Overview of Upcoming Neutrino Experiments

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Interface of Numerical Relativity with Gravitational-Wave Astronomy, Neutrino Physics & High-Energy Astrophysics
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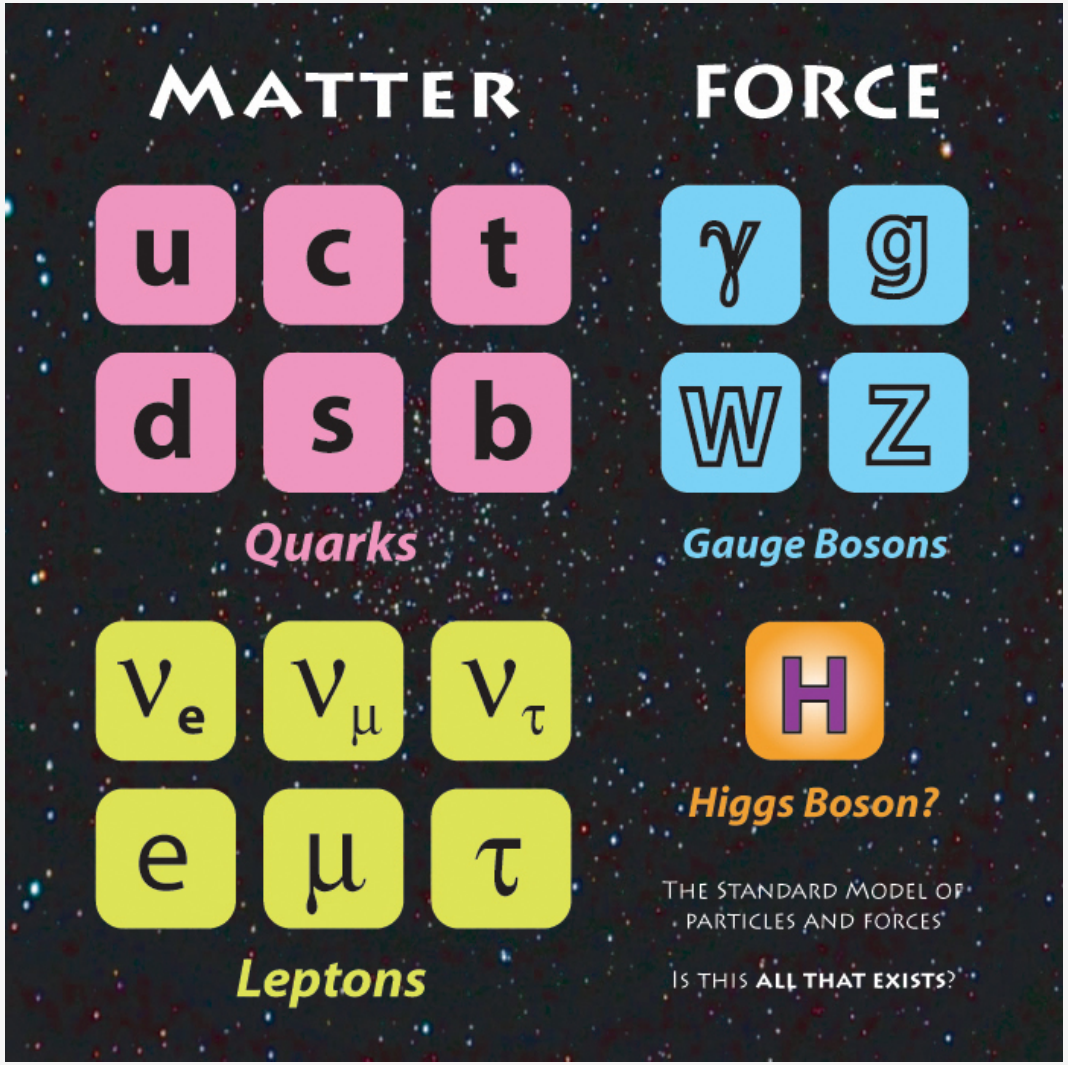
Status of Particle Physics Today



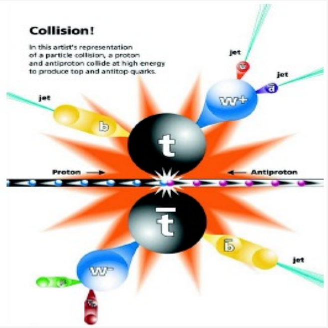
*The **Standard Model (SM)** of particle physics has been very successful in explaining most of the experimental observations so far including the observation of a Higgs like Boson at M_H ~ 126 GeV*

But there is evidence of new physics beyond the SM:

1. ***Accelerating Universe – Dark Energy***
2. ***Missing Mass – Dark Matter***
3. ***Is there Physics beyond the SM at the TeV scale?***
   Answer yet to come from LHC
4. ***Neutrino Masses & Mixing – Physics beyond the SM***

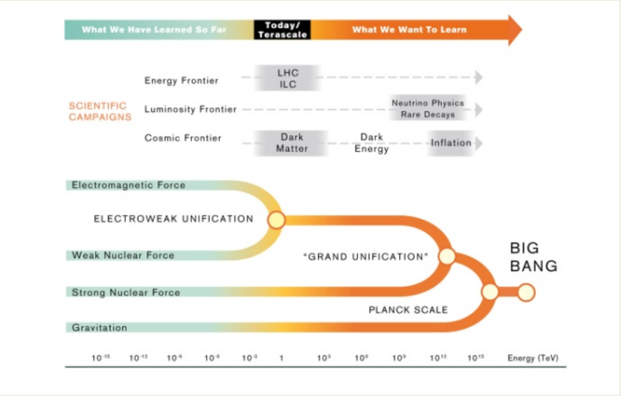
Particle Physics Today – Three Frontiers

- ***The Energy Frontier,*** *powerful accelerators create new particles, reveal their interactions, and investigate fundamental forces*
  - *New Particles (Higgs, SUSY)*
  - *Extra Dimensions, Black Holes*

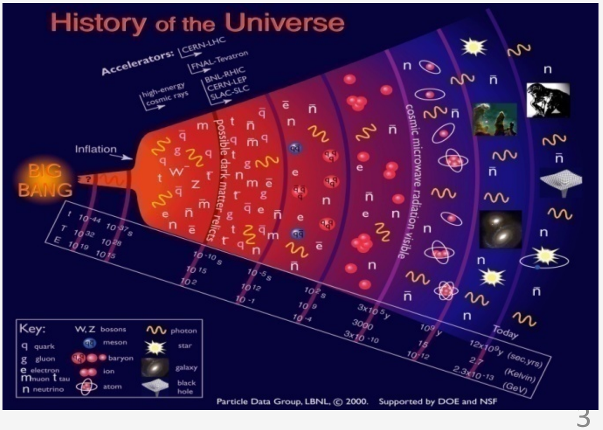


$E = mc^2$

- ***The Intensity Frontier,*** *intense particle beams and highly sensitive detectors pursue alternate pathways to investigate fundamental forces and particle interactions by studying events that occur rarely in nature*
  - *Neutrino Properties*
  - *Matter-Antimatter Asymmetry*
  - *Rare Decays, EDMs*
  - *Unification of Forces*



- ***The Cosmic Frontier,*** *ground and space-based experiments and telescopes make measurements that will offer new insight and information about the nature of dark matter and dark energy, to understand fundamental particle properties and discover new phenomena*
  - *Dark Energy →New Forces ?*
  - *Dark Matter →New Particles ?*

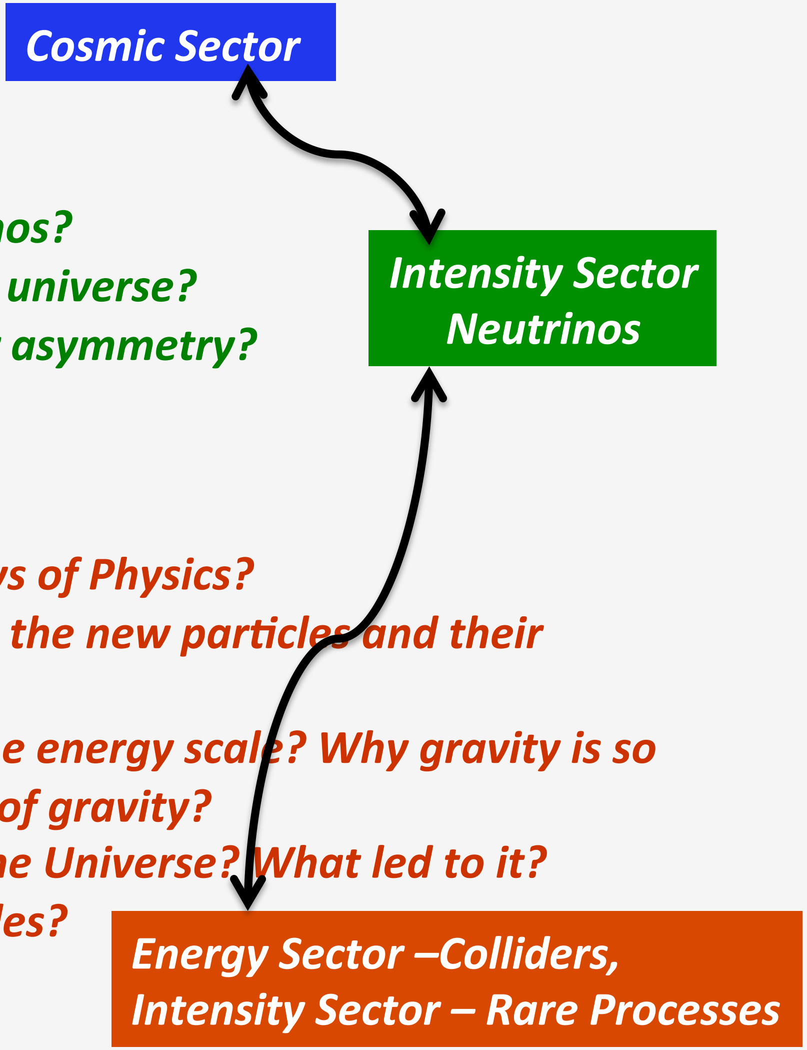


Some Open Questions in Particle Physics

1. What is the nature of dark energy which constitutes nearly 3/4th of the universe?
2. What is dark matter and how can one find it?
3. How did the Universe form?

4. What are the masses and properties of neutrinos?
5. What role did they play in the evolution of the universe?
6. How are they connected to matter anti-matter asymmetry?

7. Are elementary particles fundamental?
8. How do these particles acquire mass?
9. Does Higgs Boson exist or do we need new laws of Physics?
10. What is the physics beyond the SM? What are the new particles and their interactions?
11. Do all the forces of nature become one at some energy scale? Why gravity is so weak and does there exist a quantum theory of gravity?
12. Why there is matter anti-matter anomaly in the Universe? What led to it?
13. Why there are only three generation of particles?



Cosmic Sector

Intensity Sector
Neutrinos

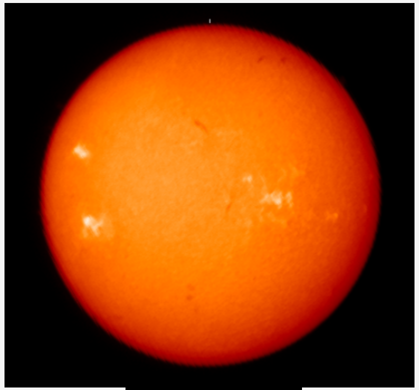
Energy Sector –Colliders,
Intensity Sector – Rare Processes

NEUTRINOS

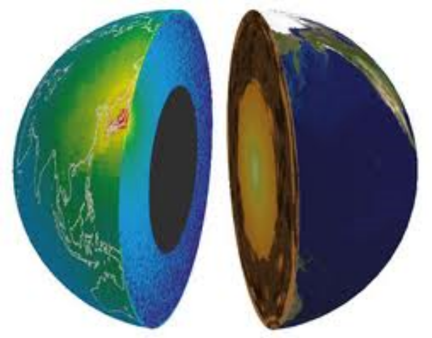
What do We Know About the Neutrinos?

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

Sources of Neutrinos



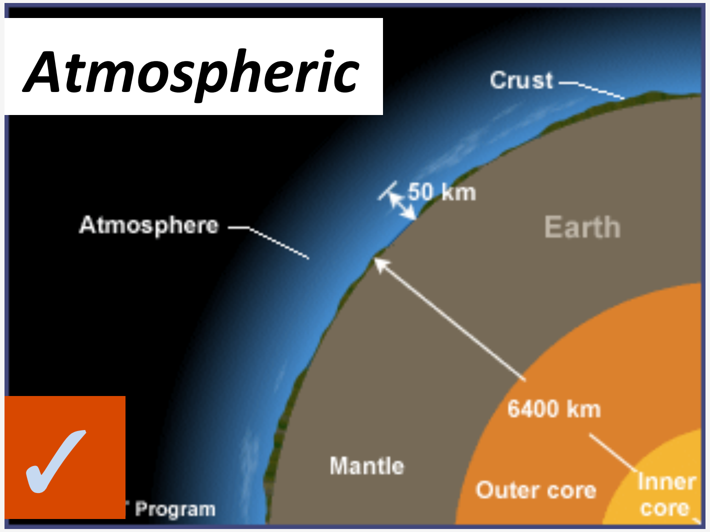
Solar



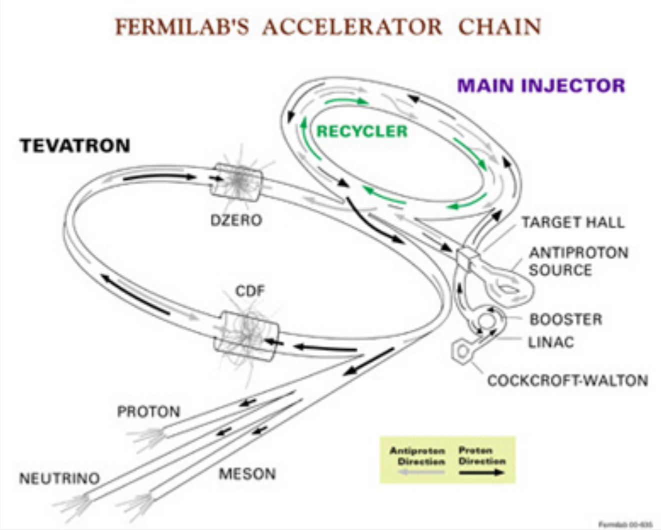
GEO

Supernova

Reactor ✓



Atmospheric ✓



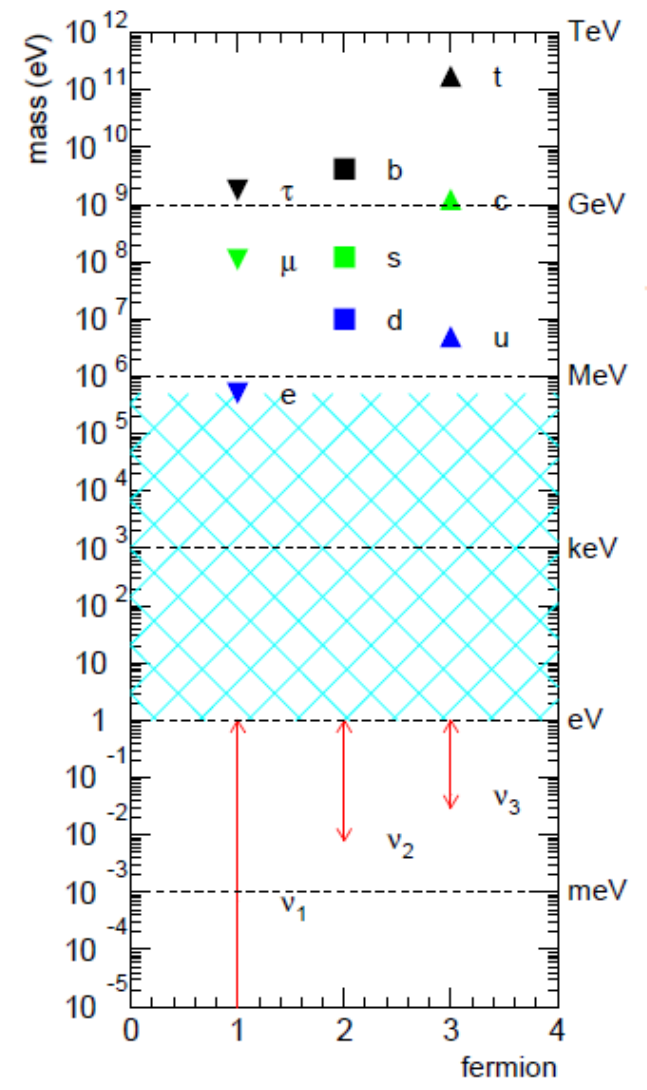
Accelerator ✓

Big-Bang ν

Why Interest in Neutrinos?

- ***Neutrinos: Of all the known massive particles, neutrinos are the most mysterious and abundant. We need to know their properties to fully understand the evolution of the Universe.***
- ***Neutrino Masses and Mixing (The most important discovery of Particle Physics in last twenty years prior to a Higgs like particle):***
  - ***Evidence of Physics Beyond the Standard Model***
  - *May signal new physics at very high energies*
  - *A new, different and complementary window on the origin of mass*
  - *Provides a different window on the problem of flavor (why three (3) generations?, why mixing?, why CP violation?)*
  - *Neutrinos are an important component of the dark matter.*
- *Lepton number and CP-violation could be at the origin of the baryon asymmetry of the Universe.*
- *The discovery of small effects in neutrino physics (violation of unitarity, sterile neutrinos, non-standard interactions, CP and CPT violations) could unveil new particles and interactions.*

What are Neutrinos Telling us?



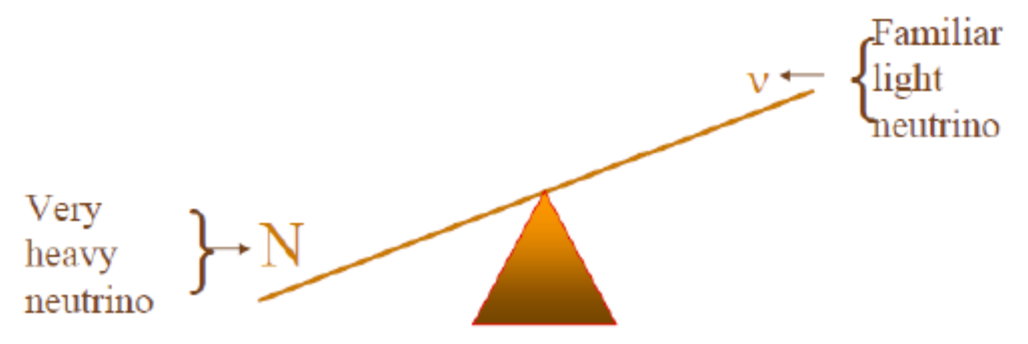
Neutrinos have tiny masses.
Not expected in the SM.

Lepton Mixing is different

A complementary window on the problem of flavor.

Something About Unification

See-Saw Mechanism



Mass (N) ~ 10^{15} GeV

The Strong, EM and Weak forces unify at ~ 10^{16} GeV

This might shed light on the physics at energy scales (unification scale?) which cannot be tested directly.

