Mass Hierarchy in Future Long-baseline Experiments

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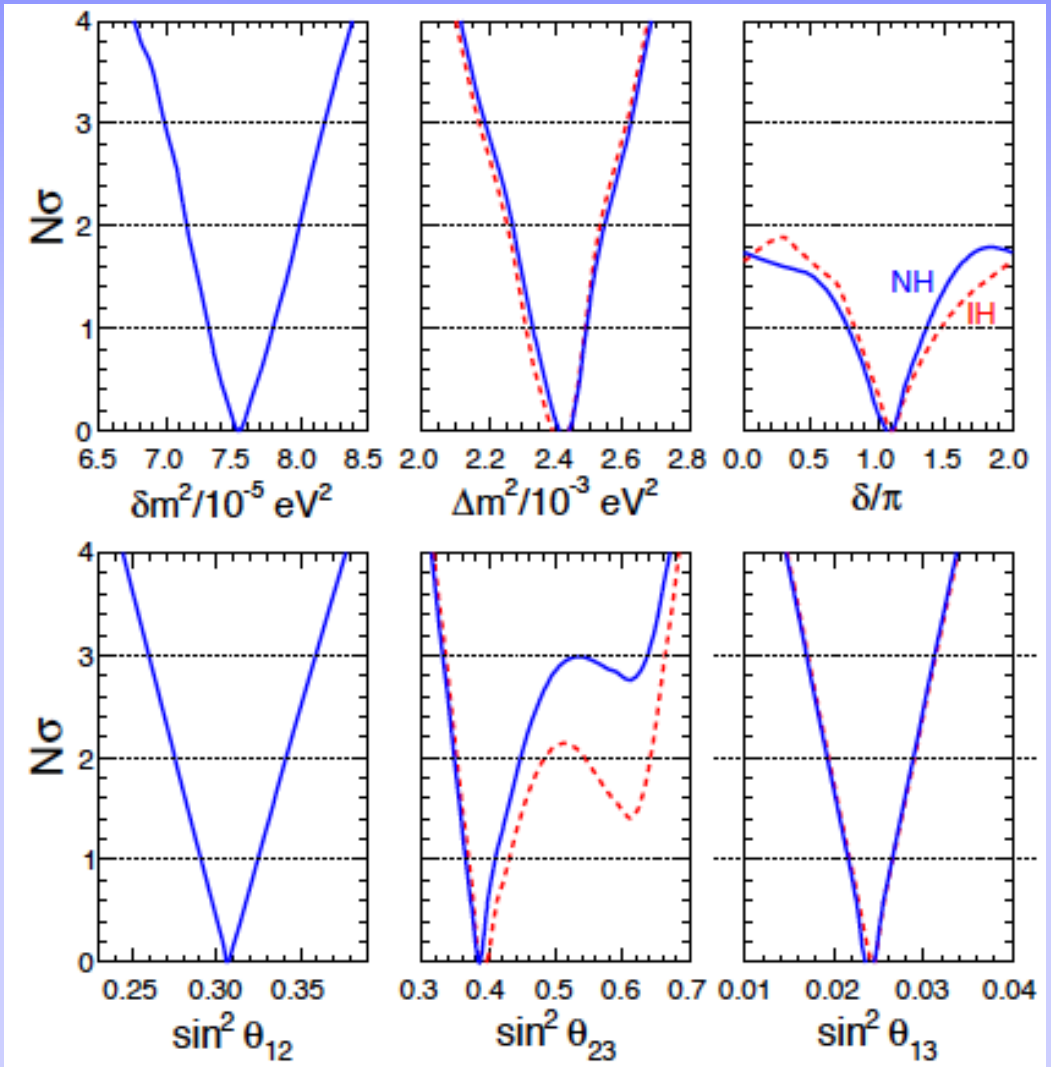
Global Analysis of World Neutrino Data



G.L. Fogli etal., arXiv: 1205.5254v3

Including Neutrino 2012 data!

