An Overview of Neutrino Physics

Srubabati Goswami

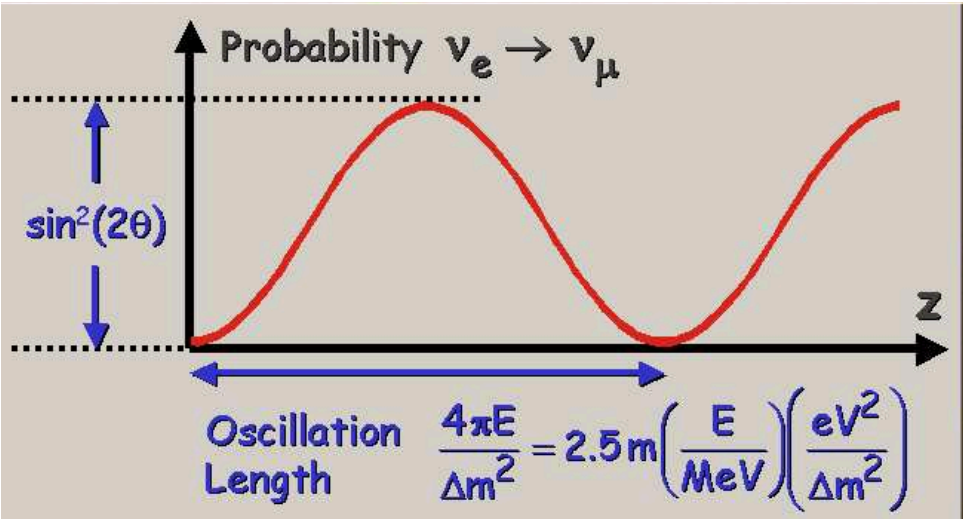
Physical Research Laboratory, Ahmedabad, India

The Outline

- Neutrino Oscillation in Vacuum
- Matter Effect
- Solar Neutrino problem and its resolution
- Atmospheric neutrino problem and its resolution
- Current Status of Oscillation Parameters
- Future Perspective

Oscilltion Probability in Vacuum

$$P_{\nu_e\nu_\mu} = \sin^2 2\theta \sin^2(\Delta m^2 L/4E) = \sin^2 2\theta \sin^2(\pi L/\lambda)$$



$\Delta m^2 = m_2^2 - m_1^2$

$\theta \rightarrow$ mixing angle

L $\rightarrow$ Distance travelled (in m/Km)

$E \rightarrow \nu$ Energy (in MeV/GeV)

- Neutrino Oscillation requires
  Non-zero neurino mass
  Non-zero mixing angles
  Oscillation effect $\Delta m^2 \sim E/L$

- Oscillation Wavelength

$\lambda = 4\pi E/\Delta m^2$

$\lambda = 2.5m(E/MeV)(eV^2/\Delta m^2)$

- $\lambda >> L, \sin^2(\pi L/\lambda) \rightarrow 0$
- $\lambda << L, \sin^2(\pi L/\lambda) \rightarrow 1/2$
- $\lambda \sim 2L, \sin^2(\pi L/\lambda) \sim 1 \rightarrow$

$\Delta m^2 \sim E/L$

Neutrino Oscillation

- Sensitivity to Δm^2 in various oscillation experiments

Experiment	Energy(E)	Distance(L)	Δm^2
Reactor	1 MeV	100m	10^{-2} eV^2
Low E Accelerator	10 MeV	100m	10^{-1} eV^2
High E Acceleraor	1 GeV	1 km	1 eV^2
Atmospheric ν	1 GeV	10,000 km	10^{-4} eV^2
Solar Neutrinos	10 MeV	10^{11} m	10^{-10} eV^2
Long-Baseline Reactor	1 MeV	1 km	10^{-3} eV ^{2}
Long-Baseline Accelerator	1 GeV	1000km	10^{-3} eV^2

Matter effects: Two Flavours

- Mass eigenvalues in matter :
  $\frac{m^2_{1m,2m}}{2E} = \frac{1}{2E}\left(\frac{A}{2} \mp \frac{1}{2}\sqrt{(\Delta m^2 \cos 2\theta - A)^2 + (\Delta m^2 \sin 2\theta)^2}\right)$

- The mass squared difference in matter:
  $\Delta {m_m}^2 = \sqrt{A - \Delta m^2 \cos 2\theta)^2 + \sin^2 2\theta}$

- Effective mixing angle θ_M in matter :

$$\tan 2\theta_M = \frac{\Delta m^2_{21} \sin 2\theta}{\Delta m^2_{21} \cos 2\theta - A}$$

$$\Delta m^2 \cos 2\theta = A = 2\sqrt{2} G_F n_e,$$

$\theta_M \to \pi/4$ MSW Resonance

L. Wolfenstein, PRD **17**, 1978

S.P. Mikheyev, A.Yu. Smirnov, SJNP **42**, 1985

- Mixing angle Maximal
- Mass squared difference in Matter Minimal

Intrinsic Neutrino Properties Δm^2, θ

- Survival probability in constant density matter is
  $P^m_{ee} = 1 - \sin^2 2\theta_m \sin^2\left(\frac{\Delta m^2_m L}{4E}\right)$

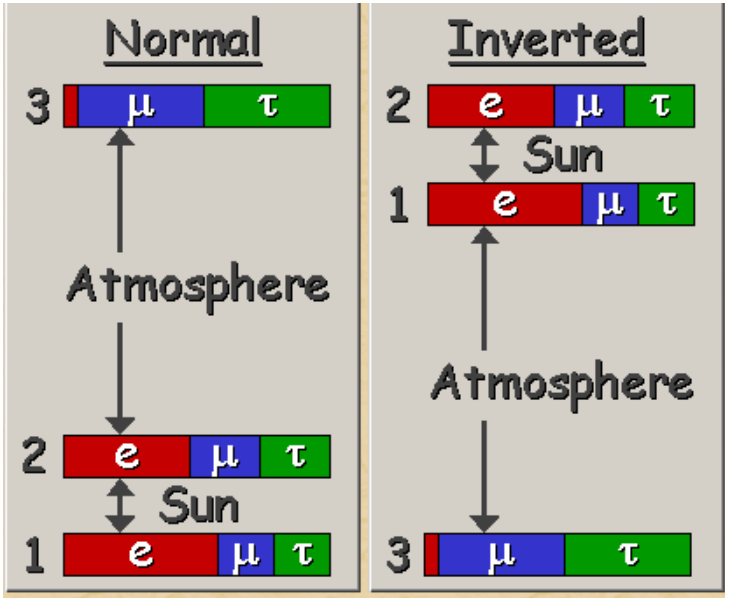
Three Neutrino oscillation parameters

- 9 unknown parameters for three neutrino flavours
  - 3 masses, m_1, m_2 and m_3
  - 3 mixing angles
  - 3 phases

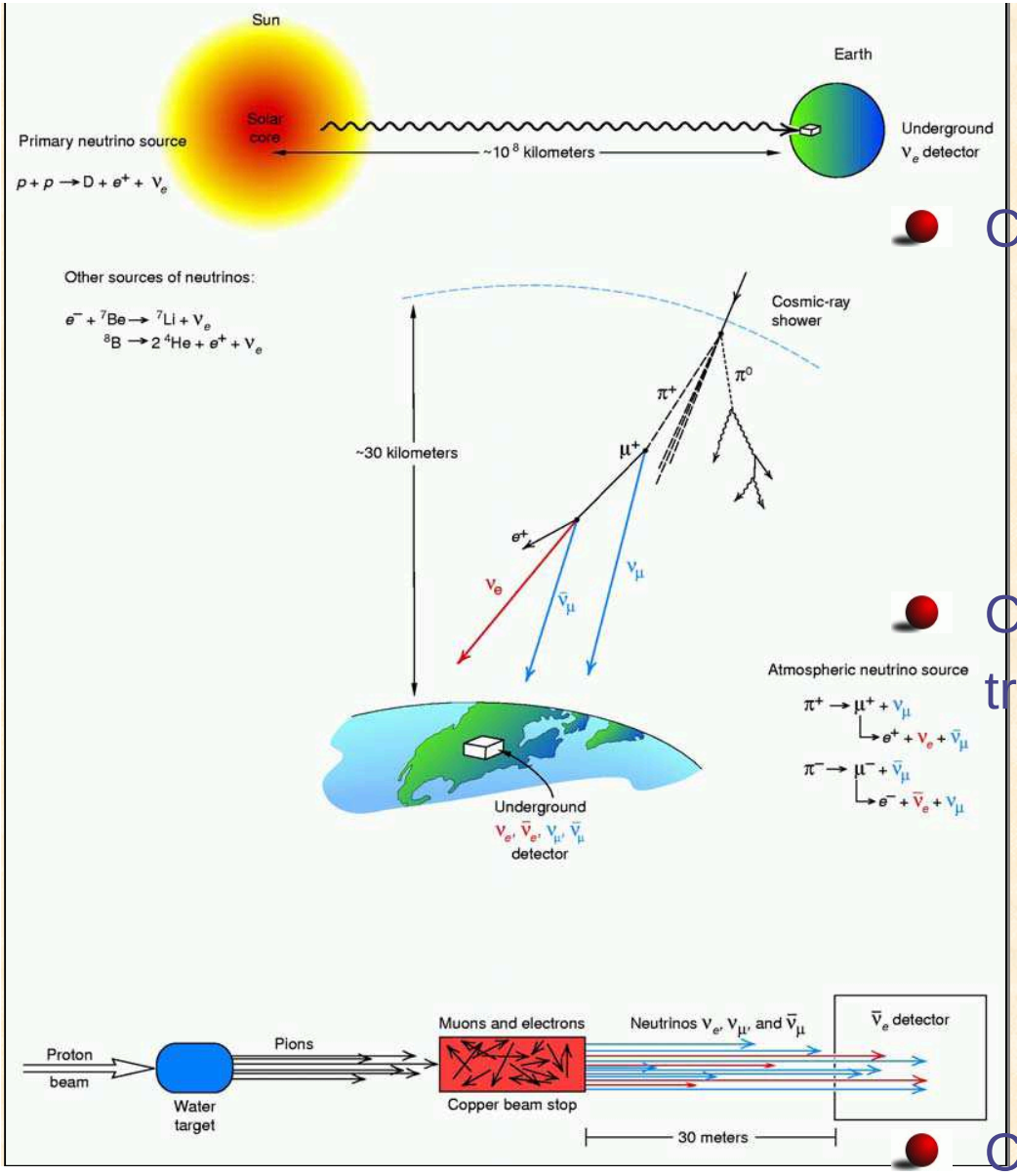
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & e^{-i\delta}s_{13} \\ & 1 & \\ -e^{i\delta}s_{13} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\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

$c_{12} = \cos\theta_{12}$ etc., δ CP-violating phase

- Oscillation experiments – sensitive to mass squared differences
- Solar : $\Delta m^2_{21} = m^2_2 - m^2_1$, θ_{12}
- Atmospheric : $\Delta m^2_{31} = m^2_3 - m^2_1$, θ_{23}
- Reactor Neutrinos : θ_{13}
- For small θ_{13} approximate 2 generation works



Experimental Evidences for Neutrino Oscillation



Solar Neutrinos

- Confirmation from reactor neutrinos

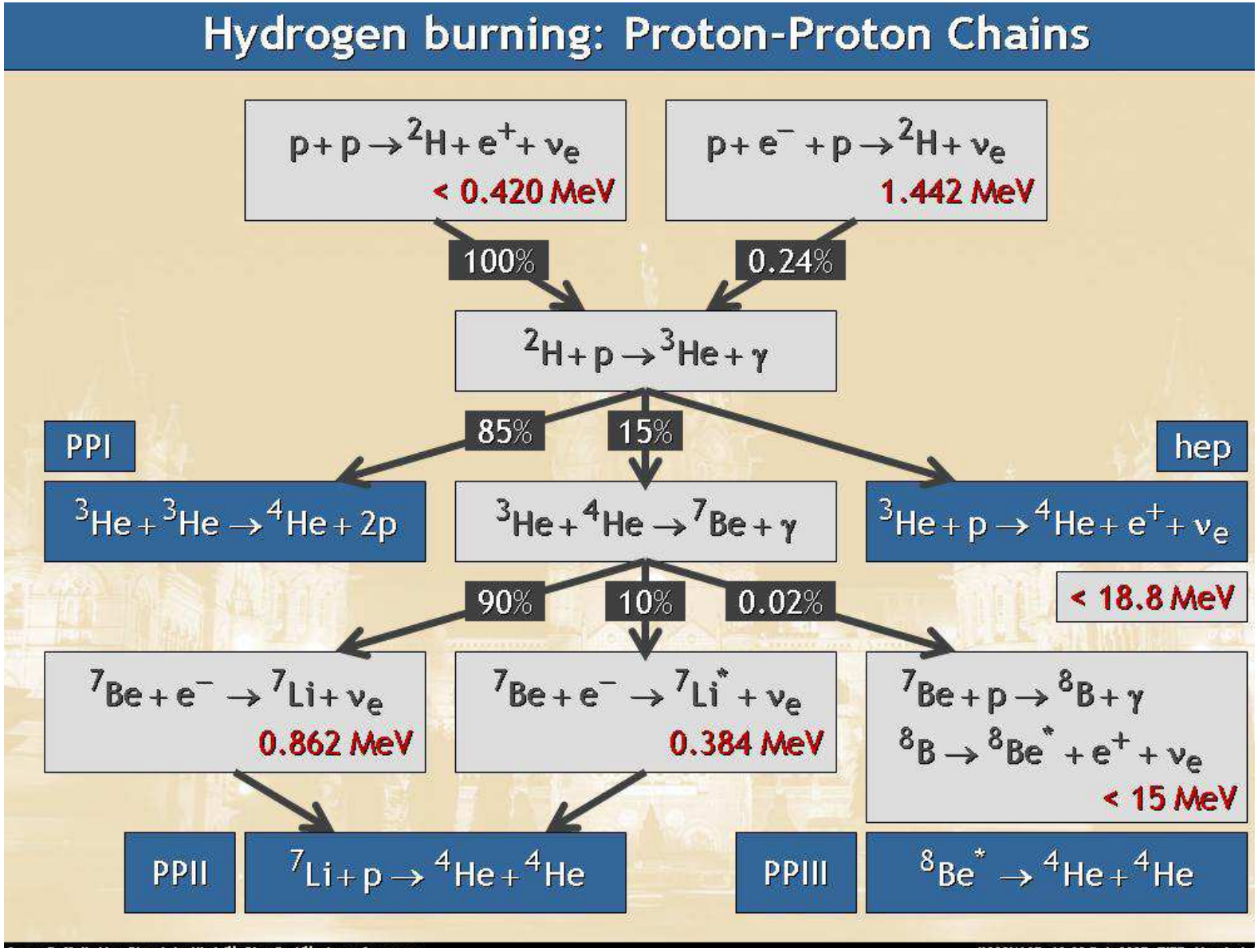
Atmospheric Neutrinos

- Confirmation from accelerator neutrinos

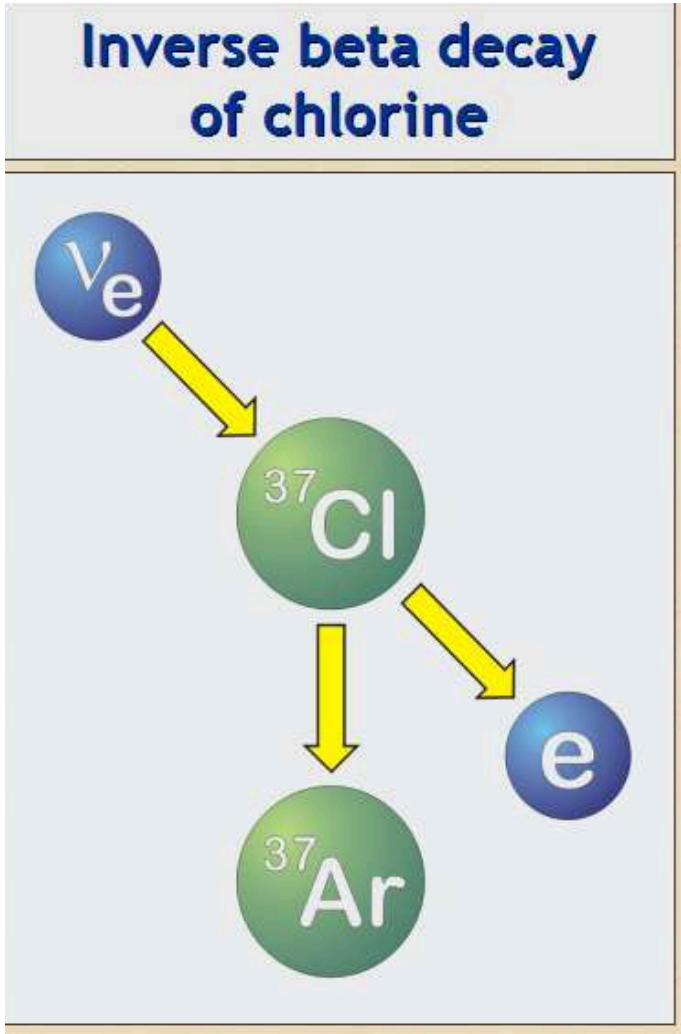
LSND Experiment

- Confirmation from MiniBoone (?)