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**

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

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

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

Atmospheric ν_μ Long Baseline

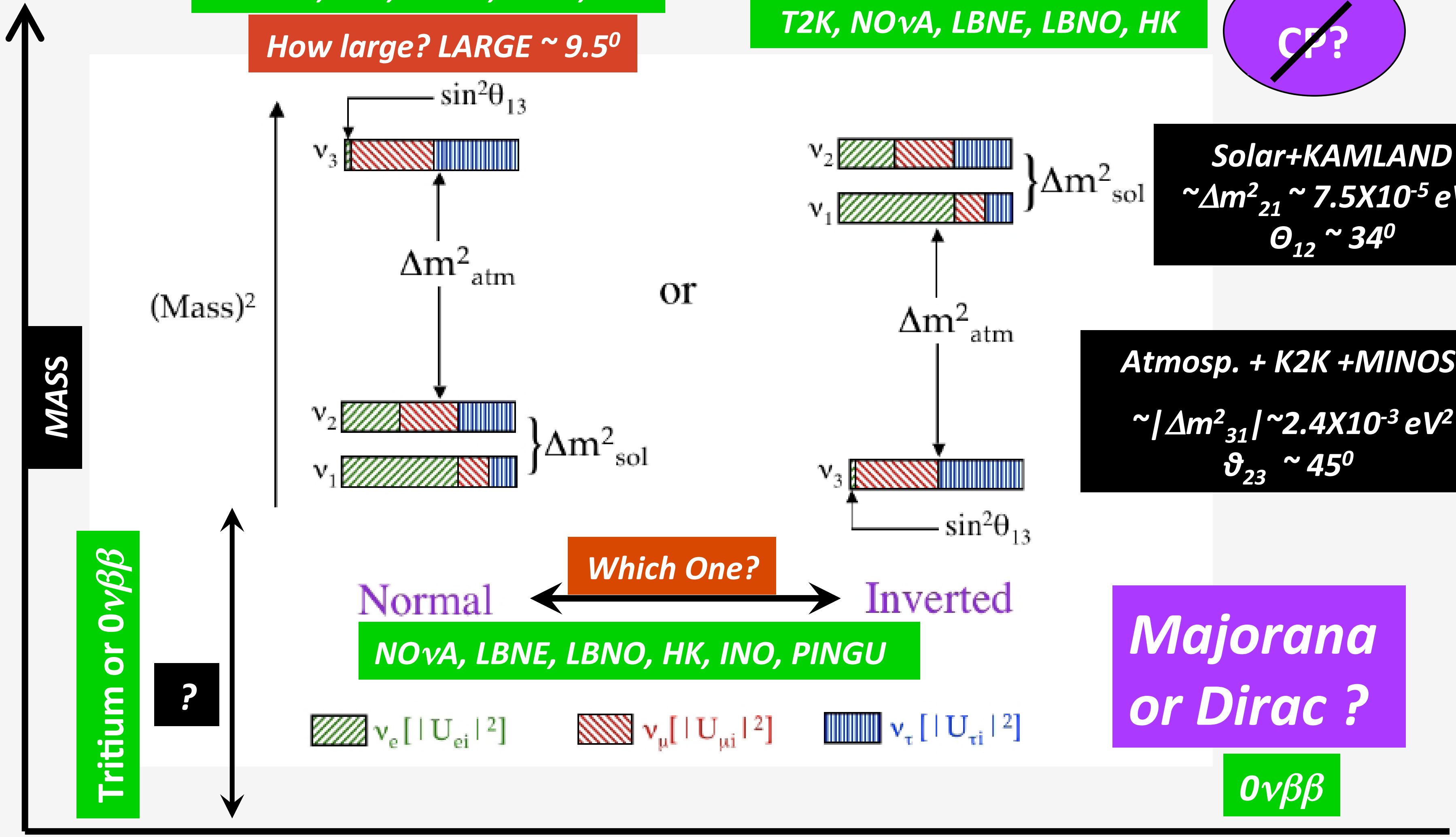
Reactor Short Baseline ν_μ Long Baseline

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



Reactor, T2K, NOνA, LBNE, HK

How large? LARGE ~ 9.5^0

T2K, NOνA, LBNE, LBNO, HK

~~CP~~?

Solar+KAMLAND
~Δm^2_{21} ~ 7.5X10^{-5} eV^2
Θ_{12} ~ 34^0

Atmosp. + K2K +MINOS
~|Δm^2_{31}|~2.4X10^{-3} eV^2
ϑ_{23} ~ 45^0

MASS

Which One?

NOνA, LBNE, LBNO, HK, INO, PINGU

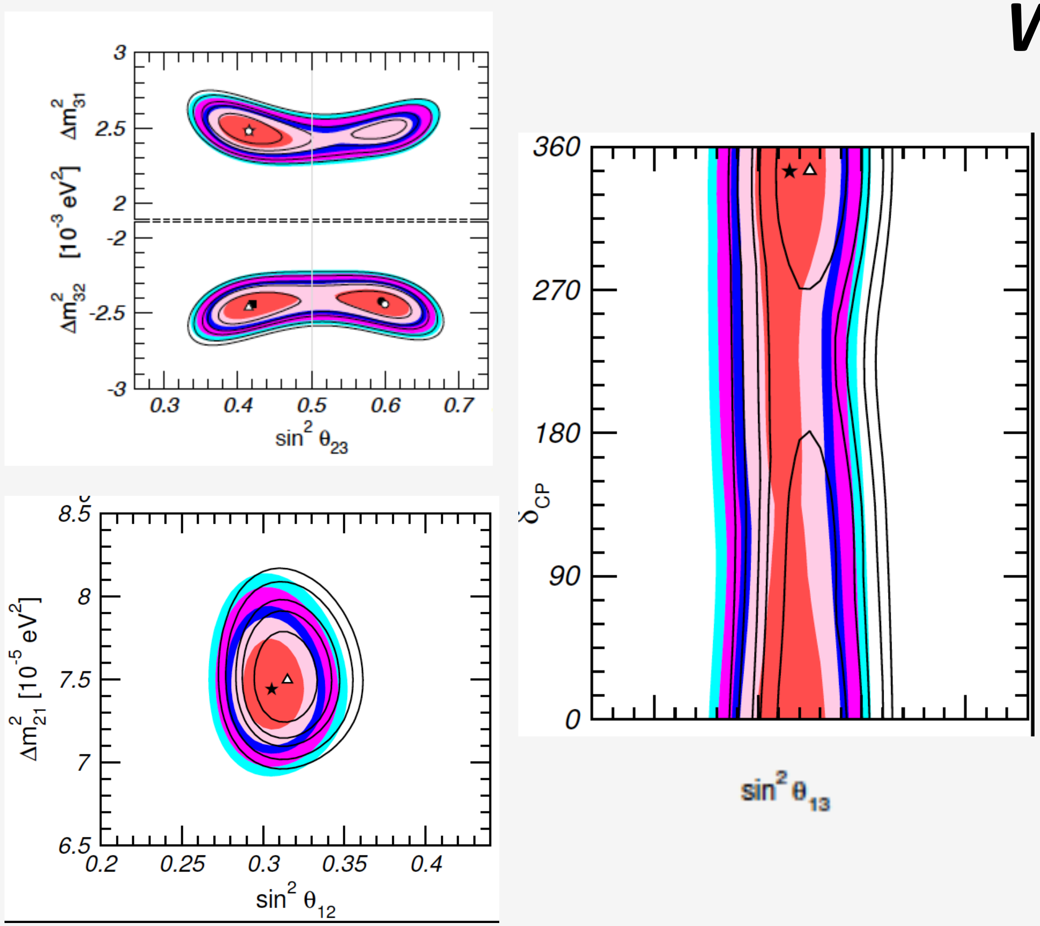
Tritium or 0*νββ*

?

Majorana or Dirac ?

0νββ

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:1209.3023v3-19Dec.12

European Strategy of Particle Physics – First Update


Accelerating science and innovation
Societal benefits of European research in particle physics

Page 22 of the Document

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

Precision value of θ_{13}

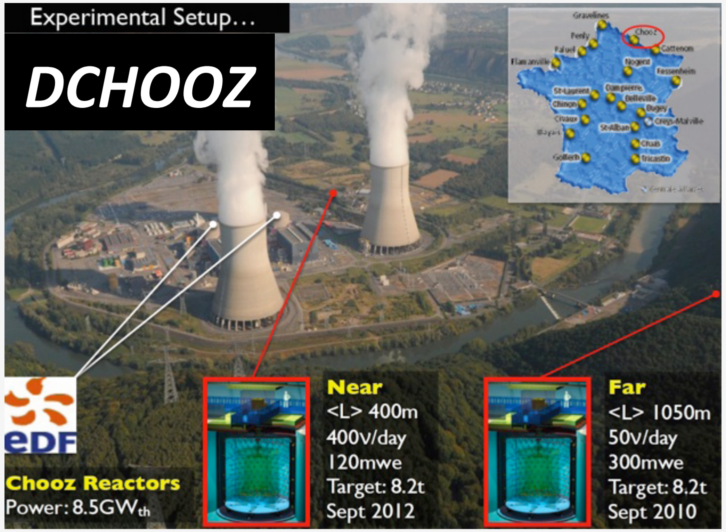
Reactors

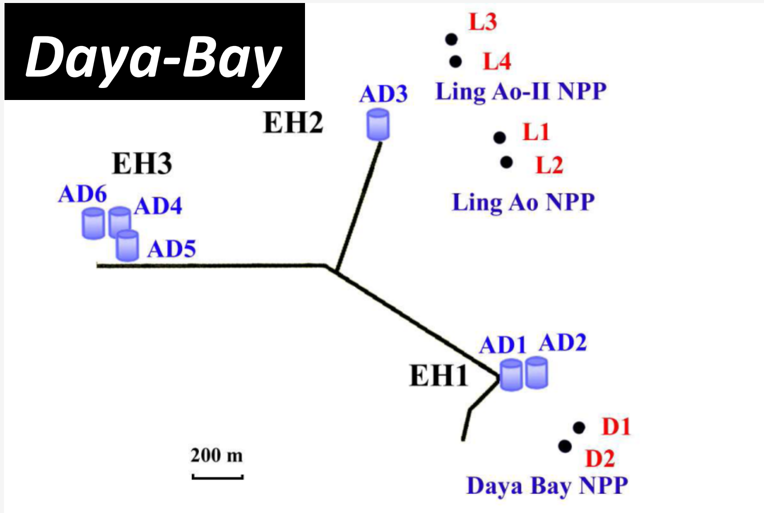
Double-Chooz, RENO, Daya-Bay

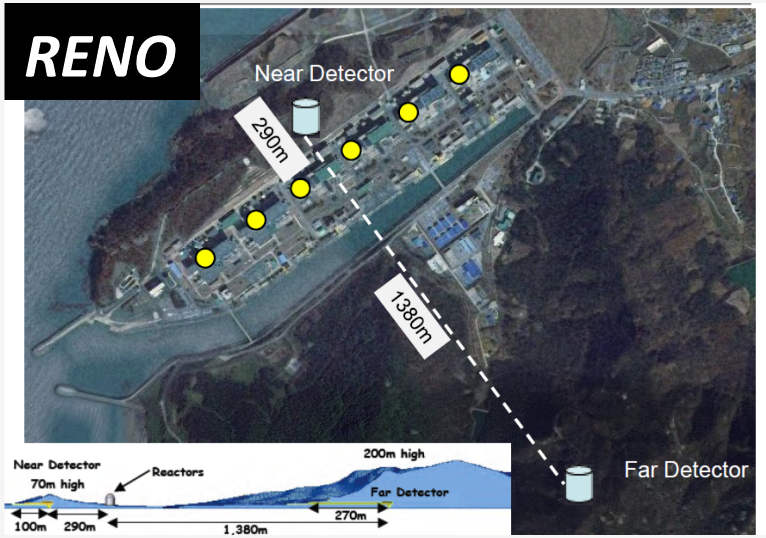
Accelerator LBL

T2K, NOνA, LBNE, HK

θ_{13} Sensitivity from Reactors







$$\bar{\nu}_e + p \rightarrow e^+ + n$$

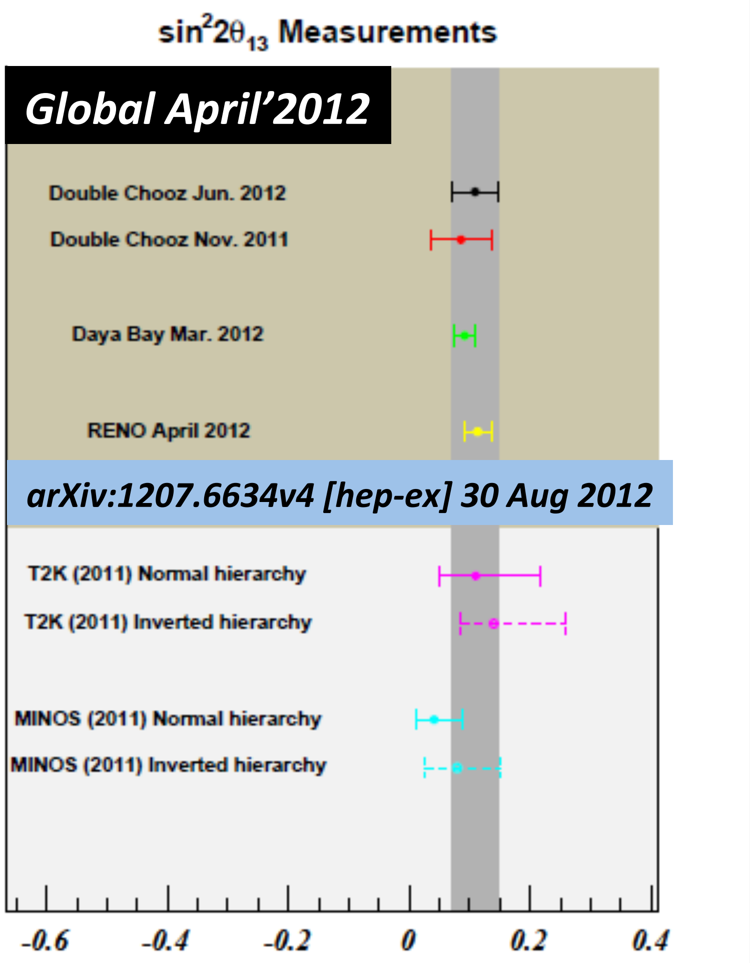
$$e^+ + e^- \rightarrow \gamma + \gamma$$

$$n + Gd \rightarrow n\gamma$$

θ_{13} Sensitivity from Reactors

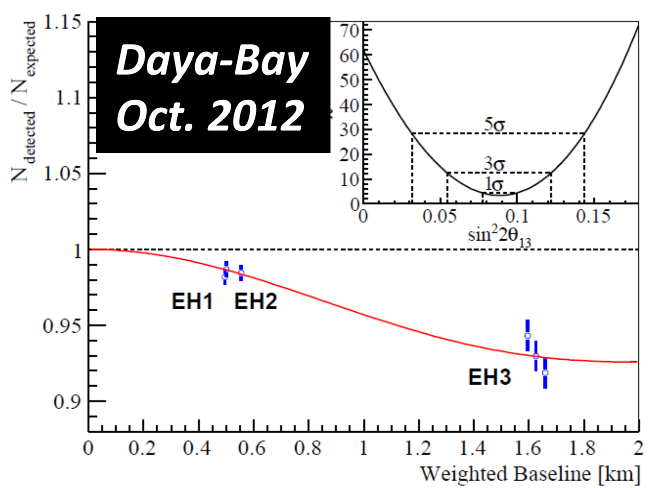
Recent results from T2K – 3.1σ – arXiv: 1304.0841v1 - 11 signal & 3.3 bkg events. Mean value same as DB

MINOS latest result PRL 110, 171801 (2013)



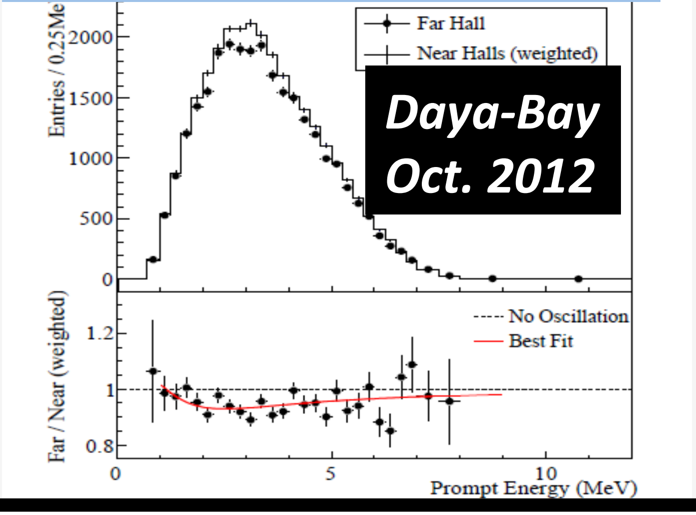
Global April'2012

arXiv:1207.6634v4 [hep-ex] 30 Aug 2012



Daya-Bay Oct. 2012

arXiv:1210.6327v1 [hep-ex] 23 Oct 2012



Daya-Bay Oct. 2012

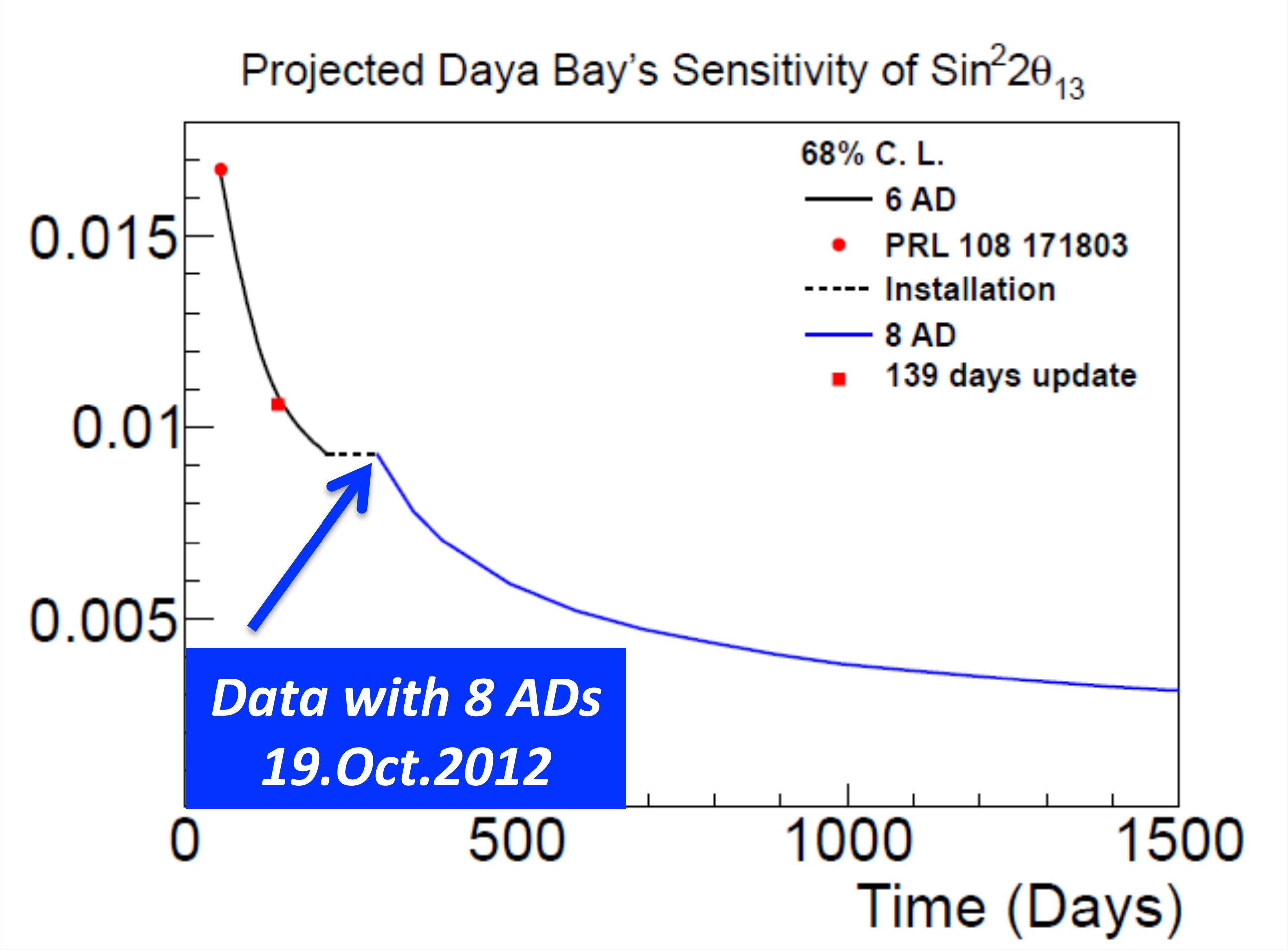
Precision limited by statistics

$$R = 0.944 \pm 0.007(\mathrm{stat.}) \pm 0.003(\mathrm{syst.})$$

7.7 σ

$$\sin^2 2\theta_{13} = 0.089 \pm 0.010(\mathrm{stat.}) \pm 0.005(\mathrm{syst.})$$

