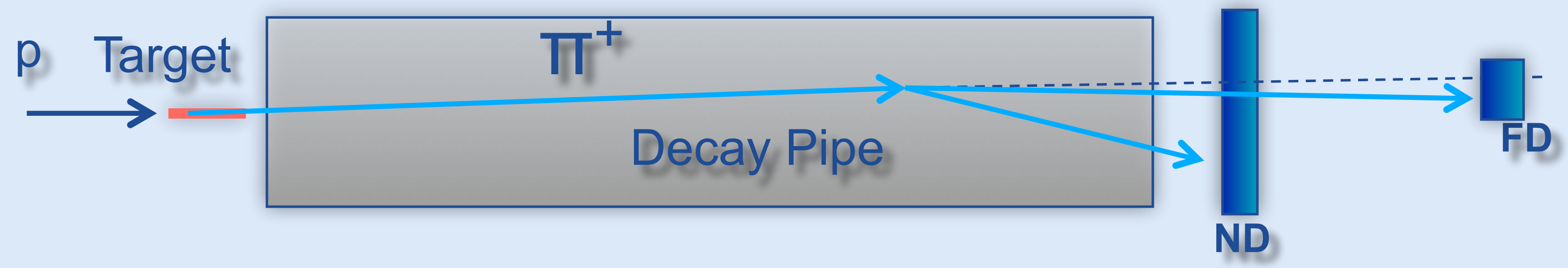
- Uncertainties determined from comparison of MC to independent data
- fits to both inclusive and exclusive channel data, in different invariant mass regions
  - 3% on the normalization of the DIS ($W > 1.7 GeV/c^2$) cross-section
  - 10% uncertainty in the normalization of the single-pion and quasi-elastic cross-sections.
  - 20% uncertainty in the relative contribution of non-resonant states to the 1π and 2π production cross-sections for $W < 1.7 GeV/c^2$.



P. Vahle SBL talk 2012

Predicting the FD background

- Use Near Detector data to predict Far Detector spectrum.
- We expect the Far Detector spectrum to be similar to $1/R^2$ scaled Near Detector spectrum, but not identical.

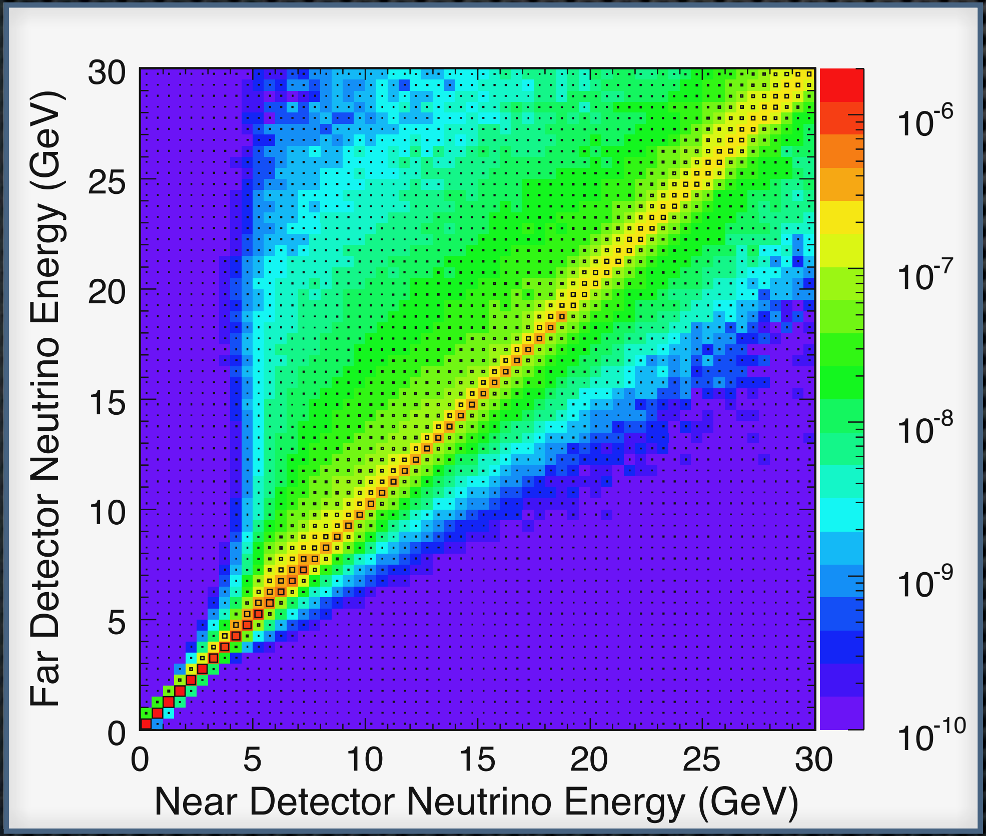


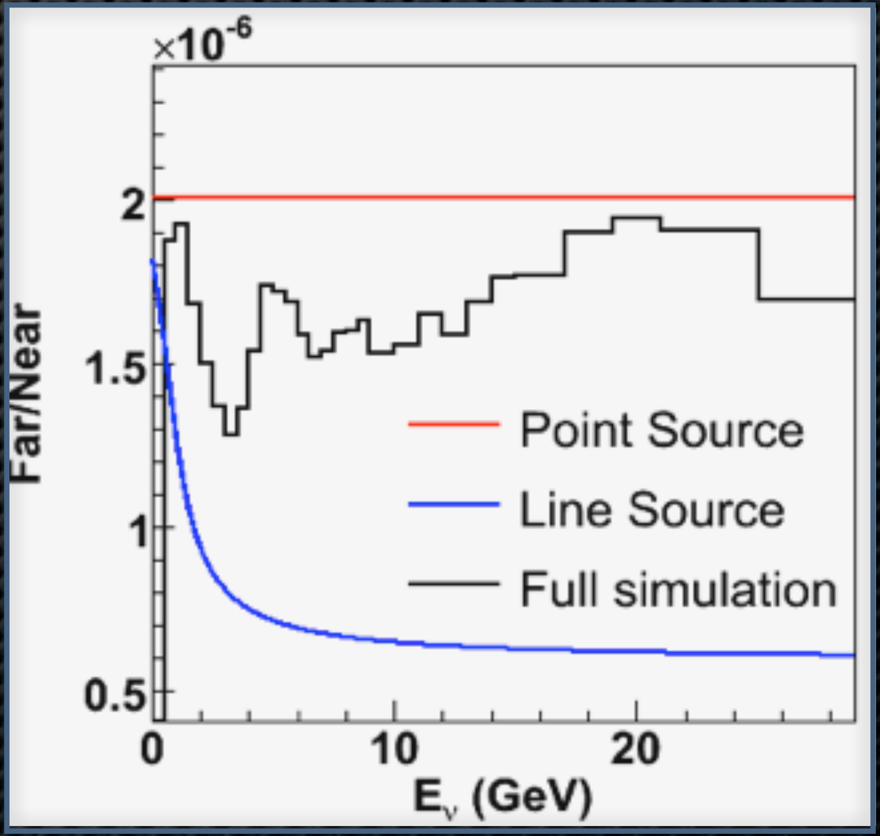
$$E_\nu = \frac{0.43 E_\pi}{1+\gamma^2\theta^2}$$

- Neutrino energy depends on angle with respect to the original pion direction and parent energy
  - higher energy pions decay further along the decay pipe
  - angular distributions different between Near and Far: line versus point source.

Predicting the FD background

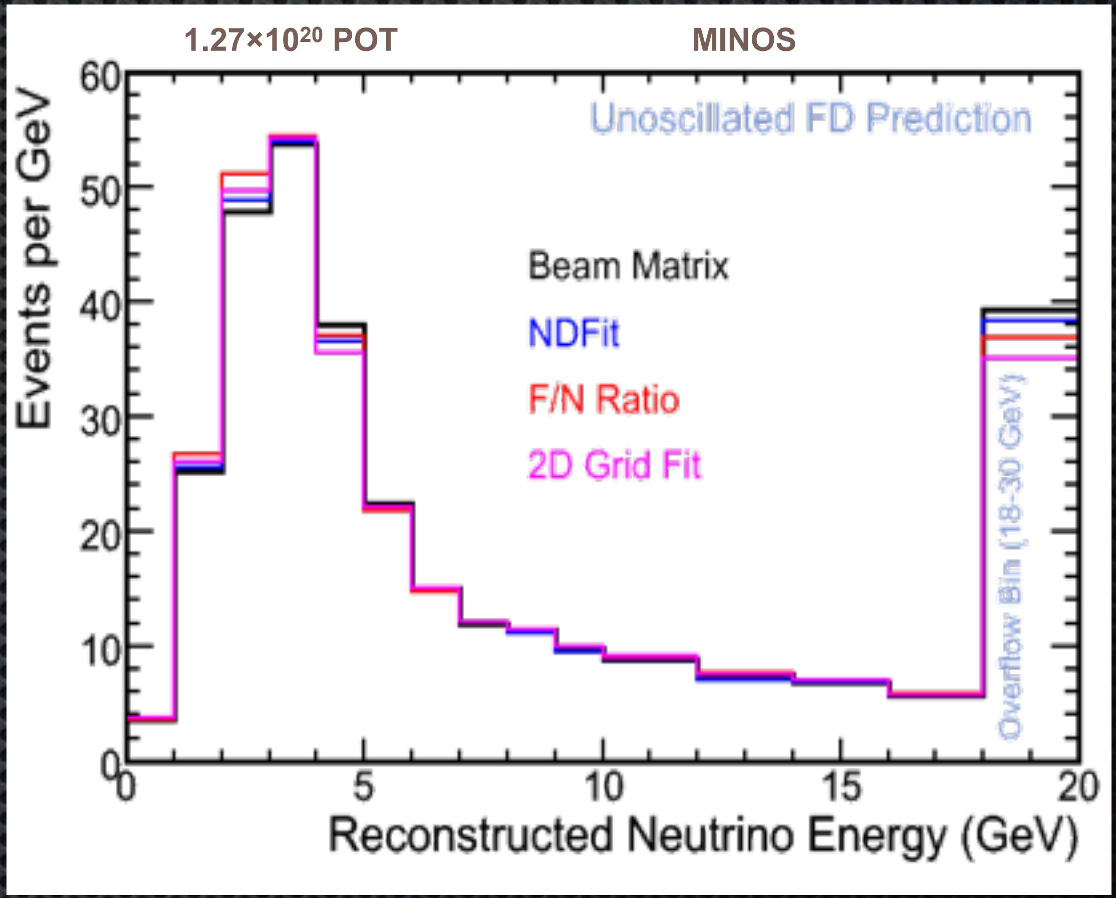
- Predict the event rate at each energy bin by correcting the expected Monte Carlo rate using either a beam matrix (CC analyses) or Far to Near spectrum ratio (Nue/NC) for Far Detector prediction of events.
- The Monte Carlo in each case provides necessary corrections due to energy smearing and acceptance.





Other extrapolation methods

- The MINOS first CC analysis had two additional extrapolation methods that described ND distributions by fitting physics quantities, predict FD spectrum from best fit (e.g., by reweighting MC)
- These other methods were less robust, as they had difficulty fitting all the features of the data distribution

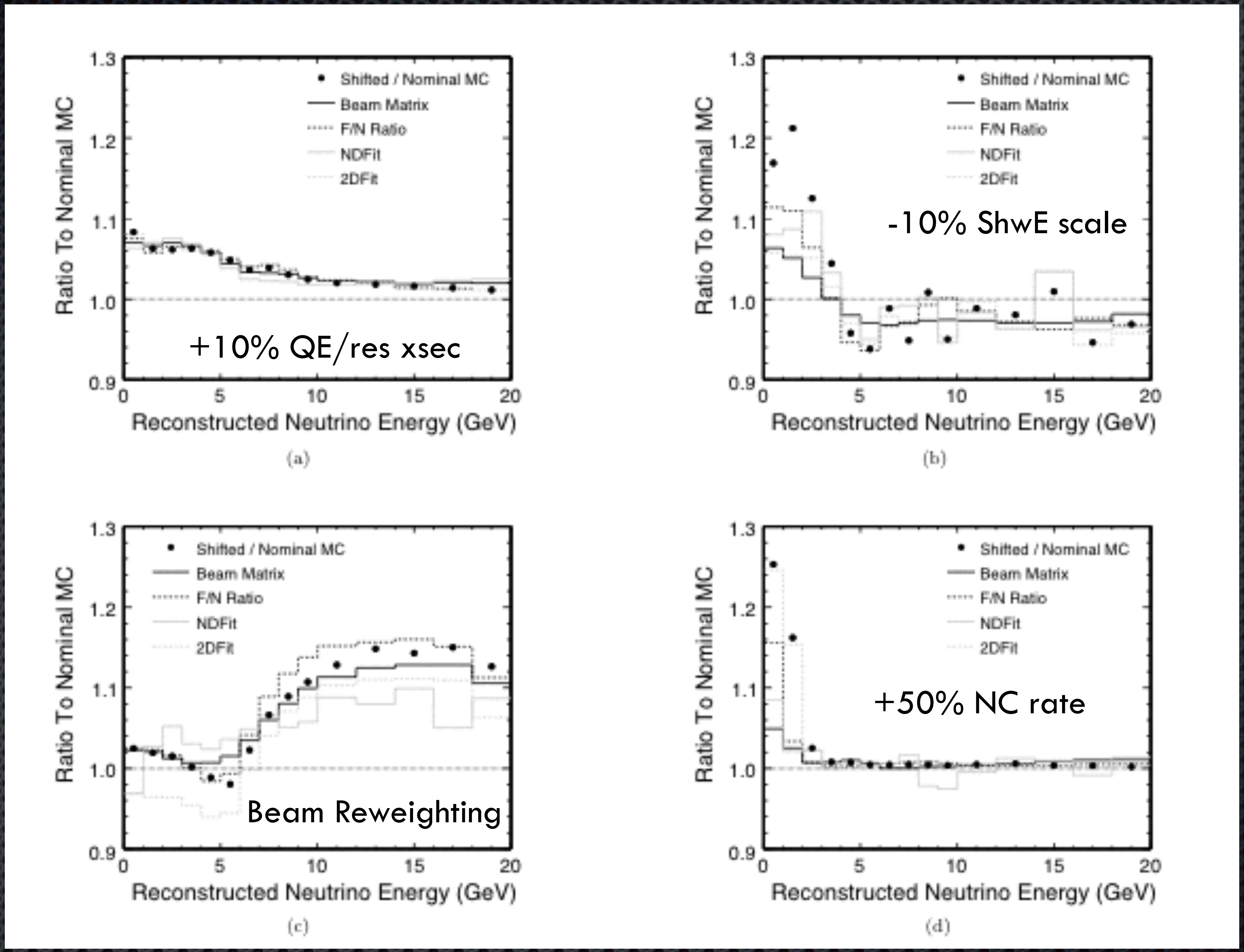


Prediction from all methods agreed to within ~ 5% bin-by-bin

P. Vahle SBL talk 2012

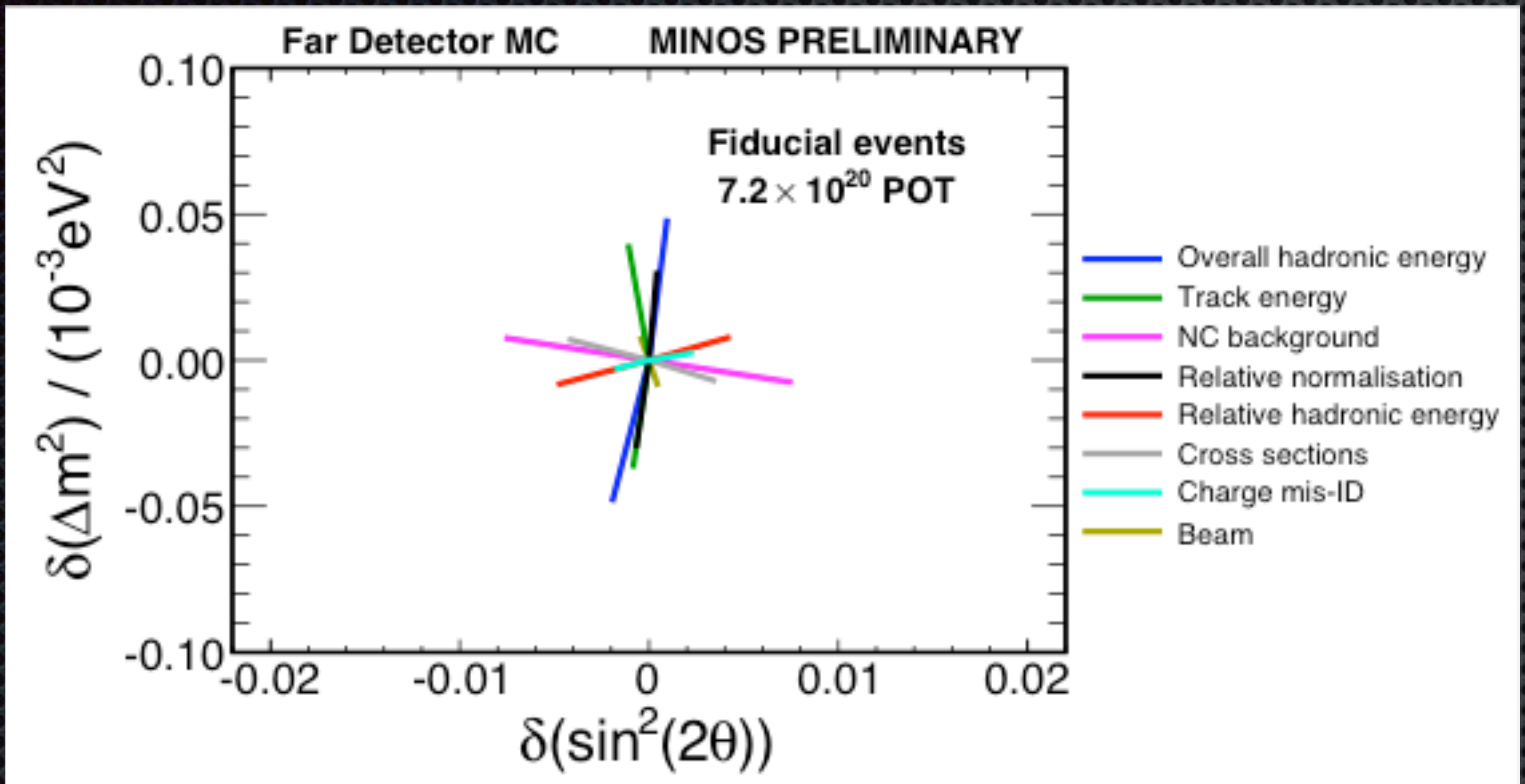
Systematic uncertainties

Phys. Rev. D76 (2007) 072005



- Some uncertainties were more sensitive to the different extrapolation methods.

Systematic uncertainties



	error on Δ	error on sin
Expected Statistical	*0.124*	*0.060*
Total Systematic	*0.085*	*0.013*

- Dominant systematic uncertainties for neutrinos included in fit as nuisance parameters:
  - hadronic energy calibration
  - track energy calibration
  - NC background
  - relative Near to Far normalization (uptime, Fid. Mass)

Searching for...

Electron neutrino appearance

- The probability of ν_e appearance in a ν_μ beam:

$$A \equiv \frac{G_f n_e L}{\sqrt{2}\Delta} \approx \frac{E}{11\ \mathrm{GeV}}$$

$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2(A-1)\Delta}{(A-1)^2} \qquad \Delta \equiv \frac{\Delta m^2_{31} L}{4E}$$
$$+2\alpha \sin\theta_{13}\cos\delta \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A}\frac{\sin(A-1)\Delta}{(A-1)}\cos\Delta$$
$$-2\alpha \sin\theta_{13}\sin\delta \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A}\frac{\sin(A-1)\Delta}{(A-1)}\sin\Delta$$

- Searching for ν_e events, we can access **$\sin^2(2\theta_{13})$**.
- Probability depends not only on **θ_{13} but also on δ_{CP}** which might be the key to matter anti-matter asymmetry of the universe. For large θ_{13}, a measurement could be possible.
- Probability is enhanced or suppressed due to **matter effects** which depend on the mass hierarchy i.e. the sign of $\Delta m^2_{31} \sim \Delta m^2_{32}$ as well as neutrino vs anti-neutrino running.

Searching for θ_{13} in MINOS

- The probability of ν_e appearance in a ν_μ beam:

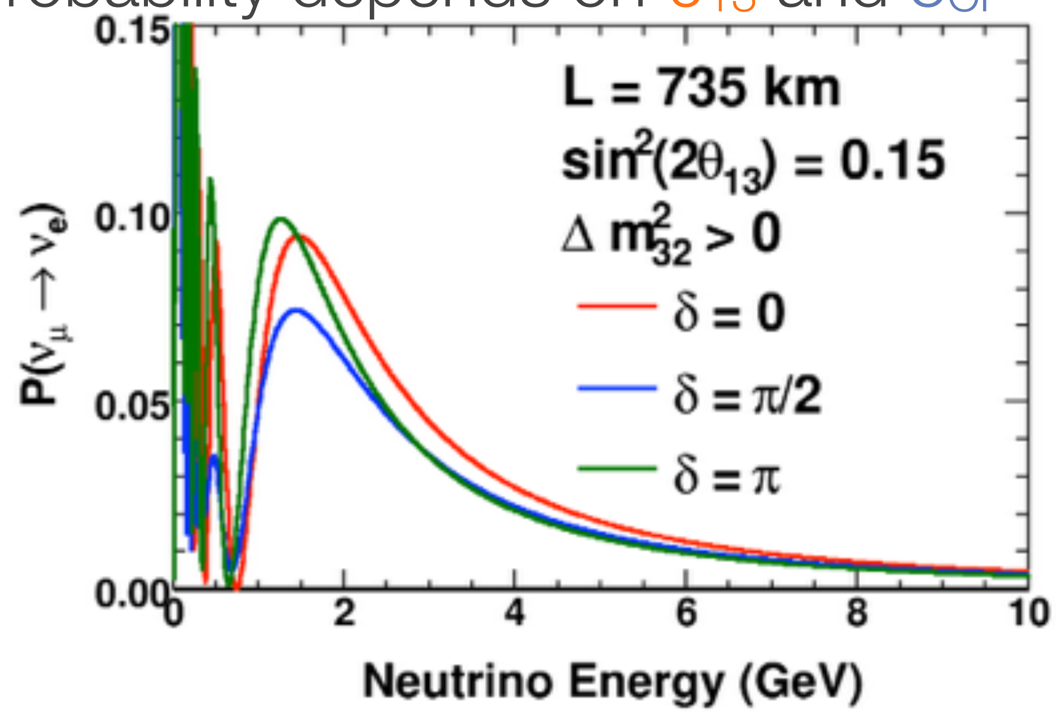
$$A \equiv \frac{G_f n_e L}{\sqrt{2}\Delta} \approx \frac{E}{11\ \mathrm{GeV}}$$

$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2(A-1)\Delta}{(A-1)^2} \qquad \Delta \equiv \frac{\Delta m^2_{31} L}{4E}$$

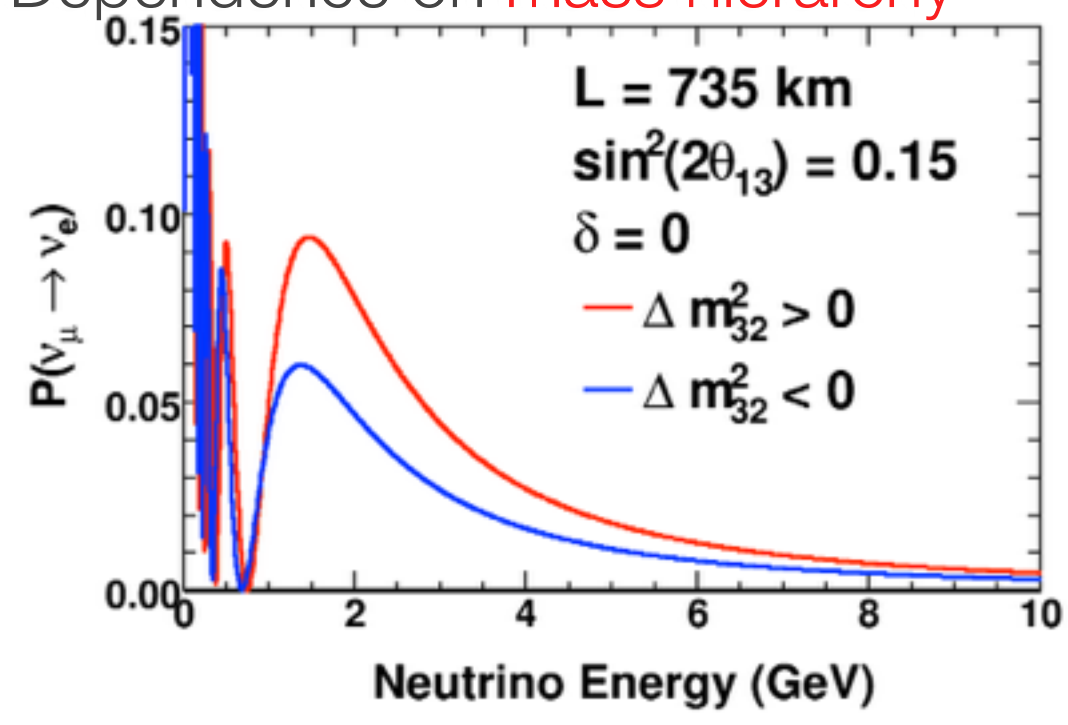
$$+2\alpha \sin\theta_{13} \cos\delta \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \cos\Delta$$

$$-2\alpha \sin\theta_{13} \sin\delta \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \sin\Delta$$

Probability depends on θ_{13} and δ_{CP}



Dependence on mass hierarchy



Appearance experiments challenges

- Electron neutrino appearance experiments are different than muon neutrino disappearance experiments:
  - Cannot cancel systematic uncertainties on the signal directly as the signal is not observed at the near detector.
  - Potentially larger backgrounds due to electromagnetic showers in neutral currents.
  - Intrinsic beam electron neutrino contamination.
  - Other systematic uncertainties are more relevant such as hadronic shower uncertainties.