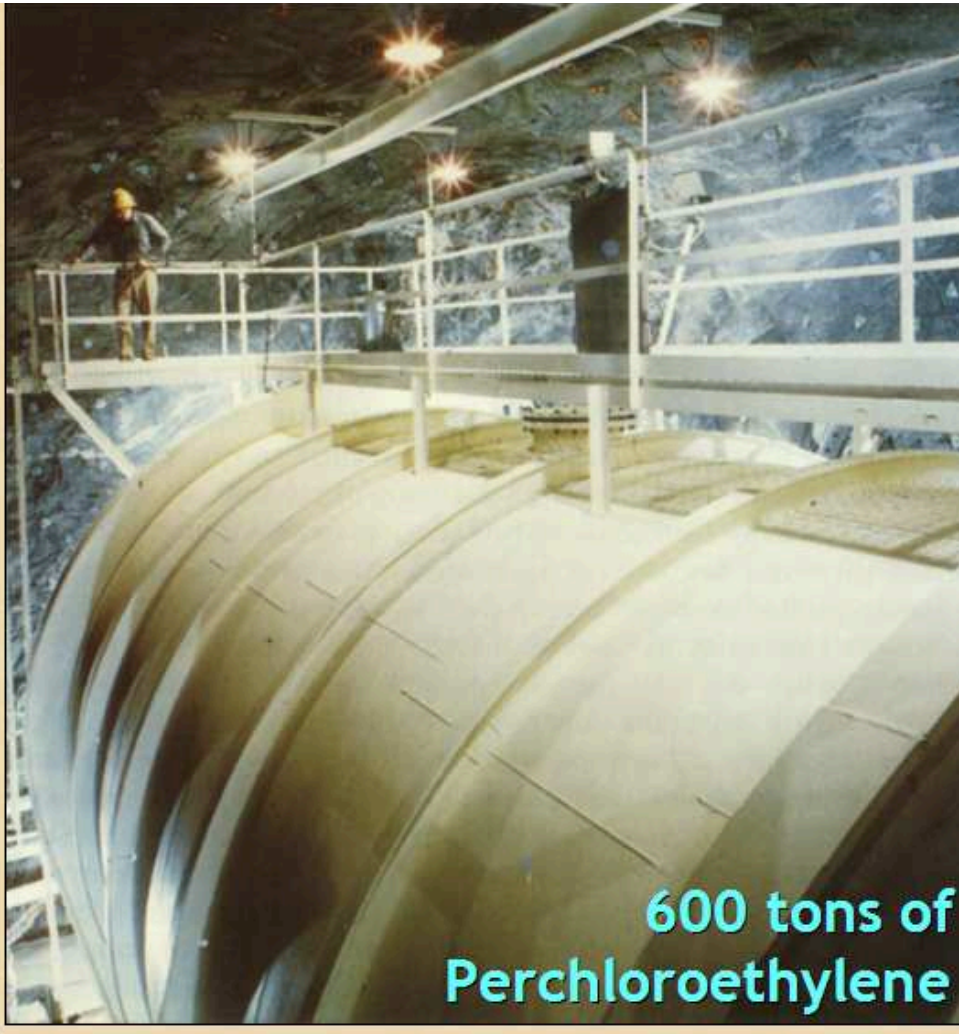
Nuclear Reaction inside the Sun



First Detection of Solar Neutrinos



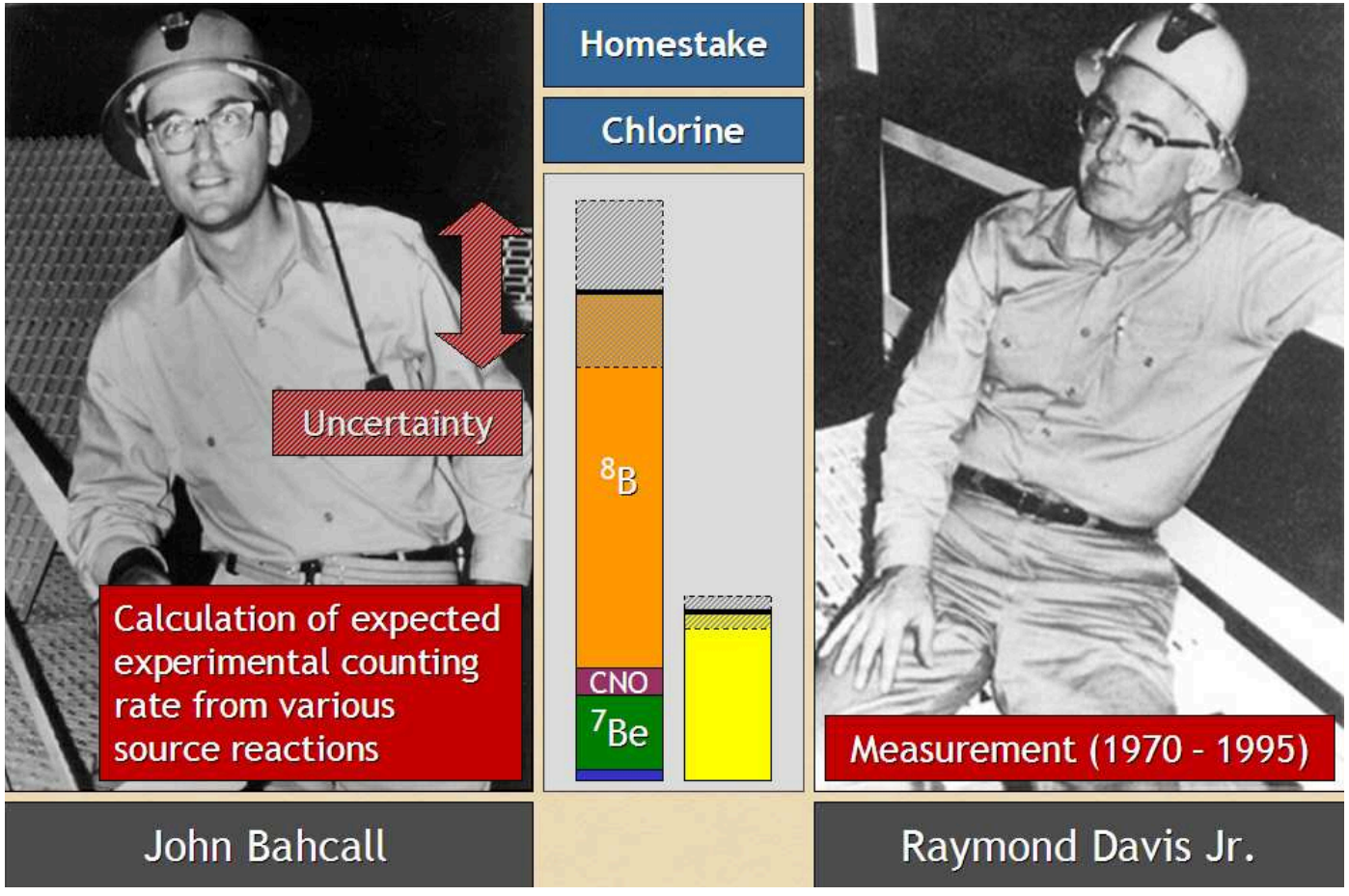
Radiochemical Method



Homestake solar neutrino observatory (1967–2002)

First Detection of Solar Neutrinos

- Pioneered by John Bahcall and Raymond Davies
- To and verify the hypothesis of energy generation in stars



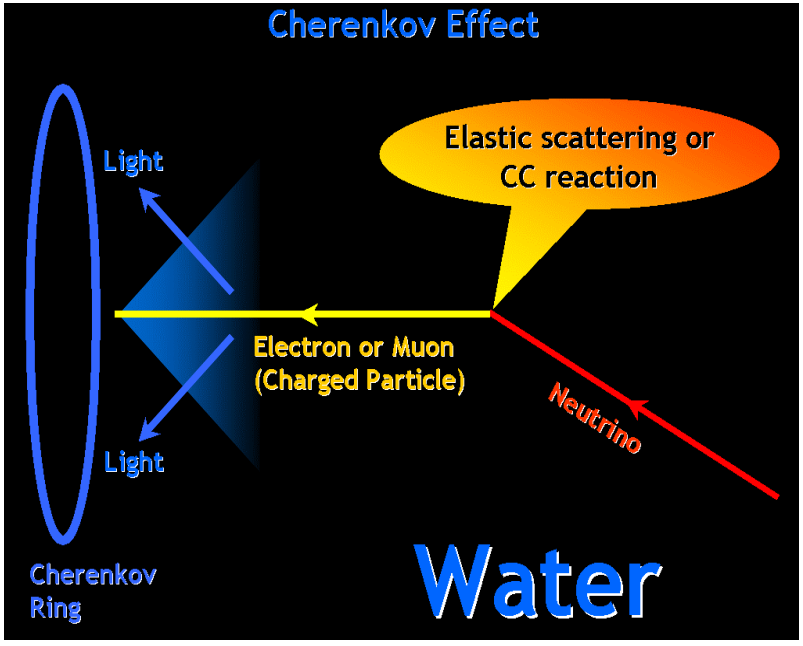
- Only $\frac{1}{3}$ rd of the predicted solar electron neutrinos observed

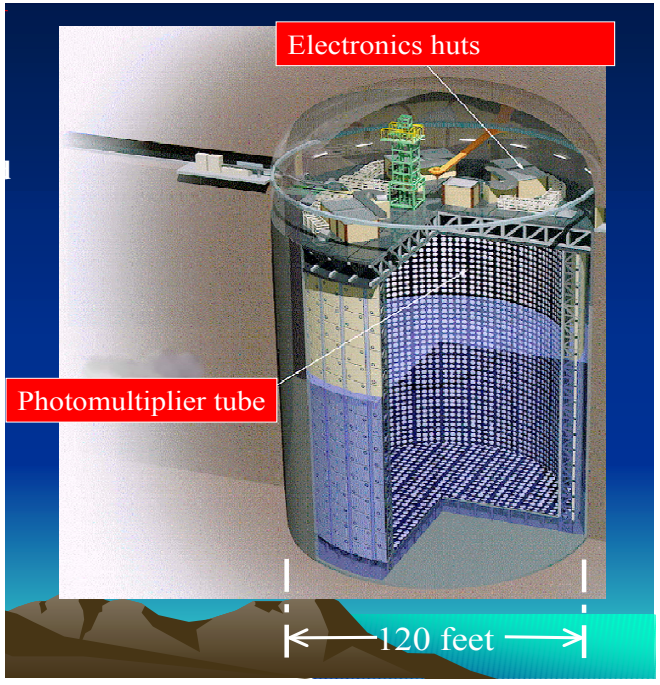
Where are the missing solar neutrinos going ?

The Infamous "Neutrino-burglar"

- The experiment is wrong – difficult to detect a handful of Ar atoms
- Solar Model calculations are wrong
- Solar electron neutrinos getting converted to muon or tau neutrinos
- New Experiments were planned to check the above results

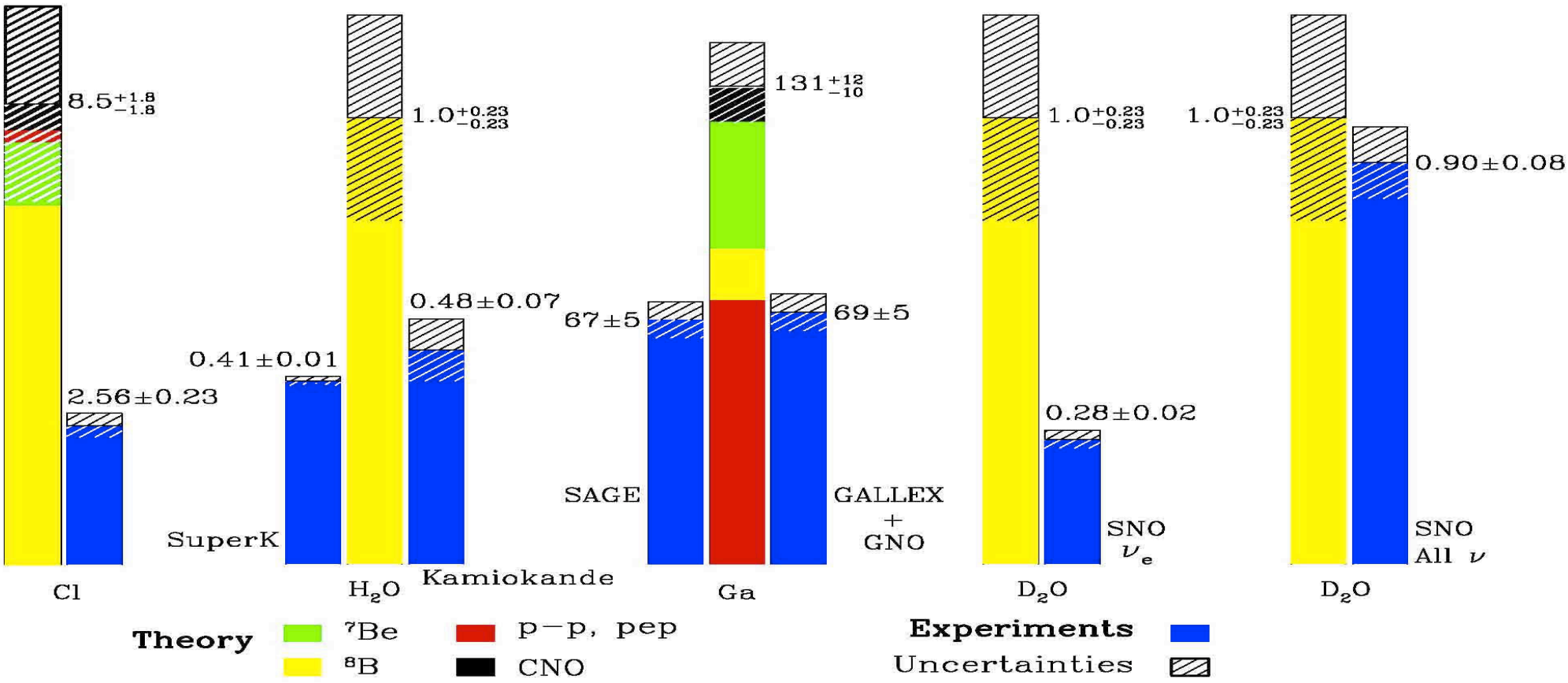
Solar Neutrino Experiments





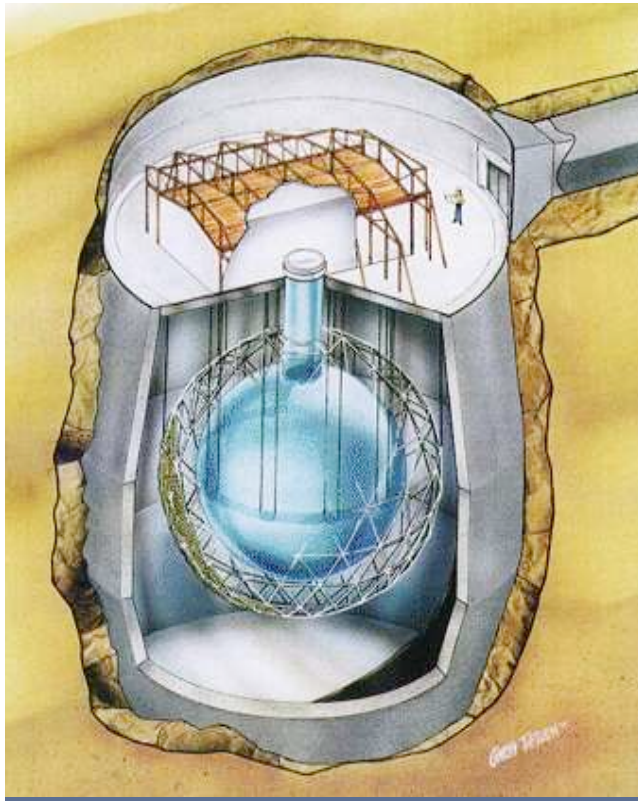
- $e^- + \nu_x \rightarrow e^- + \nu_x$
- Detection of Solar neurinos in real time
- KamioKande, Japan (1991)
- SuperKamiokande (1991-)
  - 50,000 ton of purified water
  - 3000 feet underground Japaneese Alpse
  - 13,000 photomcultiplier tubes

Solar Neutrinos: Experimental Results



- Observed ν_e flux $<$ Theoretical Prediction $\rightarrow$ solar Neutrino Problem
- Remained unresolved for 30 years

Sudbury Neutrino Observatory



- 1000 Tonnes Heavy Water (D_2O)
- 7000 feet underground in Sudbury Mine Canada
- 10,000 photomultiplier tubes

CC $d + \nu_e \rightarrow p + p + e^-$

NC $d + \nu_x \rightarrow p + n + \nu_x$

$$\frac{CC}{NC} = \frac{\nu_e}{\nu_e + \nu_\mu + \nu_\tau} < 1$$

$\longrightarrow$ indicates conversion of ν_e to ν_μ, ν_τ

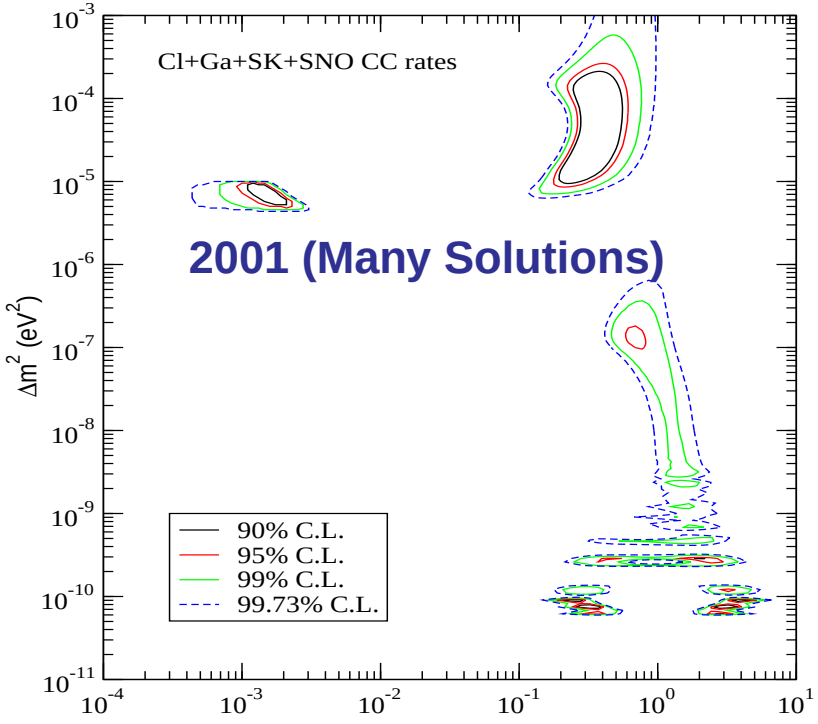
7σ evidence for a non-zero $\nu_{\mu,\tau}$ flux from SUN

