Neutrinos in the time of Higgs

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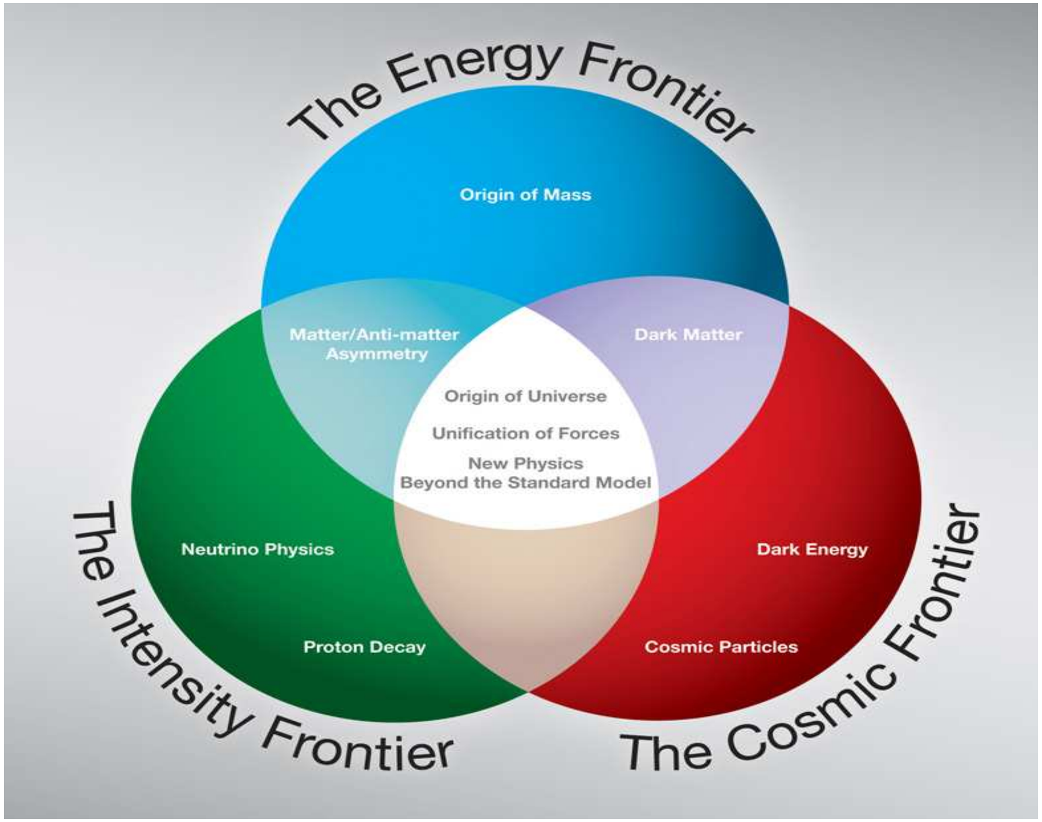
Good time for High Energy Physics



- Exciting results from all three frontiers in the past two years
- Energy Frontier
  Higgs@LHC
- Cosmic Frontier
  Planck Results, BICEP2
- Intensity Frontier
  Measurement of non-zero θ_{13}, reactor experiments

- Non-zero θ_{13} crucial for the discovery of leptonic CP violation
  $\rightarrow$ observed baryon asymmetry of the Universe via Leptogenesis

Neutrino physics in a nutshell..

- Three fundamental questions asked in the last century..
  - Do neutrinos have mass ? If so how small ? (Pauli, Fermi, 1930's)

    (Latest Planck results $\Longrightarrow \Sigma m_i \leq 0.23$ eV)
  - Do neutrinos of different flavour oscillate amongst each other ? (Pontecorvo, Maki,Nakagawa,Sakata, 1960's)

    (Neutrino Oscillations have been observed $\Rightarrow$ neutrinos have mass and there is flavour mixing)
  - Are neutrinos Majorana particles ie. can they be their own antiparticles (Majorana, 1930's)

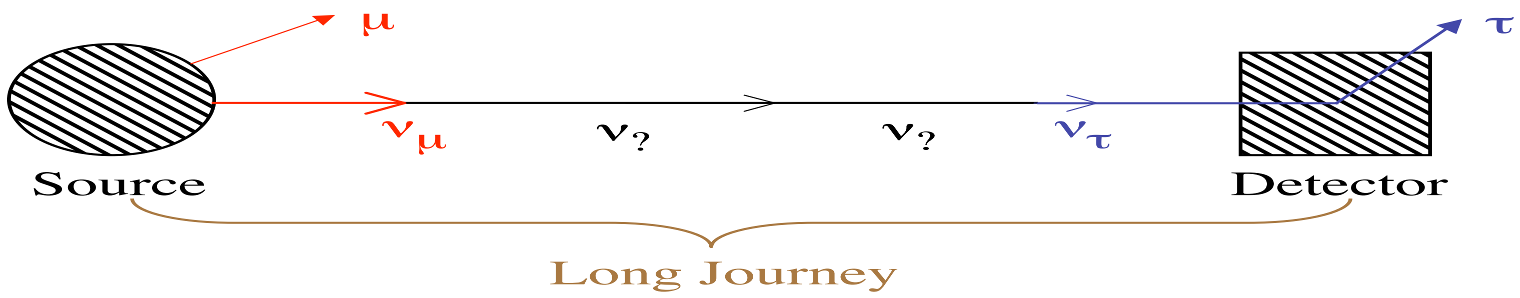
    (Can be probed by Neutrino less double beta decay. No definitive evidence yet)
- The three issues are interconnected and may throw light on the mechanism of mass generation , unification scenarios.. and more..

Plan of Talk

- Neutrino Oscillation - Current Status
- Future perspective in view of non-zero θ_{13}
- Neutrino less Double beta decay – current status
- The issue of neutrino mass - beyond Standard Model

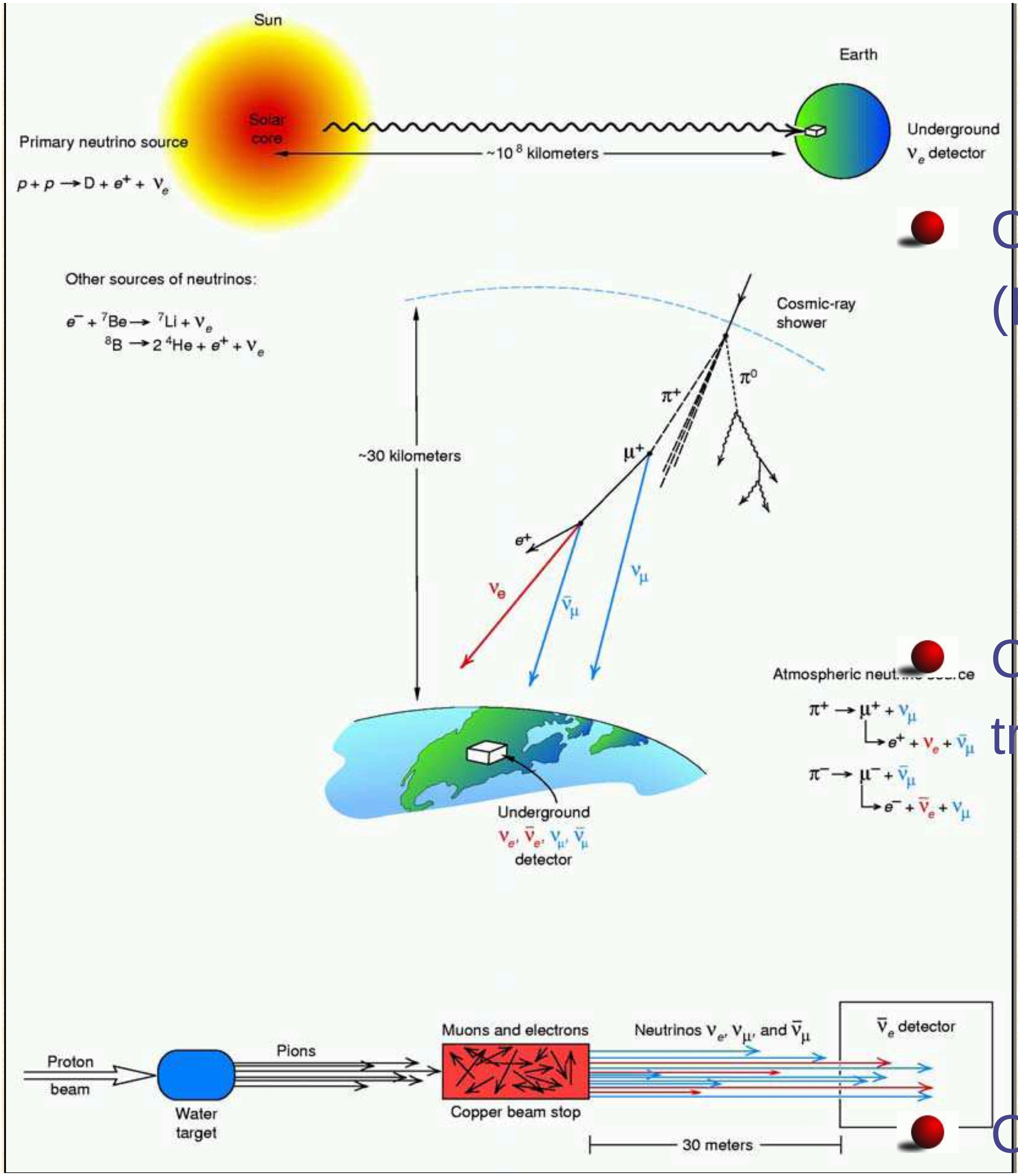
Neutrino oscillation

- It has been found that neutrinos can change flavour after passing through a distance



- This is possible if neutrinos have Mass and Mixing
- The conversion probability can be oscillatory $\longrightarrow$ Neutrino Oscillation $\rightarrow$ quantum mechanical interference phenomena

Experimental Evidences for Neutrino Oscillation



Solar Neutrinos

- Confirmation from reactor neutrinos (KamLAND)

Atmospheric Neutrinos

- Confirmation from accelerator neutrinos (K2K, MINOS,T2K)

LSND Experiment

- Confirmation from MiniBoone (?)

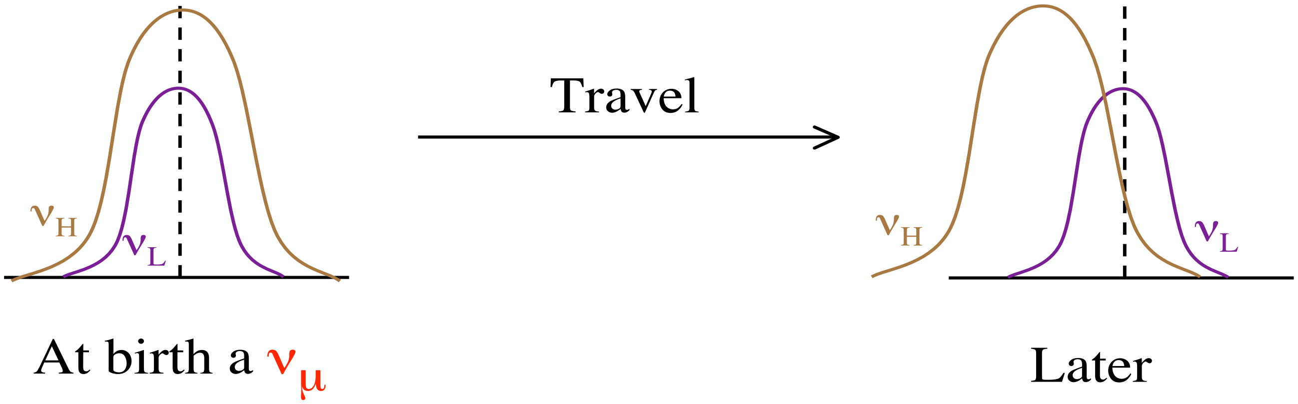
A Life Less Ordinary

- When neutrinos have mass then ν_μ, ν_τ are not particles of finite mass but are mixtures of these
- $\nu_\mu = \cos\theta \ \nu_{\text{light}} + \sin\theta \ \nu_{\text{heavy}}$
  $\nu_\tau = -\sin\theta \ \nu_{\text{light}} + \cos\theta \ \nu_{\text{heavy}}$

ν_{light} , ν_{heavy} $\rightarrow$ ν's of definite mass

$\theta \rightarrow$ mixing angle

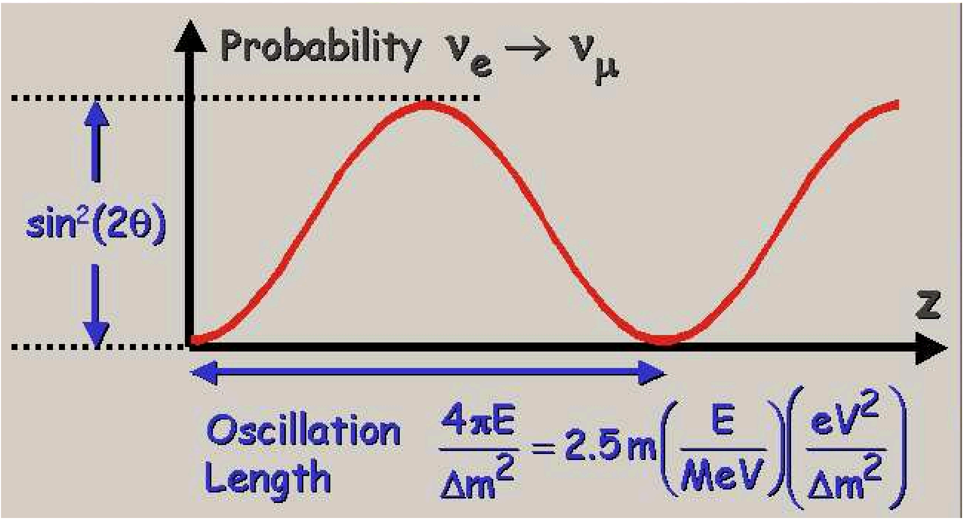
- How does superposition of mass states evolve in vacuum ?
- As the neutrino travels with energy E its heavier part falls behind
- As a result the neutrino is not a ν_μ anymore but a mixture of ν_μ and ν_τ



Oscillation Probability in Vacuum

Probability that an initial ν_e is detected as ν_μ at a later time

$$P_{\nu_e \nu_\mu} = \sin^2 2\theta \sin^2(1.27 \Delta m^2 L/E)$$



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

$\theta \to$ mixing angle

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

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

- Neutrino Oscillation requires

  Non-zero neurino mass

  Non-zero mixing angles

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

- Interaction with matter modifies the mass, mixing and probability $\to$ MSW effect

- No information on sign of Δm^2

Matter Effect

- ν_e has both CC & NC interaction with electrons in matter, while ν_μ & ν_τ have only NC interaction.
- Potential common to all 3 flavors cancels from oscillation probabilities.
- Hamiltonian in flavor basis is:

$$\tilde{H} = E + \frac{m_1^2+m_2^2}{4E} - \frac{G_F n_n}{\sqrt{2}} + \frac{\Delta m_{21}^2}{4E} \begin{pmatrix} -\cos 2\theta + \frac{2A}{\Delta m_{21}^2} & \sin 2\theta \\ \sin 2\theta & \cos 2\theta \end{pmatrix}$$

$A = 2\sqrt{2} G_F n_e E$. For anti-neutrinos, $A \to -A$.