	Best-fit	**2σ range**
$\sin^2\theta_{13}$ =	**0.0241 (NH)**	**0.0193 - 0.0290**
$\sin^2\theta_{13}$ =	**0.0244 (IH)**	**0.0194 – 0.0291**

G.L. Fogli etal., arXiv: 1205.5254v3

$\sin^2\theta_{13}$ =	**0.0246 (NH)**	**0.019 - 0.030**
$\sin^2\theta_{13}$ =	**0.0250 (IH)**	**0.020 – 0.030**

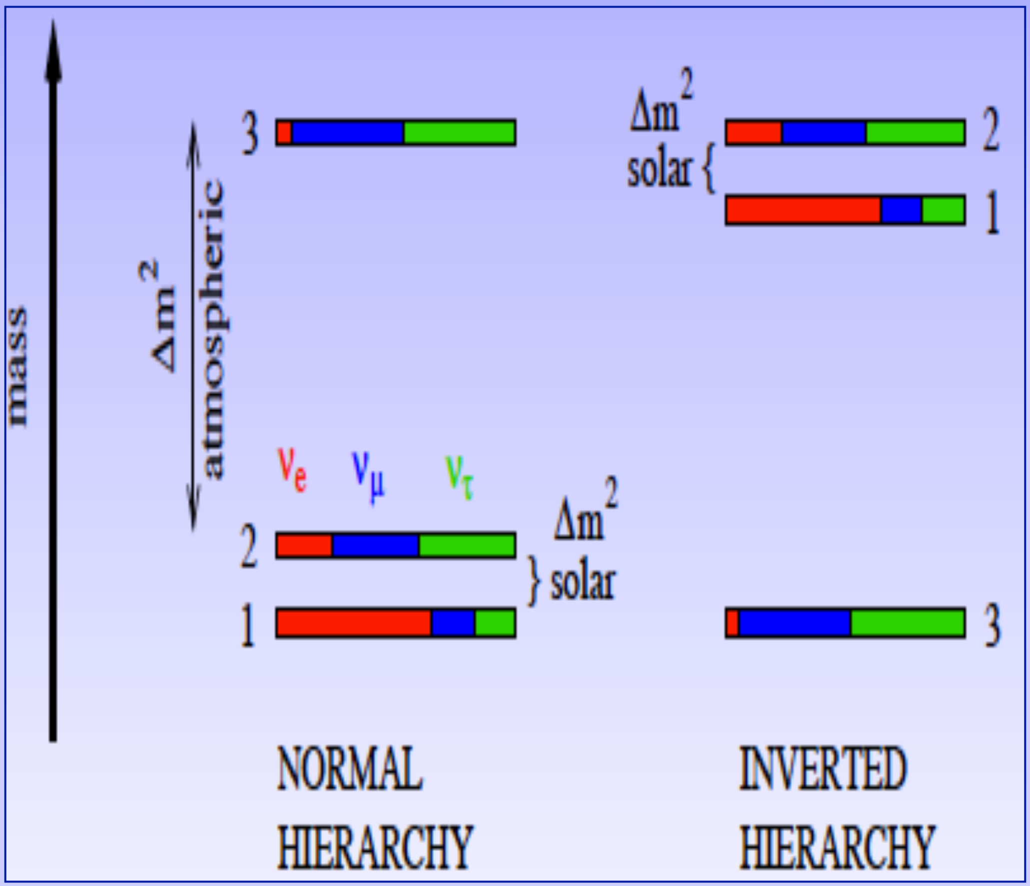
