Mass Hierarchy & CP Violation with Long-Baseline Experiments

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What do We Know About the Neutrinos?

There are three generations of light neutrinos, they have mass, hence they mix and they don't travel faster than light.

Neutrino Mixing and PMNS Matrix

FLAVOR Eigenstates

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

MASS Eigenstates

Atmospheric | **Cross Mixing** | **Solar** | **Majorana**

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\mathrm{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\mathrm{CP}}} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} e^{i\eta_1} & 0 & 0 \\ 0 & e^{i\eta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix},$$

$\nu_\mu \leftrightarrow \nu_\tau$

$\nu_e \leftrightarrow \nu_\mu, \nu_\tau$

Atmospheric
ν_μ Long Baseline

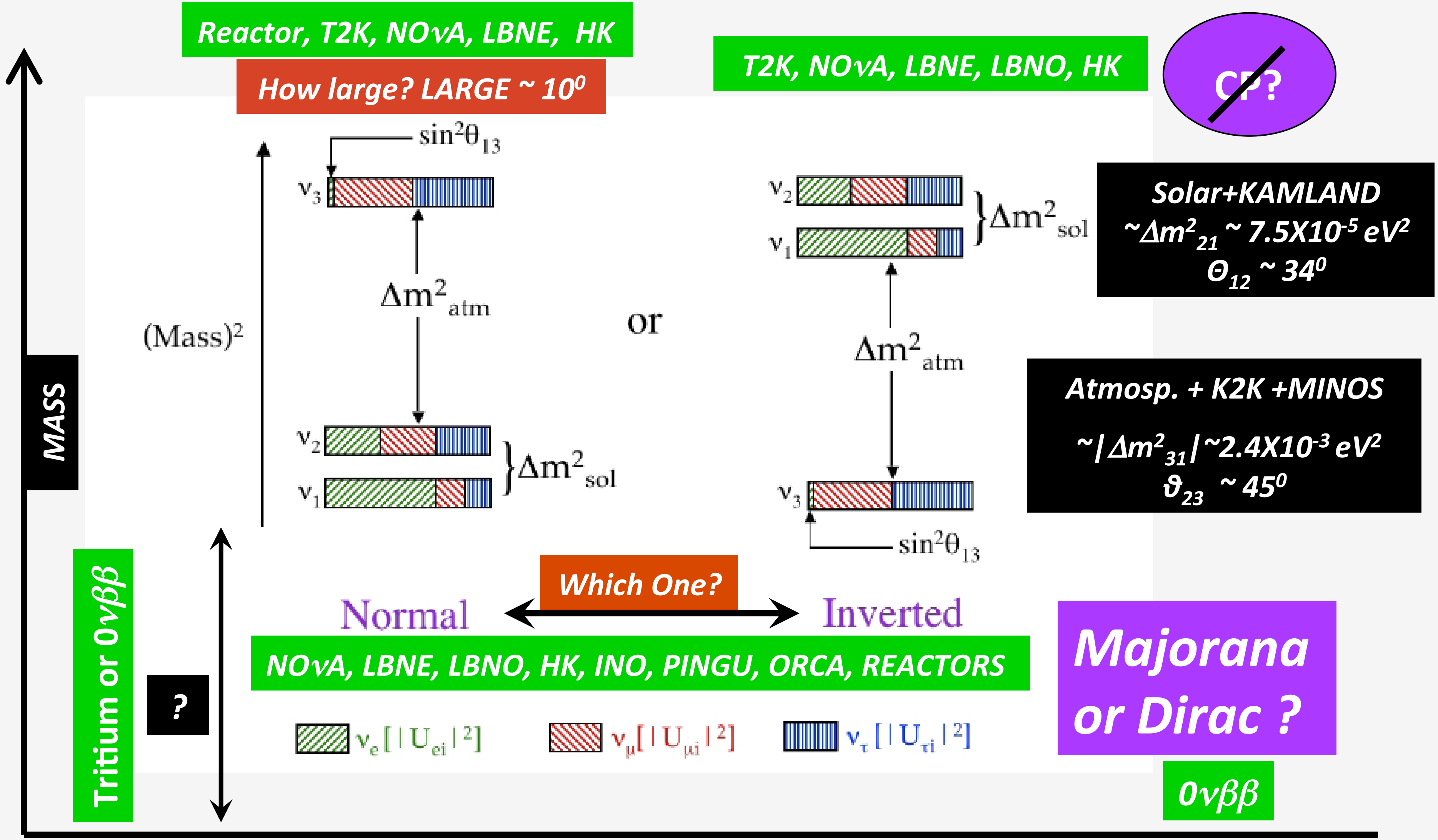
Reactor Short Baseline
ν_μ Long Baseline

Solar
Reactor Long Baseline

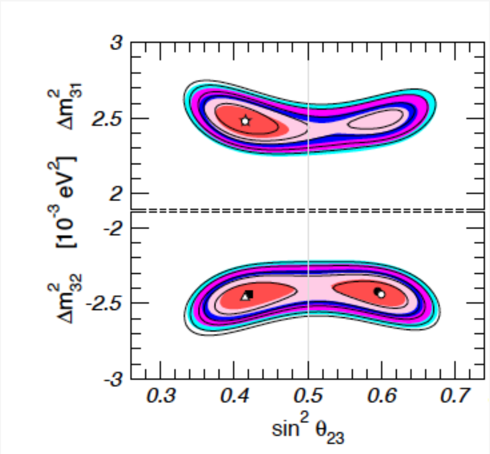
Long Baseline Accelerator Experiments

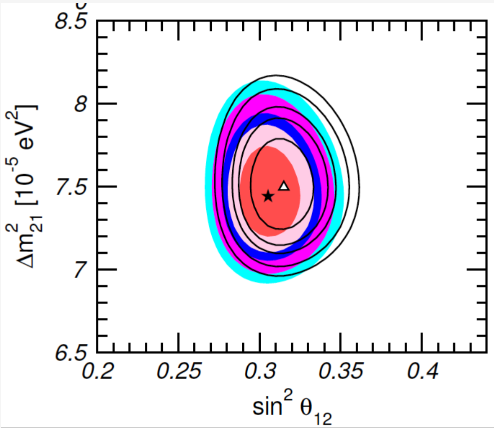
ν oscillations with 3ν's can be described by 8 parameters - 2 mass-squared (Δm^2) difference, 2 signs of mass-squared (Δm^2) differences, 3 angles and 1 phase.

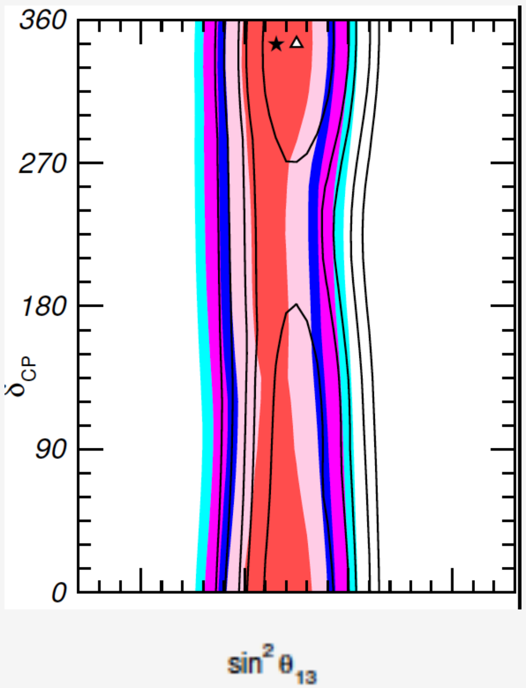
What We Know, What We Don't Know, & What We Would Like to Know



What is Known Known?







What is Known Unknown?

1. ν - Majorana or Dirac ✖
2. Absolute ν mass ✖
3. ν – MH ✔
4. CPV in ν ? ✔
5. Is ϑ_{23} maximal? If not in which octant it falls? ✔
6. Supernova ν ✖
7. Remnant Supernova ν ✖
8. Sterile ν ✖
9. Relic ν ✖

Gonzales-Garcia, Maltoni, Salvado, Schwetz

arXiv:1209.3023v3-19.Dec.12

European Strategy of Particle Physics – First Update

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Rapid progress in neutrino oscillation physics, with significant European involvement, has established a strong scientific case for a long-baseline neutrino programme exploring CP violation and the mass hierarchy in the neutrino sector. ***CERN should develop a neutrino programme to pave the way for a substantial European role in future long-baseline experiments. Europe should explore the possibility of major participation in leading neutrino projects in the US and Japan.***

Focus of the Talk – MH and CPV in Neutrinos

Also see talk on - MH at Reactors by Wei Wang & MH at PINGU & ORCA by Justine Evans

LBL ν Experiments: Future 3ν Oscillation Searches

Once positive evidence of θ_{13} has been found, the goal has moved towards search for ***neutrino mass hierarchy*** *and* ***CPV****. Need for very sensitive experiments.*

CP-violation (U Complex): ν's and anti-ν's behave differently and their oscillation probabilities are not the same

- $P(\nu_\mu \to \nu_e) = P_1 + P_2 + P_3 + P_4$ **IN VACUUM**
  - $P_1 = Sin^2(\theta_{23})\ Sin^2(2\theta_{13})\ Sin^2(1.27\ \Delta m^2_{13}\ L/E)$ *"Atmospheric"*
  - $P_2 = \pm J\ Sin(\delta)\ Sin(1.27\ \Delta m^2_{13}\ L/E)$
  - $P_3 = J\ Cos(\delta)\ Cos(1.27\ \Delta m^2_{13}\ L/E)$

    } *Atmospheric - Solar Interference*
  - $P_4 = Cos^2(\theta_{23})\ Sin^2(2\theta_{12})\ Sin^2(1.27\ \Delta m^2_{12}\ L/E)$ *"Solar"*

where

$$J = Cos(\theta_{13})\ Sin(2\theta_{12})\ Sin(2\theta_{13})\ Sin(2\theta_{23}) \times Sin(1.27\ \Delta m^2_{13}\ L/E)\ Sin(1.27\ \Delta m^2_{12}\ L/E)$$

+ for νbar and – for ν

LBL ν Experiments: Future 3ν Oscillation Searches – MATTER EFFECT

- ***In LBL experiment the neutrino beam traverses through the Earth and goes through forward coherent scattering due to interactions in matter.***
- ***In matter ν_e interacts differently compared to other flavors.***
  - ✓ ***ν_e has charged-current interaction with electrons in the matter***
  - ✓ ***ν_e, ν_μ, and ν_τ have neutral-current interactions with the matter***
  - ✓ ***ν_s has no interaction at all***
- ***Matter can change the oscillation probability due to an effective mass difference which is generated between different types of neutrinos.***
- ***This modifies the mixing angle, enhancing the probability of conversion for ν and suppressing for νbar, or vice-versa depending on the sign of Δm^2_{13}.***

LBL ν Experiments: Future 3ν Oscillation Searches – MATTER EFFECT

- In matter the effective mixing is given by:

$$\sin^2 2\theta^m_{13} \approx \sin^2 2\theta_{13} / (\cos 2\theta_{13} - A/\Delta m^2)^2$$

where $A = \pm 2\sqrt{2}\, G_F . Y.\, n_B .\, E_\nu$

n_B = Baryon Density

$Y = -2Y_n + 4Y_e$ for ν_e (Y_n = neutrons/baryons)

$Y = -2Y_n$ for $\nu\mu$ (Y_e = electrons/baryons)

$Y = 0$ for ν_s

- This enhances (suppresses) the probability of conversion for ν (νbar) to normal hierarchy and vice–versa for inverted hierarchy
- For a 2 GeV neutrino of energy, matter effect gives
  - ✓ About ±30% effect for NuMI & about ±11% effect for T2K
- By measuring $P(\nu_\mu \rightarrow \nu_e)$ and $P(\nu_\mu \rightarrow \nu_e)$, we are sensitive to θ_{13}, δ, and the type of hierarchy (or sign of Δm^2_{31})
- And this is what NOνA+T2K and LBNE/LAGUNA-LBNO will do.