Solution to the Solar Neutrino Problem

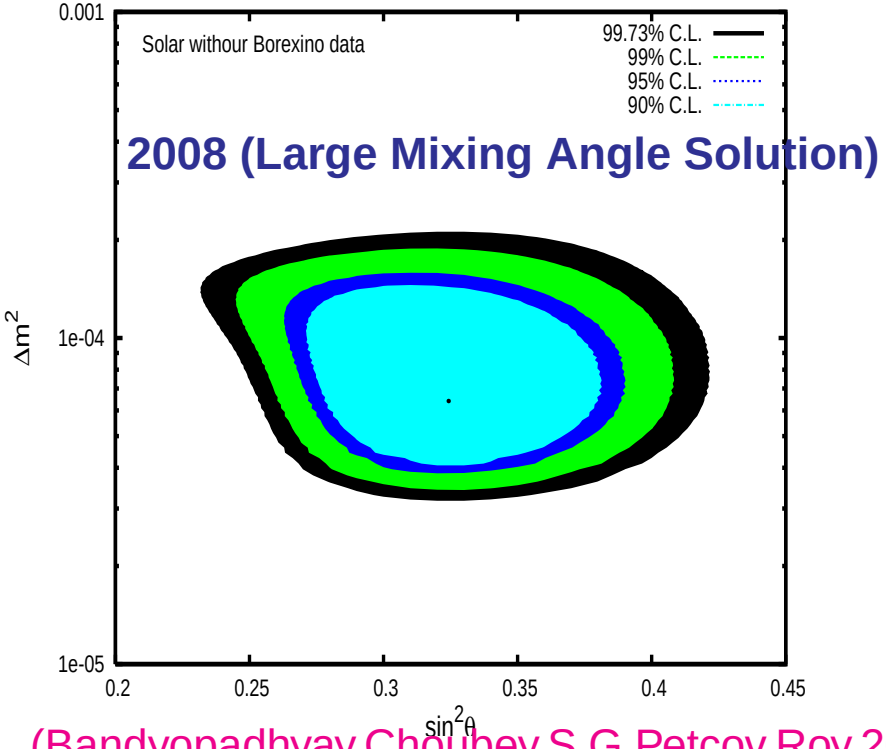
- Neutrinos undergo MSW resonant flavour conversion of ν_e inside the sun

$$\Delta m^2_{21} \cos 2\theta_{12} - 2\sqrt{2} G_F n_e E = 0$$

- Sensitive to the sign of Δm^2_{21}



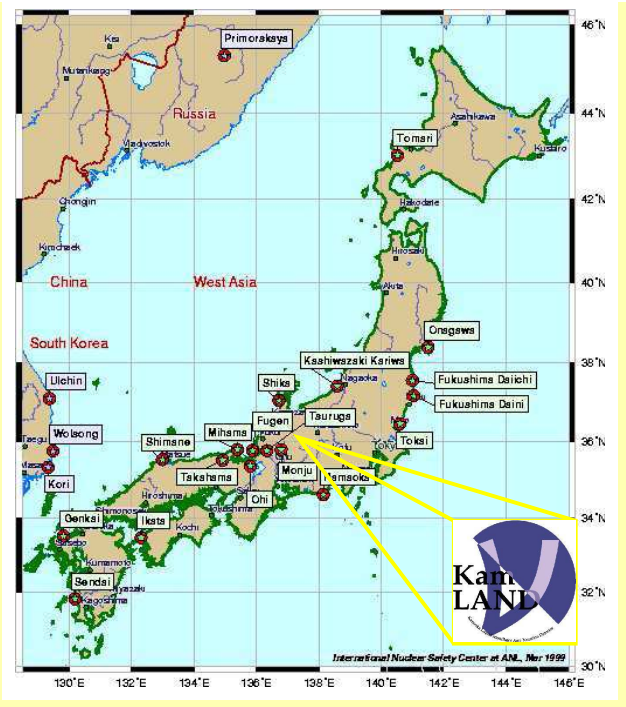
(Bandyopadhyay,Choubey,S.G,Kar,PLB,2001)



(Bandyopadhyay,Choubey,S.G,Petcov,Roy,2008)

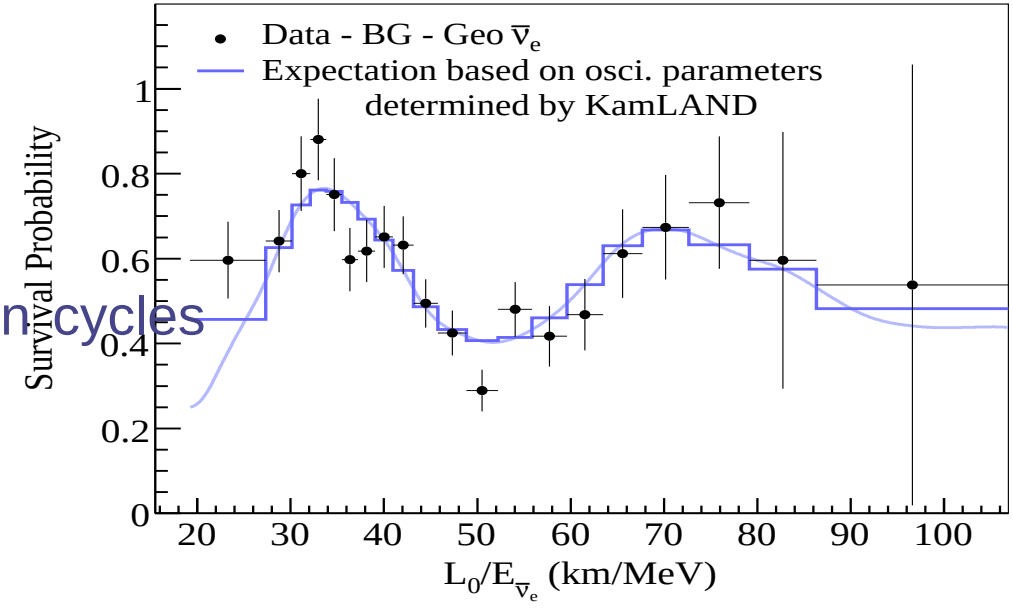
Confirmed by KamLAND experiment using reactor neutrinos

KamLAND



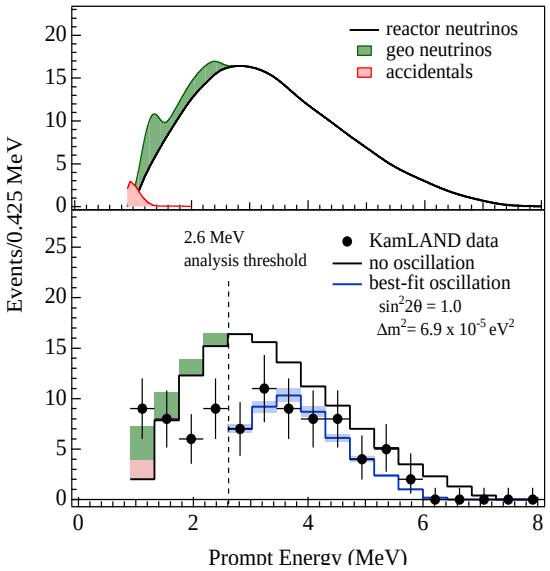
- 1 kton liquid scintillator neutrino detector at Kamioka, Japan
- detects antineutrinos coming from Japaneese nuclear reactors through: $\bar{\nu}_e + p \rightarrow n + e^+$
- $E_\nu \sim$ 3 MeV, L $\sim$ 1.8 $\times 10^5$ m , $\Delta m^2 \sim 1.6 \times 10^{-5}$ eV^2

- Data: 2002 - 2007
- Almost two complete oscillation cycles are observed

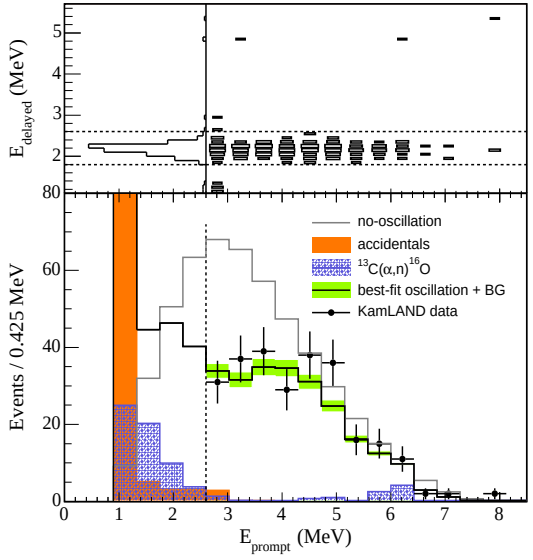


Impact of KamLAND on Oscillation Parameters

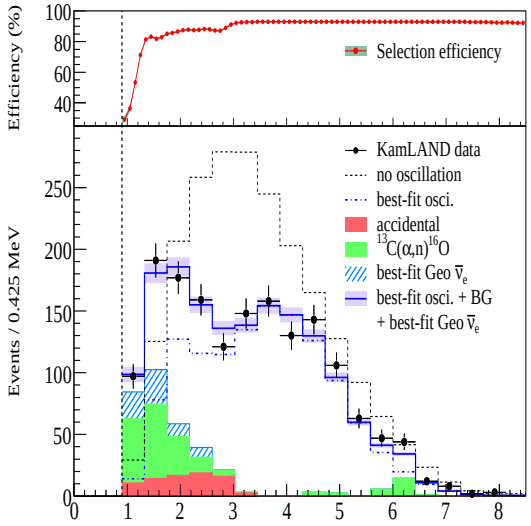
2003

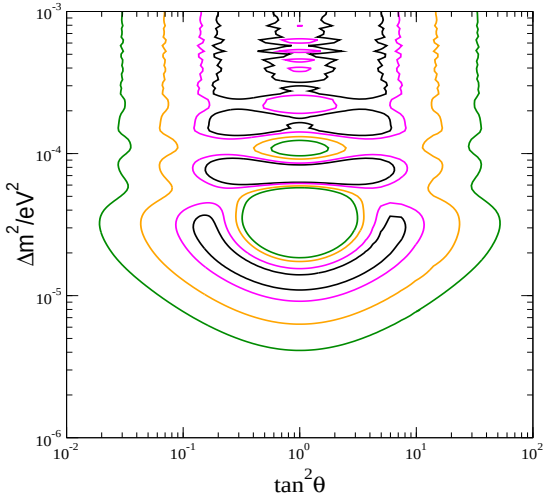


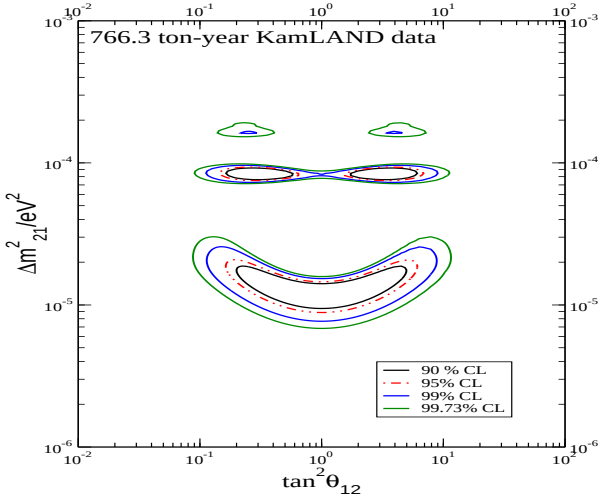
2004



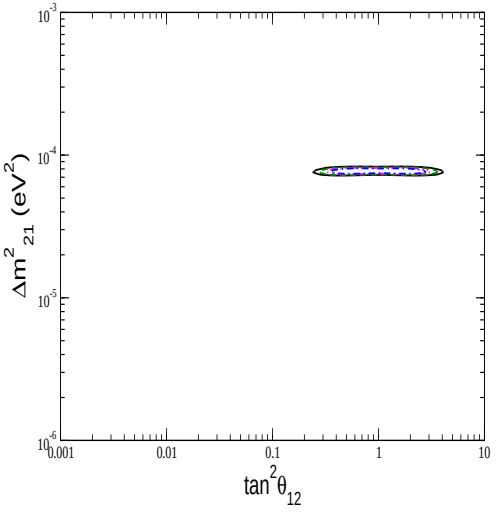
2007





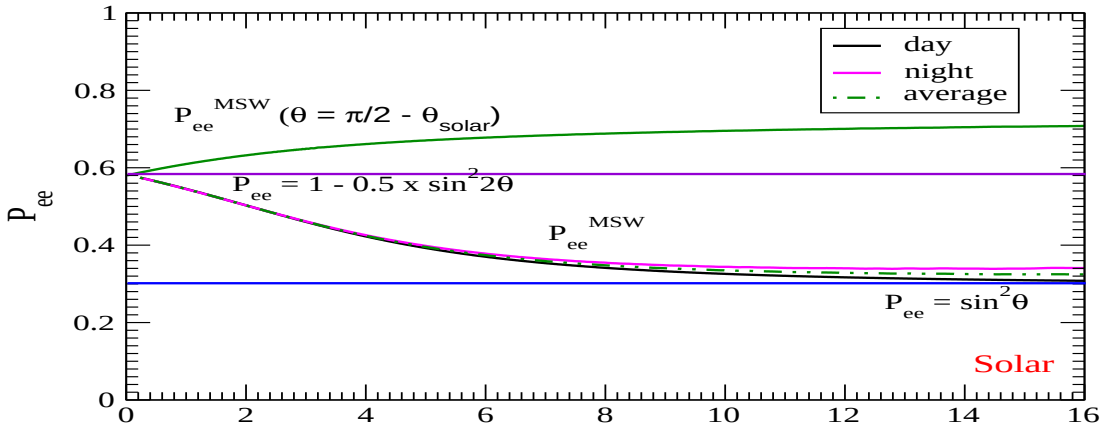


KamLAND (2007)



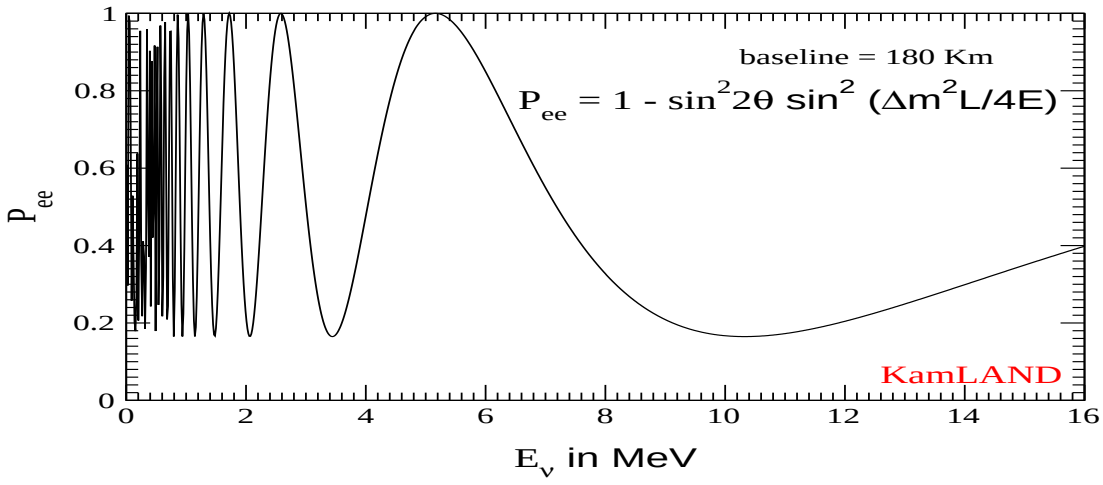
Bandyopadhyay,Choubey,Goswami,Petcov,Roy 2003, 2005, 2008

Survival Probabilities for solar and KamLAND



Solar Neutrinos

Δm^2_{21} effects are averaged out



KamLAND

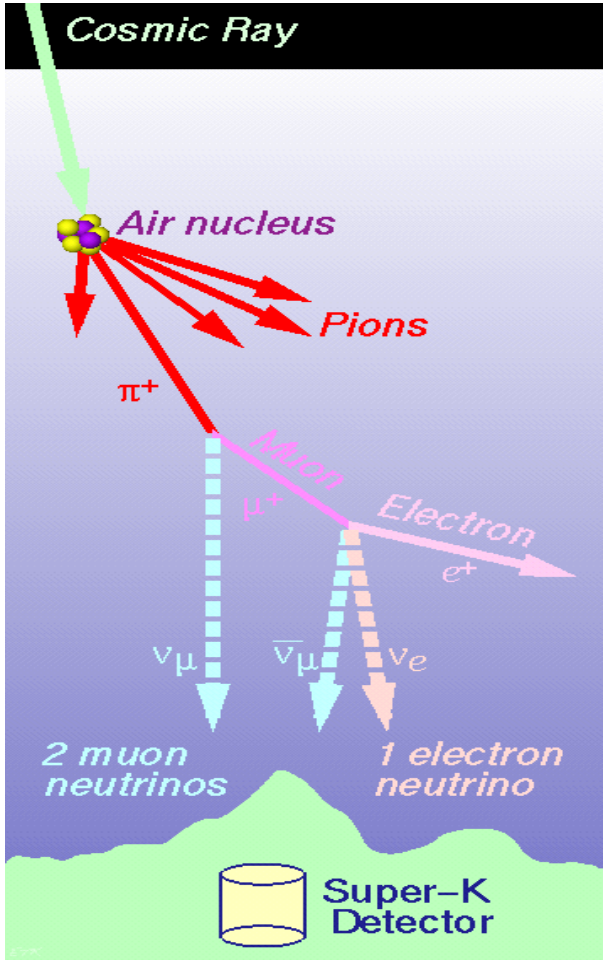
can probe the L/E dependence of the oscillations in the LMA region $\rightarrow$ unprecedented sensitivity to Δm^2

Atmospheric neutrinos . . .