D.V. Forero etal., arXiv: 1205.4018v3

Relative Precision ~ 10%

$\sin^2 2\theta_{13} \neq 0$ @ 10σ

Missing Link in ν Oscillation: Neutrino Mass Ordering

- The sign of Δm^2_{31} $(m_3^2 - m_1^2)$ is not known



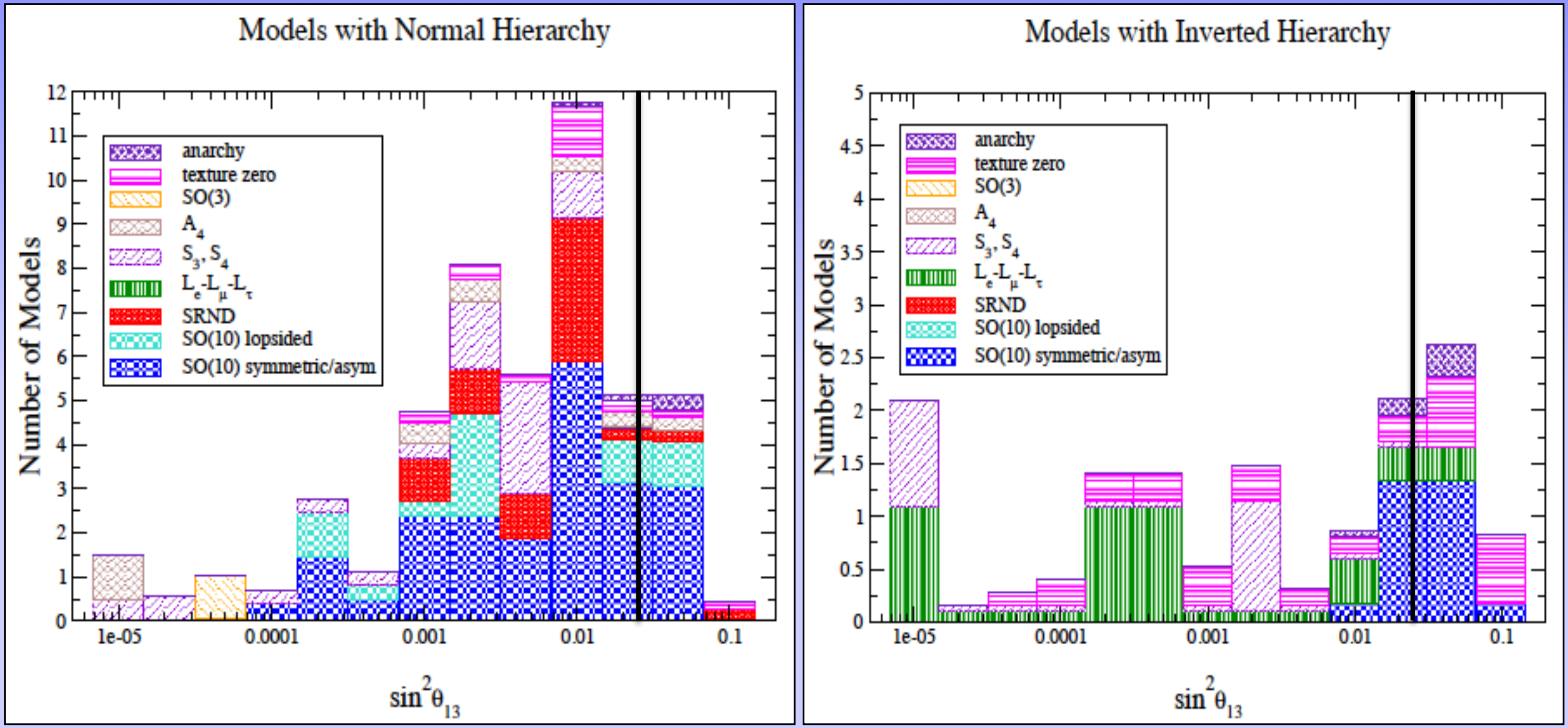
Neutrino mass spectrum can be normal or inverted hierarchical