- Effective mixing angle θ_M in matter : $\tan 2\theta_M = \frac{\Delta m_{21}^2 \sin 2\theta}{\Delta m_{21}^2 \cos 2\theta \mp A}$
- Maximal mixing or resonance:

When $A = \Delta m_{21}^2 \cos 2\theta$, flavor states mix maximally, i.e. $\theta_M = \pi/4$ even if vacuum mixing angle is small. $\longrightarrow$ MSW Matter Enhanced Resonance

L. Wolfenstein, PRD **17**, 1978 S.P. Mikhyev, A.Yu. Smirnov, SJNP **42**, 1985

- Intrinsic Neutrino Properties: Δm^2, θ
- Sensitive to the sign of Δm^2

- The mass squared difference is also different

Three Neutrino parameters

- The neutrino mass matrix

  $$m_\nu = U^*_{PMNS} Dia(m_1, m_2, m_3) U^\dagger_{PMNS}$$

- $U_{PMNS} = U.P \qquad P = \mathrm{diag}(1, e^{i\alpha}, e^{i(\beta)})$; $\alpha\ \beta \rightarrow$ Majorana Phases

- $\nu_\alpha = U_{\alpha i}\nu_i$

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

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

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

Three Neutrino parameters

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

- Six parameters can be measured in oscillation experiments

- $\Delta m_{21}^2 = m_2^2 - m_1^2$, θ_{12} : Solar and Reactor (Long baseline)
- $\Delta m_{31}^2 = m_3^2 - m_1^2$, θ_{23} : Atmospheric and beam
- θ_{13} : Reactor (Short baseline) and beam
- For small θ_{13} and $\Delta m_{21}^2 << \Delta m_{31}^2$ approximate 2 generation works
- Interesting interplay between the different sectors if θ_{13} is non-zero

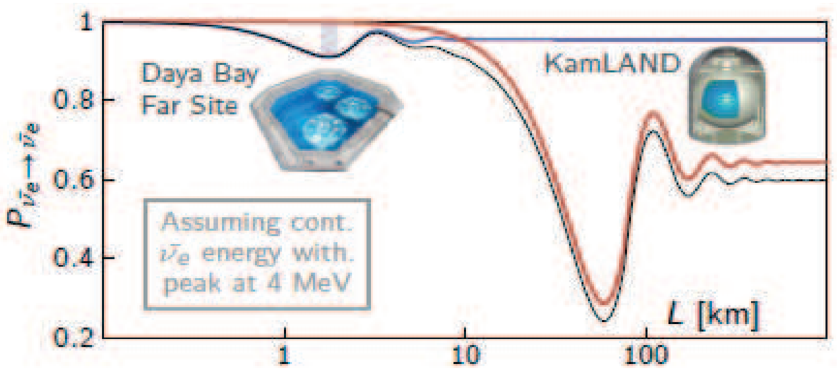
- Absolute neutrino mass : from β-decay, $0\nu\beta\beta$, cosmology
- Majorana Phases : from $0\nu\beta\beta$

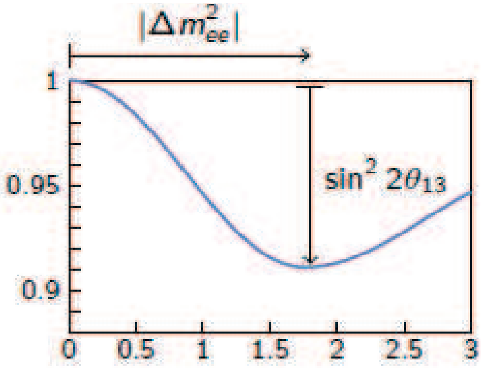
A snapshot of the oscillation results

- Results from SuperKamiokande experiment confirmed oscillation of atmospheric neutrinos $\Delta m^2 \sim 10^{-3}$ eV^2
  (Dominant solution : $\nu_\mu \to \nu_\tau$ vacuum oscillation)
- Results from the SNO solar neutrino experiment established the presence of ν_μ/ν_τ in the solar ν_e flux $\Delta m^2 \sim 10^{-4}$ eV^2 (matter effect)
- Result from the KamLAND experiment confirmed solar neutrino oscillations using reactor neutrinos $\Delta m^2 \sim 10^{-4}$ eV^2 (vacuum oscillations)
- Result from K2K, MINOS,T2K confirmed atmospheric neutrino oscillations using accelerator neutrinos $\Delta m^2 \sim 10^{-3}$ eV^2
  (Dominant solution : Vacuum oscillation of $\nu_\mu \to \nu_\tau$)
- Together these experiments have determined Δm^2_{21}, $|\Delta m^2_{31}|$, θ_{12}, θ_{23}
- The measurement of the third mixing angle θ_{13} came in 2011-2012 from reactor experiments (Double Chooz, Daya-Bay, RENO). Also confirmation from T2K.

Measurement of θ_{13}

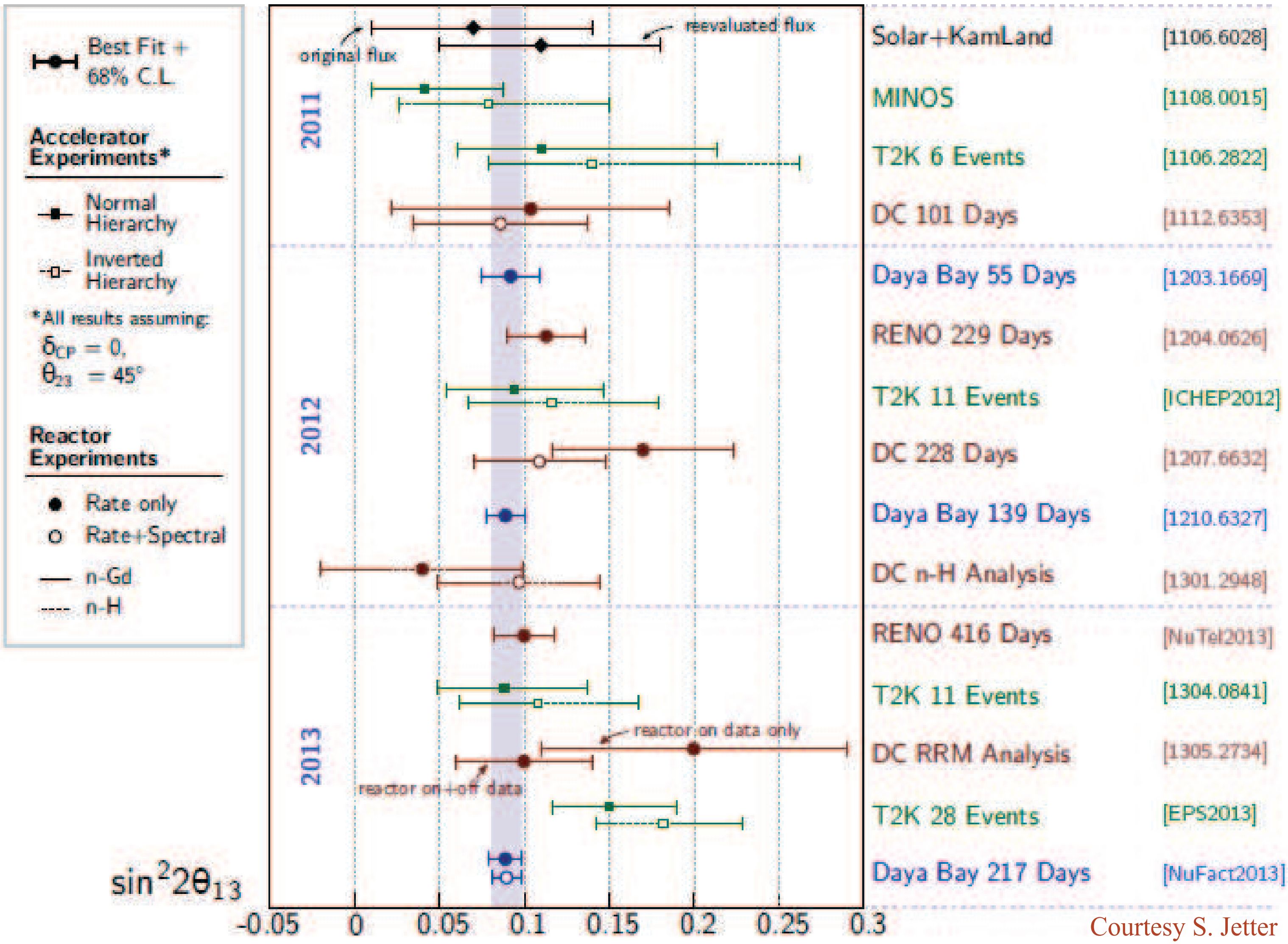
- Till 2011 : $\theta_{13} < 13^o$
- Reactor experiments - Double Chooz, Daya-Bay and RENO has measured non-zero θ_{13}
- Long Baseline: distance $\sim$ 1 km L/E $\sim$ Km/MeV
- $P_{ee} = 1 - \sin^2 2\theta_{13} \sin^2 1.27\Delta_{ee} L/E$





- The deficit is governed by θ_{13}
- L/E dependence is sensitve to Δ_{ee}

The θ_{13} Saga: Breaking Barriers



Courtesy S. Jetter

- θ_{13} is measured to a very good precision ($\sim$ 8%)

Effects of θ_{13}

- Oscillation of short-baseline reactor neutrinos goverened manily by Δ_{31} and θ_{13}
- Subleading effects in solar and KamLAND due to θ_{13}
- Subleading effects in atmospheric neutrinos due to $\theta_{13} \Longrightarrow$ matter effects and increase in ν_e events
- Long baseline accelerator data (K2K, MINOS, T2K) are sensitive mainly to Δm^2_{31}, θ_{23}, θ_{13}; Sub-dominant effect due to θ_{12}, Δm^2_{21} (input from solar and KamLAND)
- Interplay of all these in Global analysis of data

Current Status of Oscillation Parameters

Nσ ranges for single parameters (all data included):

[F. Capozzi, G.L. Fogli, E. Lisi, D. Montanino, A. Marrone, and A. Palazzo, arXiv:1312.2878]

TABLE I: Results of the global 3ν oscillation analysis, in terms of best-fit values and allowed 1, 2 and 3σ ranges for the 3ν mass-mixing parameters. See also Fig. 3 for a graphical representation of the results. We remind that Δm^2 is defined herein as $m_3^2 - (m_1^2 + m_2^2)/2$, with $+\Delta m^2$ for NH and $-\Delta m^2$ for IH. The CP violating phase is taken in the (cyclic) interval $\delta/\pi \in [0, 2]$. The overall χ^2 difference between IH and NH is insignificant ($\Delta\chi^2_{\mathrm{I-N}} = +0.3$).

Parameter	Best fit	1σ range	2σ range	3σ range
$\delta m^2/10^{-5}$ eV^2 (NH or IH)	7.54	7.32 – 7.80	7.15 – 8.00	6.99 – 8.18
$\sin^2\theta_{12}/10^{-1}$ (NH or IH)	3.08	2.91 – 3.25	2.75 – 3.42	2.59 – 3.59
$\Delta m^2/10^{-3}$ eV^2 (NH)	2.44	2.38 – 2.52	2.30 – 2.59	2.22 – 2.66
$\Delta m^2/10^{-3}$ eV^2 (IH)	2.40	2.33 – 2.47	2.25 – 2.54	2.17 – 2.61
$\sin^2\theta_{13}/10^{-2}$ (NH)	2.34	2.16 – 2.56	1.97 – 2.76	1.77 – 2.97
$\sin^2\theta_{13}/10^{-2}$ (IH)	2.39	2.18 – 2.60	1.98 – 2.80	1.78 – 3.00
$\sin^2\theta_{23}/10^{-1}$ (NH)	4.25	3.98 – 4.54	3.76 – 5.06	3.57 – 6.41
$\sin^2\theta_{23}/10^{-1}$ (IH)	4.37	4.08 – 4.96 $\oplus$ 5.31 – 6.10	3.84 – 6.37	3.63 – 6.59
δ/π (NH)	1.39	1.12 – 1.72	0.00 – 0.11 $\oplus$ 0.88 – 2.00	—
δ/π (IH)	1.35	0.96 – 1.59	0.00 – 0.04 $\oplus$ 0.65 – 2.00	—

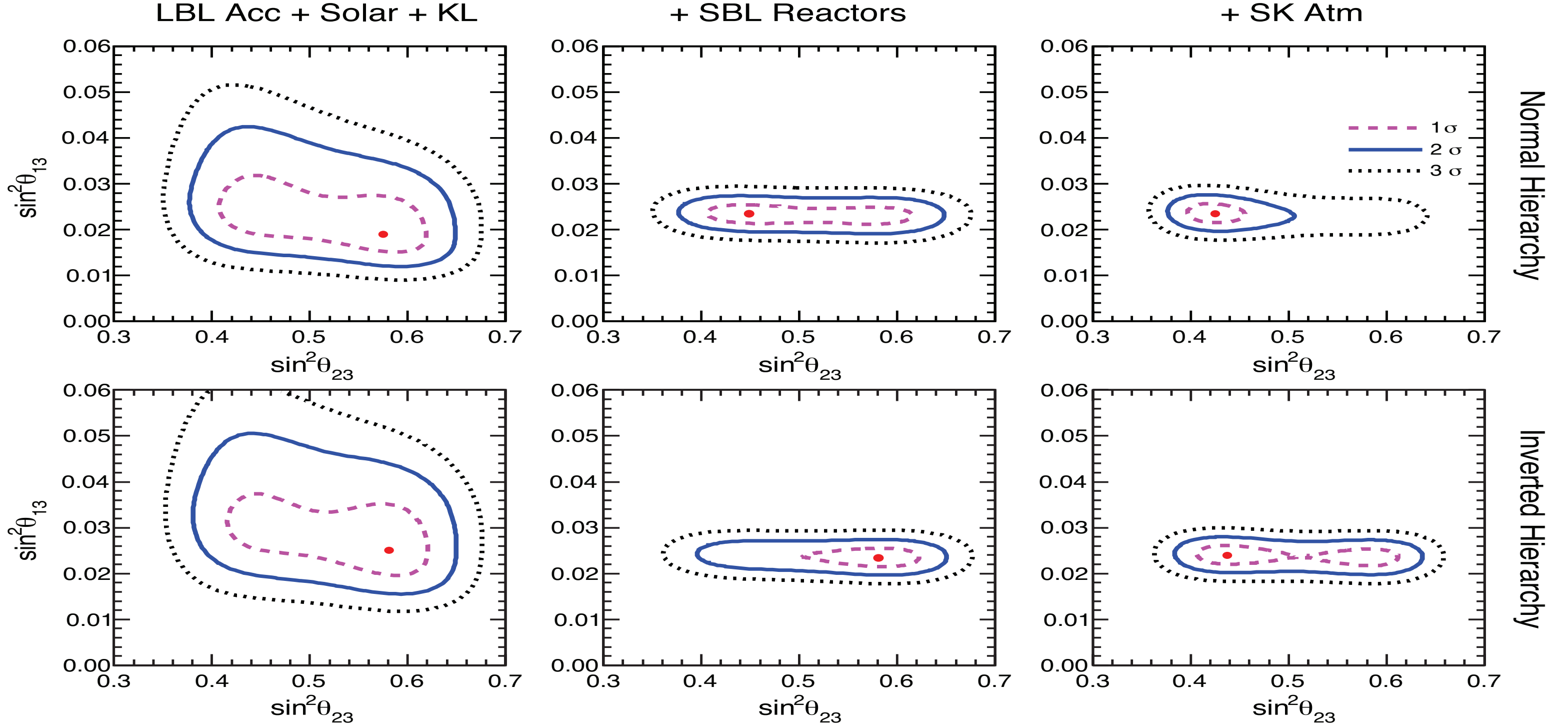
Fractional uncertainties (defined as 1/6 of 3σ ranges):

δm^2	2.6 %
Δm^2	3.0 %
$\sin^2\theta_{12}$	5.4 %
$\sin^2\theta_{13}$	8.5 %
$\sin^2\theta_{23}$	~ 11 %