Cosmic Ray + $A_{air} \rightarrow \pi^+ + \ldots$

$\pi^+ \rightarrow \mu^+ + \nu_\mu$

$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$



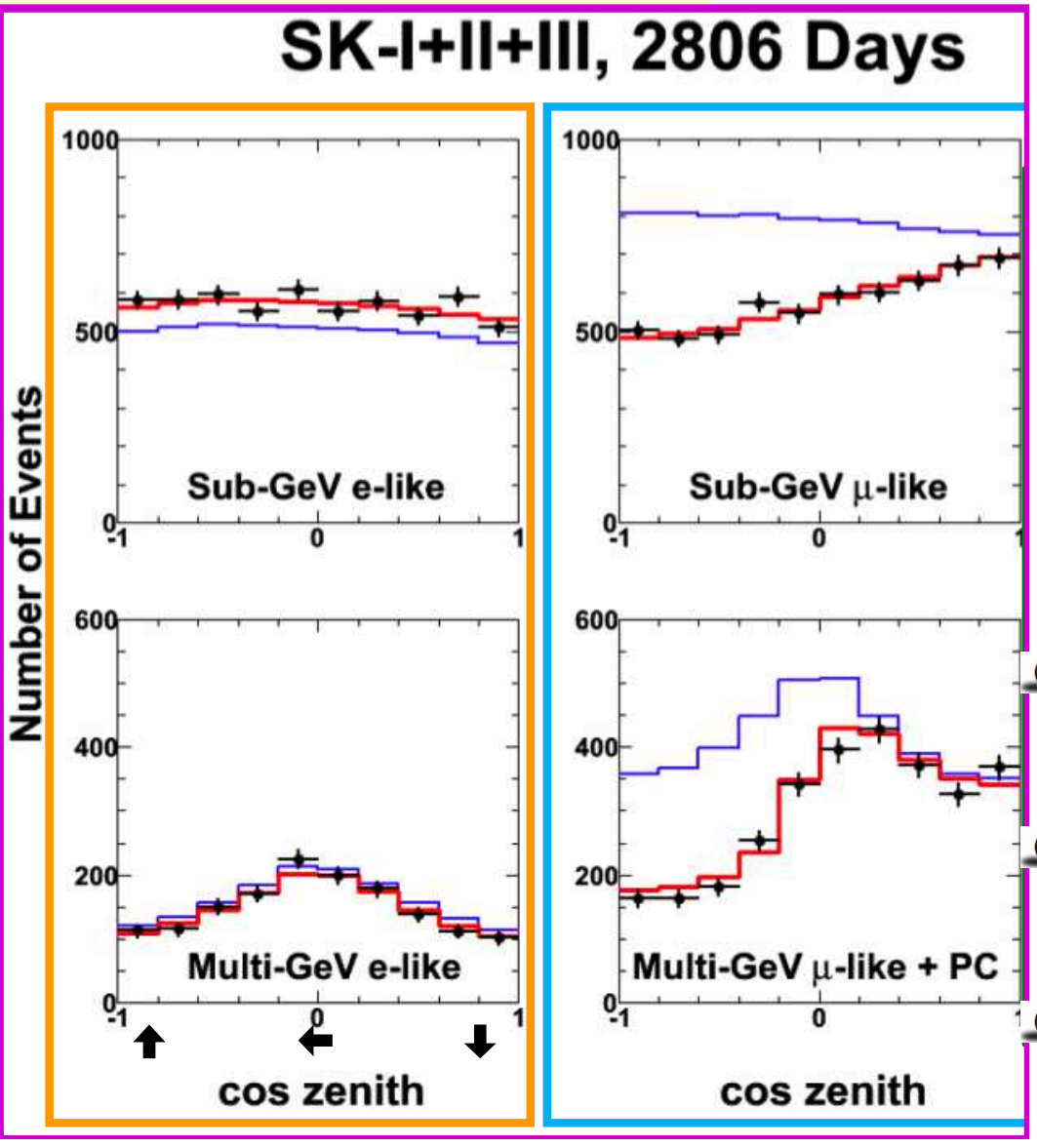
- Energy: 100 MeV - TeV
- Pathlength: 15 -13,000 km
- Provides broad L/E band

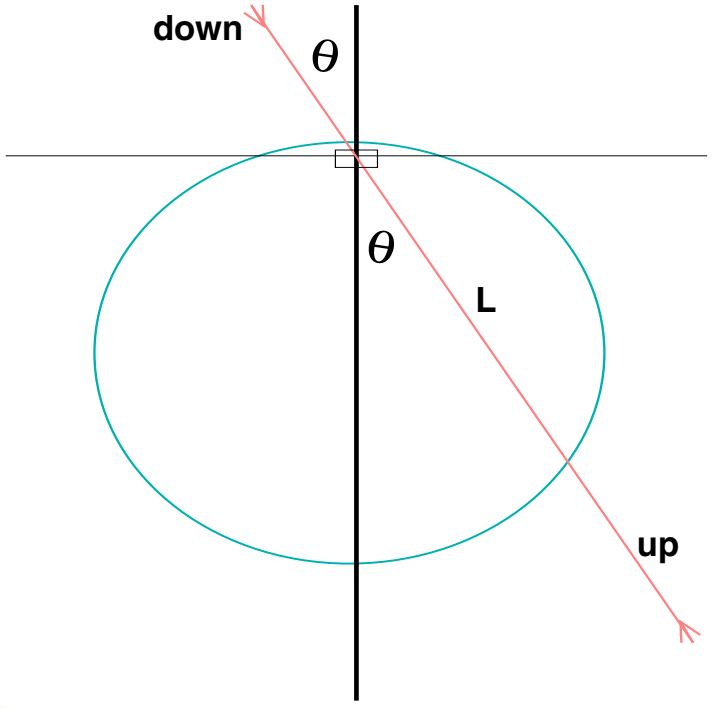
$\Longrightarrow \nu_\mu$ conversion

$\nu_\mu : \nu_e$ = 2: 1 (expected)

$\nu_\mu / \nu_e \sim$ 0.9 – 1 (observed)

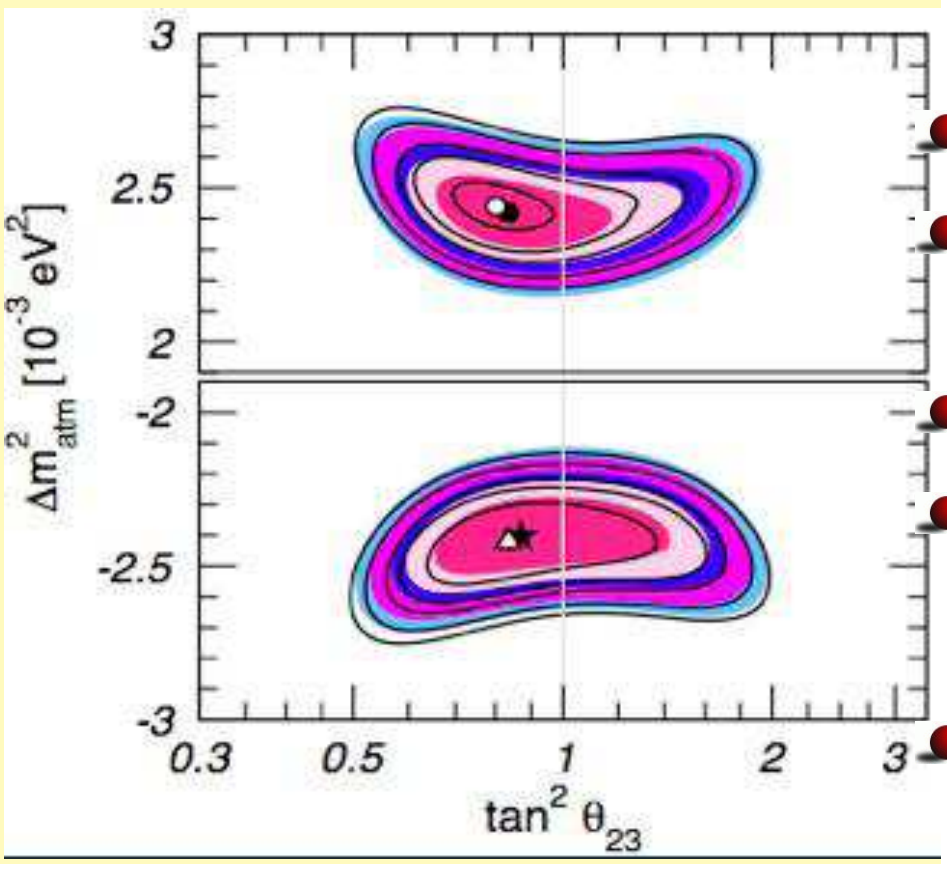
Detection of Atmospheric neutrinos at SK





- μ-events less than theoretical prediction
- The flux is up-down symmetric for E $>$ a few GeV
- Up-down asymmetry in multi-GeV μ-events $\Longrightarrow$ neutrino oscillations

Solution to the Atmospheric Neutrino Problem



- Neutrinos have mass and mixing
- Dominant solution $\nu_\mu - \nu_\tau$ oscillation in vacuum
- Not very sensitive to matter effects
- Relevant probabaility

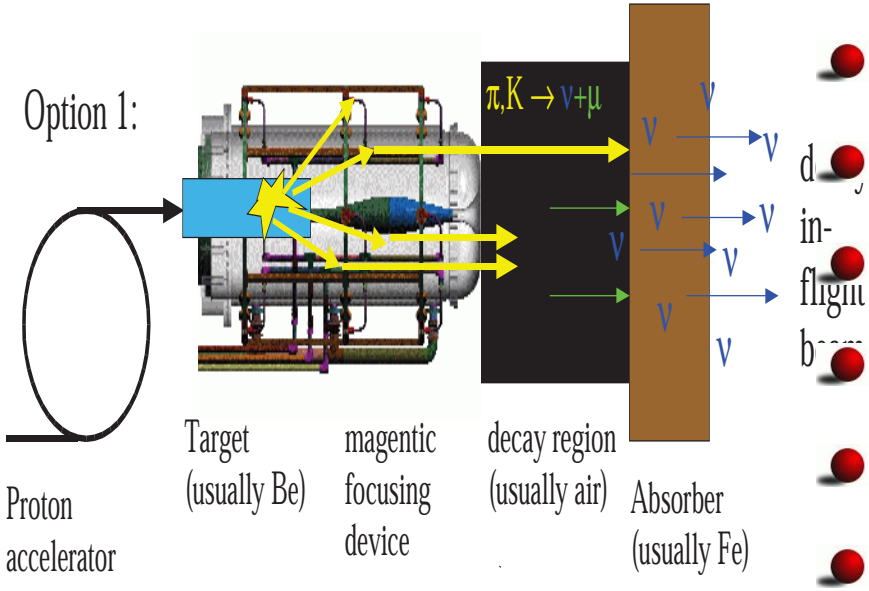
$$P_{\mu\mu} = 1 - \sin^2 2\theta_{23} \sin^2 \left(\frac{\Delta m^2_{31} L}{4E} \right)$$

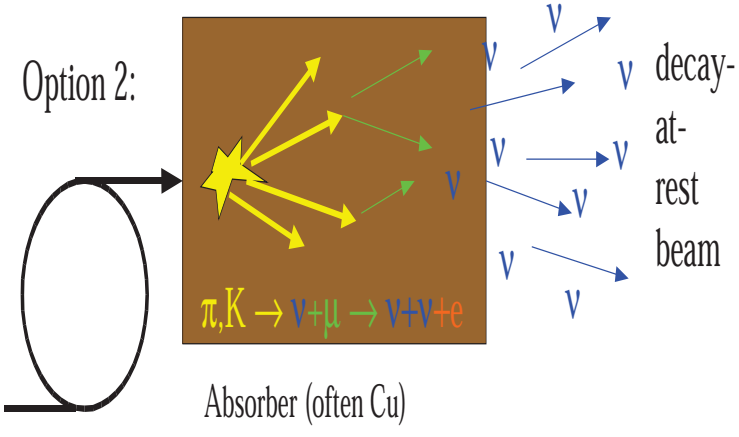
- No information on $|(\Delta m^2_{31})|$.

Fogli. et al., 2012

Long Baseline Accelerator Experiments

Making Neutrino Beams at Proton Accelerators





- Beam with well known properties
- Tune L/E to study interesting Δm^2
- Distance $>$ 100 km
- L is a particular choice
- E is always a distribution
- Decay at rest: $E_{max} \sim 50GeV$
- Decay in flight $E_{max} \sim 100GeV$

Long Baseline Accelerator Experiments: T2K

- Beam with well known properties from J-PARC
- Long Baseline Distance $\sim$ 295 km
- L/E $\sim$ 500 GeV to study Δm^2_{atm}

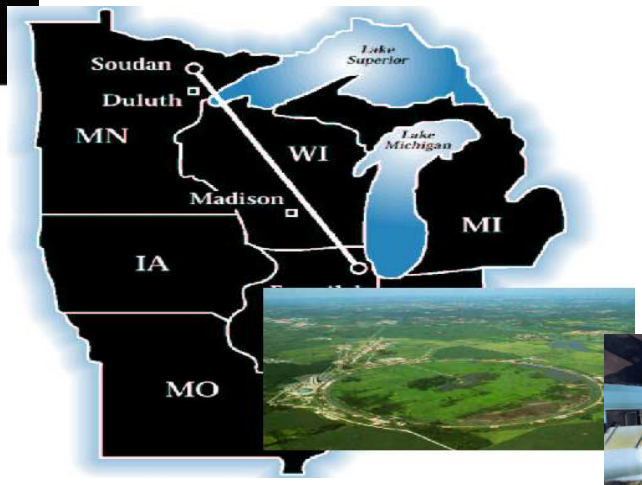
Physics Goals

- ν_e apperance $\Longrightarrow \theta_{13}$
- ν_μ disapperance $\Longrightarrow \Delta m^2_{31}, \theta_{23}$

Confirmed the atmospheric neutrino oscillations using man-made sources

Long Baseline Accelerator Experiments: MINOS

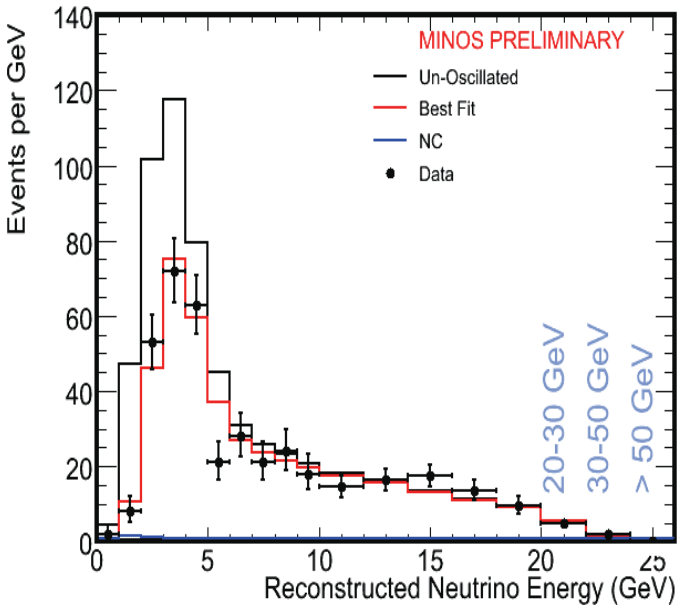
- Beam with well known properties
- Long Baseline Distance $>$ 100 km
- L/E $\sim$ 500 GeV to study Δm^2_{atm}