We only have a lower bound on the mass of the heaviest neutrino

$$\boxed{\sqrt{2.5 \cdot 10^{-3} \mathrm{eV}^2} \sim 0.05\ \mathrm{eV}}$$

We currently do not know which neutrino is the heaviest

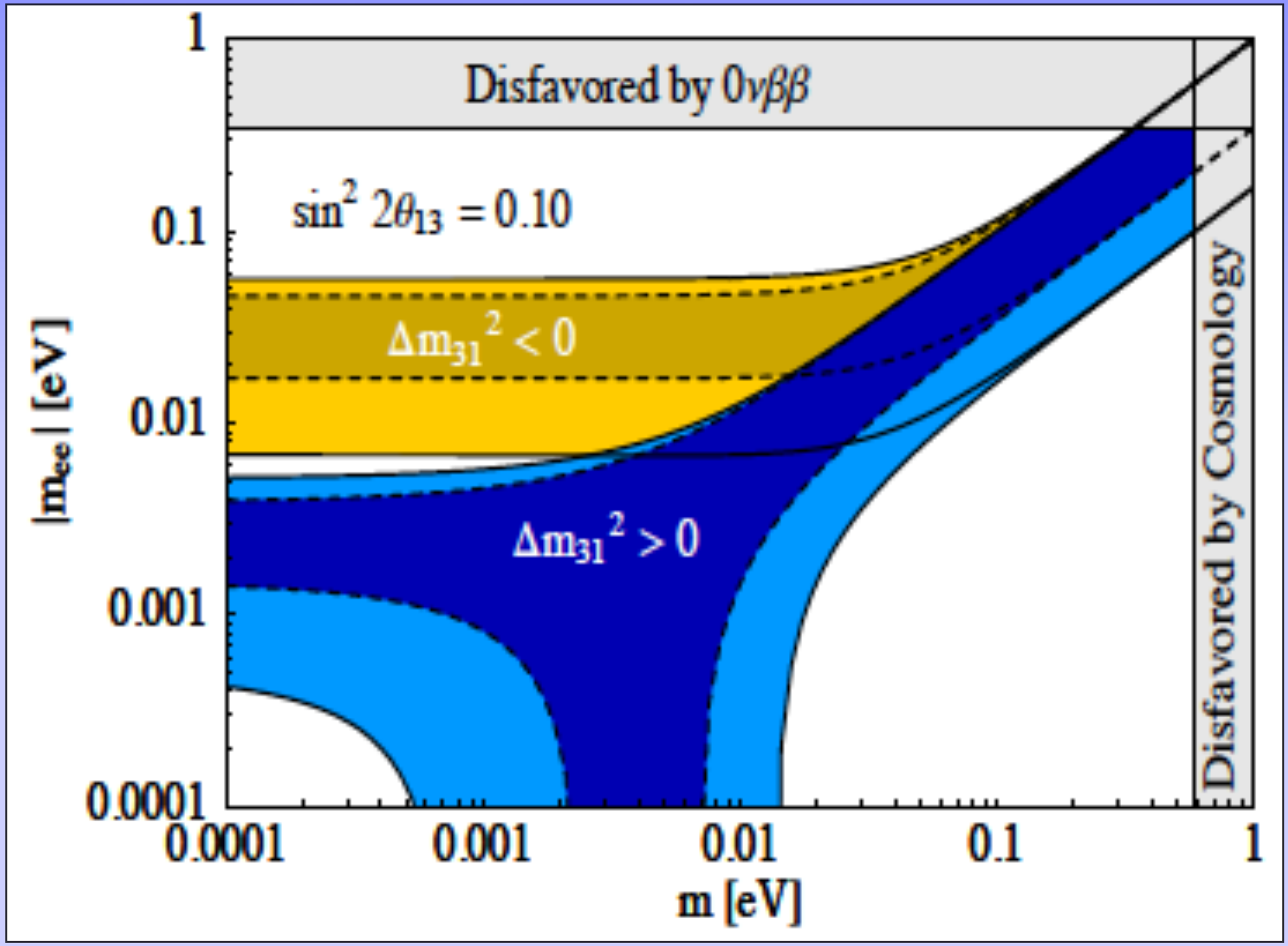
Why do we care about Neutrino Mass Ordering?



Albright and Chen, hep-ph/0608137

- Dictates the structure of ν mass matrix
- Can give vital clues towards the underlying theory of ν masses and mixing
- Acts as a powerful discriminator between various ν mass models

Connection between 0νββ and Neutrino Mass Ordering



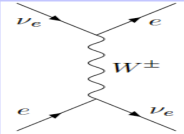
Lindner, Merle, Rodejohann , hep-ph/0512143

If hierarchy is inverted, and yet no 0νββ is observed in the very far future, strong hint that neutrinos are not Majorana particles

Neutrino Oscillations in Matter

- ***Interactions in matter modify the oscillation probability significantly***
- ***Coherent forward elastic scattering of neutrinos with matter particles***
- ***Charged current interaction of ν_e with electrons creates a potential for ν_e***

$$A = \pm 2\sqrt{2} G_F \cdot E \cdot n_e$$



n_e = electron number density and + (-) for neutrinos (anti-neutrinos)

Creates an additional phase for ν_e and changes the oscillation probability

$$P(\nu_\alpha \rightarrow \nu_\beta) - P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \neq 0$$ → ***even if δ = 0, causes fake CP asymmetry***

$$\Delta m^2 \simeq A \quad \Leftrightarrow \quad E_{\mathrm{res}}^{\mathrm{Earth}} = 6 - 8\,\mathrm{GeV}$$ → ***Resonant conversion – the MSW effect***

	ν	$\bar{\nu}$
$\Delta m^2 > 0$	MSW	-
$\Delta m^2 < 0$	-	MSW

→ ***Resonance occurs for neutrinos (anti-neutrinos) if Δm^2 is positive (negative)***

Platinum Channel ($P_{\mu e}$)

The appearance probability $(\nu_\mu \to \nu_e)$ in matter, upto second order in the small parameters $\alpha \equiv \Delta m^2_{21}/\Delta m^2_{31}$ and $\sin 2\theta_{13}$,

$$P_{\mu e} \simeq \underbrace{\sin^2 2\theta_{13}\, \sin^2\theta_{23}}_{0.05} \frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2} \Rightarrow \theta_{13}\text{ Driven}$$

