

Bimagic baseline and optimization of a LENF

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All About Neutrino Oscillation Parameters: 2011

3-flavour oscillation parameters TS, Tortola, Valle, 1108.1376

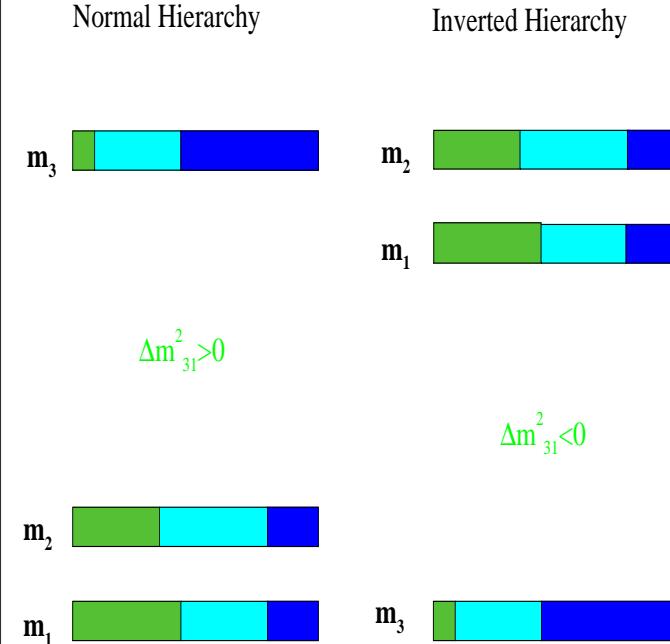
	best fit $\pm 1\sigma$	3σ range	prec@ 3σ	
$\frac{\Delta m_{21}^2}{10^{-5}\text{eV}^2}$	$7.59^{+0.20}_{-0.18}$	7.09–8.19	7%	KamLAND
$\frac{\Delta m_{31}^2}{10^{-3}\text{eV}^2}$	$2.50^{+0.09}_{-0.16}$ $-(2.40^{+0.08}_{-0.09})$	2.14 – 2.76 –(2.13 – 2.67)	12%	MINOS
$\sin^2 \theta_{12}$	$0.312^{+0.017}_{-0.015}$	0.27–0.36	14%	SNO
$\sin^2 \theta_{23}$	$0.52^{+0.06}_{-0.07}$ 0.52 ± 0.06	0.39–0.64	24%	SuperK
$\sin^2 \theta_{13}$	$0.013^{+0.007}_{-0.005}$ $0.016^{+0.008}_{-0.006}$	0.001–0.035 0.001–0.039	120%	T2K + global data
δ	$(-0.61^{+0.75}_{-0.65})\pi$ $(-0.41^{+0.65}_{-0.70})\pi$	$0 - 2\pi$	–	

upper: normal hierarchy, lower: inverted hierarchy

Double CHOOZ :
 $\sin^2 2\theta_{13}$
 $= 0.085 \pm 0.029 \pm 0.042$
(90% C.L.)
LowNU 2011, Seoul

Also Fogli et al. arXiv:1106.6028 [hep-ph]

Three Amigos



- The third leptonic mixing-angle θ_{13} (100% uncertainty at 3σ)
- The sign of Δm_{31}^2 or the **mass hierarchy**
- The **CP phase** in neutrino sector



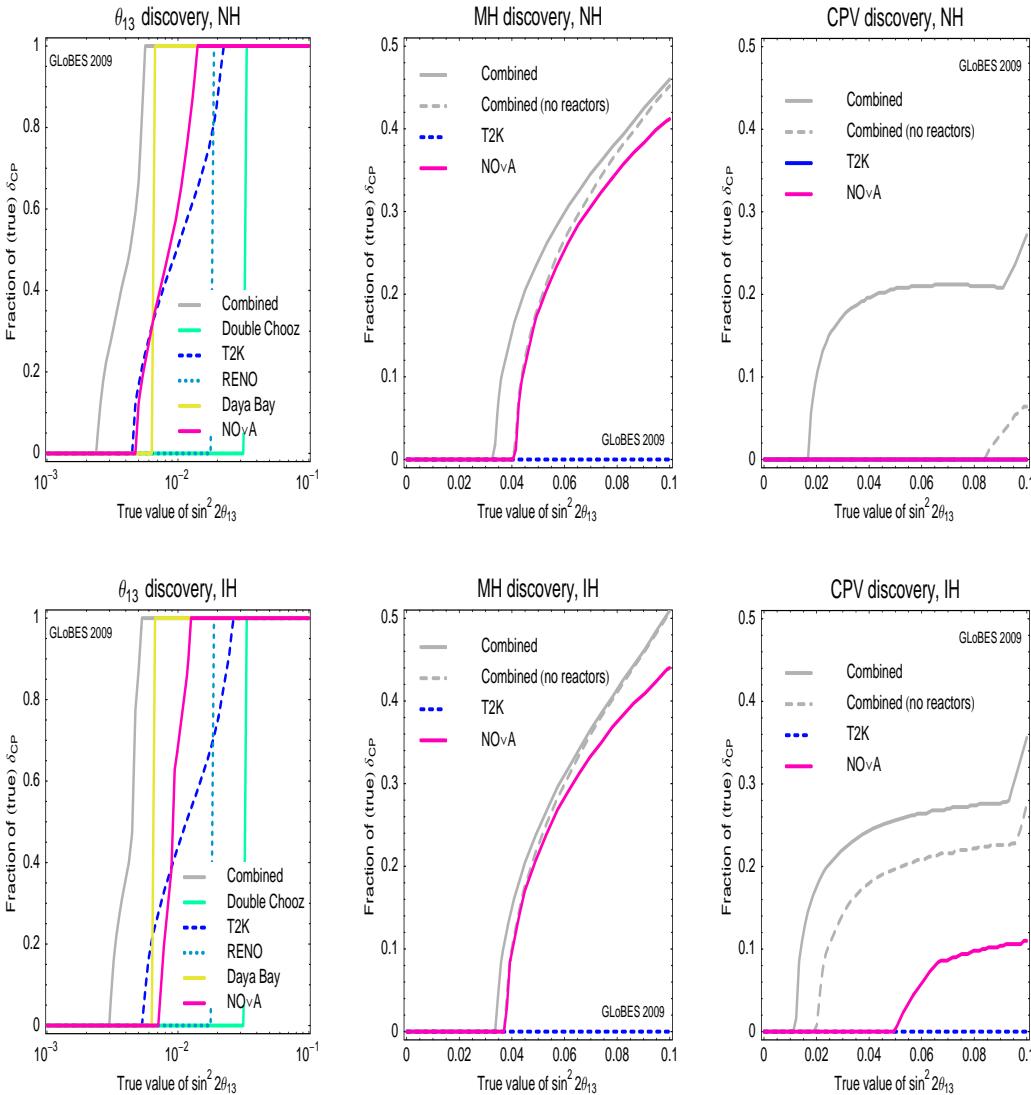
I Aim at ...



- The Bi-Magic baseline
- Determination of θ_{13} , mass hierarchy and δ_{CP} using a Low Energy Neutrino Factory at the bi-magic baseline
- Baseline Optimization of a LENF
- Energy Optimization of a LENF

A. Dighe, S. Goswami and S. Ray,
Phys. Rev. Lett. **105**: 261802, 2010.
arXiv:1110.3289 [hep-ph].

Discovery at Reactor and Superbeam Experiments



- Can probe $\sin^2 2\theta_{13}$ down to 0.002 - 0.006 \Rightarrow can confirm the current non-zero θ_{13} value
- Mass hierarchy can only be distinguished for $< 40\text{-}50\%$ values of δ_{CP} and only if $\sin^2 2\theta_{13} > 0.02$
- CP violation may be discovered for less than 20% of all possible values of δ_{CP} only if $\sin^2 2\theta_{13} > 0.02$

Huber,Lindner,Schwetz,Winter, 2009

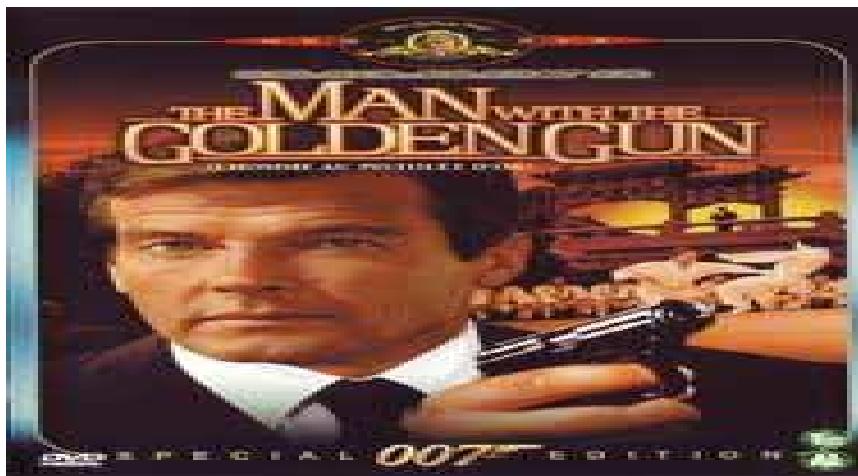
The Channel with the Golden Gun

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

- $A_S \rightarrow$ Solar amplitude depends on Δm_{21}^2 and θ_{12}
- $A_A \rightarrow$ atmospheric amplitude depends on Δm_{31}^2 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

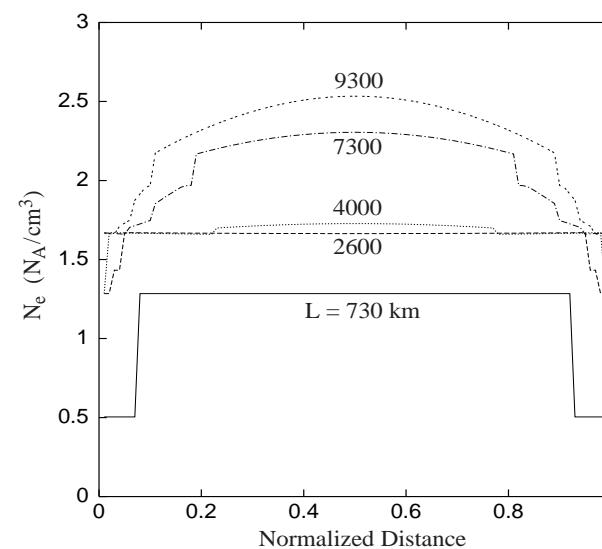
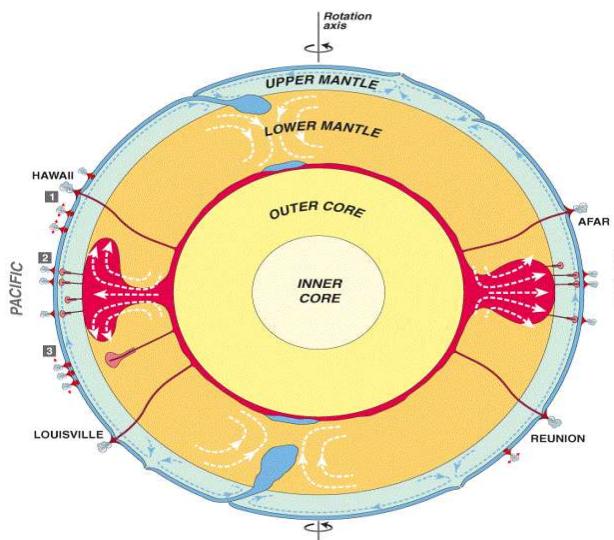
- GOLDEN because it can probe all three unknowns θ_{13} , $\text{sgn}\Delta m_{31}^2$, δ_{CP}



The Channel with the Golden Gun

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

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

• $(sgn(\Delta m_{31}^2), \delta_{CP})$ degeneracy

Minakata, Nunokawa, hep-ph/0108085

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

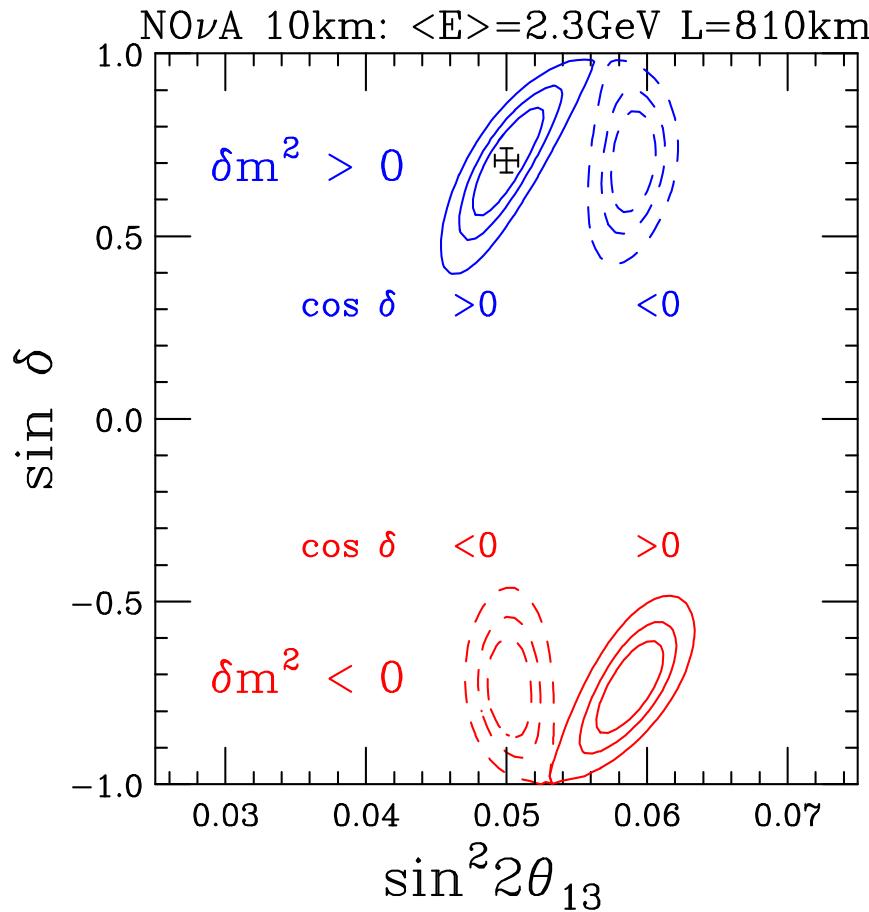
Fogli, Lisi, hep-ph/9604415



- Give rise to multiple solutions → 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