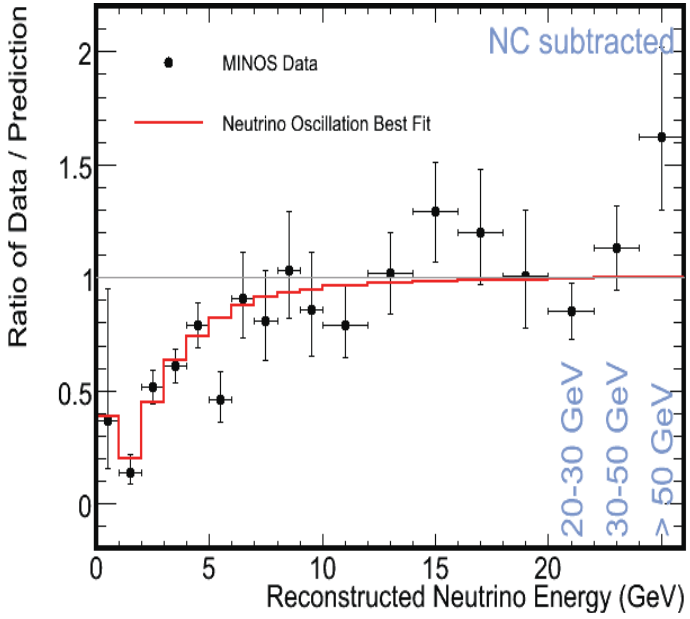


Physics Goals

- ν_μ disapperance $\Longrightarrow \Delta m^2_{31}, \theta_{23}$
- $\overline{\nu}_\mu$ disapperance $\Longrightarrow \overline{\Delta m^2_{31}}, \overline{\theta_{23}}$
- ν_e apperance $\Longrightarrow \theta_{13}$

First MINOS Result

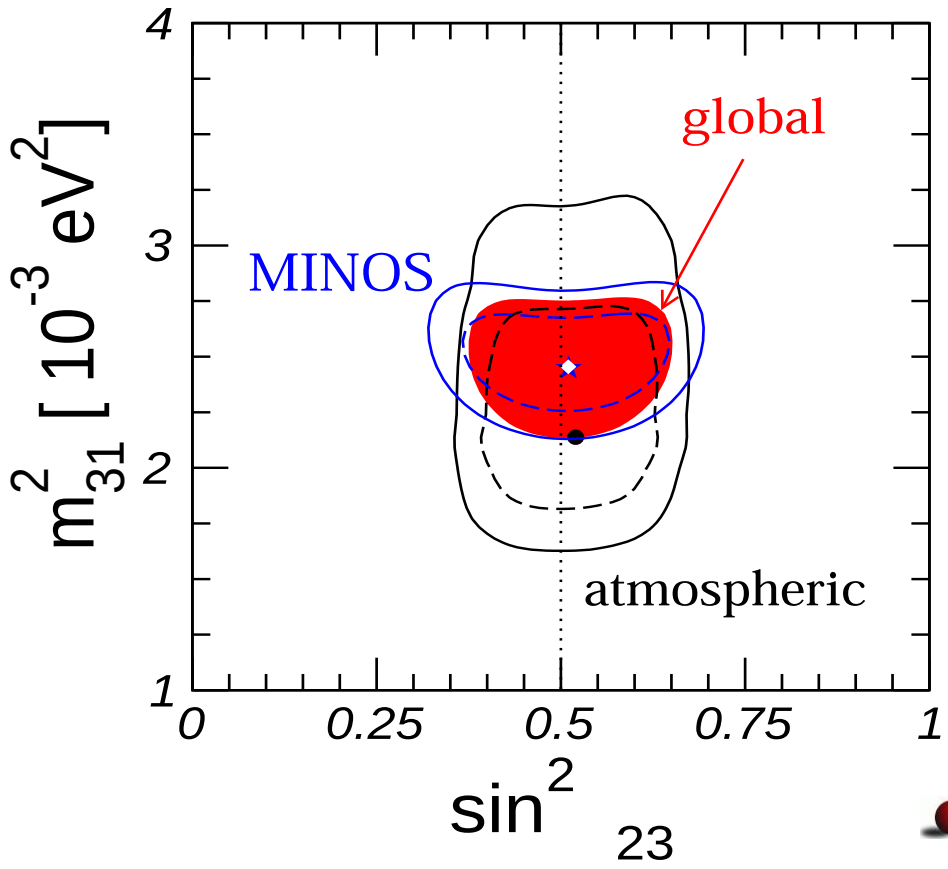




MINOS and K2K confirmed the atmospheric neutrino oscillations using man-made sources

MINOS Collaboration: arXiv:0806.2237

Atmospheric neutrino Oscillation Parameter



$|\Delta m^2_{atm}|$=2.4$\times 10^{-3}$eV^2
$\sin^2\theta_{23}$ = 0.5

- Two generation $\nu_\mu - \nu_\tau$ oscillation
- Matter Effect does not play role
- Relevant probabaility

  $$P_{\mu\mu} = 1 - \sin^2 2\theta_{atm} \sin^2\left(\frac{\Delta m^2_{atm} L}{4E}\right)$$

  $(\theta_{atm} \equiv \theta_{23}, \Delta m^2_{atm} \equiv \Delta m^2{}_{31})$
- $\theta_{23} - (\pi/2 - \theta_{23})$ symmetry
- No information on $sgn(\Delta m^2_{atm})$.

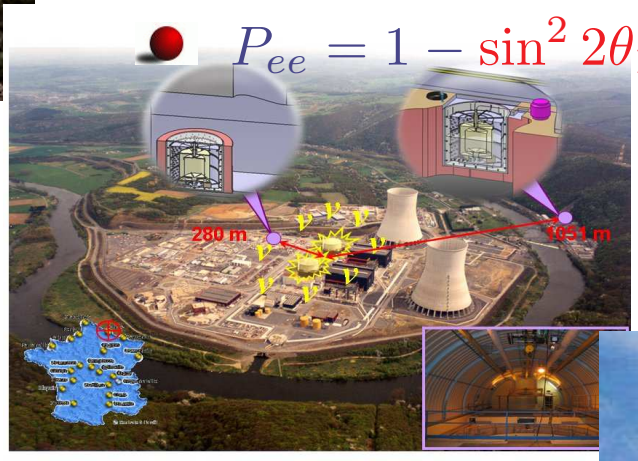
- 3σ Precision:

  $|\Delta m^2_{atm}| \sim$ 12% mainly by MINOS

  $\sin^2\theta_{23} \sim$ 24 % mainly by Atmospheric

The Last of the Mixing angles

- Till 2011 : $\theta_{13} < 13^o$
- New results from three reactor experiments
- Long Baseline: distance $\sim$ 1 km
- L/E $\sim$ Km/MeV
- $P_{ee} = 1 - \sin^2 2\theta_{13} \sin^2 4\pi E/\Delta m^2_{31}$



- $\theta_{13} \sim 9^o$

Summary of Three Neutrino Oscillation Parameters

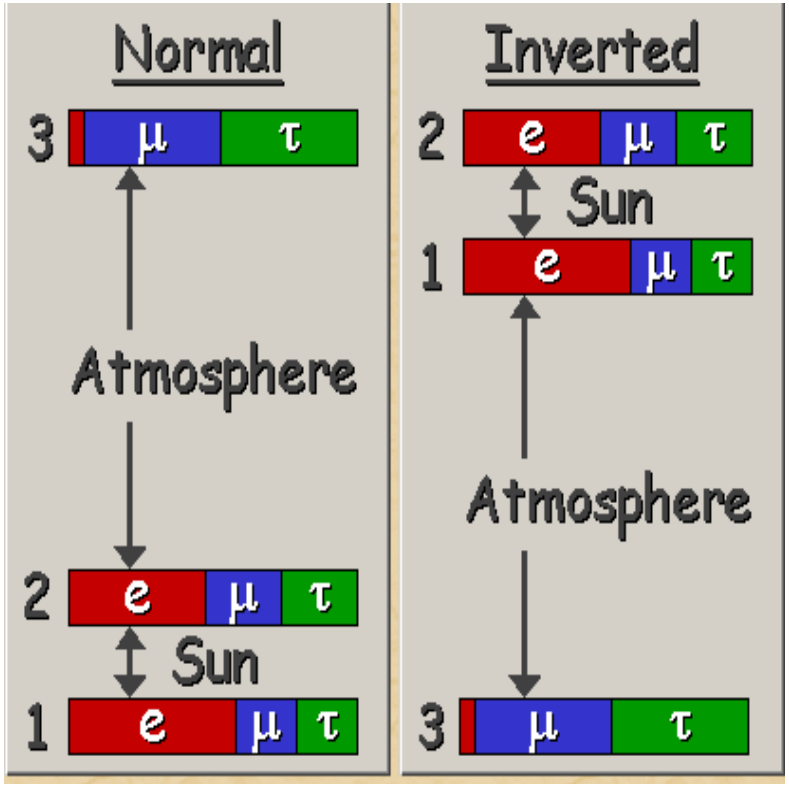
- Significant progress in measurement of neutrino oscillation parameters in the last 15 years
- The last of the unknown mixing angles θ_{13} is measured (2012)

current status of oscillation parameters

Parameter	Best fit	3σ range
$\Delta m^2_{21}(eV^2)$	7.5×10^{-5}	$(7.0 - 8.2) \times 10^{-5}$
$\lvert\Delta m^2_{31}\rvert(eV^2)$	2.4×10^{-3}	$(2.2 - 2.6) \times 10^{-3}$
$\theta_{12}(degree)$	33.6	30.6 – 36.8
$\theta_{23}(degree)$	38.4	35.1 – 53.0
$\theta_{13}(degree)$	8.9	7.5 – 10.2

- No constraint on the CP-phases

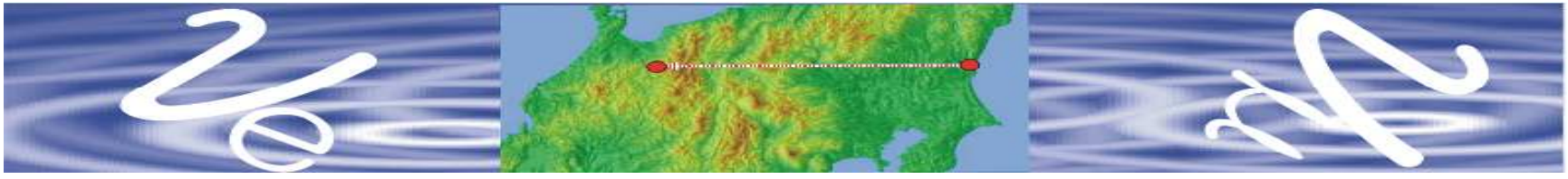
The outstanding issues



- The Neutrino Mass hierarchy
- Determination of CP phases
- The absolute neutrino mass scale
- The nature of Neutrinos : Dirac or Majorana
- Mass hierarchy can be determined by exploiting the earth matter effect if θ_{13} is appreciable.
- Determination of CP phase is possible only if θ_{13} is non-zero.

Future Longbaseline Experiments

- Superbeam Experiments (conventional accelerator beam but more power)
  - T2K: – $E \sim 0.76$ GeV, L = 295 km
  - NOνA: – $E \sim 1 - 3$ GeV, L = 810 km
  - T2K taking data, NOνA to start soon
  - LBNO in Europe $\sim$ 2200 km ,LBNE in US $\sim$ 1300 km
  - Utilizes flavour conversion of neutrinos passing through earths matter
  - Sensitive to hierarchy and δ_{cp}
  - Most useful is the conversion probability ν_e to ν_μ
- Beta-Beams, Neutrino-Factory (low and high Energy)
  - Powerful source, adequate flux at large distance ($\sim 3000 - 7000$ Km)
  - Important for small θ_{13}



Matter effects: Three Flavours

- The effective Hamiltonian is

$$\tilde{H} = \frac{1}{2E}[U \begin{pmatrix} m_1^2 & 0 & 0 \\ 0 & m_2^2 & 0 \\ 0 & 0 & m_3^2 \end{pmatrix} U^\dagger + \begin{pmatrix} A & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}]$$

excluding terms $\propto$ identity matrix. $U = R_{23}R_{13}R_{12}$

Matter effects: Three Flavours

- The effective Hamiltonian is

$$\tilde{H} = \frac{1}{2E}[U \begin{pmatrix} m_1^2 & 0 & 0 \\ 0 & m_2^2 & 0 \\ 0 & 0 & m_3^2 \end{pmatrix} U^\dagger + \begin{pmatrix} A & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}]$$

  excluding terms $\propto$ identity matrix. $U = R_{23}R_{13}R_{12}$

- Subtracting m_1^2 from the first part,

$$\tilde{H} = \frac{1}{2E}[U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m_{21}^2 & 0 \\ 0 & 0 & \Delta m_{31}^2 \end{pmatrix} U^\dagger + \begin{pmatrix} A & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Matter effects: Three Flavours

- The effective Hamiltonian is

$$\tilde{H} = \frac{1}{2E}[U \begin{pmatrix} m_1^2 & 0 & 0 \\ 0 & m_2^2 & 0 \\ 0 & 0 & m_3^2 \end{pmatrix} U^\dagger + \begin{pmatrix} A & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}]$$

  excluding terms $\propto$ identity matrix. $U = R_{23}R_{13}R_{12}$

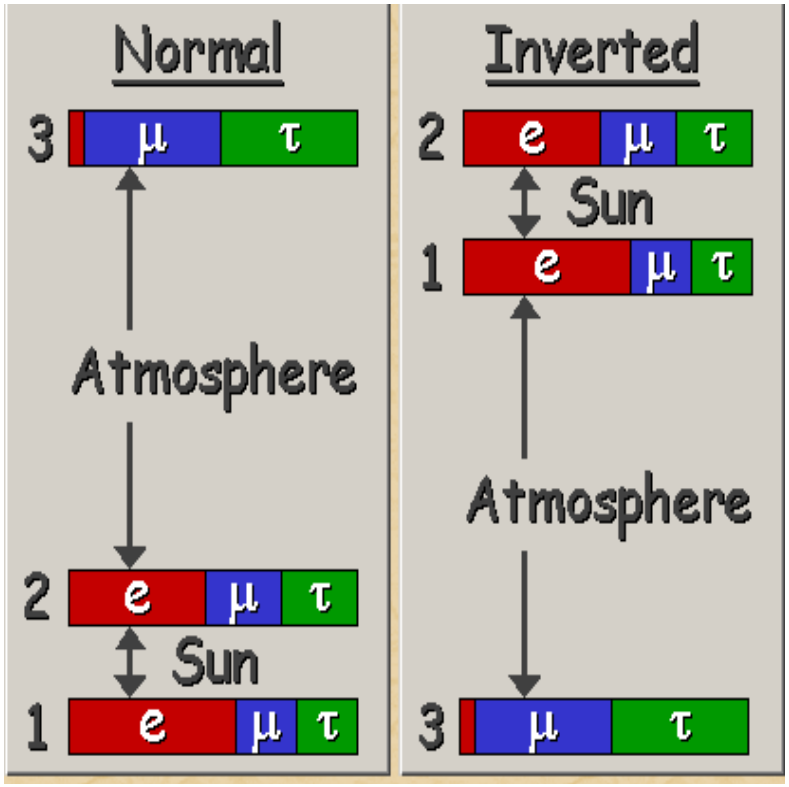
- 1 MSD ($\Delta m_{21}^2 = 0$) limit

$$\tilde{H} = \frac{1}{2E}[U \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \Delta m_{31}^2 \end{pmatrix} U^\dagger + \begin{pmatrix} A & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

  $\longrightarrow$ Resonance in the 1-3 sector

Matter Effect, θ_{13} and hierarchy

- $\tan 2\theta_{13}^m = \frac{\Delta m_{31}^2 \sin 2\theta_{13}}{\Delta m_{31}^2 \cos 2\theta_{13} \pm 2\sqrt{2} G_F n_e E}$



- For $\Delta m_{31}^2 > 0$ matter resonance in neutrinos
- For $\Delta m_{31}^2 < 0$ matter resonance in anti neutrinos
- Experiments that can differentiate between neutrinos and antineutrinos can probe matter effects
- Experiments sensitive to matter effects can probe the mass hierarchy
- Larger θ_{13}, larger will be matter effects

The Golden Channel

$$P_{e\mu} = |\cos\theta_{23} A_S e^{i\delta} + \sin\theta_{23} A_A|^2$$

- $A_S \rightarrow$ Solar amplitude depends on Δm^2_{21} and θ_{12}
- $A_A \rightarrow$ atmospheric amplitude depends on Δm^2_{31} and θ_{13}
- CP violation arises from the interference term
- Absence of CP violation requires either $A_S = 0$ or $A_A = 0$.