Do we need a near detector then?

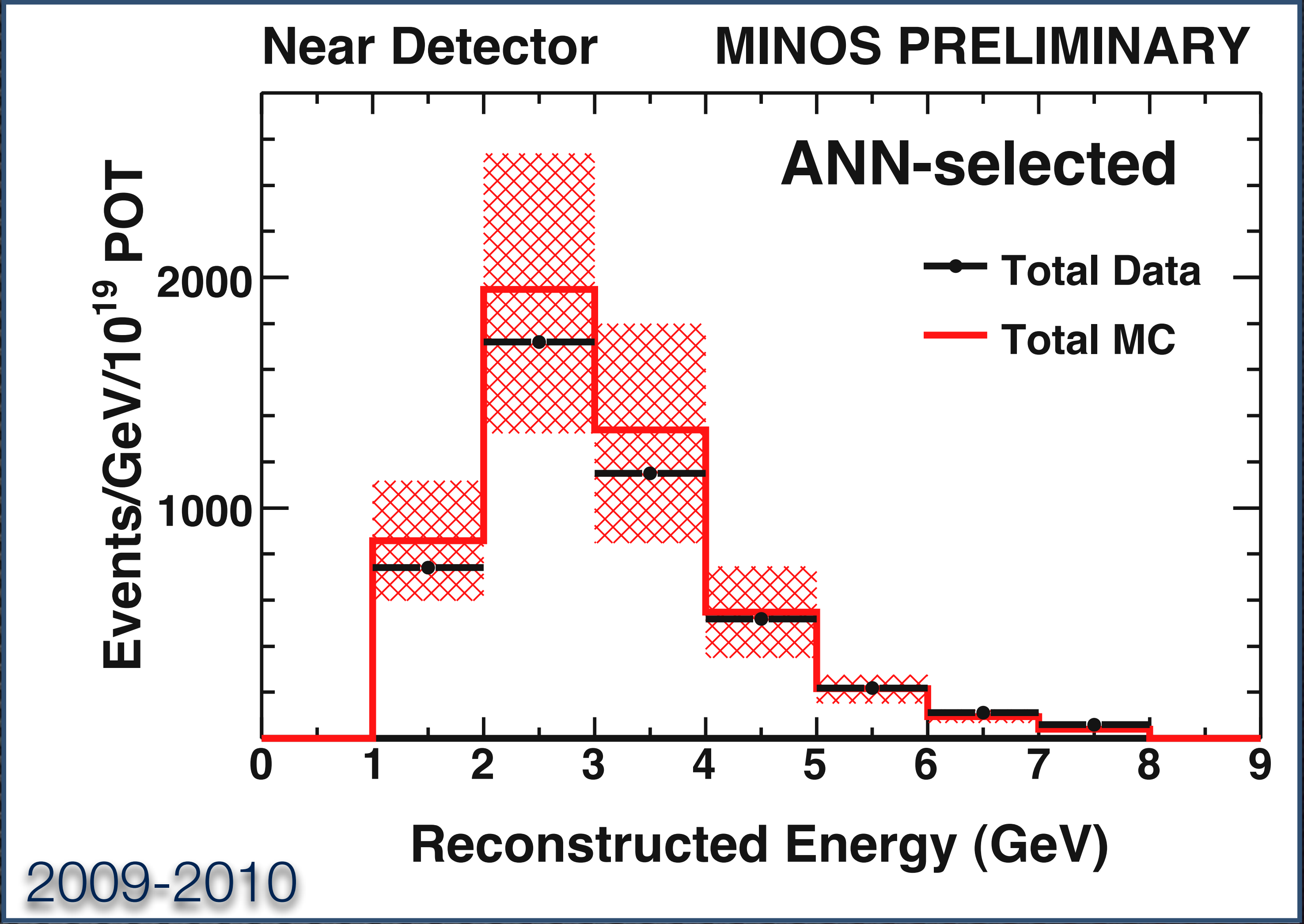
Do we need a near detector? Of course!

Experiment	Year	ν_μ-NC/CC Events	ν_e-CC Events	Background Syst.Error	Comment
BNL E734 [144]	1985	235	418	20%	No ND
BNL E776(NBB) [145]	1989	10	9	20%	No ND
BNL E776 (WBB) [146]	1992	95	40	14%	No ND
NOMAD [147]	2003	<300	5500	$< 5\%$	No ND
MiniBooNE [148]	2008	460	380	9%	No ND
MiniBooNE [49]	2013	536	782	5%	SciBooNE
MINOS [143]	2013	111	36	4%	ND–FD
T2K [149]	2013	1.1	26	9%*	ND–FD

- Summary of electron neutrino appearance experiments from arxiv:1307.7335.
- MINOS and T2K both narrow band beams are different in that MINOS small systematic uncertainty is on a large background whereas T2K is on all events which are predominantly signal.
- NBB/WBB indicates a narrow/wide band beam. No ND indicates there was no near detector, and ND-FD indicates a two (near-far) detector experiment with extrapolation of the expected background and signal from the near to the far detector.

MINOS Near Detector data

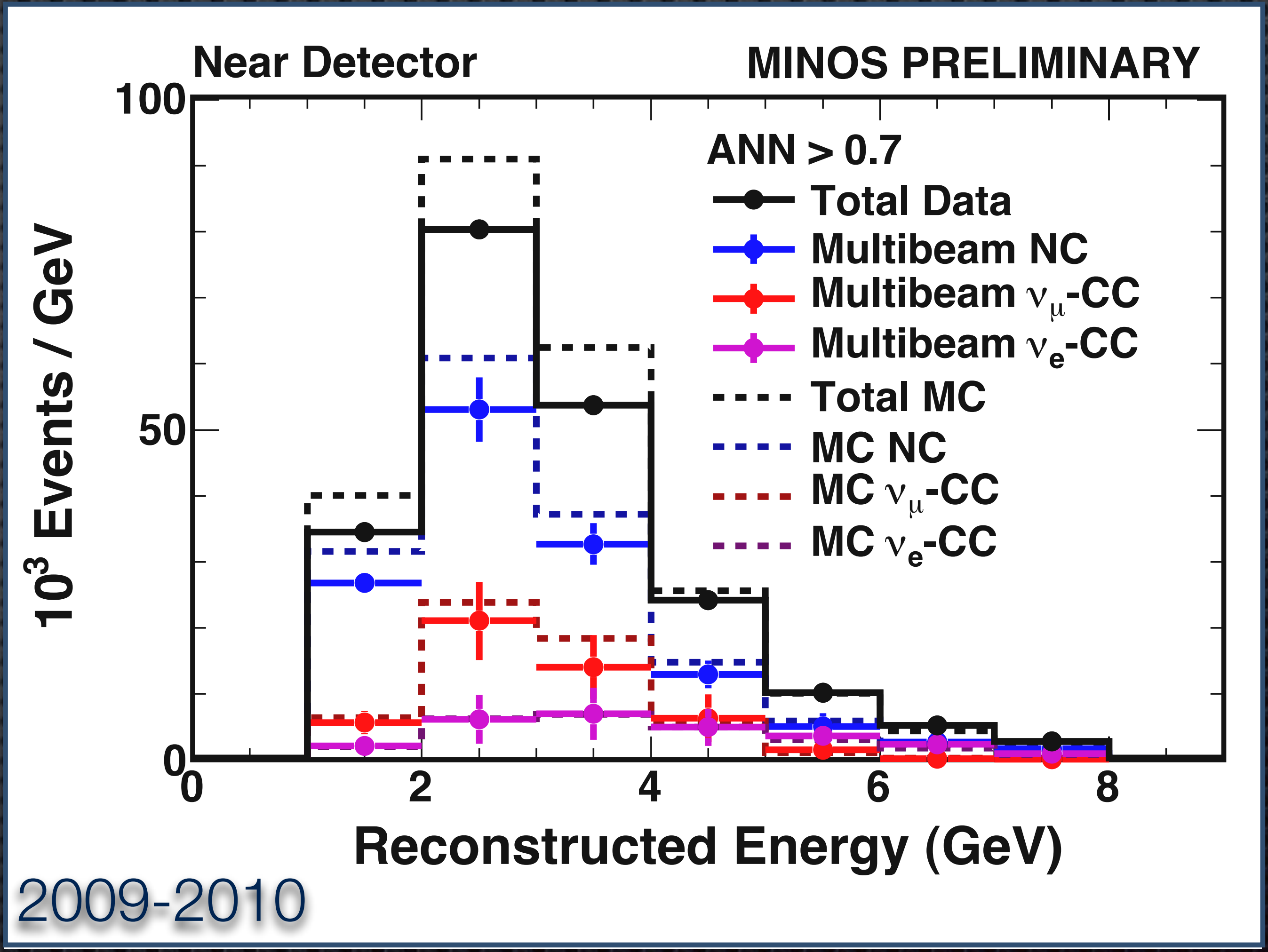
- Near Detector provides a high-statistic data sample to **estimate the background**.
  - Simulation originally predicted backgrounds ~20% higher than observed.
  - Hadronization and final state interactions uncertainties give rise to large uncertainties in ND prediction
  - External data sparse in our region of interest
  - Simulation has improved since then.



- MINOS developed **data-driven methods** to measure the different background components.

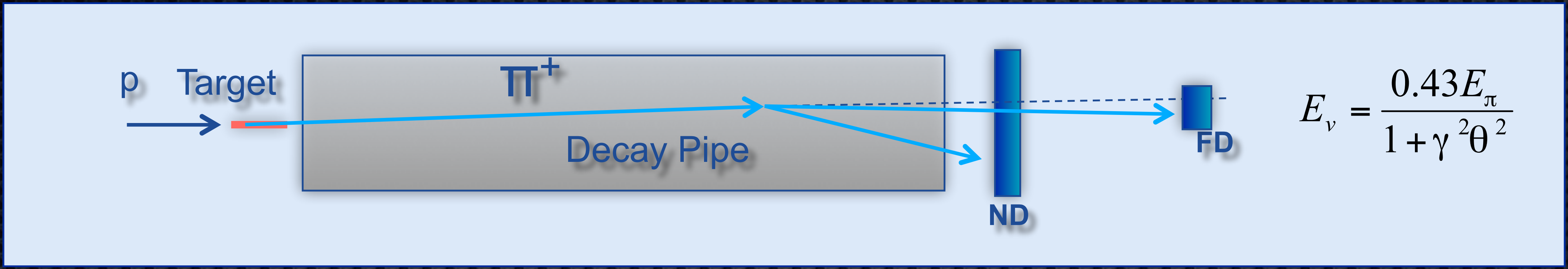
Separate background components NC vs CC

- We calculated the NC and νμ CC fractions by correcting the measurement using ratios of the different beam configurations for each components.
- This is necessary as each background component extrapolates differently to the far detector, e.g. muon neutrinos must be oscillated.



Predicting the Far Detector neutrinos

- Use Near Detector data to predict Far Detector background spectrum.
- We expect the Far Detector spectrum to be similar to $1/R^2$ scaled Near Detector spectrum, but not identical.



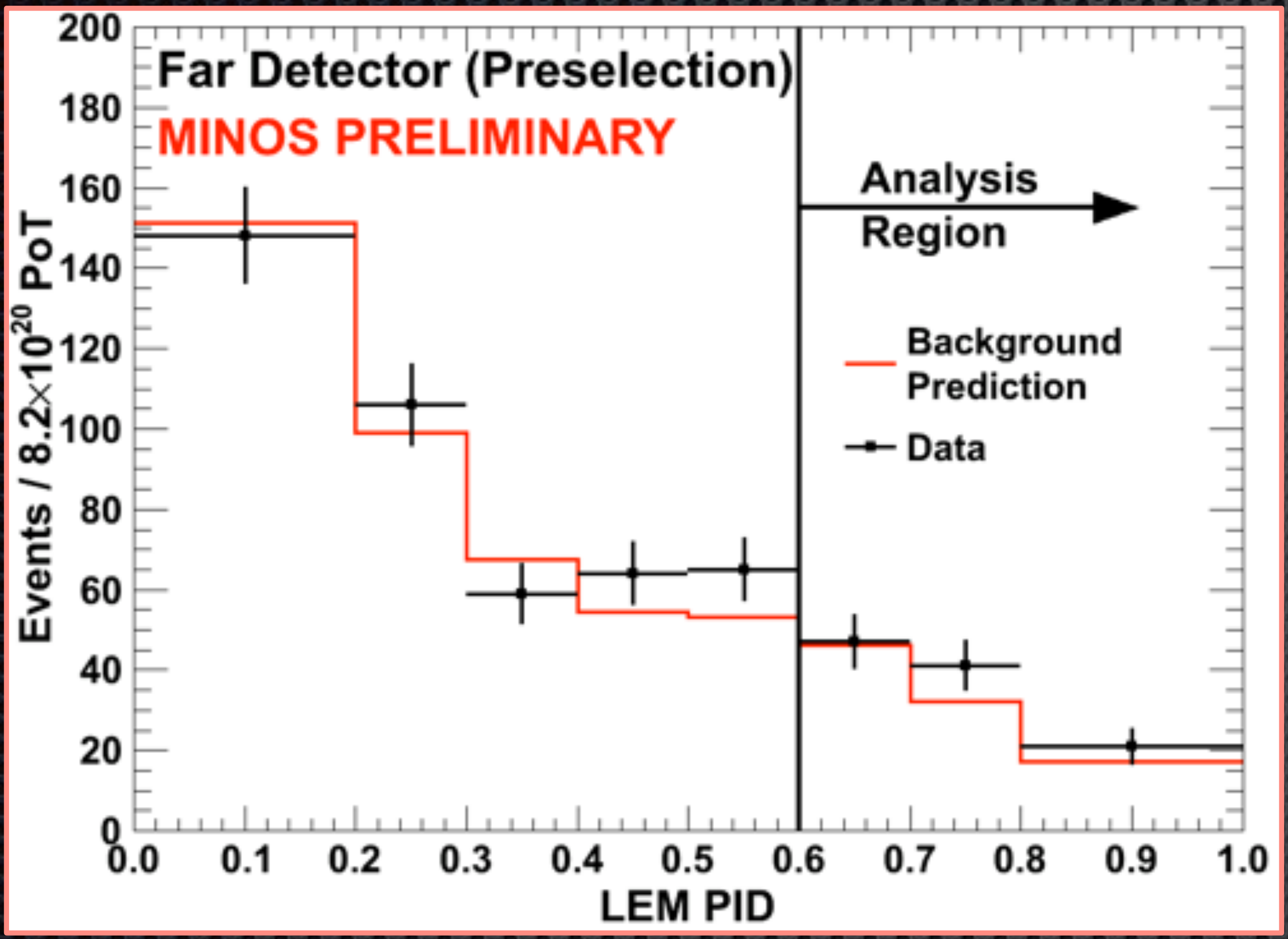
- Predict the event rate at each energy bin by correcting the expected Monte Carlo rate using the ratio of data to Monte Carlo in the Near Detector:

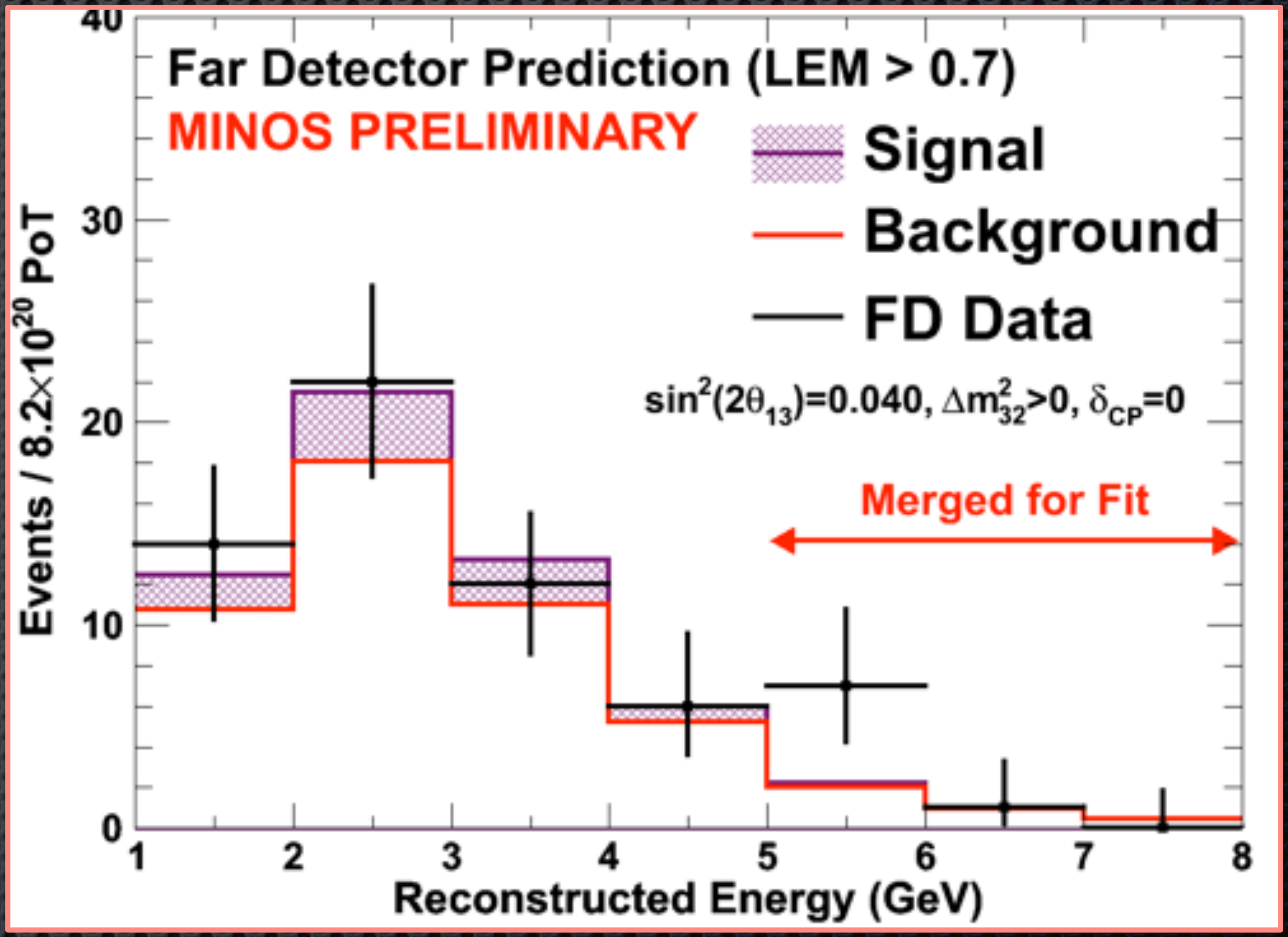
$$FD_i^{predicted} = \frac{FD_i^{MC}}{ND_i^{MC}} ND_i^{Data}$$

The Monte Carlo provides necessary corrections due to energy smearing and acceptance.

MINOS ν_e appearance

- Background/signal predictions and systematic errors finalized before looking at data in Far Detector.

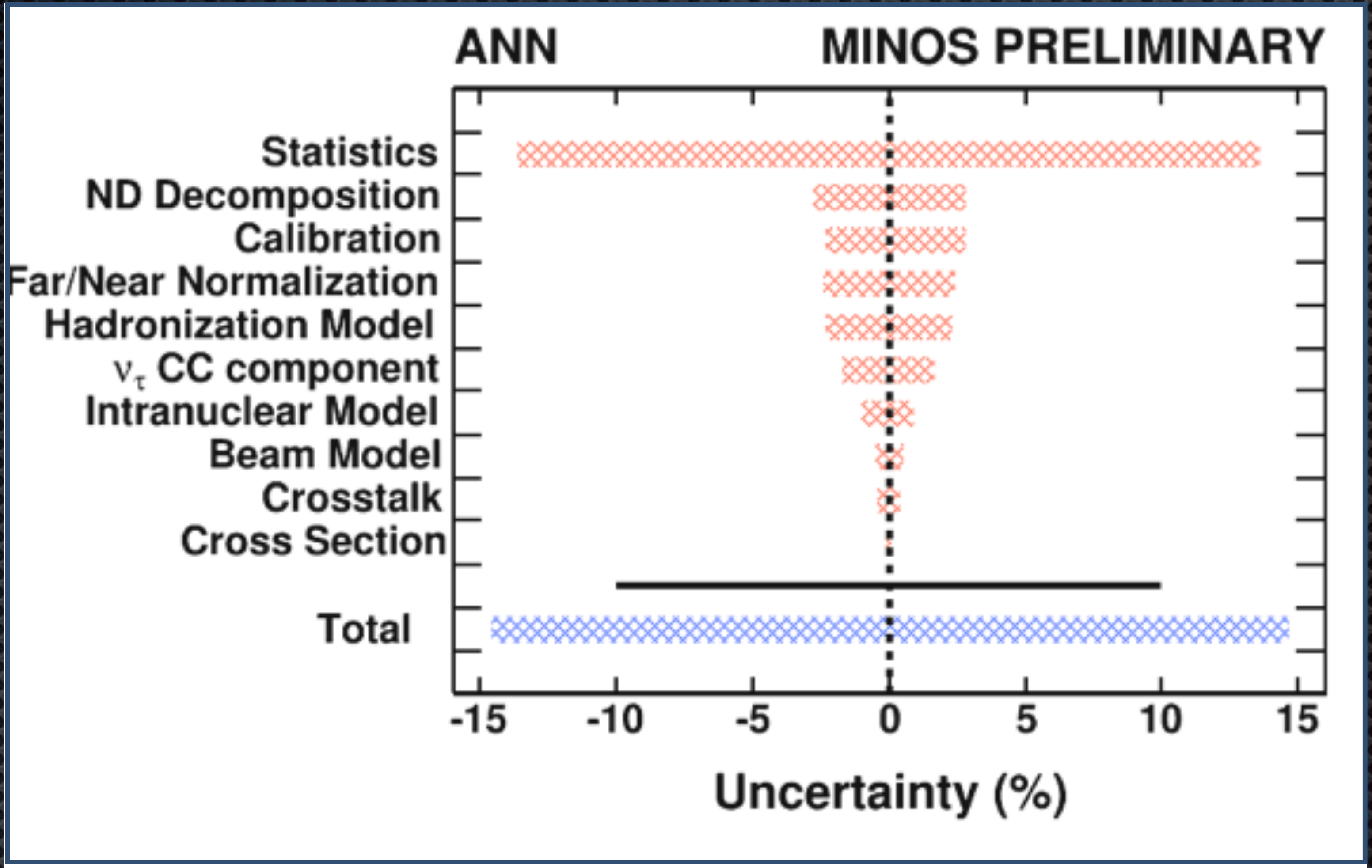




- Expect 49.5±7.0(stat)±2.8(sys). Observe 62.

Phys. Rev. Lett. 107 (2011) 181802

FD background systematics

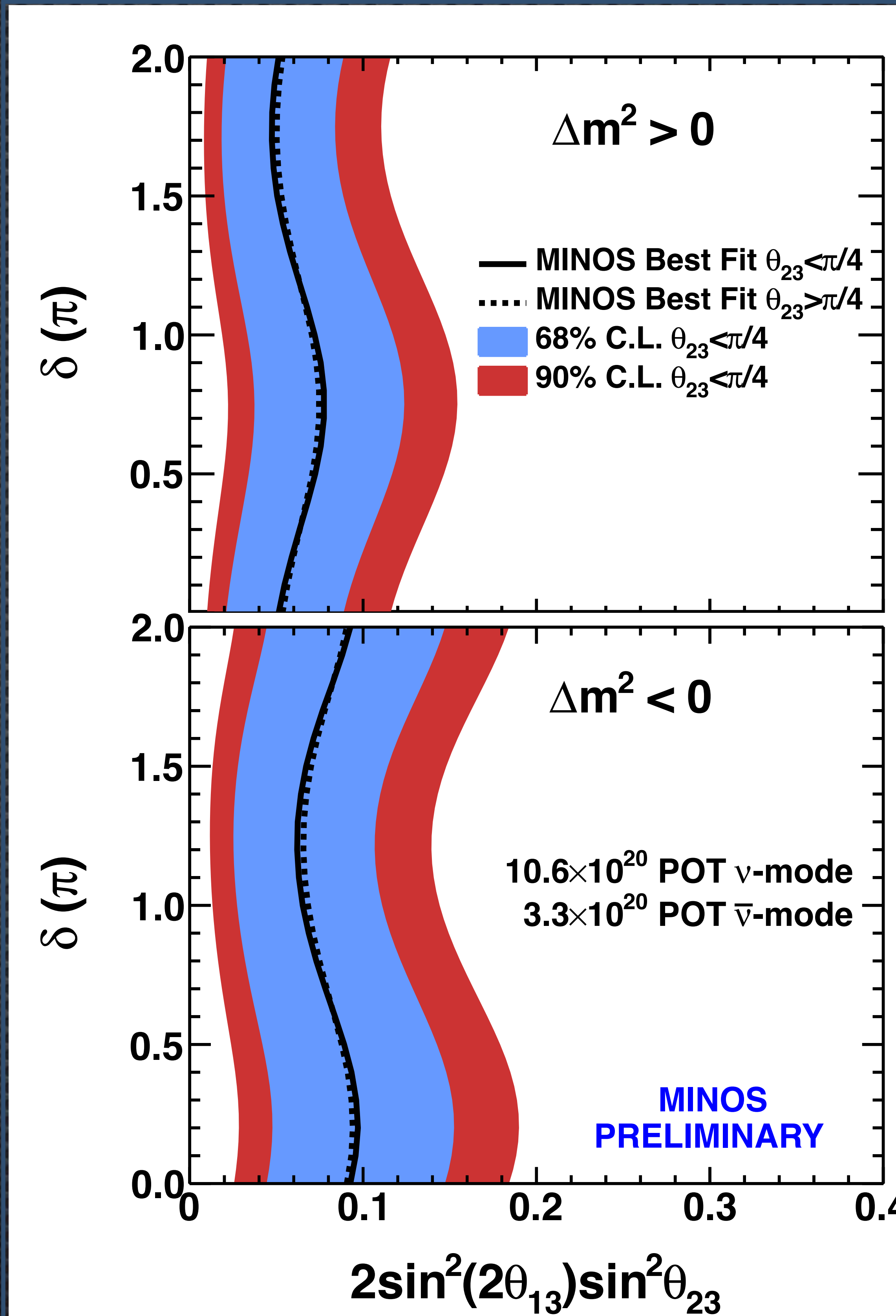


- The two detectors are very similar, however there are small differences: readout, intensity, attenuation lengths, etc.
- For the main background components the larger systematics were Decomposition, Calibration, Normalization and Hadronization. In later analyses energy scale, normalization and tau neutrino cross section dominated.
- However, for MINOS statistical errors continued to dominate.