No information of sign of Δm^2_{31}

Status of θ_{23}

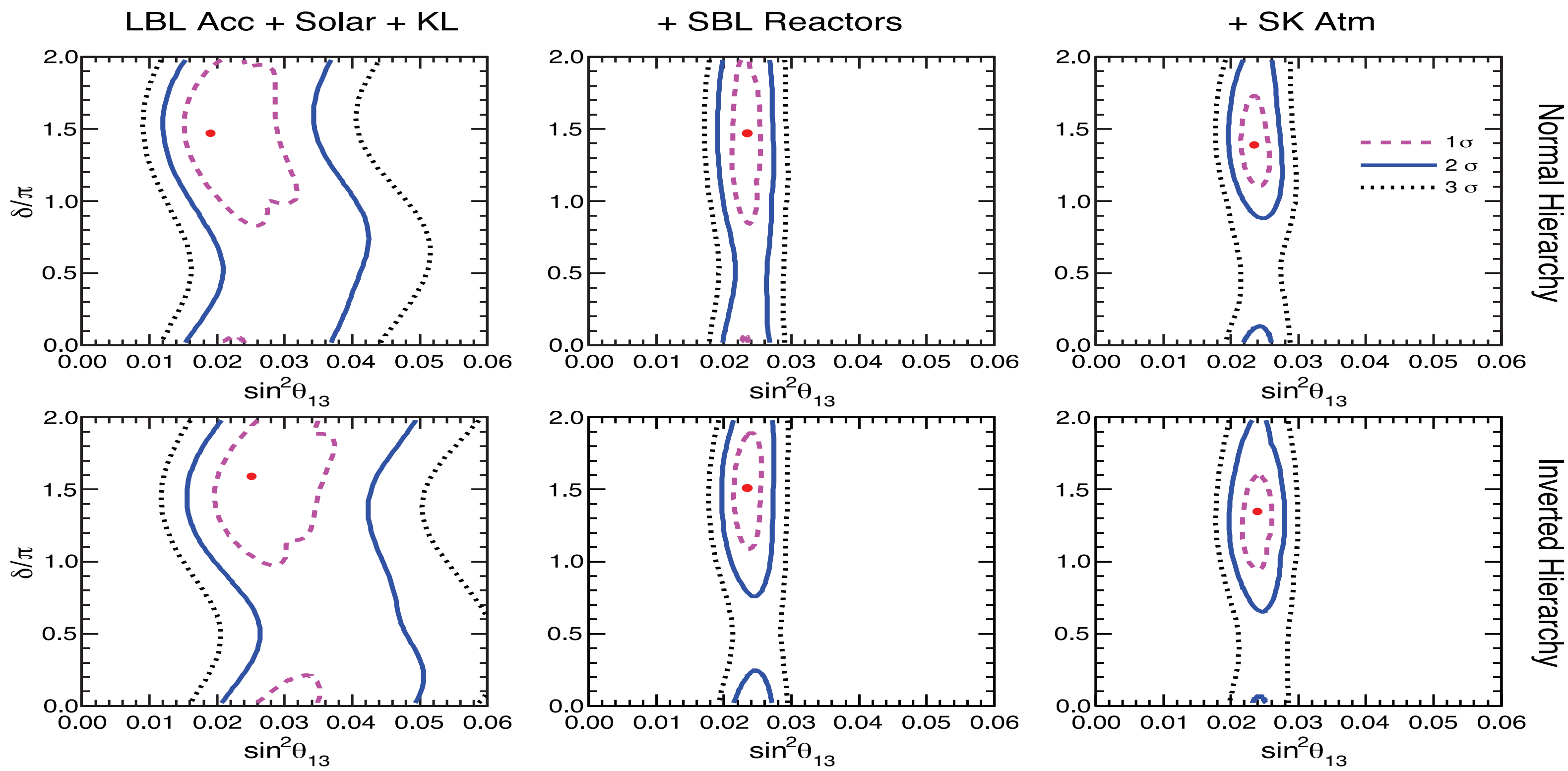
- Precision of $\sin^2\theta_{23} \sim 11\%$
- Still do not know if $\theta_{23} < 45^o$ (Lower Octant, LO) or $> 45^o$ (Higher Octant, HO)
- Global analysis of data shows an octant flip



E. Lisi, talk in NuPhys 2013

- Best-fit in the LO driven by reactor (NH) and SK atmospheric data

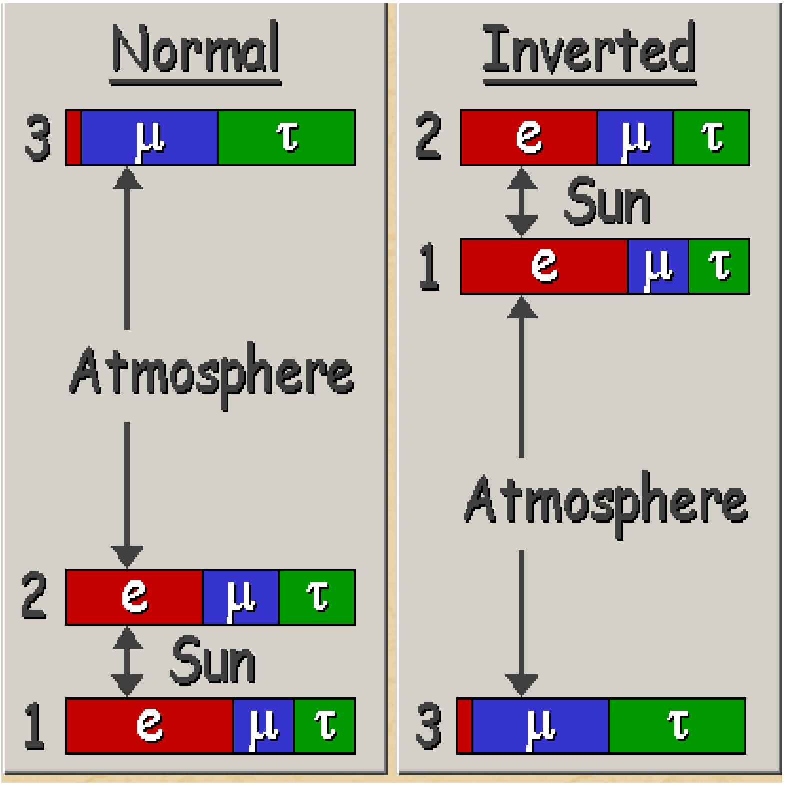
Status of δ_{CP}



E. Lisi, talk in NuPhys 2013

- Accl + solar + KL data shows a preference for $\delta \sim 1.5\pi$
- SK atmospheric data finds a prefernece for $\delta \sim \pi$
- Combined fit gives $\delta \sim 1.4\pi \Longrightarrow \sin\delta < 0$

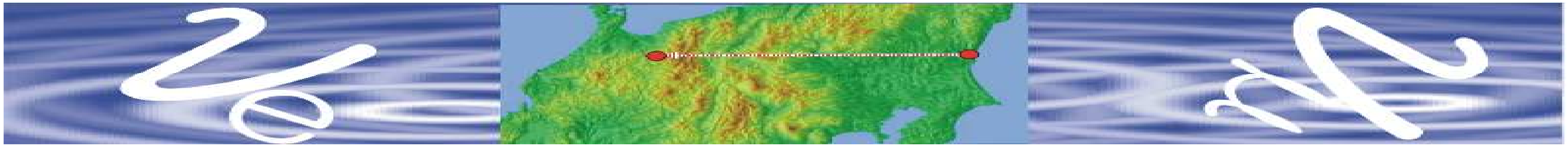
The important unknowns



- The Neutrino Mass hierarchy ($sgn\Delta m^2_{31}$)
- The octant of θ_{23}
- Leptonic CP phase
- Mass hierarchy can be determined by exploiting the earth matter effect if θ_{13} is appreciable.
- Reduced error in θ_{13} and matter effect can be helpful for octant determination
- Determination of CP phase is possible only if θ_{13} is non-zero.

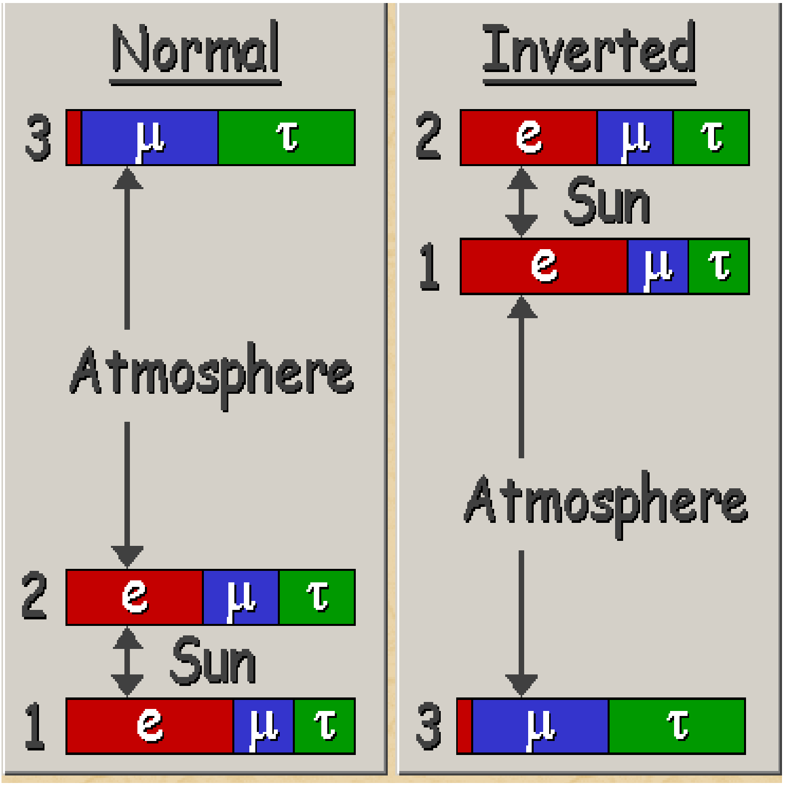
Future Longbaseline Experiments

- Current Generation Superbeam Experiments
  (conventional accelerator beam but more power)
  - T2K: Tokai to Kamioka, detector: SuperKamiokande, – $E \sim 0.76$ GeV, L = 295 km,0.75 MW, taking data
  - NOνA: NuMI beam from FNAL, 0.7 MW – $E \sim 1 - 3$ GeV, L = 810 km, to start soon
- Next generation experiments
  - T2HK J-PARC to Kamioka, detector HyperKamiokande, 1.6 MW
  - LBNO (CERN-Phyasalami) $\sim$ 2300 km, detector 20 kton LArTPC,0.77 MW
  - LBNE (FNAL-Homestake), 0.7MW $\sim$ 1300 km
  - Most useful is the conversion probability ν_e to ν_μ



Matter Effect, θ_{13} and hierarchy

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



- For $\Delta m^2_{31} > 0$ matter resonance in neutrinos
- For $\Delta m^2_{31} < 0$ 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}
- For antineutrinos: $\delta \rightarrow -\delta$
- CP violation arises from the interference term
- Absence of CP violation requires either $A_S = 0$ or $A_A = 0$.

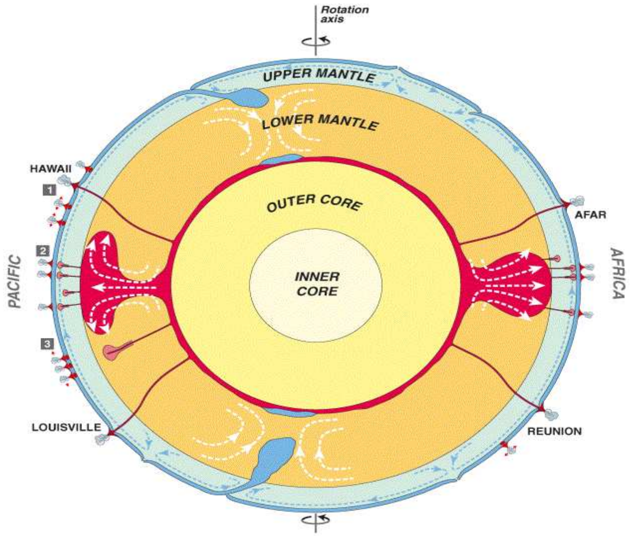
A.Yu. Smirnov, hep/ph 0610198

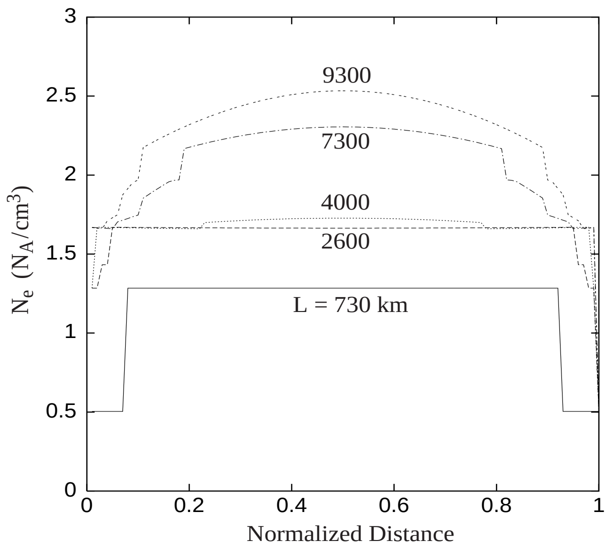
- GOLDEN because it can probe all three unknowns θ_{13}, $sgn(\Delta m^2_{31})$, δ_{CP}

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

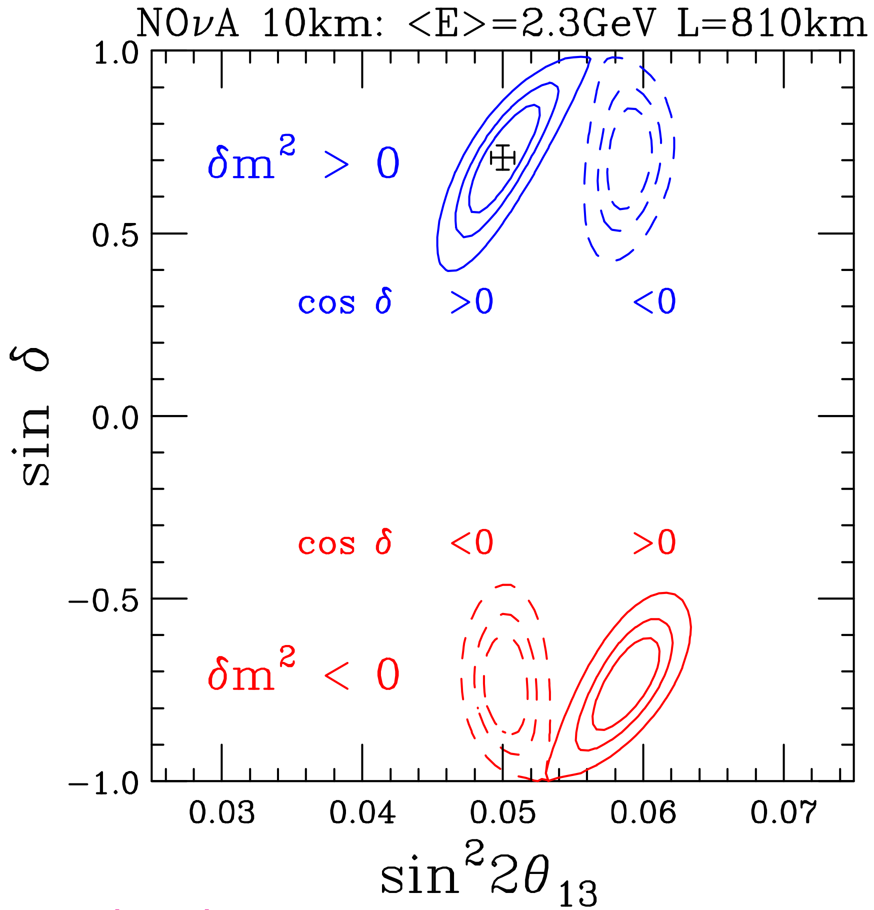
- $(\theta_{23}, \pi/2 - \theta_{23})$ degeneracy

  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

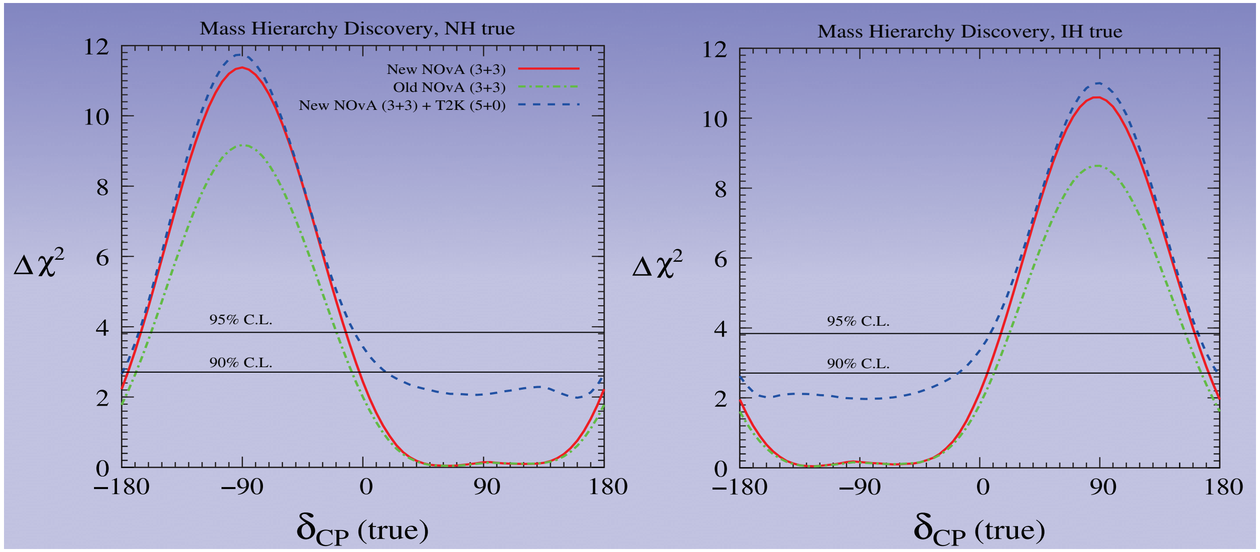
- Ghost (Degenerate) Solutions in $(\delta - \theta_{13})$ plane
- Unambiguous determination of parameters difficult



Mena and Parke, 2005

Hierarchy-δ_{CP} degeneracy

- Can hierarchy-δ_{CP} degeneracy be solved by T2K-NOνA ?