Neutrinos from Accelerator

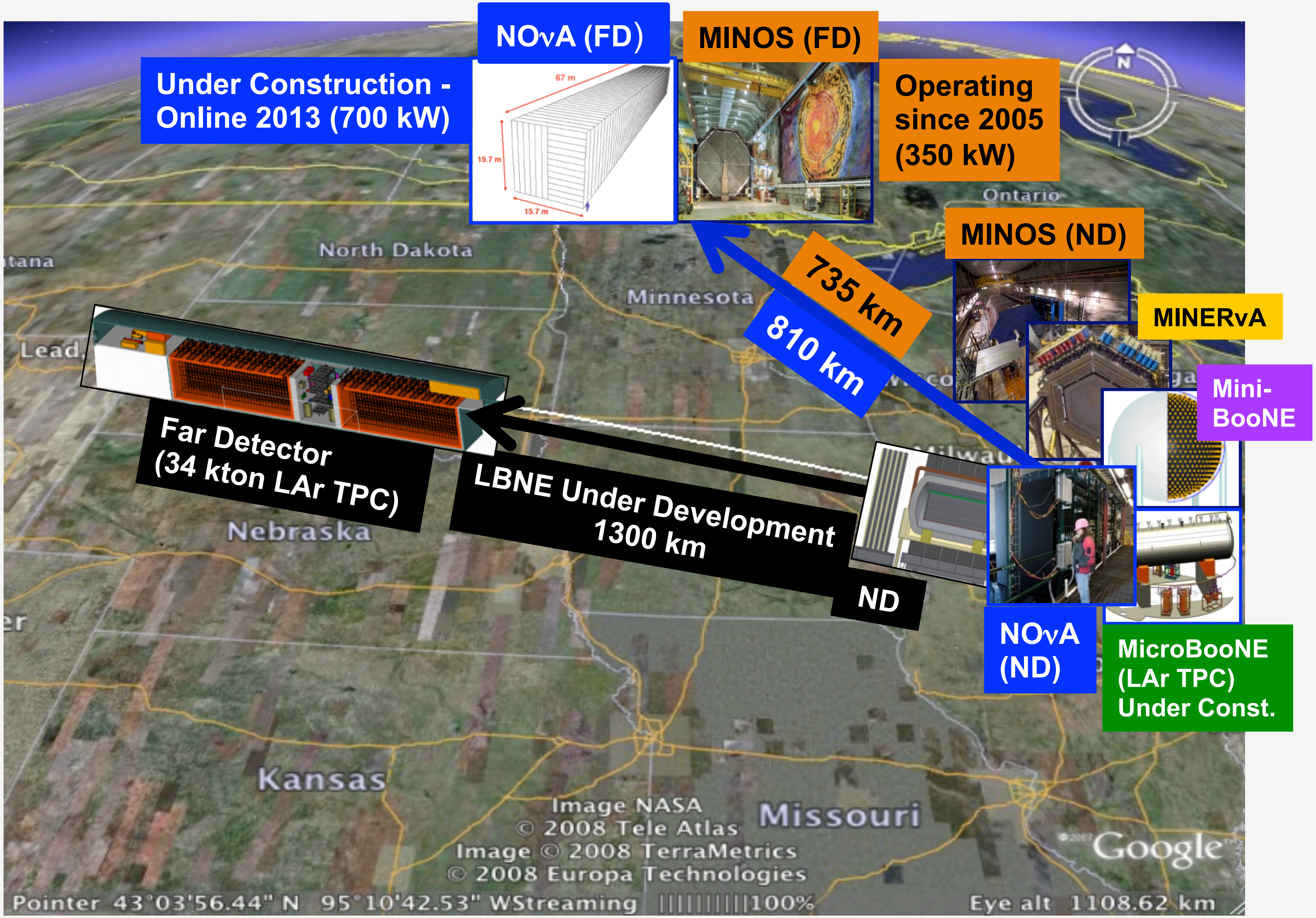
Long-Baseline Experiments

MINOS/MINOS+/NOνA/LBNE – USA-FNAL

LAGUNA-LBNO – Europe-CERN

T2K/T2HK – Japan–Tokai-Kamioka

Fermilab's Neutrino Program



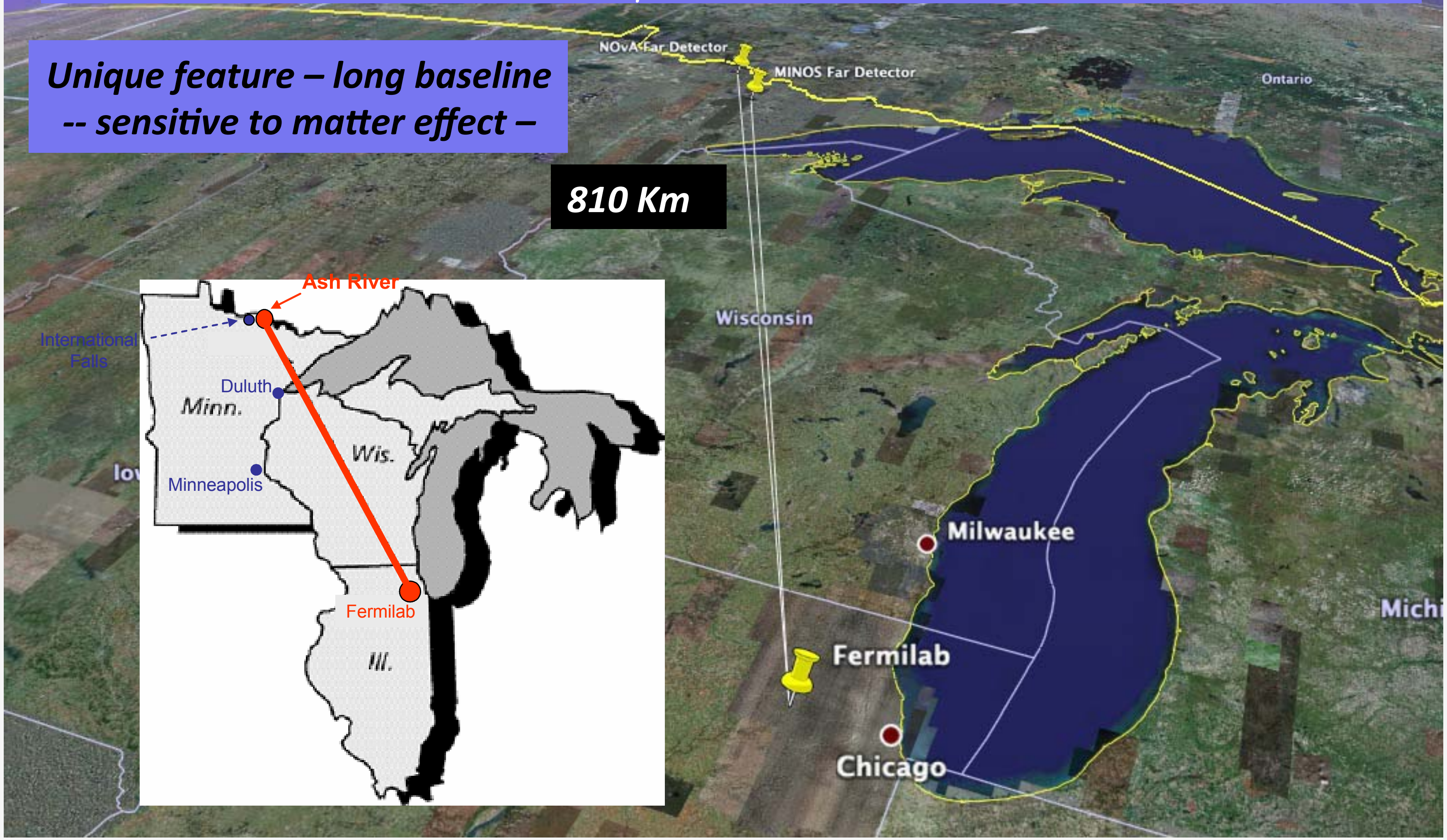
NOνA

NOνA

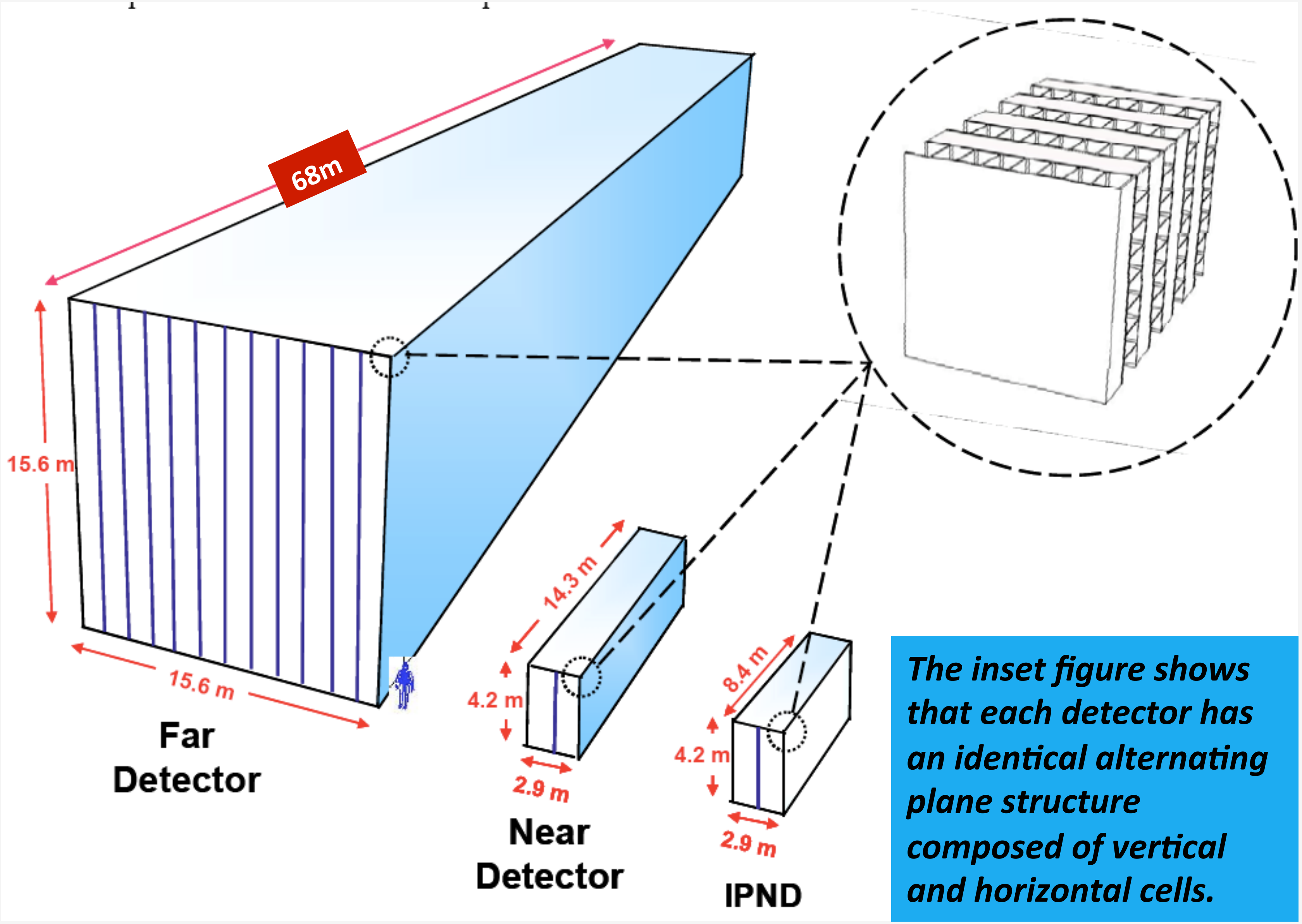
NOνA is a second-generation experiment on the NuMI beamline, which is optimized for the detection of $\nu_\mu \rightarrow \nu_e$ oscillations.

Unique feature – long baseline -- sensitive to matter effect –

810 Km



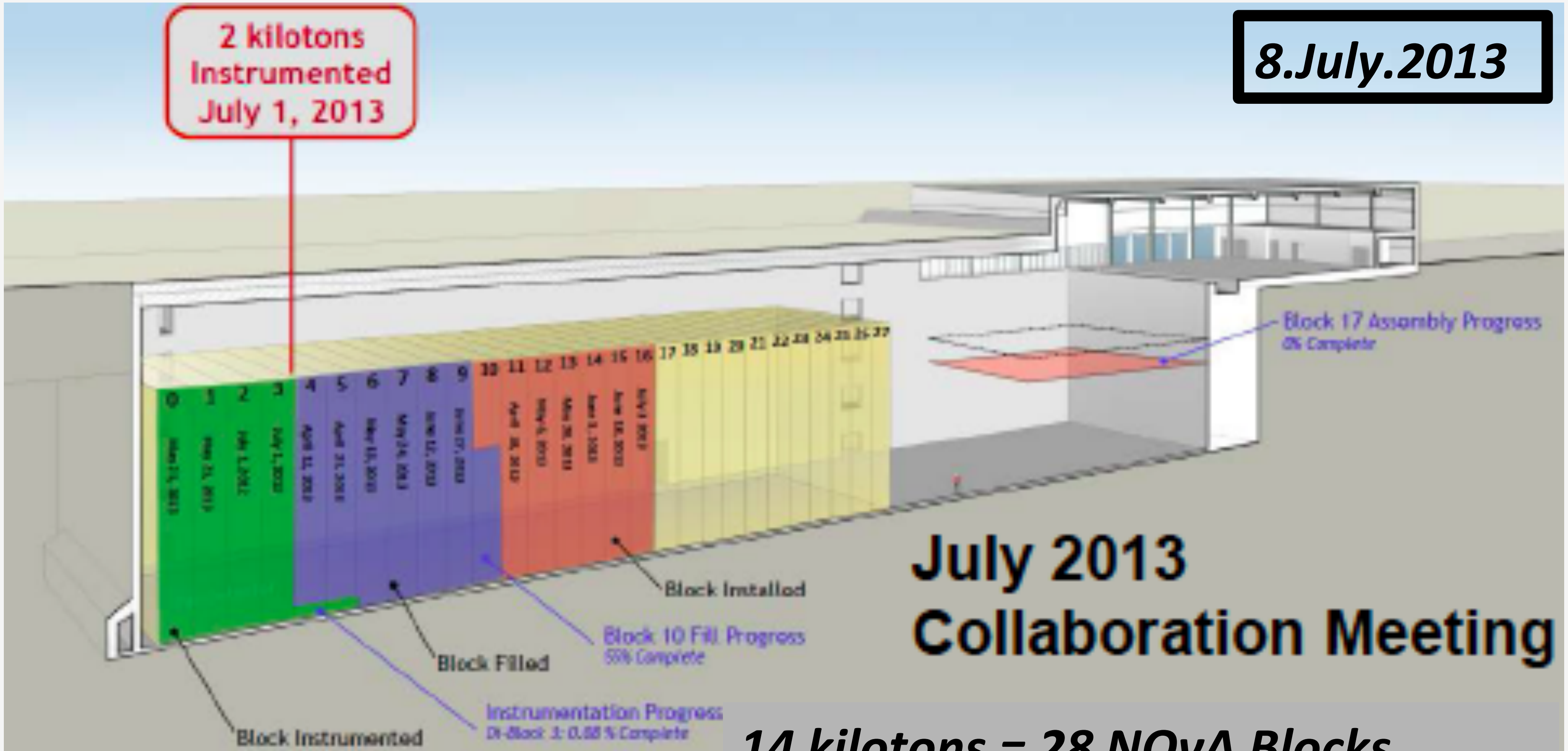
Three NOνA Detectors



The inset figure shows that each detector has an identical alternating plane structure composed of vertical and horizontal cells.

NOνA Construction Status

14 Ktons of FD to be completed by 6/2014

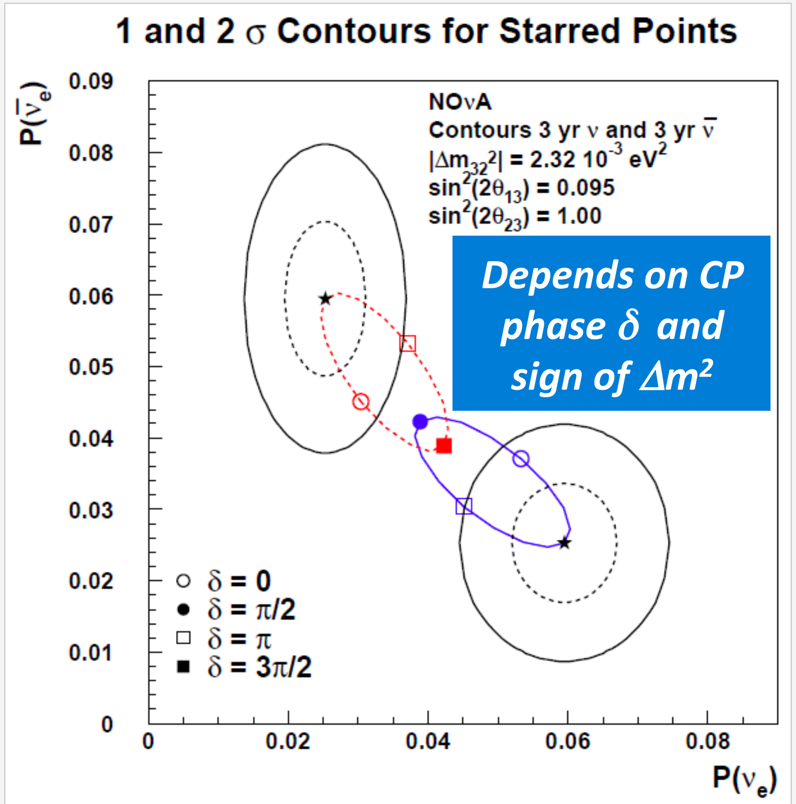


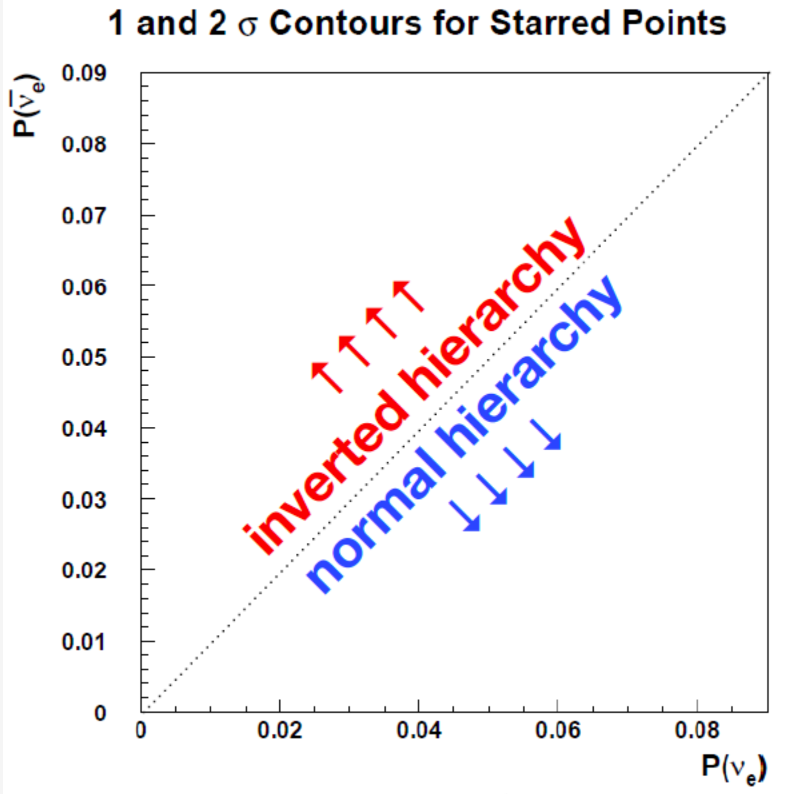
14 kilotons = 28 NOvA Blocks

17 Blocks Installed, 10.5 Modules Filled

More than 4 Blocks outfitted w/Electronics

NOνA Physics – MH





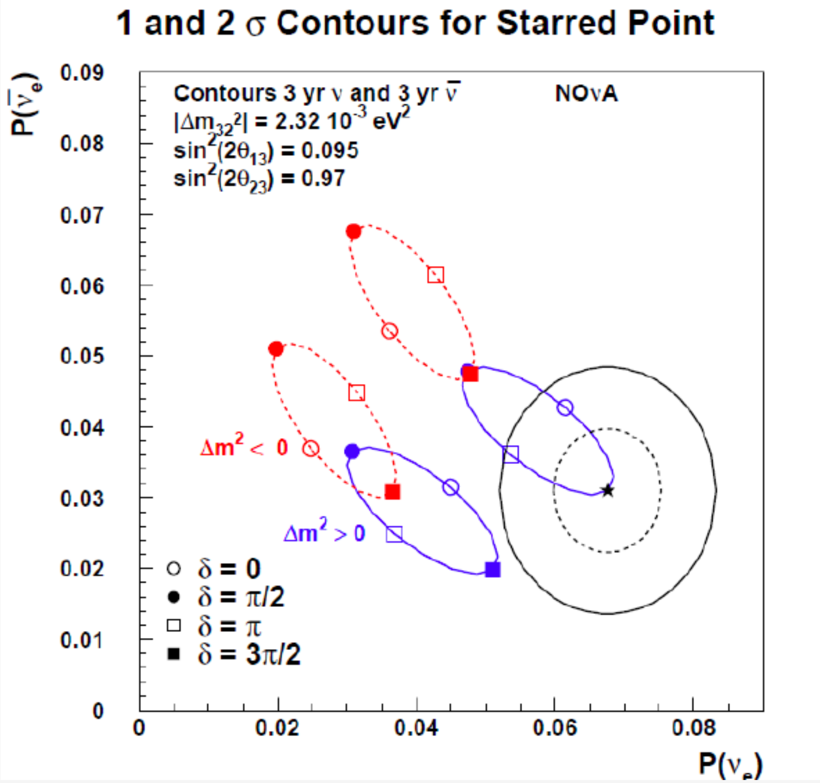
NOνA will measure $P(\nu_\mu \rightarrow \nu_e)$ & $P(\nu bar_\mu \rightarrow \nu bar_e)$ at 2 GeV