Phys. Rev. Lett. 107 (2011) 181802

MINOS ν_e appearance

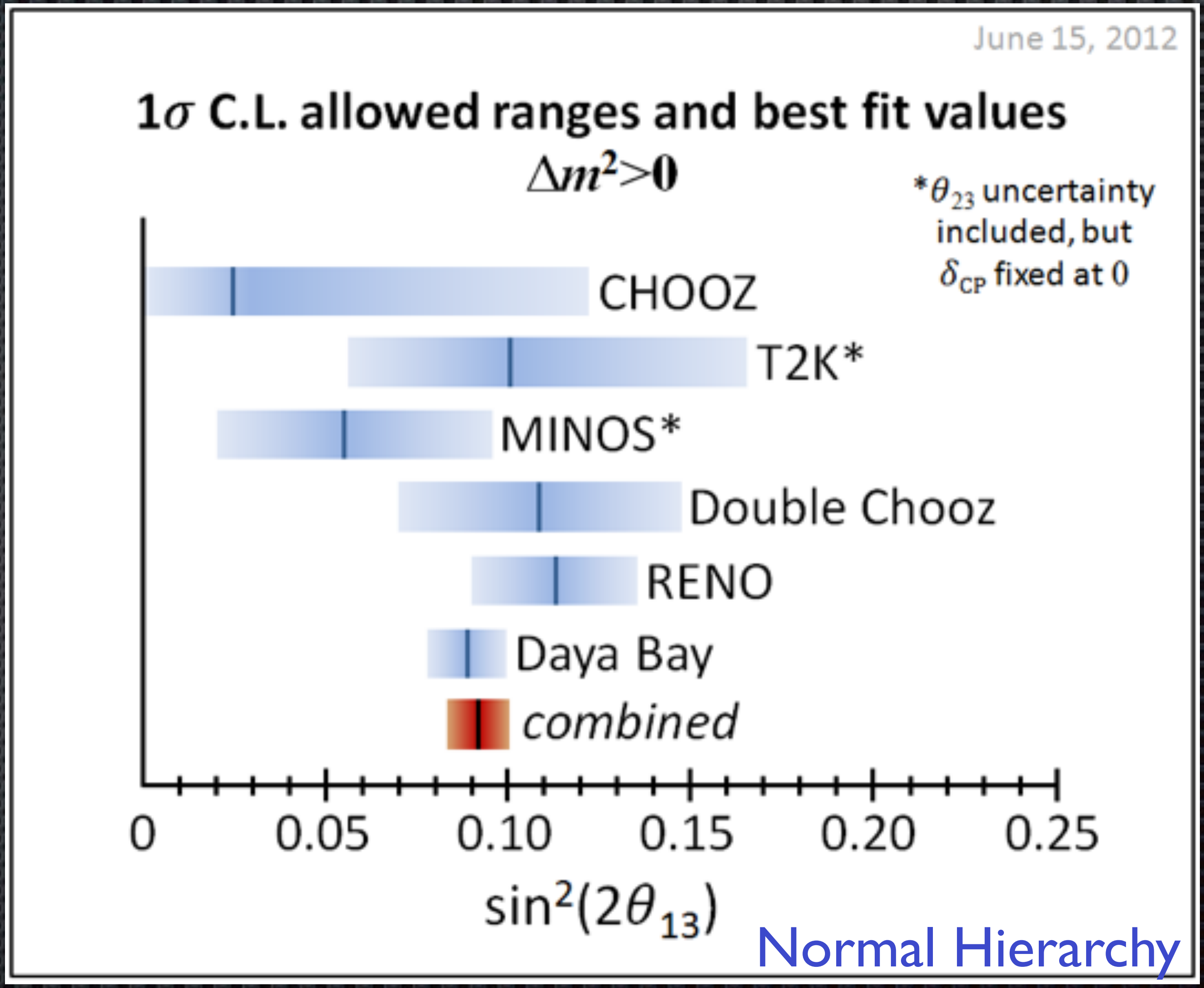
- Plot shows 90 and 68% CL limits in δ_{CP} vs. $\sin^2 2\theta_{13}$
  - for MINOS best fit value
  - for both hierarchies
- $\sin^2 2\theta_{13} = 0$ excluded at over 90% CL
- What you can do with ~170 neutrinos!



P. Adamson *et.al.*, Phys.Rev.Lett. 110 171801 (2013)
P. Adamson *et.al.*, Phys.Rev.Lett. 107 181802 (2011)
P. Adamson *et.al.*, Phys.Rev.D 82 051102 (2010)
P. Adamson *et.al.*, Phys.Rev.Lett. 103 261802 (2009)

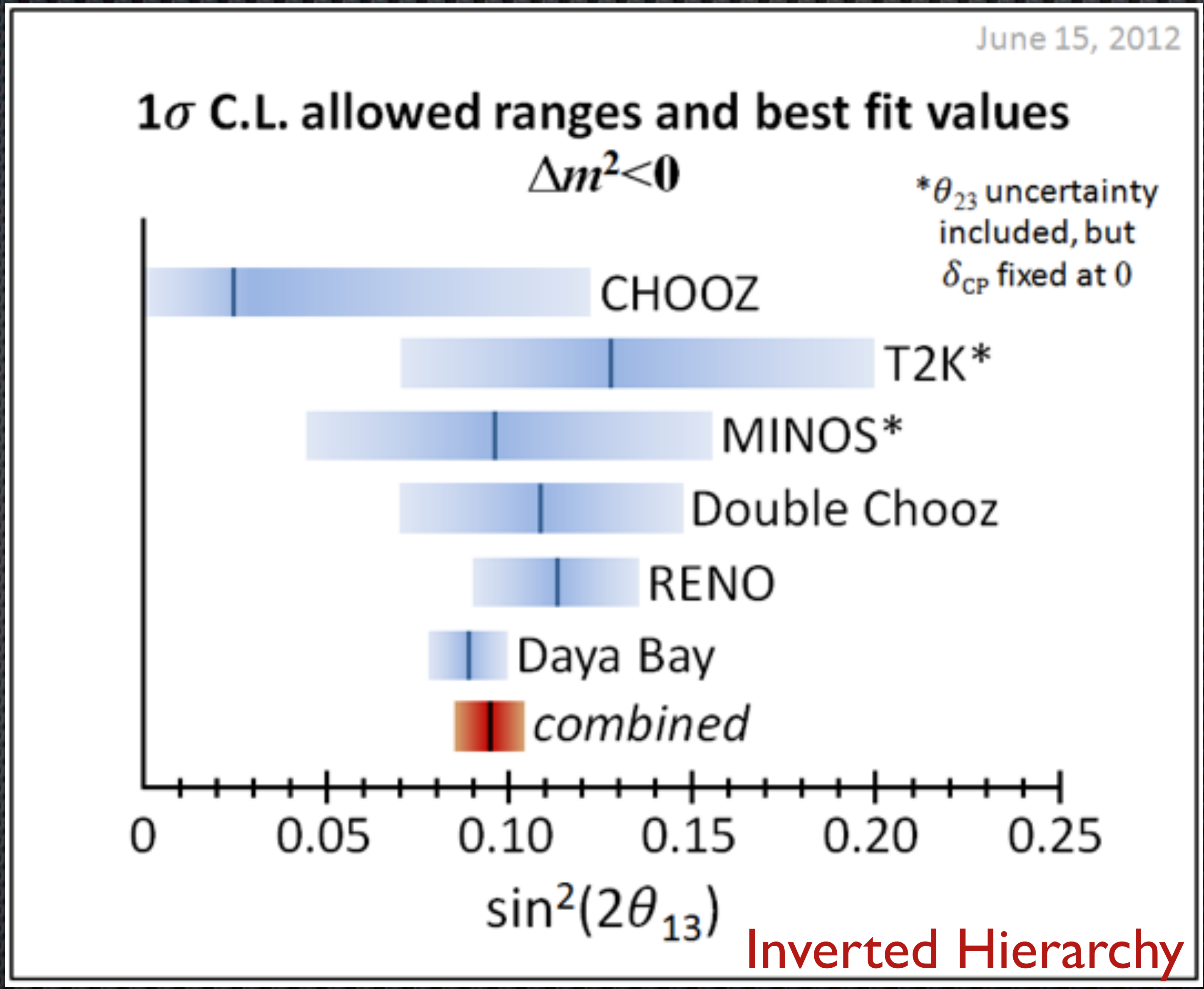
The status of θ_{13} after Neutrino 2012

- Thanks to Daya Bay we went from not knowing this parameter at all to having measured it down to 5% for θ_{13}.



The status of θ_{13} after Neutrino 2012

- Thanks to Daya Bay we went from not knowing this parameter at all to having measured it down to 5% for θ_{13}.



Mild preference for inverted hierarchy, also seen in SuperK.
About ~1 σ, not statistically significant.

Beyond measuring appearance probabilities

The Model

When matter effects are included in full three-flavor P_{surv}…

$$P(\nu_\mu \to \nu_e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \cdot \sin^2 \Delta_{31}$$ "θ_{13} term"

$$+8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21}$$

"CP term"

$$-8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \cdot \sin\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21}$$

"solar term"

$$+4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \cdot \sin^2 \Delta_{21}$$

"matter terms"

$$-8C_{13}^2 S_{13}^2 S_{23}^2 \cdot \frac{aL}{4E_\nu}(1 - 2S_{13}^2) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31}$$

$$+8C_{13}^2 S_{13}^2 S_{23}^2 \frac{a}{\Delta m_{31}^2}(1 - 2S_{13}^2) \cdot \sin^2 \Delta_{31},$$

$$\Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4E_\nu} \qquad a = 2\sqrt{2} G_F n_e E$$

$$= 7.6 \times 10^{-5} \rho \left[g/cm^3\right] \times E_\nu \left[GeV\right]$$

Lots of signs that matter:

- Δ: $\Delta m^2 < 0$?
- δ: ν vs. anti-ν
- a: ν vs. anti-ν

A reminder from Tuesday, lots of signs matter!

Beyond measuring appearance probabilities

The Model

Lots of signs that matter:

- Δ: $\Delta m^2<0$?
- δ: ν vs. anti-ν
- A: ν vs. anti-ν

On the upside:

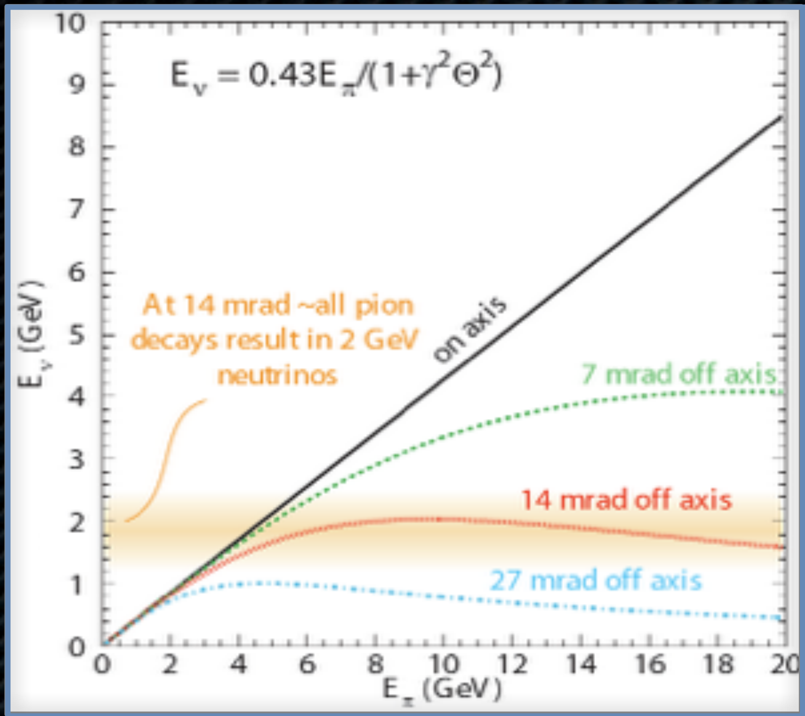
- Oscillations can tell us the mass hierarchy!
- Oscillations can tell us δ!

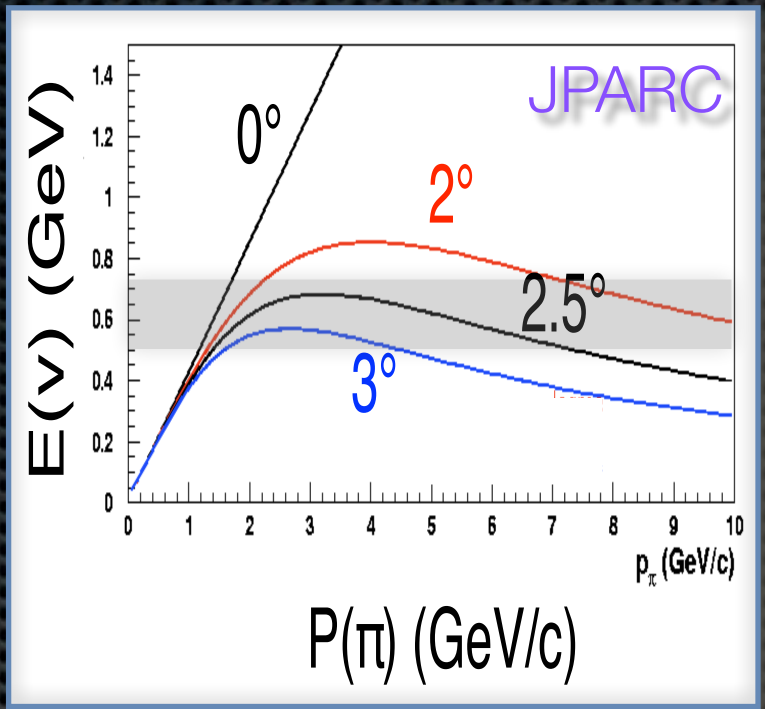
On the downside:

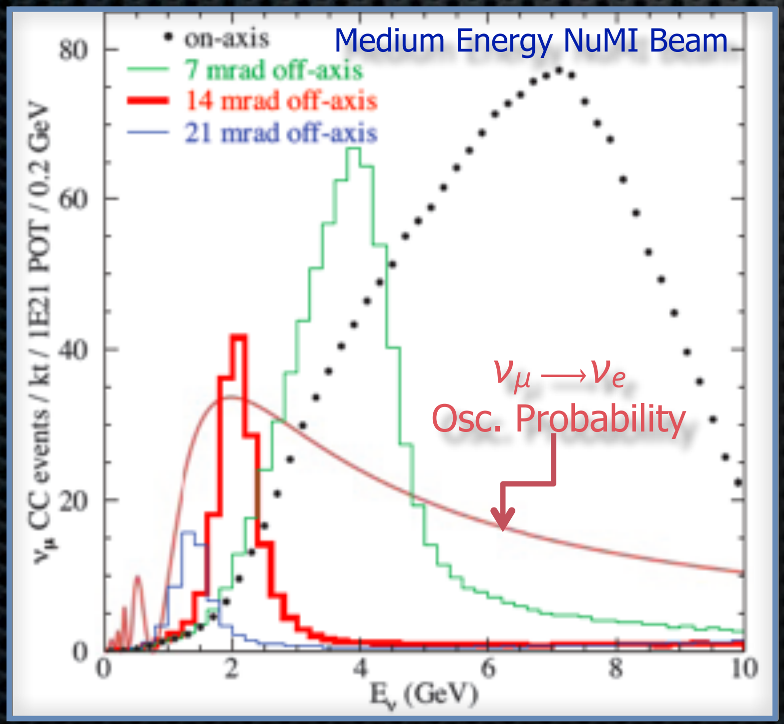
- This can be very confusing, and can even cancel—
- Matter effect enhances $\nu_\mu \rightarrow \nu_e$ for normal hierarchy, suppresses it for IH, and just the opposite for the anti-nus.

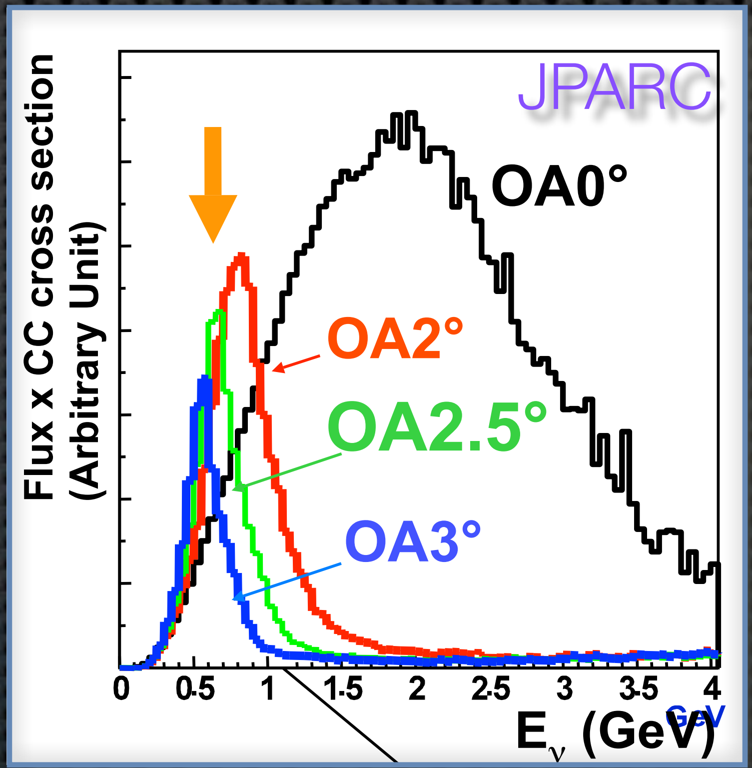
One possible solution: combine data from many exp.

Off-axis beam neutrinos





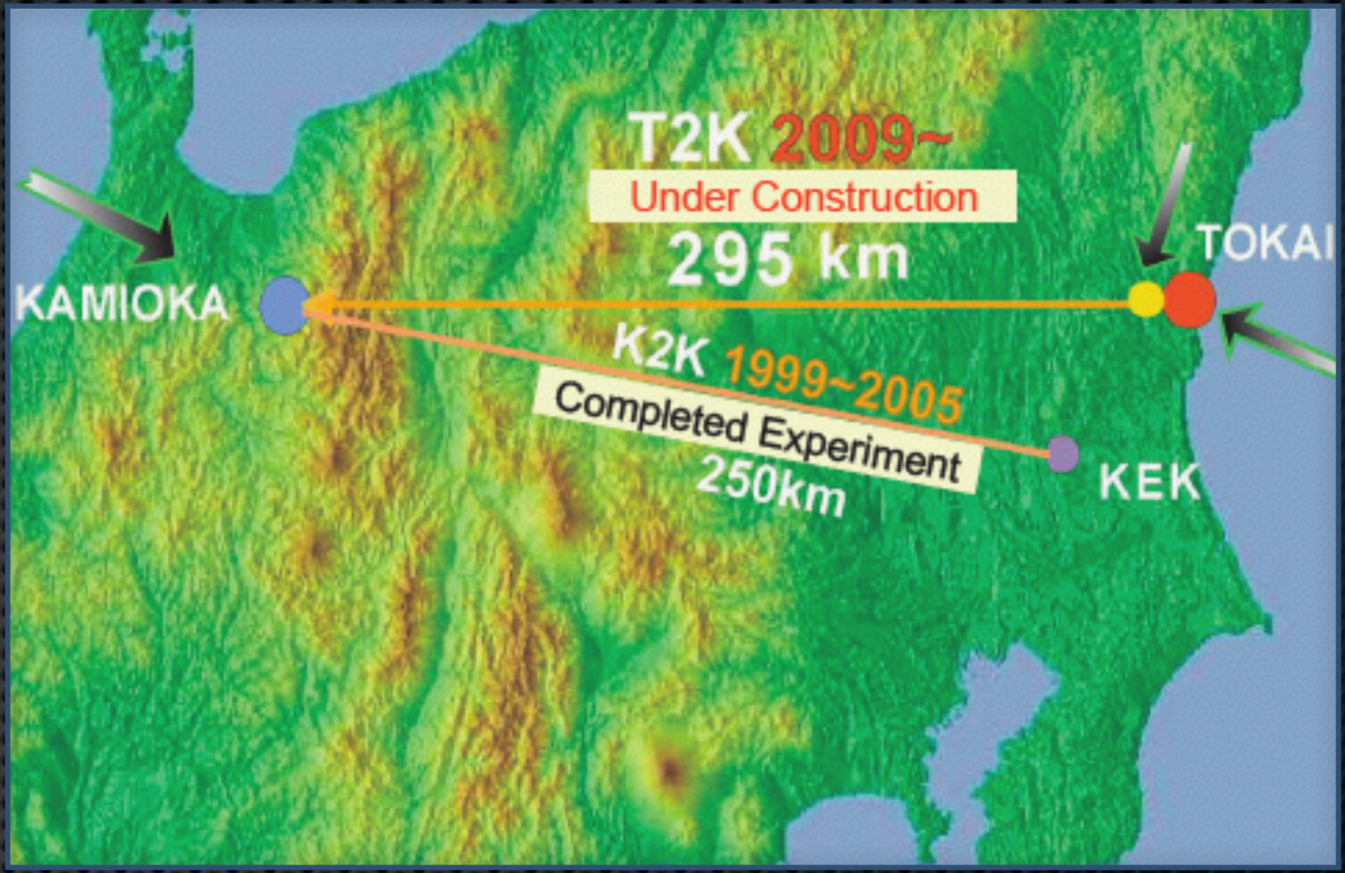




- Second generation of long-baseline experiments focuses on electron neutrino appearance searches.
- To reduce neutral current contamination from interactions with high energy neutrinos, the detectors can be placed off-axis.
- The peak is tuned to the first oscillation maximum.
- For muon neutrino disappearance measurement, this provides a perfect canvas to observe the oscillation pattern.

T2K in a nutshell

- Build a high intensity off-axis beam of muon neutrinos at JPARC (2.5º away from SuperK).
- Use existing large Water Cherenkov detector SuperK
- Build a near detector complex to understand beam, cross-sections, etc.
- If neutrinos oscillate, electron neutrinos are observed 295 km away at the Far Detector at Kamioka.