Agarwalla, Prakash, Raut, Umasankar, JHEP, 2012

For true NH $(-180^o < \delta_{CP} < 0)$ is favourable

For true IH $(0 < \delta_{CP} < 180^)$ is favourable

- Lack of knowledge of δ_{CP} reduces hierarchy sensitvity
- How does one solve the problem ?

The old idea : Magic Baseline

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

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

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

The old idea : Magic Baseline

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

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

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

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

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

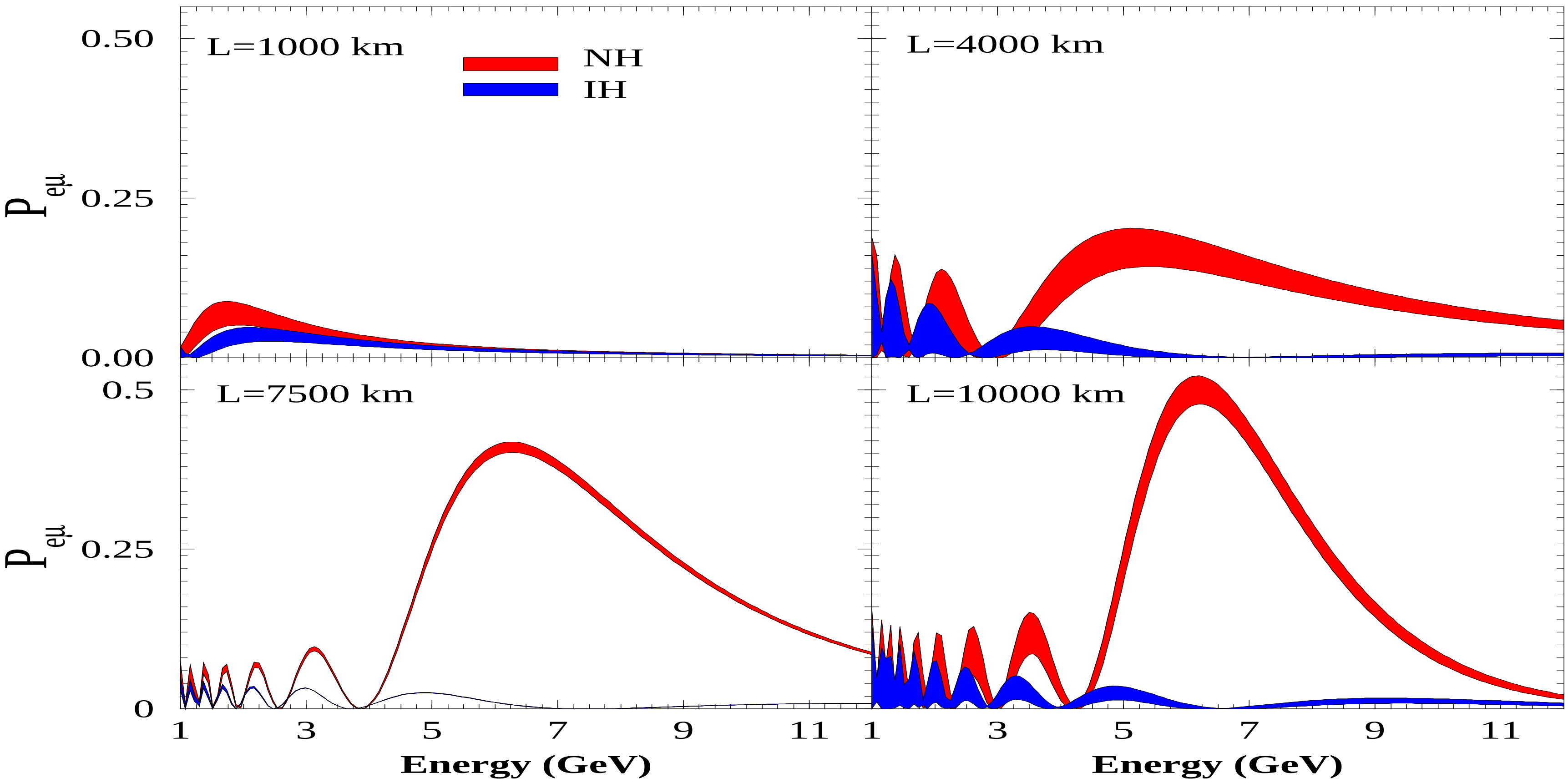
- $\sin(\hat{A}\Delta) \simeq 0 \Rightarrow \frac{1}{\sqrt{2}} G_F n_e L = \pi \Rightarrow L_{magic} \simeq 7690$ km
- Independent of neutrino parameters and energy
- True for both NH and IH

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

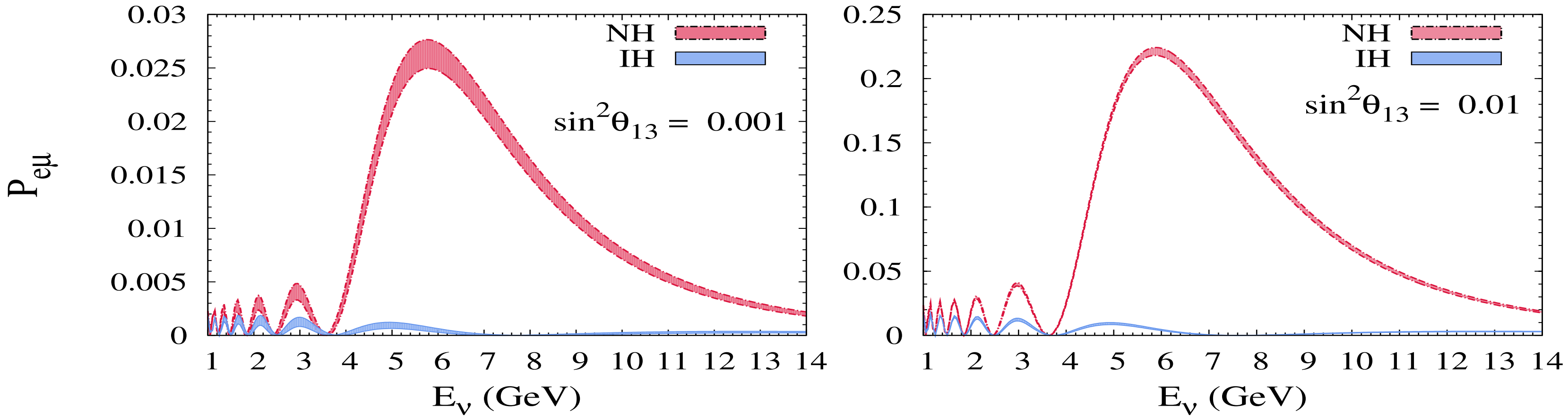


- At $\sim$ 7500 km δ_{CP} dependence negligible
- $(\delta_{CP}, sgn(\Delta m^2_{\mathrm{atm}}))$ degeneracies vanish
- Clean measurement of $sgn(\Delta m^2_{\mathrm{atm}})$

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

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

- 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

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

- In that case $P_{e\mu} \approx \mathcal{O}(\alpha^2) \to$ 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

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

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

IH–NoCP

$(1+|\hat{A}|)\cdot|\Delta| = n\pi,\ n > 0$

NH–NoCP

$(1-|\hat{A}|)\cdot|\Delta| = n\pi,\ n \neq 0$

  - Demand: Maximum hierarchy sensitivity

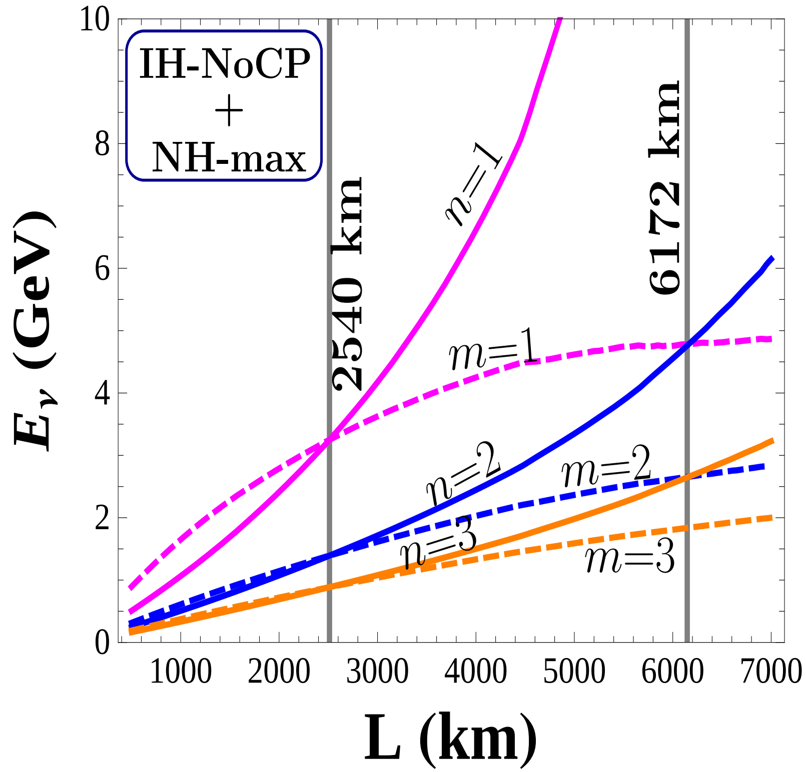
NH–max

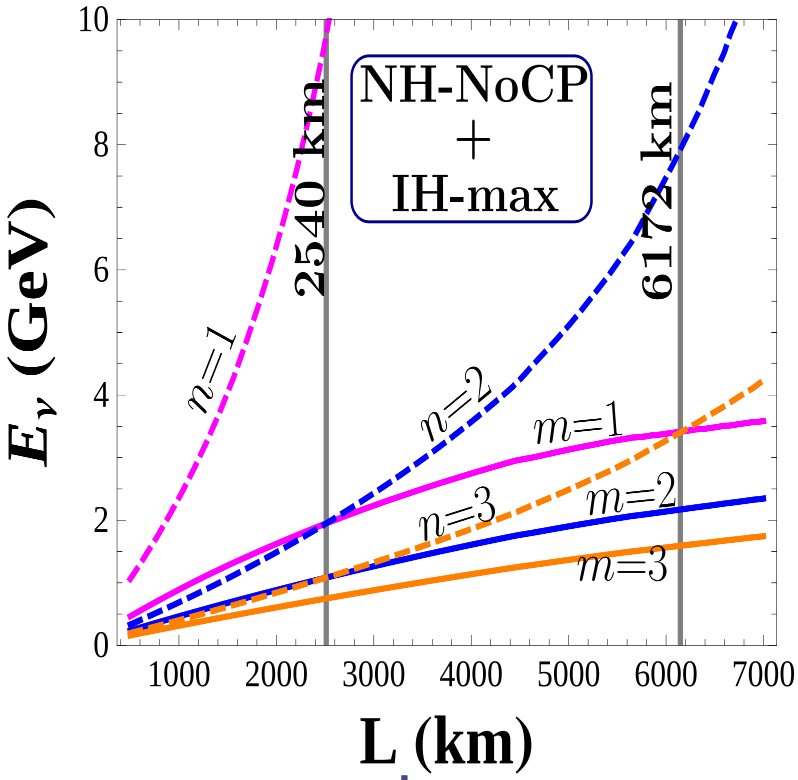
$(1-|\hat{A}|)\cdot|\Delta| = (m-\frac{1}{2})\pi$

IH–max

$(1+|\hat{A}|)\cdot|\Delta| = (m-\frac{1}{2})\pi$

The Bi-Magic baseline





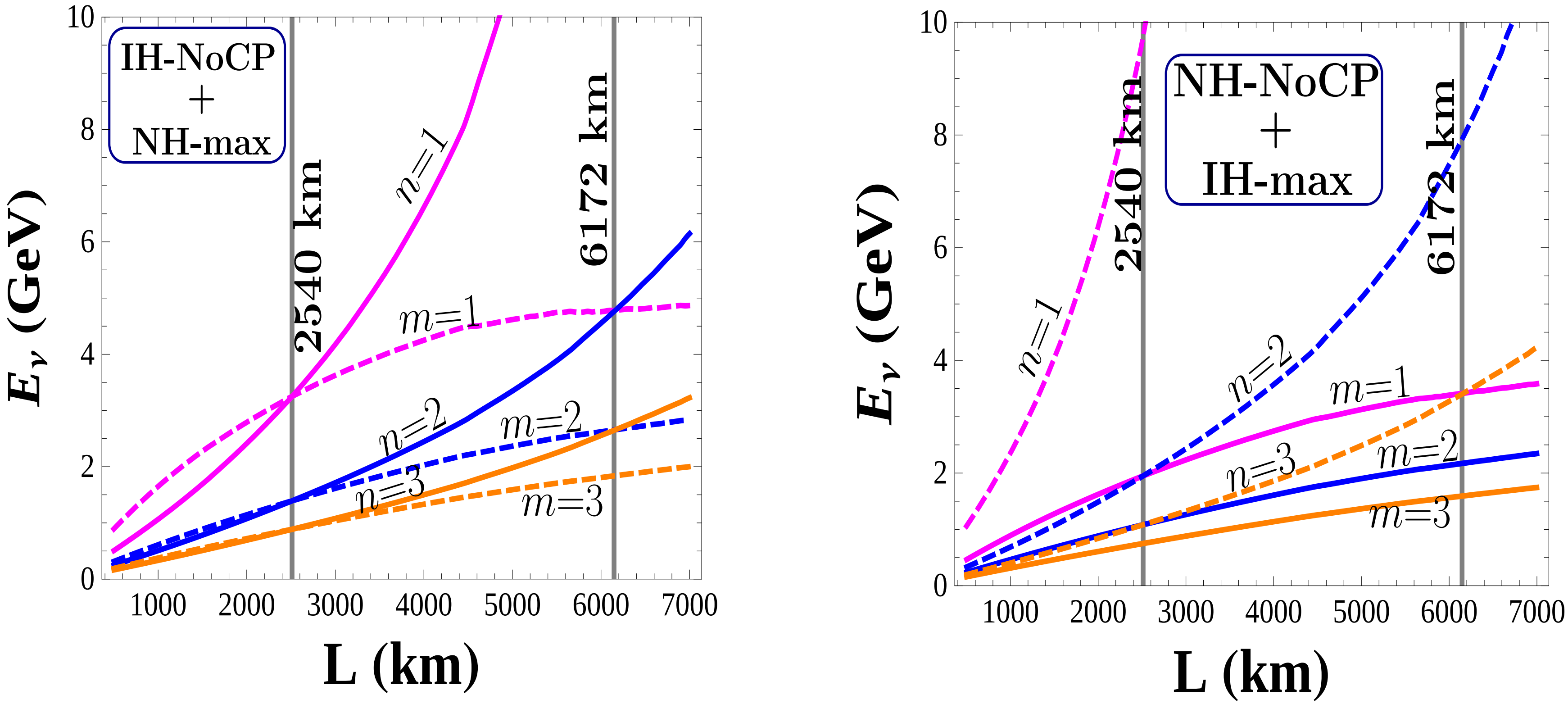
- $n = 1$ and $m = 1$
  $L \approx 2540$ km
  $E_\nu \equiv E_{IH} \approx 3.3$ GeV,