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

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

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

A New Hope: Magic Baseline

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

A New Hope: Magic Baseline

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

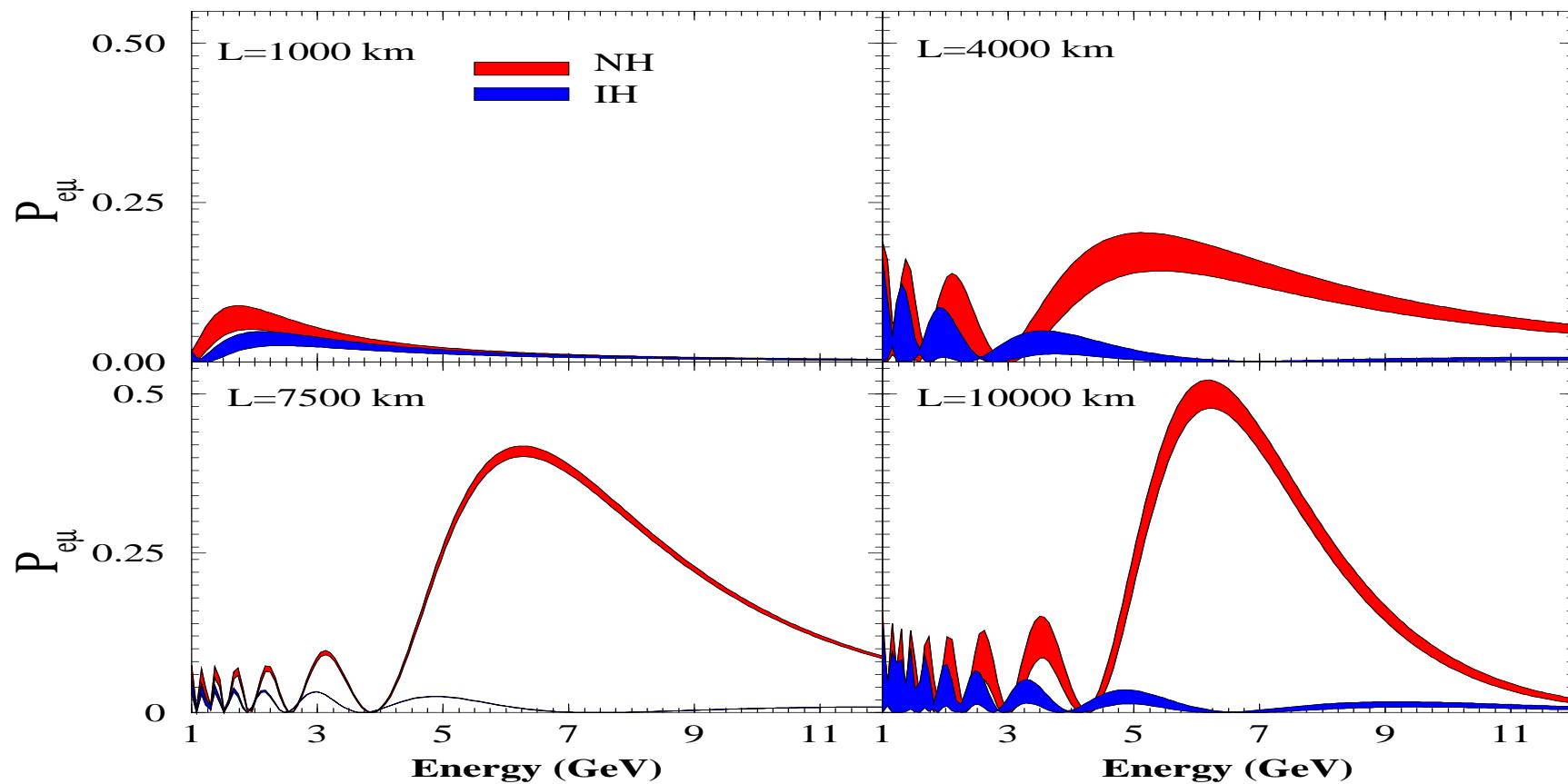
- $\sin(\hat{A}\Delta) \simeq 0 \Rightarrow \frac{1}{\sqrt{2}}G_F n_e L = \pi \Rightarrow L_{magic} \simeq 7690 \text{ km}$
- Independent of neutrino parameters and energy
- True for both NH and IH

Barger, Marfatia, Whisnant, hep-ph/0112119

Huber, Winter, hep-ph/0301257

Smirnov, hep-ph/0610198

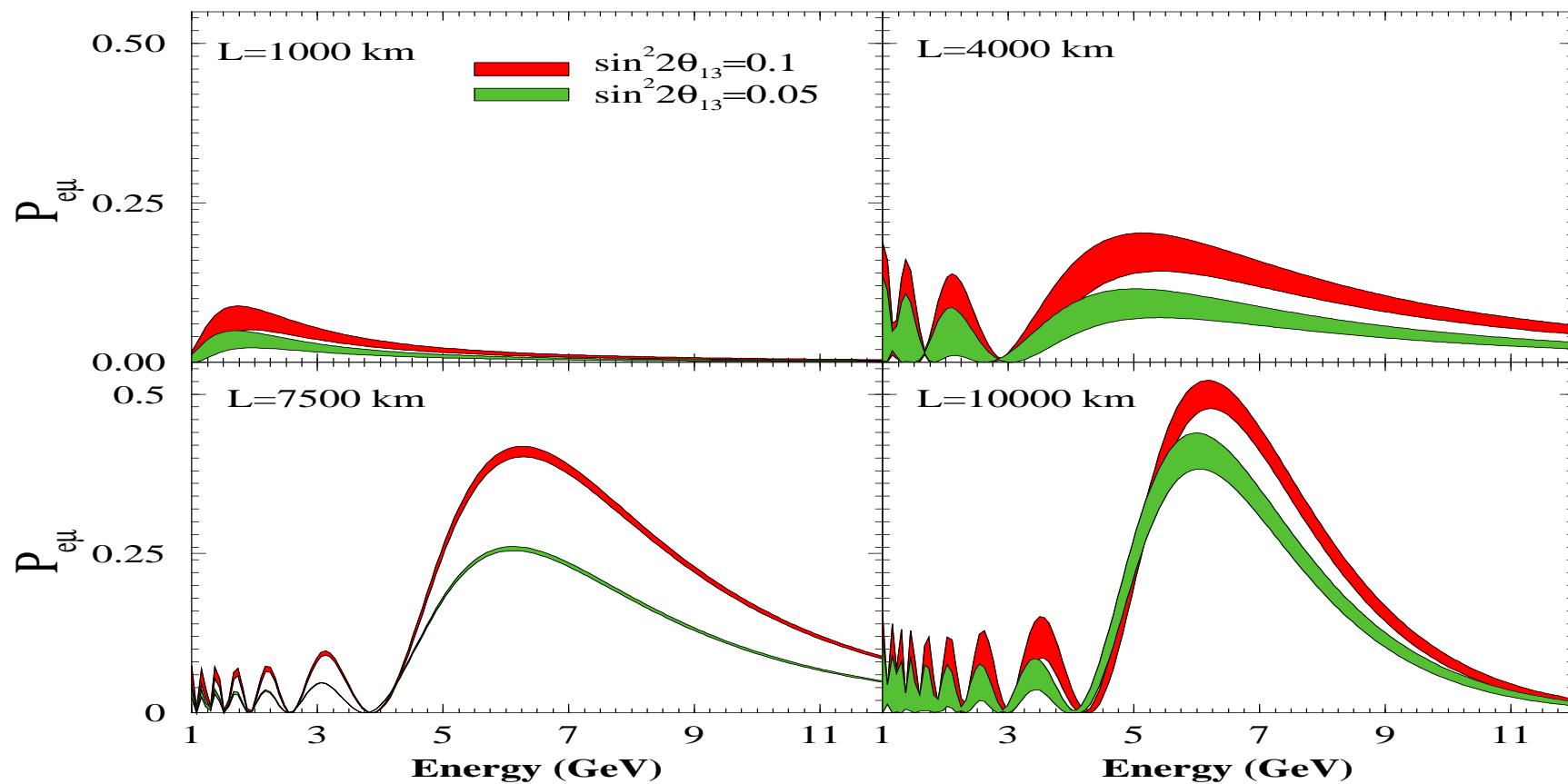
$P_{e\mu}$ for NH and IH at long baselines



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

Agarwalla, Choubey, Raychaudhuri, hep-ph/0610333

$P_{e\mu}$ for different θ_{13} at long baselines

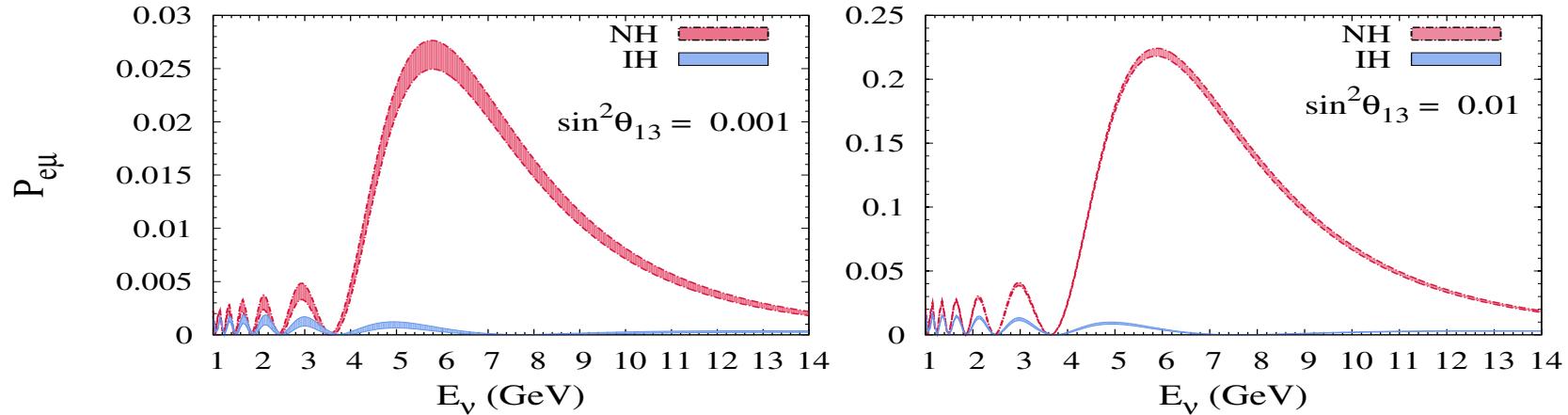


- At $\sim 7500 \text{ km}$ δ_{CP} dependence negligible
- $(\delta_{CP}, \theta_{13})$ degeneracies vanish
- Clean measurement of θ_{13}

Agarwalla, Choubey, Raychaudhuri, hep-ph/0610333

The Magic baseline: Absence of CP sensitivity

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



⇒ 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

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

- The condition $\sin(\hat{A}\Delta) \simeq 0$ is valid for both NH and IH
- If we instead make $\sin[(1 - \hat{A})\Delta] = 0$ the δ_{CP} dependent term can vanish.
- In that case $P_{e\mu} \approx \mathcal{O}(\alpha^2)$ → small
- But this condition depends on hierarchy