Projected Sensitivity $Sin^2(2\theta)_{13}$ – Daya Bay



Data with 8 ADs 19.Oct.2012

arXiv:1211.0570v1 [hep-ex] 2 Nov 2012

Expected precision ~5% in 3 years of running time with 8 ADs

Neutrinos from Accelerator

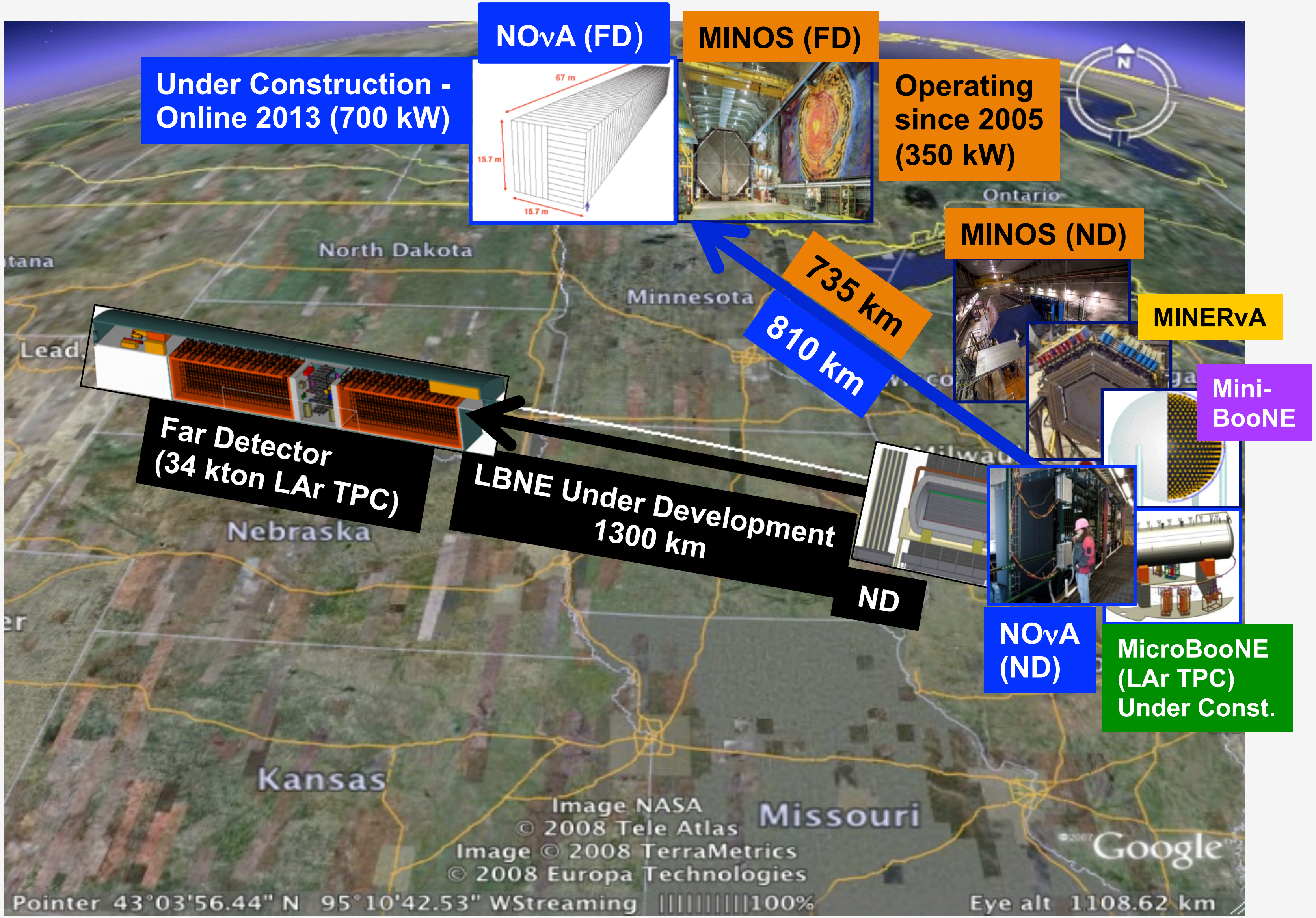
Long-Baseline Experiments

MINOS/MINOS+/NOνA/LBNE – USA-FNAL

LAGUNA-LBNO – Europe-CERN

T2K/HK – Japan–Tokai-Kamioka

Fermilab’s Neutrino Program



NOνA (FD)

Under Construction - Online 2013 (700 kW)

MINOS (FD)

Operating since 2005 (350 kW)

MINOS (ND)

MINERvA

Mini-BooNE

735 km

810 km

Far Detector (34 kton LAr TPC)

LBNE Under Development 1300 km

ND

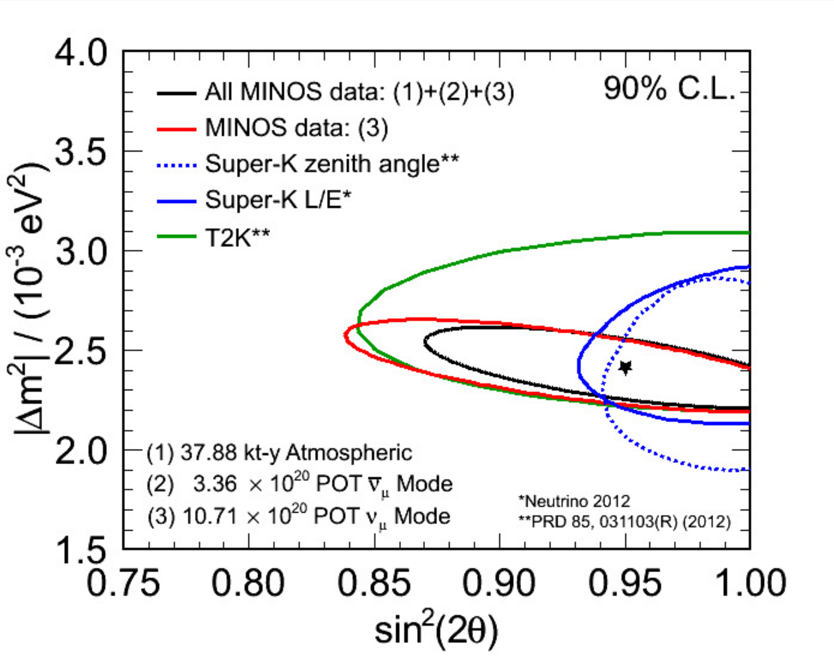
NOνA (ND)

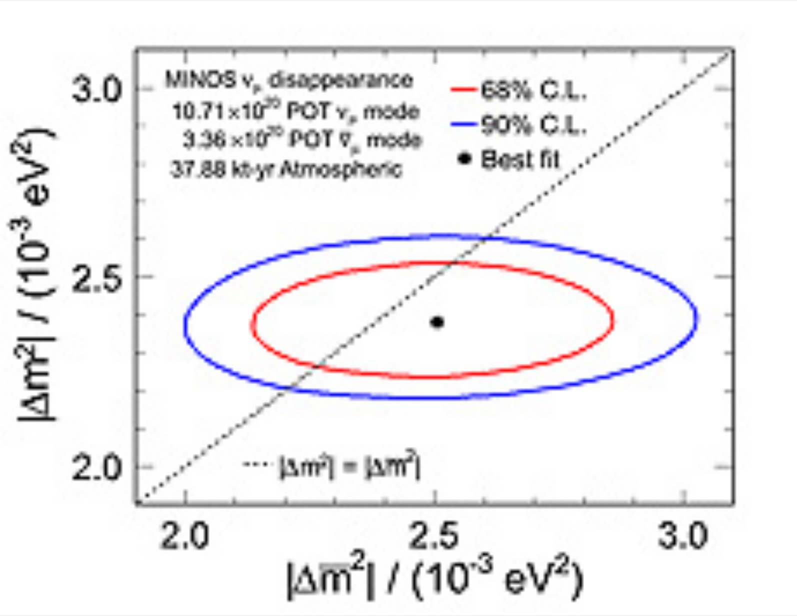
MicroBooNE (LAr TPC) Under Const.

MINOS - Disappearance

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2(1.27\, \Delta m^2_{31}\, L/E)$$

arXiv:1304.6335v2-11May13





$$\Delta m^2_{32} = (2.41^{+0.09}_{-0.10}) \text{ X } 10^{-3}\ \text{eV}^2$$

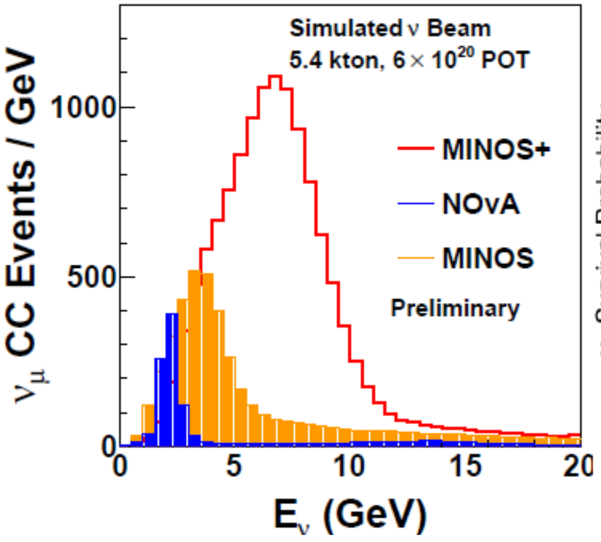
$$\sin^2(2\theta_{23}) = 0.950^{+0.035}_{-0.036}$$

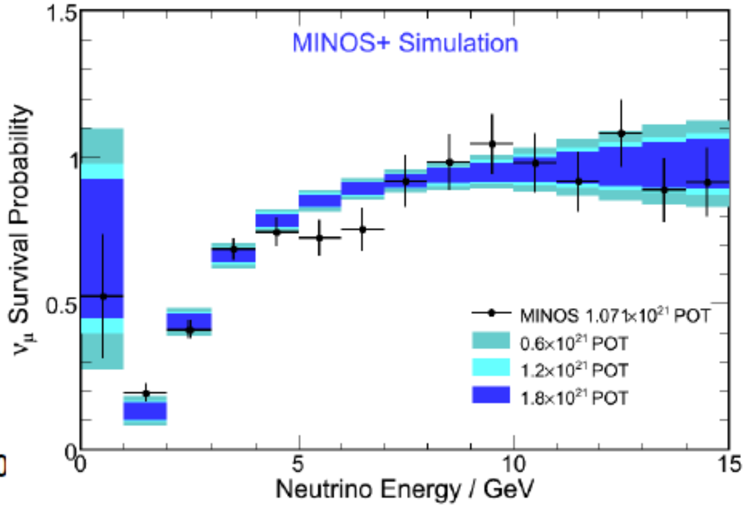
$$\overline{\Delta m}^2_{32} = (2.50^{+0.23}_{-0.25}) \text{ X } 10^{-3}\ \text{eV}^2$$

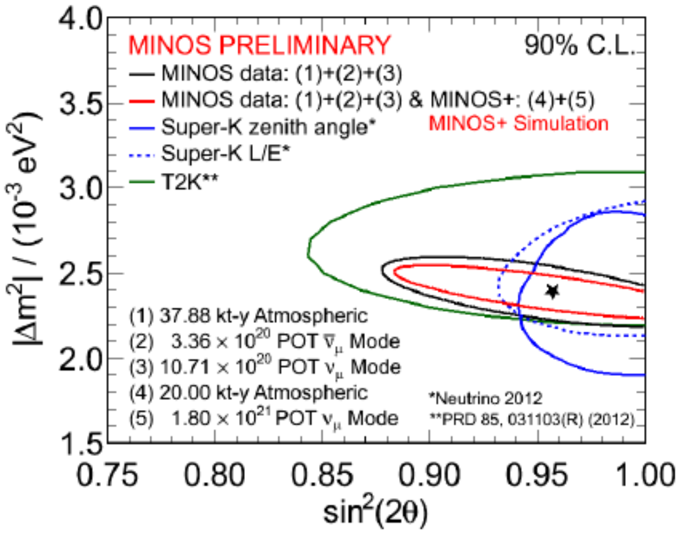
$$\sin^2(2\bar{\theta}_{23}) = 0.97^{+0.03}_{-0.08}$$

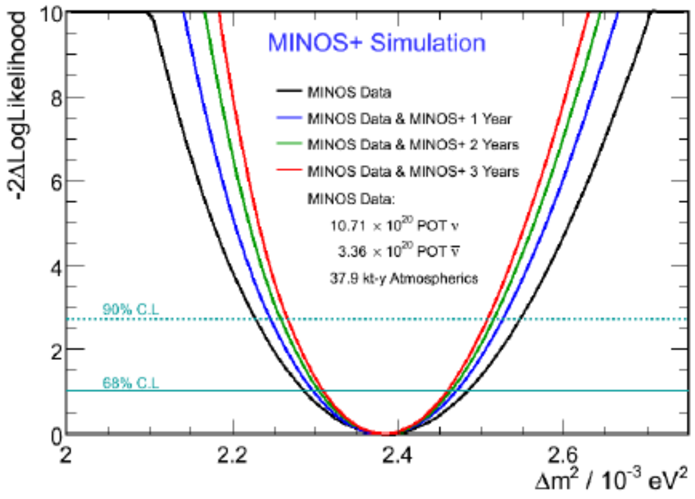
Best fit point – below maximal mixing

MINOS+


Simulated ν Beam
5.4 kton, 6 × 10²⁰ POT
MINOS+
NOvA
MINOS
Preliminary
νμ CC Events / GeV
0
500
1000
0
5
10
15
20
Eν (GeV)


MINOS+ Simulation
νμ Survival Probability
0
0.5
1
1.5
0
5
10
15
Neutrino Energy / GeV
MINOS 1.071×10²¹ POT
0.6×10²¹ POT
1.2×10²¹ POT
1.8×10²¹ POT

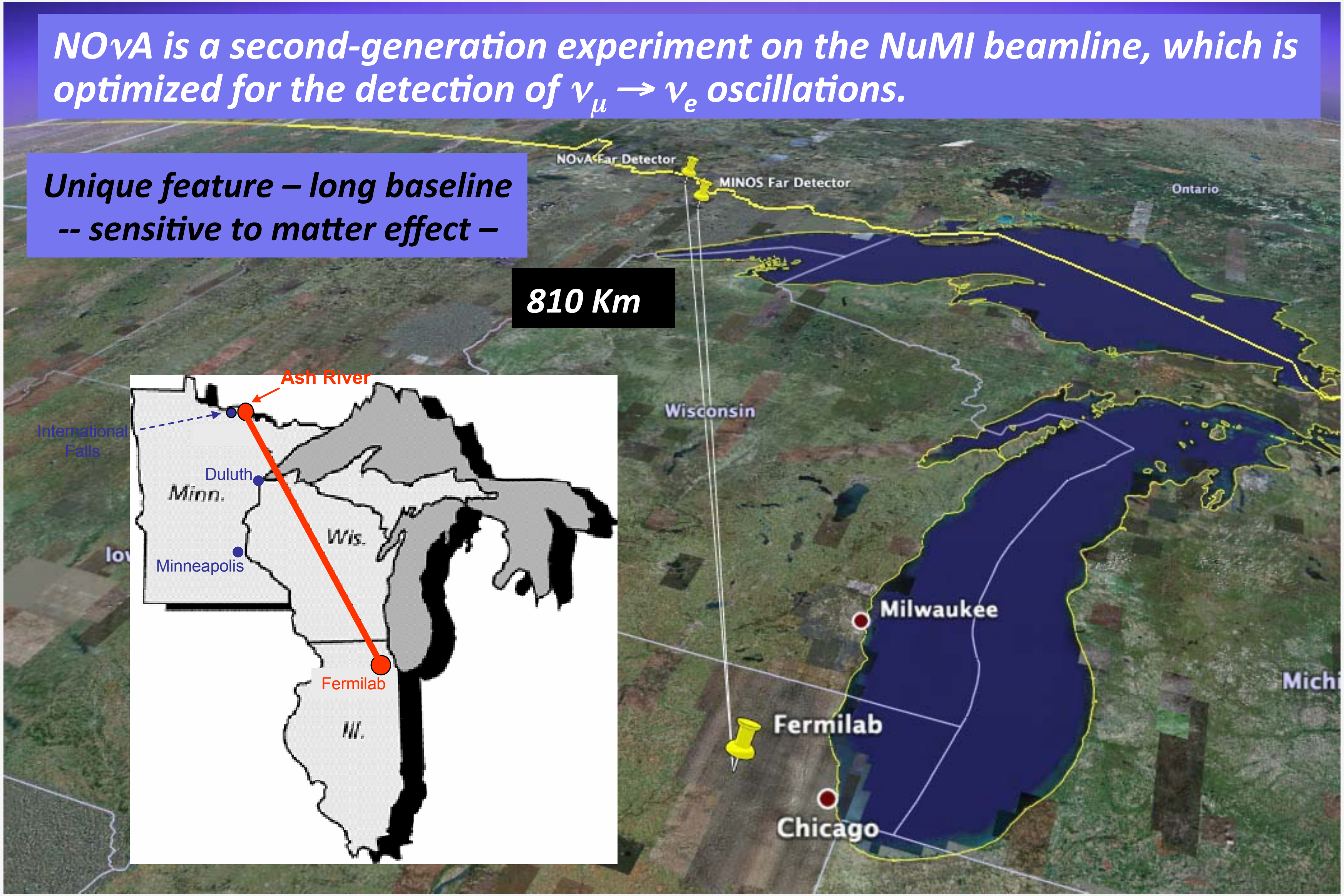

MINOS PRELIMINARY
90% C.L.
MINOS data: (1)+(2)+(3)
MINOS data: (1)+(2)+(3) & MINOS+: (4)+(5)
Super-K zenith angle*
Super-K L/E*
T2K**
MINOS+ Simulation
(1) 37.88 kt-y Atmospheric
(2) 3.36 × 10²⁰ POT ν̄μ Mode
(3) 10.71 × 10²⁰ POT νμ Mode
(4) 20.00 kt-y Atmospheric
(5) 1.80 × 10²¹ POT νμ Mode
*Neutrino 2012
**PRD 85, 031103(R) (2012)
|Δm²| / (10⁻³ eV²)
1.5
2.0
2.5
3.0
3.5
4.0
0.75
0.80
0.85
0.90
0.95
1.00
sin²(2θ)


MINOS+ Simulation
MINOS Data
MINOS Data & MINOS+ 1 Year
MINOS Data & MINOS+ 2 Years
MINOS Data & MINOS+ 3 Years
MINOS Data:
10.71 × 10²⁰ POT ν
3.36 × 10²⁰ POT ν̄
37.9 kt-y Atmospherics
90% C.L.
68% C.L.
-2ΔLogLikelihood
0
2
4
6
8
10
2
2.2
2.4
2.6
Δm² / 10⁻³ eV²

NOνA

NOνA

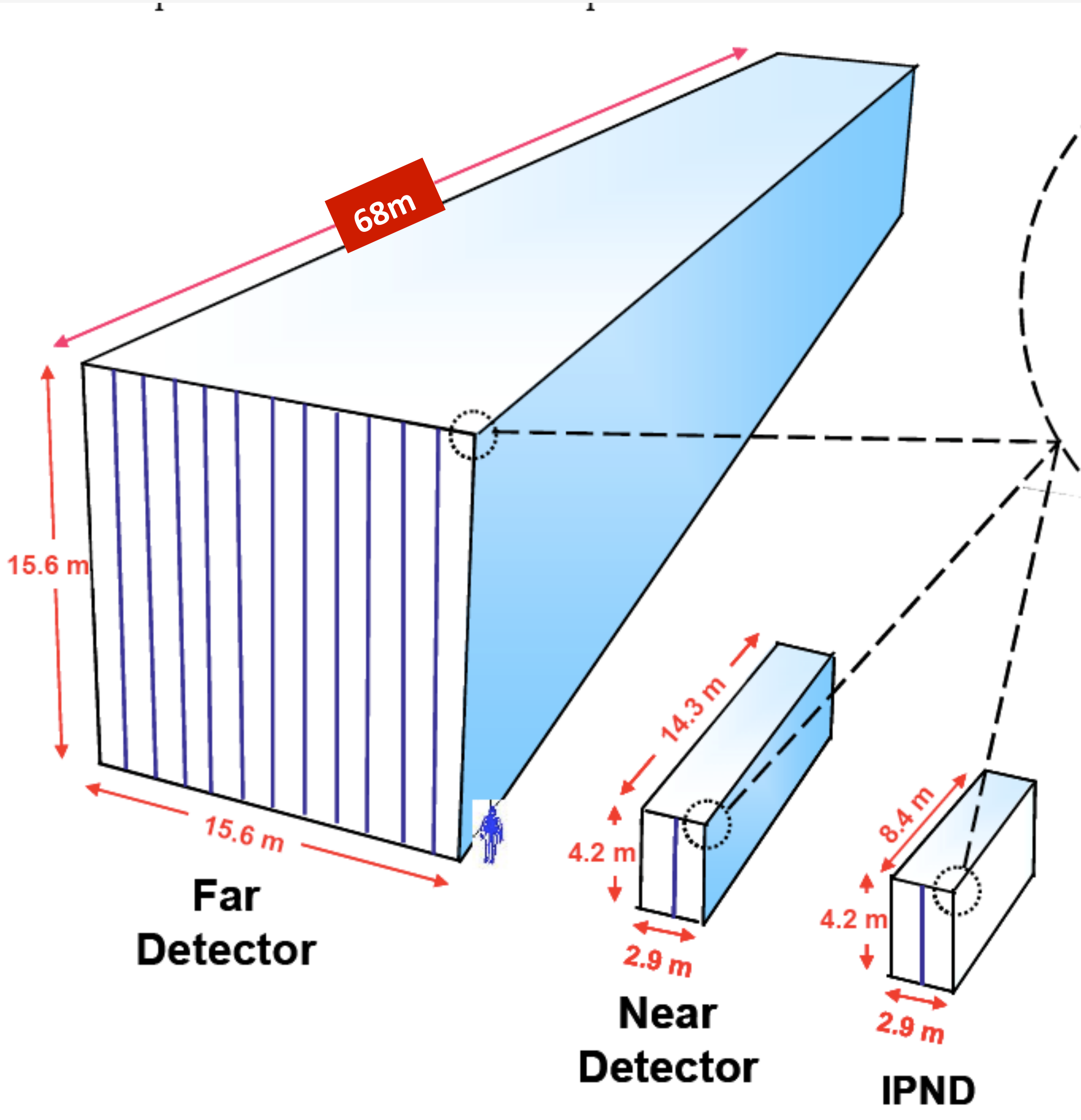
NOνA is a second-generation experiment on the NuMI beamline, which is optimized for the detection of $\nu_\mu \rightarrow \nu_e$ oscillations.