  Raut, Singh, UmaShankar,PRD, 2009

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

  Dighe,Goswami,Ray, PRL, 2010

The Bi-Magic baseline

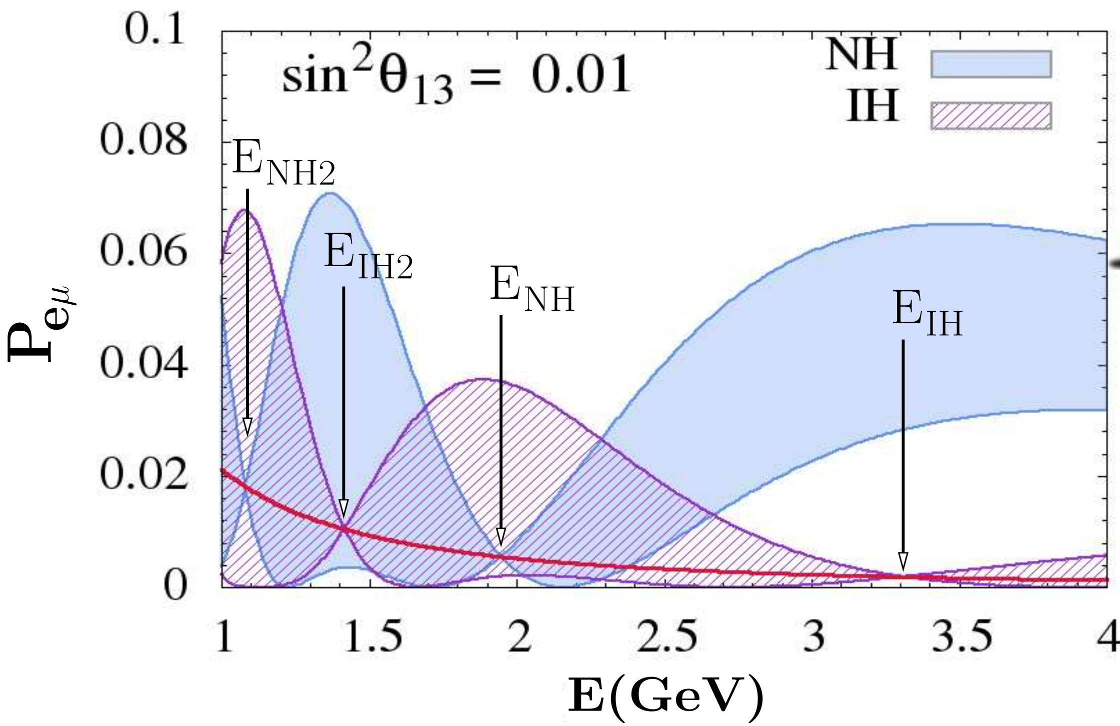


- Lowest Bi-magic Baseline $\sim$ 2540 km
- Higher n,m $\Rightarrow$ Lower E_ν to satisfy no CP condition low flux, low efficiency
- More bimagics 6172 km, 8950 km, 106900 km

Baselines close Bi-Magic baseline

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

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



- NH, IH interchanged for antineutrinos

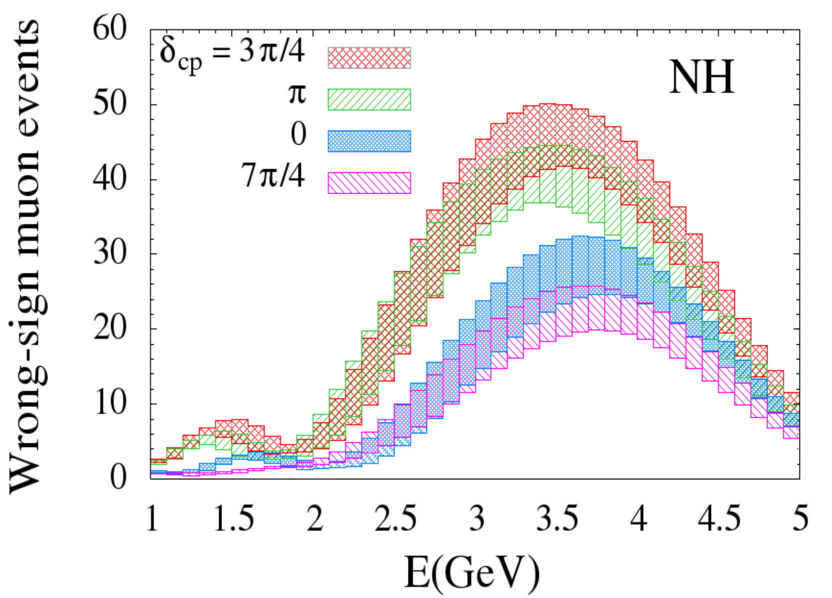
E_{IH} = 1.9 GeV

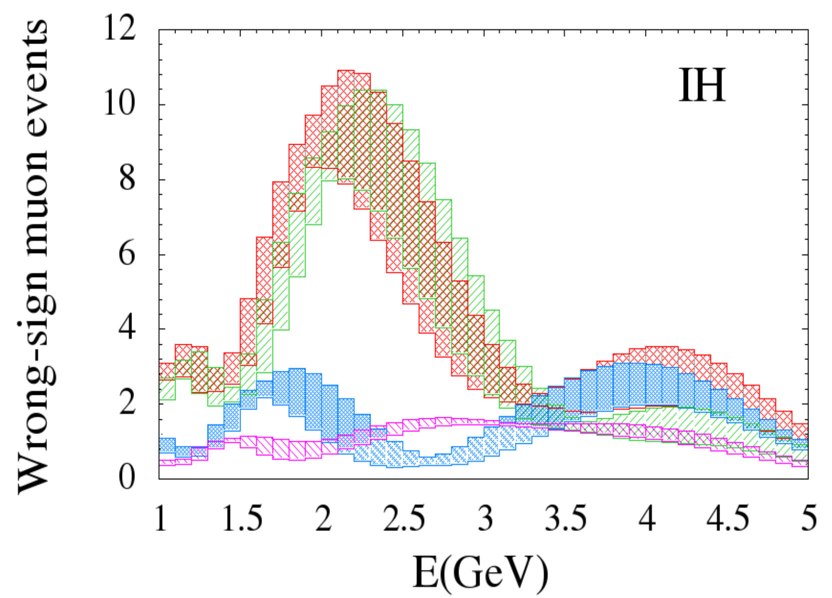
- NH probability independent of δ_{CP} but δ_{CP} band in IH large
- δ_{CP} sensitivity for IH

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

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

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

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

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

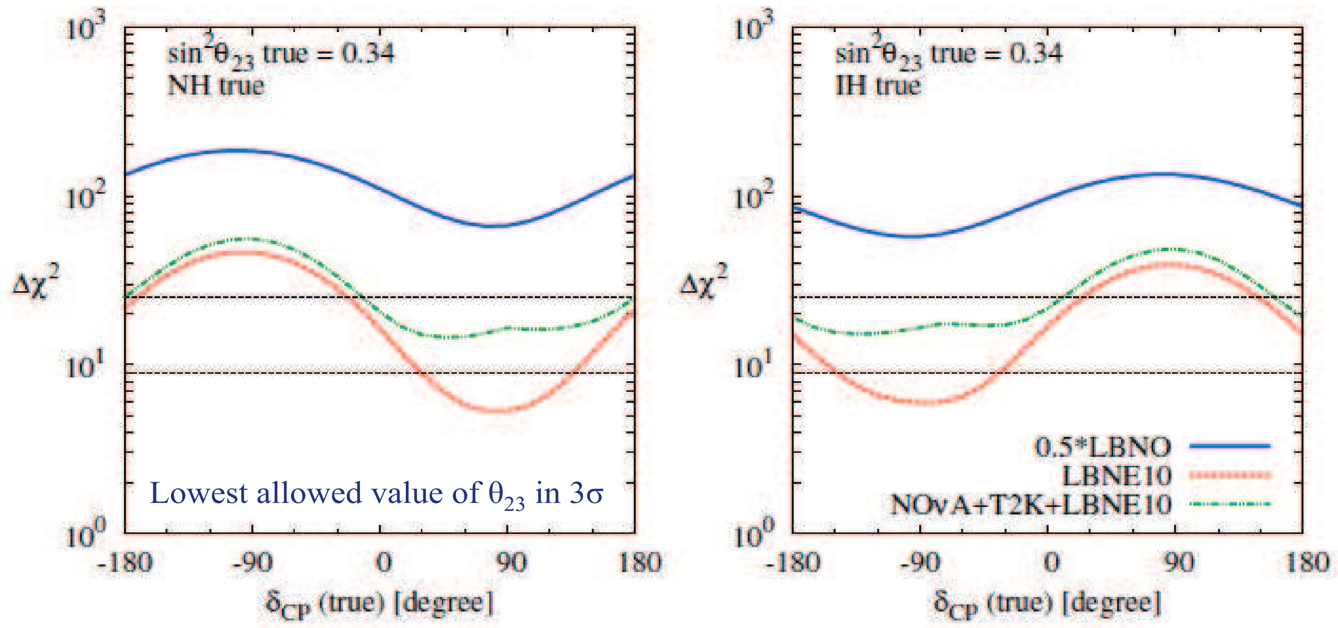
$$P_{e\mu}(\mathrm{IH}) \approx 50\alpha^2 s_{12}^2 c_{12}^2 c_{23}^2 + \frac{25}{9} s_{13}^2 s_{23}^2$$

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

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

Hierarchy Sensitvity: LBNE vs LBNO

- LBNE $\sim$ 1300km, LBNO $\sim$ 2290 km



Agarwalla, Prakash, Sankar, arXiv:1304.3251 [hep-ph]

- $\Delta\chi^2 = \chi^2_{NH} - \chi^2_{IH}$

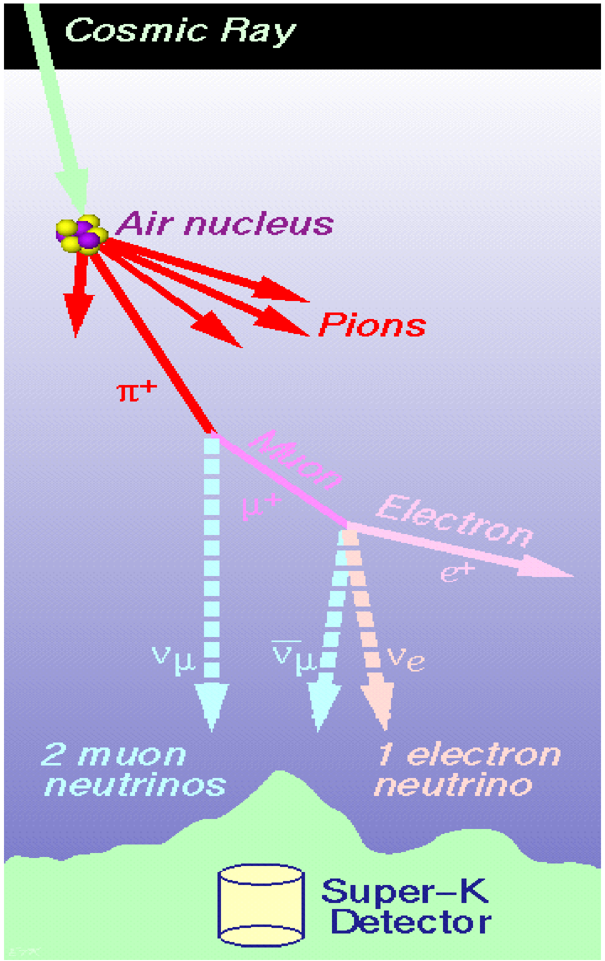
- LBNO (10 kt) $> 7\sigma$ sensitvity for the worst case of θ_{23}, δ_{CP}, hierarchy.
- LBNE (10 kt) + T2K + NOνA $> 3\sigma$ hierarchy sensitivity.
- Exceptional hierarchy sensitvity of LBNO is due to its proximity to bi-magic baseline.

Can Atmospheric Neutrinos help ?

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

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

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

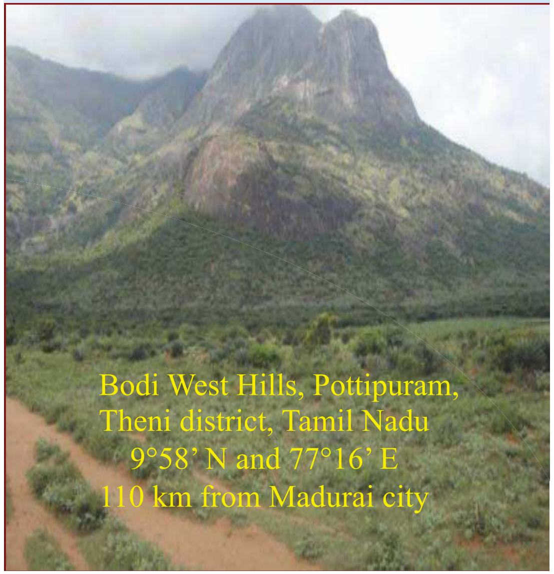


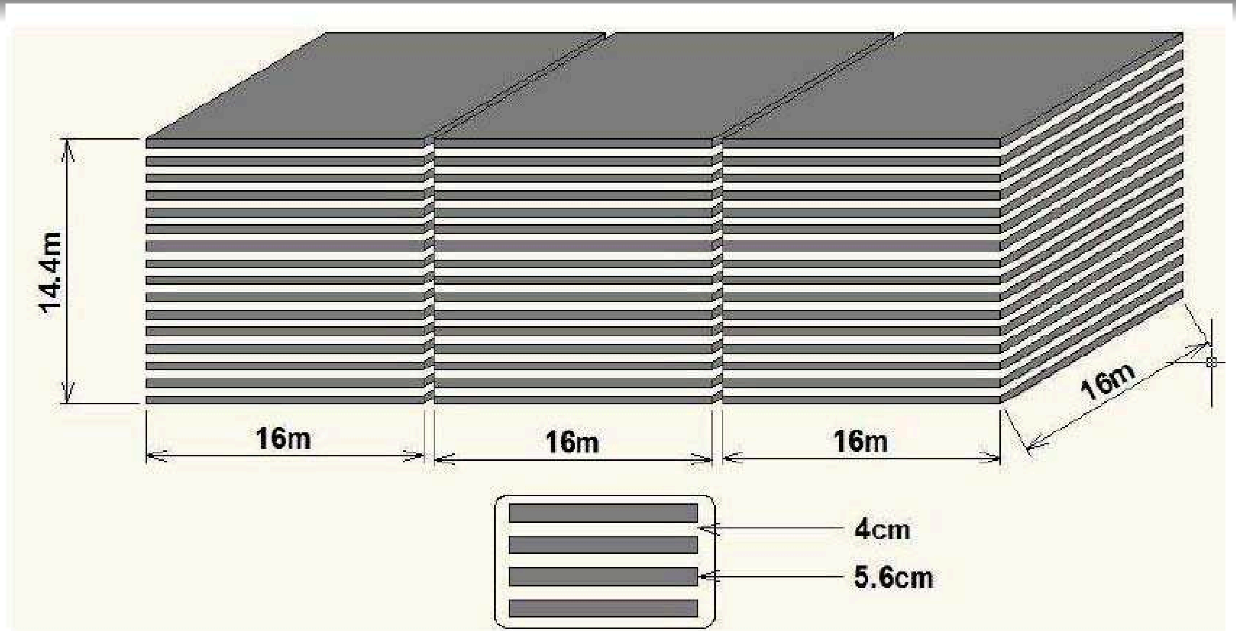
- Salient Features:
  - ➢ Provides a broad range of energy as compared to any other natural and artificial sources
  - ➢ Provides a wide range of path-length
  - ➢ Hence a broad L/E band (1 to 10^5 km/GeV).
  - ➢ The longer baseline allow matter effects to develop (large θ_{13} conducive)
  - ➢ Source of both neutrinos and antineutrinos
  - ➢ Source of both ν_e and ν_μ
  - ➢ All these for free !!