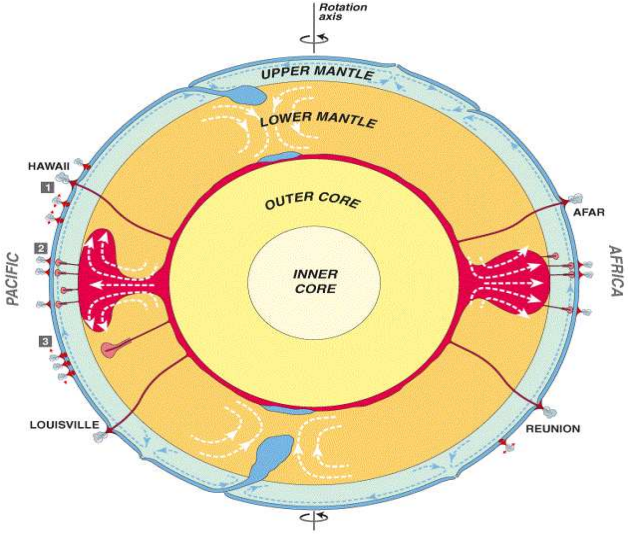
A.Yu. Smirnov, hep/ph 0610198

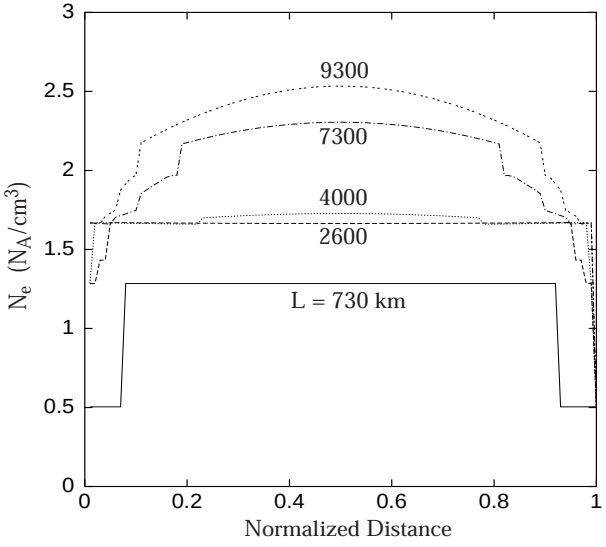
- GOLDEN because it can probe all three unknowns θ_{13}, $sgn\Delta m^2_{31}$, δ_{CP}

The Golden Channel

$$P_{e\mu} \simeq \sin^2\theta_{23}\,\sin^2 2\theta_{13}\,\frac{\sin^2(1-\hat{A})\Delta}{(1-\hat{A})^2}$$
$$+\ \alpha\,\sin 2\theta_{13}\,\sin 2\theta_{12}\,\sin 2\theta_{23}\,\cos(\Delta-\delta_{\rm CP})\,\frac{\sin(\hat{A}\Delta)}{\hat{A}}\,\frac{\sin(1-\hat{A})\Delta}{(1-\hat{A})}$$
$$+\ \alpha^2\,\cos^2\theta_{23}\,\sin^2 2\theta_{12}\,\frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}$$

- $\alpha = \Delta m^2_{31}/\Delta m^2_{31} \approx 0.04 \quad \sin^2\theta_{13} \sim 0.01$
- $\hat{A} \equiv 2\sqrt{2}G_F n_e E_\nu/\Delta m^2_{31}\ , \quad \Delta \equiv \Delta m^2_{31} L/(4E_\nu)\ ,$
- Expanded in small parameters α and $\sin^2\theta_{13}$ (contant matter density)





Attack of the Clones

- δ_{CP} can vary from (0 to 2π) and creates the problem of Parameter Degeneracies

- $(\theta_{13}, \delta_{CP})$ intrinsic degeneracy

  Burguet-Castell, Gavela, Gomez-Cadenas, Hernandez, Mena, hep-ph/0103258

- $(sgn(\Delta m^2_{31}), \delta_{CP})$ degeneracy

  Minakata, Nunokawa, hep-ph/0108085

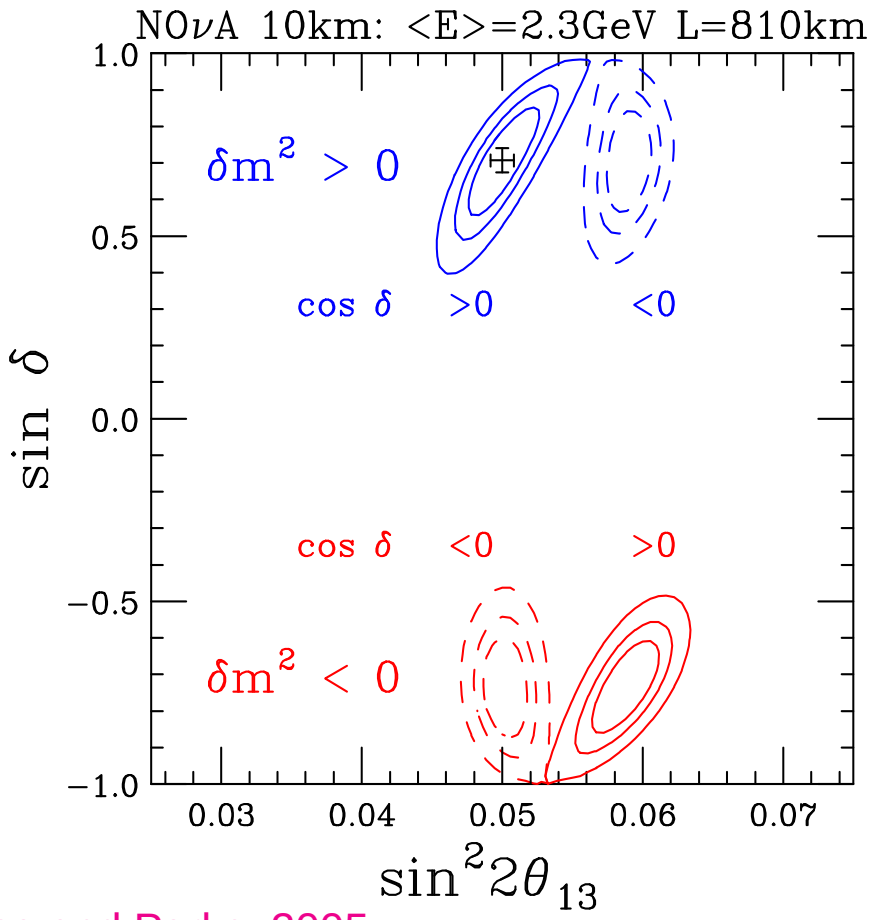
- $(\theta_{23}, \pi/2 - \theta_{23})$ degeneracy

  Fogli, Lisi, hep-ph/9604415

- Different set of parameters producing equally good fit to the data
- Give rise to multiple solutions $\rightarrow$ Eightfold degeneracy

The Phantom Menace

- Ghost (Degenerate) Solutions in $(\delta - \theta_{13})$ plane
- Unambiguous determination of parameters difficult



Mena and Parke, 2005

A New Hope: Magic Baseline

$$P_{e\mu} \simeq \sin^2\theta_{23}\,\sin^2 2\theta_{13}\,\frac{\sin^2(1-\hat{A})\Delta}{(1-\hat{A})^2}$$
$$+\ \alpha\,\sin 2\theta_{13}\,\sin 2\theta_{12}\,\sin 2\theta_{23}\,\cos(\Delta-\delta_{\rm CP})\,\frac{\sin(\hat{A}\Delta)}{\hat{A}}\,\frac{\sin(1-\hat{A})\Delta}{(1-\hat{A})}$$
$$+\ \alpha^2\,\cos^2\theta_{23}\,\sin^2 2\theta_{12}\,\frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}$$

- If $\frac{\sin(\hat{A}\Delta)}{\hat{A}} = 0$

$\Longrightarrow P_{e\mu}$ independent of δ_{CP}

A New Hope: Magic Baseline

$$P_{e\mu} \simeq \sin^2\theta_{23}\,\sin^2 2\theta_{13}\,\frac{\sin^2(1-\hat{A})\Delta}{(1-\hat{A})^2}$$

$$+\ \cancel{\alpha\,\sin 2\theta_{13}\,\sin 2\theta_{12}\,\sin 2\theta_{23}\,\cos(\Delta-\delta_{\rm CP})\,\frac{\sin(\hat{A}\Delta)}{\hat{A}}\,\frac{\sin(1-\hat{A})\Delta}{(1-\hat{A})}}$$

$$+\ \cancel{\alpha^2\,\cos^2\theta_{23}\,\sin^2 2\theta_{12}\,\frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}}$$

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$$+\ \cancel{\alpha^2\,\cos^2\theta_{23}\,\sin^2 2\theta_{12}\,\frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}}$$

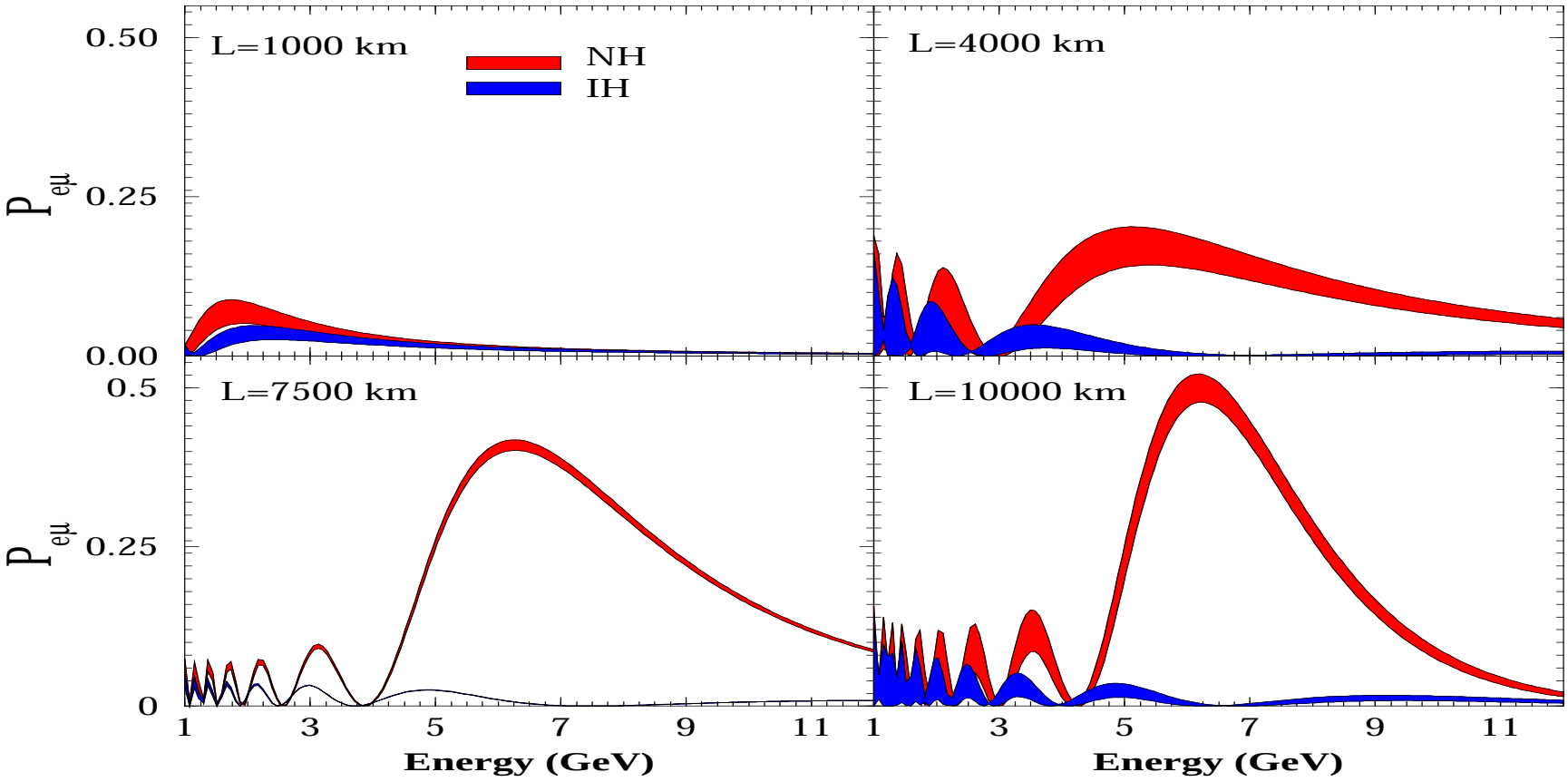
- $\sin(\hat{A}\Delta) \simeq 0 \Rightarrow \frac{1}{\sqrt{2}} G_F n_e L = \pi \Rightarrow L_{magic} \simeq 7690\ \mathrm{km}$
- Independent of neutrino parameters and energy
- True for both NH and IH

Barger, Marfatia, Whisnant, hep-ph/0112119

Huber, Winter, hep-ph/0301257

Smirnov, hep-ph/0610198

$P_{e\mu}$ for NH and IH at long baselines

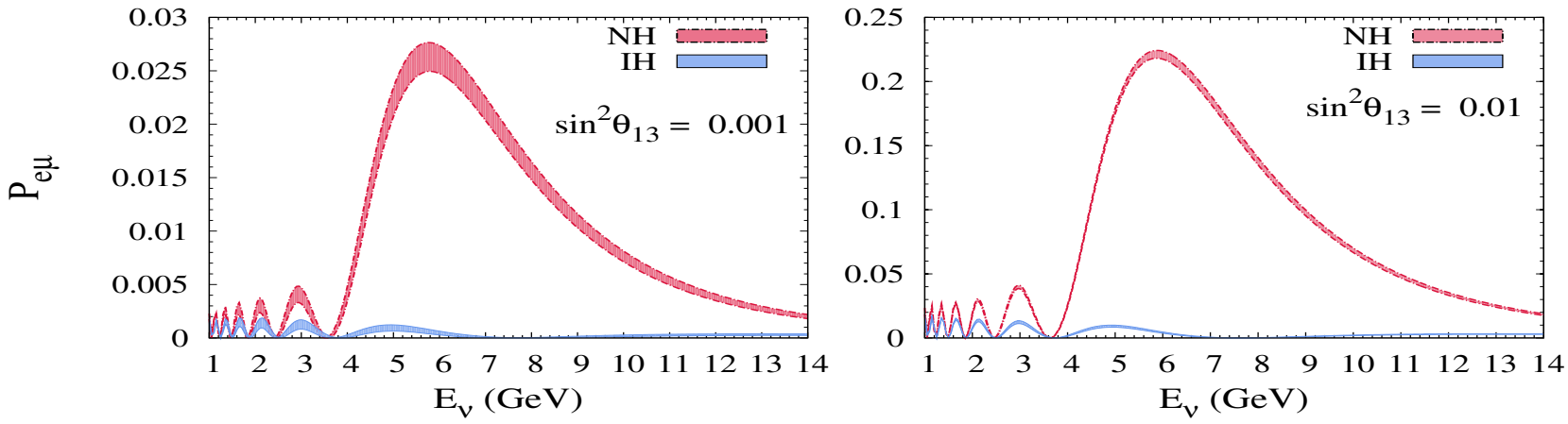


- At $\sim$ 7500 km δ_{CP} dependence negligible
- $(\delta_{CP}, sgn(\Delta m^2_{\rm atm}))$ degeneracies vanish
- Clean measurement of $sgn(\Delta m^2_{\rm atm})$

Agarwalla, Choubey, Raychaudhuri, hep-ph/0610333

The Magic baseline: Absence of CP sensitivity

$$P_{e\mu} \simeq \sin^2\theta_{23}\,\sin^2 2\theta_{13}\,\frac{\sin^2(1-\hat{A})\Delta}{(1-\hat{A})^2}$$



$\Longrightarrow$ No CP sensitivity

- Recomemndation of International Design Study of Neutrino Factory Group: another experiment at 4000 km for δ_{CP} with $E_\mu = 25$ GeV
- Requires high acceleration of the muons, also $1/r^2$ fall in flux
- Can there be a single experiment at a shorter baseline and lower energy that can determine all the three parameters ?

Enters The Bi-Magic baseline

$$P_{e\mu} \simeq \sin^2\theta_{23}\,\sin^2 2\theta_{13}\,\frac{\sin^2(1-\hat{A})\Delta}{(1-\hat{A})^2}$$
$$+\ \alpha\,\sin 2\theta_{13}\,\sin 2\theta_{12}\,\sin 2\theta_{23}\,\cos(\Delta-\delta_{\rm CP})\,\frac{\sin(\hat{A}\Delta)}{\hat{A}}\,\cancel{\frac{\sin(1-\hat{A})\Delta}{(1-\hat{A})}}\ 0$$
$$+\ \alpha^2\,\cos^2\theta_{23}\,\sin^2 2\theta_{12}\,\frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}$$

- The condition $\sin(\hat{A}\Delta) \simeq 0$ implies vanishing of δ_{CP} dependent terms
- If we instead make $\sin[(1-\hat{A})\Delta]$ =0 the δ_{CP} dependent term can vanish.