Enters The Bi-Magic baseline

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

- 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

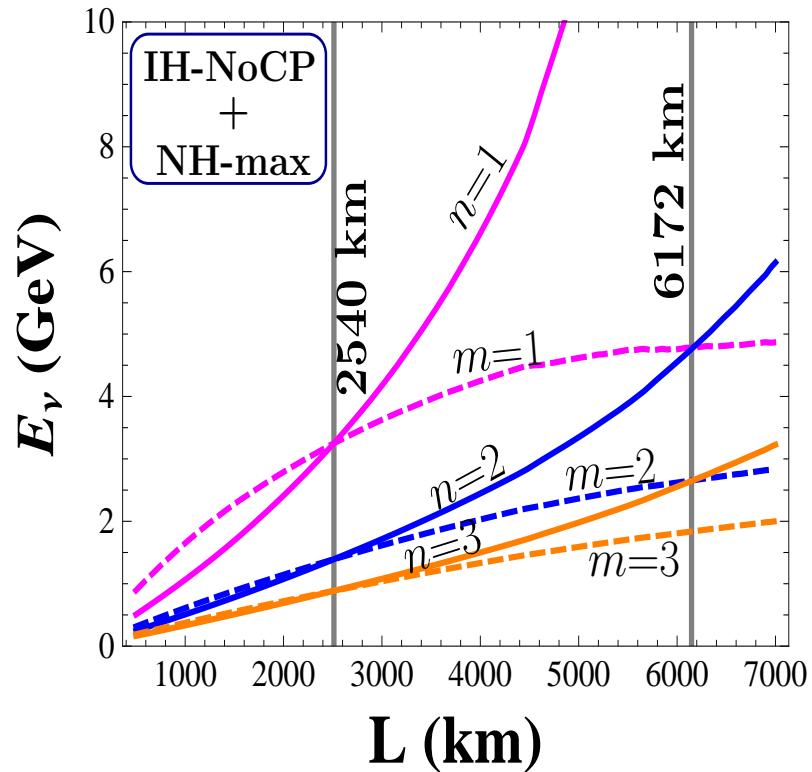
NH–max

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

IH–max

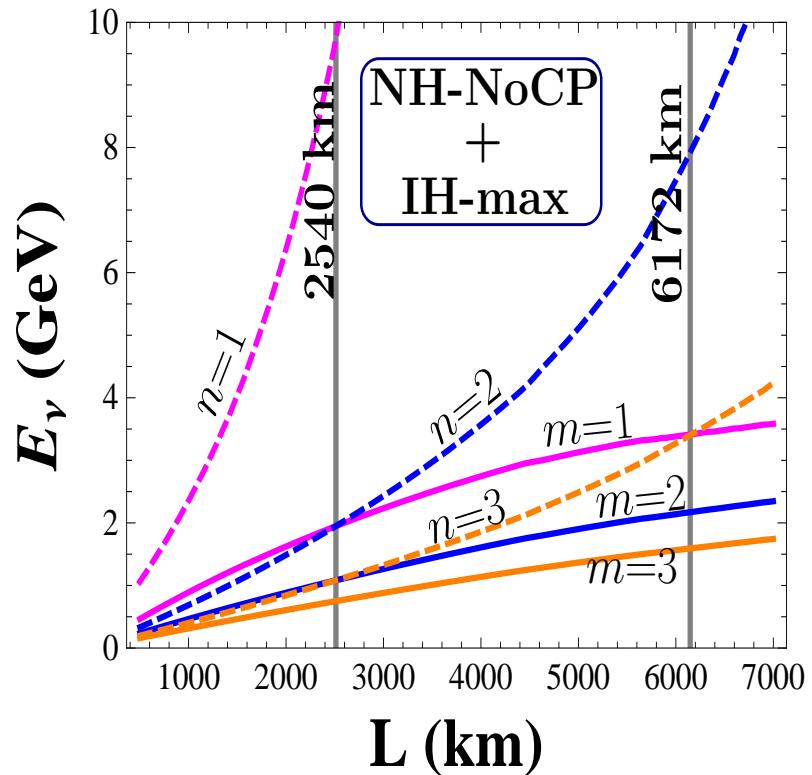
$$(1 + |\hat{A}|) \cdot |\Delta| = (m - \frac{1}{2})\pi$$

The Bi-Magic baseline



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

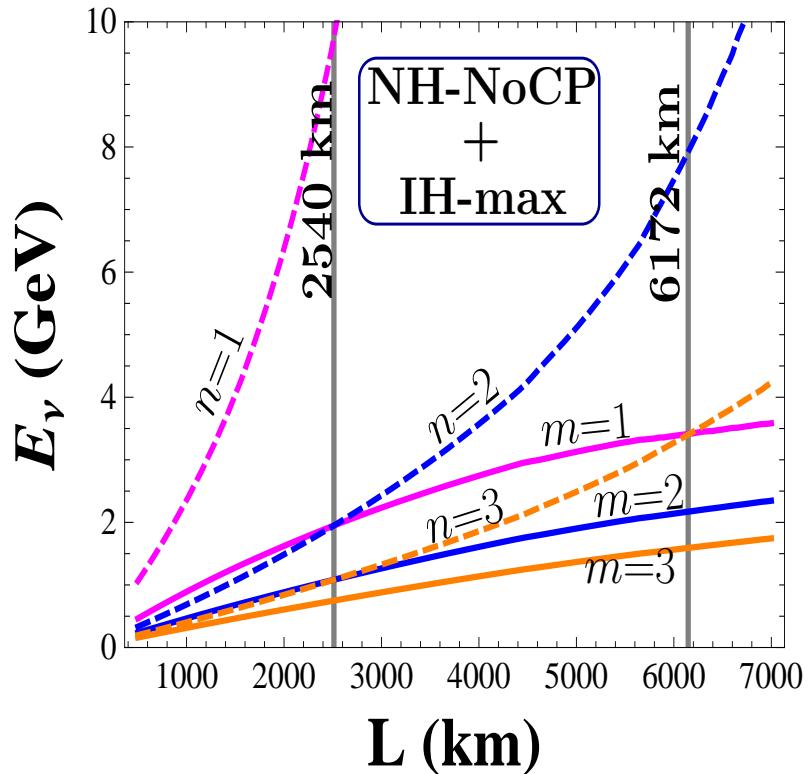
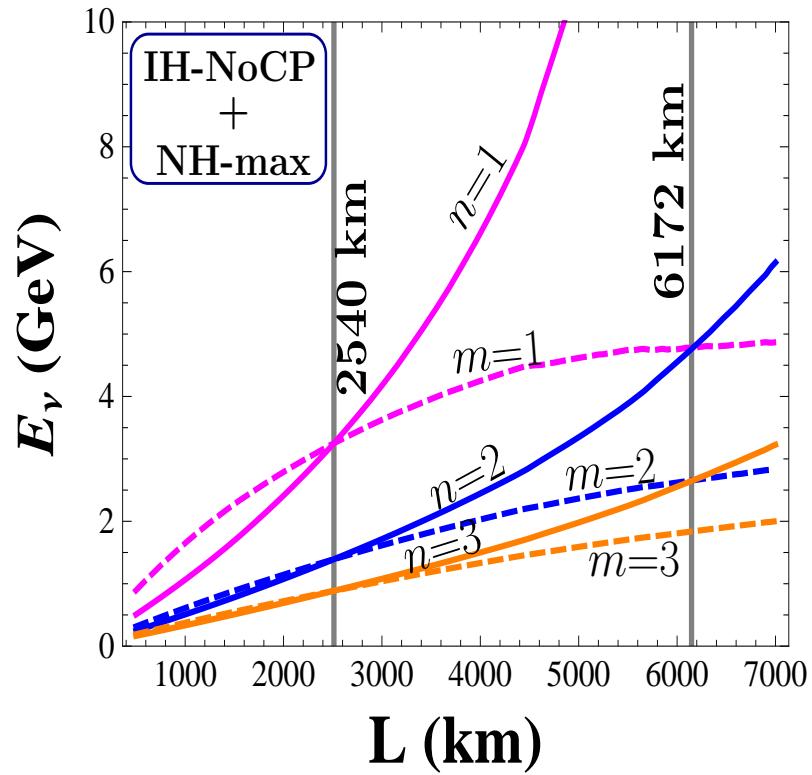
Raut, Singh, UmaShankar, 2009



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

Dighe,Goswami,Ray, 2010

The Bi-Magic baseline



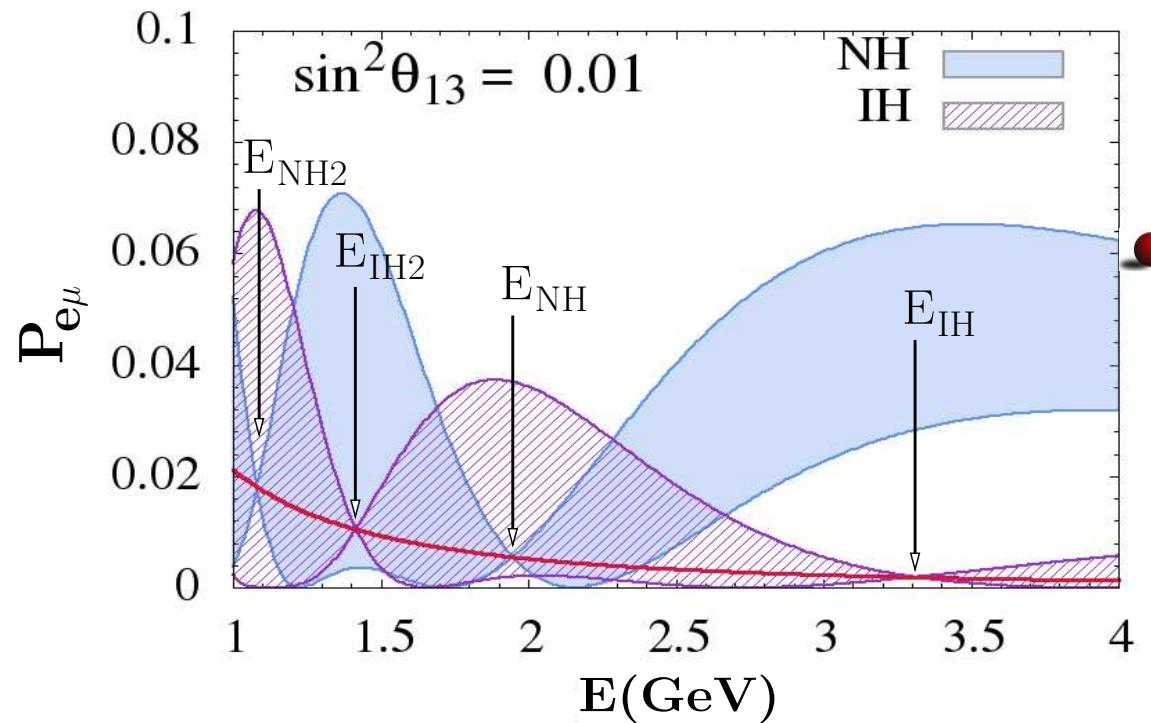
- Lowest Bi-magic Baseline ~ 2540 km
- Higher $n, m \Rightarrow$ Lower E_ν to satisfy no CP condition low flux, low efficiency
- More bimagics 6172 km, 8950 km, 106900 km

Baselines close Bi-Magic baseline

- CERN - PhyÅsalmi : 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 facilities 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

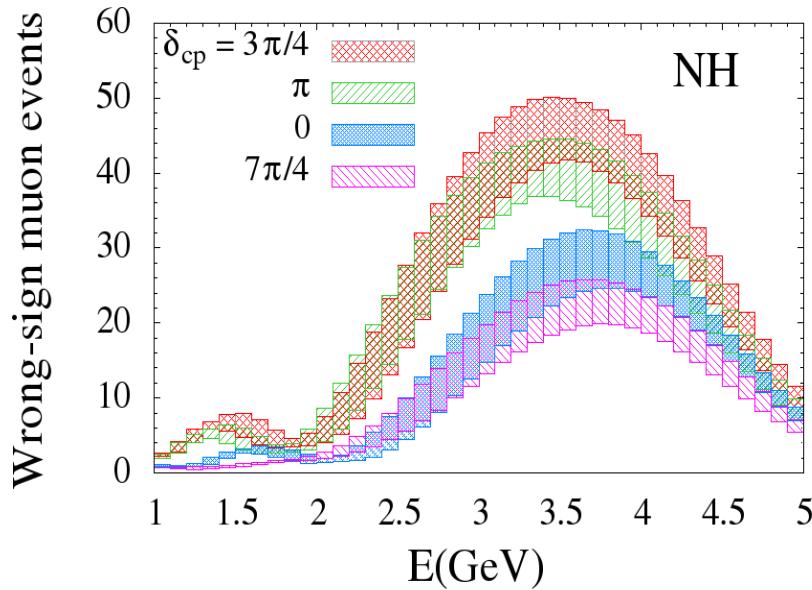
$$E_{IH} = 1.9 \text{ GeV}$$

- NH probability independent of δ_{CP} and θ_{13} but δ_{CP} band in IH large
- θ_{13} sensitivity for IH • δ_{CP} sensitivity for IH

$$E_{IH} = 3.3 \text{ GeV}$$

- IH probability independent of δ_{CP} and θ_{13} and non-overlapping with NH
- θ_{13} sensitivity for NH • δ_{CP} sensitivity for NH

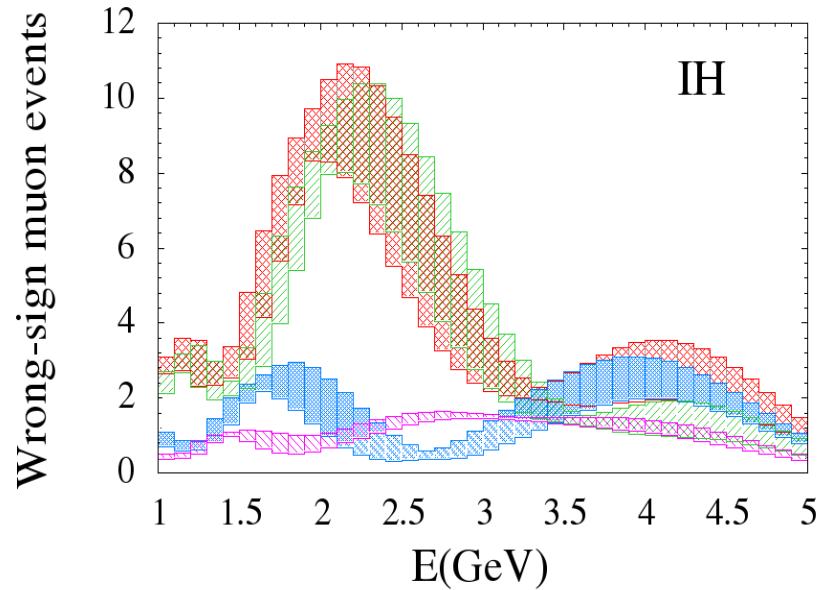
The Return of the CP sensitivity



$$E_{IH} = 3.3 \text{ GeV}$$

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

$$\begin{aligned} P_{e\mu}(NH) \approx & 18\alpha^2 s_{12}^2 c_{12}^2 c_{23}^2 + 9s_{13}^2 s_{23}^2 \\ & - 18\sqrt{2}\alpha s_{12} c_{12} s_{23} c_{23} s_{13} \cos(\delta_{CP} + \pi/4) \end{aligned}$$