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

810 Km

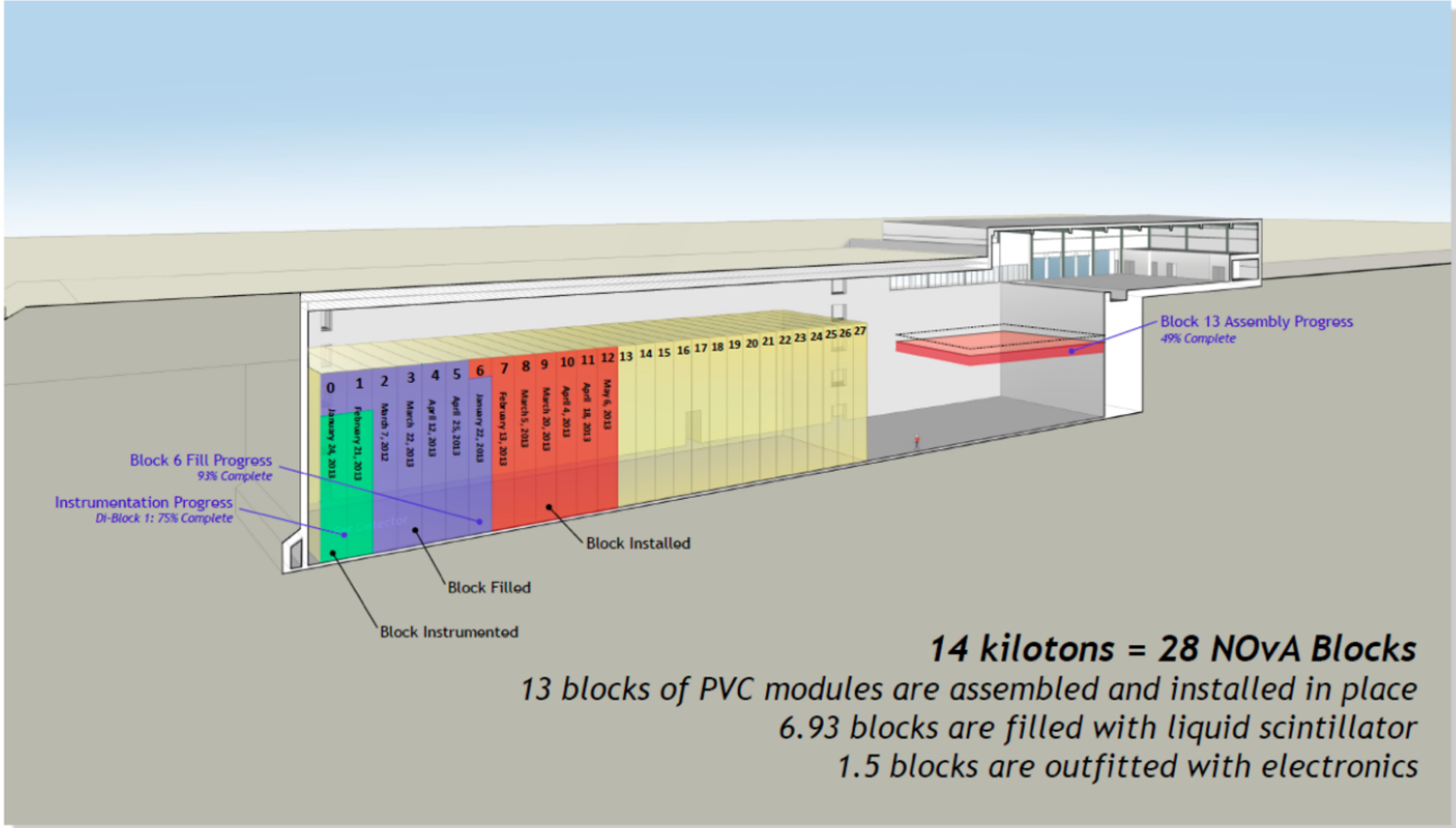
Three NOνA Detectors



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

NOνA Construction Status

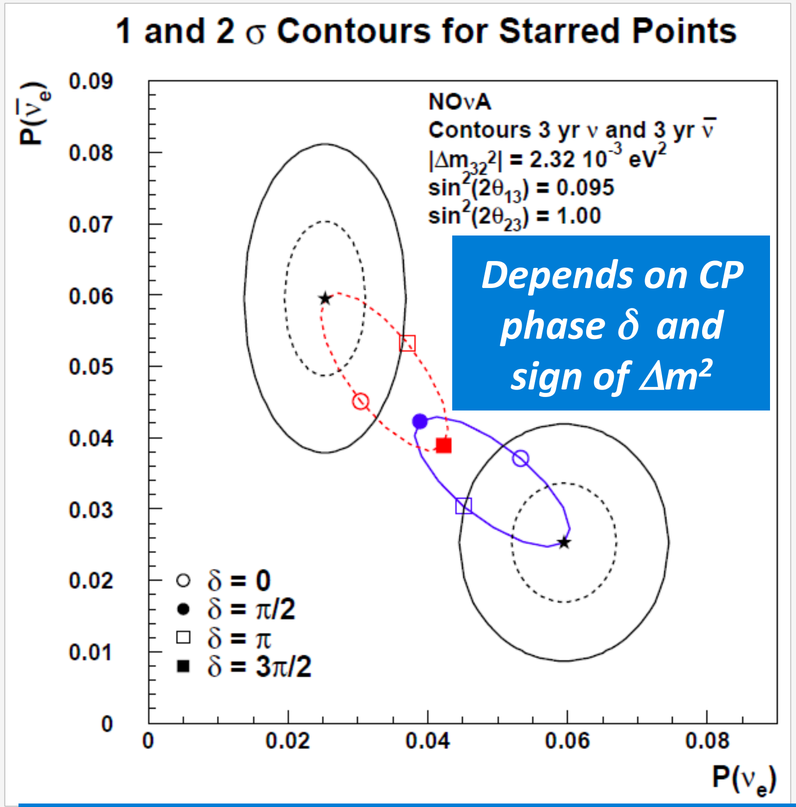
14 Ktons to be completed by 6/2014



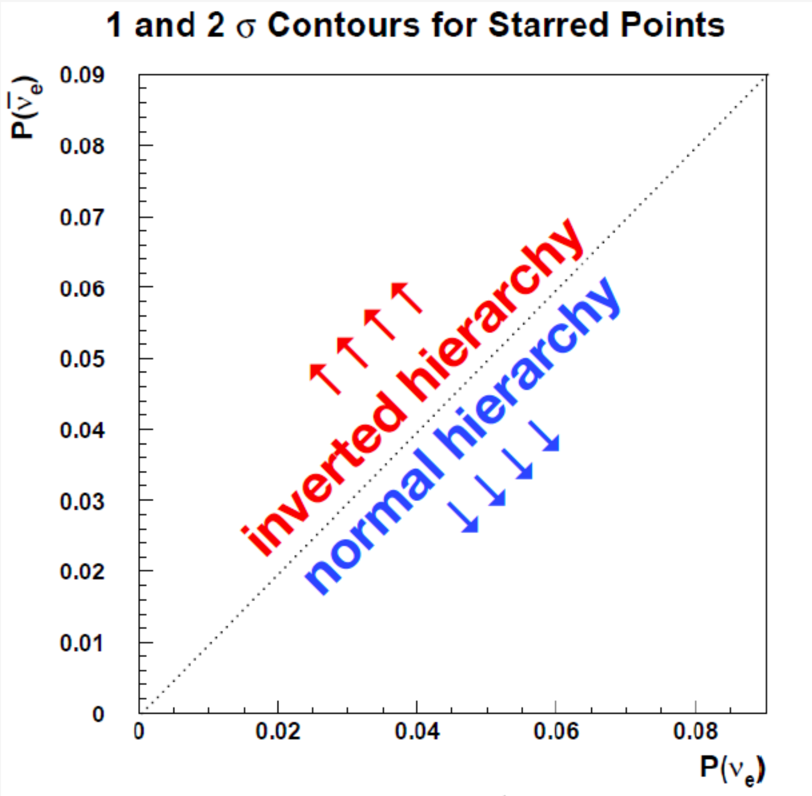
14 kilotons = 28 NOνA Blocks

13 blocks of PVC modules are assembled and installed in place
6.93 blocks are filled with liquid scintillator
1.5 blocks are outfitted with electronics

NOνA Physics – MH



Depends on CP phase δ and sign of Δm²



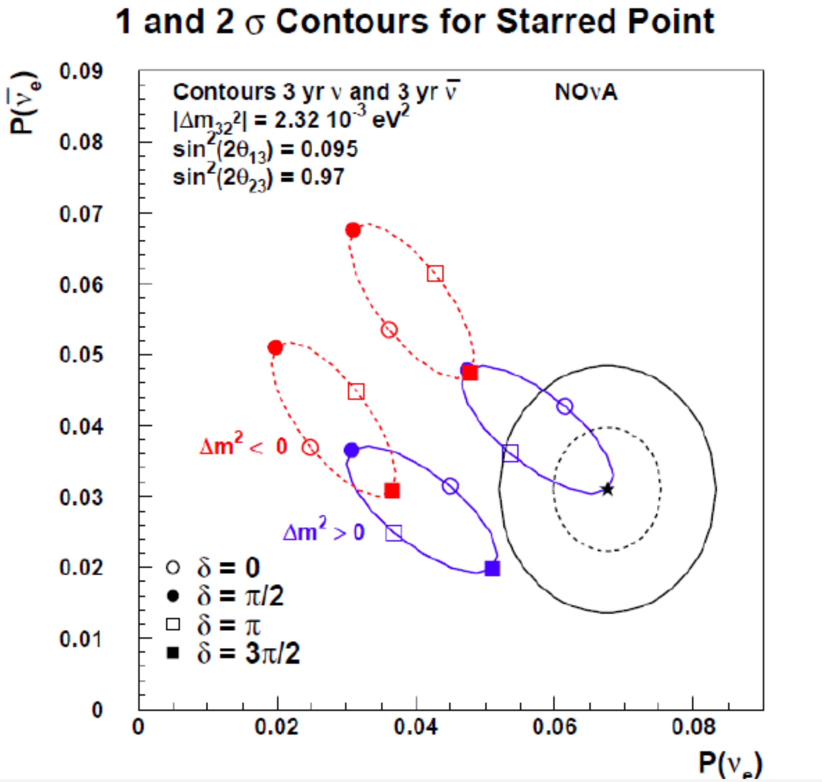
NOνA will measure P($\nu_\mu \rightarrow \nu_e$) & P(νbar$_\mu \rightarrow$ νbar$_e$) at 2 GeV

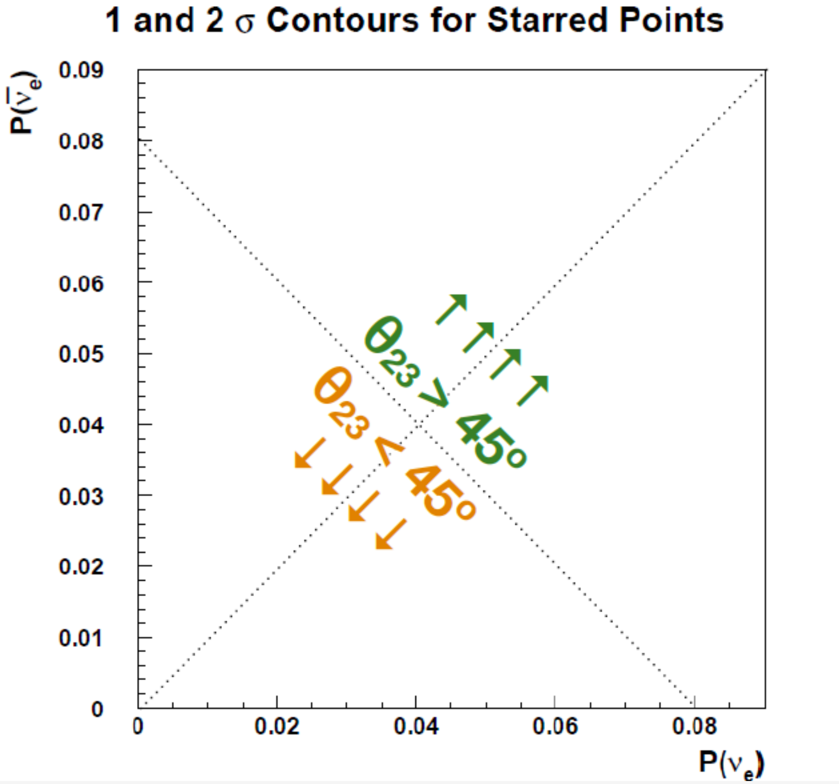
Large θ_{13} is better for NOνA. It reduces the overlap between these bi-polarity ellipses, reducing the likelihood of degeneracy

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

From M Messier

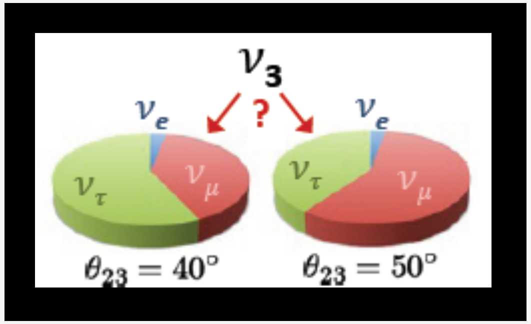
NOνA Physics – Octant Resolution


1 and 2 σ Contours for Starred Point


1 and 2 σ Contours for Starred Points

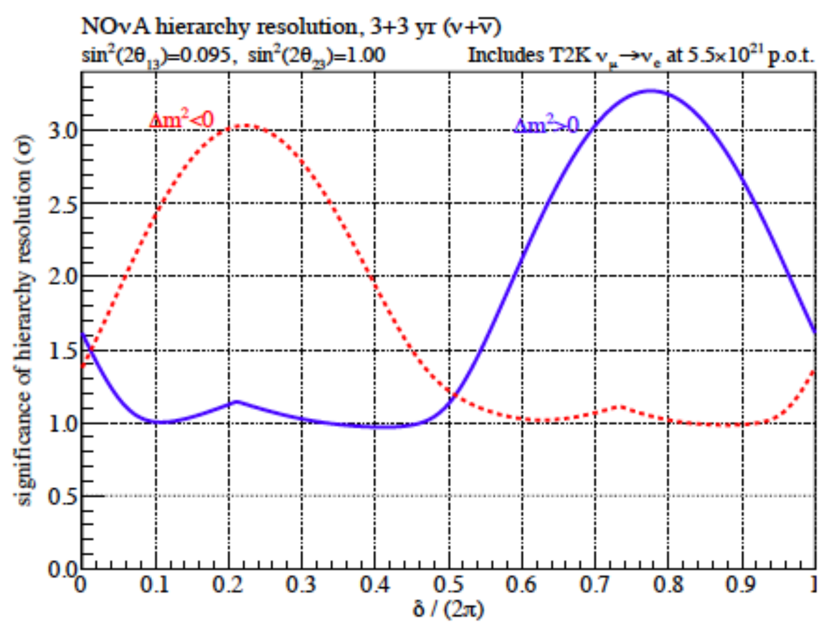
$P(\nu_e) \propto \sin^2(\theta_{23})\ \sin^2(2\theta_{13})$

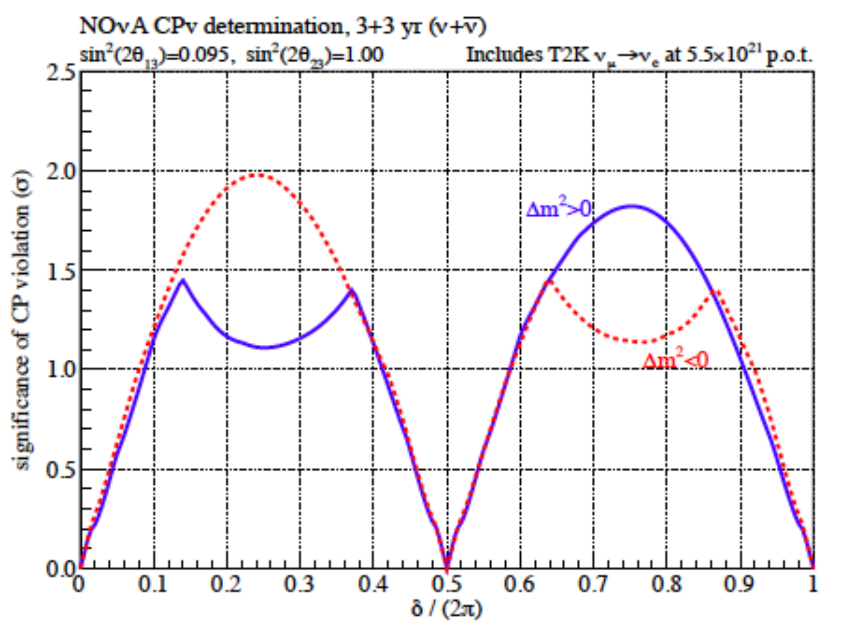
→ θ_{23} octact sensitivity

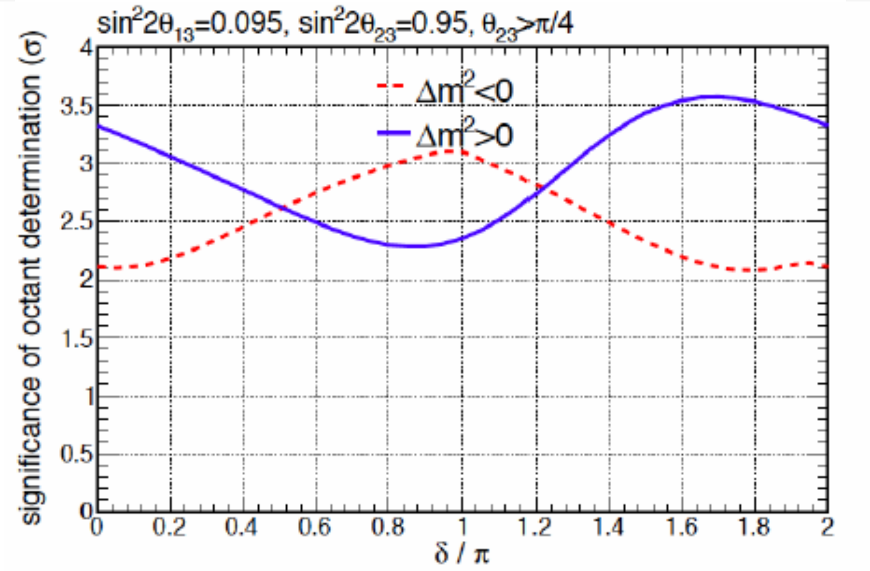


From M Messier

NOνA+T2K - MH, CPV & Octant Degeneracy



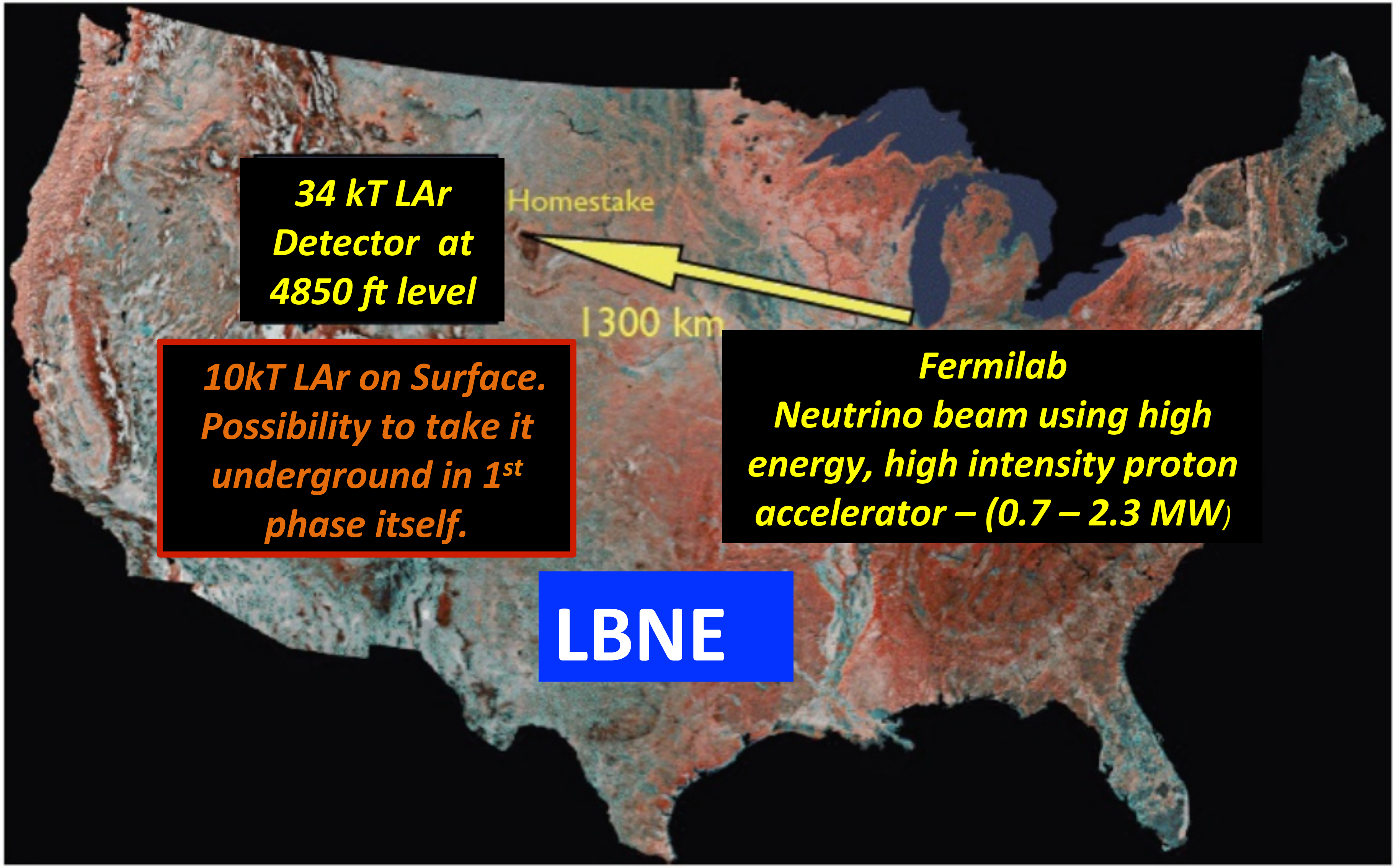




- ***3 + 3 years of running in neutrino and anti-neutrino mode.***
- ***NOVA data will yield regions in P (ν_e) vs. P(νbar$_e$) space.***
- ***A measurement of the probabilities might allow resolving the MH and provide information on δ_{CP}***
- ***Additional sensitivity from T2K***

LBNE

Long Baseline Neutrino Experiment



34 kT LAr Detector at 4850 ft level

10kT LAr on Surface. Possibility to take it underground in 1st phase itself.