Enters The Bi-Magic baseline

$$P_{e\mu} \simeq \cancel{\sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(1-\hat{A})\Delta}{(1-\hat{A})^2}}$$
$$+ \cancel{\alpha\sin 2\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\cos(\Delta-\delta_{CP})\frac{\sin(\hat{A}\Delta)}{\hat{A}}\frac{\sin(1-\hat{A})\Delta}{(1-\hat{A})}}$$
$$+ \alpha^2\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}$$

- In that case $P_{e\mu} \approx \mathcal{O}(\alpha^2) \rightarrow$ small
- The condition $\sin(\hat{A}\Delta) \simeq 0$ is valid for both NH and IH
- But this condition depends on hierarchy

Enters The Bi-Magic baseline

$$P_{e\mu} \simeq \sin^2\theta_{23}\,\sin^2 2\theta_{13}\,\frac{\sin^2(1-\hat{A})\Delta}{(1-\hat{A})^2}$$
$$+\ \alpha\,\sin 2\theta_{13}\,\sin 2\theta_{12}\,\sin 2\theta_{23}\,\cos(\Delta-\delta_{\rm CP})\,\frac{\sin(\hat{A}\Delta)}{\hat{A}}\,\cancel{\frac{\sin(1-\hat{A})\Delta}{(1-\hat{A})}}\ 0$$
$$+\ \alpha^2\,\cos^2\theta_{23}\,\sin^2 2\theta_{12}\,\frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}$$

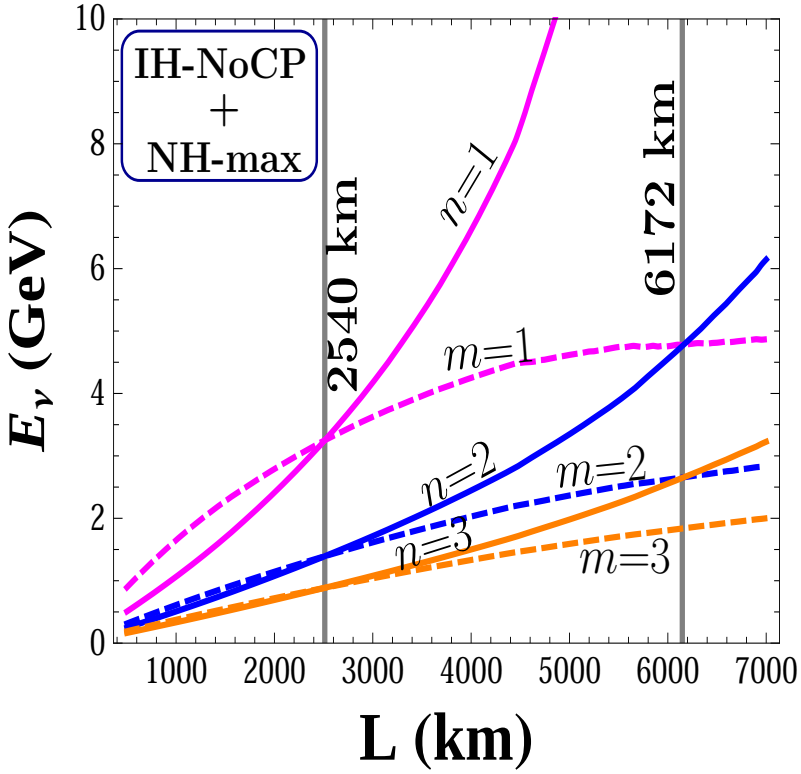
- For IH $\hat{A} = -\hat{A}$, $\Delta = -\Delta$
  - Magic condition depends on hierarchy

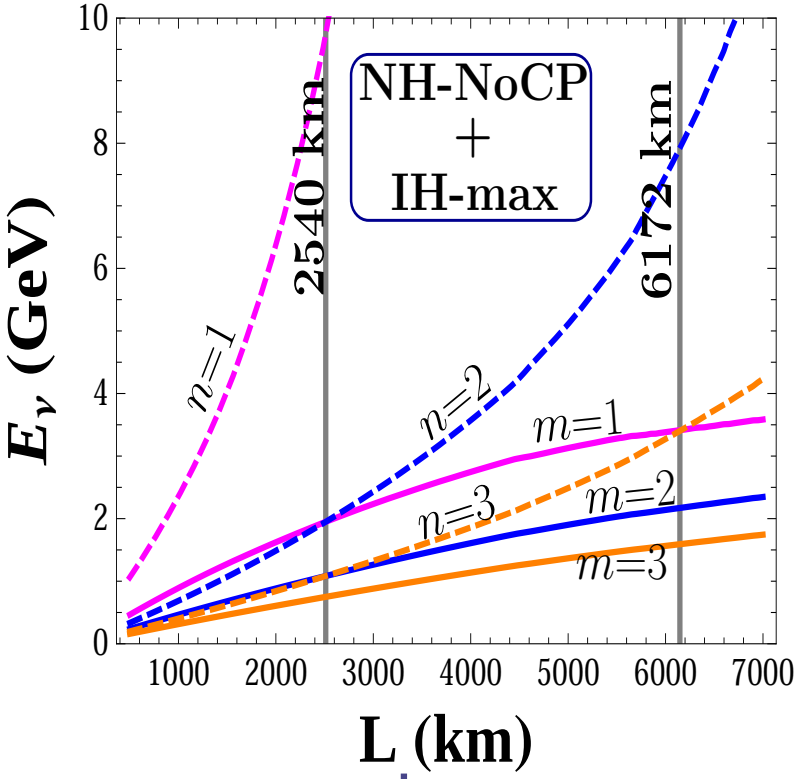
IH–NoCP	NH–NoCP
$(1+\lvert\hat{A}\rvert)\cdot\lvert\Delta\rvert = n\pi,\ n>0$	$(1-\lvert\hat{A}\rvert)\cdot\lvert\Delta\rvert = n\pi,\ n\neq 0$

  - Demand: Maximum hierarchy sensitivity

NH–max	IH–max
$(1-\lvert\hat{A}\rvert)\cdot\lvert\Delta\rvert = (m-\frac{1}{2})\pi$	$(1+\lvert\hat{A}\rvert)\cdot\lvert\Delta\rvert = (m-\frac{1}{2})\pi$

The Bi-Magic baseline





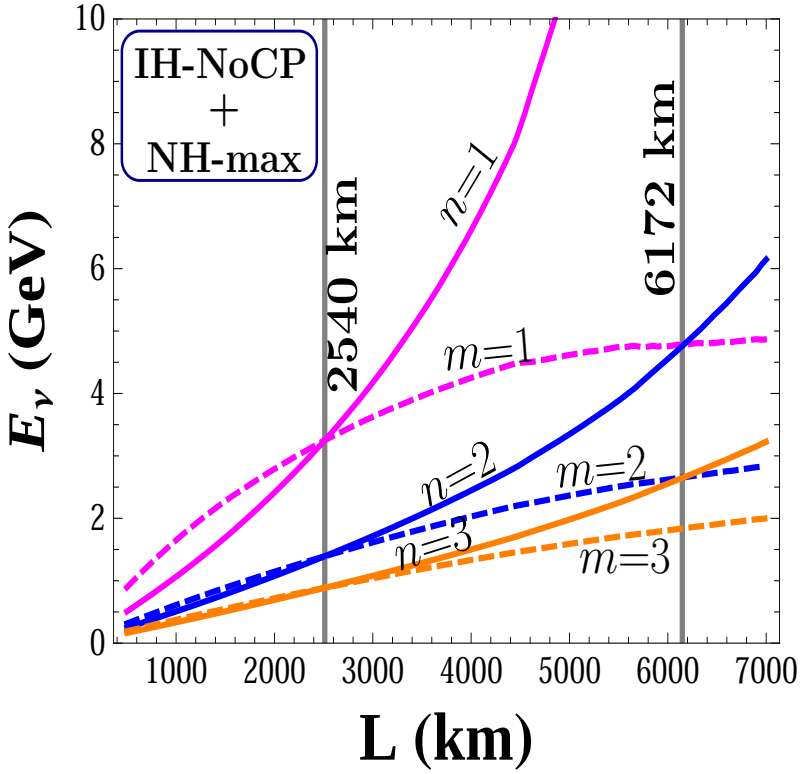
- $n = 1$ and $m = 1$
  $L \approx 2540$ km
  $E_\nu \equiv E_{IH} \approx 3.3$ GeV,

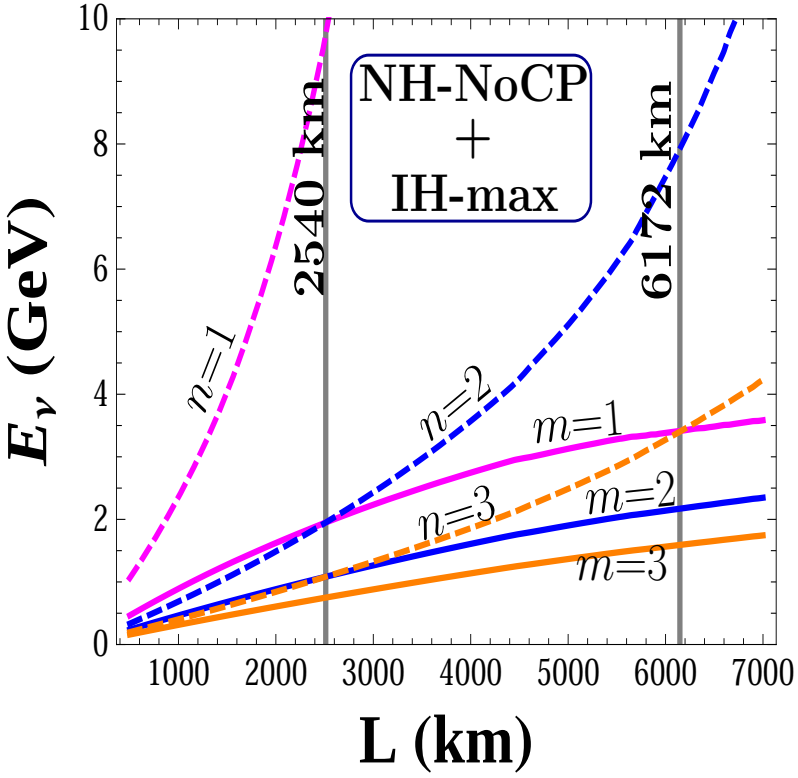
  Raut, Singh, UmaShankar, 2009

- $n = 1$ and $m = 2$,
  $L \approx 2540$ km
  $E_\nu \equiv E_{NH} \approx 1.9$ GeV.

  Dighe,Goswami,Ray, 2010

The Bi-Magic baseline





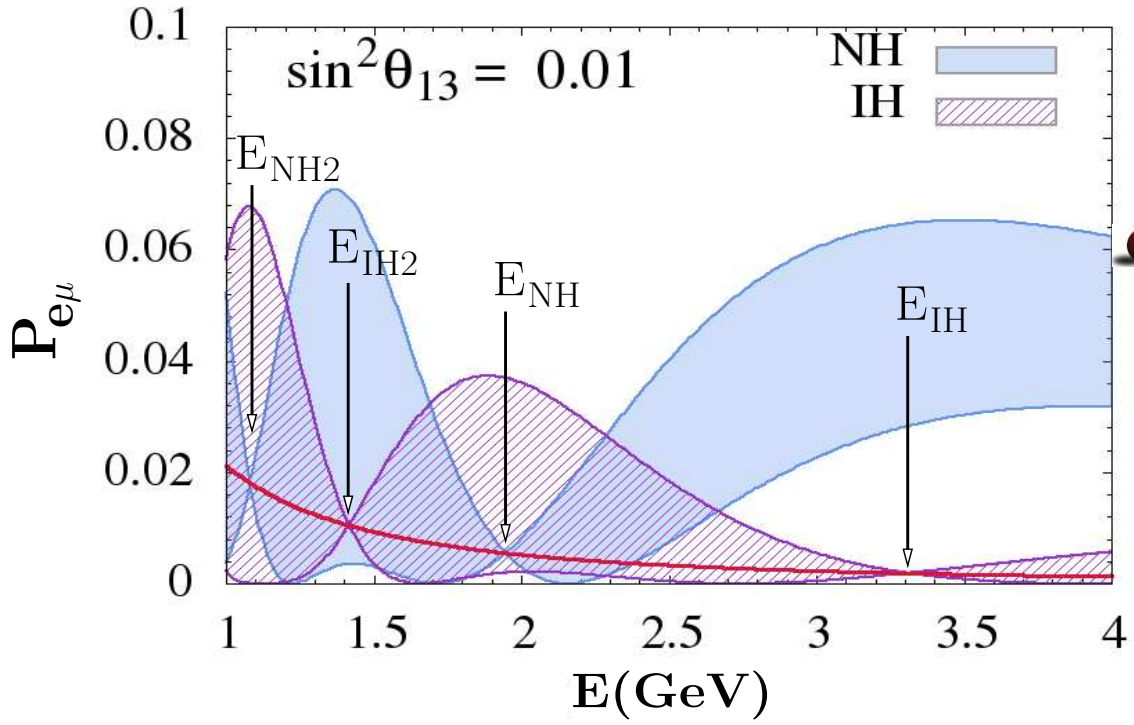
- Lowest Bi-magic Baseline $\sim$ 2540 km
- Higher n,m $\Rightarrow$ Lower E_ν to satisfy no CP condition low flux, low efficiency
- More bimagics 6172 km, 8950 km, 106900 km

Baselines close Bi-Magic baseline

- CERN - PhyÃsalmi : 2288 km (LAGUNA)
- CERN - GranCanaria: 2780 km
- BNL- Homestake : 2540 km
- Fermilab-Icicle Creek : 2610 km
- Fermilab - SanJacinto: 2610 km

For a compilation of baselines from different accelerator facilites and underground laboratories see Agarwalla et. al. arXiv:1012.1872 [hep-ph]

$P_{e\mu}$ at the Bi-Magic baseline



- NH, IH interchanged for antineutrinos

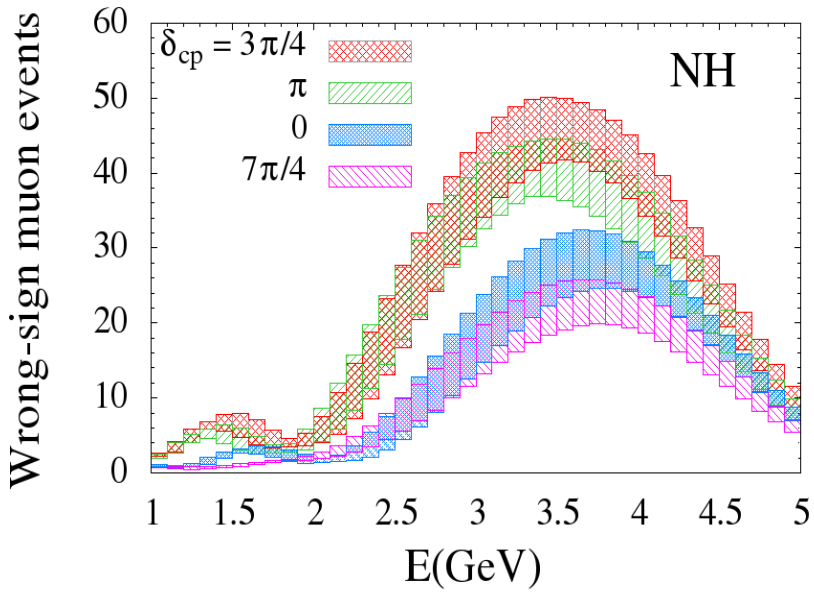
E_{IH} = 1.9 GeV

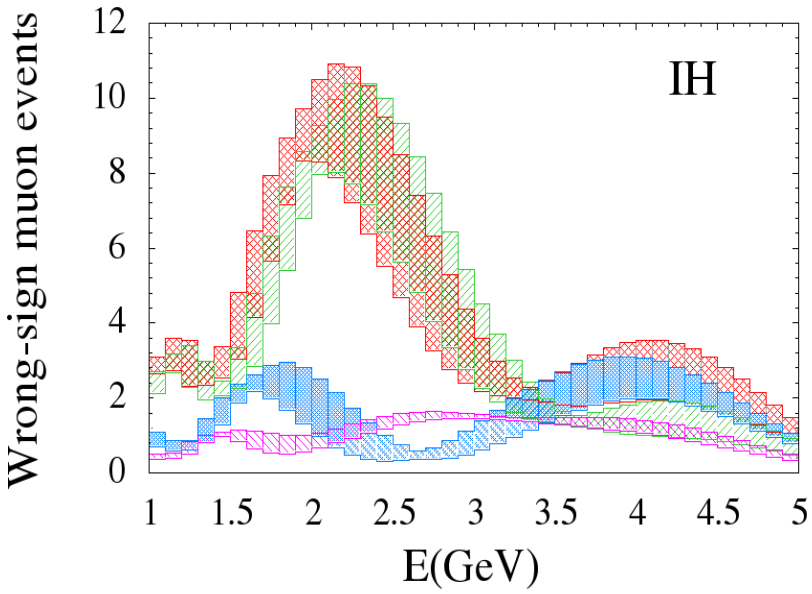
- NH probability independent of δ_{CP} but δ_{CP} band in IH large
- δ_{CP} sensitivity for IH

E_{IH} = 3.3 GeV

- IH probability independent of δ_{CP} and non-overlapping with NH
- δ_{CP} sensitivity for NH

The Return of the CP sensitivity





$E_{\rm IH}$ = 3.3 GeV

$E_{\rm NH}$ = 1.9 GeV

$P_{e\mu}(\mathrm{IH}) \approx \mathcal{O}(\alpha^2)$

$P_{e\mu}(\mathrm{NH}) \approx 18\alpha^2 s_{12}^2 c_{12}^2 c_{23}^2 + 9 s_{13}^2 s_{23}^2$

$-18\sqrt{2}\alpha s_{12} c_{12} s_{23} c_{23} s_{13} \cos(\delta_{\rm CP} + \pi/4)$

$P_{e\mu}(\mathrm{NH}) \approx \mathcal{O}(\alpha^2)$

$P_{e\mu}(\mathrm{IH}) \approx 50\alpha^2 s_{12}^2 c_{12}^2 c_{23}^2 + \frac{25}{9} s_{13}^2 s_{23}^2$

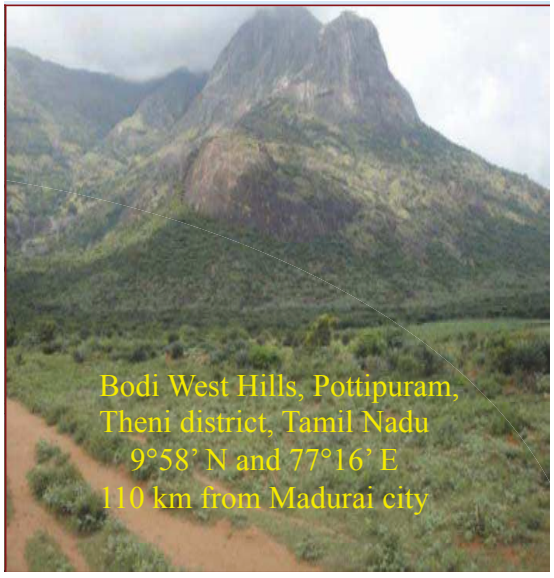
$-\frac{50\sqrt{2}}{3}\alpha s_{12} c_{12} s_{23} c_{23} s_{13} \cos(\delta_{\rm CP} + \pi/4)$