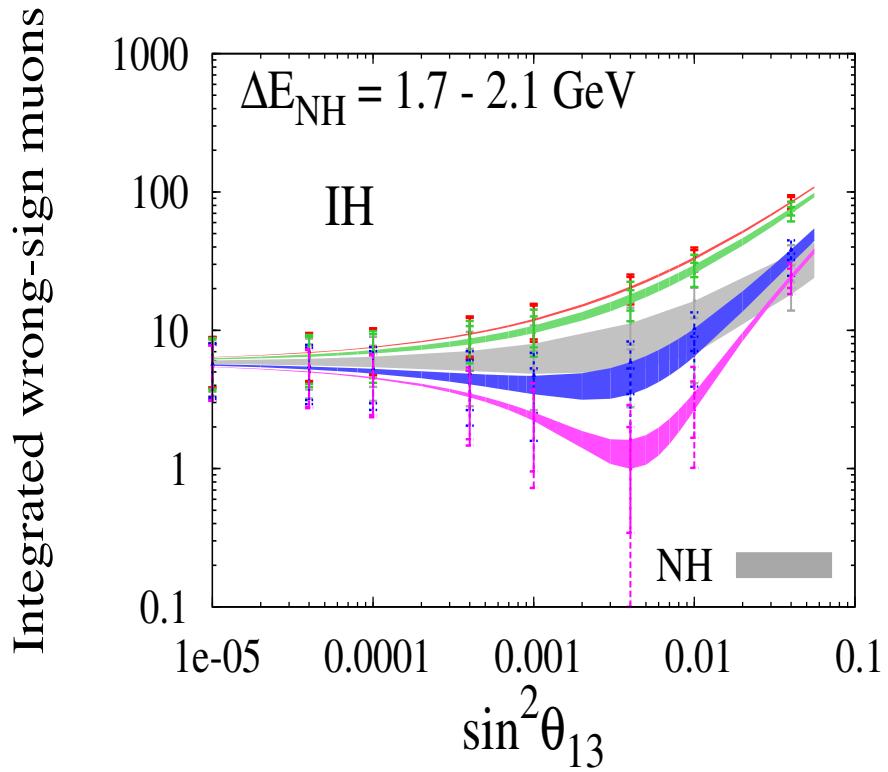
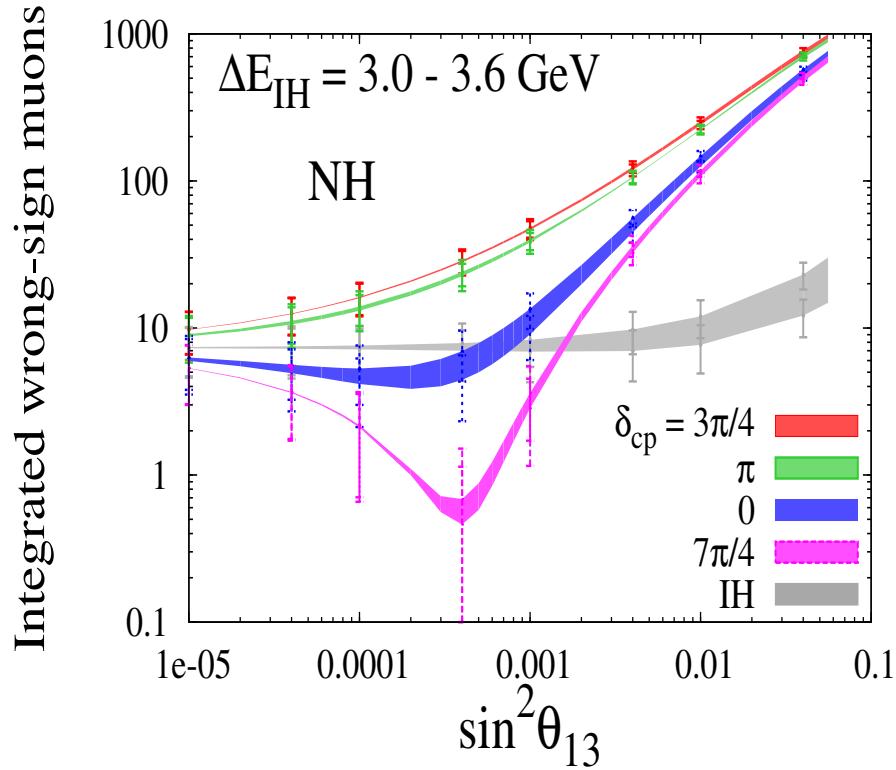
$$E_{NH} = 1.9 \text{ GeV}$$

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

$$\begin{aligned} P_{e\mu}(IH) \approx & 50\alpha^2 s_{12}^2 c_{12}^2 c_{23}^2 + \frac{25}{9}s_{13}^2 s_{23}^2 \\ & - \frac{50\sqrt{2}}{3}\alpha s_{12} c_{12} s_{23} c_{23} s_{13} \cos(\delta_{CP} + \pi/4) \end{aligned}$$

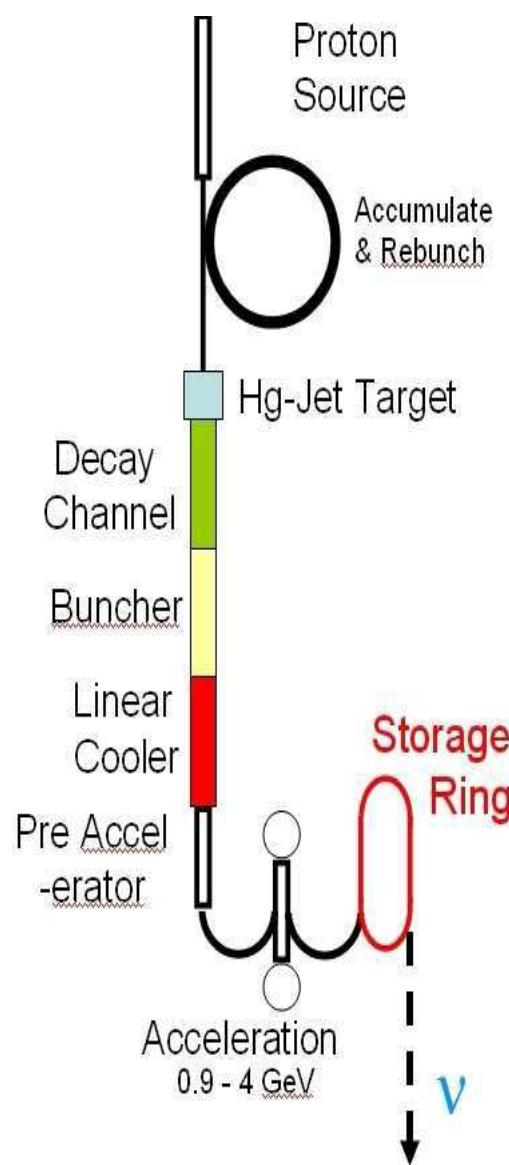
$P_{e\mu}$ largest at $\delta_{CP} = 3\pi/4$, lowest at $\delta_{CP} = 7\pi/4$.

The Expanded Magic Bins



- The statistical error bars indicate hierarchy, θ_{13} and CP sensitivity for $\sin^2 \theta_{13} > 10^{-4}$ for NH (near 3.3 GeV) and $\sin^2 \theta_{13} > 10^{-3}$ for IH (near 1.9 GeV)

Neutrino Factory in a nutshell



- Muons are accelerated and injected into a storage ring

- Muons decay as

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

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

- Wrong sign Muons

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

$$\nu_e \rightarrow \nu_\mu \rightarrow \mu^-$$

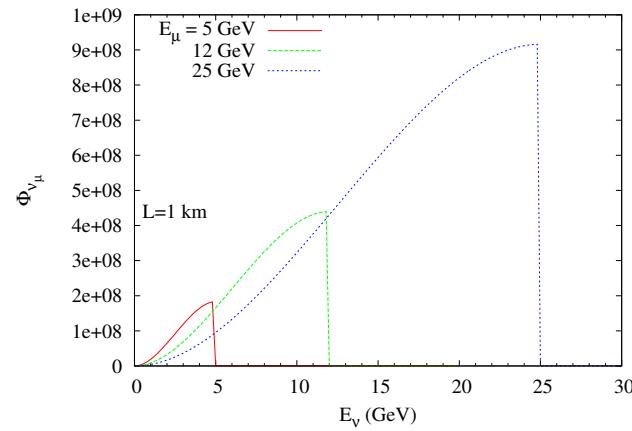
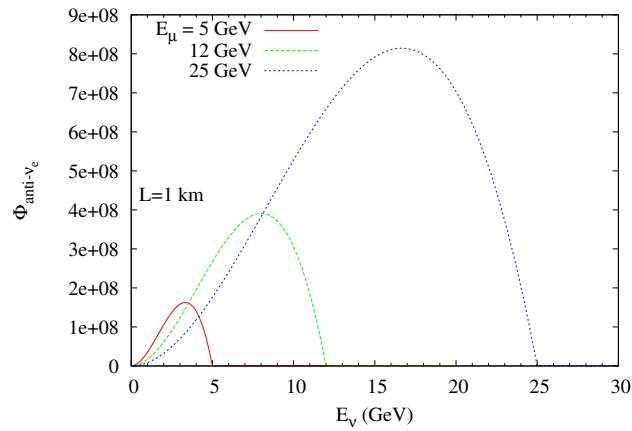
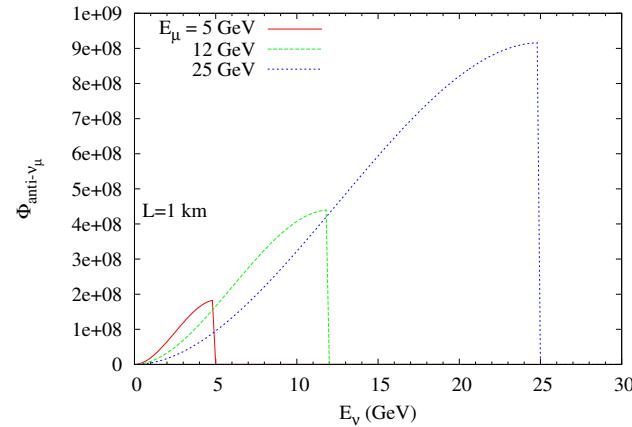
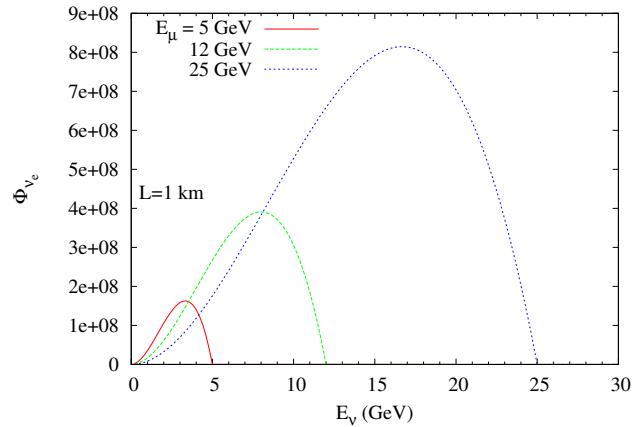
- Right Sign Muons