5.2 times

$$- \underbrace{\alpha\, \sin 2\theta_{13}\, \xi}_{0.0096}\, \sin\delta_{CP}\, \sin(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \Rightarrow \text{CP odd}$$

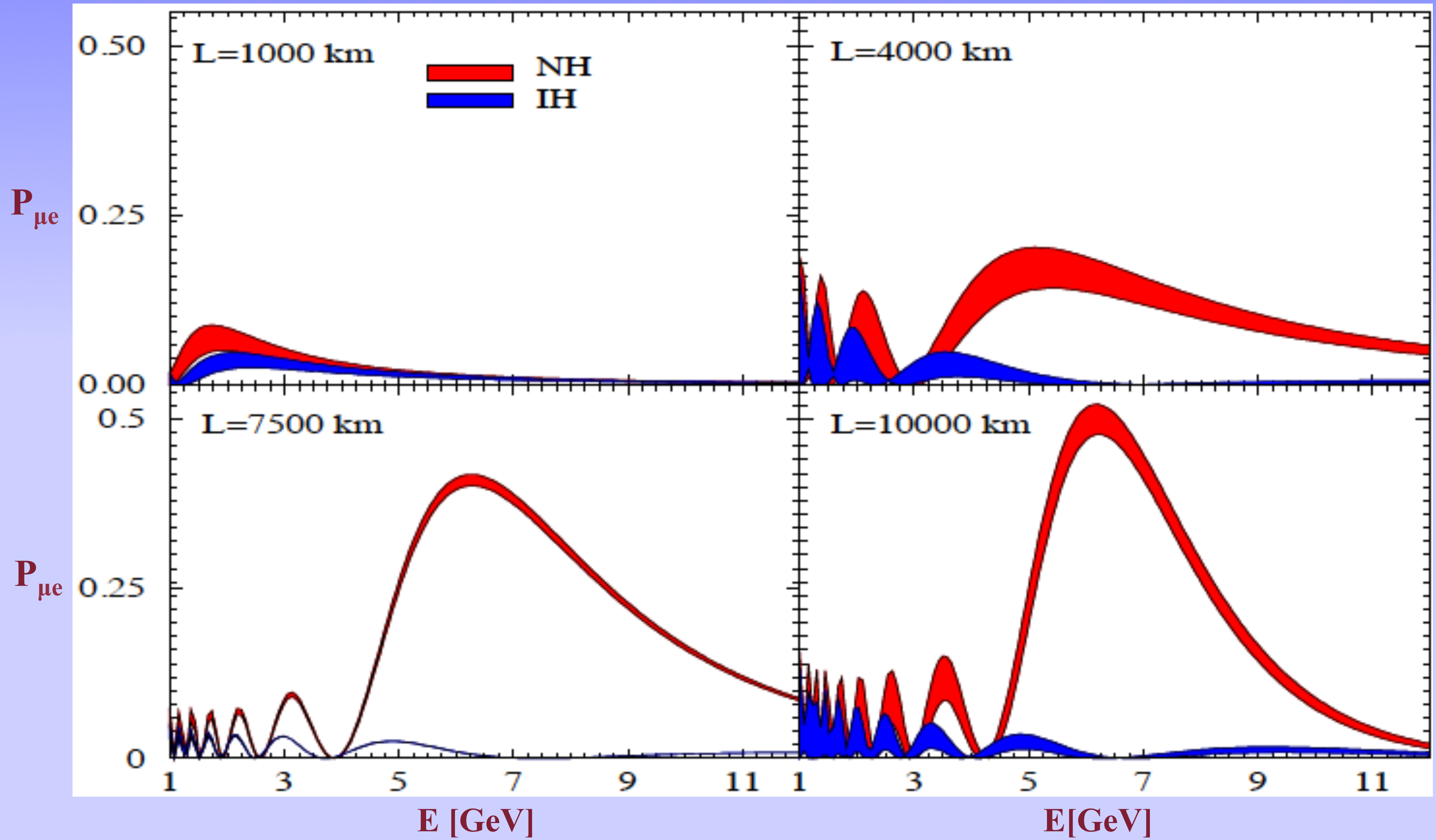
$$+ \alpha\, \sin 2\theta_{13}\, \xi\, \cos\delta_{CP}\, \cos(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \Rightarrow \text{CP even}$$