2nd generation
long baseline

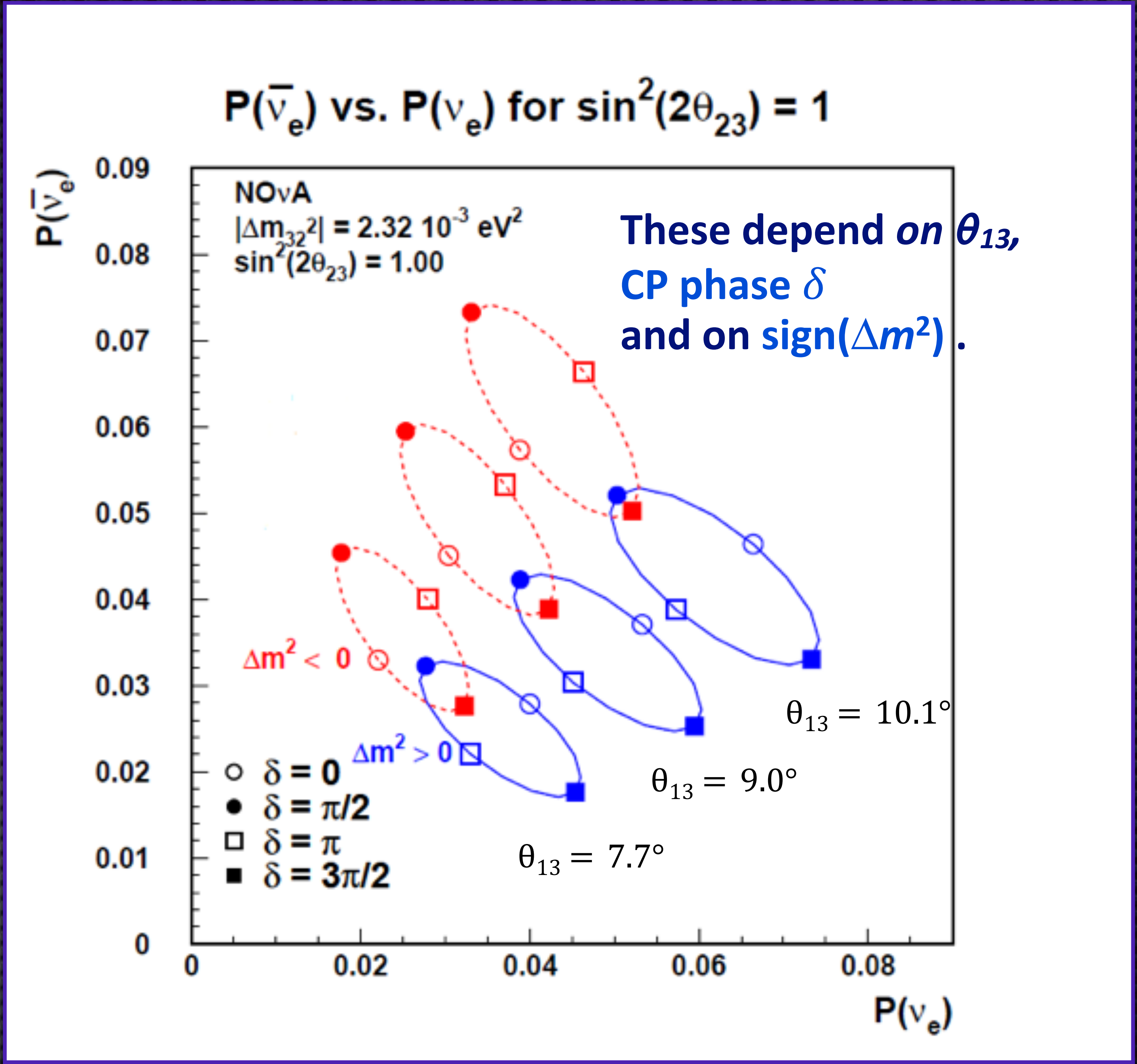
NOvA in a nutshell

- Upgrade high intensity beam of muon neutrinos at Fermilab to 700kW.
- Construct a totally active liquid scintillator detector off the main axis of the beam.
    - Detector is 14 mrad off-axis.
    - Location reduces background for the search.
- If neutrinos oscillate, electron neutrinos are observed at the Far Detector in Ash River, 810 km away.
- Plan to run 3 years in neutrino and 3 years in anti-neutrino.

2nd generation
← long baseline →

NOvA physics

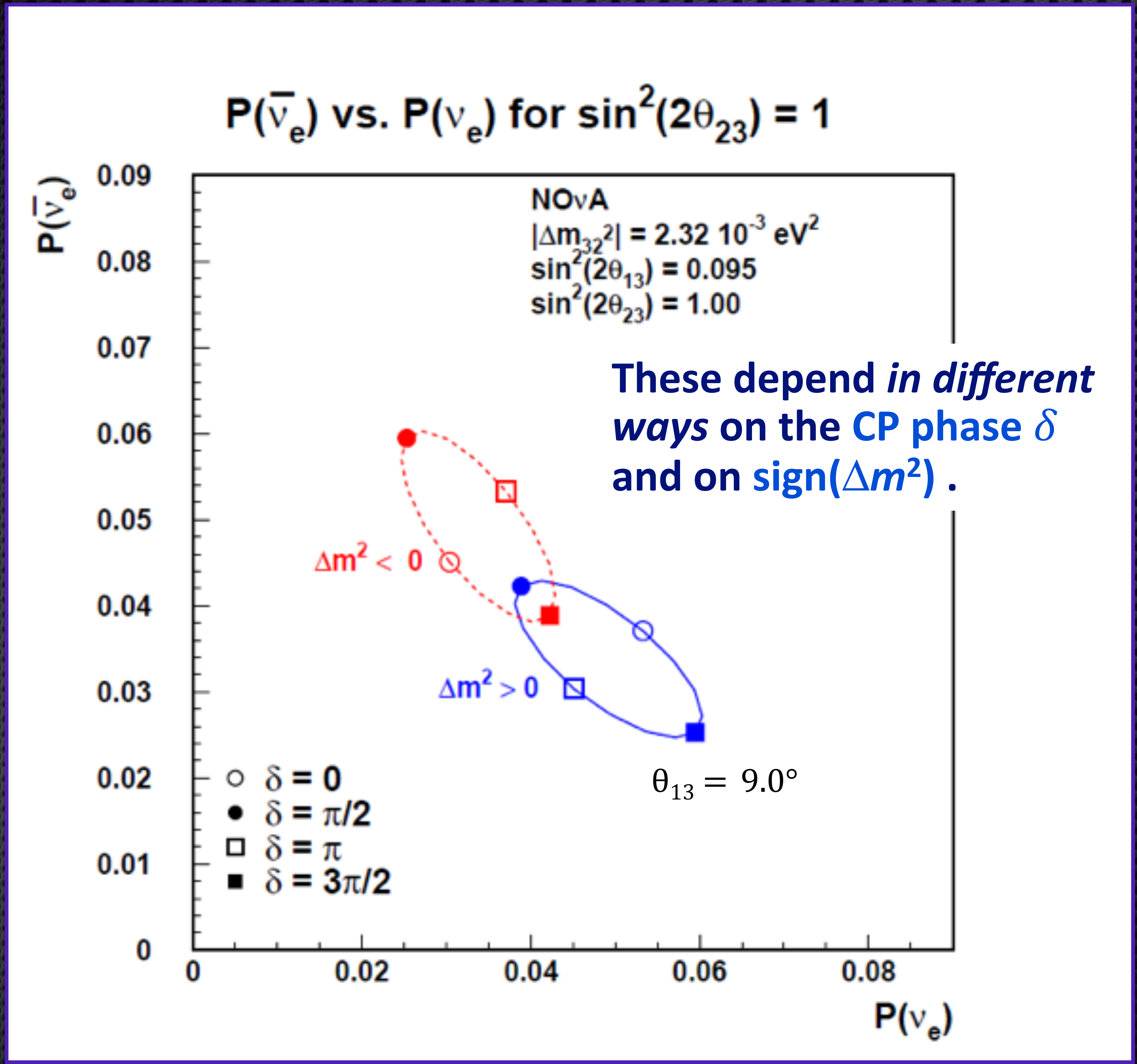
NOνA will measure: $P(\nu_\mu \to \nu_e)$ **at 2 GeV** *and* $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ **at 2 GeV**



Now we know θ_{13} ~ 9 degrees

NOvA physics

NOνA will measure: ***P***$(\nu_\mu \to \nu_e)$ **at 2 GeV** *and* ***P***$(\bar{\nu}_\mu \to \bar{\nu}_e)$ **at 2 GeV**



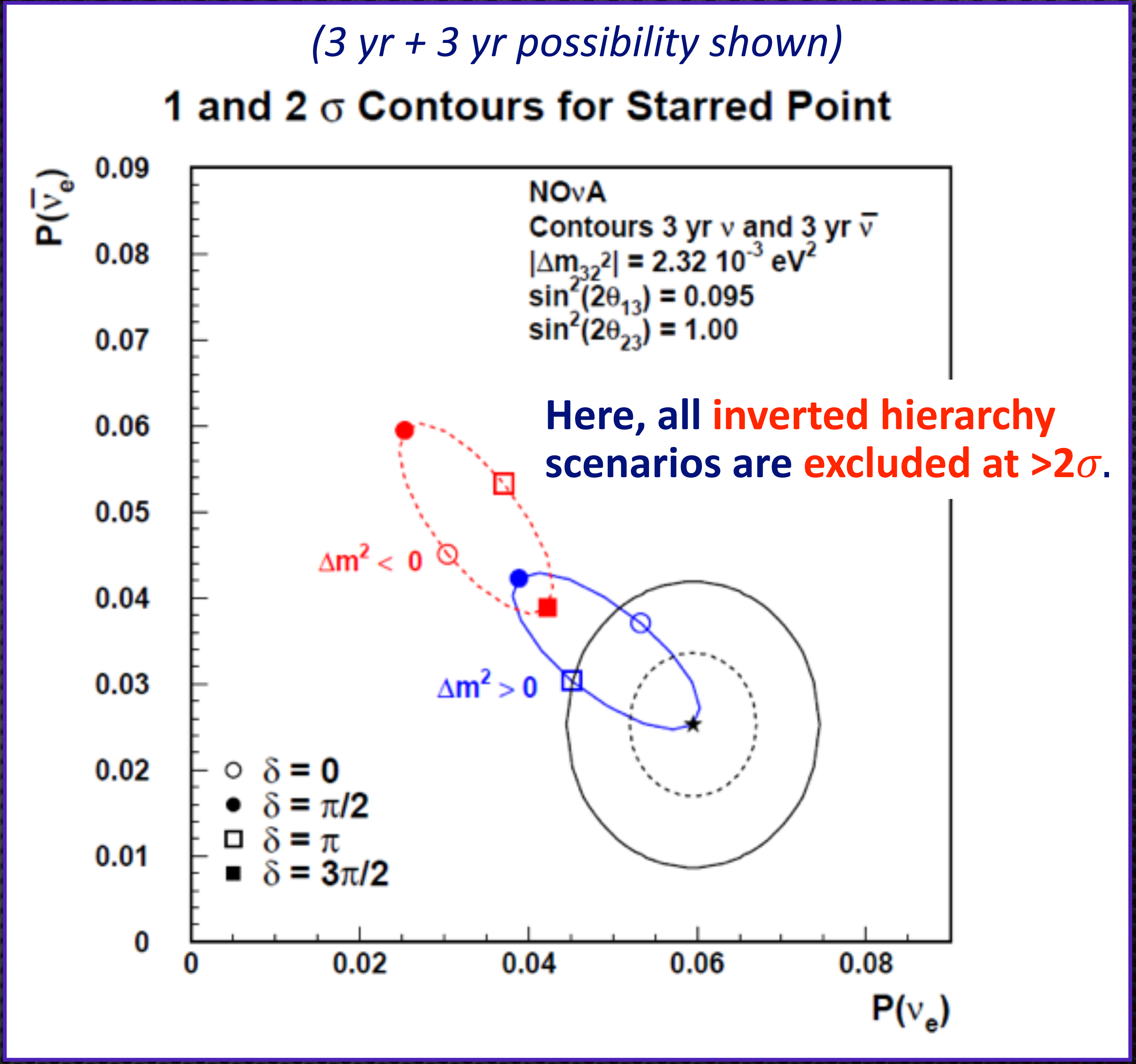
- Large θ_{13} is good news for NOvA. It reduces the overlap between these bi-probability ellipses, reducing the likelihood of degeneracies.

NOvA physics

Example NOνA result…

Our data will yield allowed regions in $P(\bar{\nu}_e)$ vs. $P(\nu_e)$ space

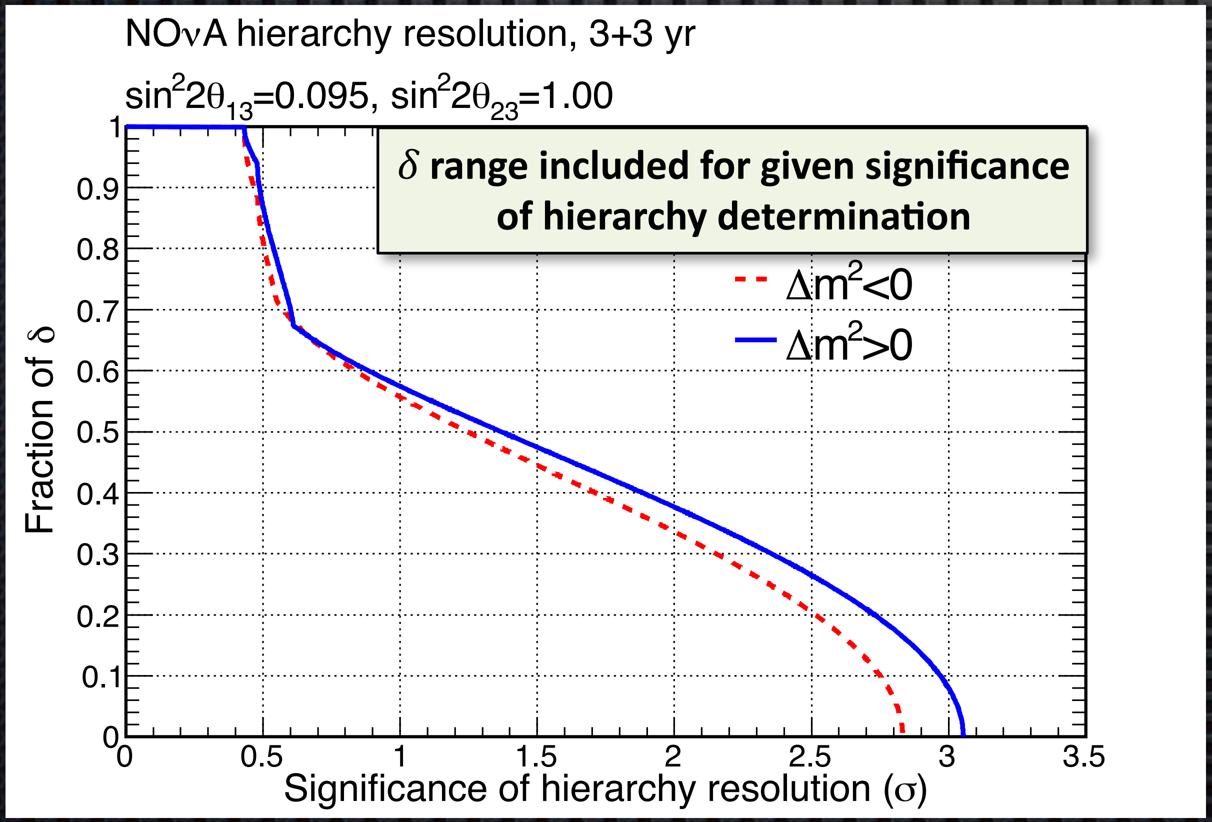
(3 yr + 3 yr possibility shown)

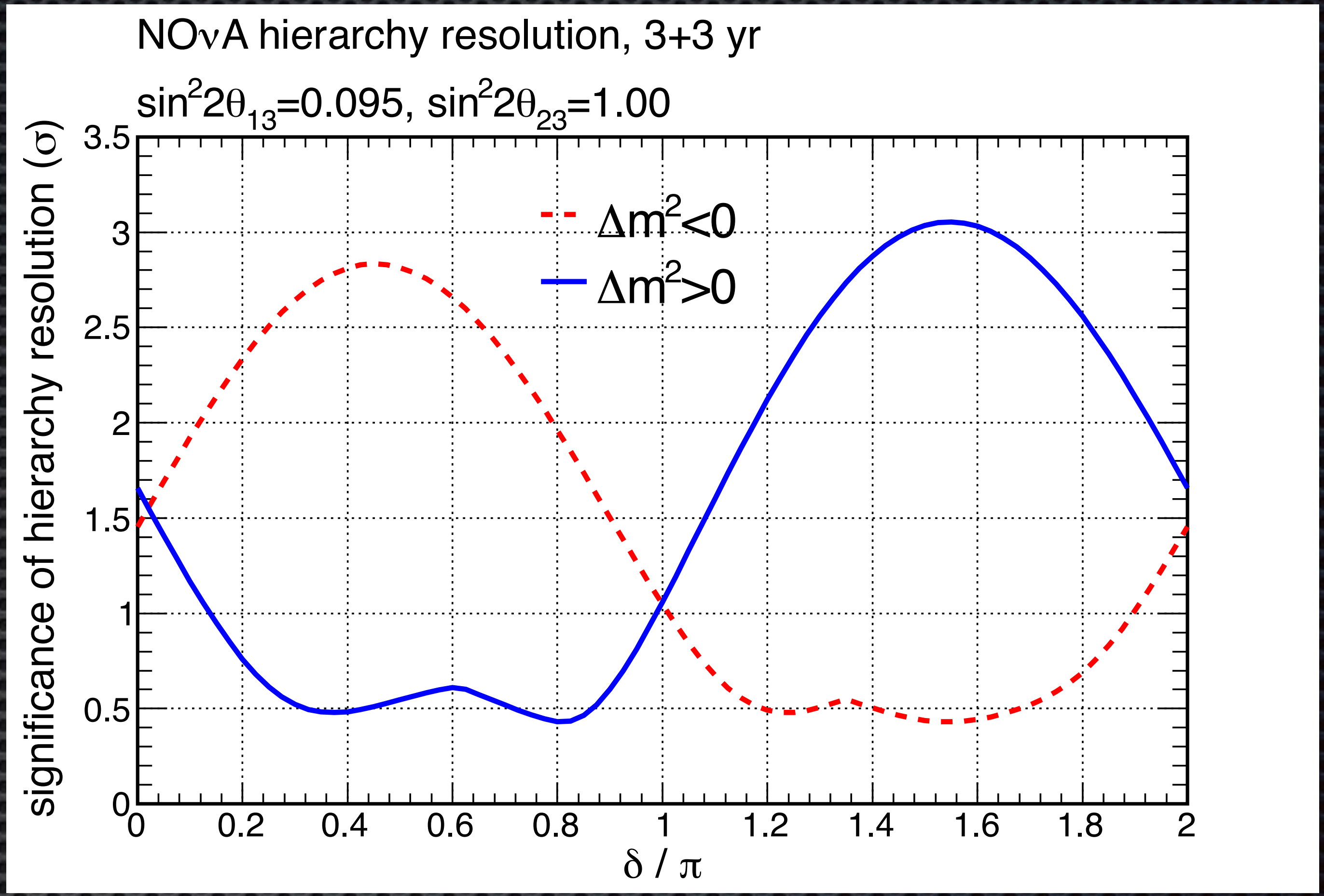


- A measurement of the probabilities might allow resolving the mass hierarchy and provide information on δ_{CP}.

Resolution of the mass hierarchy

- Significance of mass hierarchy resolution using energy spectrum.
- Energy fit provides improvement on the fully degenerate δ_{CP} values.

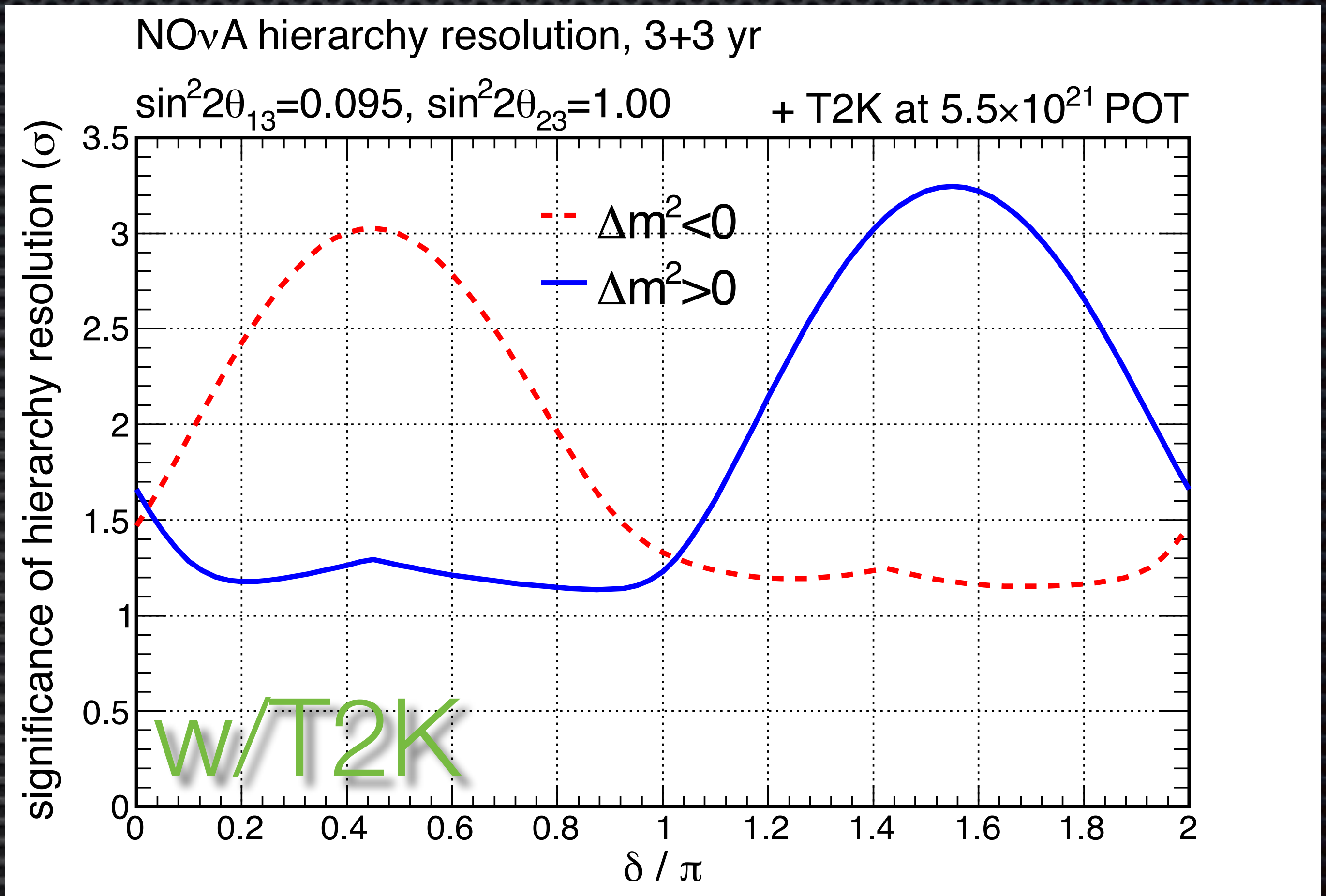


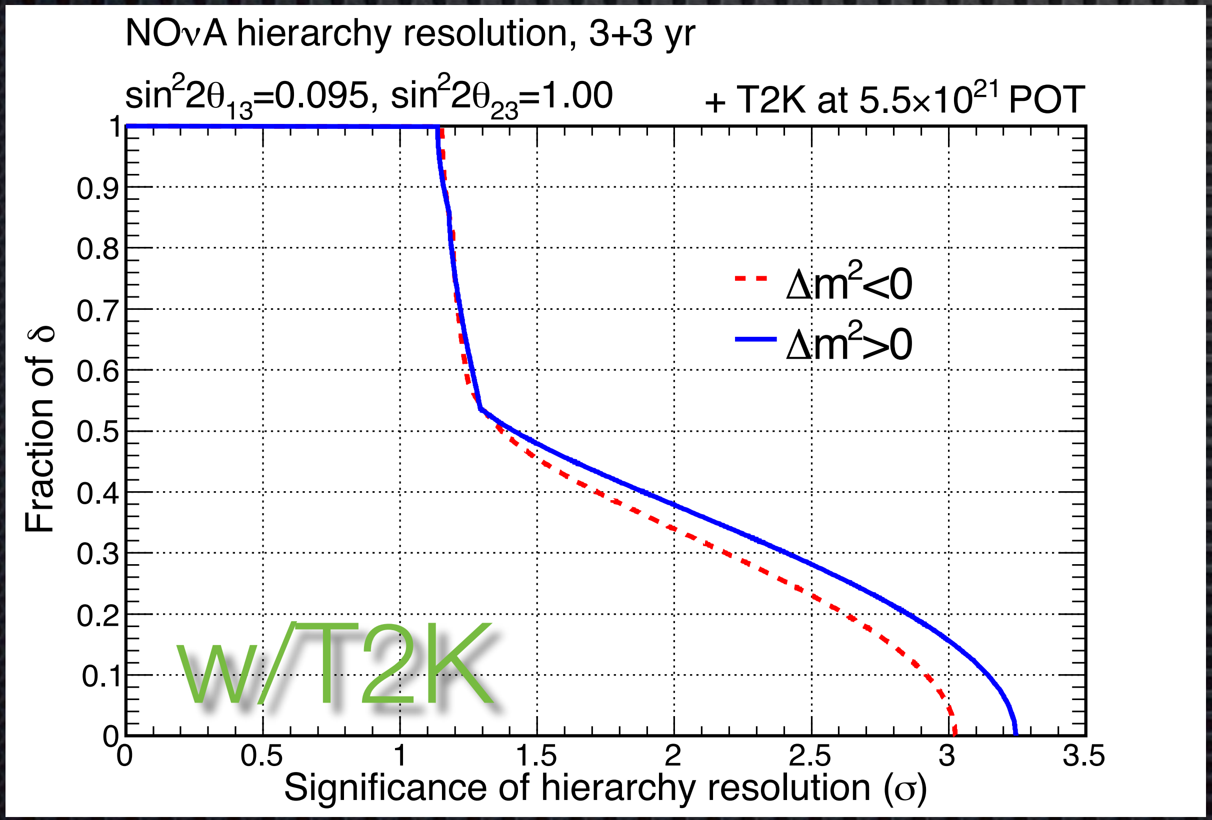


- Results from full simulation, reconstruction, selection, and analysis framework.
  - FD only. Extrapolation methods from ND in progress.