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

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

- Detector with charge identification capabilities suitable

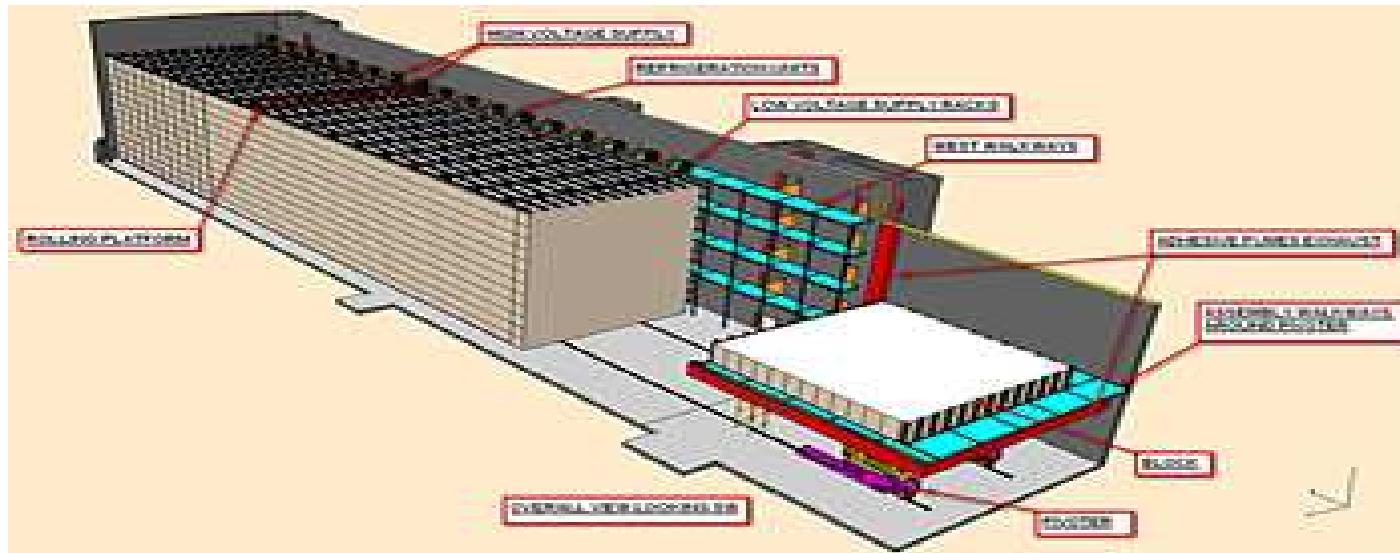
Low Energy Neutrino Factory



- For $E_\mu = 5 \text{ GeV}$ E_ν (ν_e) peaks at $\sim 3 \text{ GeV}$

The Detector

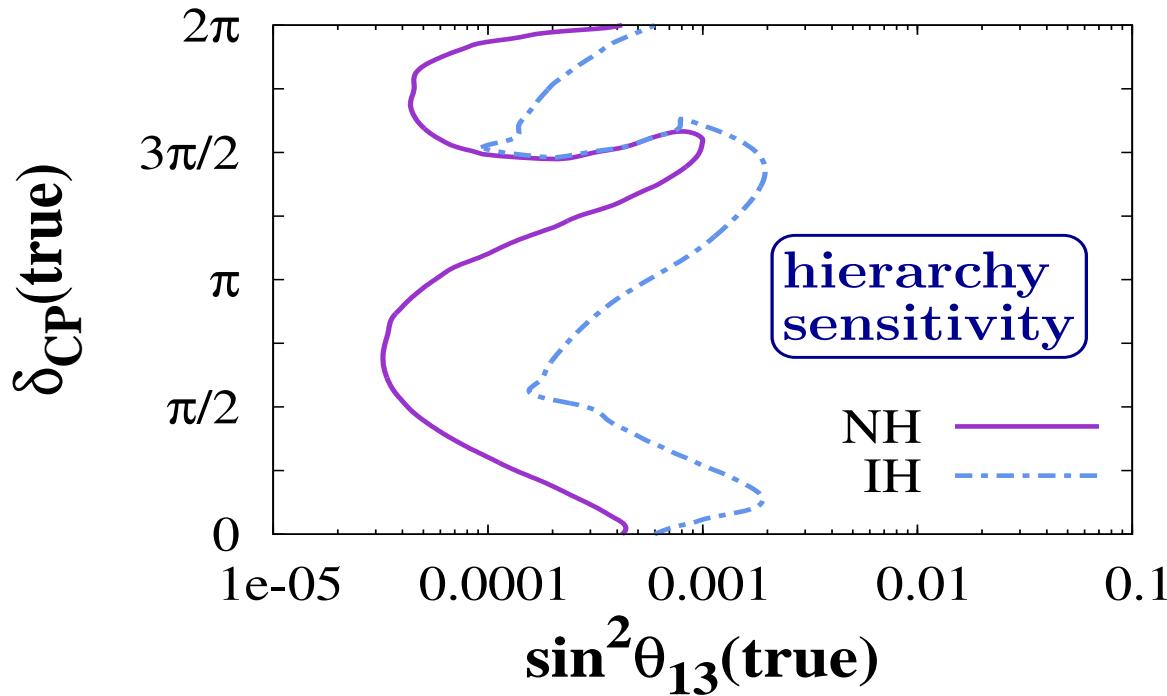
- Magentized totally active scintillating detector (TASD)
 - When a neutrino strikes an atom in the liquid scintillator, it releases a burst of charged particles. As these particles come to rest in the detector, they release energy which is collected by photo-detectors
 - Using the pattern of light seen by the photo-detectors one can detect the neutrino and measure its energy.
 - Can detect both electron and muon and their charge



The set-up

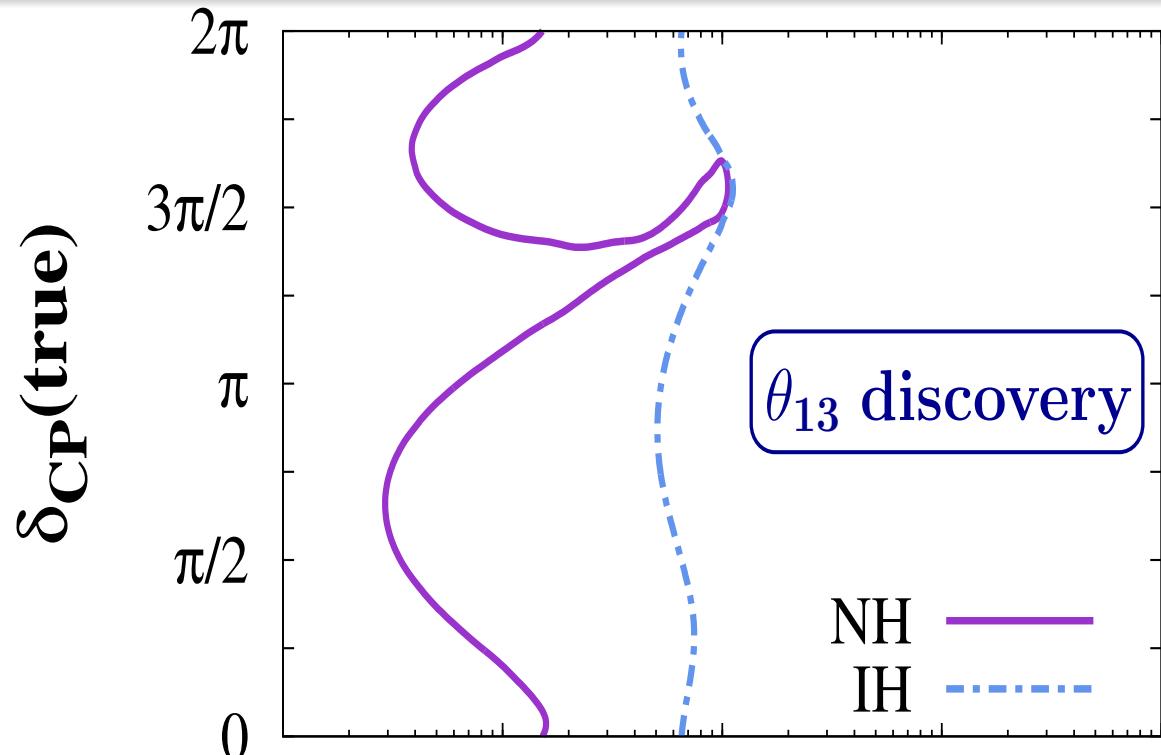
- For the LENF beam we assume
 - $1.4 \times 10^{21} \mu^+$ decay per year
 - 2.5 years running
- For the TASD we assume
 - Detector fiducial mass 20 kton
 - μ^\pm detection efficiency of 94 %
 - Background of 10^{-3} on the $\bar{\nu}_\mu$ appearance and disappearance channels
 - Energy Resolution, $dE/E \sim 10\%$
- For the χ^2 analysis we assume
 - 4% error on Δm_{21}^2 , θ_{12}
 - 5% error on $|\Delta m_{31}^2|$ and θ_{23}
 - 20% error on θ_{13}
- We use **GLoBES** software for the analysis

Hierarchy Sensitivity



- Results for 2.5 years run with μ^+ beam Dighe, Goswami, Ray, 2010
- Hierarchy sensitivity for $\sin^2 \theta_{13} \sim 3 \times 10^{-5}$ (depending on δ_{CP}) if true hierarchy is NH and for $\sin^2 \theta_{13} \sim 10^{-4}$ if true hierarchy is IH

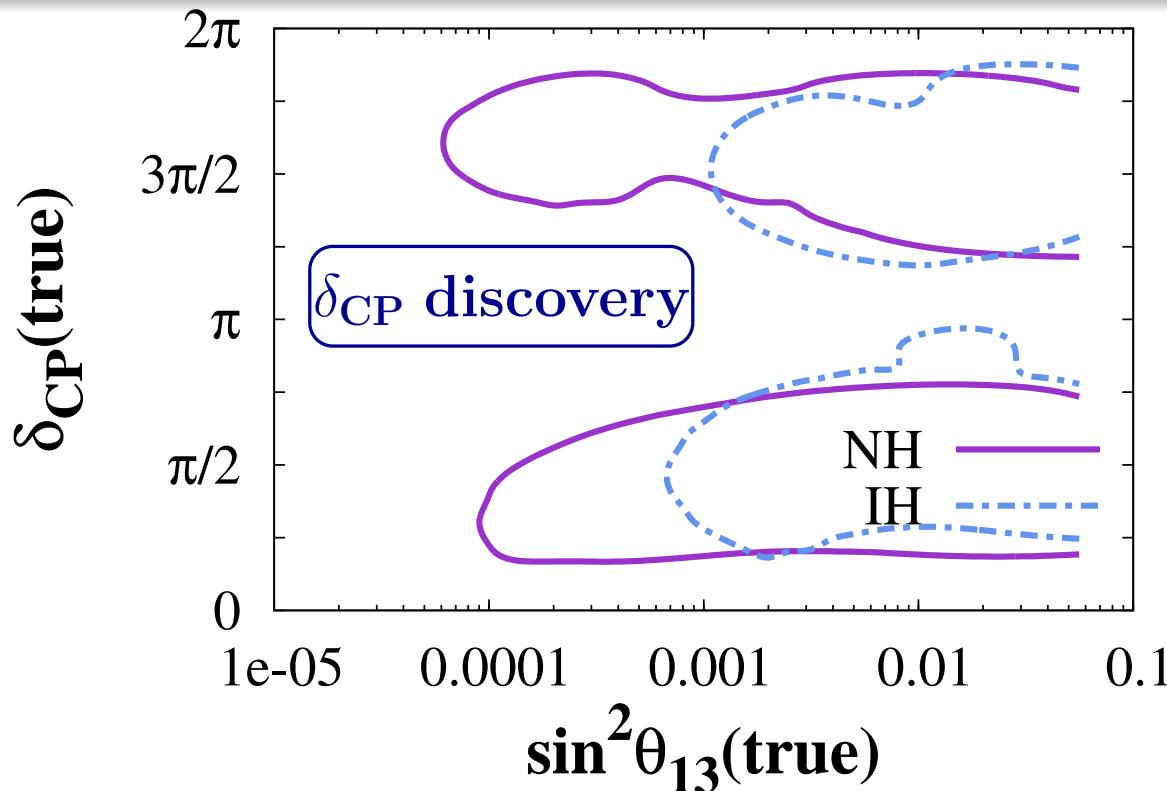
θ_{13} Discovery



- θ_{13} discovery \Rightarrow how far a true non-zero θ_{13} is different from $\theta_{13} = 0$
- If NH is true hierarchy then it is possible to discover $\sin^2 \theta_{13} \sim 3 \times 10^{-5}$ (depends on δ_{CP})
- If IH is true hierarchy then it is possible to discover $\sin^2 \theta_{13} \sim 7 \times 10^{-4}$ (not very sensitive to δ_{CP})

Dighe, Goswami, Ray, 2010

δ_{CP} Discovery



- δ_{CP} discovery \implies at what σ a true non-zero δ_{CP} is different from $\delta_{CP} = 0$
- Possible to discover δ_{CP} for low values of θ_{13}

Dighe, Goswami, Ray, 2010

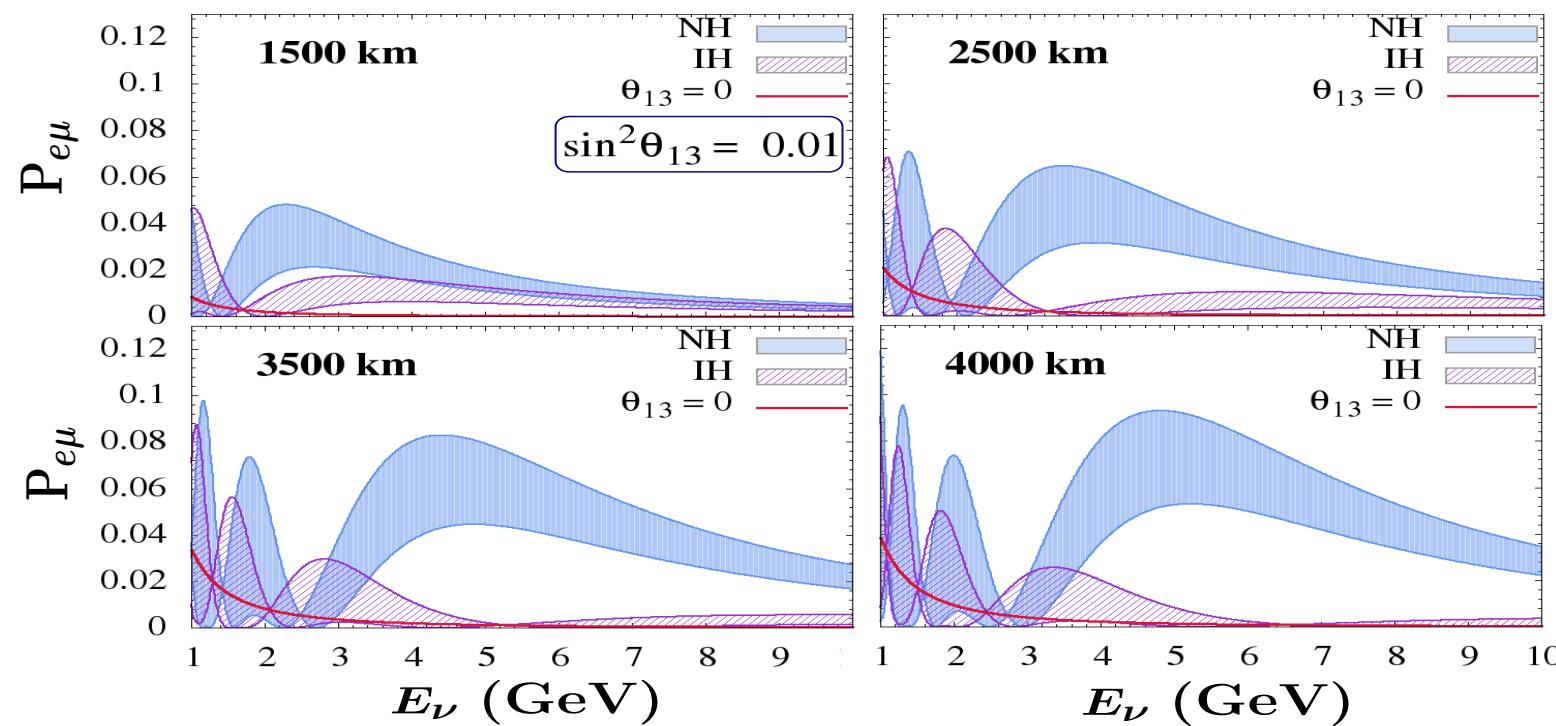
Summary of a LENF experiment at 2540 km

- Exceptional sensitivity to hierarchy
- Also can probe low values of θ_{13}
- Can discover δ_{CP} for very low values of θ_{13}
- For the current best-fit θ_{13} can discover all the three unknowns at 3σ
- One can be more ambitious and aim for a 5σ discovery
- Is this The Optimal Baseline ?
- Baseline optimization of a LENF
- Energy optimization of a LENF