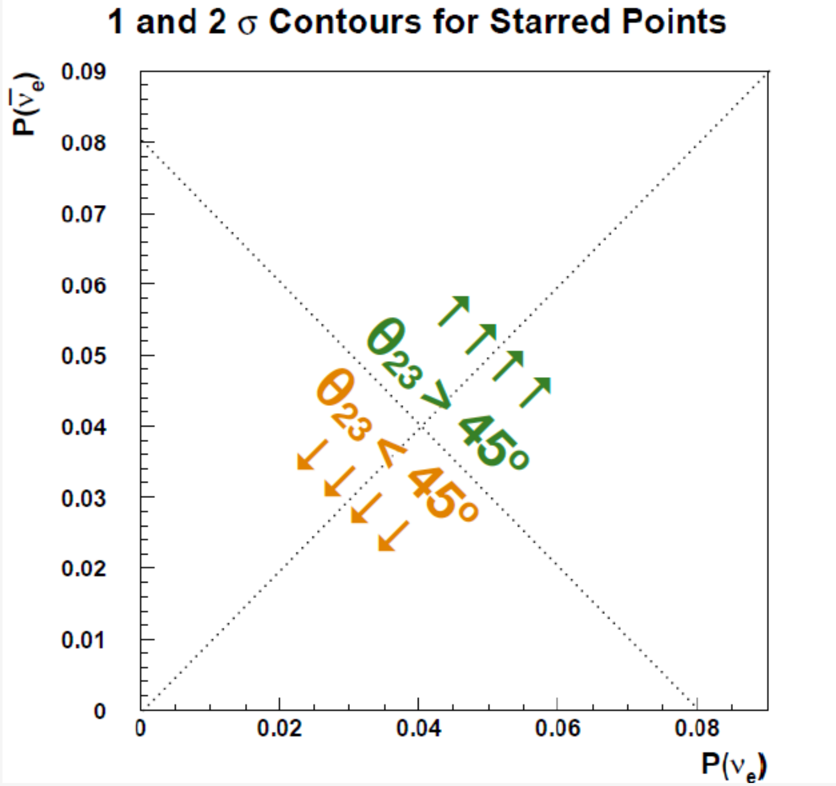
Large θ_{13} is better for NOνA. It reduces the overlap between these bi-polarity ellipses, reducing the likelihood of degeneracy

Signal efficiency = 45%, NC fake rate = 0.1%.
Data – 6E20 – 3 yrs in each mode.

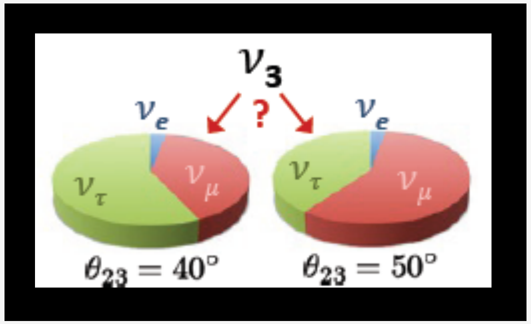
From M. Messier

NOνA Physics – Octant Resolution



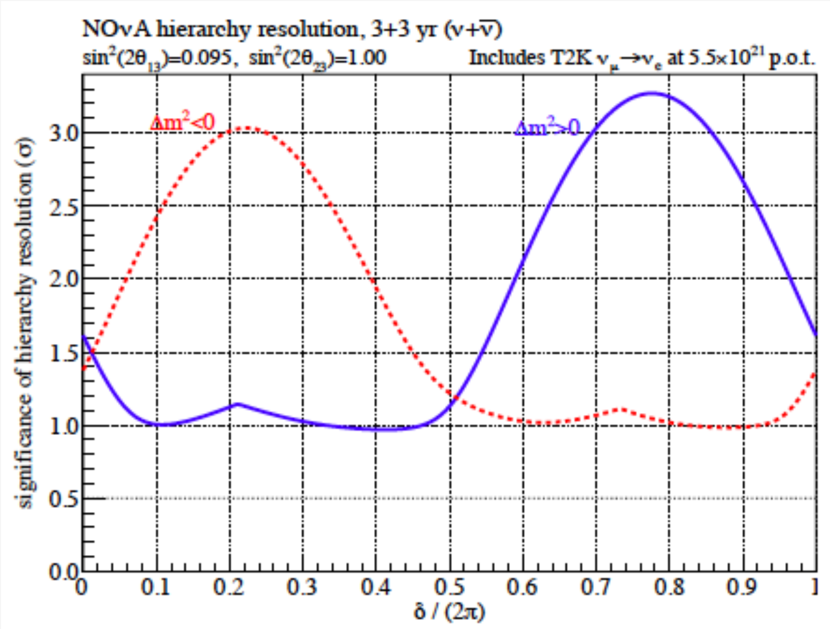


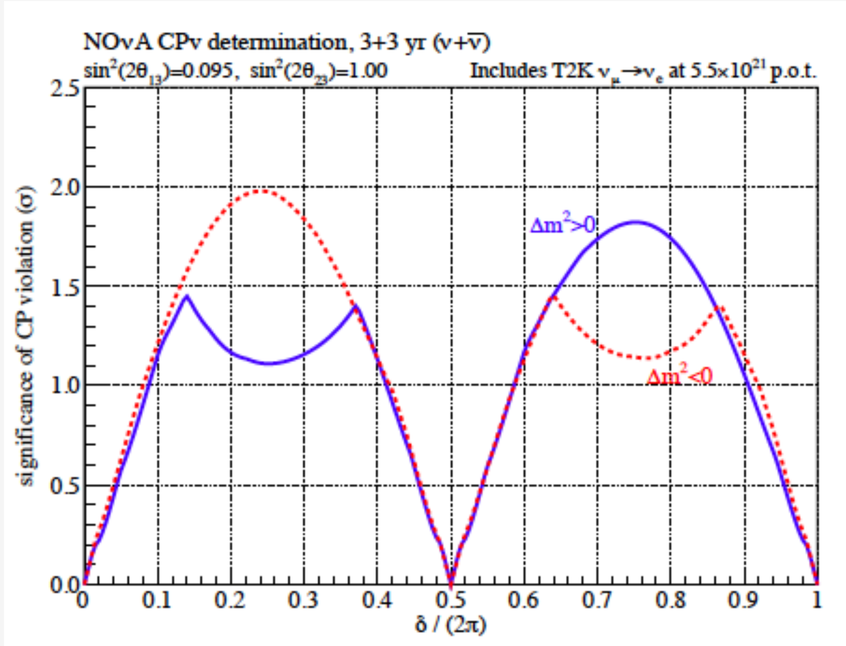
$P(\nu_e) \propto \sin^2(\theta_{23})\ \sin^2(2\theta_{13})$
$\rightarrow \theta_{23}$ octact sensitivity

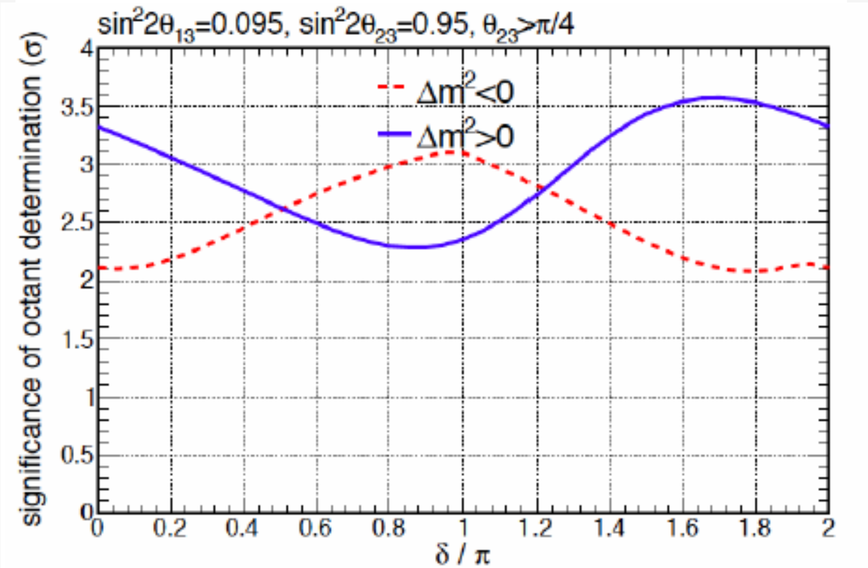


From M. Messier

NOνA+T2K - MH, CPV & Octant Degeneracy



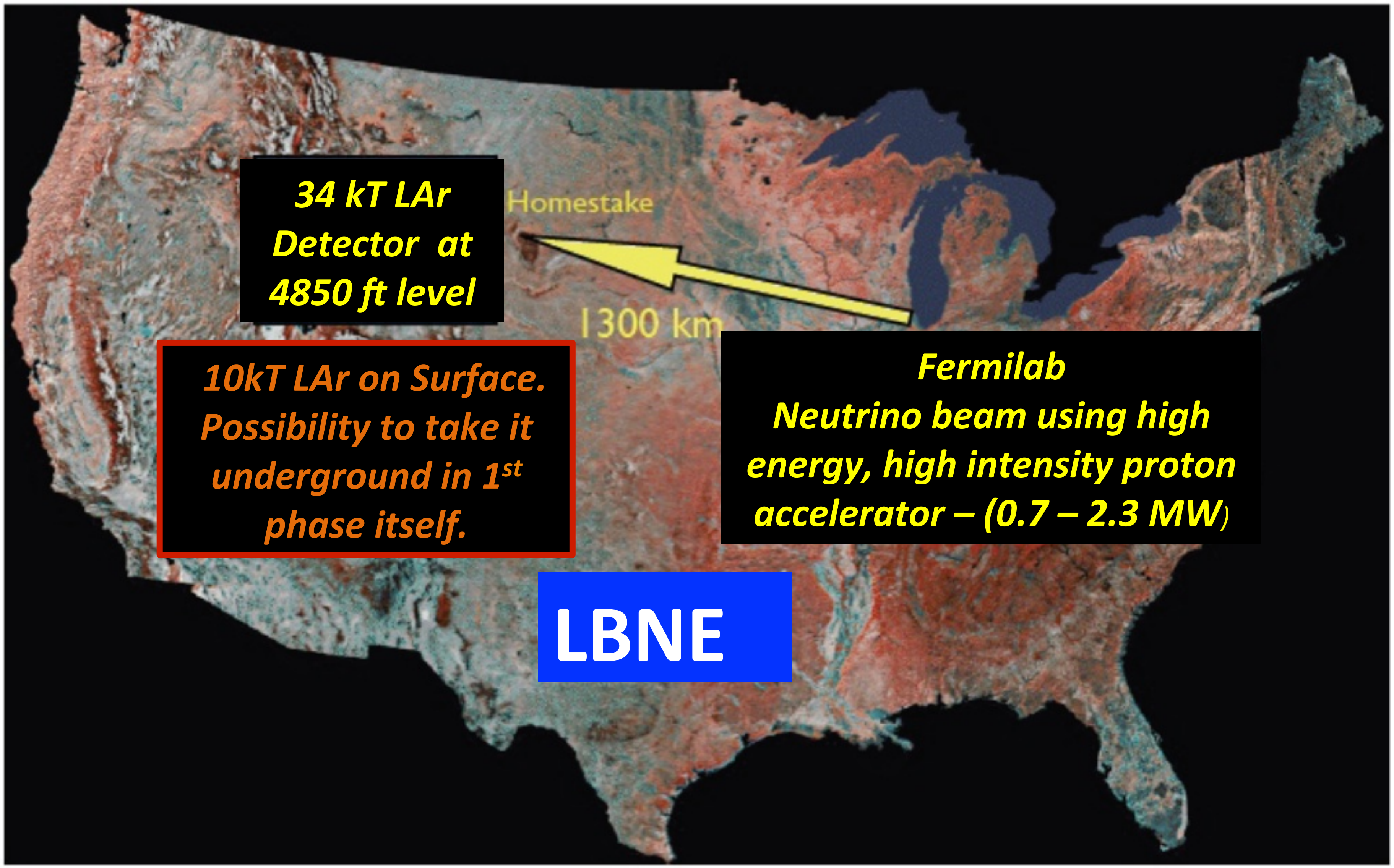




- *3 + 3 years of running in neutrino and anti-neutrino mode.*
- *NOVA data will yield regions in P (ν_e) vs. P(νbar_e) space.*
- *A measurement of the probabilities might allow resolving the MH and provide information on δ_{CP}*
- *Additional sensitivity from T2K*

LBNE

Long Baseline Neutrino Experiment



Physics Aims of Modified LBNE (10Kton LAr Detector on Surface)

a) Long Baseline Physics Reach
   i. Precision measurement of θ_{13} — YES
   ii. Determination of Mass Hierarchy — YES
   iii. CP Violation in Neutrinos — YES
   iv. Precise measurement of Δm^2_{31} and θ_{23} — YES