Fermilab

Neutrino beam using high energy, high intensity proton accelerator – (0.7 – 2.3 MW)

LBNE

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**

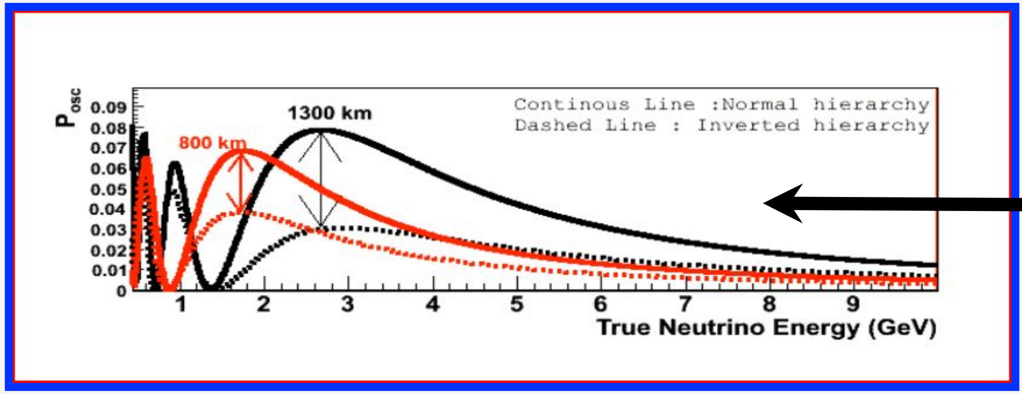
e)Atmospheric Neutrinos **YES**

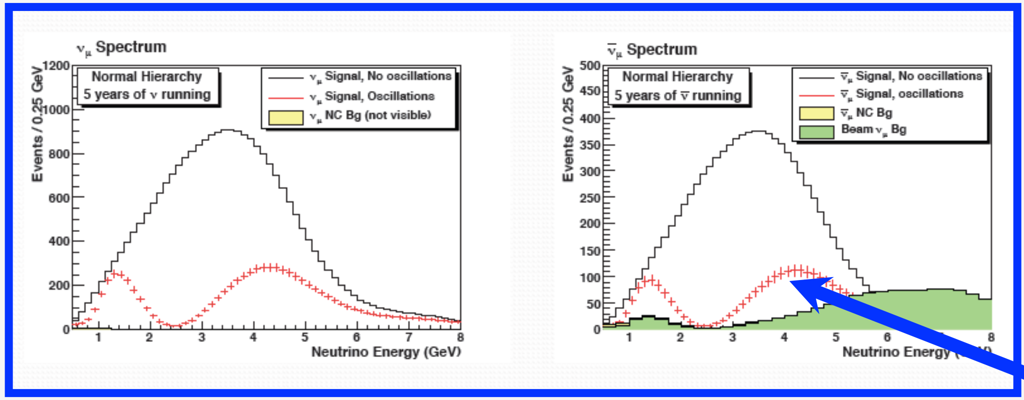
f) High Energy Neutrinos **Difficult**

g)Solar Neutrinos **No**

Hope to Improve on this - from very beginning

LBNE Beam

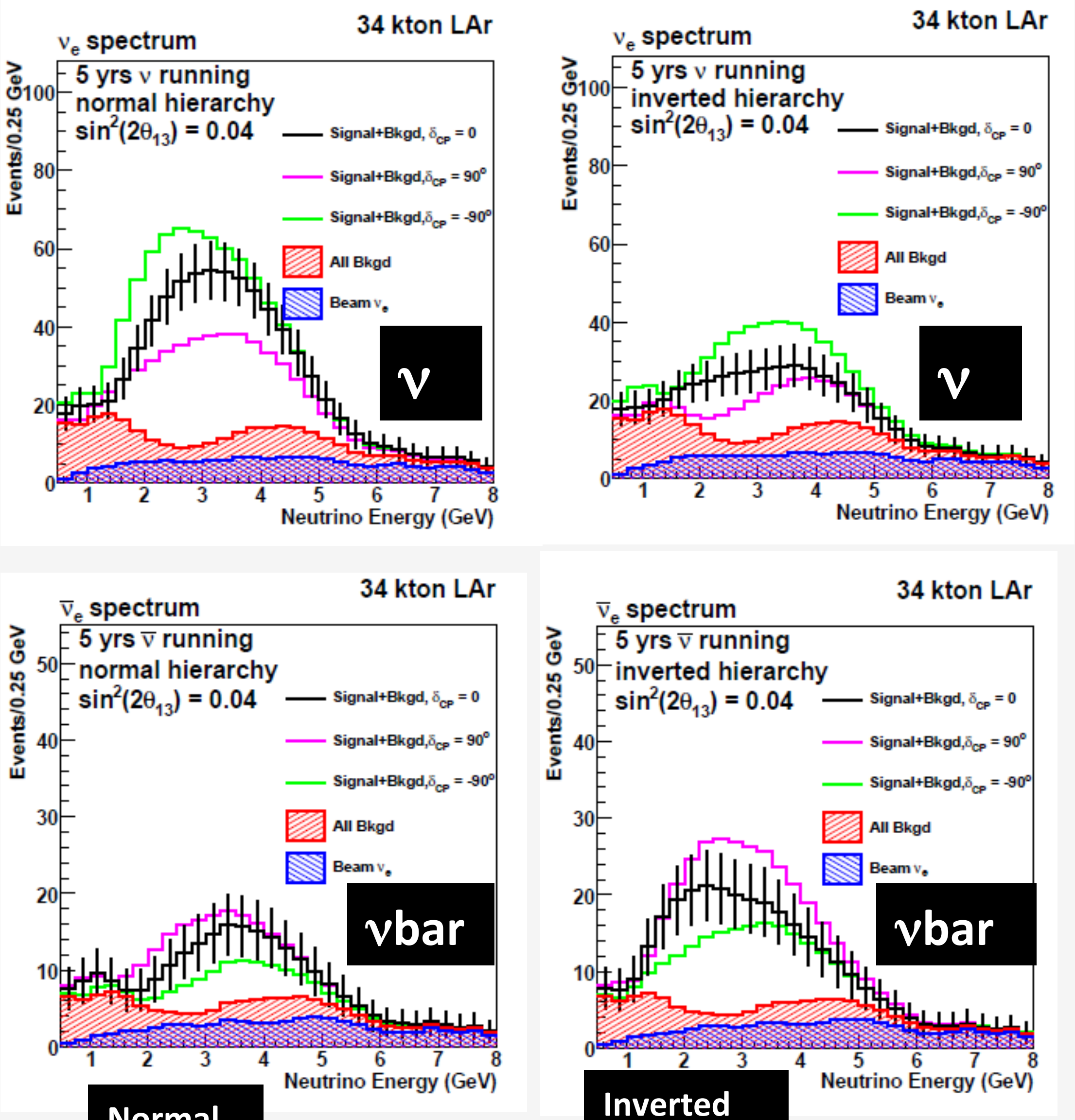




1. ***Fermilab – Homestake (South Dakota) = 1290 Km***
2. ***Wide Band Low Energy Beam – Information from 1st and 2nd maxima at achievable neutrino energy***
3. ***Larger separation between normal and inverted hierarchy***
4. ***All neutrino parameters measured in the same detector complex***

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*



Normal

Inverted

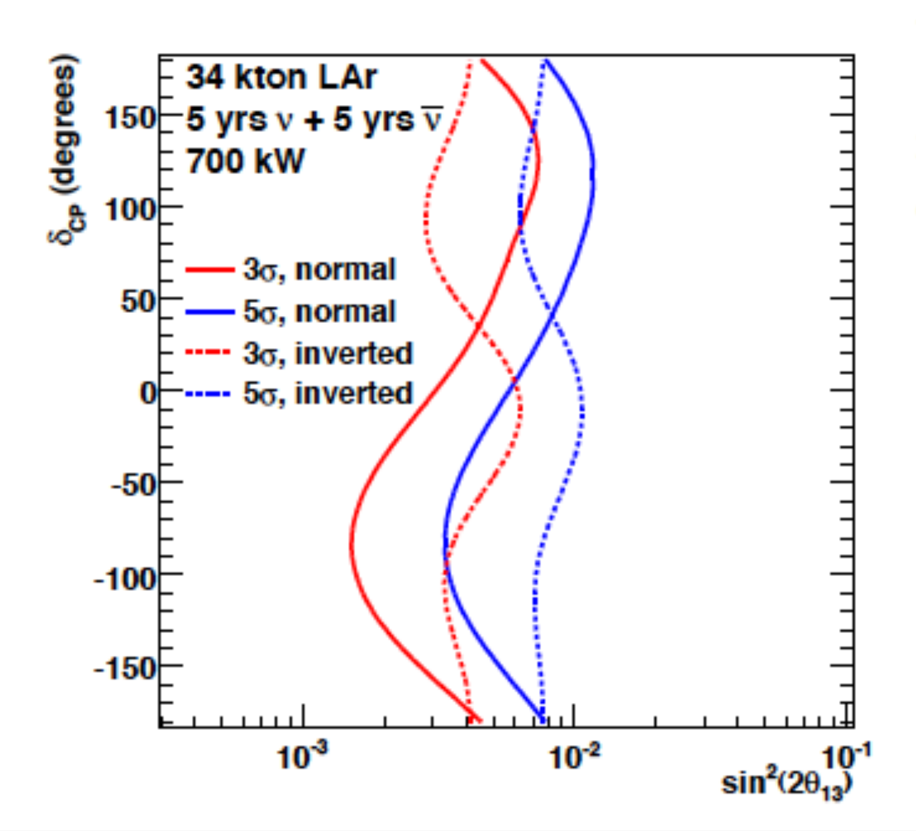
- ✓ 120 GeV protons on target
- ✓ 700 kW power
- ✓ 34 kTon LAr detecor
- ✓ 5 yr ν exposure

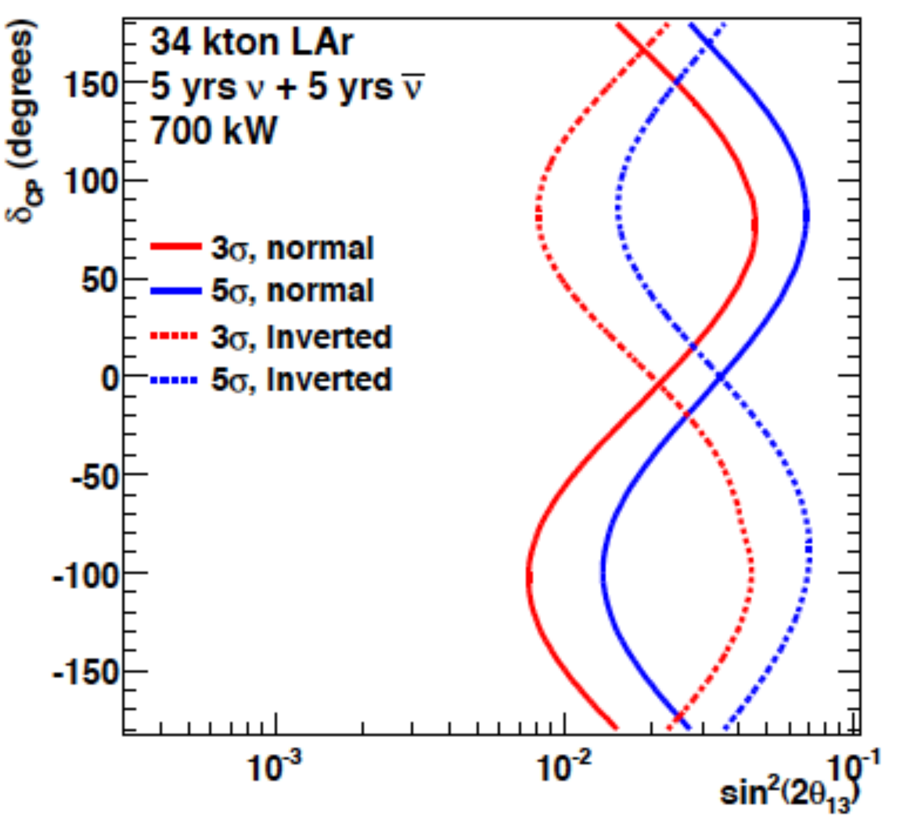
  \+

  5yr νbar exposure
- ✓ $2\text{x}10^7$ sec/yr
- ✓ δ_{CP} = 0, +90 & -90
- ✓ Background all beam

θ_{13} Sensitivity

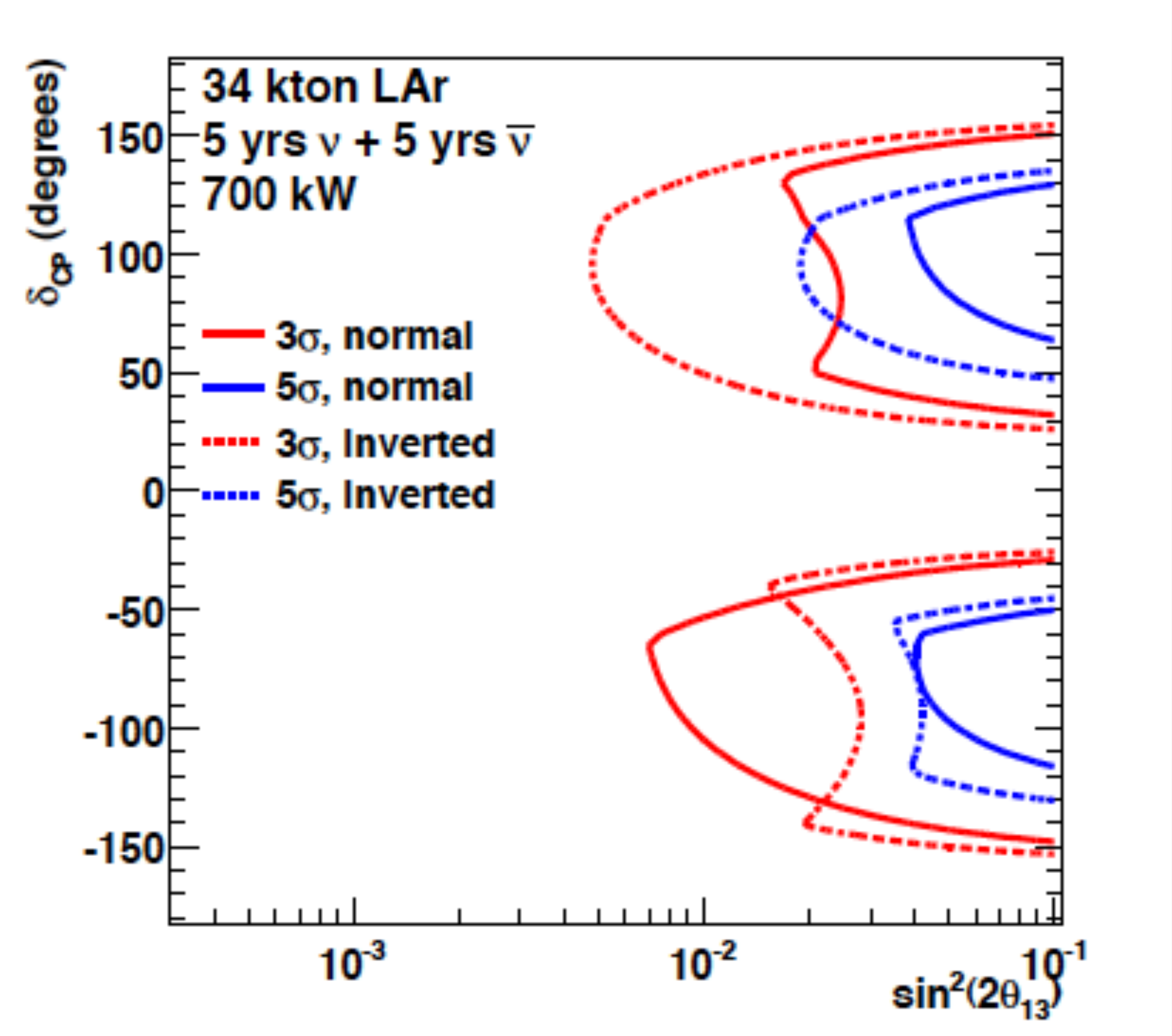
Mass Hierarchy





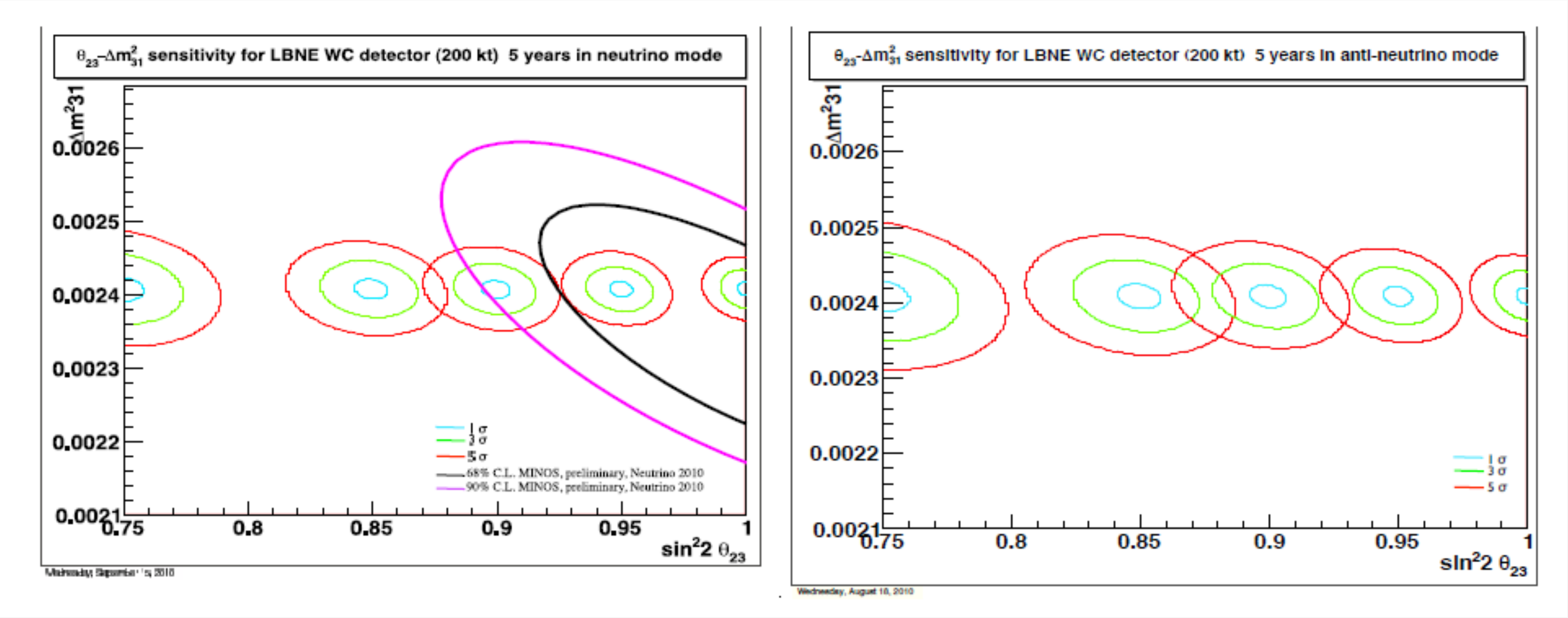
5σ+ for all δ_{CP} for the current value of ϑ_{13}