Baseline Wars: Optimization over L

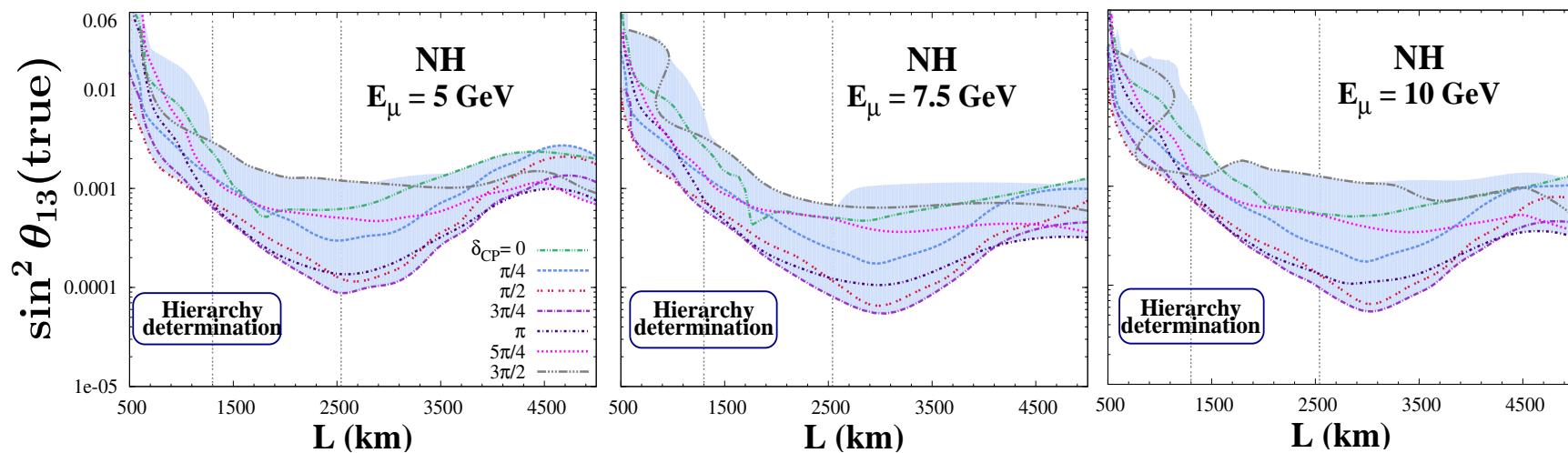
- Episode I : Hierarchy
- Episode II : θ_{13}
- Episode III : δ_{CP}
- Cast and Crew
 - True Values: $\Delta m_{21}^2 = 7.65 \times 10^{-5} \text{ eV}^2$,
 $\sin^2 \theta_{12} = 0.30$, $|\Delta m_{31}^2| = 2.4 \times 10^{-3} \text{ eV}^2$ $\sin^2 \theta_{23} = 0.5$,
 - Undisplayed parameters marginalized over
 - 4% error on solar parameters, 5% error on atmospheric parameters
 - 2% error on matter density profile
- Next generation experiment → 5σ discovery essential

$P_{e\mu}$ at different baselines



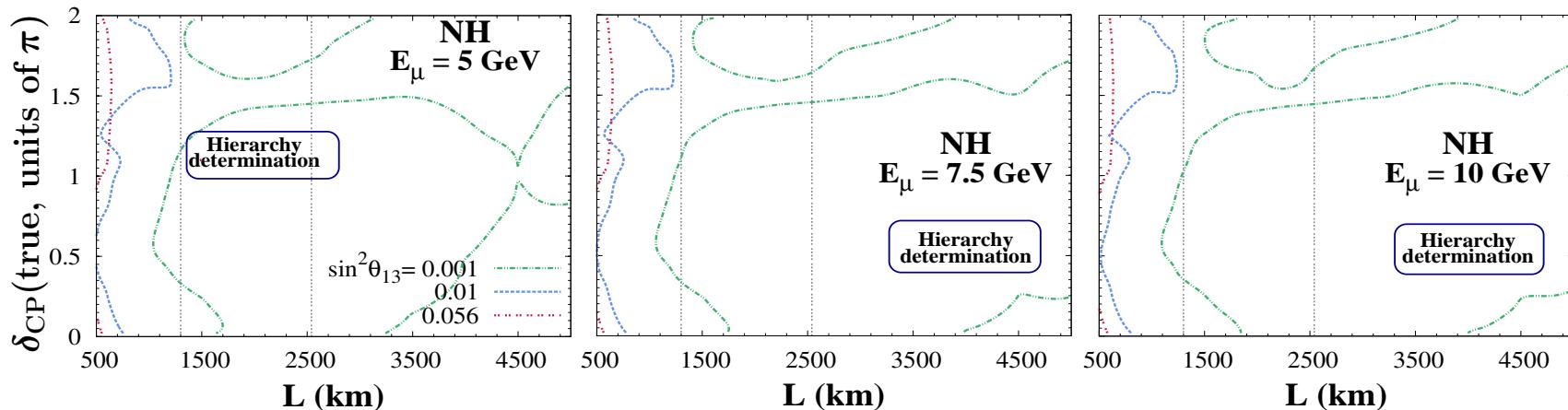
- NH-max and IH-noCP shifts towards high E_ν
- $E_{max}^{NH} = E_{noCP}^{IH}$ not satisfied exactly
- $P_{e\mu}^{NH}$ increases and $P_{e\mu}^{IH}$ decreases with E_ν
- Integrated effect → at higher E_μ better hierarchy sensitivity at higher L,

Optimal Baseline for Hierarchy



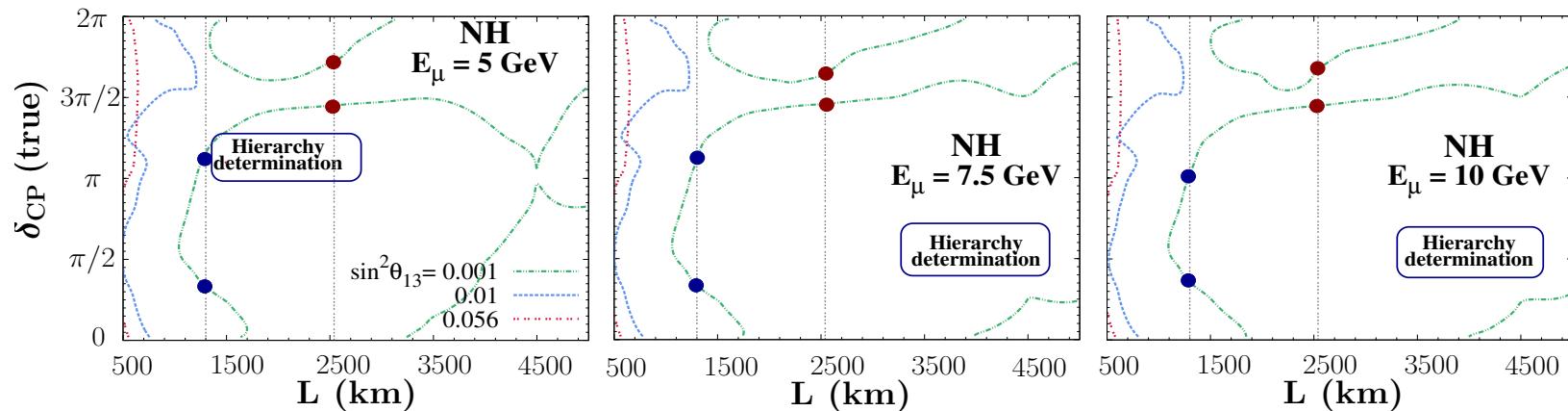
- The band denotes δ_{CP} variation over $0 - 2\pi$
- The upper (lower) limit → worst (best) sensitivity
- Knowledge of true value of δ_{CP} crucial
- For $E_\mu = 5 \text{ GeV}$, $L \sim 2500 \text{ km}$, the best possible reach is at $\delta_{CP} = 3\pi/4$
- Higher $E_\mu \rightarrow L \sim 3000 \text{ km}$
- 7.5 - 10 GeV no significant change in sensitivity → saturation
- Depend to some extent on the true value of δ_{CP}

Optimal Baseline for Hierarchy: $\delta_{CP} - L$ plots



- Shows for which **exact** values of δ_{CP} sensitivity is possible → information missing in plots showing **CP fraction**
- $\sin^2 \theta_{13} = 0.056$, → $L \gtrsim 700$ km
- $\sin^2 \theta_{13} = 0.01$, → $L \gtrsim 1000$ km if $\delta_{CP} \geq 3\pi/2$
- $\sin^2 \theta_{13} = 0.001$
 - If $\delta_{CP} \sim \pi/2$ → $L \sim 1300$ km
 - Larger fraction of δ_{CP} for $L \sim 1800 - 2500$ km
 - CP fraction Increases with E_μ**
 - No determination possible for $\delta_{CP} \sim 3\pi/2$
 - Complimentarity with higher baselines and energy**

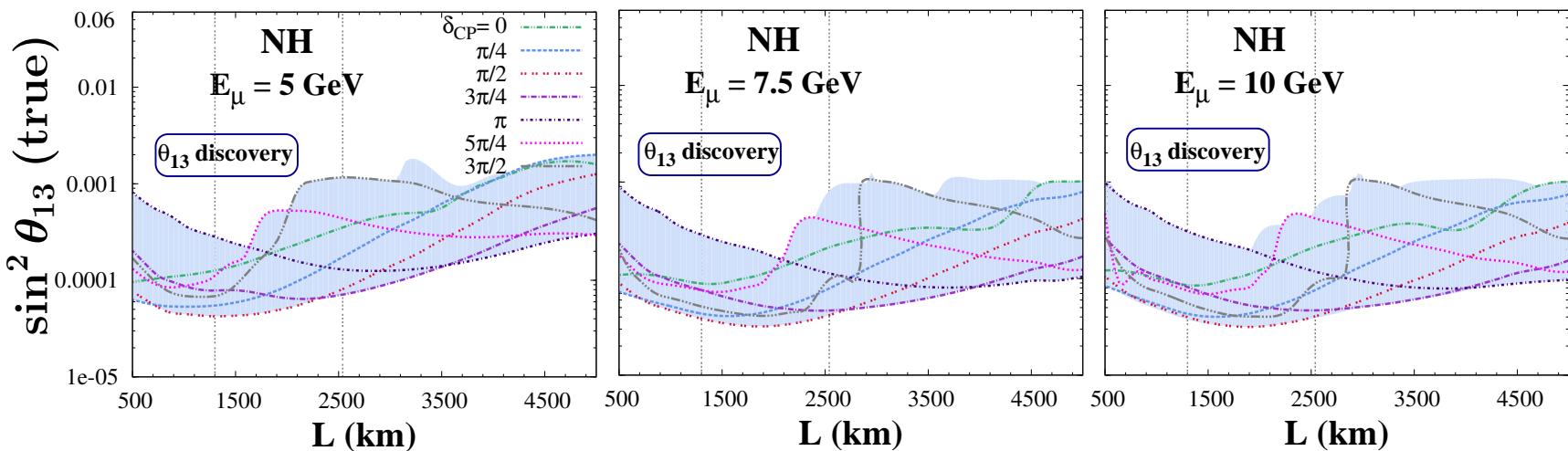
Optimal Baseline for Hierarchy: $\delta_{CP} - L$ plots



- The CP fraction for which 5σ discovery is possible ($\sin^2 \theta_{13} = 0.001$)
- $L \sim 1300 \text{ km} \rightarrow 40.6\% - 33.7\%$ ($E_\mu = 5 - 10 \text{ GeV}$)
- $L \sim 2540 \text{ km} \rightarrow 86.4\% - 88.4\%$ ($E_\mu = 5 - 10 \text{ GeV}$)

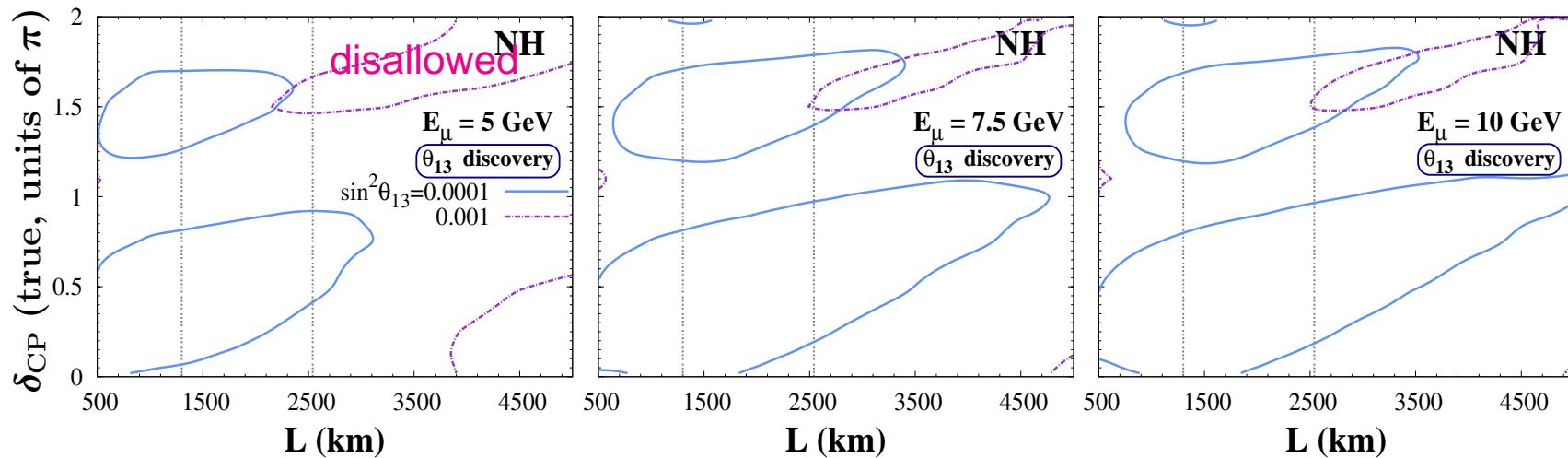
Hierarchy at 5σ for larger CP fraction at $L \sim 2540 \text{ km}$