Will only cover this section

b) Proton Decay — Possibly

c) Supernova Neutrino Bursts — Very difficult

d) Diffuse Supernova Neutrinos — Very difficult

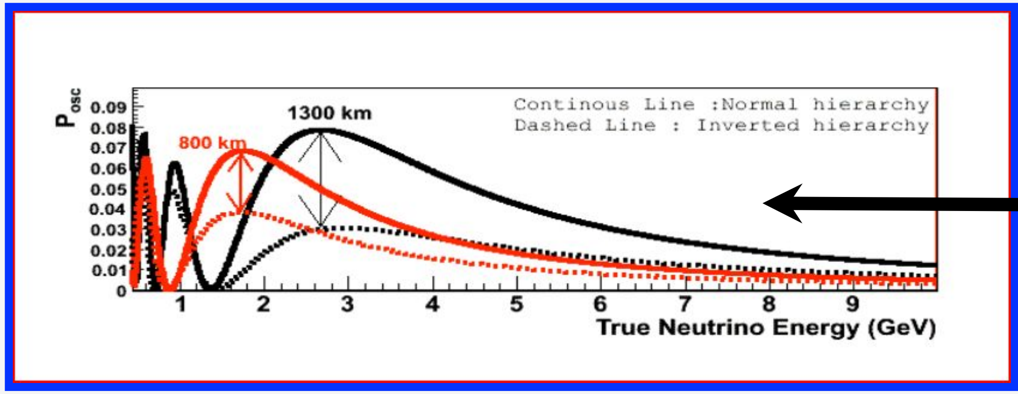
e) Atmospheric Neutrinos — YES

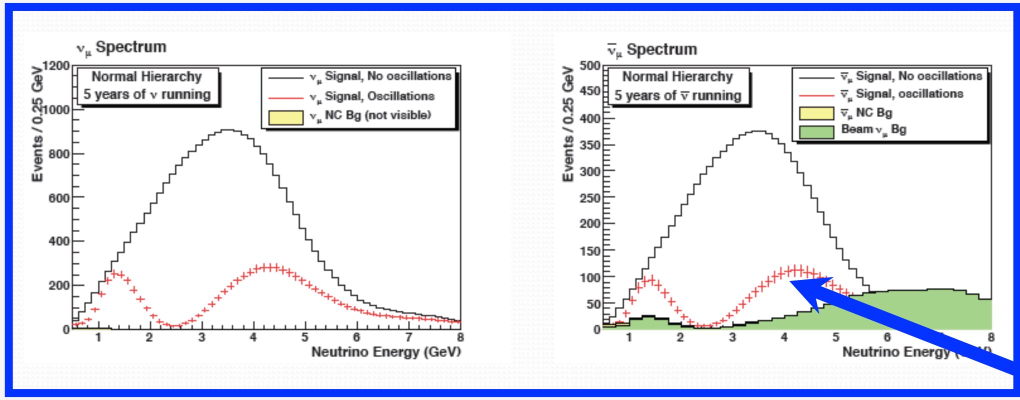
f) High Energy Neutrinos — Difficult

g) Solar Neutrinos — No

Hope to Improve on this - from very beginning

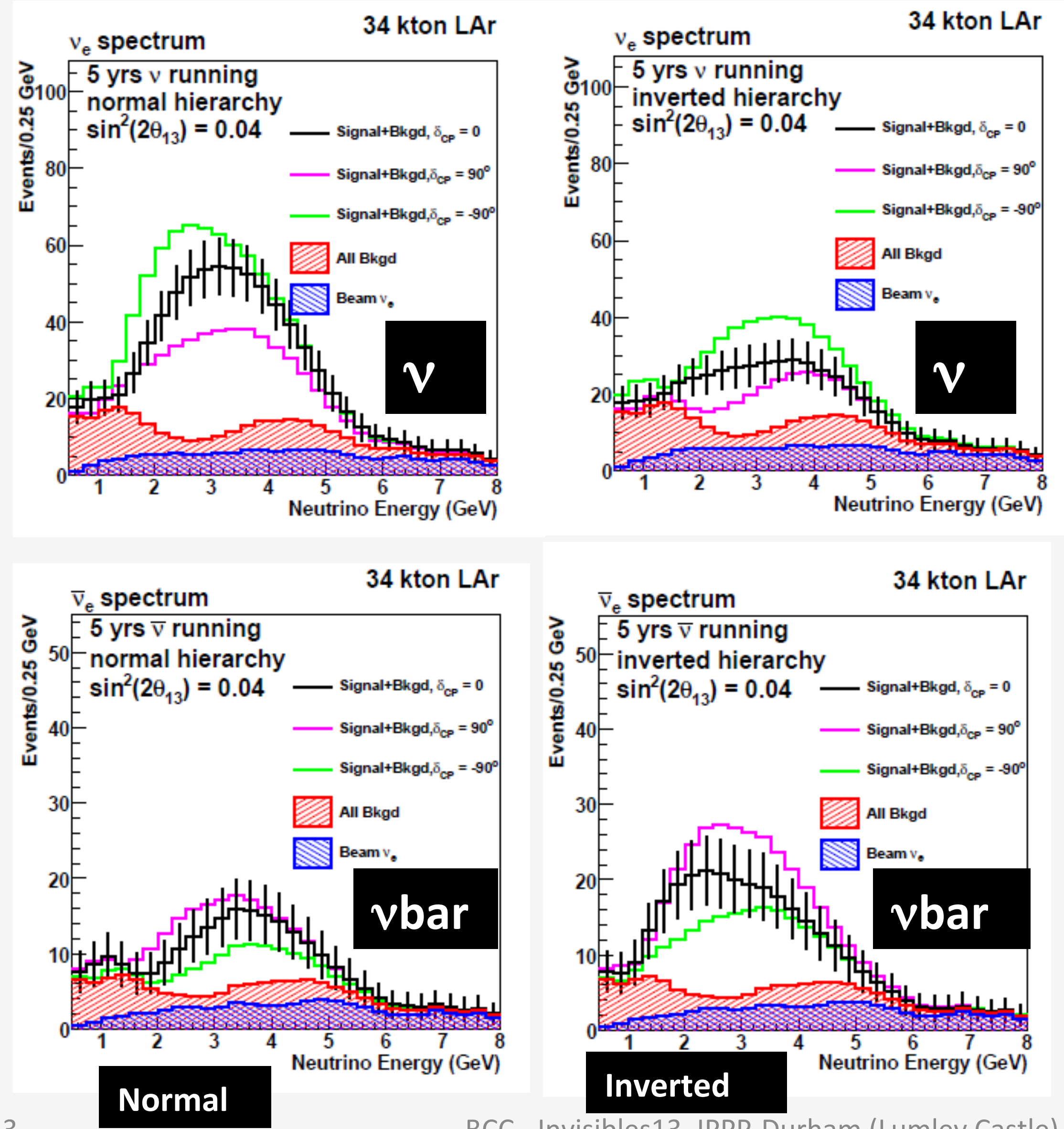
LBNE Beam





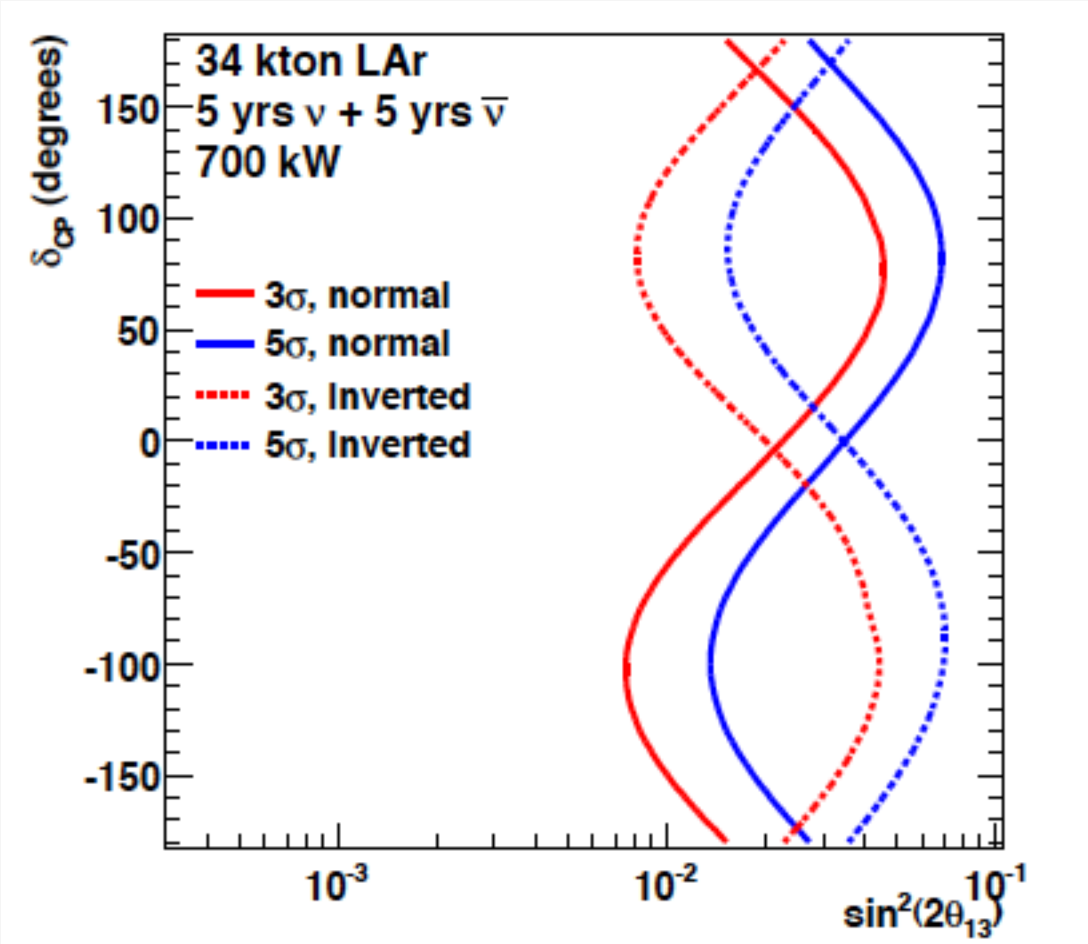
1. ***Fermilab – Homestake (South Dakota) = 1290 Km***
2. ***Wide Band Low Energy Beam – Information from 1st and 2nd maxima at achievable neutrino energy***
3. ***Larger separation between normal and inverted hierarchy***
4. ***All neutrino parameters measured in the same detector complex***
5. ***Expected spectra in 34kT LAr TPC w/ and w/o oscillation for 5 yrs running with neutrino (L) and anti-neutrinos (R)***
6. ***Clear bi-nodal oscillation spectrum***

$\nu_\mu \rightarrow \nu_e$ *Appearance Spectra – LAr Detector*



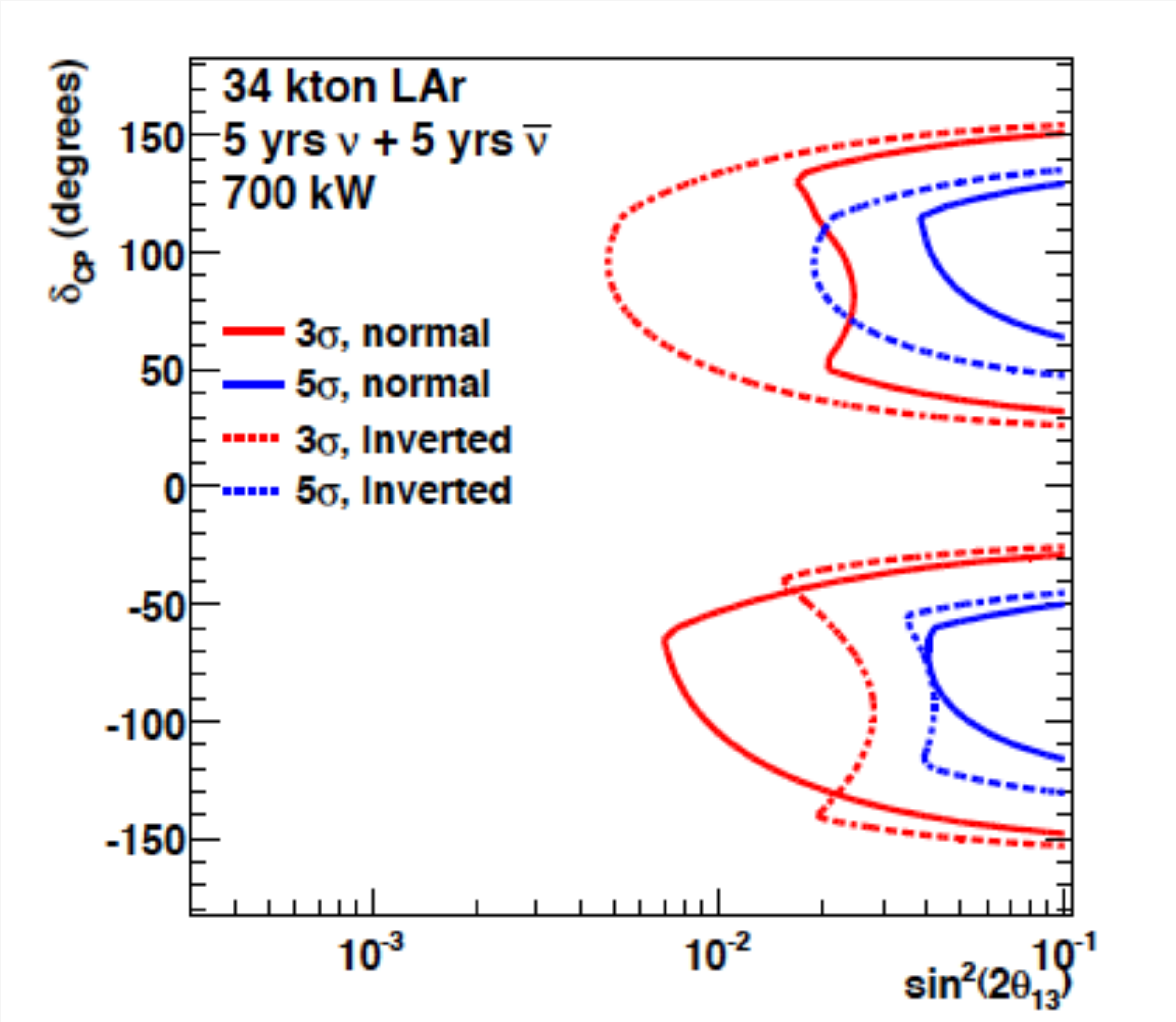
- ✓ 120 GeV protons on target
- ✓ 700 kW power
- ✓ 34 kTon LAr detecor
- ✓ 5 yr ν exposure
  +
  5yr νbar exposure
- ✓ $2\text{x}10^7$ sec/yr
- ✓ δ_{CP} = 0, +90 & -90
- ✓ Background all beam

Mass Hierarchy



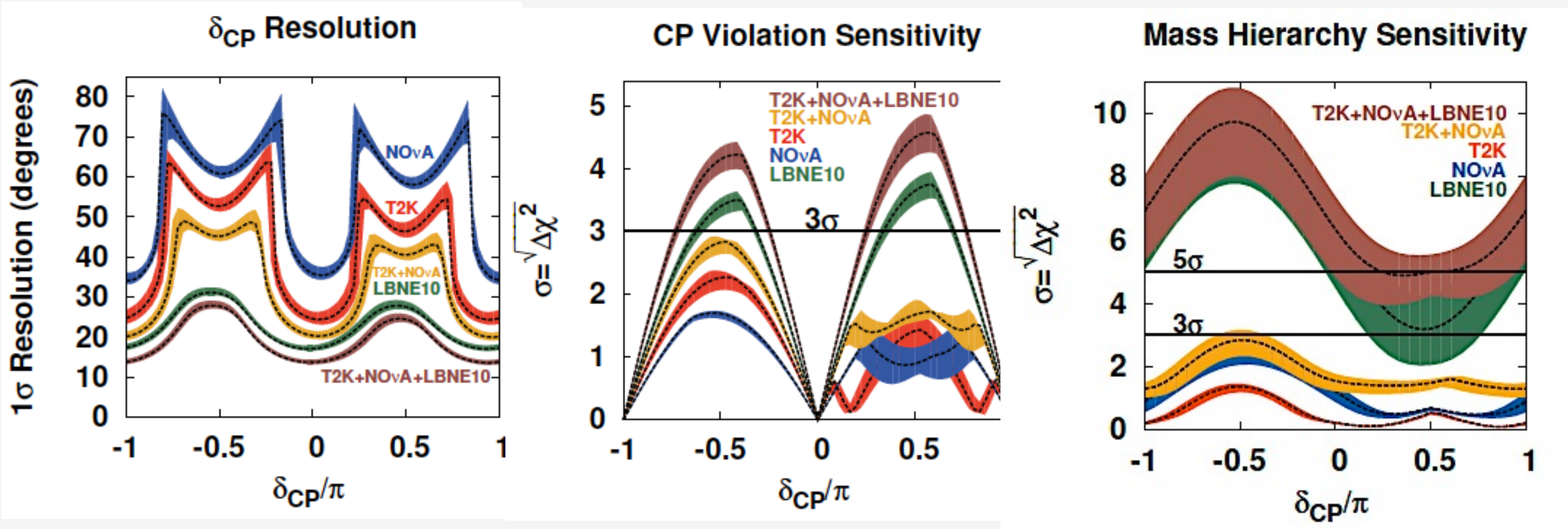
5σ+ for all δ_{CP} for the current value of ϑ_{13}

CP Violation



$3\sigma \sim 70 - 75\%\ \delta_{CP}$ for $\sin^2(2\theta_{13}) = 0.095$

Even LBNE10 Would be a Major Advance



Bands: 1σ variations of ϑ_{13}, ϑ_{23}, Δm_{31}^2 (Fogli et al. arXiv:1205.5254v3)