Resolution of the mass hierarchy

- Significance of mass hierarchy resolution using energy spectrum.
- Energy fit provides improvement on the fully degenerate δ_{CP} values.

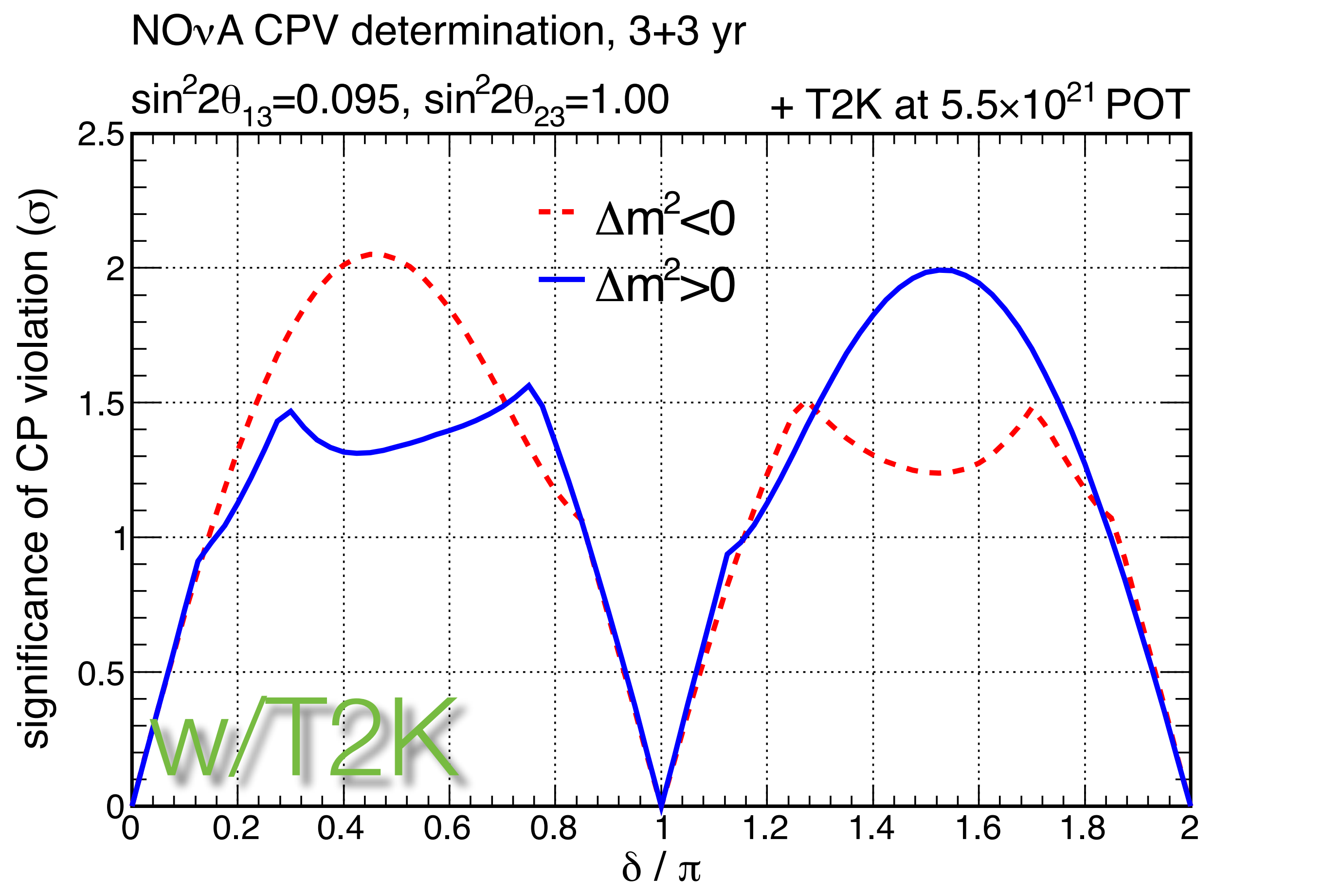


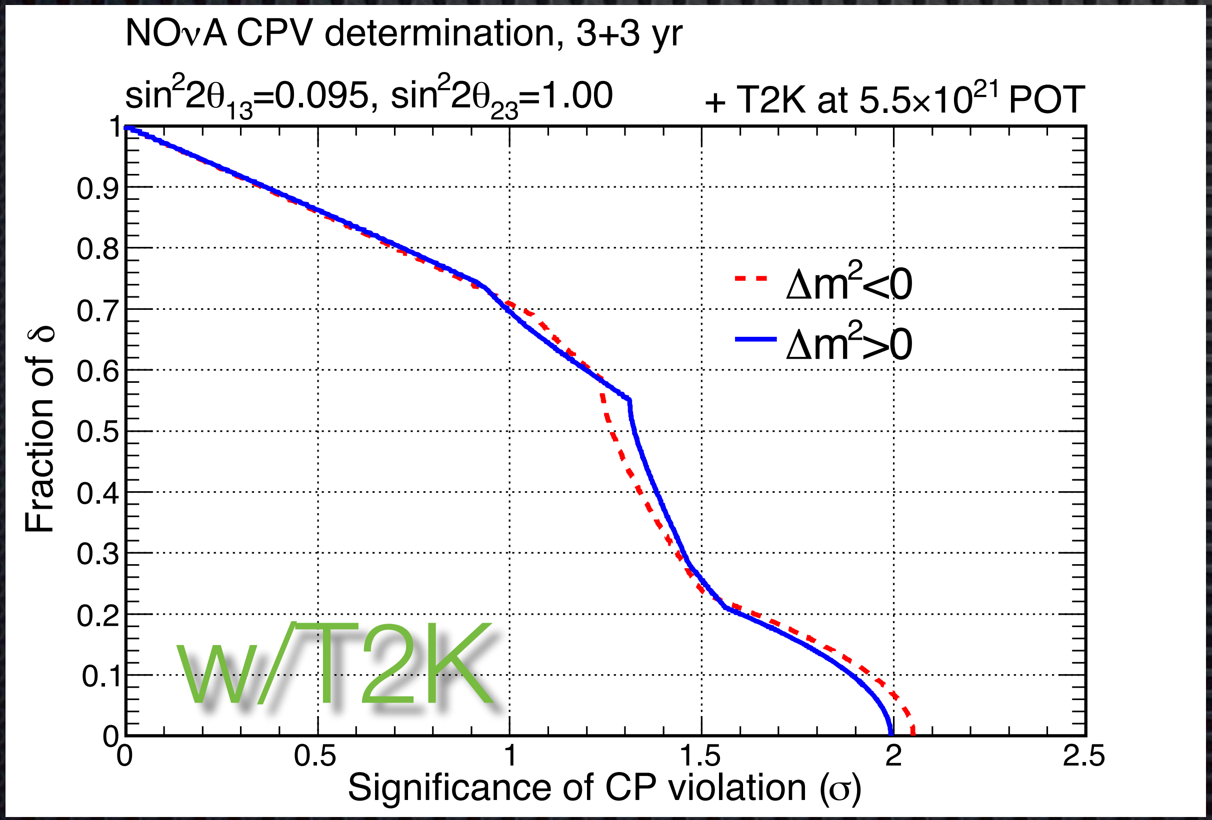


- Differences in baseline/ matter effects between NOvA and T2K can provide additional information.

Study of CP violation

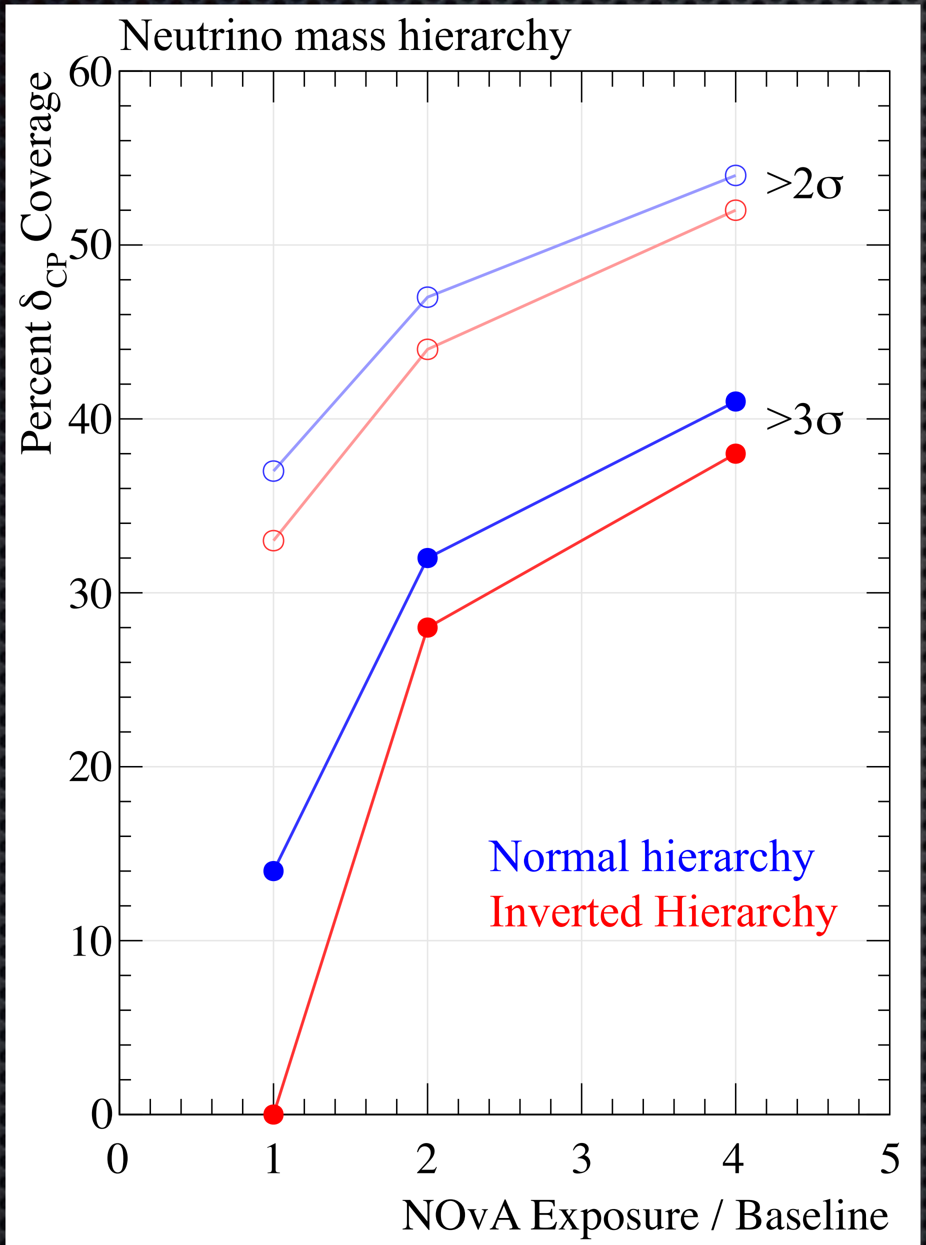
- Significance of CP violation using energy spectrum.
- Assumes that mass hierarchy is unknown.

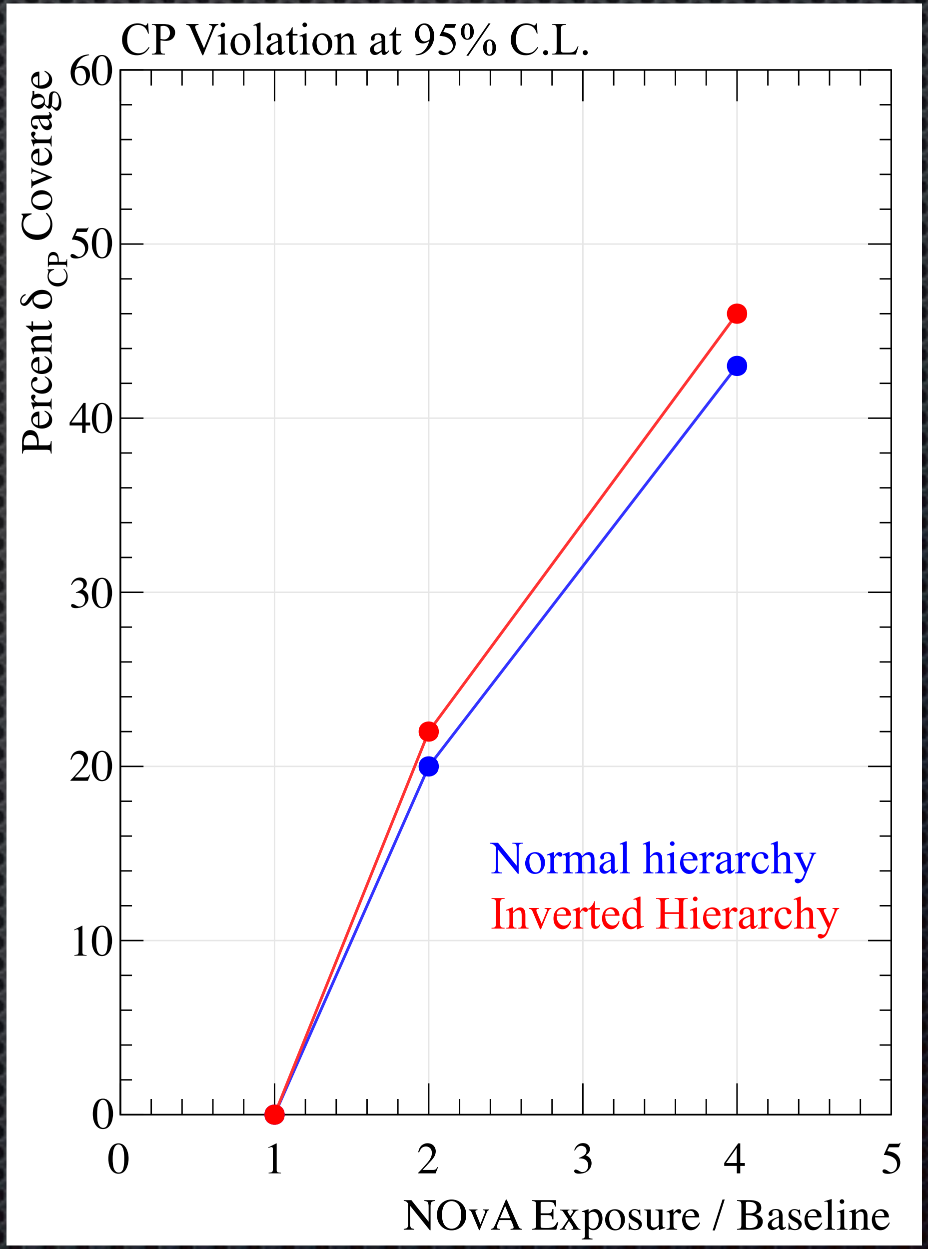




- Differences in baseline/ matter effects between NOvA and T2K can provide additional information.

What if you run NOvA longer? Beyond 6 years of running



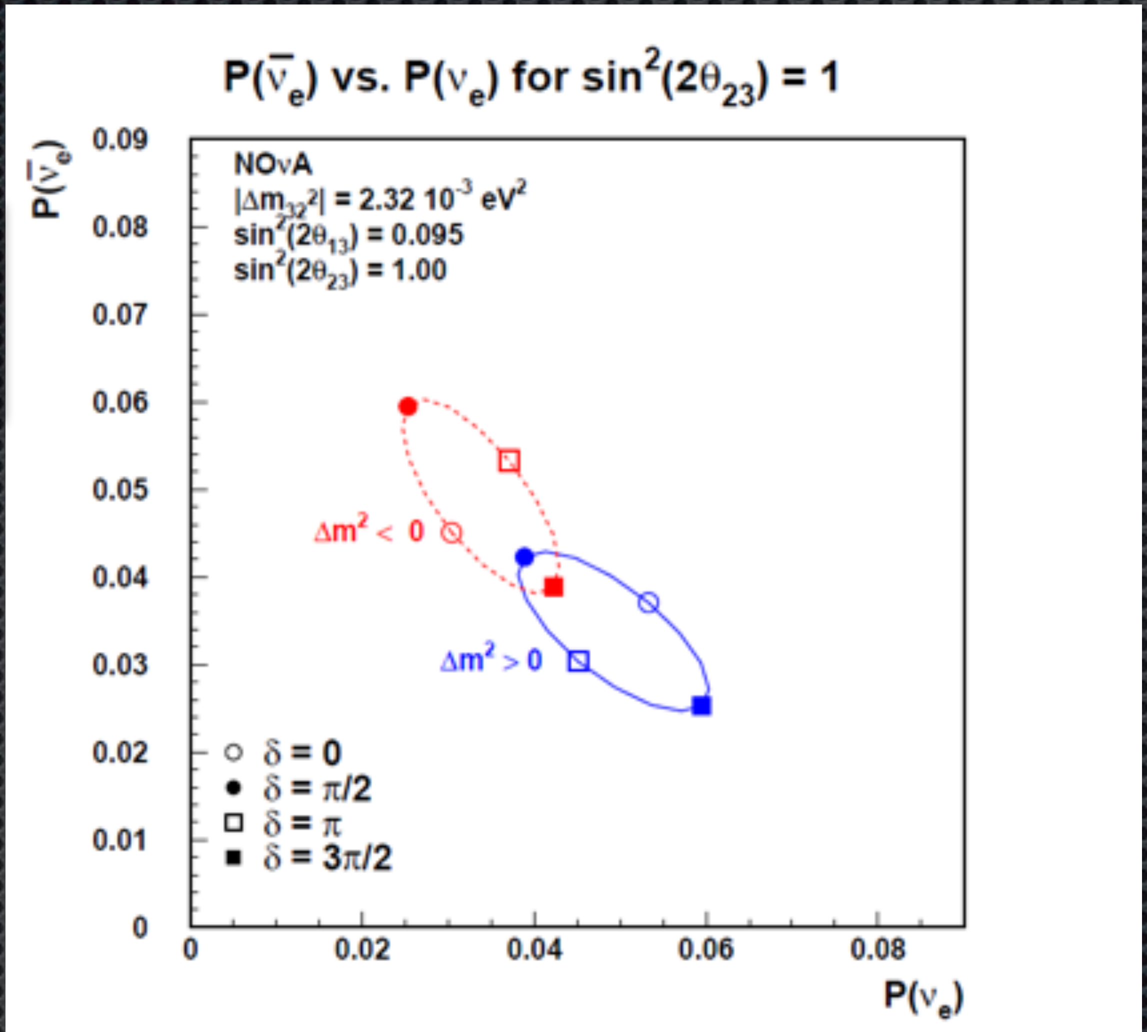


Running for 10 years and adding 4 ktons of mass would increase the baseline exposure by 2.1

Non-maximal $\sin^2 2\theta_{23}$

$P(\nu_e) \propto \sin^2(\theta_{23})\sin^2(2\theta_{13})$

⇨ ***θ_{23} octant sensitivity***

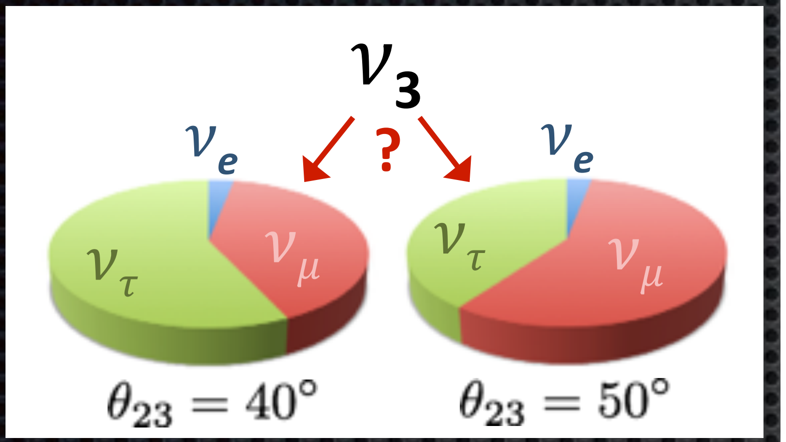


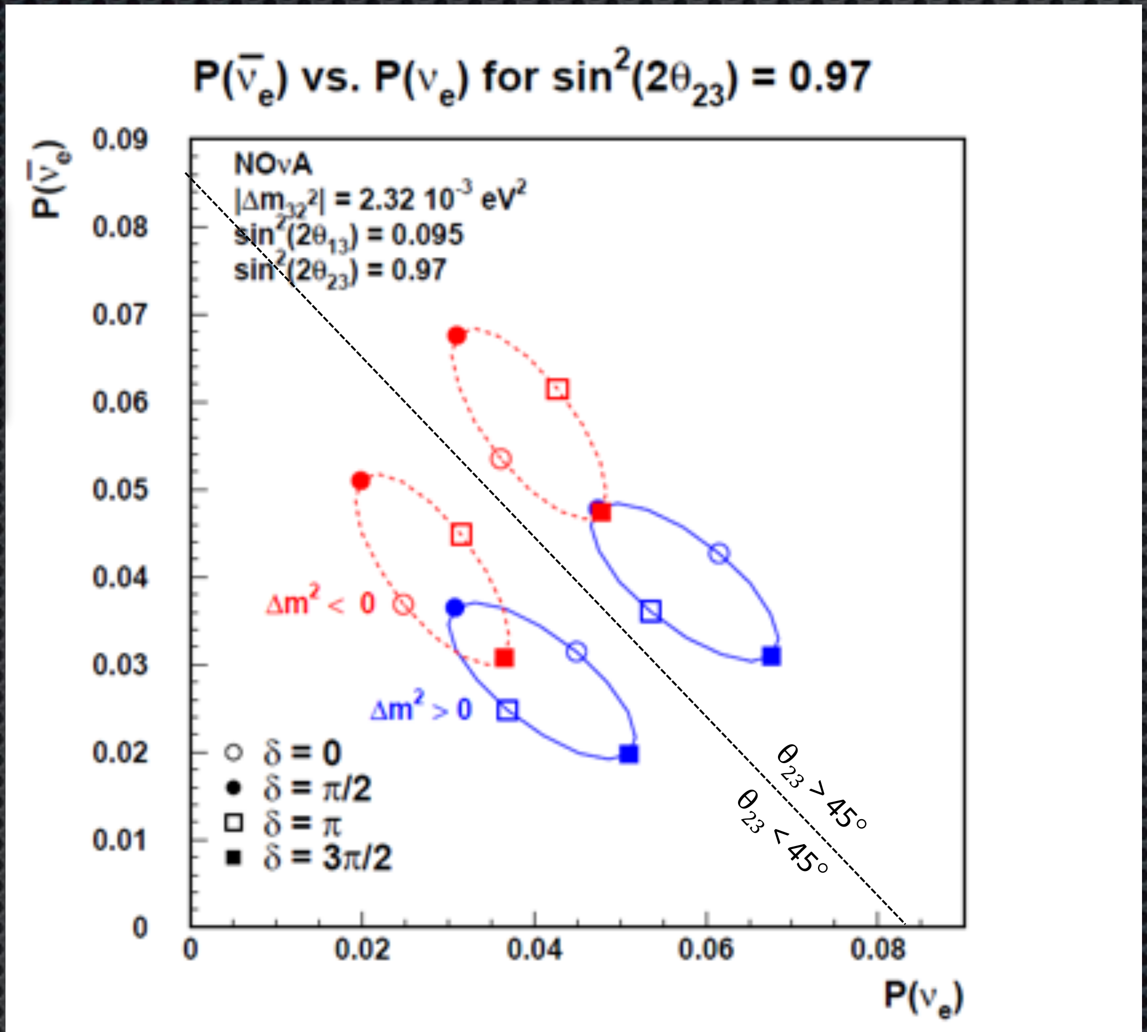
- If $\sin^2(2\theta_{23})$ is not maximal there is an ambiguity as to whether θ_{23} is larger or smaller than 45°.
- The $\sin^2(\theta_{23})$ term is unimportant when comparing accelerator experiments; however, it is crucial in comparing accelerator to reactor experiments