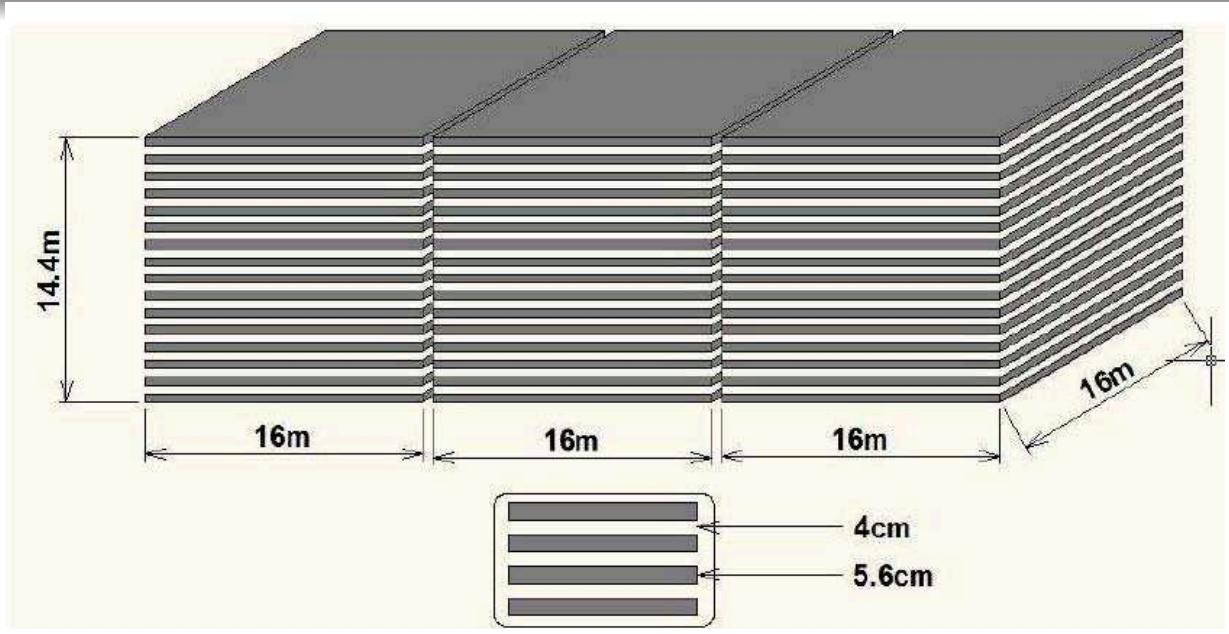
$P_{e\mu}$ largest at $\delta_{CP} = 3\pi/4$, lowest at $\delta_{CP} = 7\pi/4$.

Can Atmospheric Neutrinos help ?

- Atmospheric neutrinos travel through a large path length in earths matter
- Large measured $\theta_{13} \Longrightarrow$ appreciable matter effect
- Three proposals
  (i) HyperKamiokande – upgraded version of SuperK, sensitive to both electron and muons
  (ii) India-Based Neutrino Observatory (INO) – sensitive to muons, have charge sensitvity
  (iii) PINGU – Huge statistics

INO

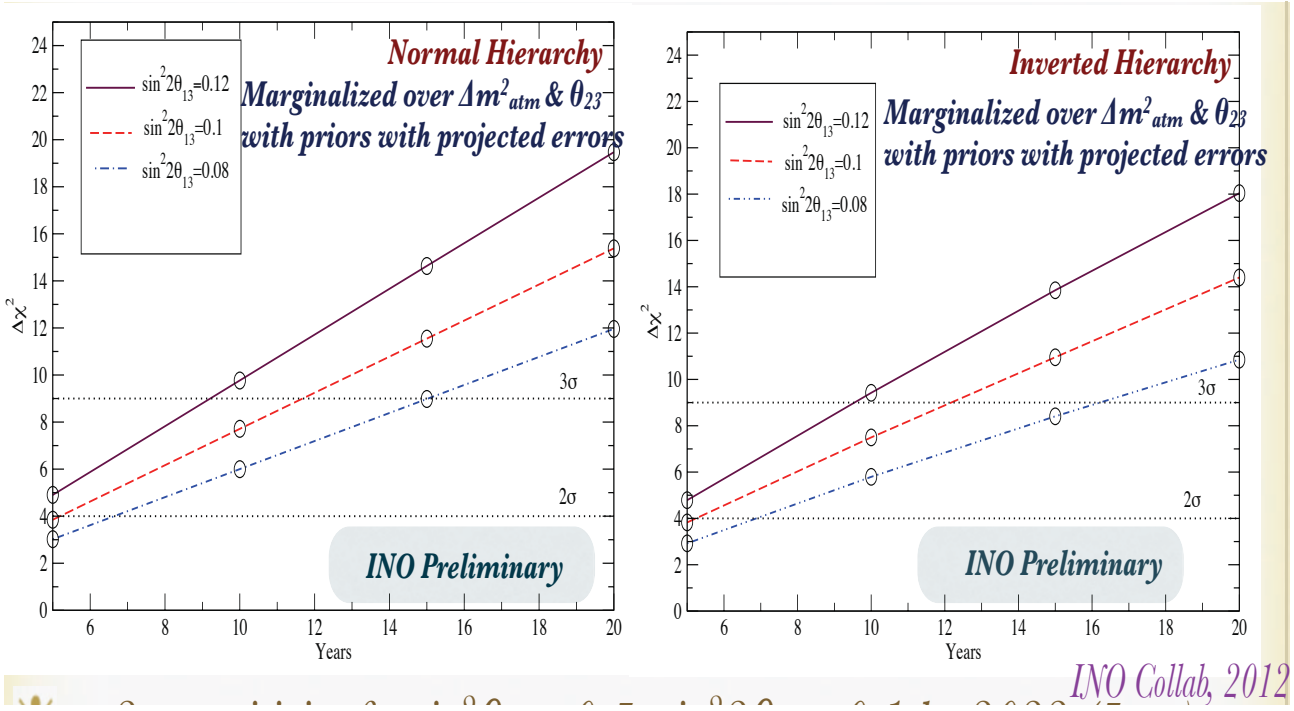




- 50 kton magnetized iron detector Sensitive to muons
- Good Energy determination from
  - Track length • Track curvature in a magnetic field
- Directionality from tracking and ns timing resolution
- Charge identification from track curvature in magnetic field
- Hadron Shower reconstruction
- Coming Soon in Bodi Hills, Tamilnadu

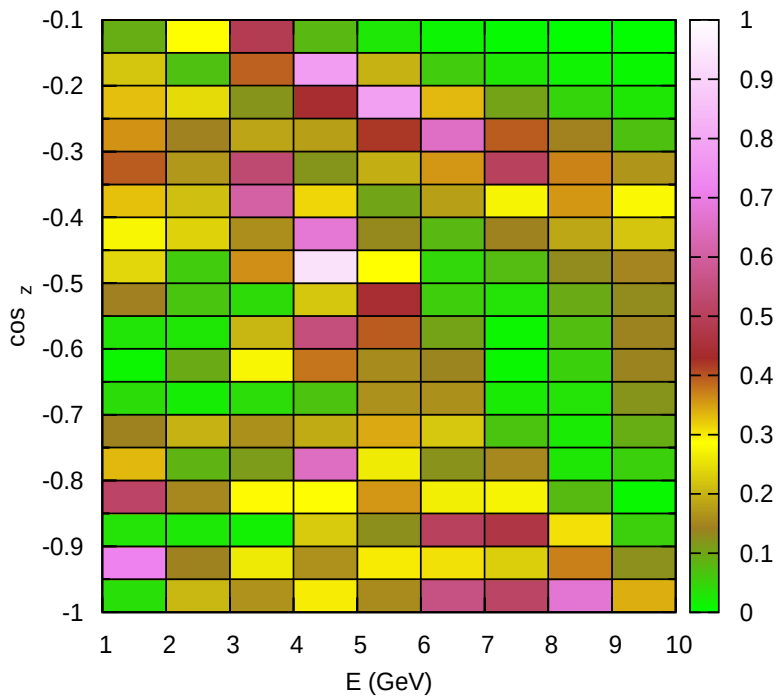
Hierarchy Sensitivity from INO simulation

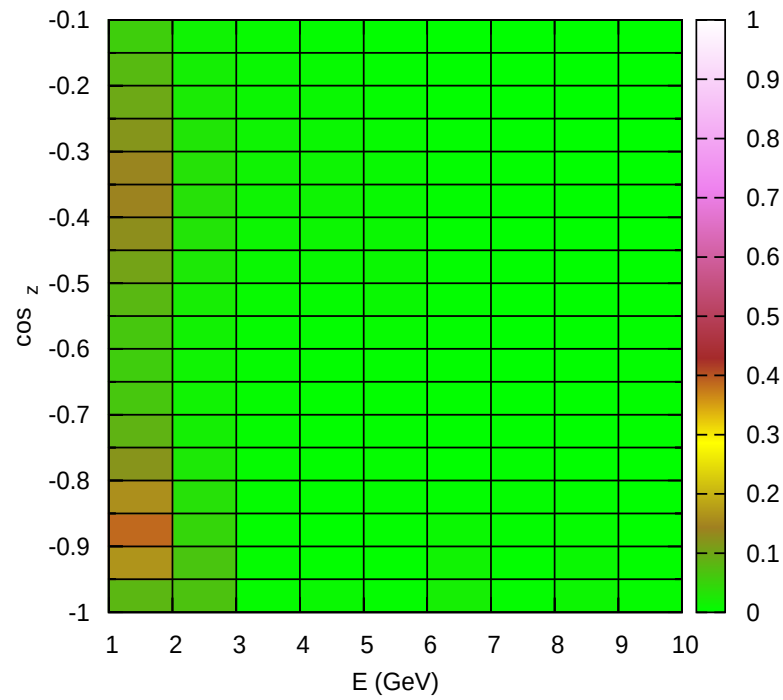
- Using 50 Kton detector and events generated from NUANCE
- Using ICAL resolutions in Muon energy and Zenith Angle
- Using efficiency and Charge-ID from ICAL simulations



- For $\sin^2 2\theta_{13} = 0.1 \sim 2.7\ \sigma$ sensitivity in 10 years

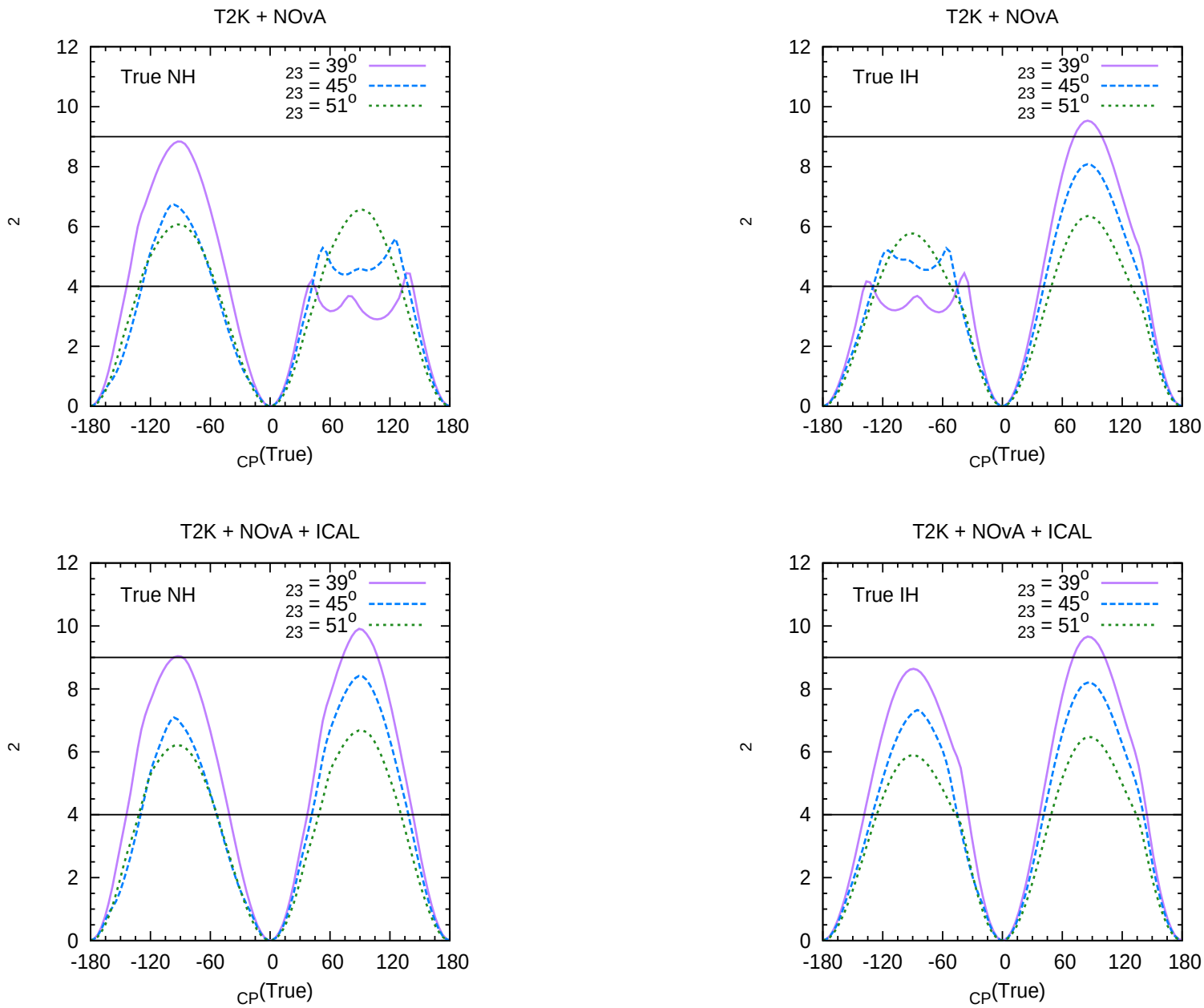
δ_{CP} sensitivity of Atmospheric Neutrinos





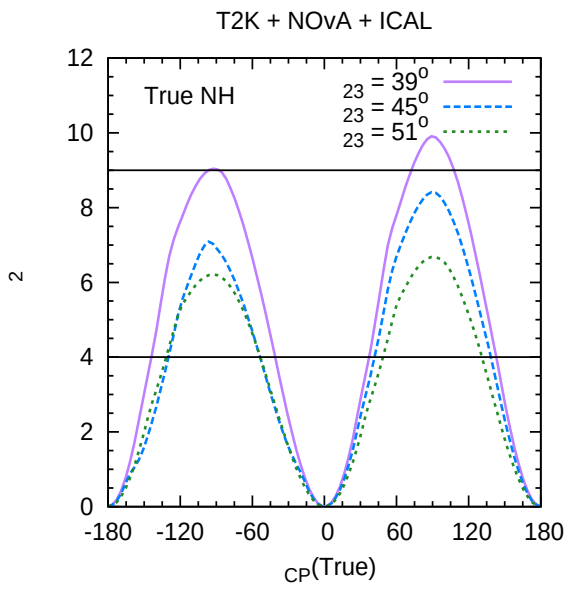
- $S_\mu + S_{\overline{\mu}} = (\Delta N_\mu)^2 / N_\mu(\text{avg})$,
- ΔN_μ is the maximum difference in events by varying δ_{CP}, $N_\mu(\text{avg})$ is the average number of events over all values of δ_{CP}.
- A measure of δ_{CP}-sensitivity in the $E - cos_{\theta_z}$ plane; the grid represents bins in energy and $\cos\theta_z$.
- $\sin^2 2\theta_{13} = 0.1$, $\sin^2\theta_{23} = 0.5$ and NH.

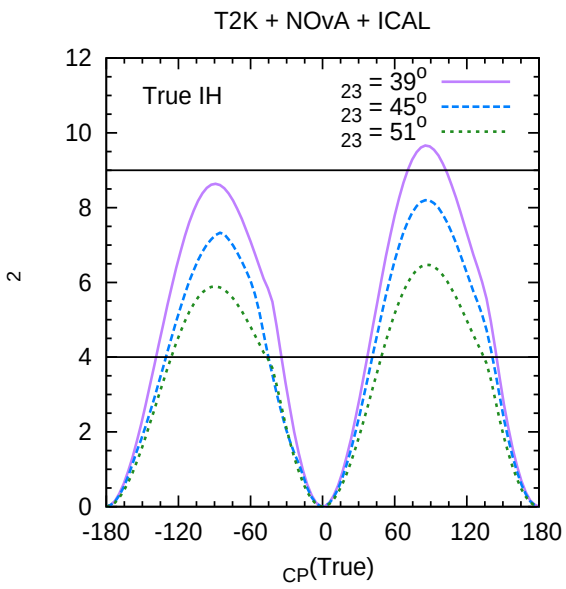
NOνA+T2K+ICAL CP violation discovery



(Monojit Ghosh, Pomita Ghoshal, Suchaboti Goswami, Sushant K. Raut, arxiv:1306.6509)

NOνA+T2K+ICAL CP violation discovery





- $\sin^2 2\theta_{13} = 0.1$, 500 kt yr exposure
- 3σ sensitvity possible in the wrong hierarchy region also.
- **For unfavourable parameter values the first signature of CPV can come after including ICAL data to T2K+NOνA**
- Unfavourable for T2K+NOνA :($\rightarrow$ favourable for INO :)