T2K 750 kW x 5 yr ν

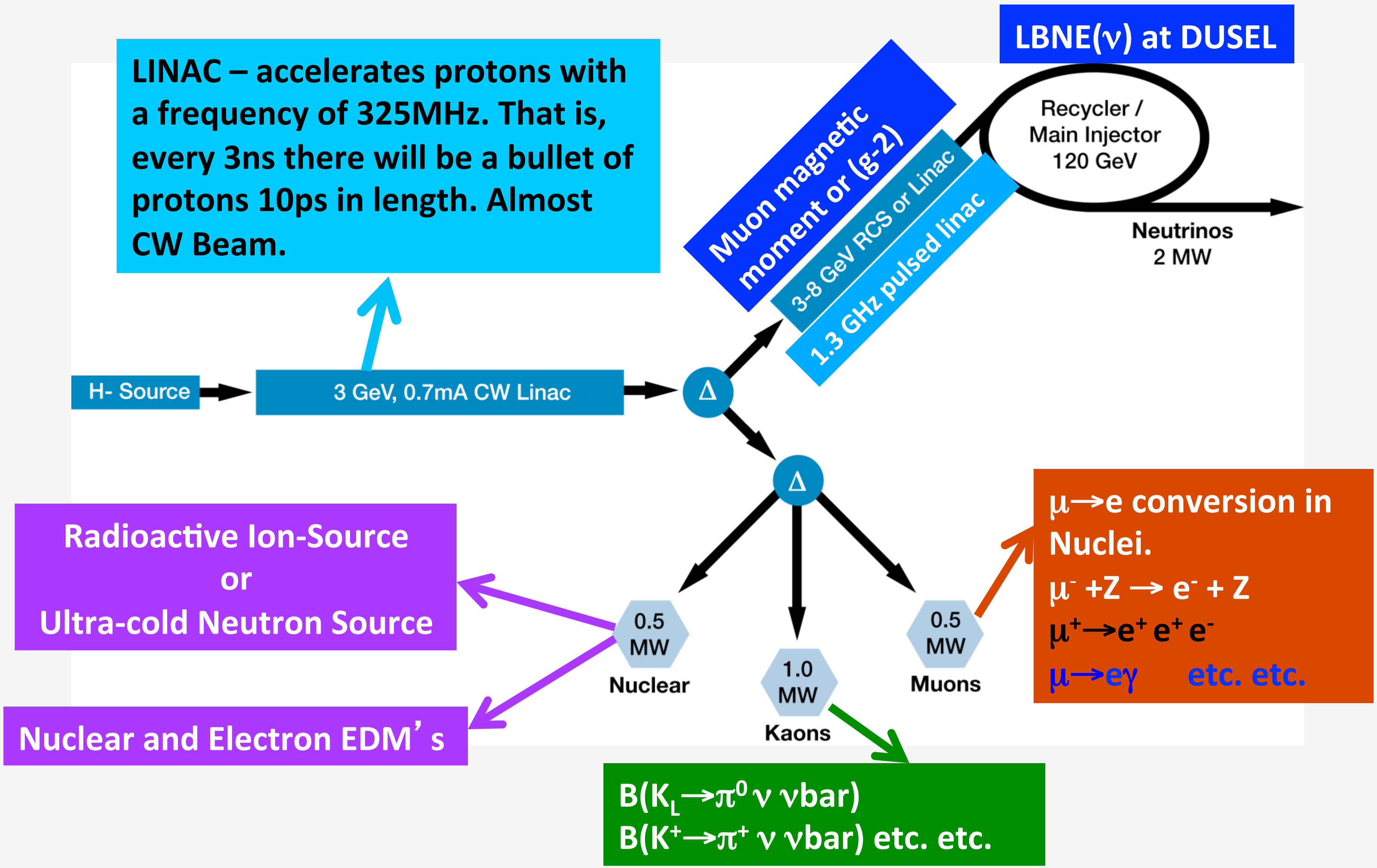
NOνA 700 kW x (3 yr ν + 3 yr $\bar{\nu}$)

LBNE10 (80 GeV*) 700 kW x (5 yr ν + 5 yr $\bar{\nu}$)

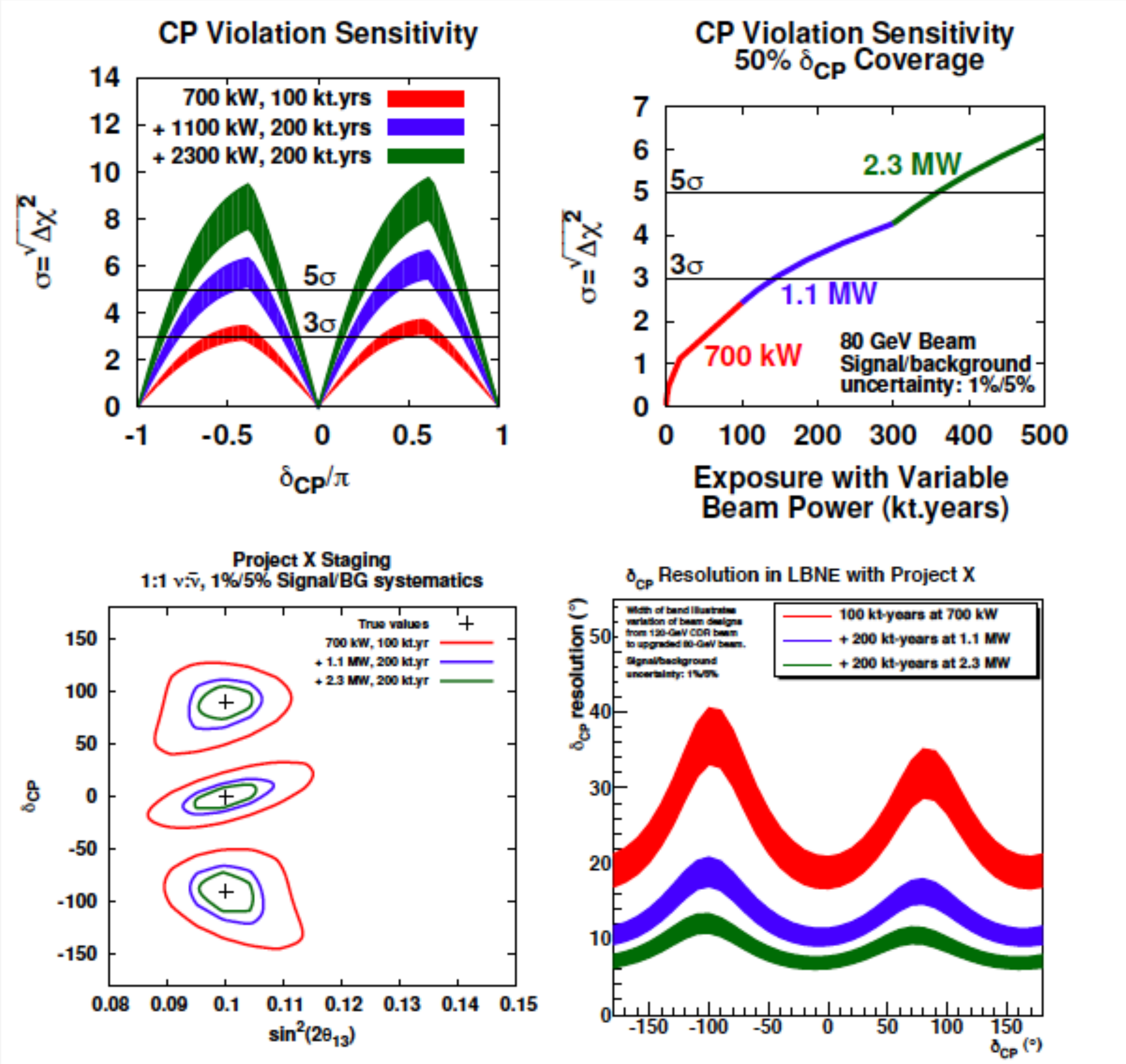
Project-X

- ✓ *Project-X is a proposed new high-intensity proton source with beam energy ranging from 3 GeV to 120 GeV based on a 3 GeV CW H- linac. With further acceleration to 8 GeV, and injection into existing RR/MI complex, it would support long-baseline neutrino experiments.*
- ✓ *Project-X would provide 2 MW of total beam power to the 3 GeV program for physics of rare processes (muon, kaon and nuclear physics), simultaneously with 2 MW to a neutrino production target at 60-120 GeV.*
- ✓ *Due to unprecedented flexibility in the timing structure of beams – pulsed or continuous wave, varying gaps between pulses, fast or slow spill – and in the variety of simultaneously delivered secondary beam – one will be able to perform cutting edge experiments in neutrino, muon, kaon and nuclear physics simultaneously.*

Project-X – Basic Concept of the Accelerator



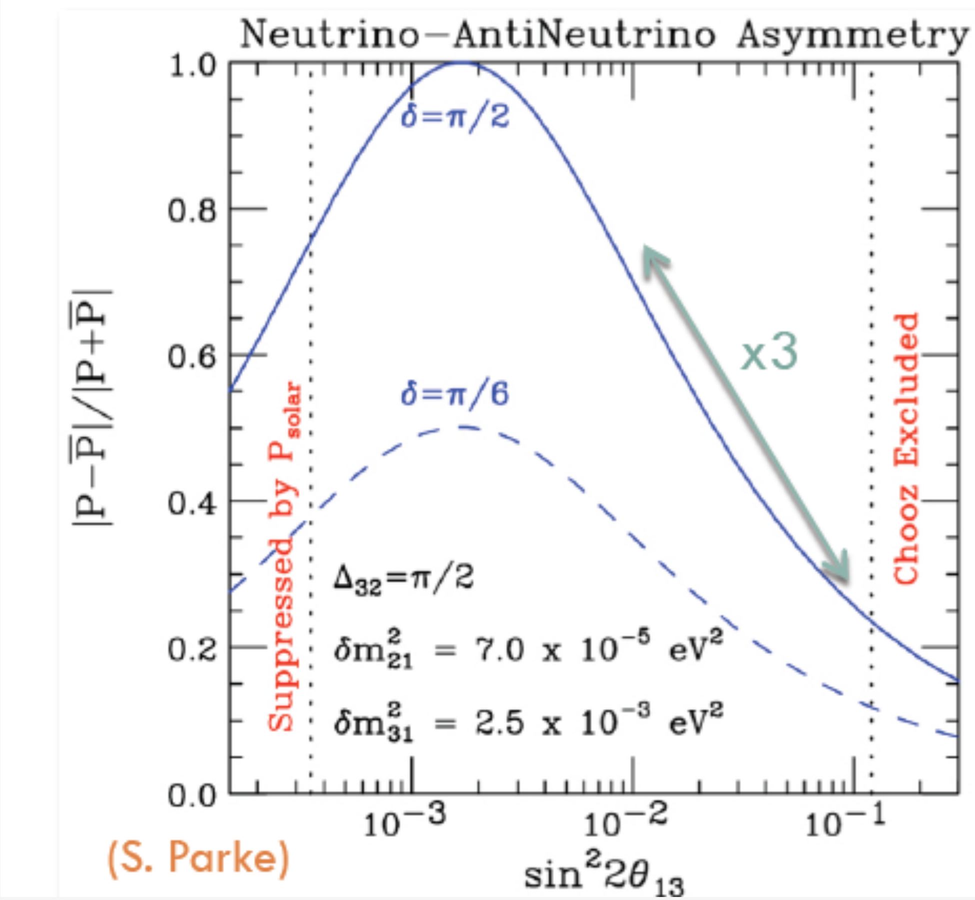
LBNE Summary in the Project-X Era



Large θ_{13} – What Does It Mean for CPV & δ_{CP}?

- ✓ ***With larger value of θ_{13} --- will the measurement of CPV become any easier?***
- ✓ ***While the number of oscillated event sample increases leading to quicker determination of "Matter Hierarchy", the measurement of CPV and δ_{CP} is largely unaffected by the value of $\sin^2 2\vartheta_{13}$***
- ✓ ***To the first order, this is due to two competing effects…***
  - ***size of asymmetry one is trying to measure, and***
  - ***the size of the event samples***

ν vs. νbar Asymmetry In Vacuum



Ignoring the matter effect and background for now

Understanding systematic will be the key to CP measurement

- ✓ **Signal rate increases with θ_{13}** - *A factor of ~10 increase in signal in going from $\sin^2 2\vartheta_{13}$ = 0.01 to 0.10, so x3 improvement in statistical significance of signal*
- ✓ • The asymmetry

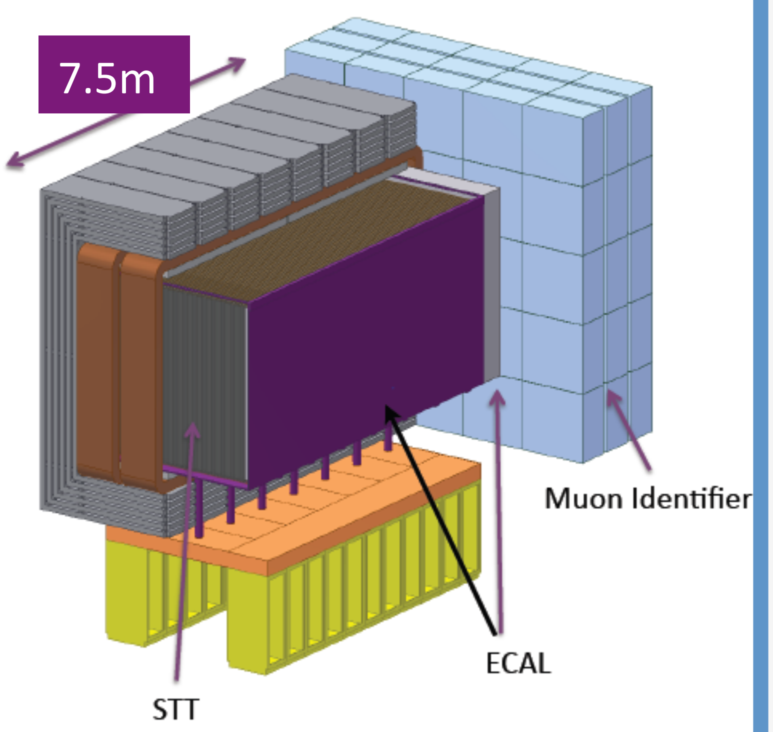
$$\frac{P(\nu_\mu \rightarrow \nu_e) - P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e)}$$

is proportional to ~$1/\sin\theta_{13}$

- ✓ **the asymmetry gets smaller as θ_{13} increases** - *a factor ~3 reduction in CP asymmetry going from $\sin^2 2\vartheta_{13}$ = 0.01 to 0.10 (independent of baseline)*

The role of the ND becomes increasingly important.