Future Detectors for Atm ν

- Magnetized Iron Detector (Prototype: INO)
  ➢ 50 - 100 kT
  ➢ Excellent Muon energy measurement, direction reconstruction and $\&$ charge discrimination capability
  ➢ Can determine the neutrino energy through Hadron shower reconstruction
- Megaton Water Cerenkov Detector (HK, MEMPHYS)
  ➢ Large volume ($\sim$ Mega Ton)
  ➢ SK-type detector with no charge ID
  ➢ Both electron and muon events can be used
- Liquid Argon detector (ICARUS) ➢ Time projection chamber
  ➢ Both electron and muon events can be used, charge ID for both?
- (IceCube, PINGU)
  ➢ Huge Volume (Multi-Mton)

INO

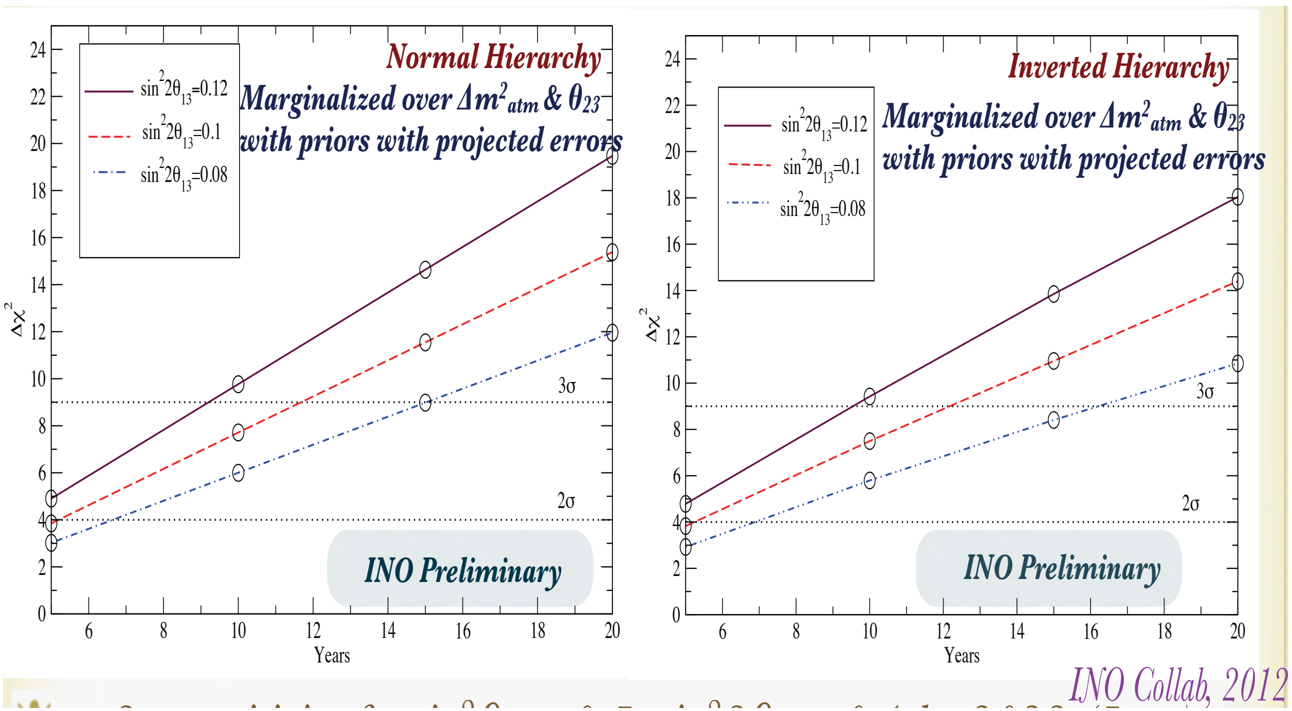




- 50 kton magnetized iron detector Sensitive to muons
- Good Energy determination from
  - Track length • Track curvature in a magnetic field
- Directionality from tracking and ns timing resolution
- Charge identification from track curvature in magnetic field
- Hadron Shower reconstruction
- Site Bodi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

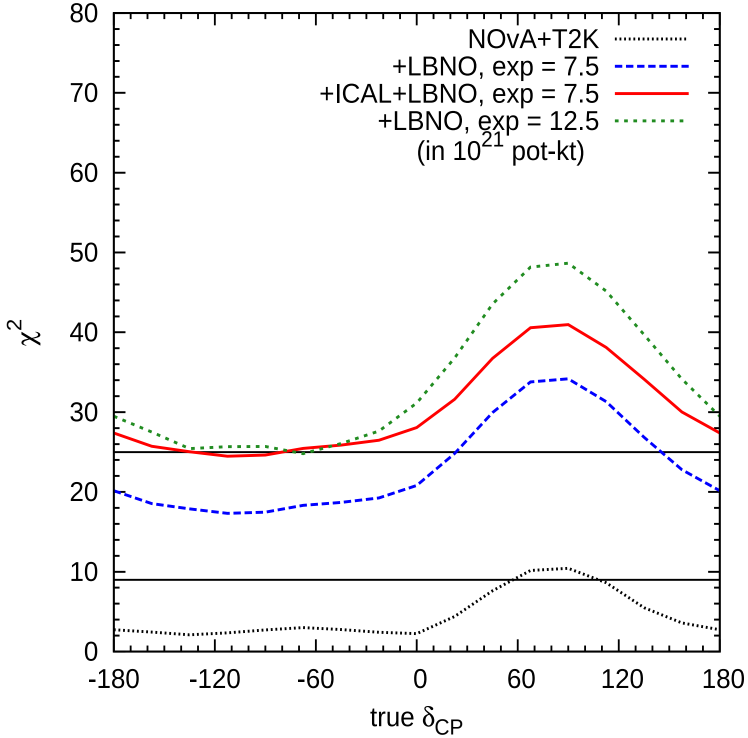
Hierarchy Sensitivity from INO simulation

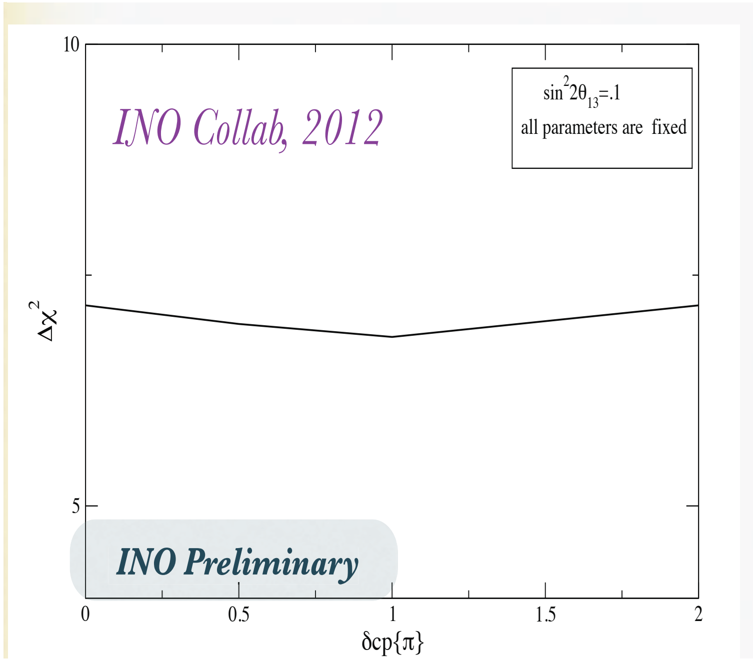
- Using 50 Kton detector and events generated from NUANCE
- Using ICAL resolutions in Muon energy and Zenith Angle
- Using efficiency and Charge-ID from ICAL simulations



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

Synergy with Long Baseline Experiments

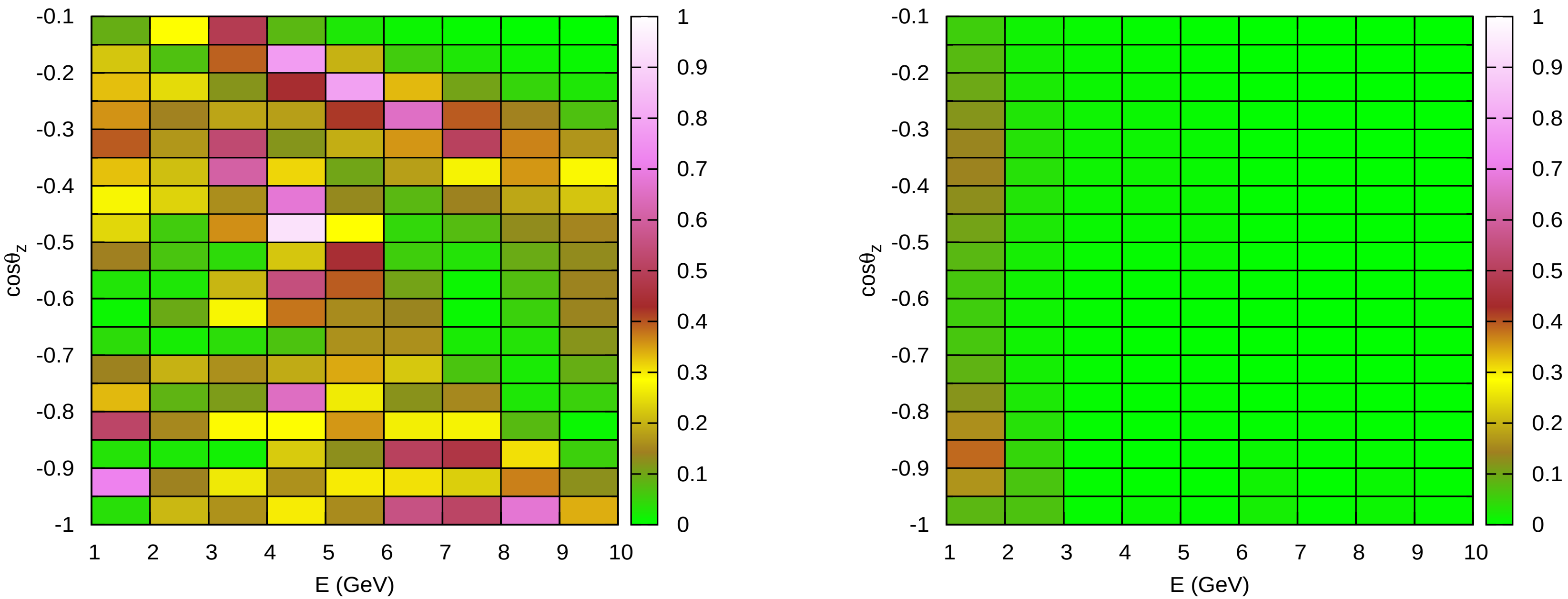




- Hierarchy sensitvity of INO is indpendent of δ_{CP}
- Addition of INO data to T2K/NOνA can enhance the hierarchy sensitvity for unfavourable values of δ_{CP}
- LBNO/LBNE can reach same sensitvity with a lower exposure/lower detector volume

Ghosh, Ghosal,Goswami, Raut, JHEP, 2013

δ_{CP} sensitivity of Atmospheric Neutrinos



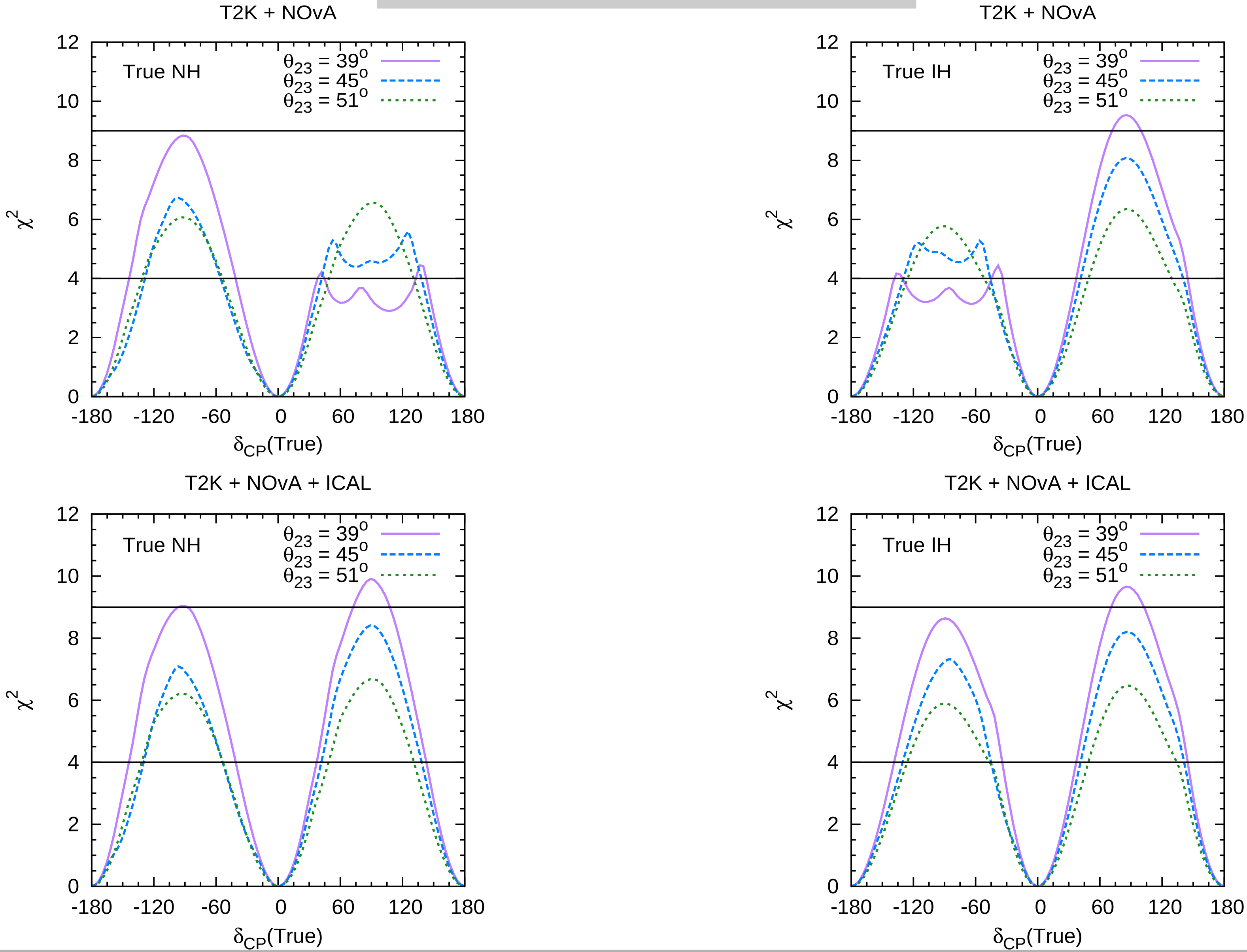
- $S_\mu + S_{\overline{\mu}} = (\Delta N_\mu)^2 / N_\mu(\text{avg})$,

Ghosh,Ghoshal,Goswami,Raut,PRD,2013

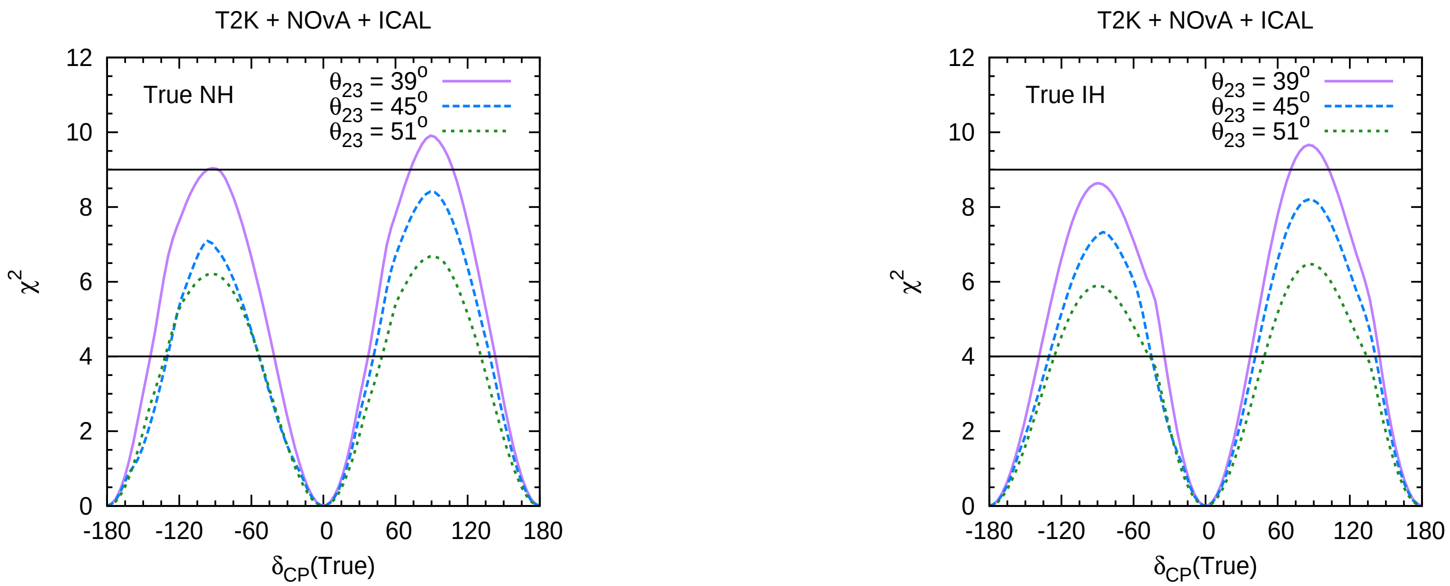
- ΔN_μ is the maximum difference in events by varying δ_{CP}, $N_\mu(\text{avg})$ is the average number of events over all values of δ_{CP}.
- A measure of δ_{CP}-sensitivity in the $E - cos_{\theta_z}$ plane; the grid represents bins in energy and $\cos\theta_z$.
- CP sensitvity is washed away by angular and energy smearing