CP Violation



3σ ~ 70 - 75% δ_{CP} for $\sin^2(2\theta_{13}) = 0.095$

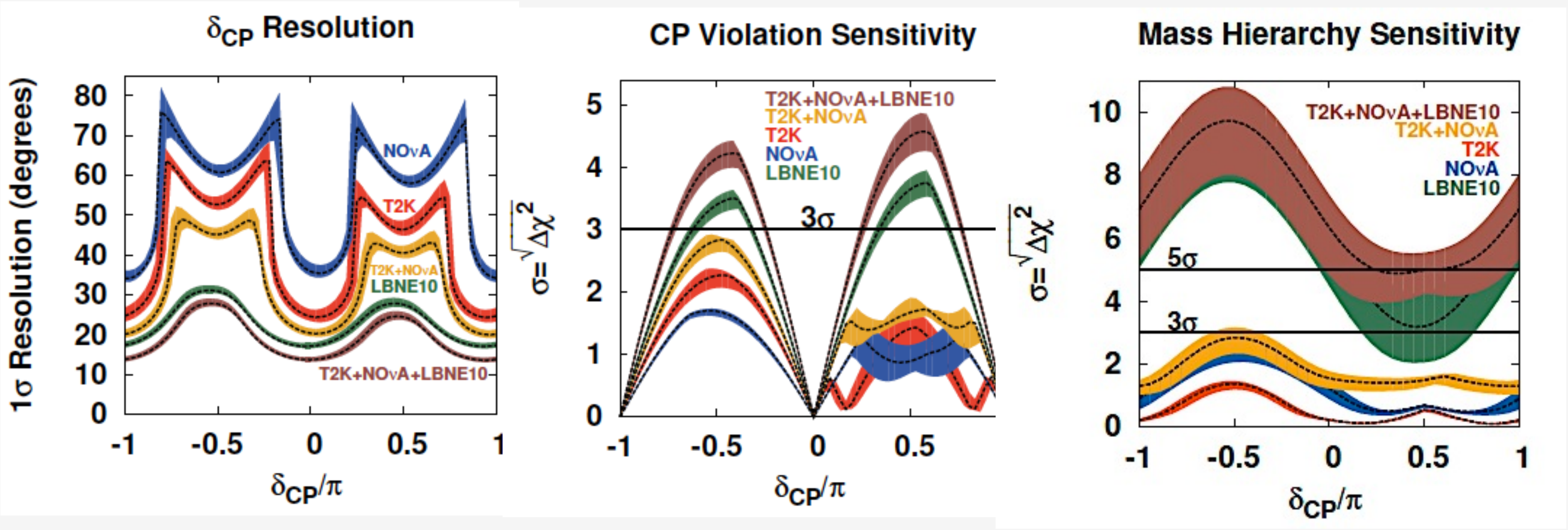
Simultaneous Measurement of Δm^2_{23} & $Sin^2 2\theta_{23}$



- ✓ *120 GeV protons on target*
- ✓ *700 kW power*
- ✓ *34 kTon LAr*
- ✓ *5 yr ν exposure*
- ✓ *$2x10^7$ sec/yr*

<1% measurement of Δm^2_{31} & $Sin^2 2\theta_{23}$ possible (at 1σ) with 34 kTon LAr detector. With anti-ν similar measurement possible at similar exposure.

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

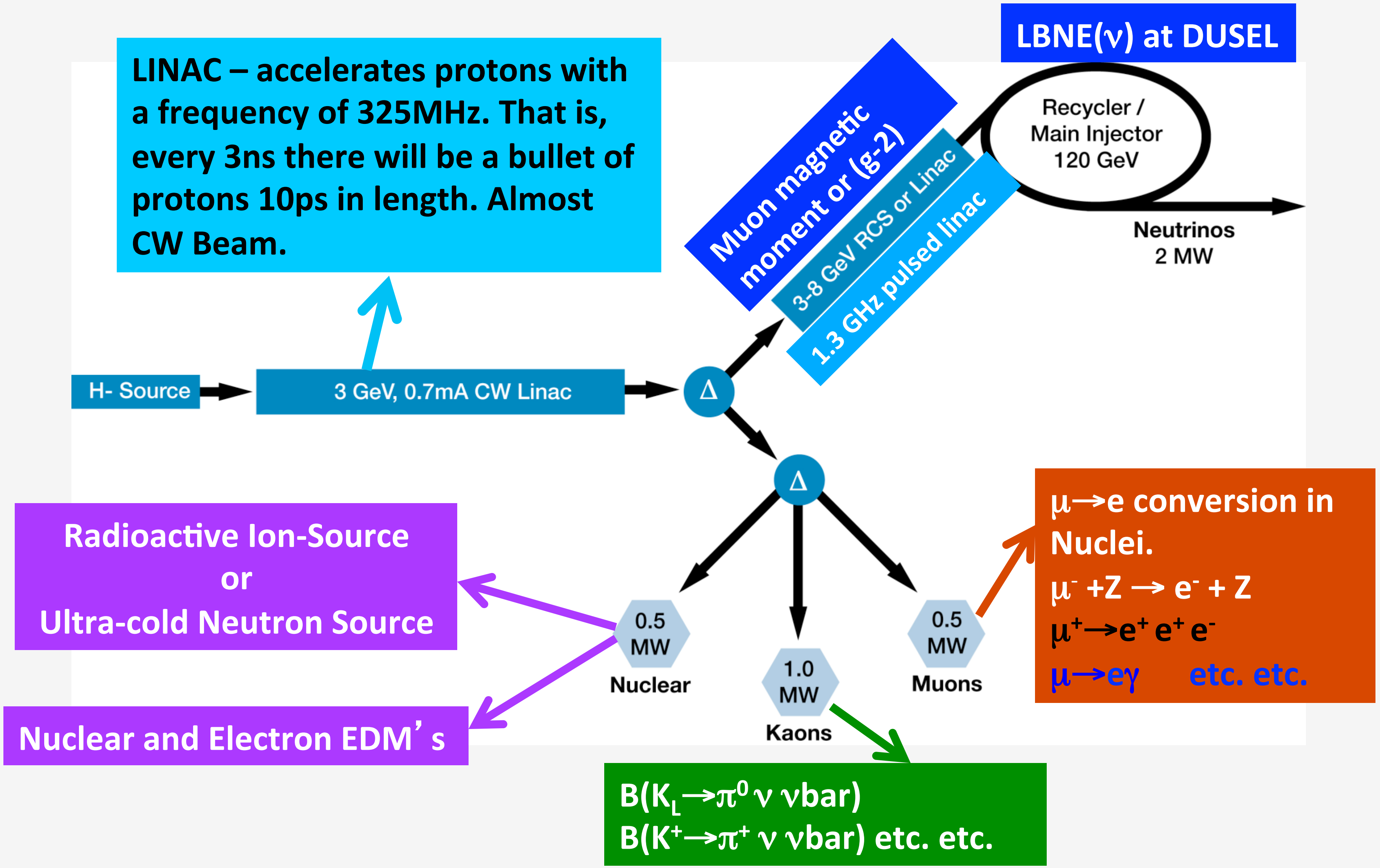
NOνA 700 kW x (3 yr ν + 3 yr $\bar{\nu}$)

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 has the potential to be the flagship of discovery at the intensity frontier.***
- ✓ ***Project-X is the first step toward potential future particle physics facilities, such as neutrino factory or an energy-frontier muon collider.***

Project-X – Basic Concept of the Accelerator



LBNE(ν) at DUSEL

LINAC – accelerates protons with a frequency of 325MHz. That is, every 3ns there will be a bullet of protons 10ps in length. Almost CW Beam.

Muon magnetic moment or (g-2)

Radioactive Ion-Source
or
Ultra-cold Neutron Source

Nuclear and Electron EDM's

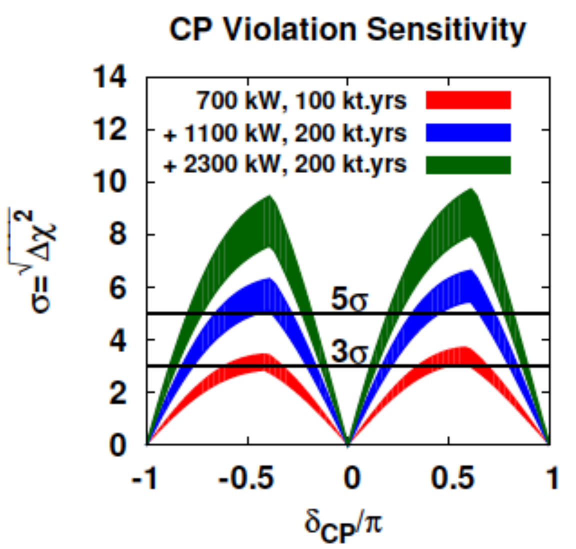
$\mu \to e$ conversion in Nuclei.
$\mu^- + Z \to e^- + Z$
$\mu^+ \to e^+ e^+ e^-$
$\mu \to e\gamma$ etc. etc.

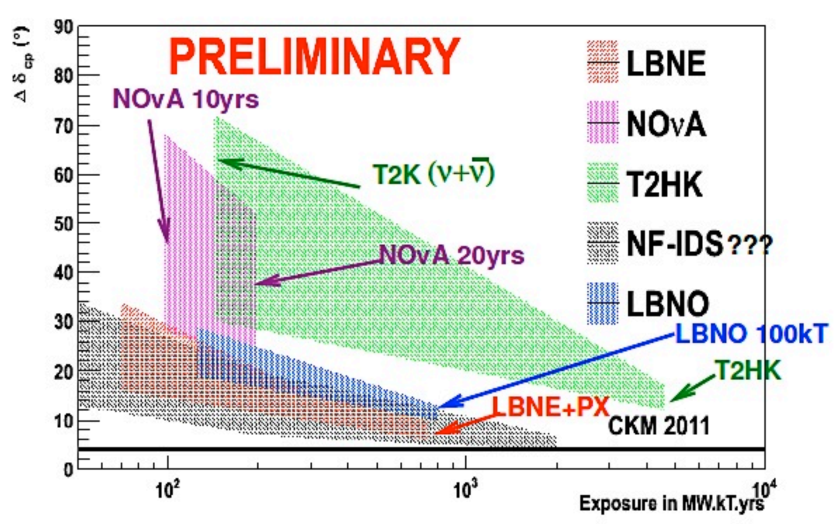
B($K_L \to \pi^0$ ν νbar)
B($K^+ \to \pi^+$ ν νbar) etc. etc.

LBNE Summary in the Project-X Era

- ✓ *A 2.3 MW wide band beam with 120 GeV protons, aimed at a 34 kTon LAr detector 1290 km away, during a period of 9 years – with equal ν and anti-ν running can achieve sensitivities at 3σ:*

	$Sin^2 2\theta_{13}$ > 0	
$Sin^2 2\theta_{13} \neq 0$	0.004	All δ_{CP}
Sign (Δm^2_{31})	0.014	All δ_{CP}
CP Violation	0.012	50% δ_{CP}





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

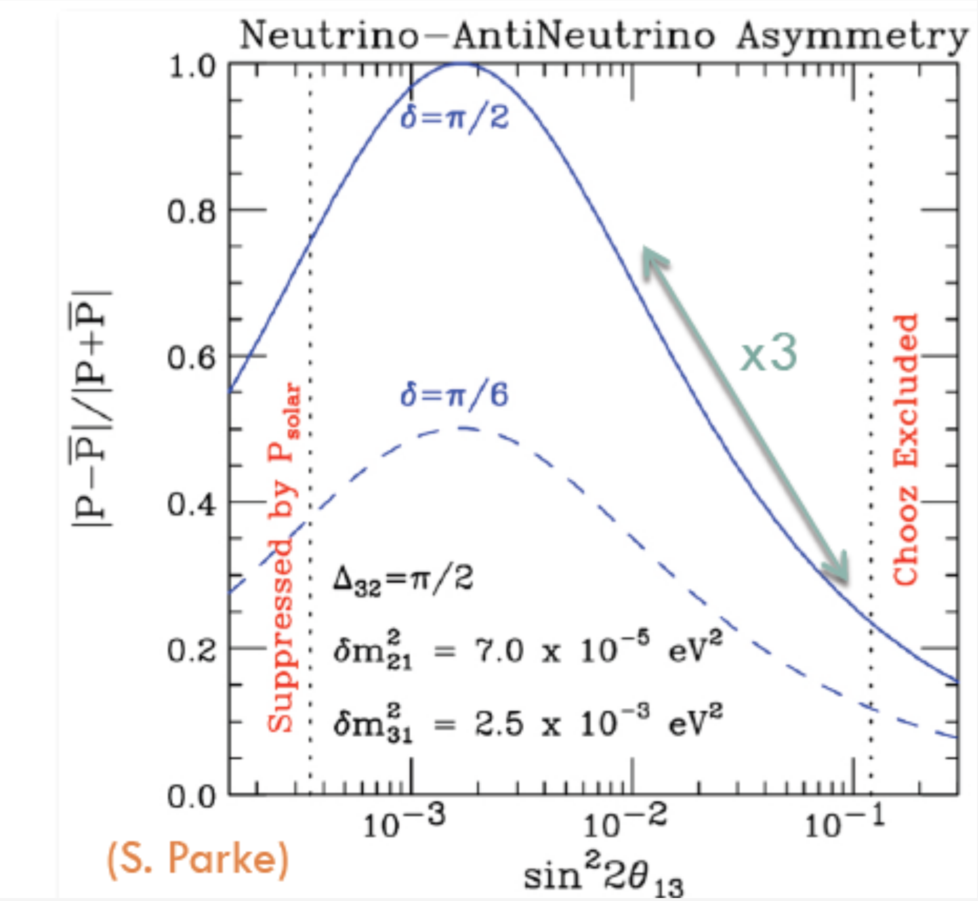
✓ ***With larger value of θ_{13} --- will the measurement of CPV become any easier?***

✓ ***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



(S. Parke)

- ✓ **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

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

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

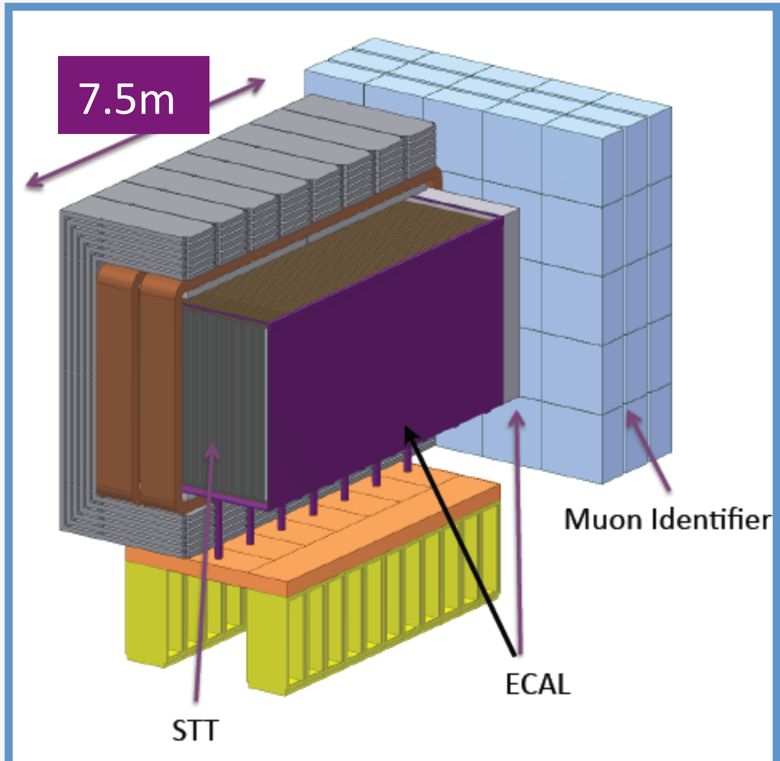
- ✓ **the asymmetry gets smaller as θ_{13} increases** - *a factor ~3 reduction in CP asymmetry going from $\sin^2 2\vartheta_{13}$ = 0.01 to 0.10 (independent of baseline)*

Ignoring the matter effect and background for now

Understanding systematic will be the key to CP measurement

The role of the ND becomes increasingly important.

ND Concept for LBNE



Fine grained tracker ~0.14T Ar@140 atm

- *4m X 4m 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, $\bar{\nu}_e$, 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*

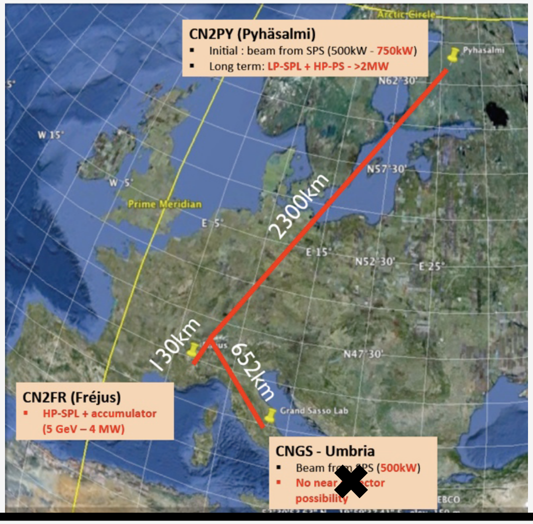
Greatest Scientific Return.

With external contribution, it would be possible to build a higher-resolution and larger-ND (4m X 4m X 7.5m) capable of fulfilling oscillation needs and precision measurements/searches.