Non-maximal $\sin^2 2\theta_{23}$

$P(\nu_e) \propto \sin^2(\theta_{23})\sin^2(2\theta_{13})$

⇨ θ_{23} ***octant sensitivity***

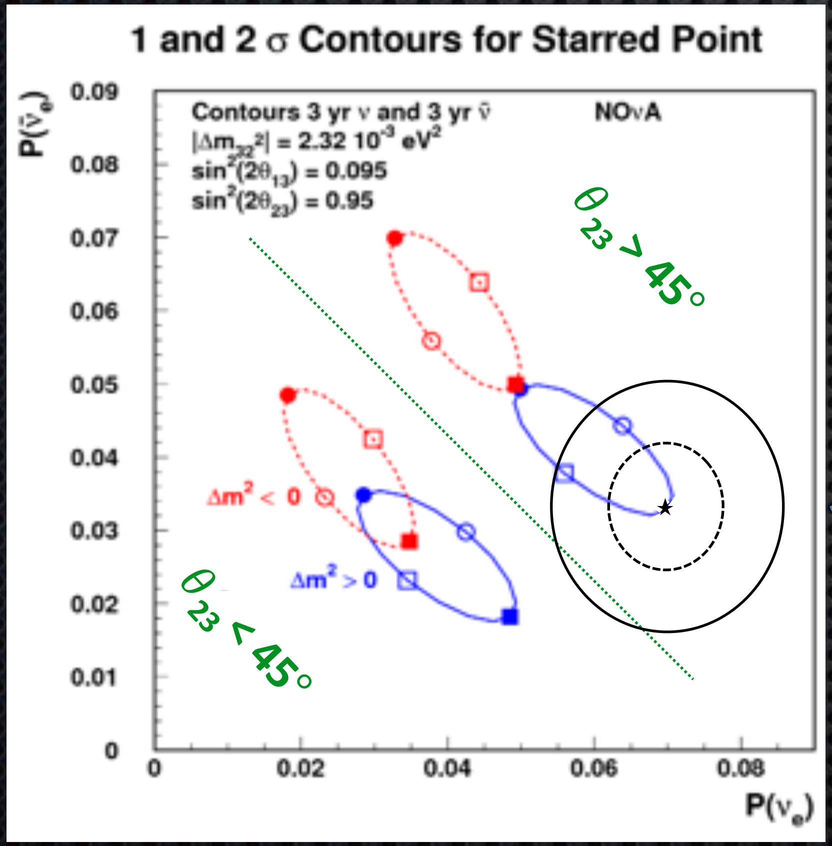


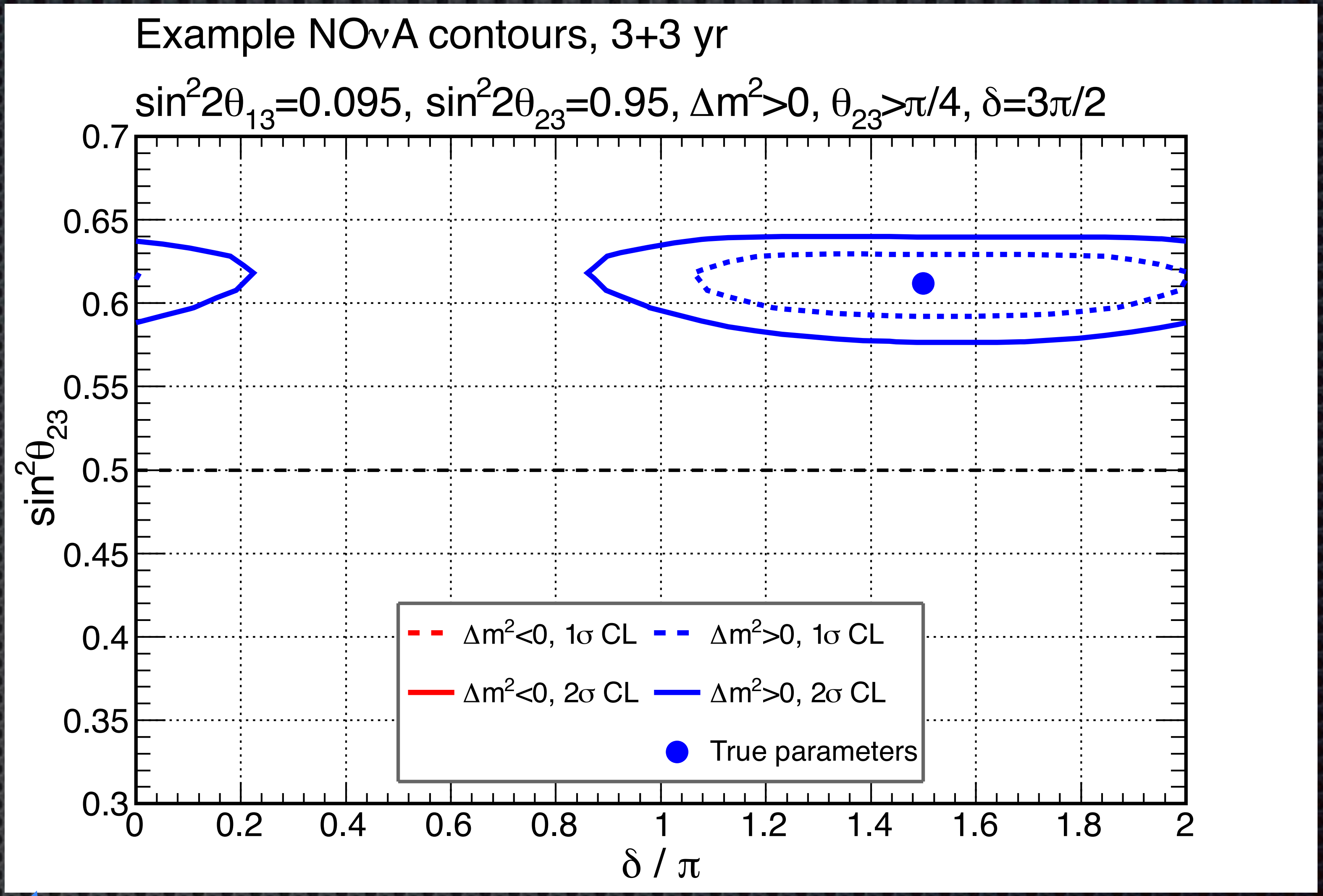


- If $\sin^2(2\theta_{23})$ is not maximal there is an ambiguity as to whether θ_{23} is larger or smaller than 45°.
- The $\sin^2(\theta_{23})$ term is unimportant when comparing accelerator experiments; however, it is crucial in comparing accelerator to reactor experiments

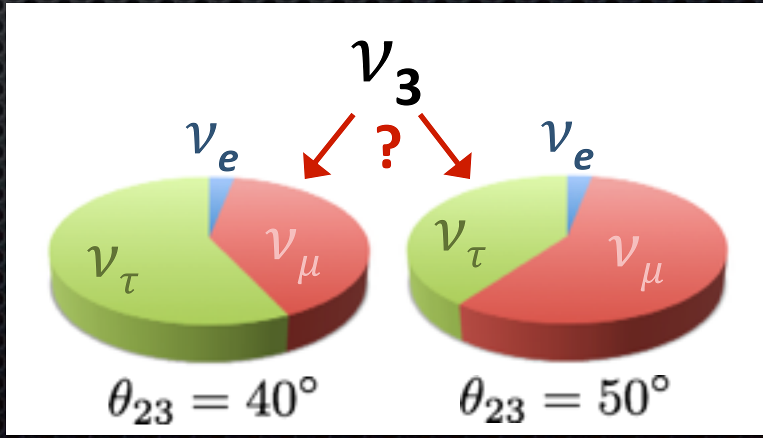
Non-maximal $\sin^2 2\theta_{23}$ and NOvA

- Expected contours for one example scenario using 3 years of data for each neutrino mode.



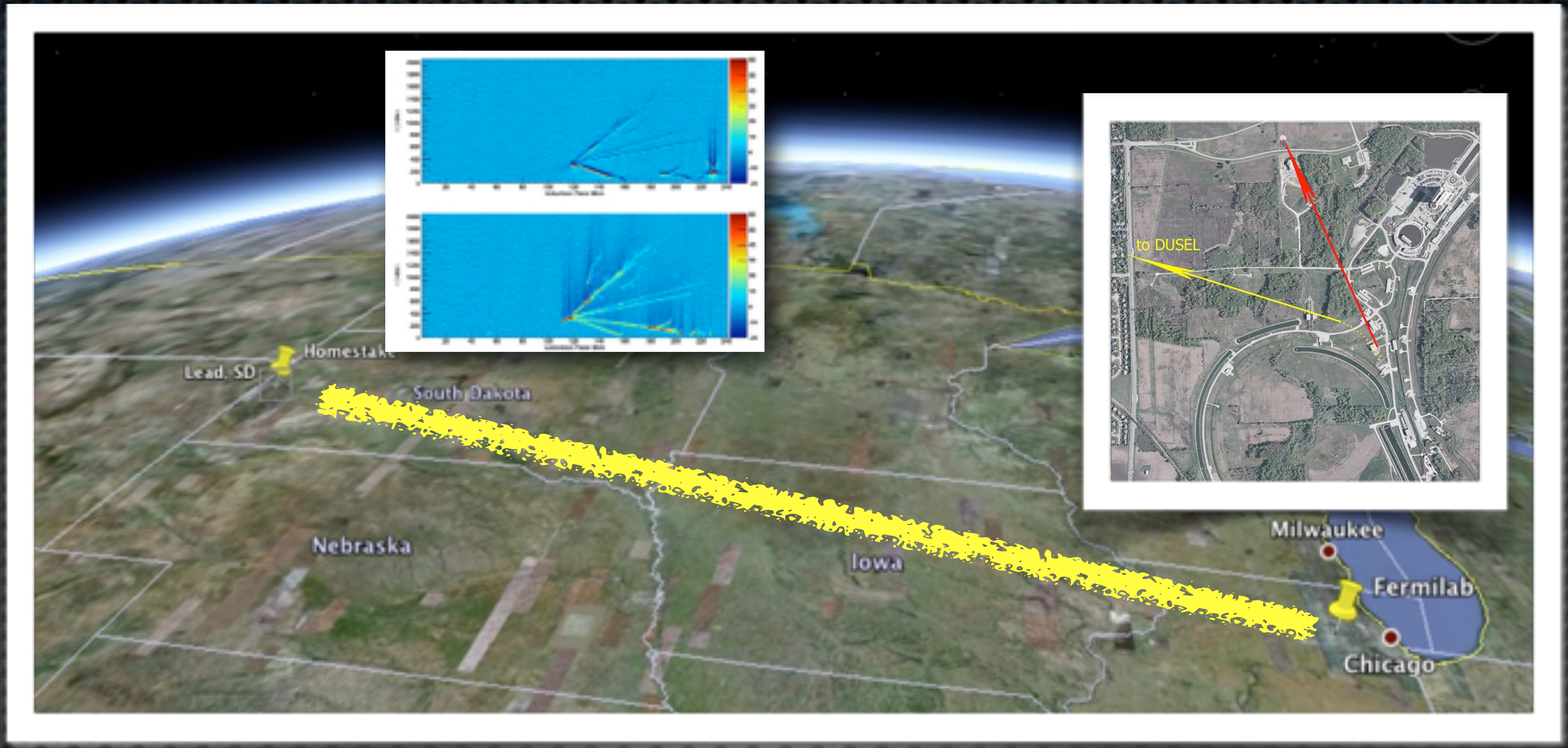


Simultaneous hierarchy, CP phase, and θ_{23} octant information from NOvA

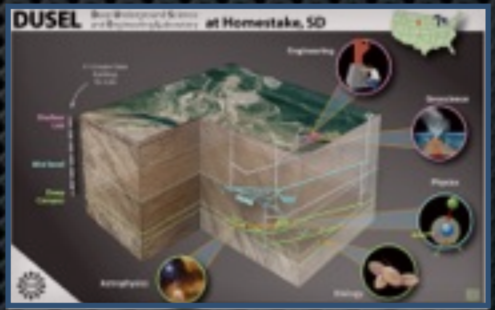


LBNE in a nutshell

- Redirect and intensify a wide band beam of muon neutrinos from Fermilab.
- Construct even bigger detectors farther away (1300 km) on-axis.
- If neutrinos oscillate, electron neutrinos are observed at the Far Detector at Homestake.
- **Similar ideas are being pursued in Europe and in Japan.**

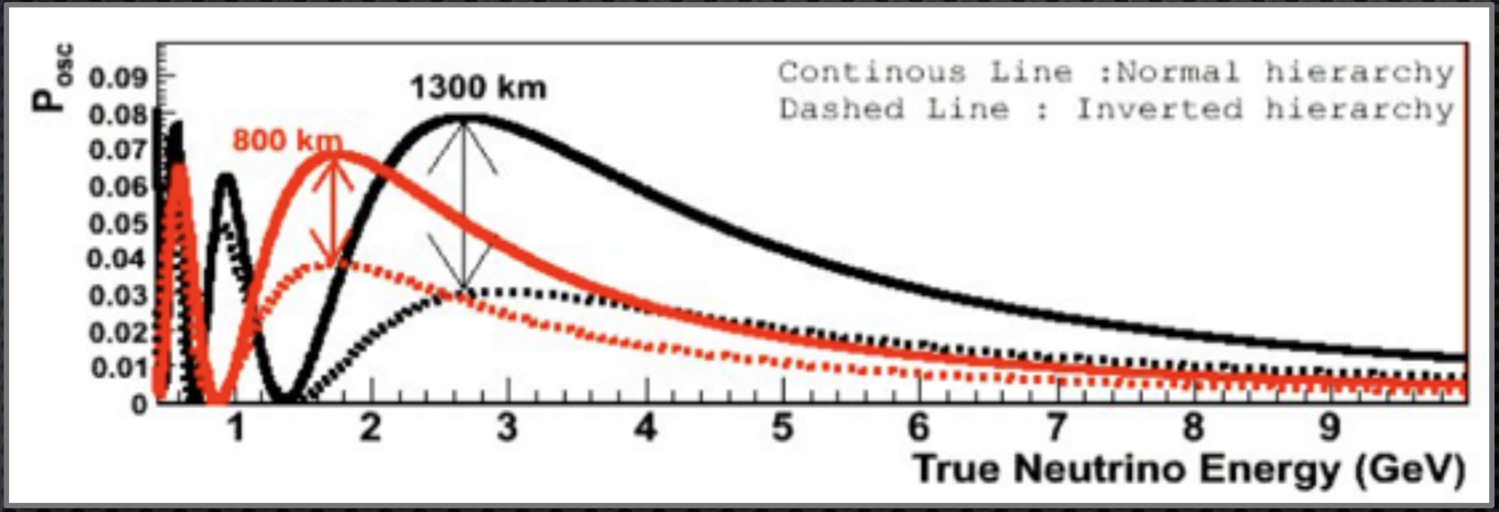


- Plan to eventually build a 34 kton fiducial/50 kton total liquid argon detector. Might start in a first phase with at least a 10 kton detector.

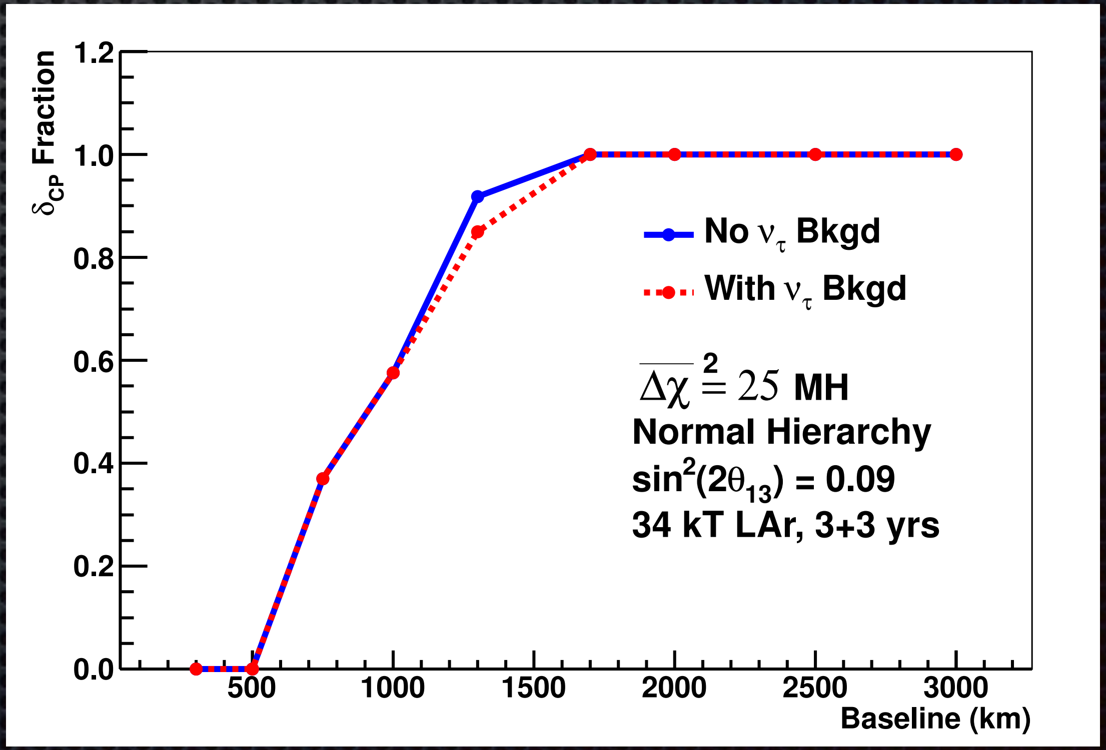


3rd generation
← long baseline →

Beyond measuring appearance probabilities

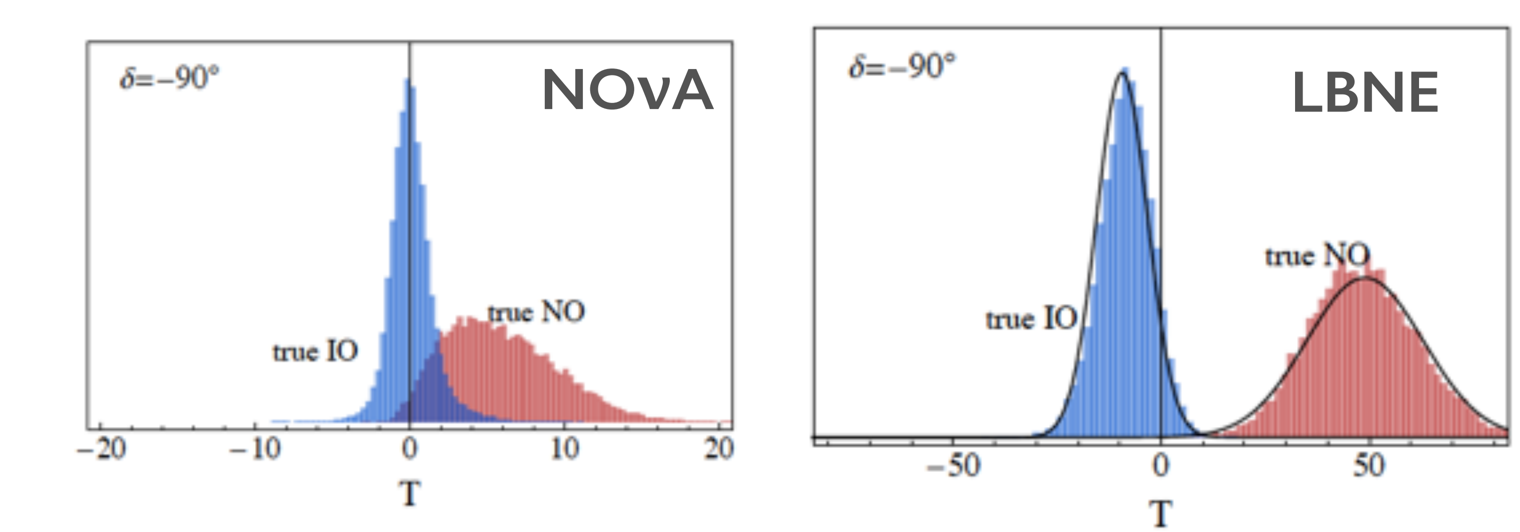


- A longer baseline provides more matter effects enhancing the asymmetry between neutrino and antineutrino appearance probabilities, the sign of which depends on the mass hierarchy.
- The sensitivity depends on the actual values of mixing parameters (mainly δ_{CP} and $\sin^2(2\theta_{23})$), as well as the true value of the MH itself.



A note about the sensitivity to the mass hierarchy

- In the mass hierarchy determination, only two discrete results are considered, as the true mass hierarchy: either normal (NH) or inverted (IH).
- The $T = \Delta\chi^2(\theta)$ test metric we typically use does not follow a χ^2 distribution for mass ordering (i.e. Wilks' theorem not valid)
- Instead, T is approximately gaussian, with mean T0 and width $2(T_0)^{1/2}$, where T_0 is the value for the data set without statistical fluctuations
- Need to check gaussianity using MC for each experiment. Quote median sensitivity instead of $(T_0)^{1/2}$.

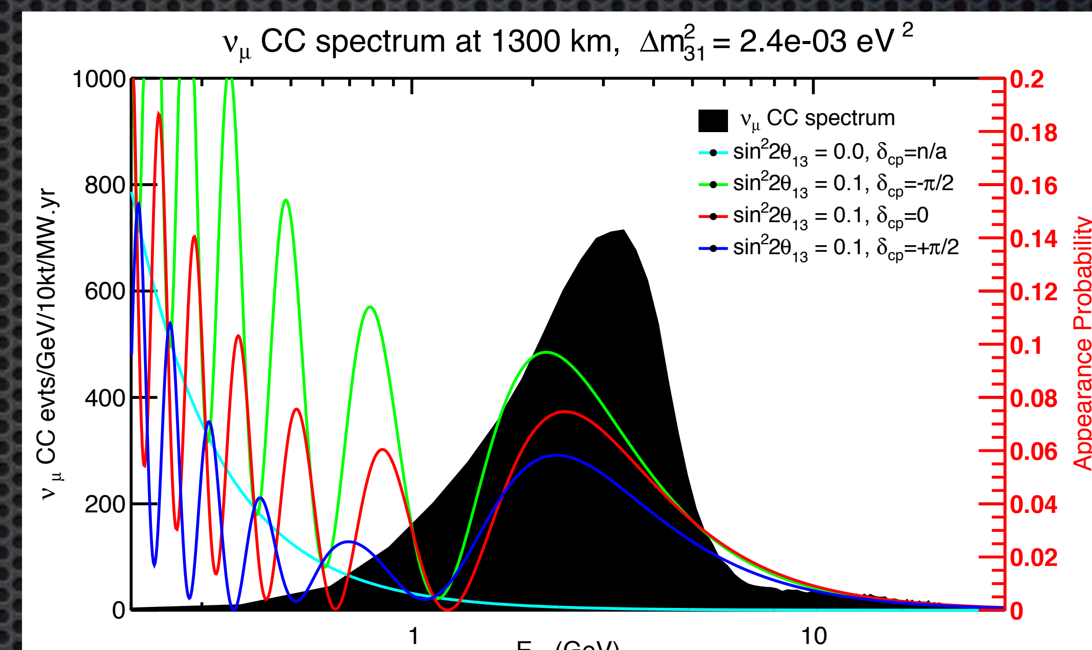


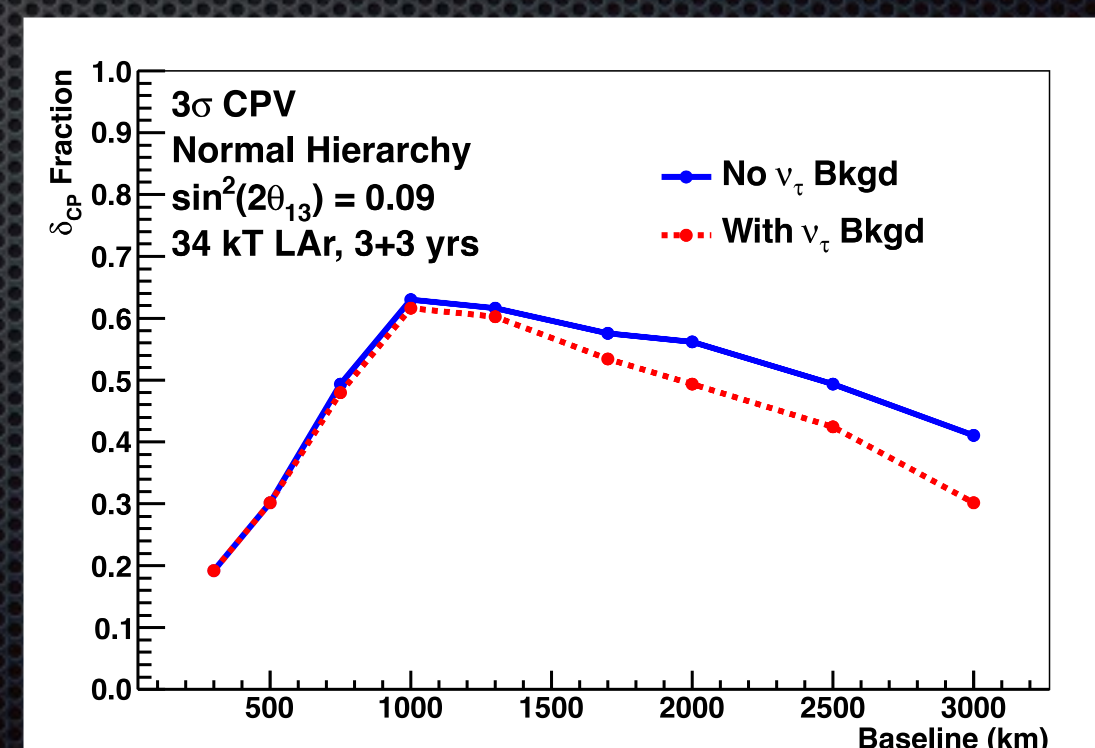
T_0	std. sens.		median sens.	
9	99.73%	(3.0σ)	99.87%	(3.2σ)
16	99.9937%	(4.0σ)	99.9968%	(4.2σ)
25	99.999943%	(5.0σ)	99.999971%	(5.1σ)

From arxiv:1311.1822

Beyond measuring appearance probabilities

- The large value of θ_{13} provides a large signal for appearance experiments. Unfortunately it also reduces the observable asymmetry related to cp violation.