NOνA+T2K+ICAL CP violation discovery

$$\Delta\chi^2 = \chi^2(\delta_{CP}^{true}) - \chi^2(\delta_{CP}^{test})$$



NOνA+T2K+ICAL CP violation discovery



- $\sin^2 2\theta_{13} = 0.1$, 500 kt yr exposure
- 3σ sensitivity 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 :)

(Talk by Monojit Ghosh, this meeting)

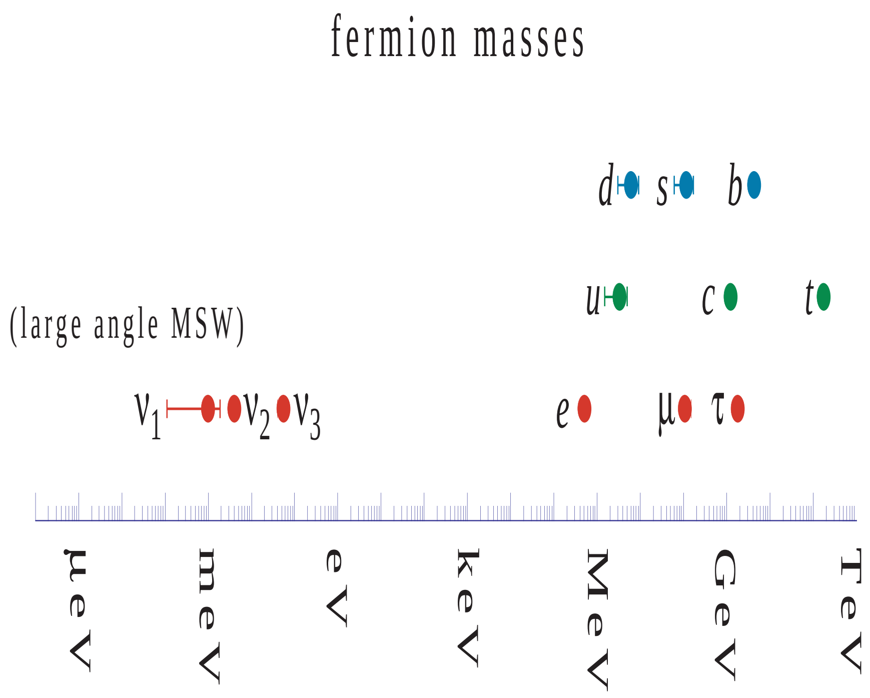
Ghosh, Ghosal,Goswami, Raut, PRD, 2013

To Summarise

- From Neutrino Oscillation experiments we have information on mass squared differences and mixing angles
- Two major unknown parameters are sign of $|\Delta m^2_{31}|$ and the leptonic CP phase δ_{CP}
- Current generation long baseline experiments T2K/NOνA and future even longer baseline experiments LBNE and/or (?) LBNO to look for this
- Synergy between various experiments specially long-baseline and atmospheric experiments could play an important role in planning future facilities
- Models of neutrino mass should explain the values of masses and mixing angles inferred from data
- Future high precision measurements on mixing angles, mass ordering and CP phase will help in restricting models.

Neutrino masses: Key issues

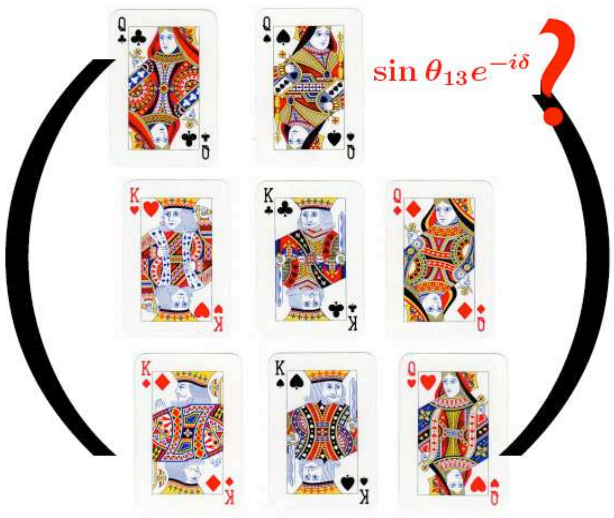
- $\Delta m^2_{21} \sim 7.5 \times 10^{-5}$ eV^2, $|\Delta m^2_{31}| = 2.3 \times 10^{-3}$ eV^2
- Cosmological mass bound $\Sigma m_i \leq 0.2 - 1.3$ eV
- Neutrino masses much smaller than the quark and charged lepton masses



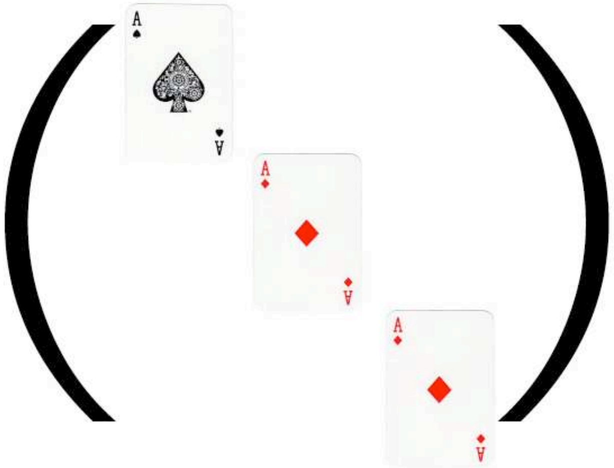
Mixing angles: key issues

- Why two large and one small mixing angle unlike in quark sector where all mixing angles are small

$U_{PMNS} \sim$



$V_{CKM} \sim$

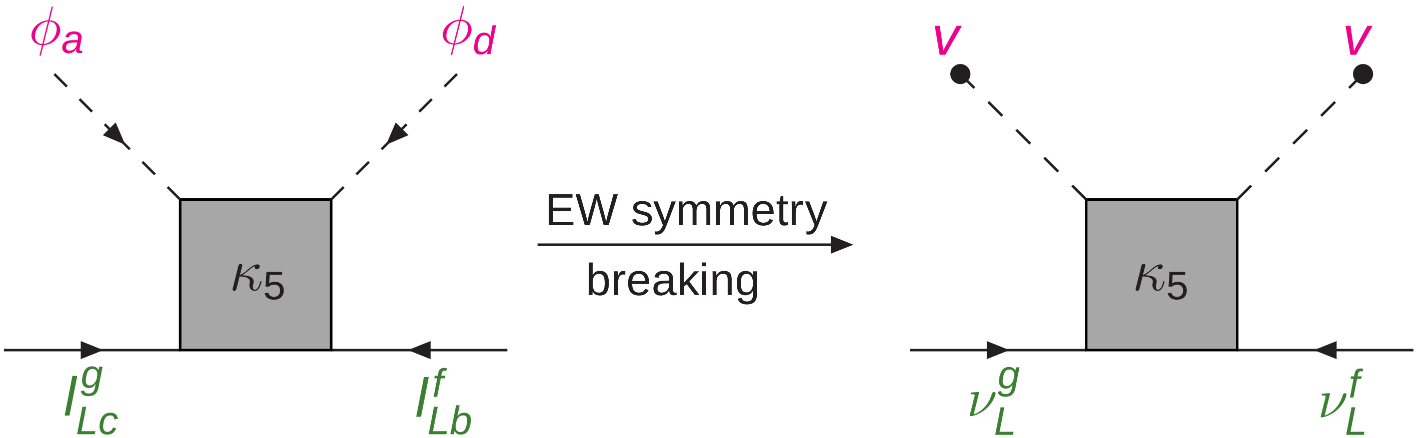


- Current data $\Rightarrow \theta_{23} = 39^o$, $\theta_{12} = 31^o$, $\theta_{13} = 8^o$ $\delta_{CP} = \sim 250^o(?)$
- Quark mixing angles $\theta_{23} = 2.3^o$, $\theta_{12} = 13^o$, $\theta_{13} = 0.2^o$,$\delta_{CP} = 68.5^o$
- Flavour Symmetries, Anarchy..

Why neutrino masses are small ?

- The most natural explanation $\rightarrow$ seesaw mechanism
- Relates the smallness of neutrino masses to new physics at high scale
- Heavy field present at high scale Λ
- Tree level exchange of this heavy particle $\Longrightarrow$ effective dimension 5 operator at low scale $\mathcal{L} = \kappa_5 l_L l_L \phi\phi, \;\; \kappa_5 = y_\kappa/\Lambda$

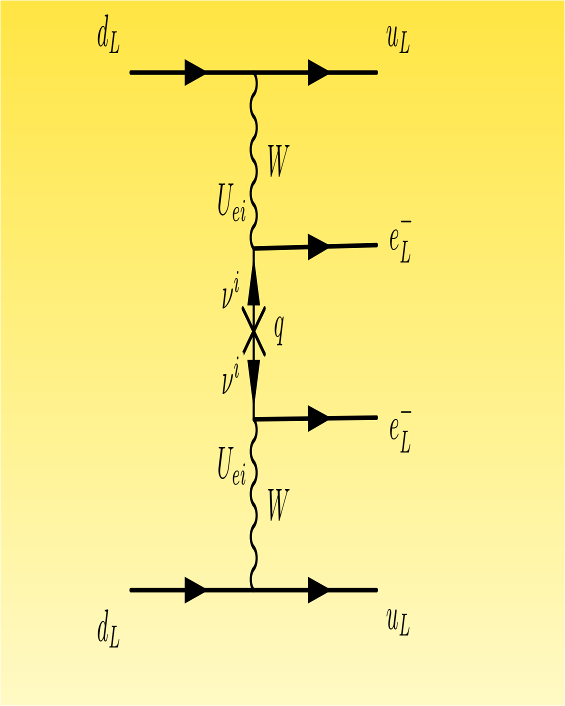
Weinberg, 79



- Lepton number violation $\Longrightarrow$ neutrinos are Majorana particles
- Correct neutrino mass $\Longrightarrow M \sim 10^{15}$ GeV. Can the new physics be GUT ?
- TeV scale seesaw ?

Neutrinoless Double Beta decay

- $(A, Z) \to (A, Z+2) + 2e^- \implies$ signifies violation of Lepton Number by 2 units
- Standard Picture: $0\nu\beta\beta$ mediated by the light neutrinos



$$\frac{\Gamma^{0\nu\beta\beta}}{\ln 2} = G\,|\mathcal{M}_\nu|^2\,|m_\nu^{ee}|^2$$

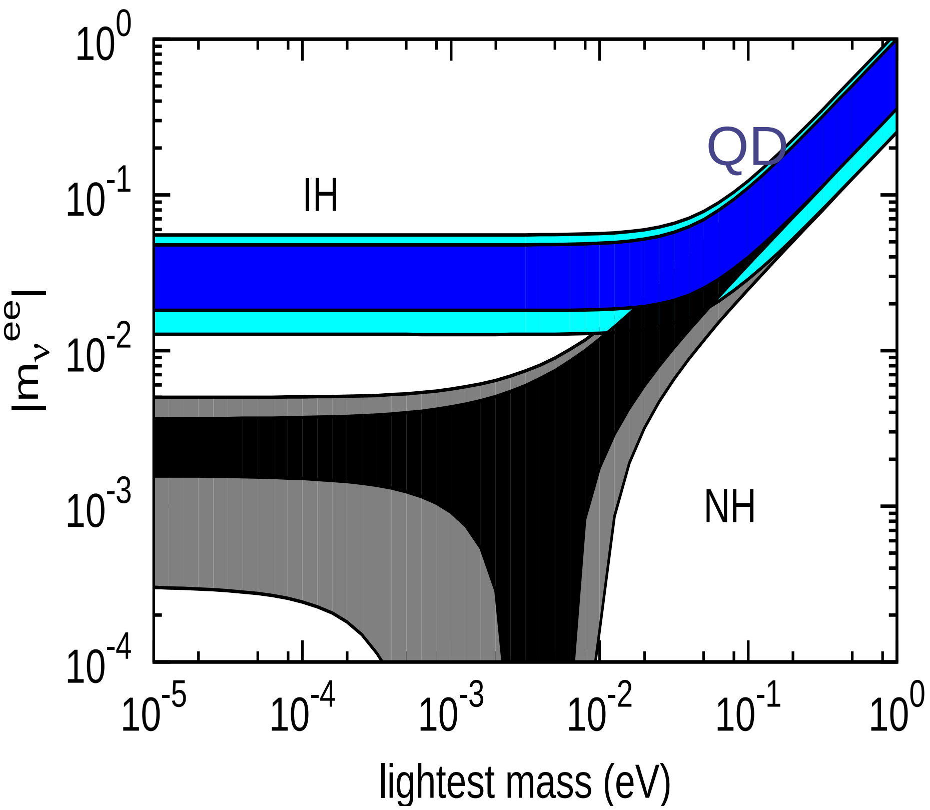
- $G \to$ contains the phase space factors (calculable)
- $\mathcal{M}_\nu$ is the nuclear matrix element (complicated).
- $|m_\nu^{ee}| = |U_{ei}^2\, m_i| \to$ the effective mass, (interesting)

The effective mass

$$|m_\nu^{ee}| = |m_1 U_{e1}^2 + m_2 U_{e2}^2 e^{2i\alpha_1} + m_3 U_{e3}^2 e^{2i\alpha_2}|$$

- ν Mass Spectrum • Absolute ν Mass Scale • CP phases

- Depends on 7 out of 9 parameters of neutrino mass matrix



NH: $m_1 << m_2 << m_3$

IH: $m_3 << m_1 \approx m_2$

QD: $m_1 \approx m_2 \approx m_3$

$0\nu\beta\beta$: Experimental Results

- Positive claim by part of HM group:
  $T^{0\nu}_{1/2} = 2.23^{+0.44}_{-0.31} \times 10^{25}$ yr at 68% CL using ^{76}Ge

  H. V. Klapdor-Kleingrothaus *et al.* Phys. Lett. B **586**, 198 (2004).

- New results from experiments using ^{136}Xe
  $T^{0\nu}_{1/2} > 1.9 \times 10^{25}$ yr at 90% CL (KamLAND-ZEN) (2013)
  $T^{0\nu}_{1/2} > 1.6 \times 10^{25}$ yr at 90% C.L. (EXO) (2012)
  $T^{0\nu}_{1/2} > 3.4 \times 10^{25}$ yr at 90% CL (Combined, 2013)

- To test the compatibility between the claim in ^{76}Ge and the null results in ^{136}Xe it is useful to study the correlation between their half-lives

- $\frac{1}{T^{0\nu}_{1/2}} = G_{0\nu}|\mathcal{M}_\nu|^2 \left|\frac{m^\nu_{ee}}{m_e}\right|^2 ,$

- Eliminating m^ν_{ee}: $T^{0\nu}_{1/2}(^{136}\mathrm{Xe}) = \left(3.61^{+1.18}_{-0.83} \times 10^{24}\ \mathrm{yr}\right) \left|\frac{\mathcal{M}_{0\nu}(^{76}\mathrm{Ge})}{\mathcal{M}_{0\nu}(^{136}\mathrm{Xe})}\right|^2$

- Experimental bound on $T^{0\nu}_{1/2}(^{136}\mathrm{Xe}) >$ the predicted value from the above equation $\Longrightarrow$ inconsistency with the positive claim

$0\nu\beta\beta$: Compatibility between Experiments

NME			$T^{0\nu}_{1/2}(^{136}\mathrm{Xe})$
Method	$\mathcal{M}_{0\nu}(^{76}\mathrm{Ge})$	$\mathcal{M}_{0\nu}(^{136}\mathrm{Xe})$	$[10^{25}$ yr]
EDF(U)	4.60	4.20	0.33 - 0.57
ISM(U)	2.81	2.19	0.46 - 0.79
IBM-2	5.42	3.33	0.74 - 1.27
pnQRPA(U)	5.18	3.16	0.75 - 1.29
SRQRPA-B	5.82	3.36	0.84 - 1.44
SRQRPA-A	4.75	2.29	1.19 - 2.06
QRPA-B	5.571	2.460	1.43 - 2.46
QRPA-A	5.157	2.177	1.56 - 2.69
SkM-HFB-QRPA	5.09	1.89	2.02 - 3.47

- Experimental limits :
  - $T^{0\nu}_{1/2} > 1.9 \times 10^{25}$ yr at 90% CL (KamLAND-ZEN)
  - $T^{0\nu}_{1/2} > 1.6 \times 10^{25}$ yr at 90% C.L. (EXO)
  - $T^{0\nu}_{1/2} > 3.4 \times 10^{25}$ yr at 90% CL