LAGUNA

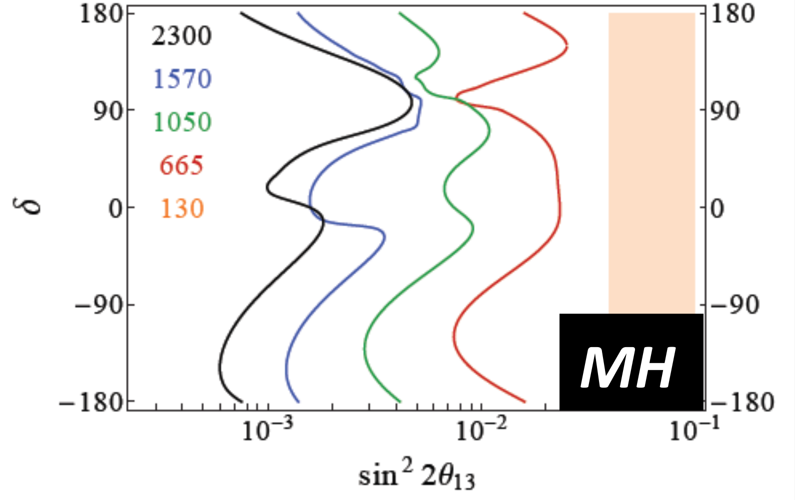
LBNO

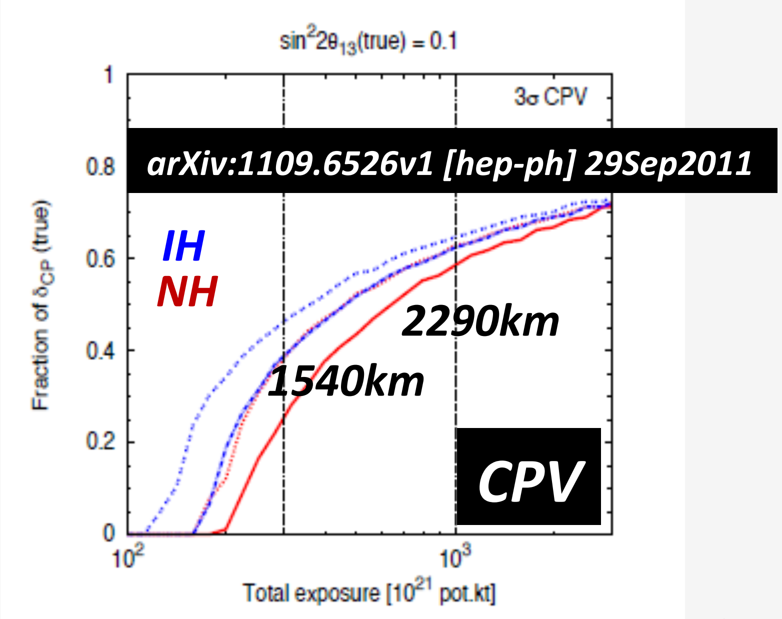
LAGUNA – LBNO – Choice of Baselines



100 Kton LAr + 10 yr operation + 1.66 MW

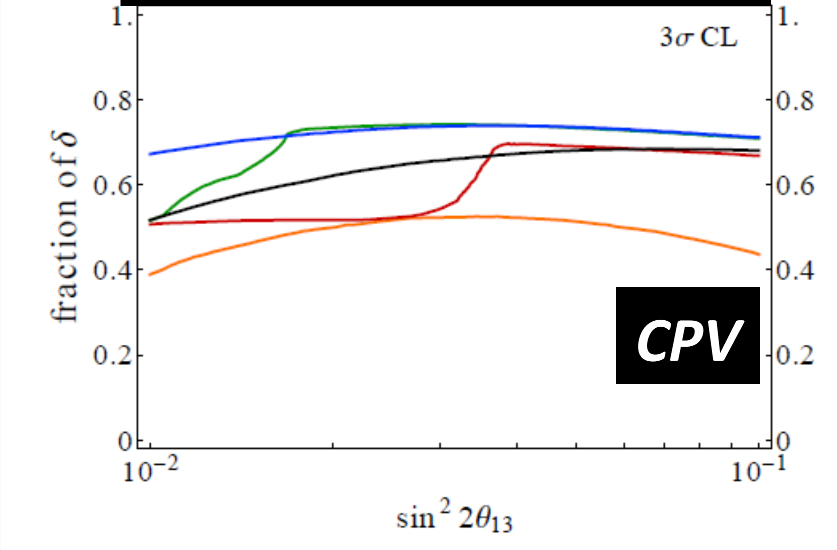
arXiv:1206.4038v1 [hep-ph] 18Jun2012





arXiv:1109.6526v1 [hep-ph] 29Sep2011

arXiv:1206.4038v1 [hep-ph] 18Jun2012



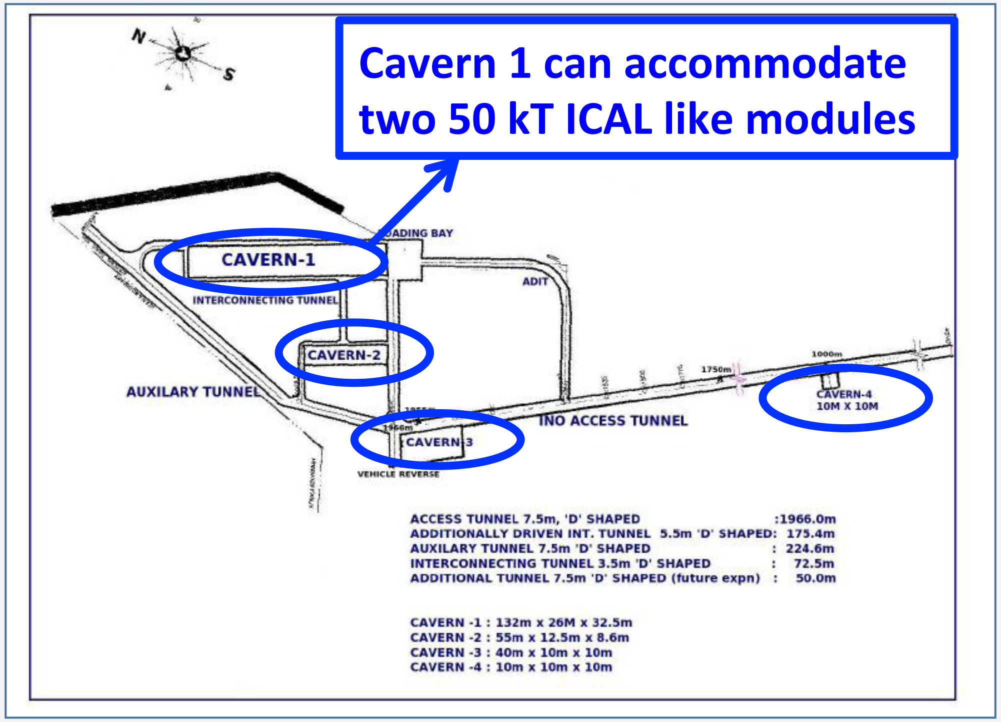
Atmospheric Neutrinos

Mass Hierarchy

ICAL@INO, PINGU, HK

INDIA-BASED NEUTRINO OBSERVATORY

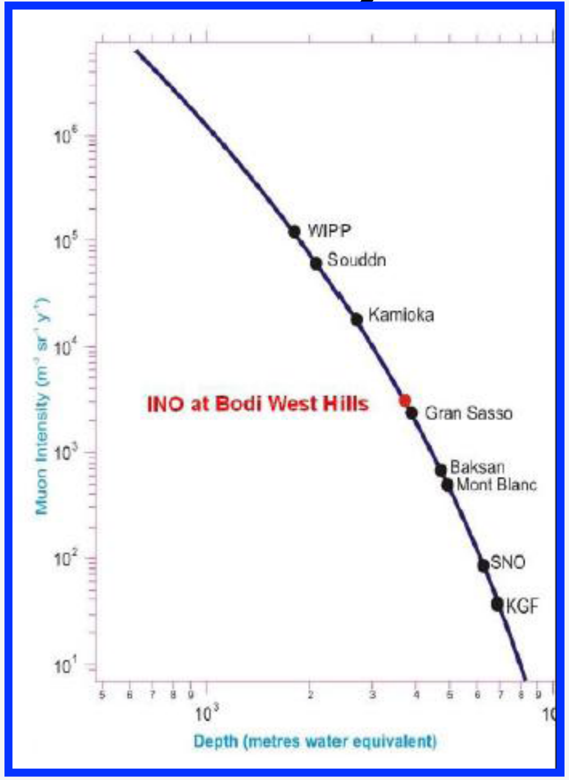
INDIA-Based Neutrino Observatory



Cavern 1 can accommodate two 50 kT ICAL like modules

ACCESS TUNNEL 7.5m, 'D' SHAPED :1966.0m
ADDITIONALLY DRIVEN INT. TUNNEL 5.5m 'D' SHAPED: 175.4m
AUXILARY TUNNEL 7.5m 'D' SHAPED : 224.6m
INTERCONNECTING TUNNEL 3.5m 'D' SHAPED : 72.5m
ADDITIONAL TUNNEL 7.5m 'D' SHAPED (future expn) : 50.0m

CAVERN -1 : 132m x 26M x 32.5m
CAVERN -2 : 55m x 12.5m x 8.6m
CAVERN -3 : 40m x 10m x 10m
CAVERN -4 : 10m x 10m x 10m



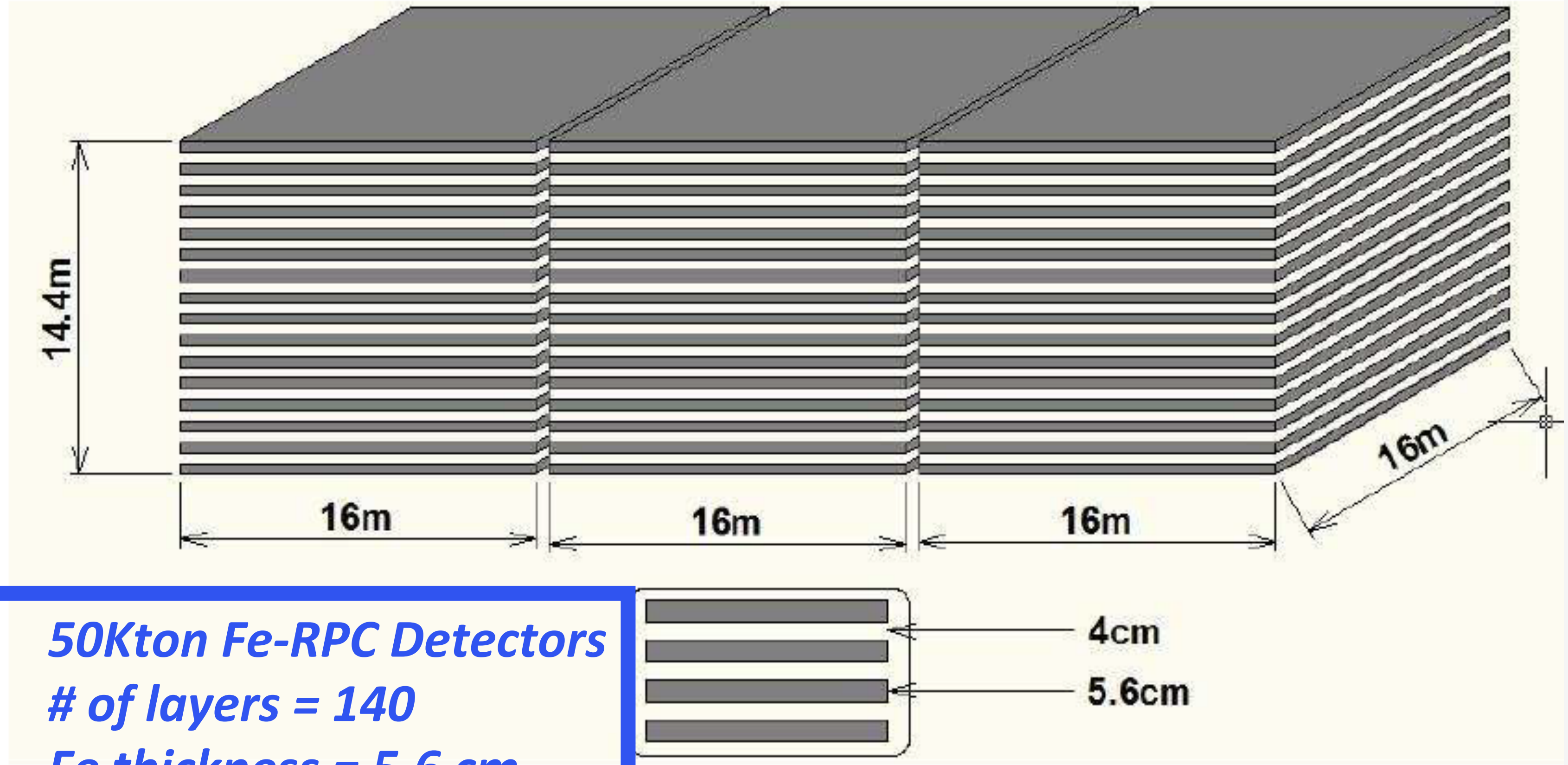
- ✓ *Underground laboratory in South India (9^0 58' N, 77^0 16'E)*
- ✓ *With ~1 km - rock cover - through a 2 km long tunnel.*

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).***
- ***Detector R & D almost complete.***

INO-ICAL Detector

Number of Institutions ~ 25+

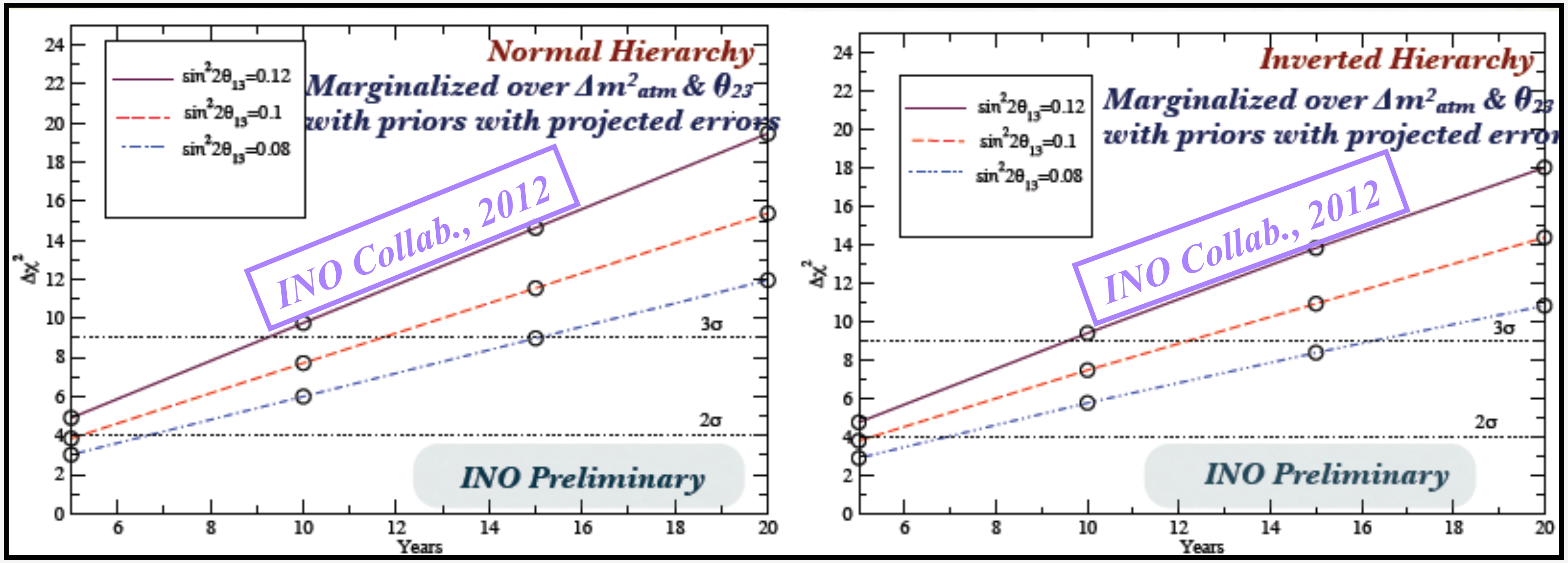


- ✓ ***50Kton Fe-RPC Detectors***
- ✓ ***# of layers = 140***
- ✓ ***Fe thickness = 5.6 cm***
- ✓ ***Magnetic Field ~ 1.3T***
- ✓ ***# of RPCs ~ 27K***
- ✓ ***# of channels ~ 3.6M***

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

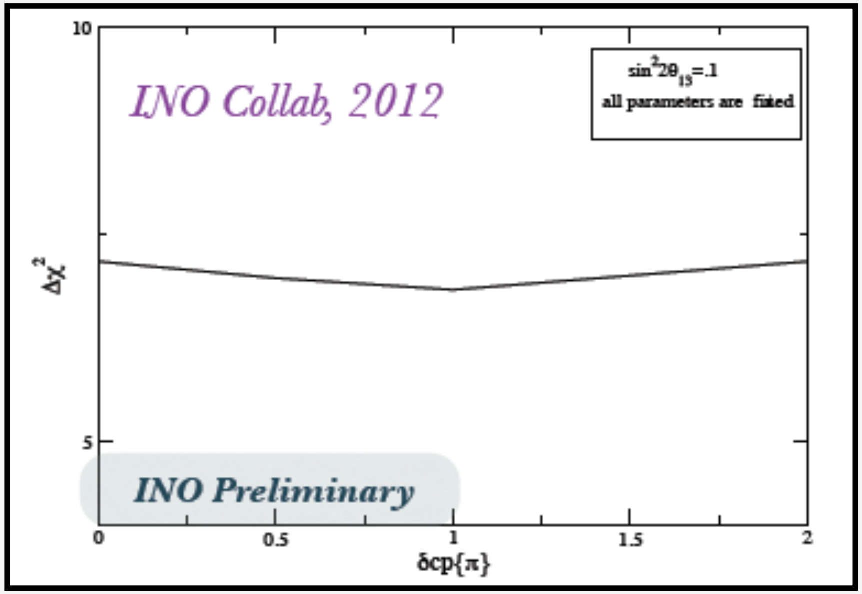
Mass Hierarchy with ICAL@INO

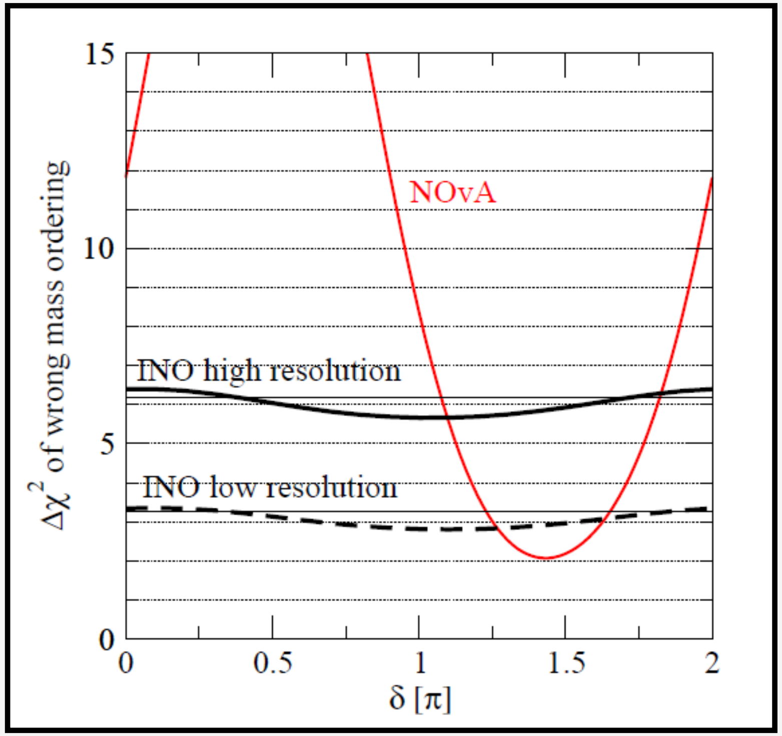
Events generated using Nuance & ICAL resolution in E and cosθ_{zenith}



~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





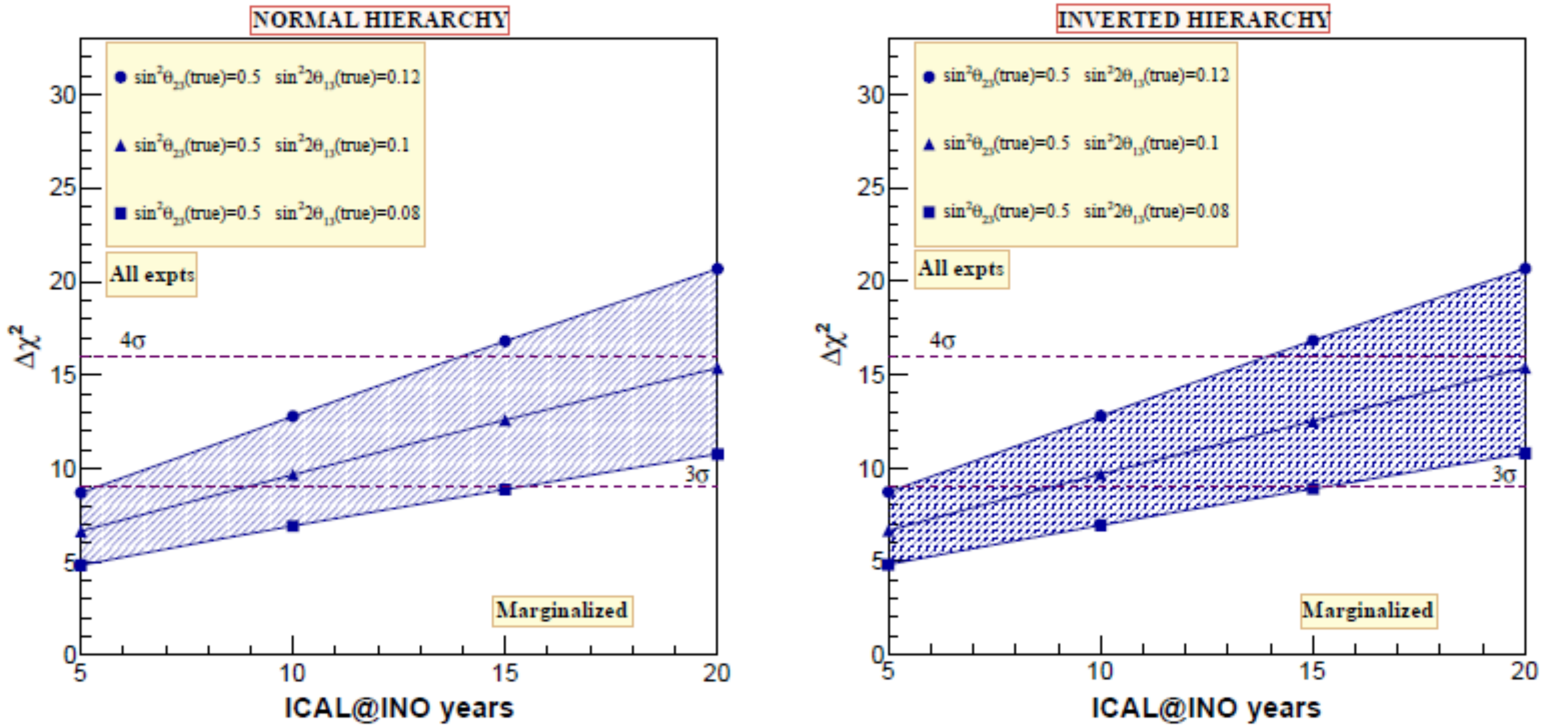
arXiv:1203.3388v1-Blennow, Schwetz

Data generated at δ_{CP} = 0 and fitted at non-zero δ_{CP}

INO will give MH sensitivity almost independent of δ_{CP}

ICAL@INO + NOvA + T2K + Double CHOOZ + Reno + Daya Bay

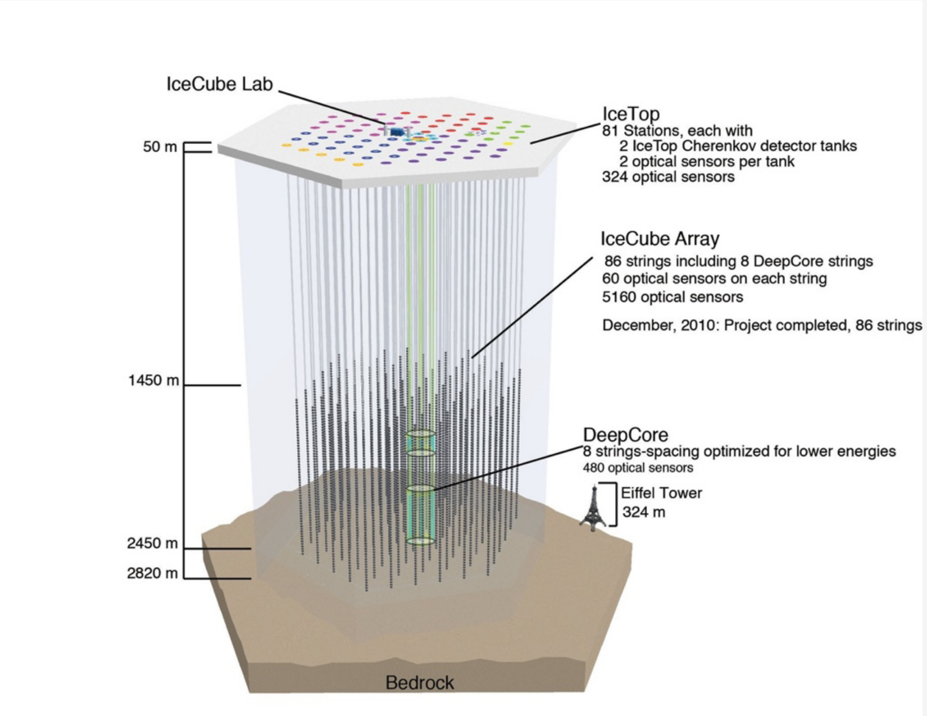
arXiv:1205.7071v5 [hep-ph] 2Dec 2012 – Anushree Ghosh, Tarak Thakore, Sandhya Choubey