ND Concept for LBNE



Fine grained tracker ~0.14T Ar@140 atm

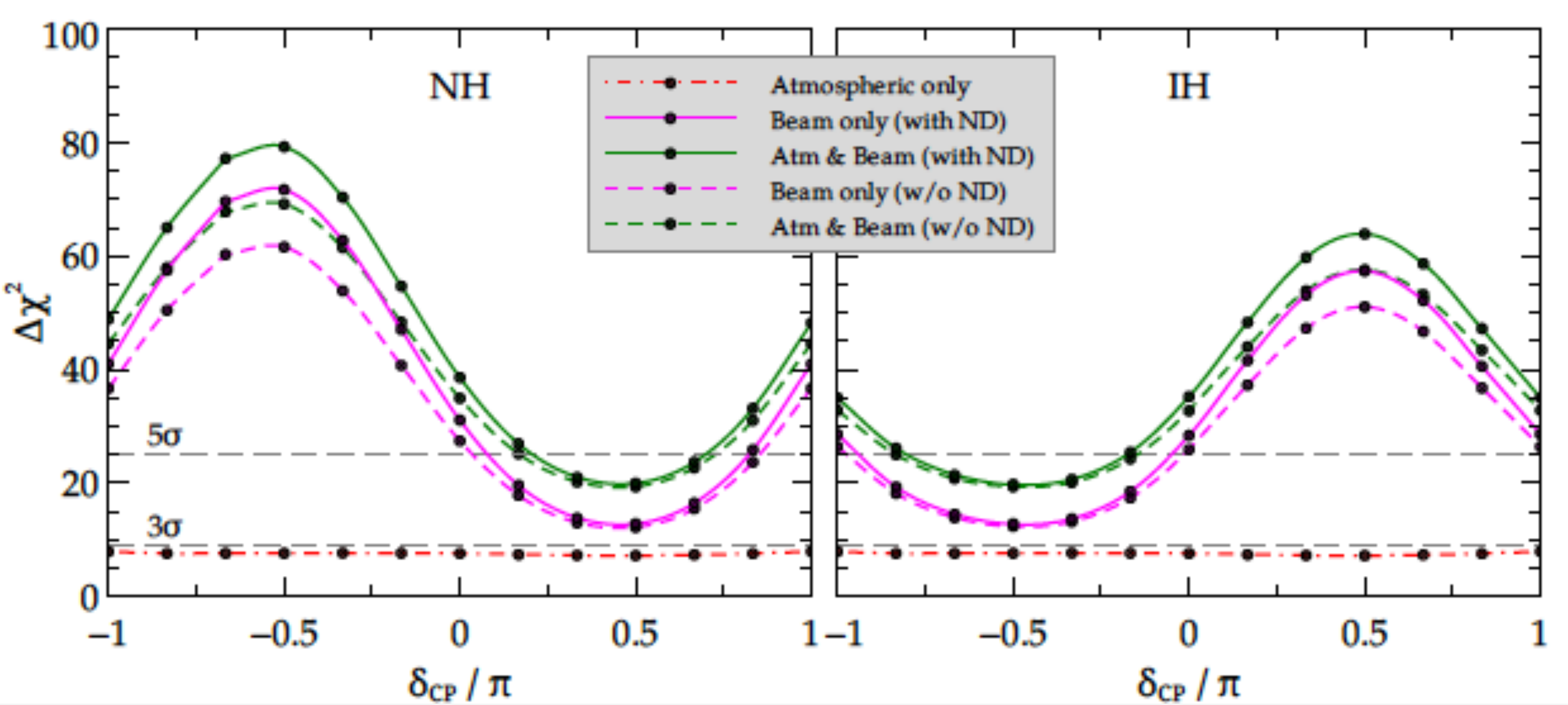
- 3.5m X 3.5m X 7.5m (ρ ~ 0.1 gm/cm^3) STT
- 4π ECAL
- Dipole Field (0.4T)
- Muon-detection (RPC) in Dipole and downstream
- ✓ Transition radiation – distinguished $e^{\pm}$, and γ thus distinguishing ν_e, $\bar{\nu}_e$ (νbar$_e$), and π^0
- ✓ dE/dX – separates p, $\pi^{\pm}$, $K^{\pm}$
- ✓ Muon + Magnet - $\mu^{\pm}$
- ✓ QE-Proton ID → Absolute Flux measurement
- ✓ Pressurized Ar-Target (~X5 FD stat) → LAr-FD
- ✓ H_2O (D_2O) – Fe targets – nuclear effect

Greatest Scientific Return.

With external contribution, it would be possible to build a higher-resolution and larger-ND (3.5m X 3.5m X 7.5m) capable of fulfilling oscillation needs and precision measurements/searches.

LBNE w & w/o ND – Mass Hierachy – 100 kT-yr – 10kT FD – 5 yrs ν & νbar

arXiv:1307.2519v1 -9July13



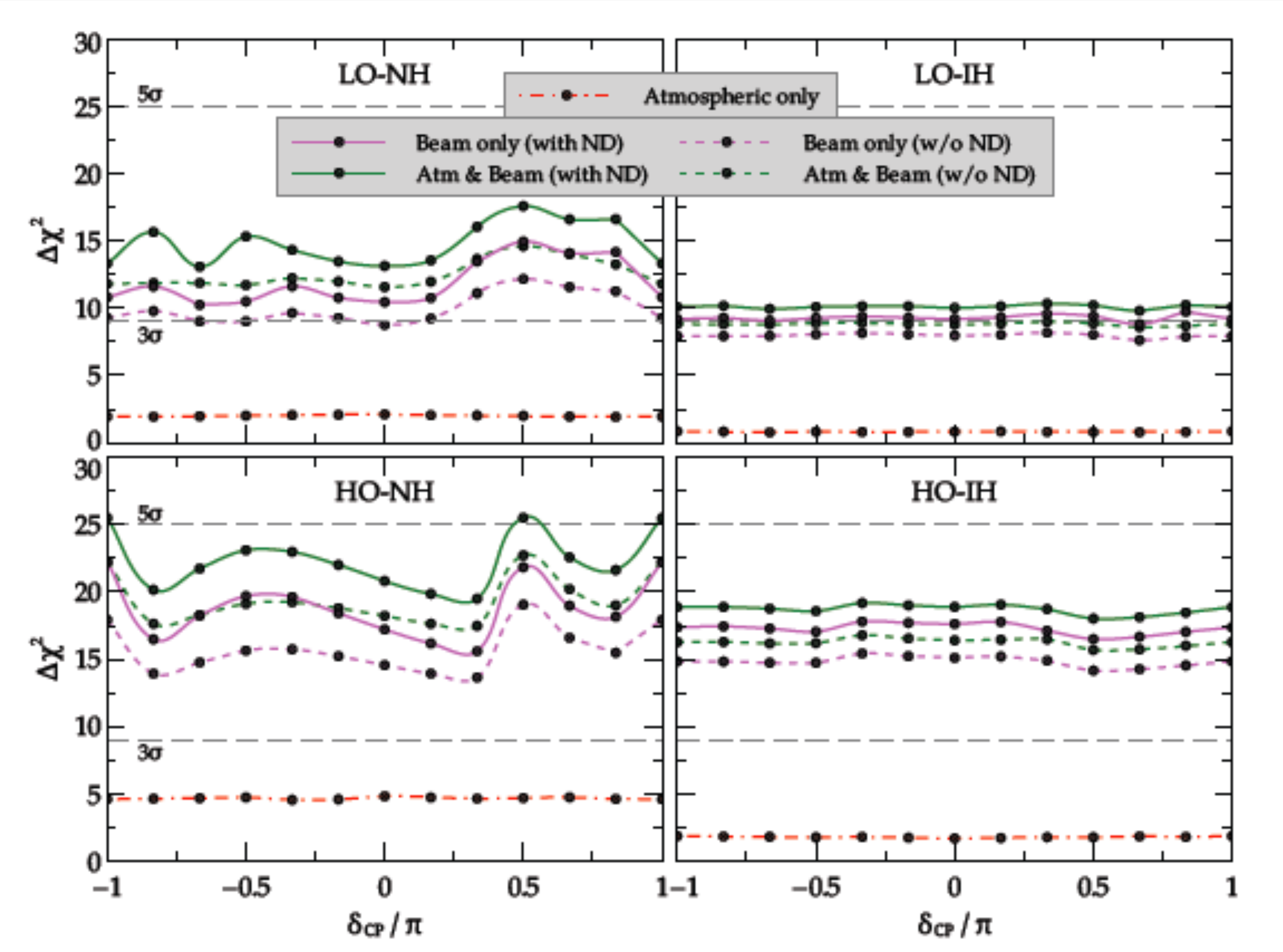
- ◆ *Assumption: FD to be always underground for Atmospheric neutrinos*
- ✓ *FD w/Beam only even w/o ND (------) can measure MH – better than 3σ for full CP*
- ✓ *FD w/Beam + Atmospheric w/o ND (-------) better than FD+ND w/Beam*

Barger, Bhattacharya, Chatterjee, Gandhi, Marfatia, Masud

LBNE w & w/o ND – Octant Degeneracy – 100 kT-yr – 10kT FD – 5 yrs ν & νbar

Barger, Bhattacharya, Chatterjee, Gandhi, Marfatia, Masud

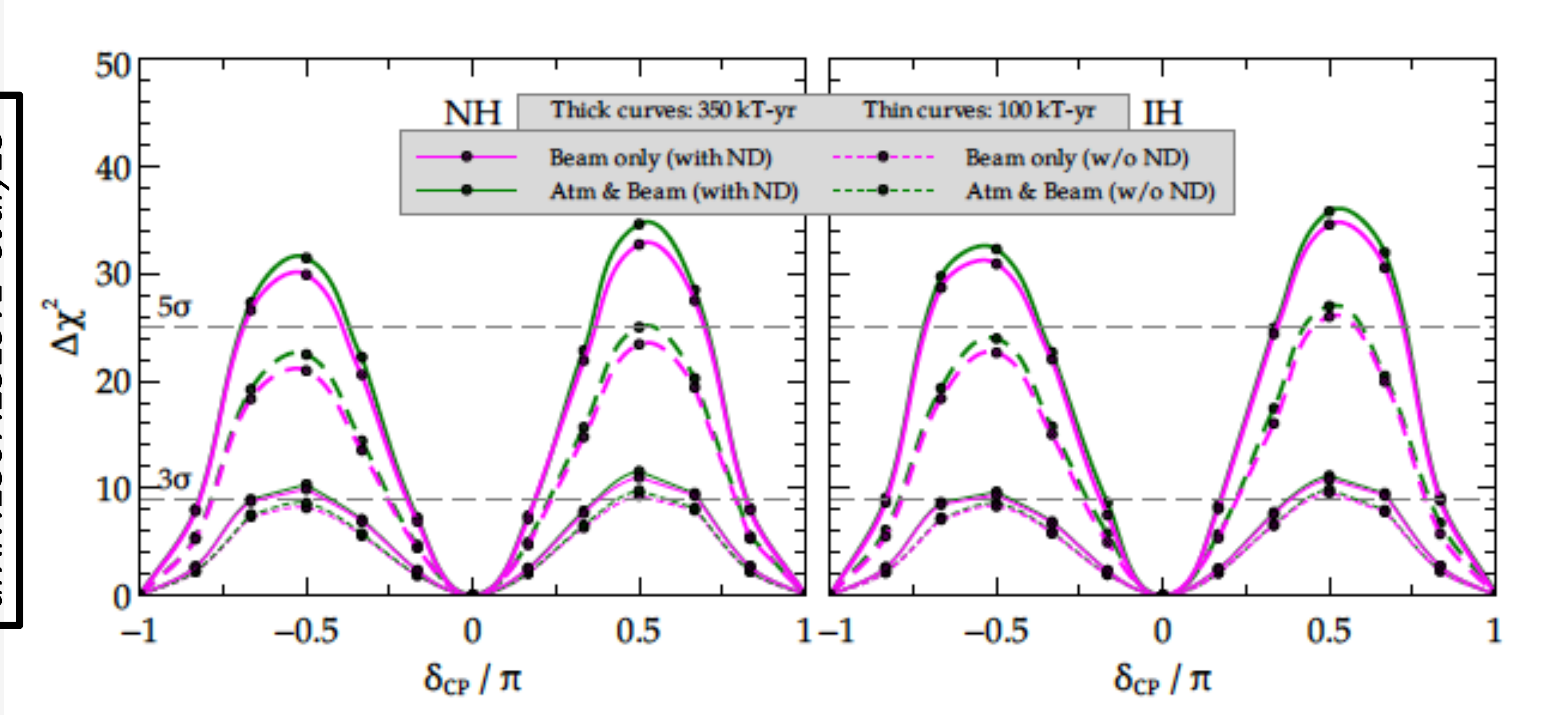
arXiv:1307.2519v1 -9July13



✓ *FD w/Beam + Atmospheric w/o ND (-------) better than FD+ND w/Beam (———)*

LBNE w & w/o ND – CPV – 350 kT-yr & 100 kT-yr – in 10 yrs – 5 yrs ν & νbar

arXiv:1307.2519v1 -9July13



With 100kT-yr w/ or w/o ND – one hardly gets 3σ sensitivity in CPV
With 350kT-yr - FD+ND with Beam (———) only much better than only FD w/ Beam+ Atmospheric w/o ND (-------). Beam only with FD+ND can do CPV to 5σ. At 350kT-yr – it's the systematics that matters.

Barger, Bhattacharya, Chatterjee, Gandhi, Marfatia, Masud

LAGUNA

LBNO

From the Newsroom of Maury Goodman

June 2013 Long-Baseline Neutrino Experiment

**** LBNE + LBNO*

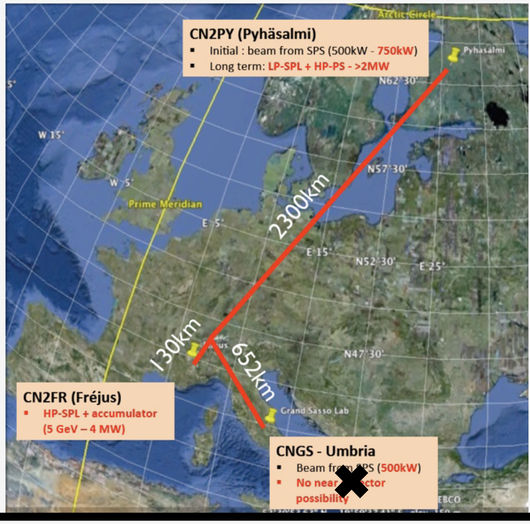
Discussions about joining forces are taking place between the mostly U.S. LBNE collaboration (Long-Baseline Neutrino Experiment) and the mostly European LBNO collaboration (Long-Baseline Neutrino Oscillation). Nobody has proposed calling it LBNI.

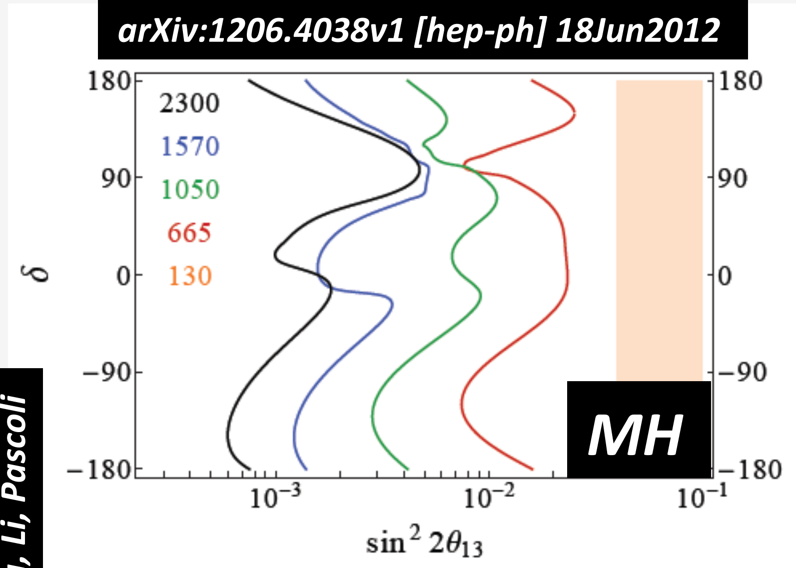
Preparation for Snowmass

FROM YKK Talk

- LBNE
  - Collaboration is preparing the LBNE Book.
  - International contributions are absolutely critical for the success of LBNE starting with Phase 1
    - India
    - Italy
    - U.K.
    - Brazil
    - Japan-US neutrino task force
    - Hot news – this week: working toward LBNE-LBNO combination!! This opens the door for CERN and European institutions to partner with U.S. on this project
    - ….