Inconsistent for most NME's

Dev, S.G, Mitra, Rodejohann,PRD,2013

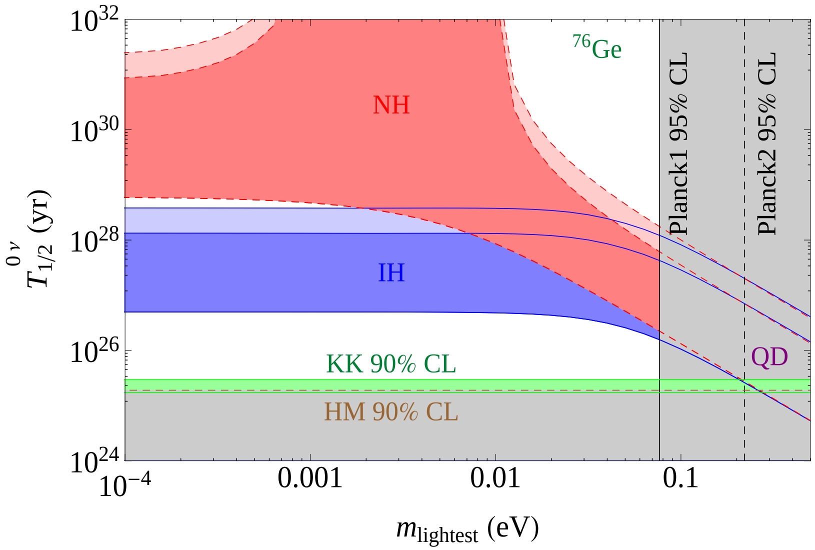
$0\nu\beta\beta$: Experimental Bounds

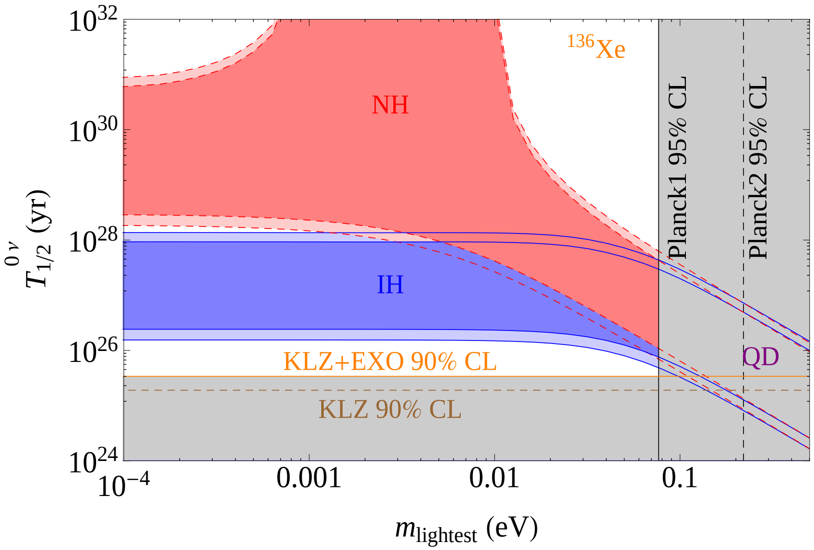
- Recent results from GERDA : $T^{0\nu}_{1/2}(^{76}\mathrm{Ge}) > 2.1 \times 10^{25}$ yr at 90% CL
- GERDA + IGEX + HM : $T^{0\nu}_{1/2}(^{76}\mathrm{Ge}) > 3.0 \times 10^{25}$ yr at 90% CL
- Can be translated into lower bound on m^{ν}_{ee}

NME	Limit on m^{ν}_{ee} (eV)				
	^{76}Ge			^{136}Xe	
	GERDA	comb	KK	KLZ	comb
EDF(U)	0.32	0.27	0.27-0.35	0.15	0.11
ISM(U)	0.52	0.44	0.44-0.58	0.28	0.21
IBM-2	0.27	0.23	0.23-0.30	0.19	0.14
pnQRPA	0.28	0.24	0.24-0.31	0.20	0.15
SRQRPA-B	0.25	0.21	0.21-0.28	0.18	0.14
SRQRPA-A	0.31	0.26	0.26-0.34	0.27	0.20
QRPA-B	0.26	0.22	0.22-0.29	0.25	0.19
QRPA-A	0.28	0.24	0.24-0.31	0.29	0.21
SkM-HFB-QRPA	0.29	0.24	0.24-0.32	0.33	0.25

- GERDA and KK barely consistent
- Inconsistent with combined KLZ+EXO limit for most NME's

$0\nu\beta\beta$: Compatibility between Experiments

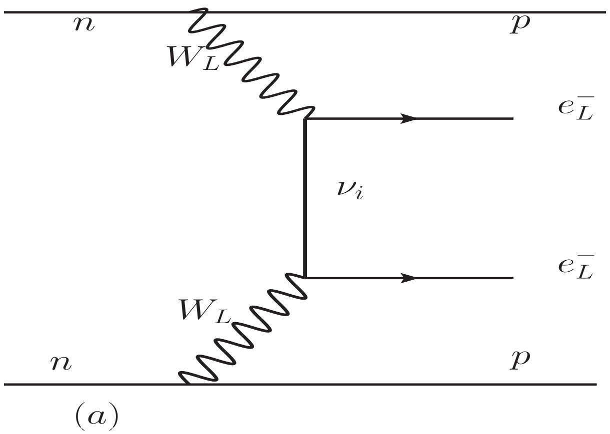


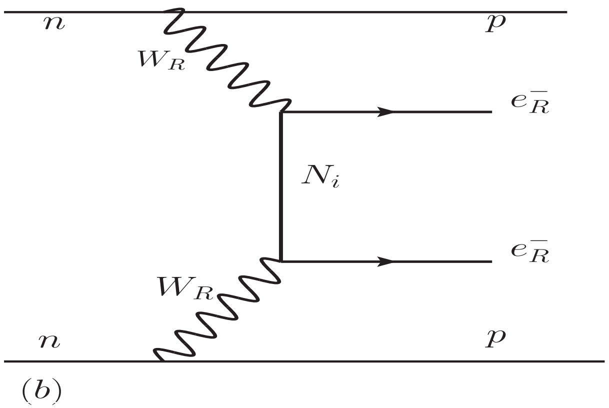


Dev, S.G, Mitra, Rodejohann,PRD,2013

- The cosmological mass bound $\Sigma m_i < 0.23 - 0.63$ eV from Planck
- Tension with the positive $0\nu\beta\beta$ claim of ^{76}Ge experiment
- KamLAND-Zen+EXO bound can be reached only for higher masses
- New physics ??
- TeV scale Left-Right Symmetric model; Accessible at LHC

$0\nu\beta\beta$ in Type-II LR model : Additional Diagrams





Light neutrino exchange

$$\mathcal{A}_{\nu}^{LL} \propto \frac{1}{M_{W_L}^4}\frac{U_{L_{e\,i}}^2 m_i}{p^2}$$

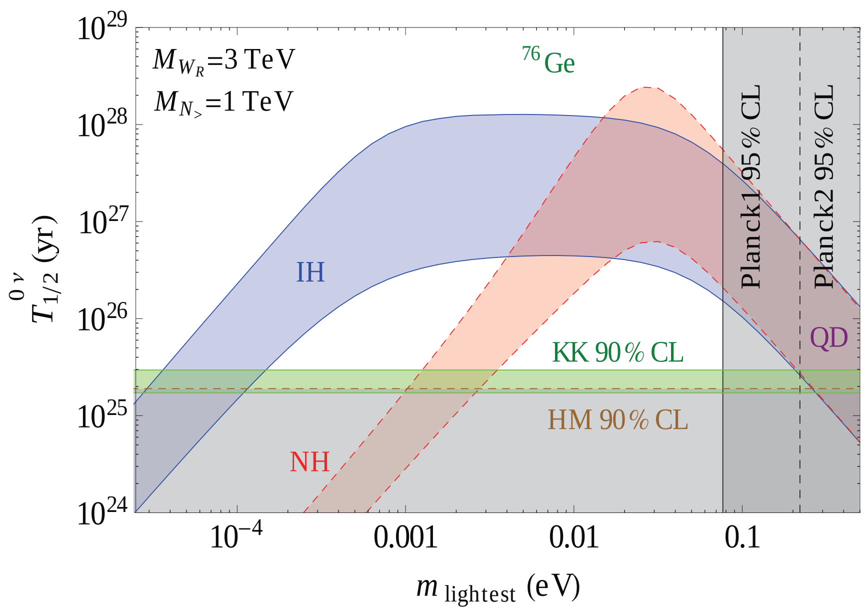
Heavy neutrino exchange

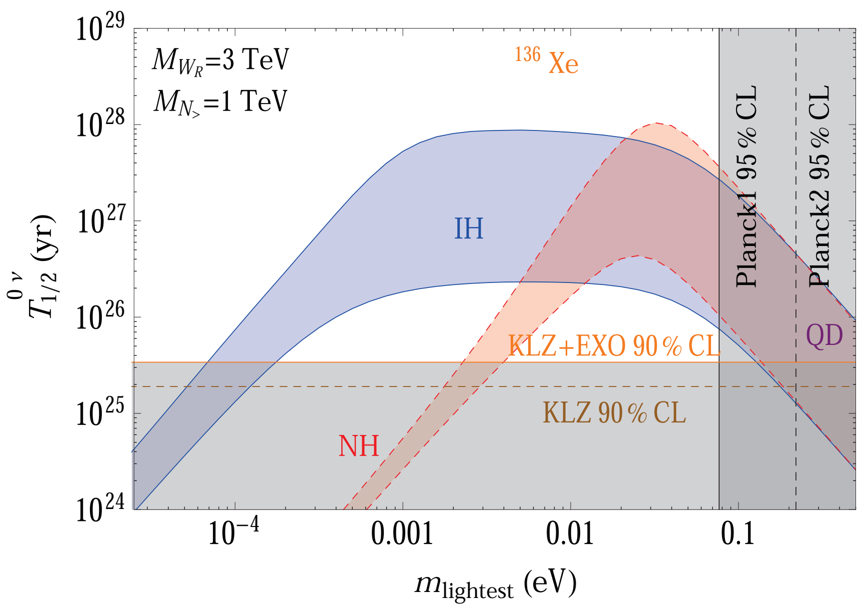
$$\mathcal{A}_{N}^{RR} \propto \frac{1}{M_{W_R}^4}\frac{(U^*_{R_{e\,i}})^2}{M_i}$$

- The different dependence on mass comes since propagator $\sim \frac{m^2}{p^2 - m^2}$
- The different dependence on mass comes since propagator $\sim \frac{m^2}{p^2 - m^2}$ and $m_i << p << M_i$
- $p \sim 100$ MeV, $m_i \sim 0.01 - 0.1$ eV, $M_i \sim 100$ GeV
- Typical values $M_{W_R} = 3.5$ TeV, $M_R \sim 500$ GeV

Tello,Nemevsek,Nesti,Senjanovic,Vissani, Phys. Rev. Lett. **106**, 151801 (2011).

$0\nu\beta\beta$ in Type-II TeV scale LR model

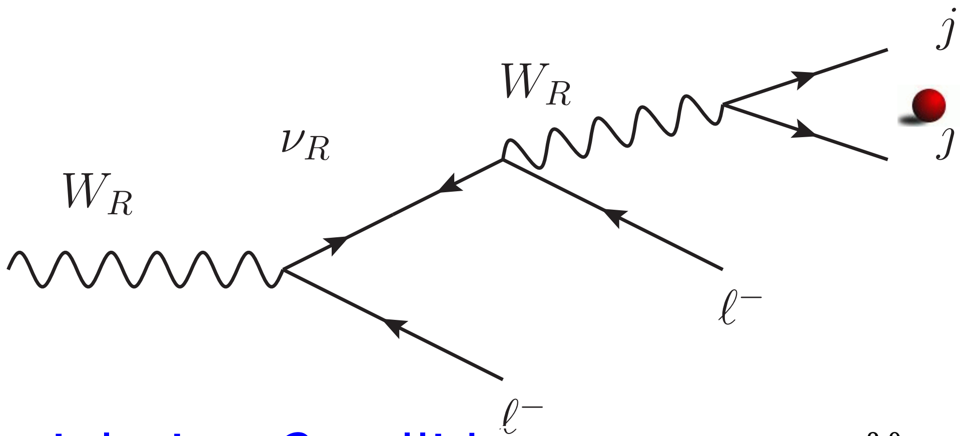




- Current experimental bound can be staurated by hierarchical neutrinos
- For lower values of masses the experimental limit is crossed $\Longrightarrow$ lower bound on neutrino masses
- Typical bounds are (2-3) meV (NH) and (0.07 -0.2) meV for IH
- KK claim can be reached for lower values of masses..

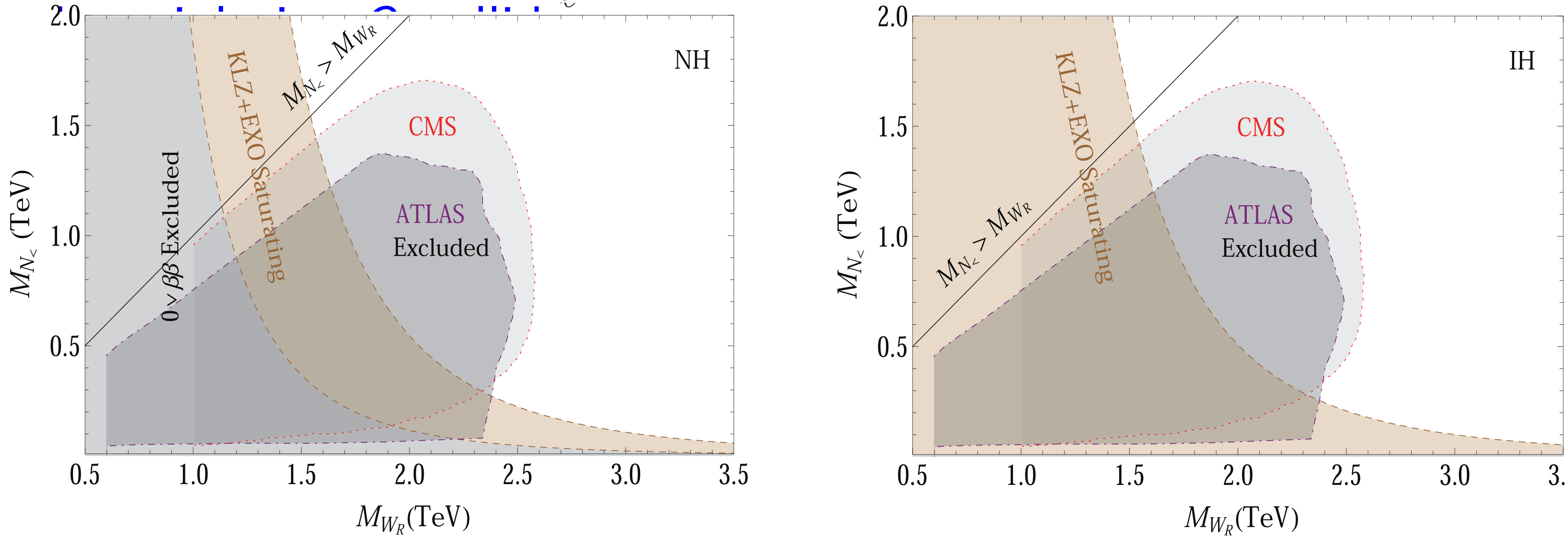
Dev, S.G, Mitra, Rodejohann,PRD,2013

Lepton Number violation at Colliders



- Same sign di-leptons + jet , Golden Channel

[Keung Senjanovic '83]



- Complimentary constraints for NH

Dev, S.G, Mitra, Rodejohann,2013

Tello,Nemevsek,Nesti,Senjanovic,arXiv:1112.3061.

Summary

- $0\nu\beta\beta$ implies violation of Lepton number
- Positive $0\nu\beta\beta \implies$ Majorana nature of Neutrinos
- Intimately connected to the mechanism of Neutrino mass generation
- A positive signal of $0\nu\beta\beta$ in QD region may be in conflict with cosmology
- The current bounds can be saturated only in the QD regime.
- New Physics ?
- LR symmetric model with $M_{W_R} \sim$ 3.5 TeV
- Can be accessible at LHC
- Smaller half-lives even for hierarchical neutrinos
- Signature of TeV scale LR symmetry at LHC can result in a completely different interpretation of effective neutrino mass in $0\nu\beta\beta$ process.

Concluding Remark

- Neutrinos in the time of LHC

—- A complimentary window to probe physics beyond the Standard Model

Concluding Remark