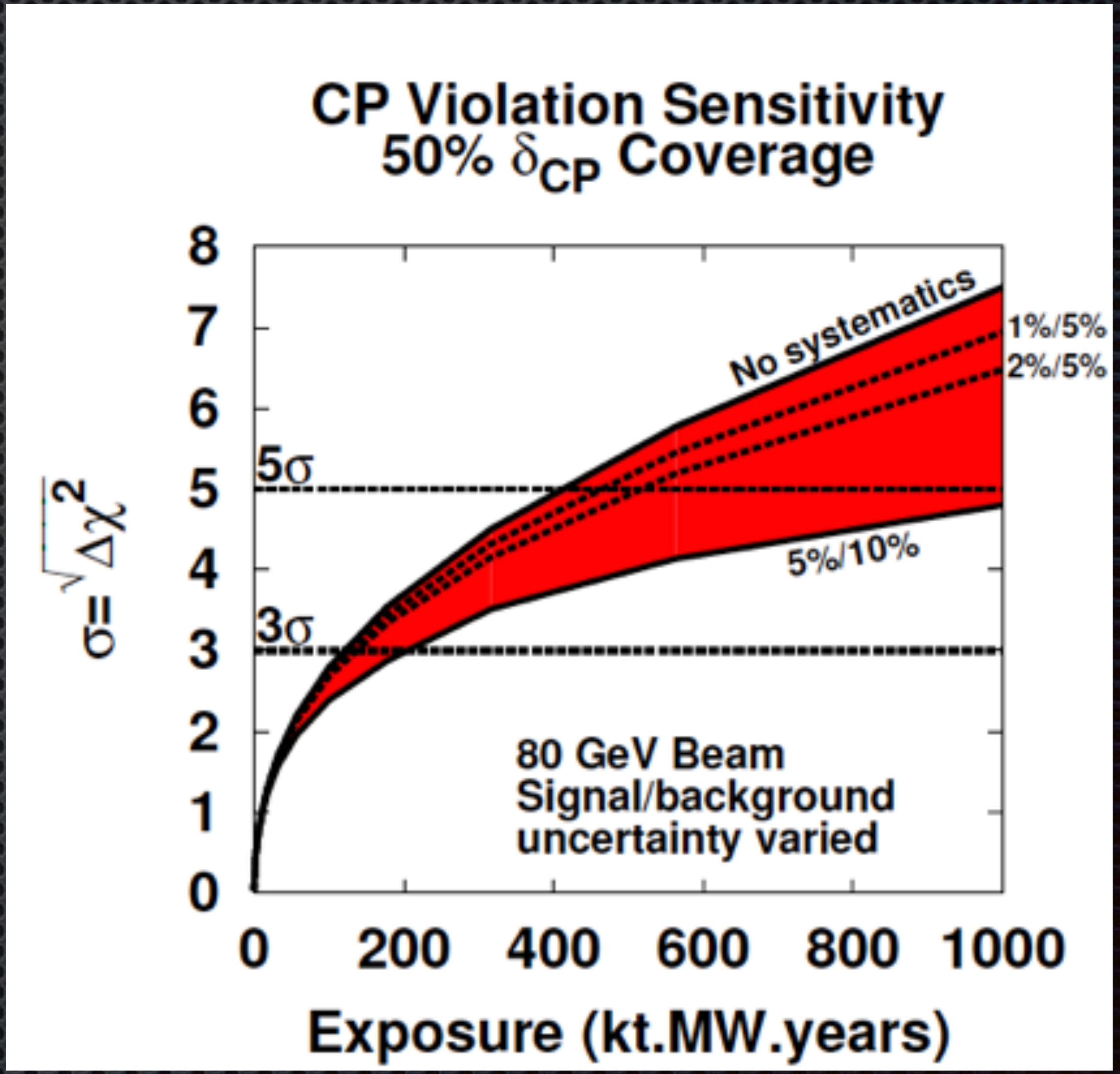


$$\mathcal{A}_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\overline{\nu}_\mu \to \overline{\nu}_e)}.$$

$$\mathcal{A}_{CP} \sim \frac{\cos\theta_{23}\sin 2\theta_{12}\sin\delta_{\rm CP}}{\sin\theta_{23}\sin\theta_{13}}\left(\frac{\Delta m^2_{21} L}{4E_\nu}\right) + \text{matter effects}$$

Beyond measuring appearance probabilities

- Large statistics for the signal but small asymmetry implies that we need to keep the systematic uncertainties at the percent level.
- In long-baseline appearance experiments, signal at FD is ν_e (for a ν_μ beam), so cross-section uncertainties do not cancel out between ND and FD.

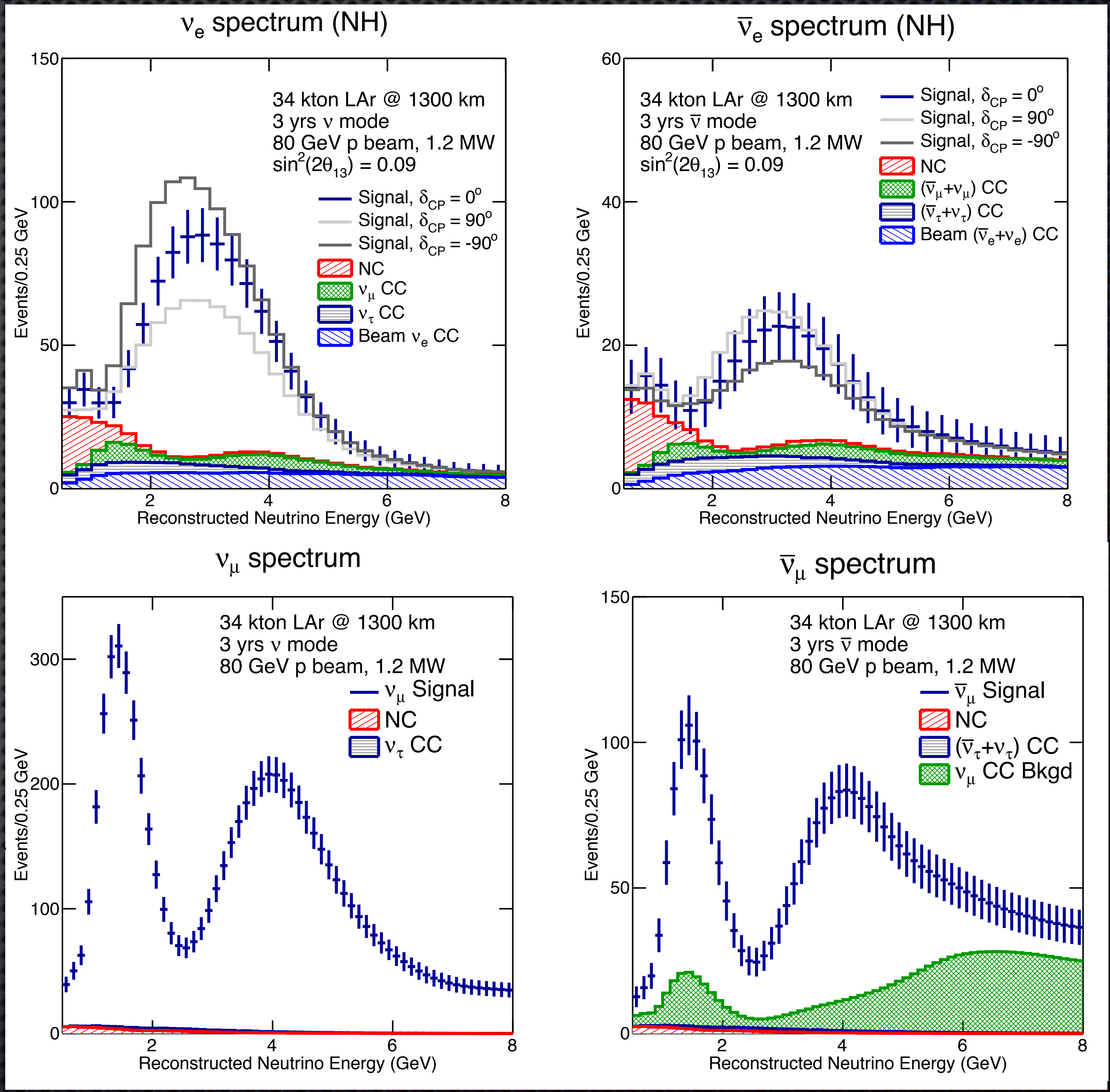


A strong program of cross section measurements, hadron production experiments and test beams is required

LBNE's plan

- Run neutrino and anti-neutrinos for 5 years each.
- Distributions shown for normal hierarchy and different values of δ_{CP}.
- At 1300 km the full oscillation structure visible in the energy spectra.
- A combined spectral fit can resolve all oscillation parameter ambiguities with a single experiment.

Assumes 34 kton LAr detector

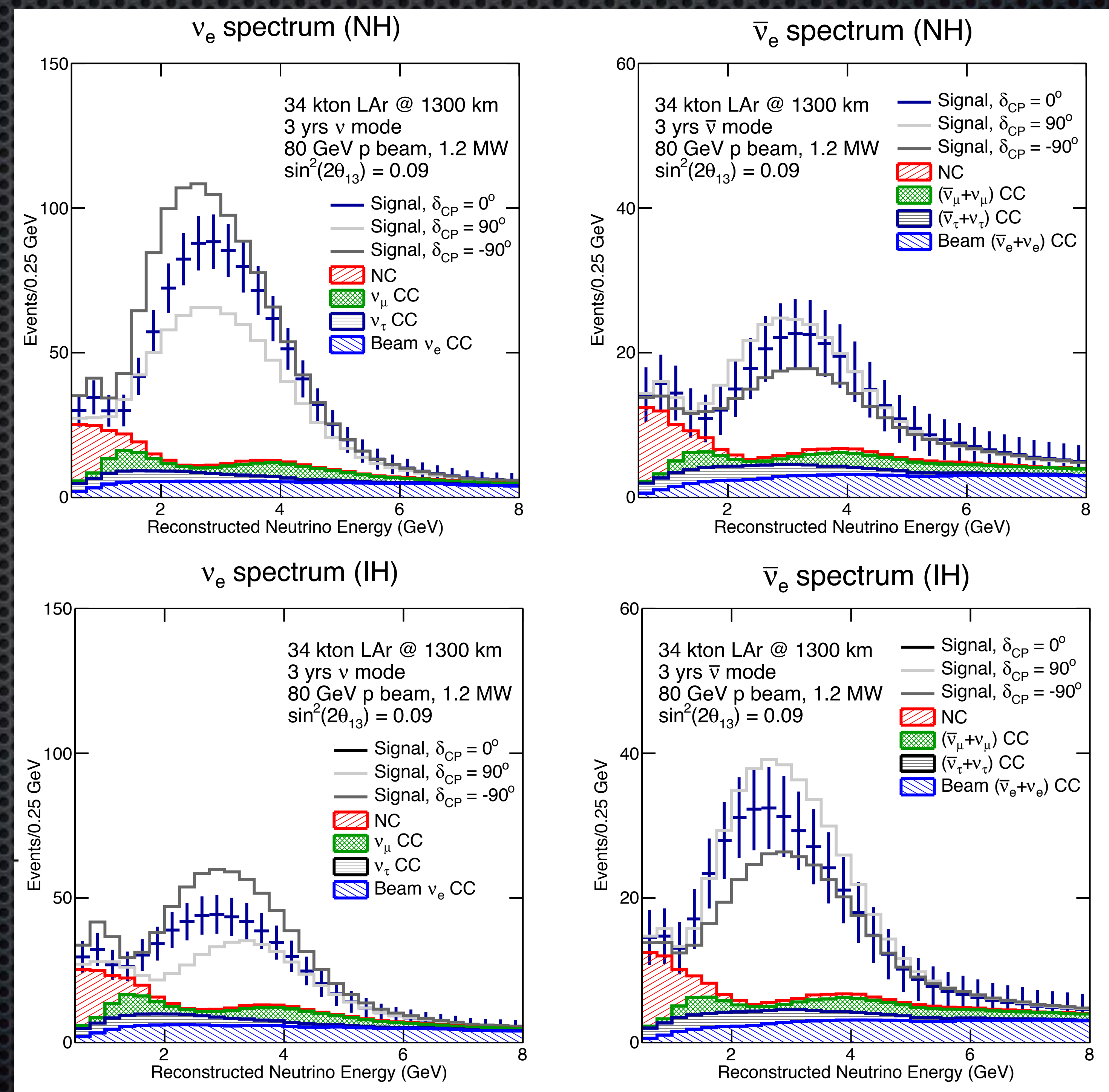


From arxiv:1307.7335

LBNE's plan

- Run neutrino and anti-neutrinos for 5 years each.
- Distributions shown for normal hierarchy and different values of δ_{CP}.
- At 1300 km the full oscillation structure visible in the energy spectra.
- A combined spectral fit can resolve all oscillation parameter ambiguities with a single experiment.

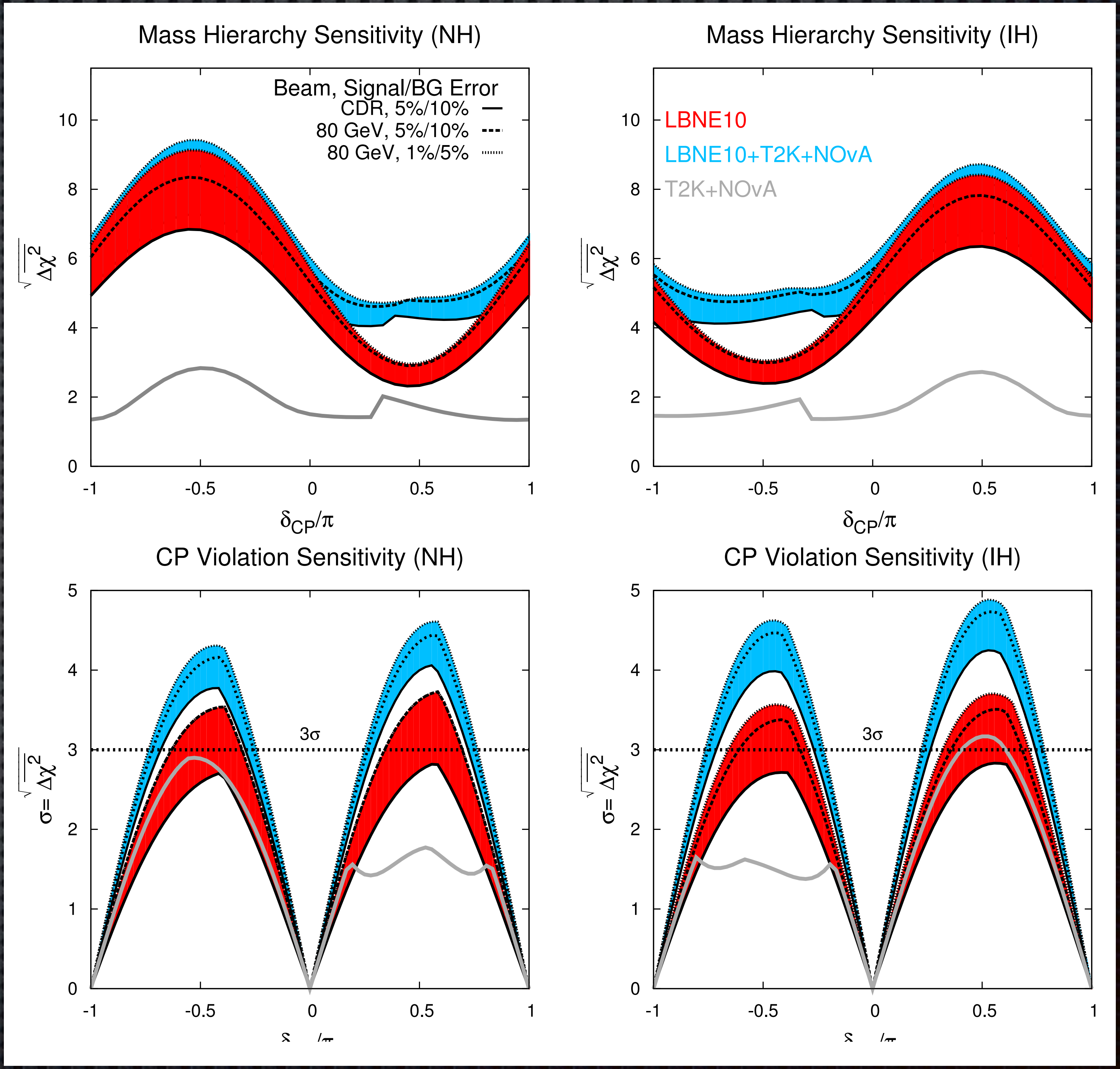
Assumes 34 kton LAr detector



From arxiv:1307.7335

Measuring the mass hierarchy and cp violation

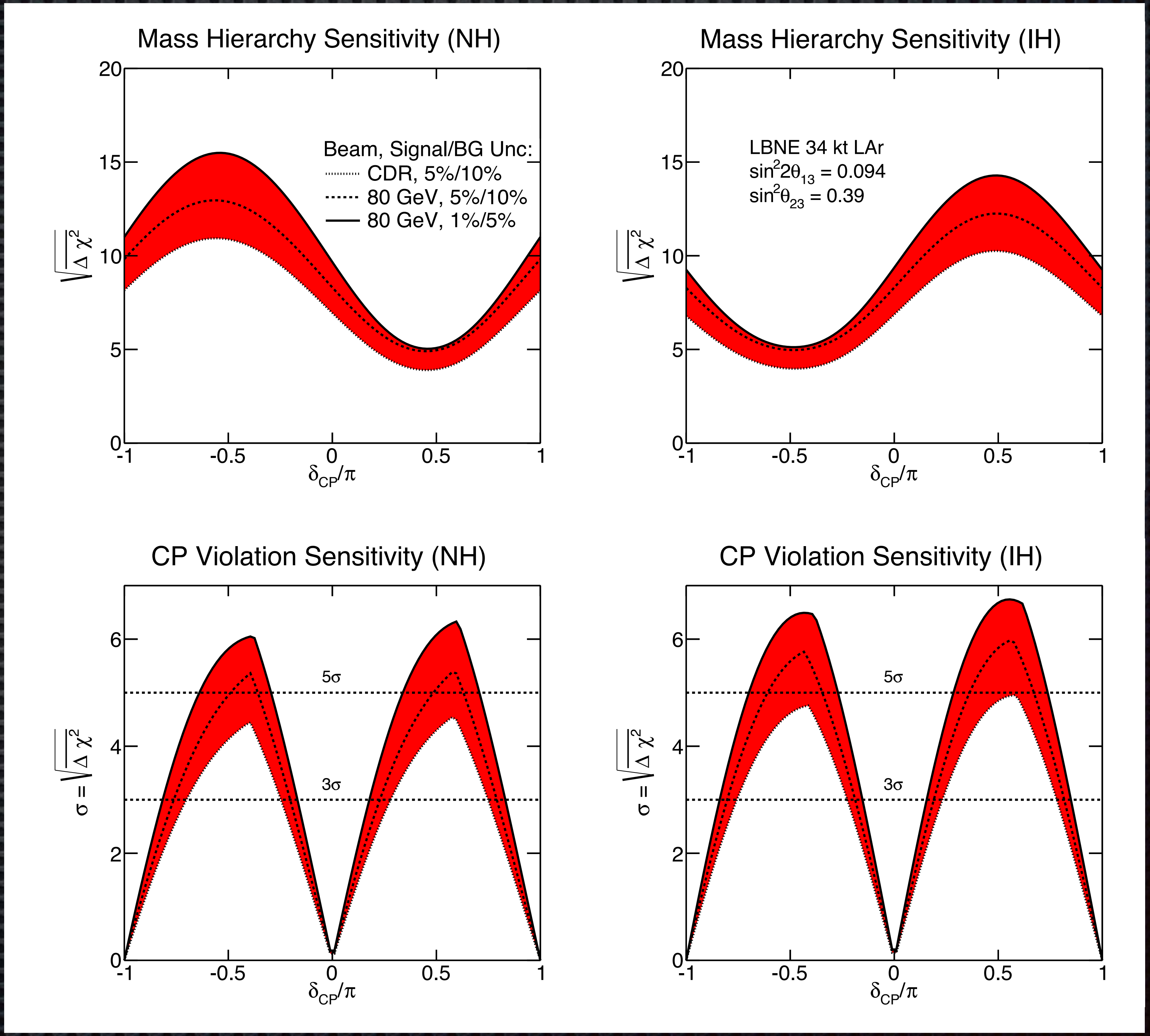
- The red band shows the sensitivity that is achieved by a typical experiment with the LBNE 10kt configuration alone, where the width of the band shows the range of sensitivities obtained by varying the beam design and the signal and background uncertainties.
- The cyan band shows the sensitivity obtained by combining the 10kt LBNE with T2K and NOvA, and the gray curves are the expected sensitivities for the combination of NOvA and T2K.



From arxiv:1307.7335

Measuring the mass hierarchy and cp violation

- The significance with which the mass hierarchy (top) and CP violation can be determined by a typical LBNE experiment with a 34kt far detector as a function of the value of δ_{CP}.
- The width of the red band shows the range of sensitivities that can be achieved by LBNE when varying the beam design and the signal and background uncertainties.



From arxiv:1307.7335

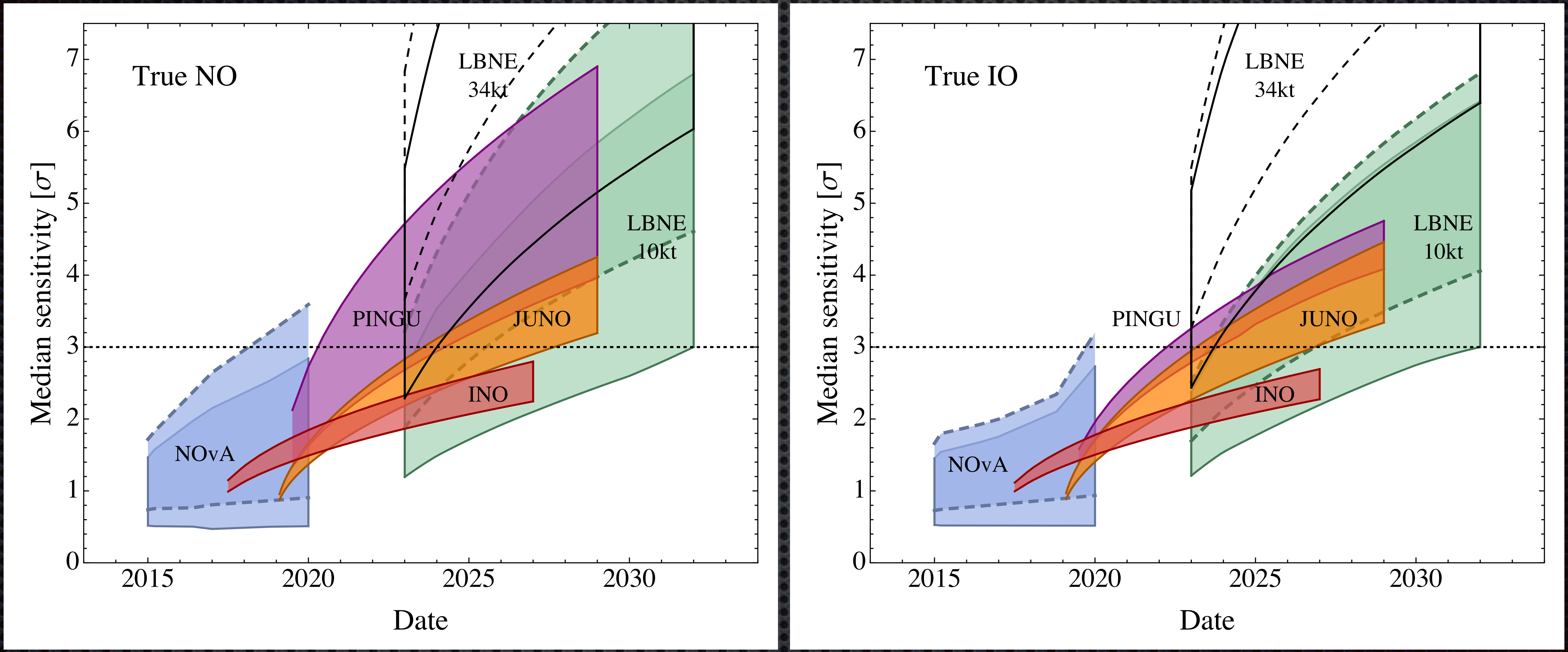
LBNE systematic uncertainties

- The dominant systematic uncertainties on the appearance signal prediction.
- For the MINOS uncertainties absolute refers to the total uncertainty.
- The LBNE uncertainties are the total expected uncertainties on the appearance signal which include both correlated and uncorrelated uncertainties in the three-flavor fit.