LAGUNA – LBNO – Choice of Baselines

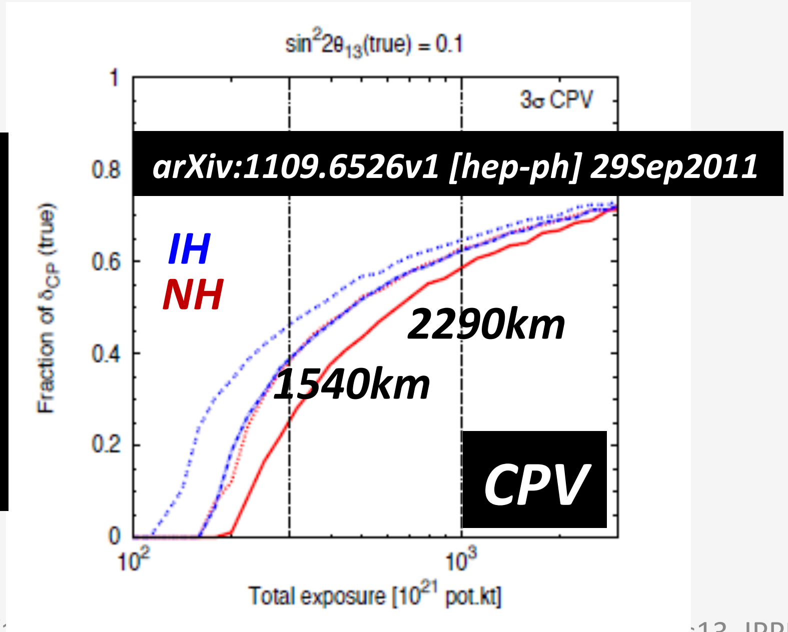


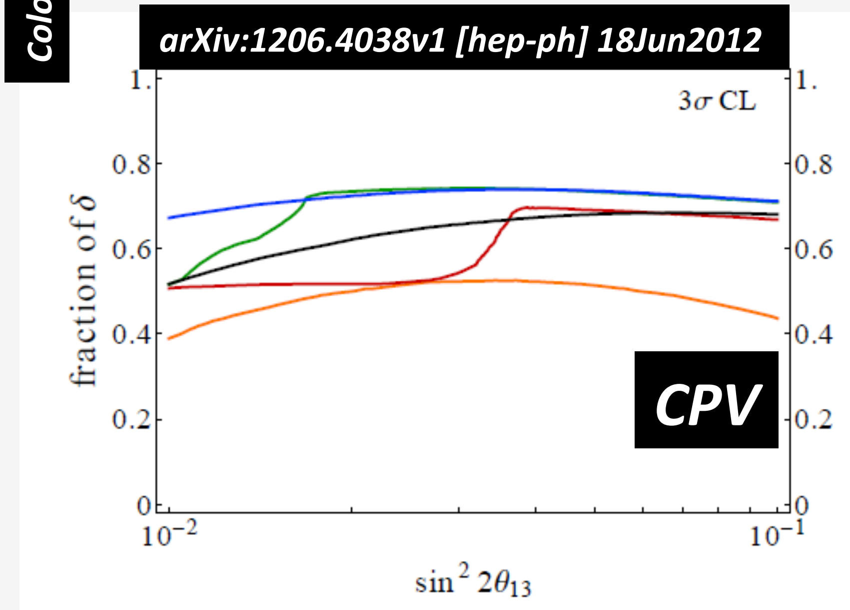


100 Kton LAr + 10 yr operation + 1.66 MW

Coloma, Li, Pascoli

Agarwalla, Li, Rubbia

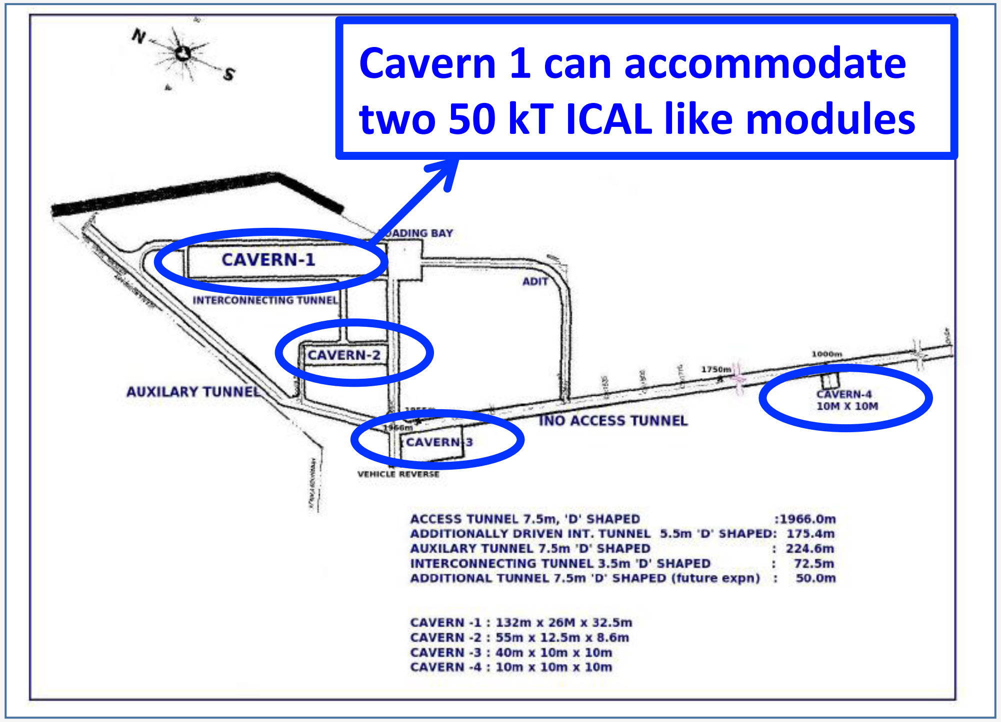


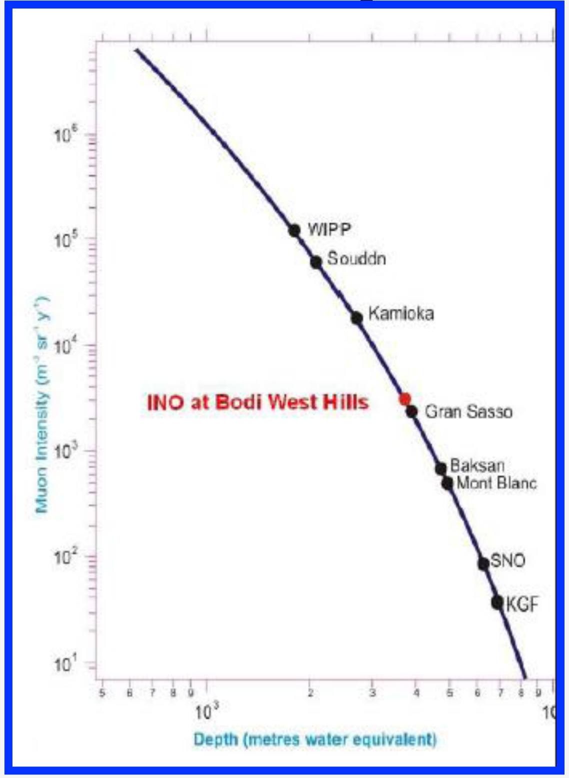


INDIA-BASED NEUTRINO OBSERVATORY

- Mass Hierarchy with Atmospheric ν's

INDIA-Based Neutrino Observatory





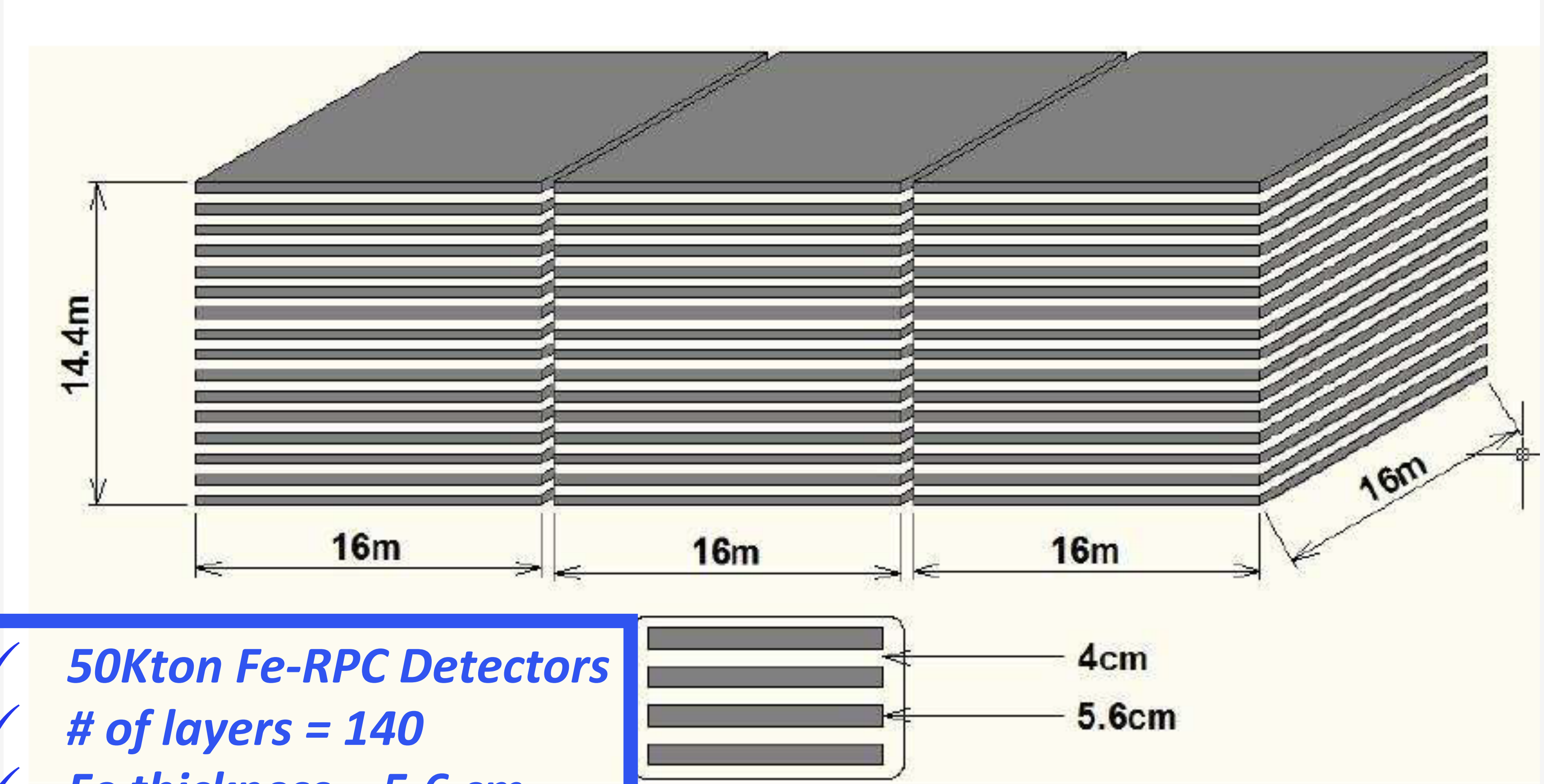
- ✓ ***Underground laboratory in South India (9^0 58' N, 77^0 16'E)***
- ✓ ***With ~1 km - rock cover - through a 2 km long tunnel.***

Status of the Project

- ***Project approved by the Indian funding agencies. Environment & forest clearance obtained. 26 hectares of land acquired at the detector site. Construction of lab & surface facility to begin.***
- ***Construction of a 50kT magnetized Iron Calorimeter (ICAL) detector to study properties of neutrinos.***
- ***Development of INO center (a Detector R&D center) at Madurai (~100Km from INO).***
- ***Human resource development (INO graduate training program going on for last several years).***
- ***Detector R & D almost complete.***

INO-ICAL Detector

Number of Institutions ~ 25+

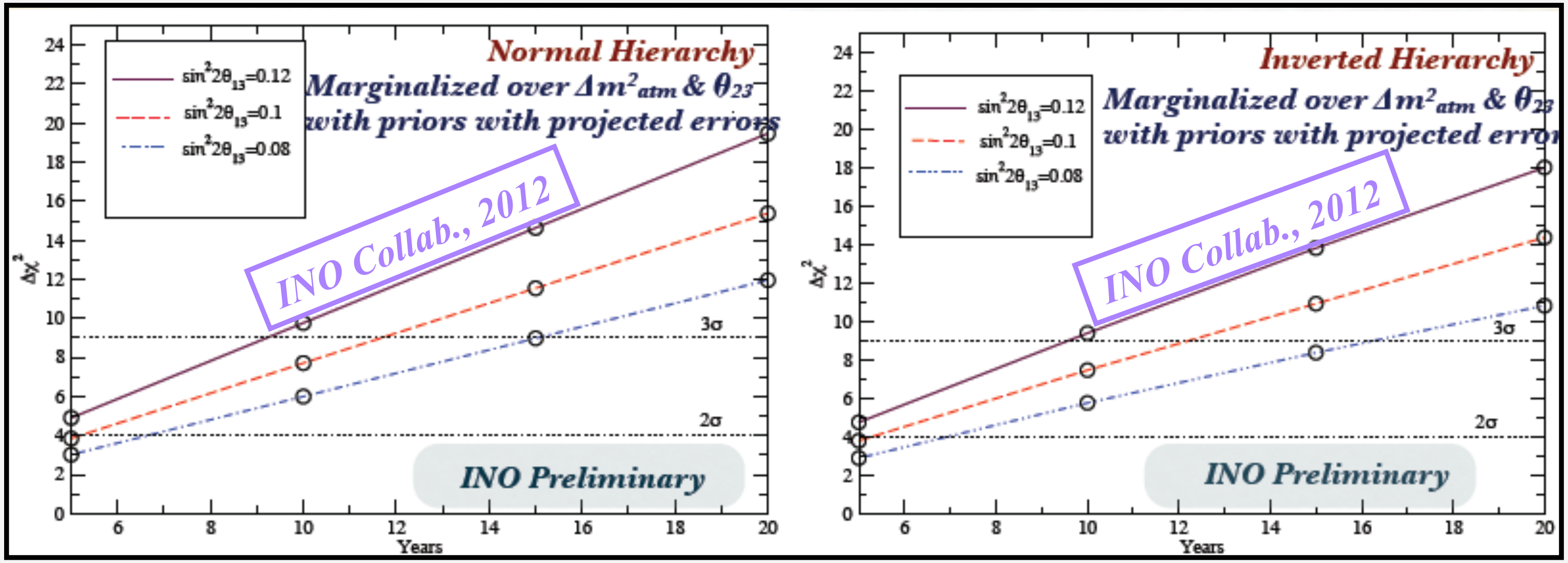


- ✓ *50Kton Fe-RPC Detectors*
- ✓ *# of layers = 140*
- ✓ *Fe thickness = 5.6 cm*
- ✓ *Magnetic Field ~ 1.3T*
- ✓ *# of RPCs ~ 27K*
- ✓ *# of channels ~ 3.6M*

- ✓ *Mass Hierarchy*
- ✓ *Octant Degeneracy*

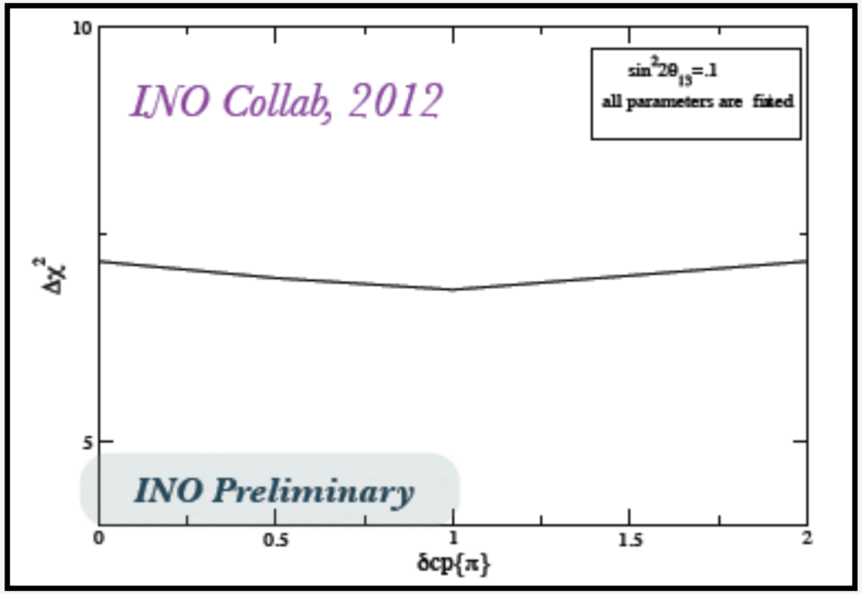
Mass Hierarchy with ICAL@INO

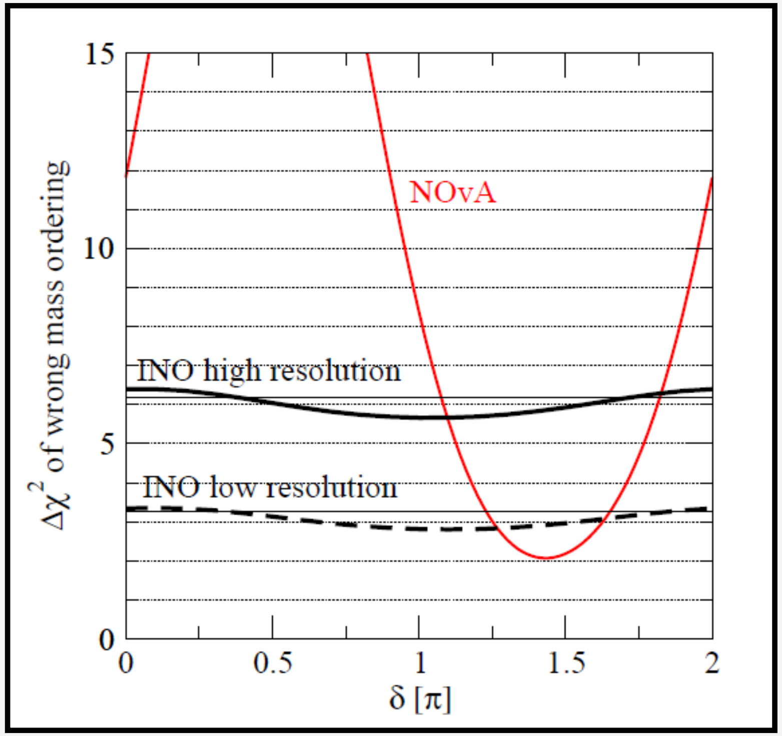
Events generated using Nuance & ICAL resolution in E and cosθ_{zenith}



~2.0σ sensitivity for sin$^2\theta_{23}$ = 0.5, Sin$^2 2\theta_{13}$ = 0.1 in 5 yrs.
~2.7σ sensitivity for sin$^2\theta_{23}$ = 0.5, sin$^2 2\theta_{13}$ = 0.1 in 10 yrs.