Optimal Baseline for θ_{13}



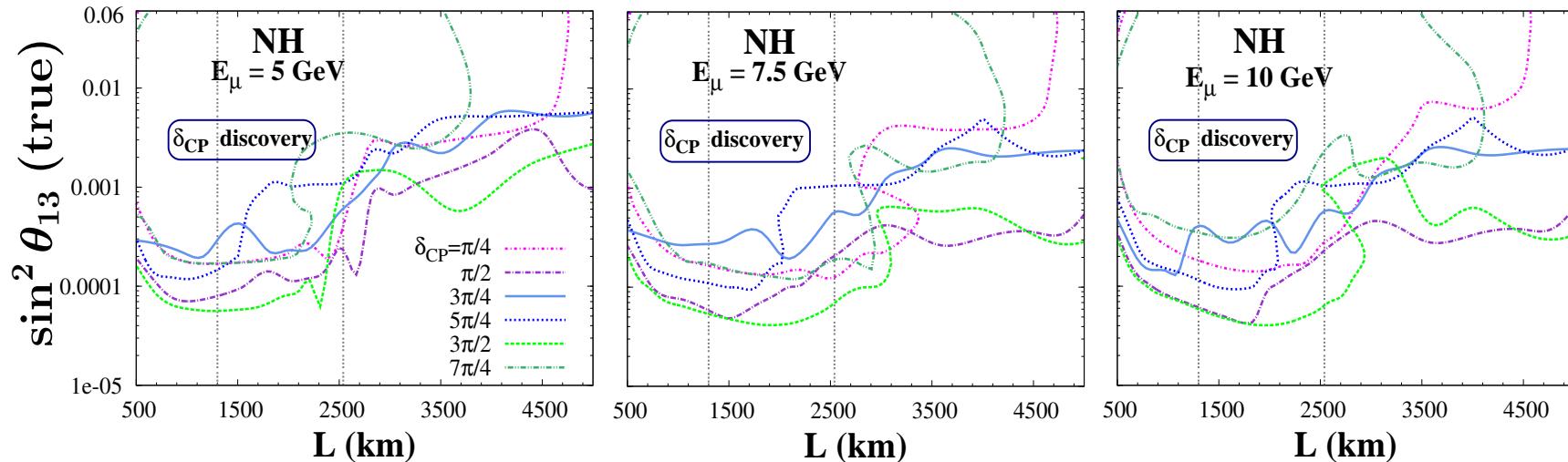
- The best sensitivity
 - $E_\mu = 5$ GeV, $L \sim 800-1600$ km
 - $E_\mu = 7.5 - 10$ GeV, $L \sim 1500 - 2500$ km
- For the worst case true value of δ_{CP} , $L \sim 2000$ km
- Saturation effect from 7.5 GeV $\rightarrow 10$ GeV present
- Sensitivity depends crucially on true δ_{CP}

Optimal Baseline for θ_{13} : $\delta_{CP} - L$ plots



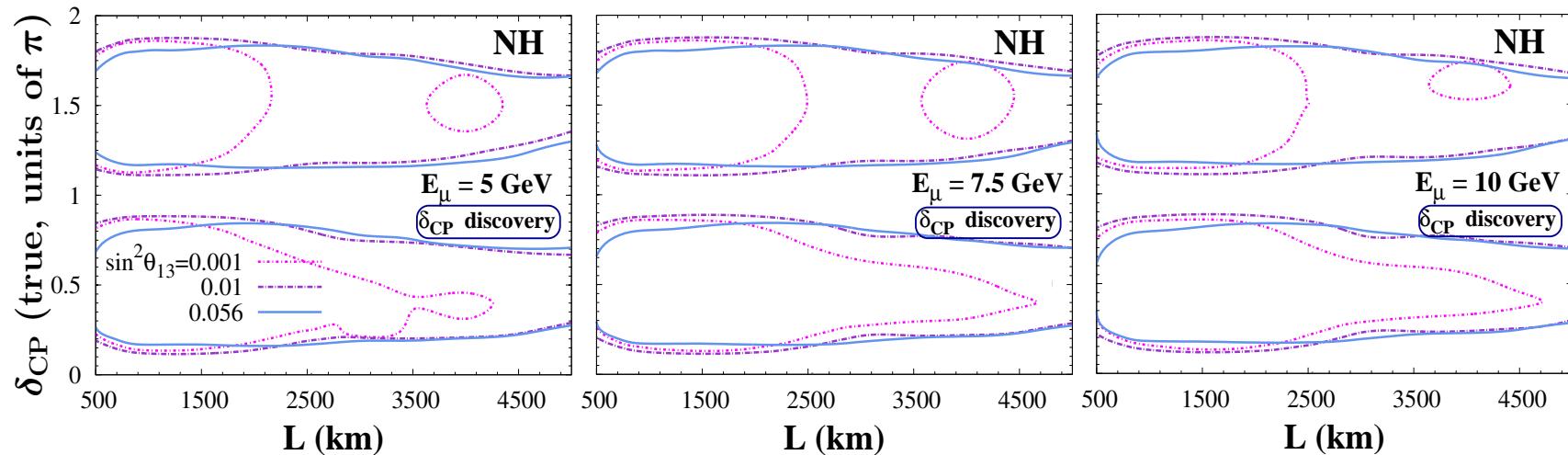
- $\sin^2 \theta_{13} = 0.01 \rightarrow \theta_{13}$ can be discovered at 5σ in the whole plane
- $\sin^2 \theta_{13} = 0.001 \rightarrow L \lesssim 2100 \text{ km}$
- $\sin^2 \theta_{13} = 0.0001 \rightarrow$ smaller $L \lesssim 2500 - 2700 \text{ km}$ preferred
- With increasing E_μ increased sensitivity at higher baselines

Optimal Baseline for 5σ discovery of δ_{CP}



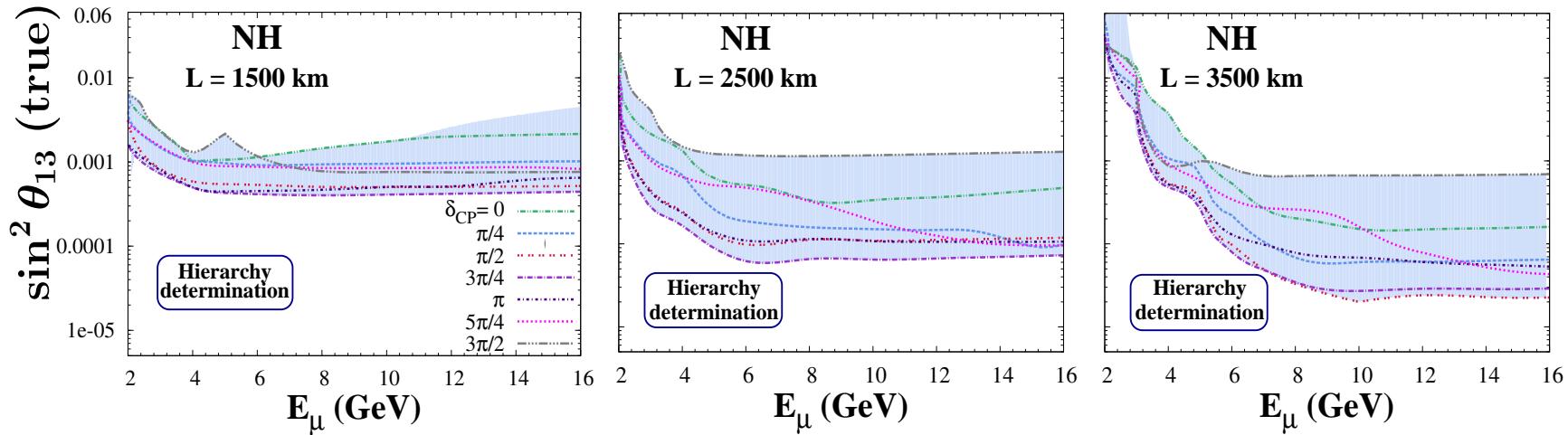
- Sensitivity depends strongly on true δ_{CP}
- Best sensitivity (lowest reach in θ_{13}) for true $\delta_{CP} = \pi/2, 3\pi/2 \rightarrow$ CP violation maximum
- $L \lesssim 2000$ km more efficient
- Saturation effect present

Optimal Baseline for 5σ discovery of δ_{CP}



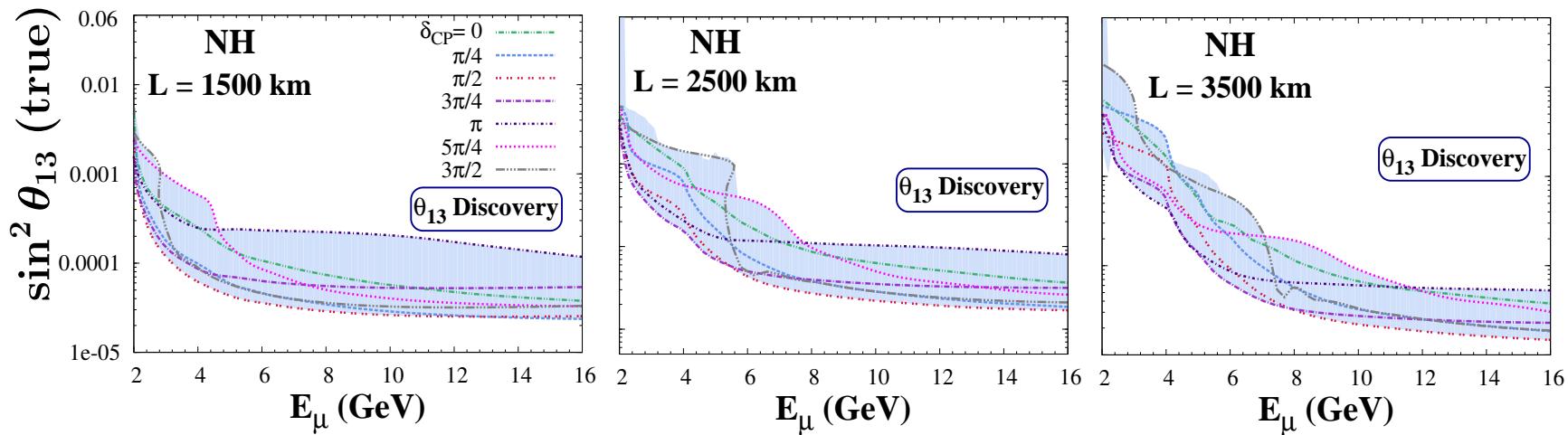
- $\sin^2 \theta_{13} > 0.01, \rightarrow \delta_{CP} = (0.3 - 0.7)\pi, (1.3 - 1.7)\pi \rightarrow L \lesssim 2500$ km
- $0.001 \lesssim \sin^2 \theta_{13} \lesssim 0.01 \rightarrow L \lesssim 2100$ km

Optimal Energy for Hierarchy



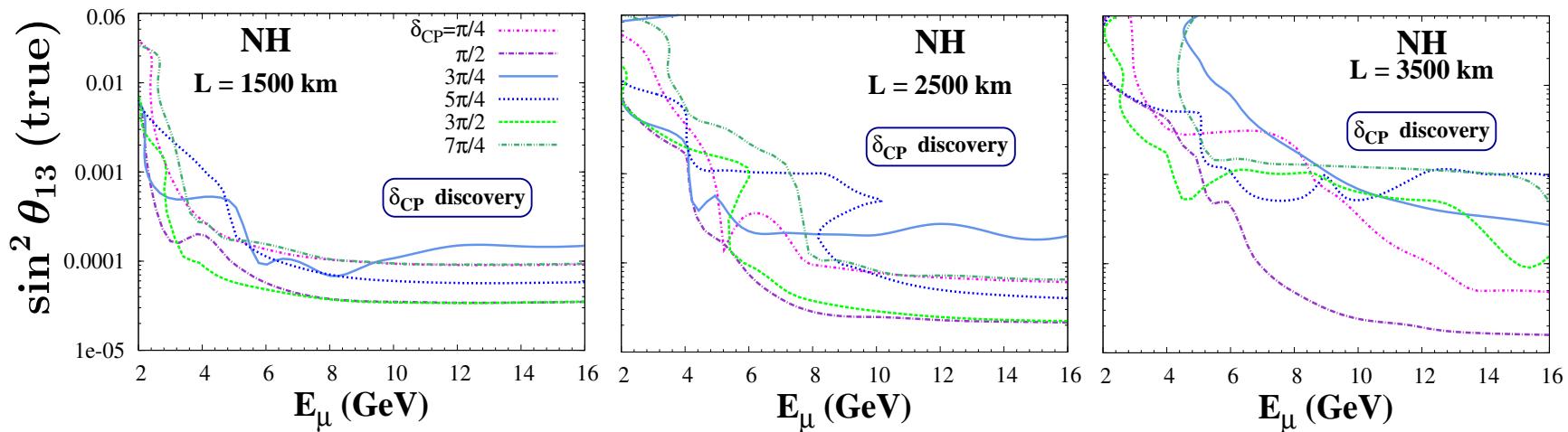
- Sensitivity increases with E_μ and then saturates
- E_μ^{sat} increases with L : $\sim 5 \text{ GeV}$ for 1500 km , $\sim 7 \text{ GeV}$ for 2500 km , $\sim 10 \text{ GeV}$ for 3500 km
- Best hierarchy reach is at $L = 3500 \text{ km}$, $E_\mu \sim 10 \text{ GeV}$
- Strong dependence on true value of δ_{CP}