The paper concludes: With 10 years of ICAL@INO data combined with T2K, NOνA and reactor data, one could get about 2.2 – 5.5σ discovery of the neutrino mass hierarchy, depending on the true value of $\sin^2\theta_{23}$ [0.4 – 0.6], $\sin^2 2\theta_{13}$ [0.08 – 0.12] and

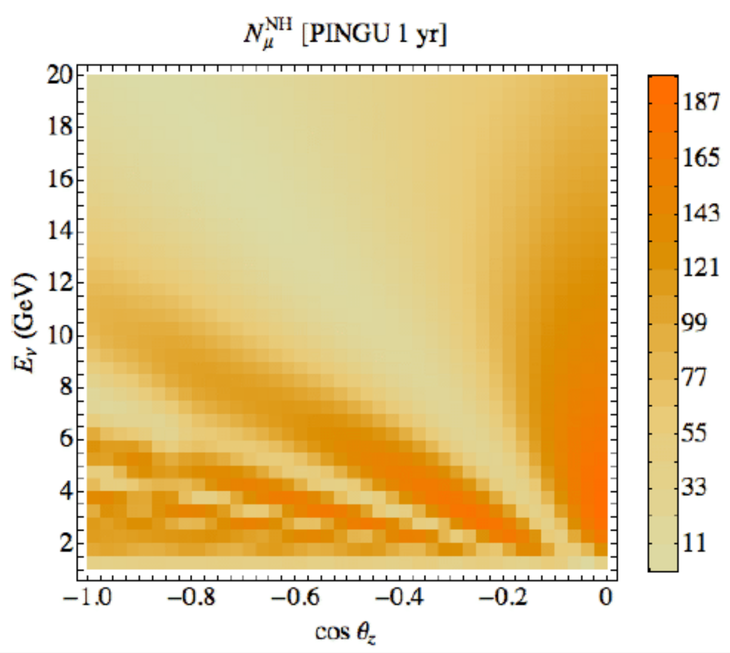
ICE-CUBE, DEEPCORE, PINGU

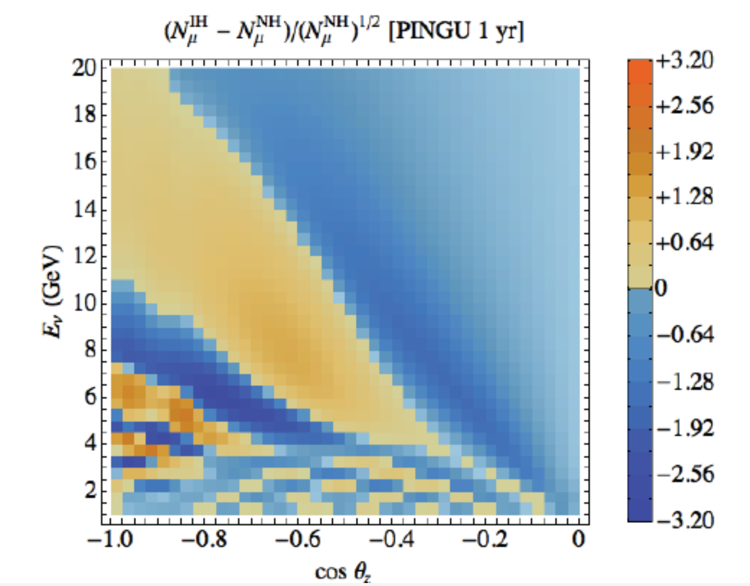
ICE-CUBE, DEEPCORE, PINGU



1. ***DeepCore is inside the IceCube. It has 8 special high density PMT strings + 12 regular IC strings adjacent to it. Depth => 2.1 Km water equivalent.***
2. ***30 Megaton Detector, E_{ν}= 10 GeV threshold.***
3. ***Will collect about $2X10^5$ atmospheric neutrinos per year.***
4. ***PINGU – more strings – 2 MT at 2 GeV and 20 MT at 20 GeV***

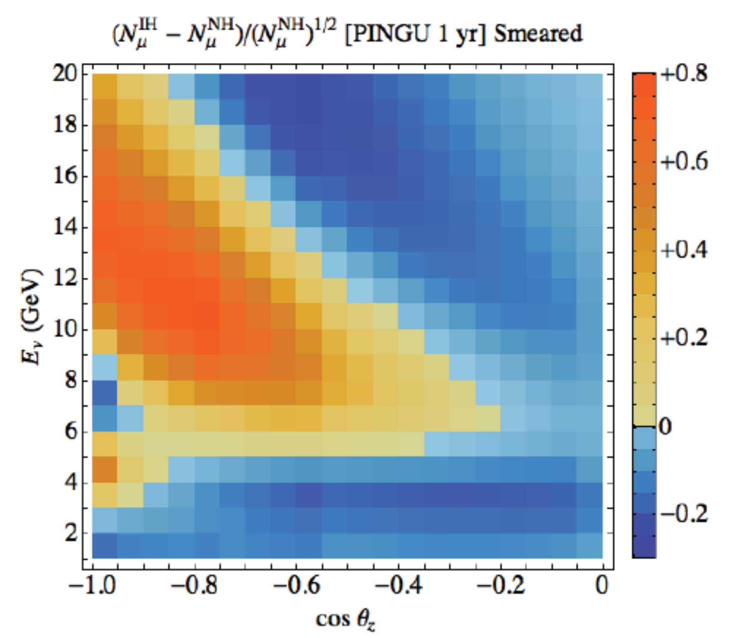
PINGU – Phased IceCube next Generation Upgrade





arXiv:1205.7071v5 [hep-ph] 2Dec 2012

Akhmedov, Razzaque and Smirnov have claimed that PINGU can do mass hierarchy to better than 3sigma in 5 years. Exact sensitivity will depend on energy and angular resolution.



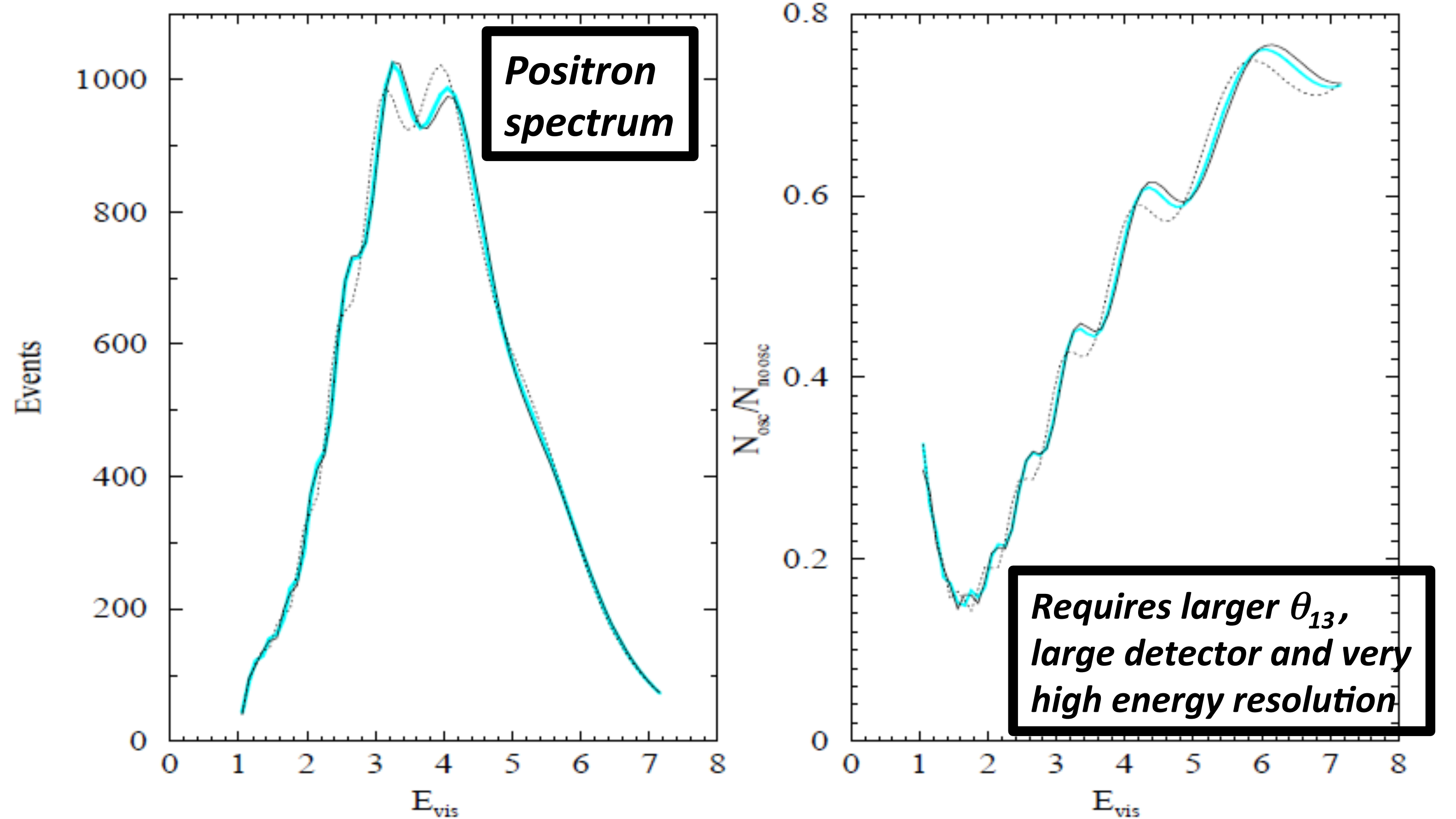
Reactor Neutrinos

Mass Hierarchy

Daya-Bay

Mass Hierarchy – DAYA BAY

arXiv:hep-ph/0306017v1 2 Jun 2003



Positron spectrum

Requires larger θ_{13}, large detector and very high energy resolution

Thick cyan line NH & $\Delta m^2_{atm} = 2.5\mathrm{X}10^{-3}\ \mathrm{ev}^2$

Dotted line IH & $\Delta m^2_{atm} = 2.5\mathrm{X}10^{-3}\ \mathrm{ev}^2$

Thin solid line IH & $\Delta m^2_{atm} = 2.6\mathrm{X}10^{-3}\ \mathrm{ev}^2$

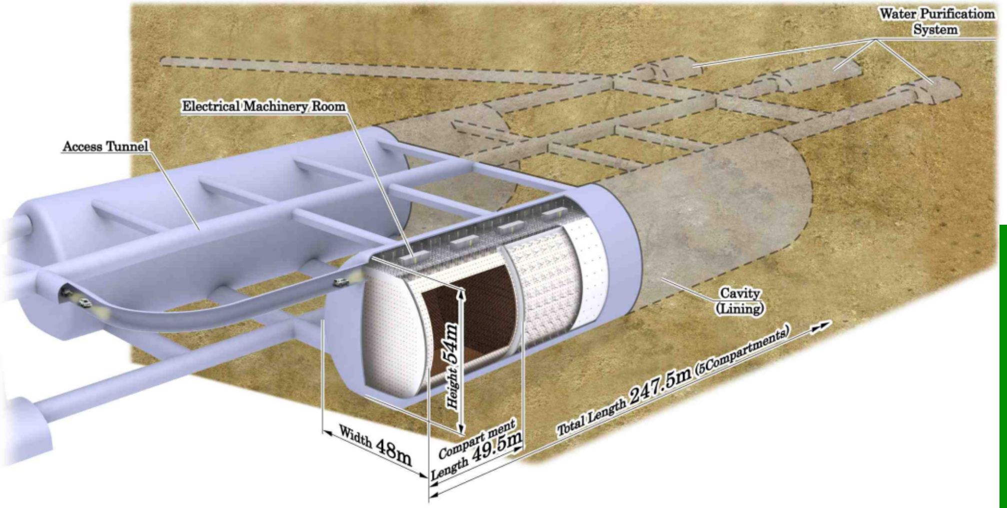
Daya Bay experiment considering detectors at 60 Km.

Petcov, Piai - 2002; Choubey, Petcov, Piai – 2003; Ghosal, Petcov – 2012; Ciuffoli, Evslin, Wang - 2012 ; Xian, Tan, Wang, Ling, Mckeown, Zhang - 2012

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

HYPER-KAMIOKANDE in JAPAN

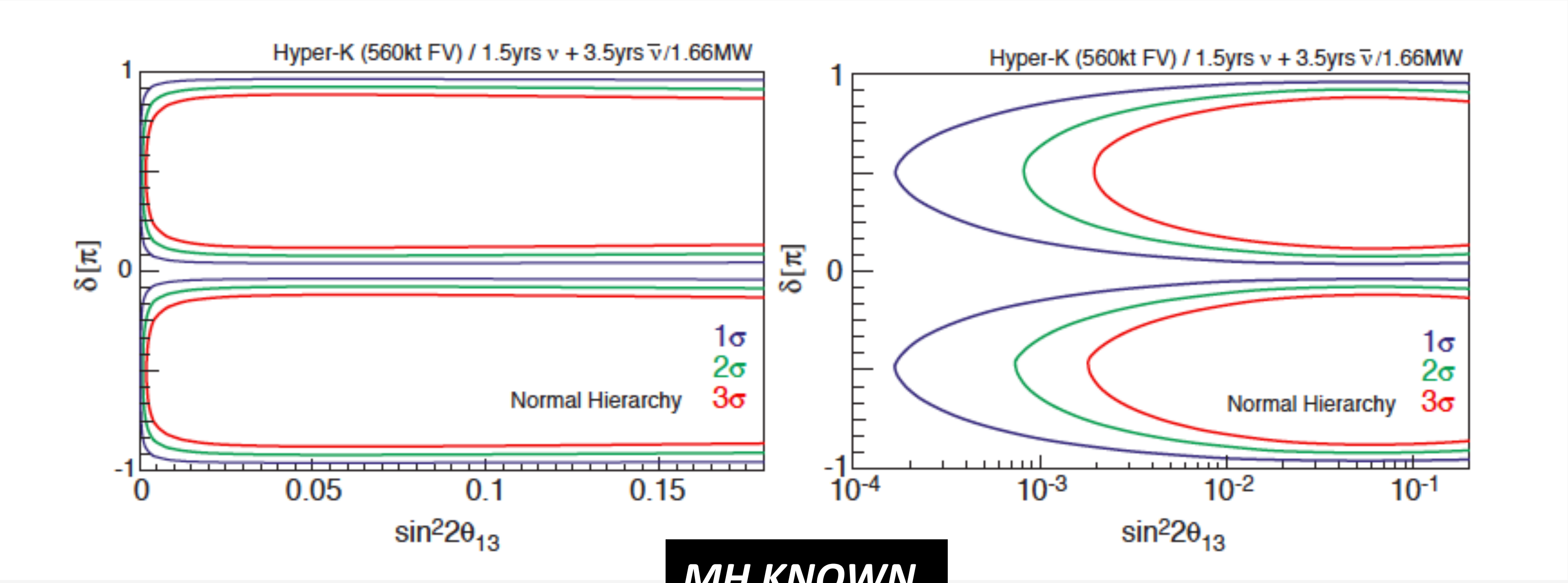
HK-LOI - arXiv:1109.3263v1 [hep-ex] 15 Sep 2011



- *2.5 degree off-axis*
- *1.66 MB Beam power (10^7 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

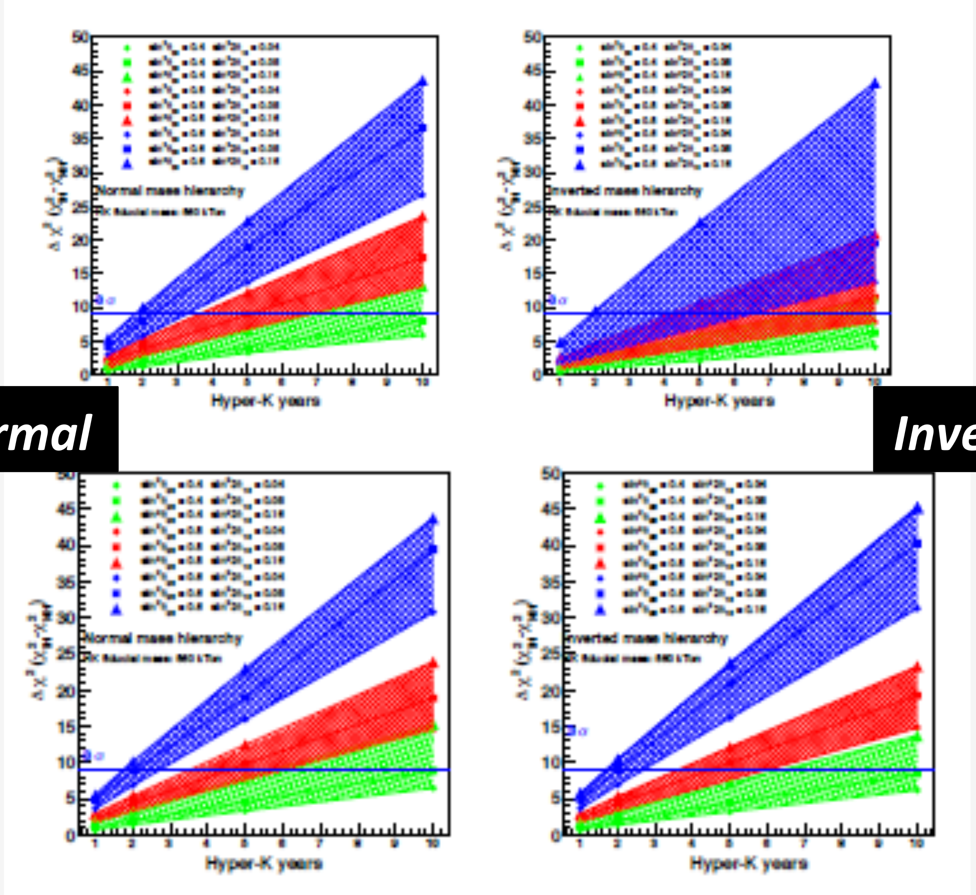


MH KNOWN

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.

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***



Normal

Inverted

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

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. Daya-Bay-II and PINGU may have a statement in the same time frame. 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