Impact of δ_{CP} on MH at ICAL@INO





arXiv:1203.3388v1-Blennow, Schwetz

Data generated at δ_{CP} = 0 and fitted at non-zero δ_{CP}
INO will give MH sensitivity almost independent of δ_{CP}

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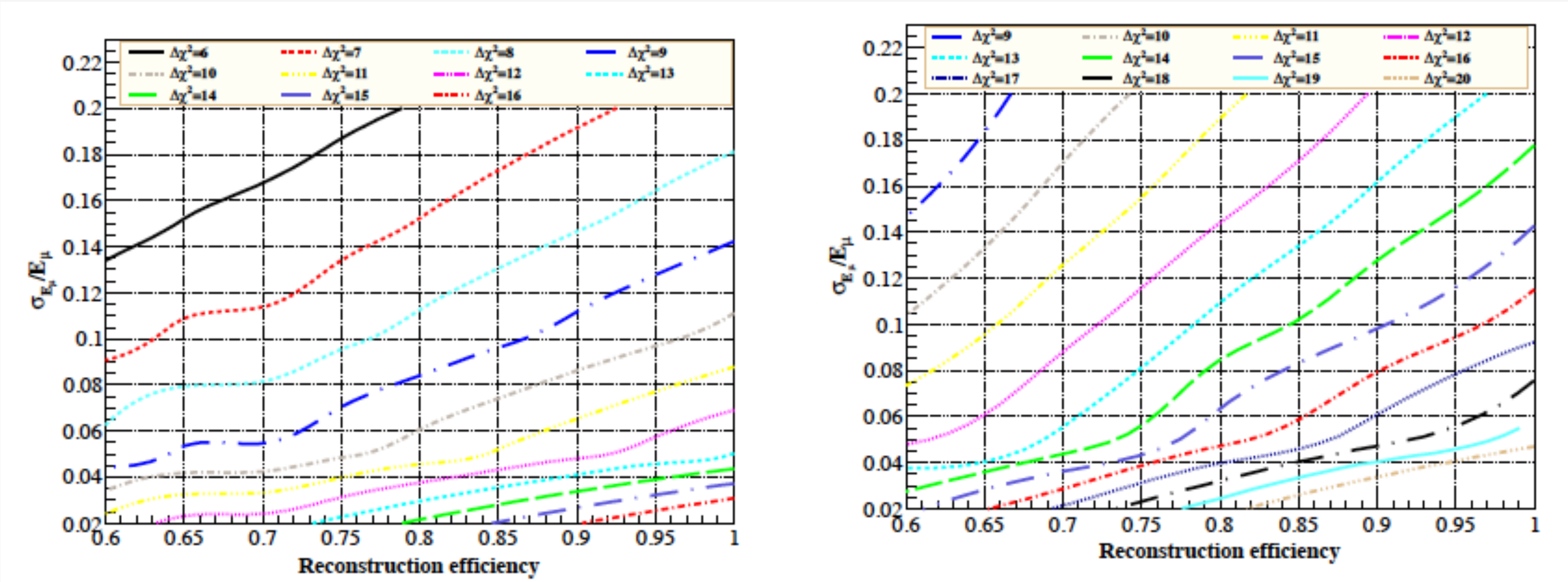
Mass Hierarchy with ICAL@INO



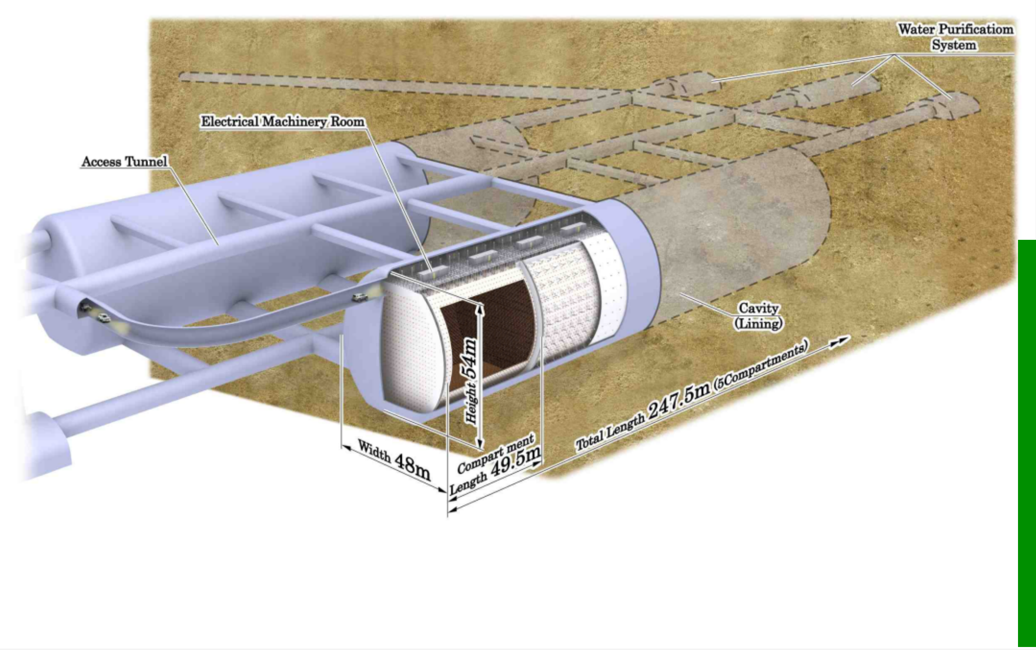
arXiv:1306.1423v1 [hep-ph] 6Jun2013 - Ghosh, Choubey

- ✓ ***$Sin^2 2\vartheta_{13}$ = 0.1, $Sin^2\vartheta_{23}$ = 0.5, 500kTon Exposure***
- ✓ ***Muon Energy Resolution = 2(5)%, Reconstruction Eff. = 80%***
- ✓ ***MH sensitivity - 4.5 (4.0)σ***

Hyper-Kamiokande CPV (LBL) & MH (Atmospheric)

HYPER-KAMIOKANDE in JAPAN

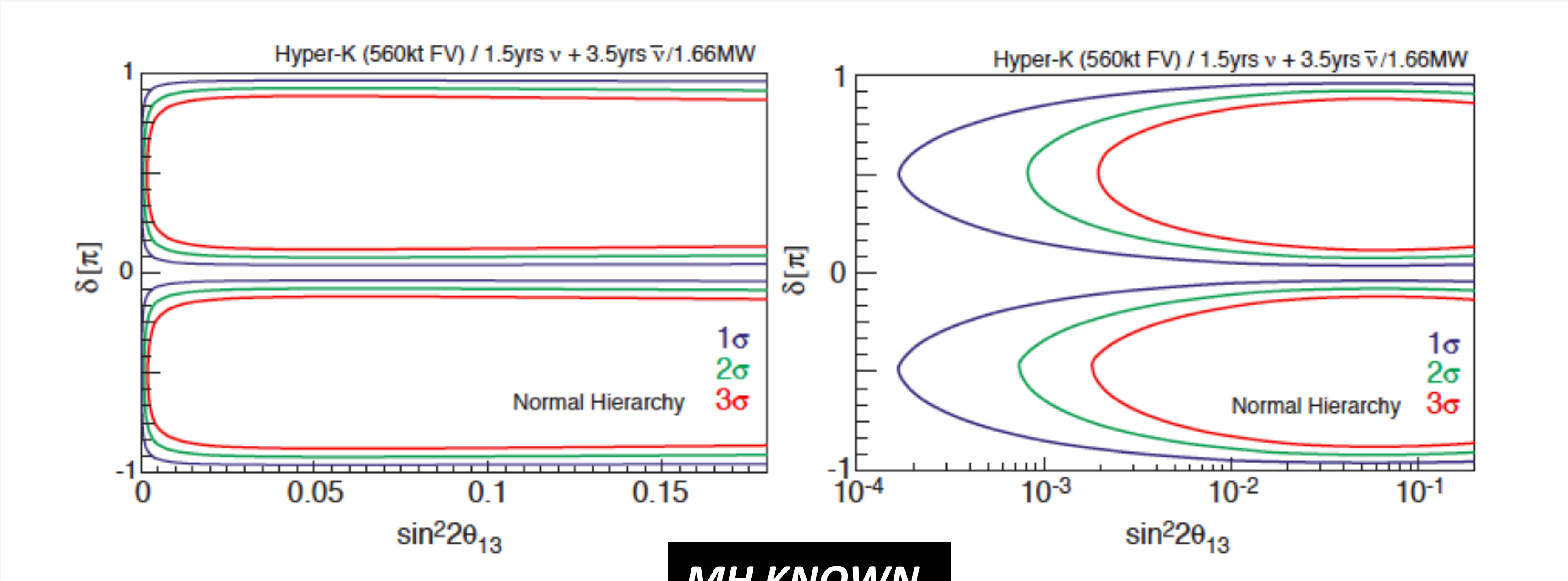
HK-LOI - arXiv:1109.3263v1 [hep-ex] 15 Sep 2011



- *2.5 degree off-axis*
- *1.66 MB Beam power (10⁷ seconds/year)*
- *DATA for 5 yrs*
  ν (1.5 yr) + νbar (3.5 yr)

- ✓ *295 Km from J-PARC, 8 Km from Super-K*
- ✓ *Two Cylindrical Tanks - 48m (W) X 54m (H) X 250m (L)*
- ✓ *Total/Fiducial Mass = 0.99 (0.56) Mega Ton*
- ✓ *90,000 20-inch PMT's, 20% photocathode coverage*

CPV with HYPER-KAMIOKANDE



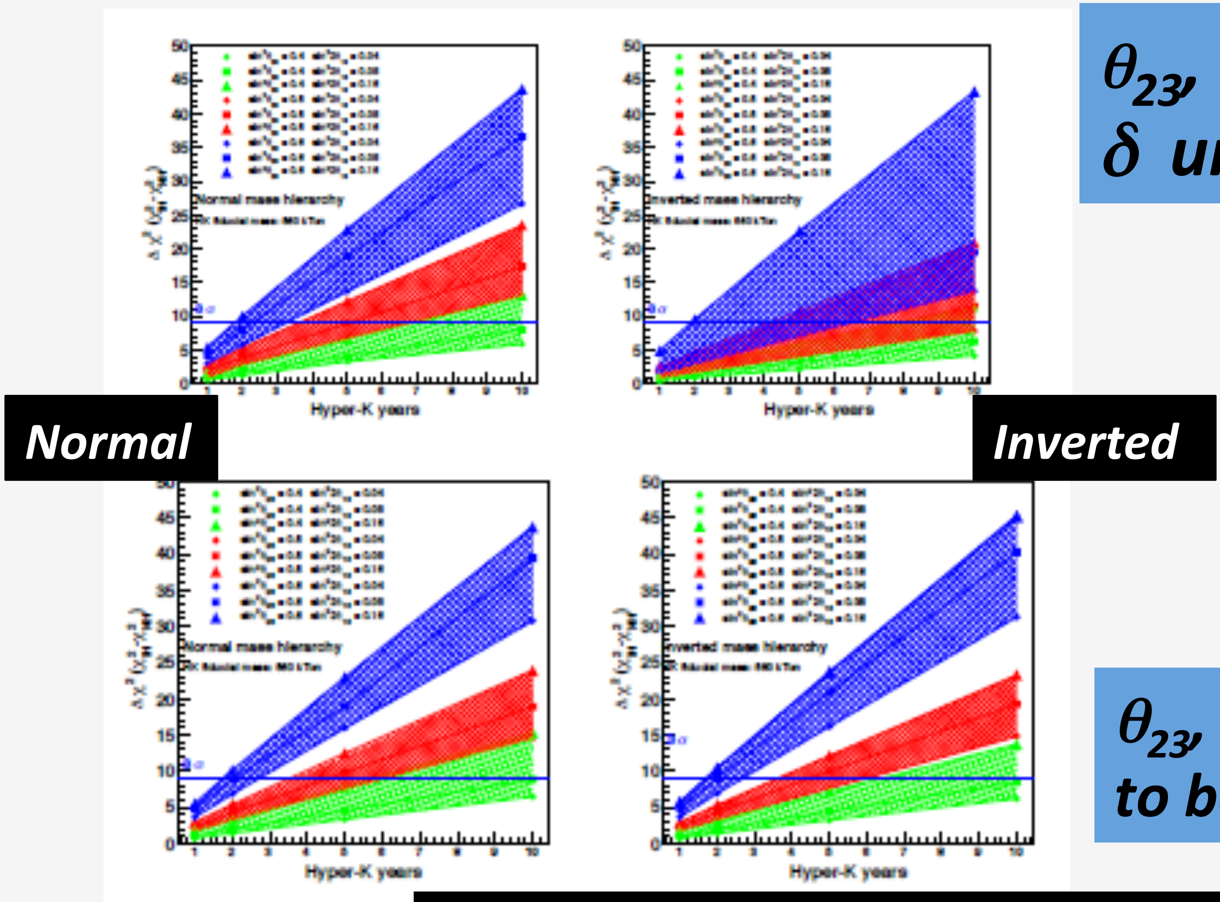
MH KNOWN

If MH in known, 3σ CPV for 74% of the δ parameter space.
CP Phase δ can be determined ~ 18 degrees for all δ.
If MH not known, sensitivity decreases slightly due to degeneracy

HK-LOI - arXiv:1109.3263v1 [hep-ex] 15 Sep 2011

MH w/HYPER-KAMIOKANDE – 10 yrs Atmospheric Data

- ❖ *HK can determine MH at more than 3σ for $Sin^2\theta_{23} > 0.4$*
- ❖ *Can solve octant degeneracy – i.e, $sin^2\theta_{23} > 0.5$ or < 0.5 for $sin^2 2\theta_{23} < 0.99$*



θ_{23}, θ_{13} and δ unknown

$Sin^2\theta_{23} = 0.4$

$Sin^2\theta_{23} = 0.5$

$Sin^2\theta_{23} = 0.6$

θ_{23}, θ_{13} assumed to be known

HK-LOI - arXiv:1109.3263v1 [hep-ex] 15 Sep 2011 inνisibles13

Summary and Conclusions

- ✓ ***Neutrino physics has moved in last 15 years from discovery to precise measurements.***
- ✓ ***Discovery of large ϑ_{13} by reactors has opened the possibility of determining MH and measuring CPV in neutrinos.***
- ✓ ***If nature is kind – current LBL experiments NOνA and T2K to make statement on MH by 2020-22. Atmospheric and future LBL will determine MH at high confidence level.***
- ✓ ***To measure CPV – one needs large detectors, high beam power and extended exposure. Future LBL experiments - LBNE, LAGUNA-LBNO and T2-HK are the possible experiments which can measure δ_{CP}.***

Thank You