Optimal Energy for θ_{13}



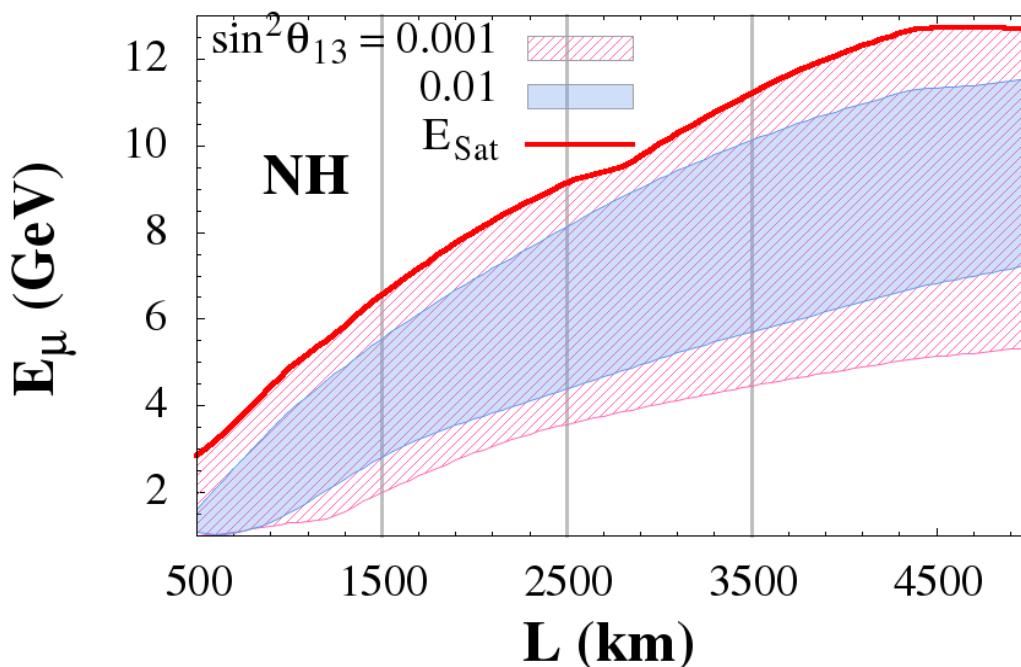
- Optimal energy at a particular baseline also depends on true value of δ_{CP}
- $L = 1500 \text{ km}$, $E_\mu > 6 \text{ GeV}$, $L = 2500 \text{ km}$, $E_\mu > 6 \text{ GeV}$, $L = 3500 \text{ km}$, $E_\mu > 10 \text{ GeV}$
- Lowest θ_{13} reach at $L = 3500 \text{ km}$ and $E_\mu \sim 14 \text{ GeV}$

Optimal Energy for δ_{CP}



- The **optimal** energy for each baseline depends on **true** δ_{CP}
- In general the discovery potential **improves** with **energy** till $E_{\mu_{sat}}$
- ~ 6 GeV for 1500 km, ~ 8 GeV for 2500 km, ~ 12 GeV for 3500 km
- Best sensitivity for $\delta_{CP} = \pi/2, 3\pi/2 \rightarrow$ maximum CP violation
- ~ 2500 km ~ 8 GeV best though for $\delta_{CP} = \pi/2$ 3500 km can have a lower reach in θ_{13}
- But for majority of $\delta_{CP} \sim 1500$ km, ~ 6 GeV best

Estimation of optimal E_μ



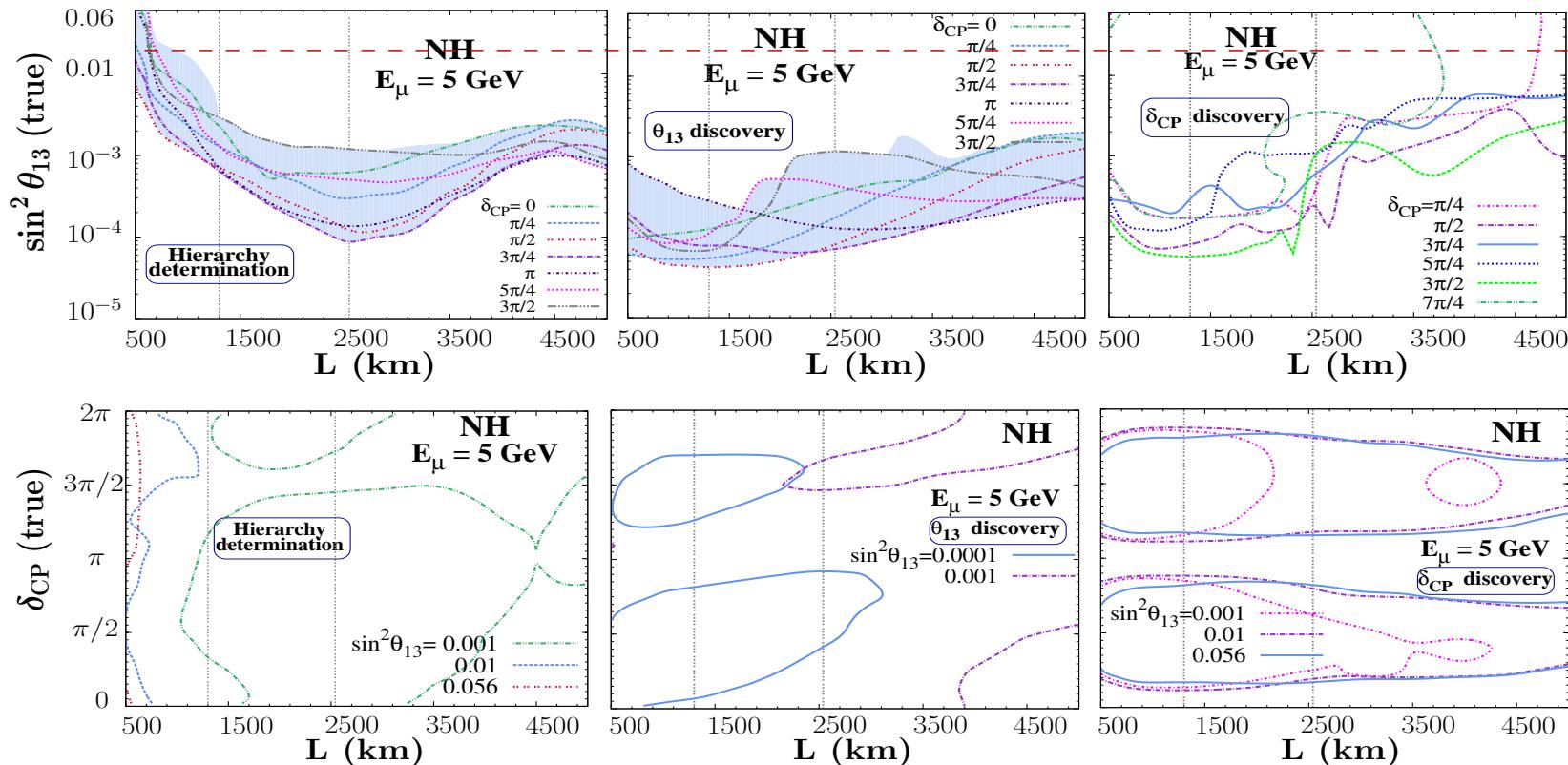
Quality factor:

$$Q = \frac{\int \Phi_{\nu_e} P_{e\mu} \sigma_{\nu_\mu} dE_{\nu_e}}{\int \Phi_{\nu_e} \sigma_{\nu_\mu} dE_{\nu_e}}$$

- For each L and E_μ find Q
- Maximum of Q gives the optimal E_μ
- Depends on mixing parameters
- Matches with that obtained from numerical analysis
- Beyond this $E_{\mu_{sat}}$ no significant improvement in performance

If θ_{13} is Large

0.000



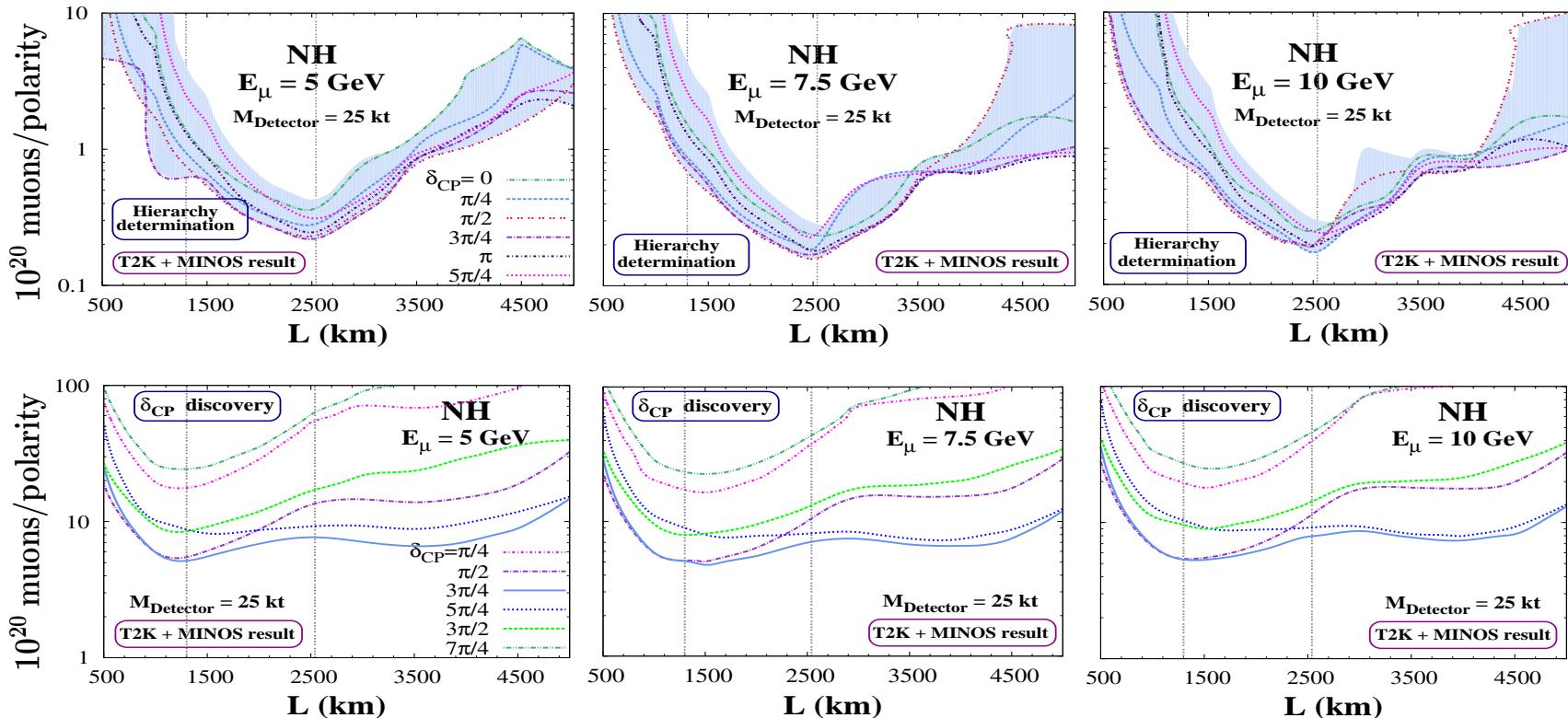
- T2K + MINOS: $\sin^2 \theta_{13} = 0.021^{+0.007}_{-0.008}$ Global : $\sin^2 \theta_{13} = 0.013^{+.007}_{-.005}$
- Hierarchy for $L \gtrsim 1000 \text{ km}$ for all δ_{CP}
- θ_{13} : 500 - 5000 km
- $\delta_{CP} = (0.3 - 0.7)\pi$ and $(1.3 - 1.7)\pi$: (500 - 2500) km

If θ_{13} is Large

The results shown are obtained with

- 5×10^{21} useful muon decays
- 2.5 year run with each polarity,
- 25 kt detector
- Can we be more ambitious ?
- Minimum exposure needed for 5σ discovery ?
- Optimization with respect to exposure

If θ_{13} is Large



- Hierarchy : $L \sim 2540$ km, $E_\mu \sim 7.5$ GeV, useful muon decays $\sim 1/10$
- δ_{CP} : ~ 1300 km, $E_\mu \sim 7.5$ GeV optimal for most true values of δ_{CP}
- 2540 km needs ~ 1.5 times exposure
- Exposure required for δ_{CP} is 10 times that required for hierarchy

Conclusion

- Bi-Magic baseline → 2540 km → a shorter baseline with magical properties
- The magic condition depends on hierarchy, energy
- Remarkable sensitivity to hierarchy as well as sensitivity to θ_{13} and δ_{CP}
- Results with a low energy neutrino factory and TASD detector promising .
- Is it the optimal baseline ?
- Optimal baseline depend on true δ_{CP} and true θ_{13}
- For each baseline there is a saturation energy
- For a given L best sensitivity at optimal energy

Conclusion

- There is evidence of large θ_{13} reported by T2K, MINOS and Double-CHOOZ
- What is the optimal baseline for a LENF for 5σ discovery of hierarchy and δ_{CP} in view of this ?
- Optimization with respect to exposure
- Hierarchy : $L \sim 2540$ km, $E_\mu \sim 7.5$ GeV, useful muon decays $\sim 1.5 \times 10^{20}$
- δ_{CP} : ~ 1300 km, $E_\mu \sim 7.5$ GeV optimal for most true values of δ_{CP}
- 2540 km needs ~ 1.5 times exposure
- Exposure required for δ_{CP} is 10 times that required for hierarchy
- For each baseline there is a saturation energy
- For a given L best sensitivity at optimal energy