Source of Uncertainty	MINOS Absolute/ν_e	T2K ν_e	LBNE ν_e	Comments
Beam Flux after N/F extrapolation	3%/0.3%	2.9%	2%	MINOS is normalization only. LBNE normalization and shape highly correlated between ν_μ/ν_e.
Detector effects				
Energy scale (ν_μ)	7%/3.5%	included above	(2%)	Included in LBNE ν_μ sample uncertainty only in three-flavor fit. MINOS dominated by hadronic scale.
Absolute energy scale (ν_e)	5.7%/2.7%	3.4% includes all FD effects	2%	Totally active LArTPC with calibration and test beam data lowers uncertainty.
Fiducial volume	2.4%/2.4%	1%	1%	Larger detectors = smaller uncertainty.
Neutrino interaction modeling				
Simulation includes: hadronization cross sections nuclear models	2.7%/2.7%	7.5%	$\sim 2\%$	Hadronization models are better constrained in the LBNE LArTPC. N/F cancellation larger in MINOS/LBNE. X-section uncertainties larger at T2K energies. Spectral analysis in LBNE provides extra constraint.
Total	**5.7%**	**8.8%**	**3.6 %**	**Uncorrelated ν_e uncertainty in full LBNE three-flavor fit = 1-2%.**

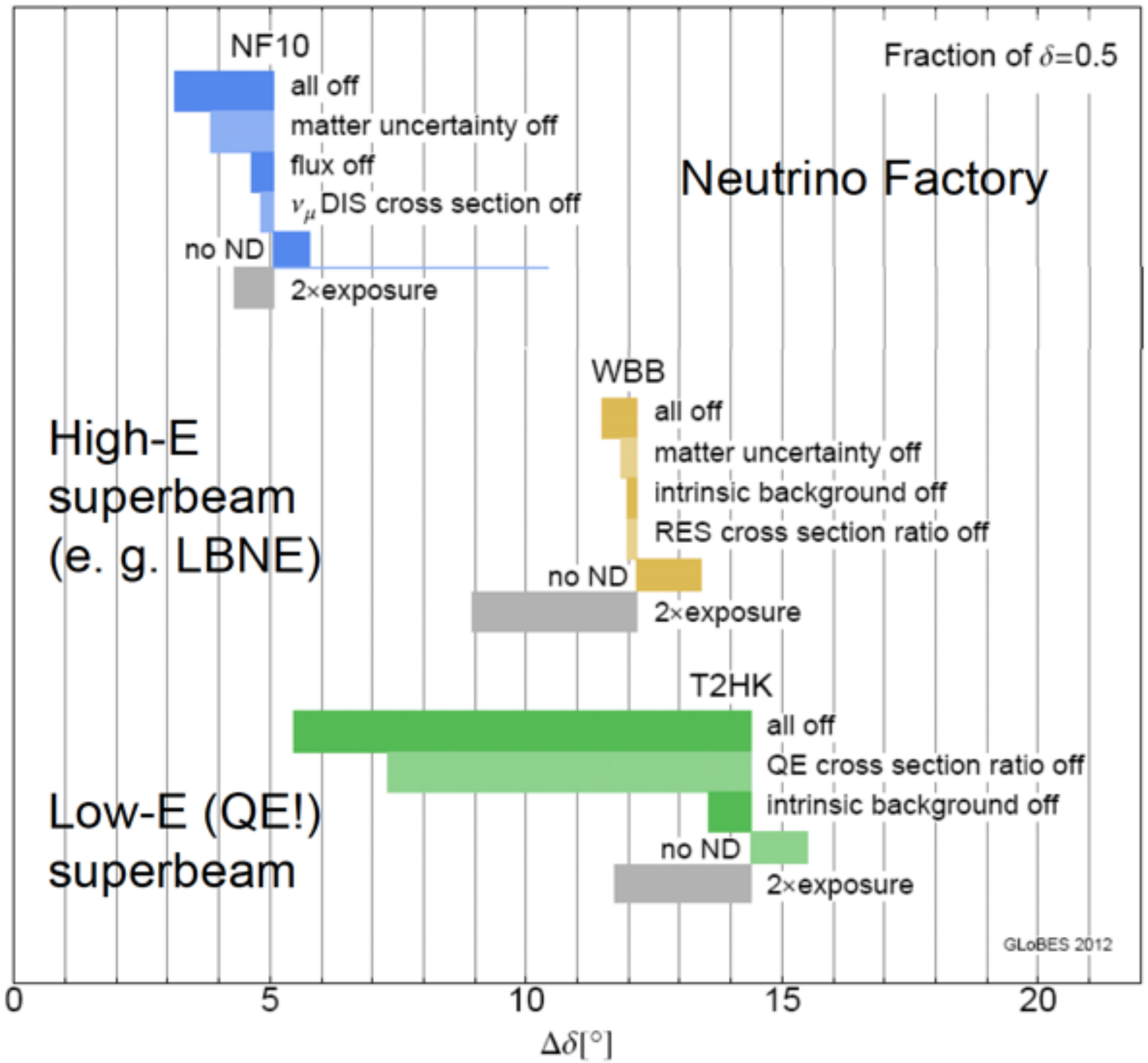
From arxiv:1307.7335

Measuring the mass hierarchy



- Median sensitivity for the mass hierarchy for various experiments.

Systematics of dcp



(Coloma, Huber, Kopp, Winter, arXiv:1209.5973)

Robust wrt systematics

Main impact:
Matter density uncertainty

Operate in statistics-limited regime

Exposure more important than near detector

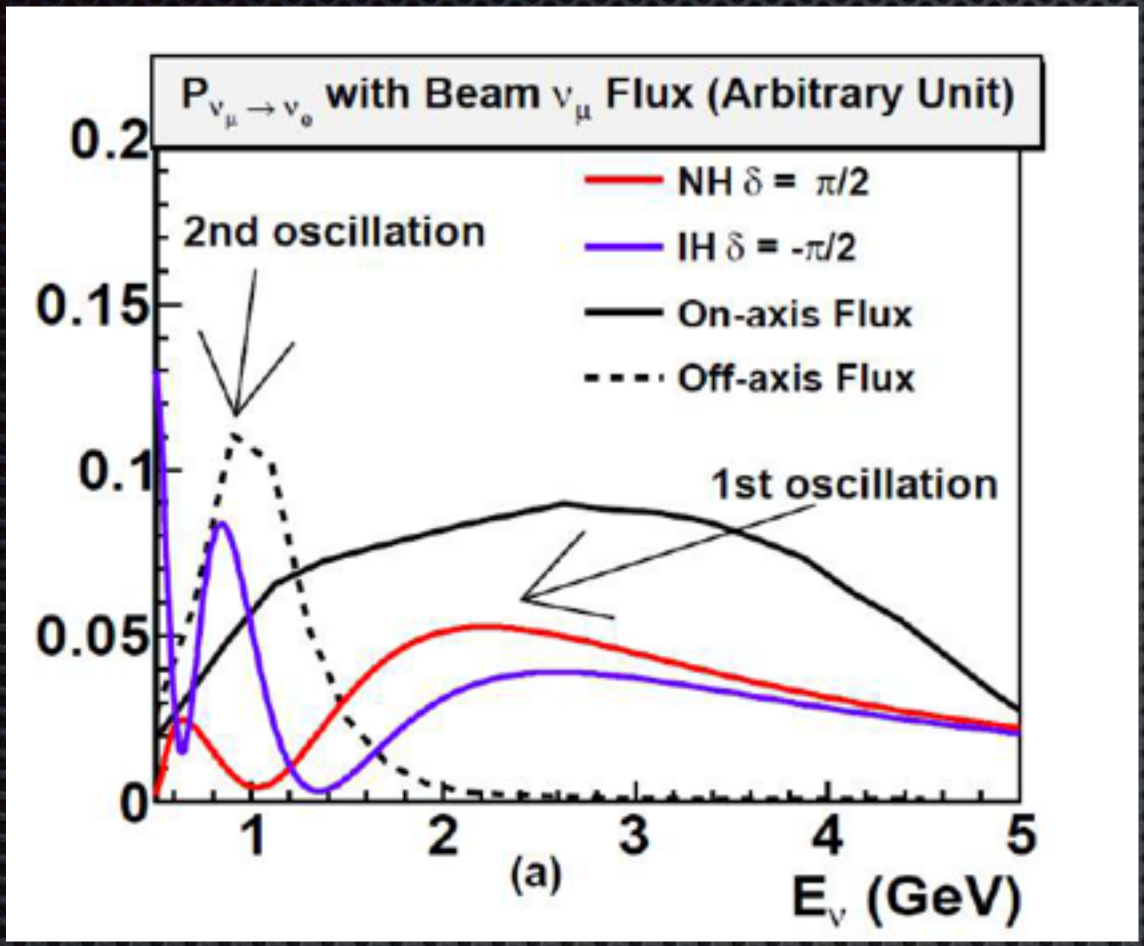
QE ν_e X-sec critical:
cannot be measured in near detector

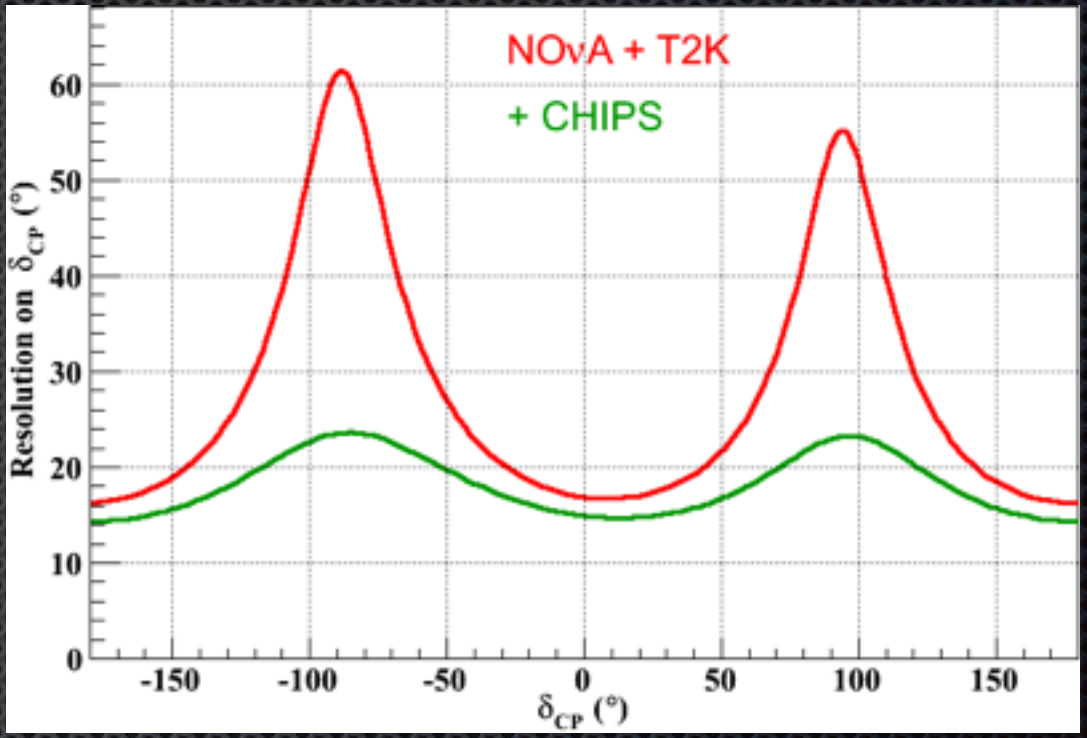
Theory: ν_e/ν_μ ratio?
Experiment: νSTORM

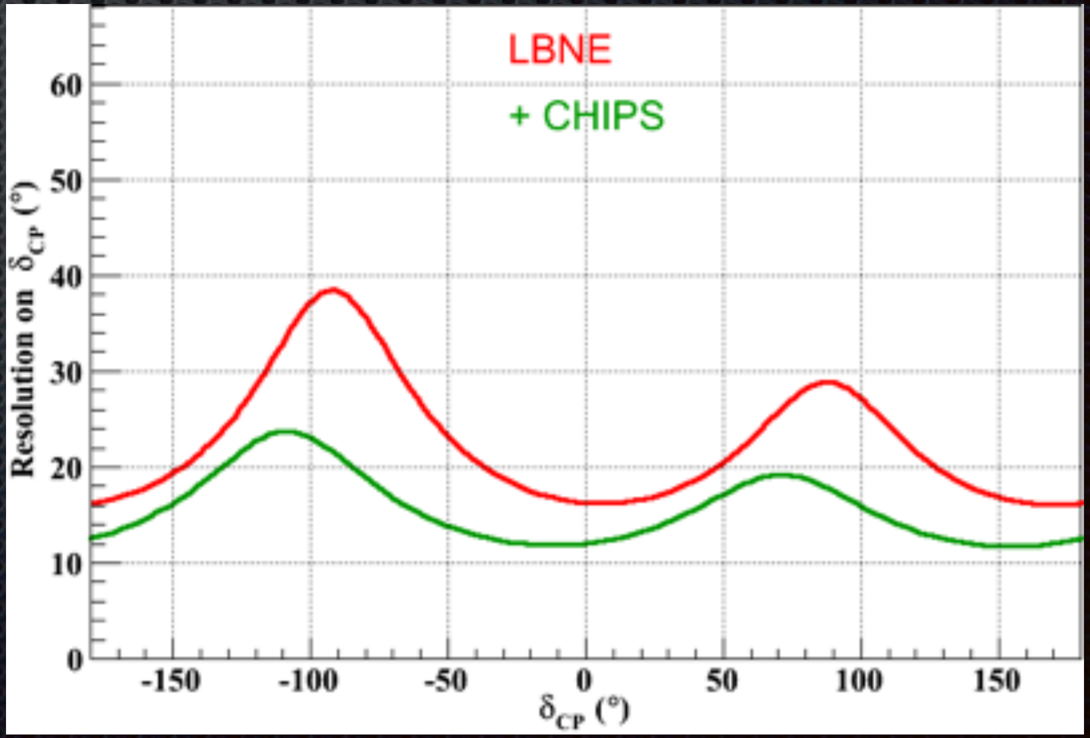
$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

Measuring the second oscillation minimum

- From: arXiv:1307.5918







- The idea of targeting the second oscillation minimum has been proposed.
- Improvement in δ_{CP} resolution by placing a large detector slightly off-axis.

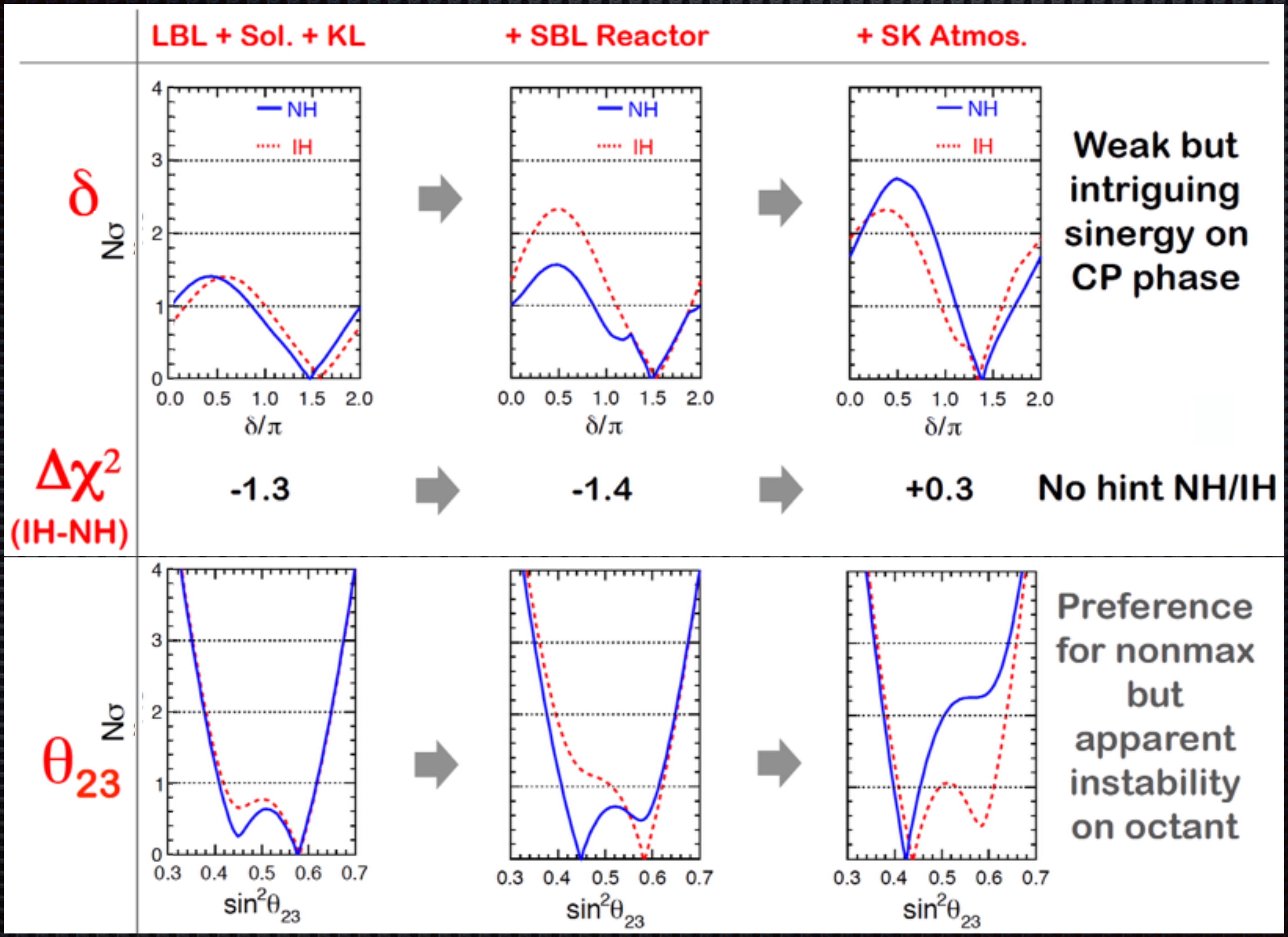
The current state of precision

Gonzalez-Garcia, Maltoni, Salvado, Schwetz, JHEP 1212 (2012) 123

NuFIT 1.2 (2013)

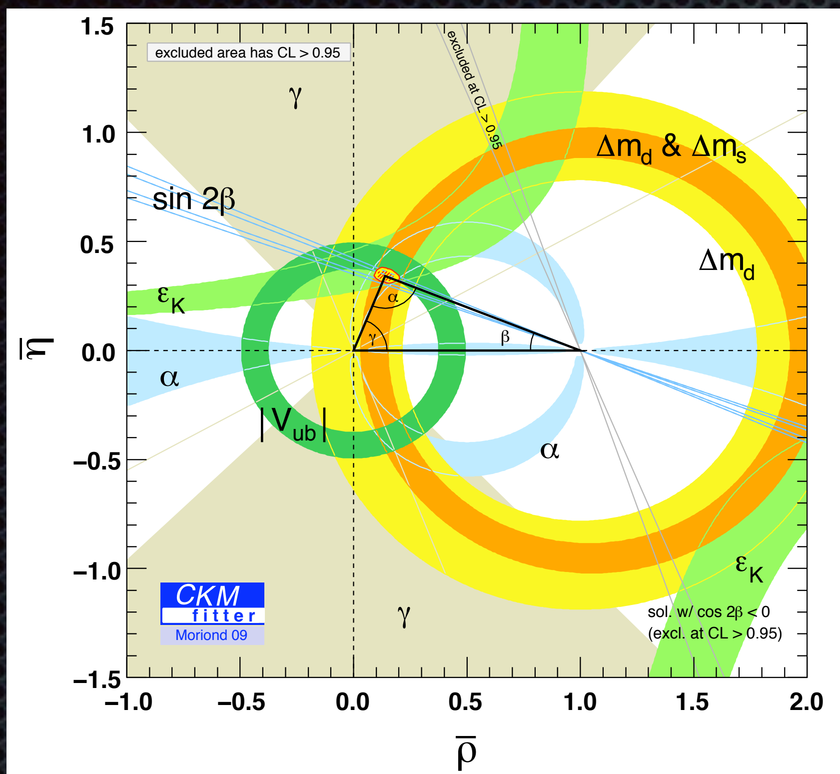
	bfp $\pm 1\sigma$	3σ range	
$\sin^2\theta_{12}$	$0.306^{+0.012}_{-0.012}$	$0.271 \to 0.346$	± 2%
$\theta_{12}/^\circ$	$33.57^{+0.77}_{-0.75}$	$31.38 \to 36.01$	
$\sin^2\theta_{23}$	$0.446^{+0.007}_{-0.007} \oplus 0.587^{+0.032}_{-0.037}$	$0.366 \to 0.663$	± 4% (or better)
$\theta_{23}/^\circ$	$41.9^{+0.4}_{-0.4} \oplus 50.0^{+1.9}_{-2.2}$	$37.2 \to 54.5$	
$\sin^2\theta_{13}$	$0.0229^{+0.0020}_{-0.0019}$	$0.0170 \to 0.0288$	± 4%
$\theta_{13}/^\circ$	$8.71^{+0.37}_{-0.38}$	$7.50 \to 9.78$	
$\delta_{CP}/^\circ$	265^{+56}_{-61}	$0 \to 360$	
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.45^{+0.19}_{-0.16}$	$6.98 \to 8.05$	± 3%
$\frac{\Delta m^2_{31}}{10^{-3}\ \text{eV}^2}$ (N)	$+2.417^{+0.013}_{-0.013}$	$+2.247 \to +2.623$	± 3%
$\frac{\Delta m^2_{32}}{10^{-3}\ \text{eV}^2}$ (I)	$-2.410^{+0.062}_{-0.062}$	$-2.602 \to -2.226$	

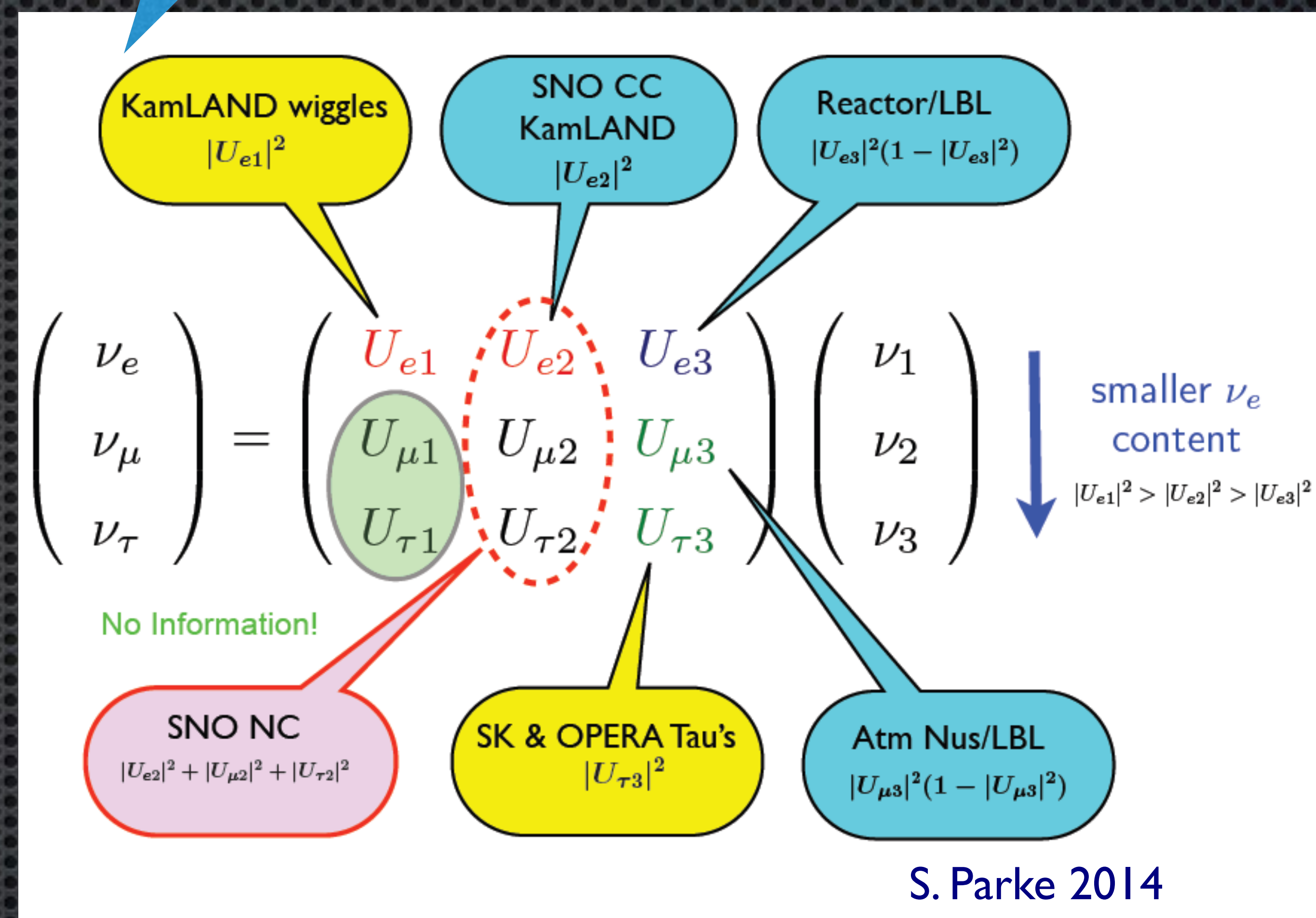
The current state of affairs



E. Lisi, ICFA Neutrino Panel, Paris (Jan. 2014)

The ultimate goal:





- Do for the lepton sector, what has been done for the quark sector: over-constrain the parameters of the model. Measure more, not less!

- **Long-baseline experiments continue to make fundamental contributions to the measurement of neutrino properties.**
  - Shown the US centric view of the long-baseline experiments, but international effort is ongoing.
- Just two years ago **the last unmeasured neutrino mixing angle, θ_{13},** was around the corner.
  - Today results seem to still be consistent among experiments.
  - Will there soon be indications on what is the mass hierarchy? and CP violation? Stay tuned. Neutrino 2014 coming up!
- **The determination of the mass hierarchy and CP violation are the next challenges.**
  - NOvA will play the opening in the exploration of the mass hierarchy and CP violation parameter space as well as the octant.
  - LBNE will follow with more power thanks to more matter effects.
  - A full program of cross section measurements, hadron production experiments and test beam will be required to achieve the desired levels of precision.