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

where $\Delta \equiv \Delta m^2_{31} L/(4E)$, $\xi \equiv \cos\theta_{13}\, \sin 2\theta_{21}\, \sin 2\theta_{23}$,
and $\hat{A} \equiv \pm(2\sqrt{2} G_F n_e E)/\Delta m^2_{31}$

Cervera etal., hep-ph/0002108
Freund etal., hep-ph/0105071

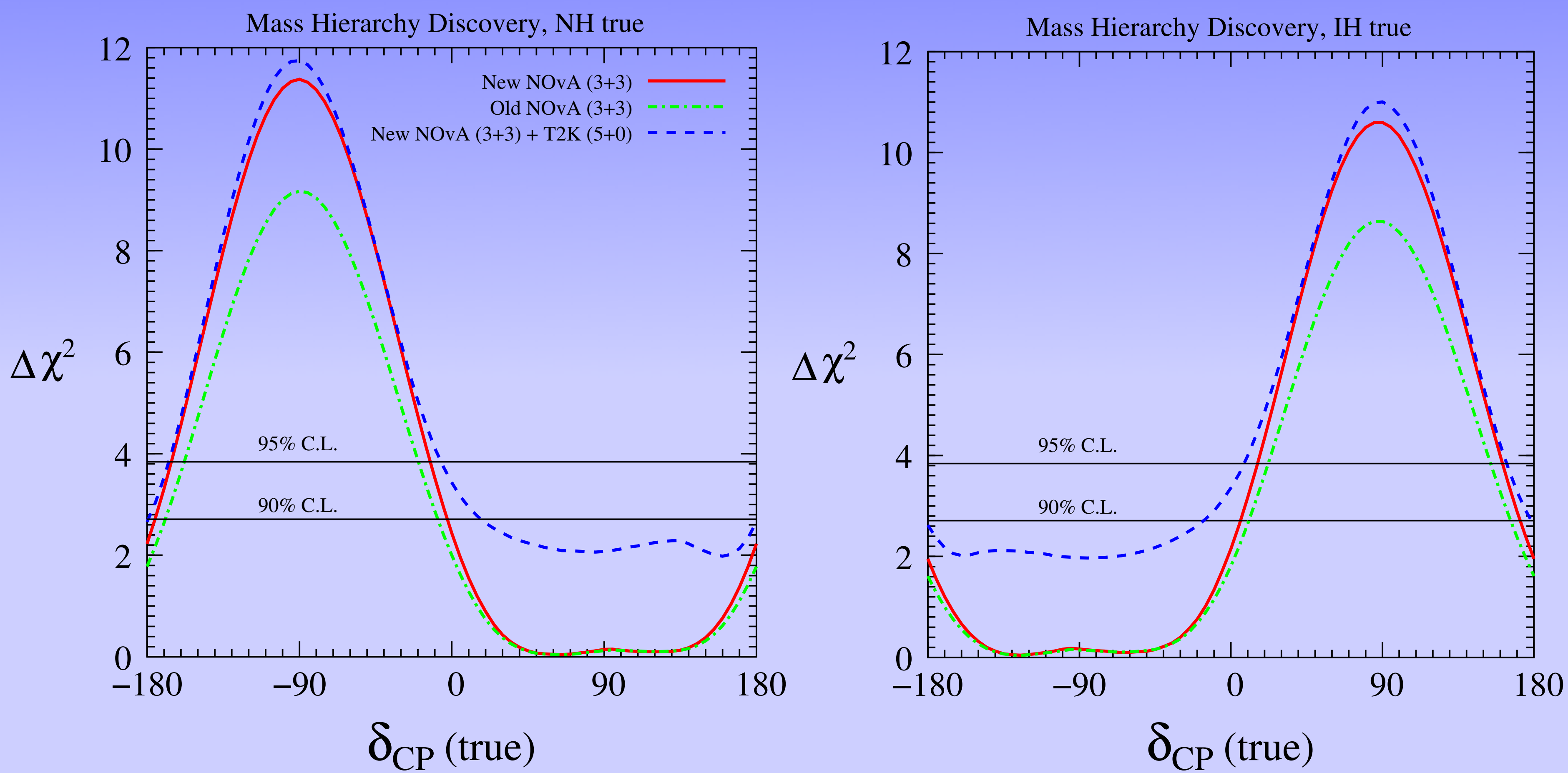
Transition Probability ($P_{\mu e}$)



Agarwalla, Choubey, Raychaudhuri, hep-ph/0610333

Normal .vs. Inverted Hierarchy and $\sin^2 2\theta_{13} = 0.1$

Present Generation Experiments: T2K and NOvA

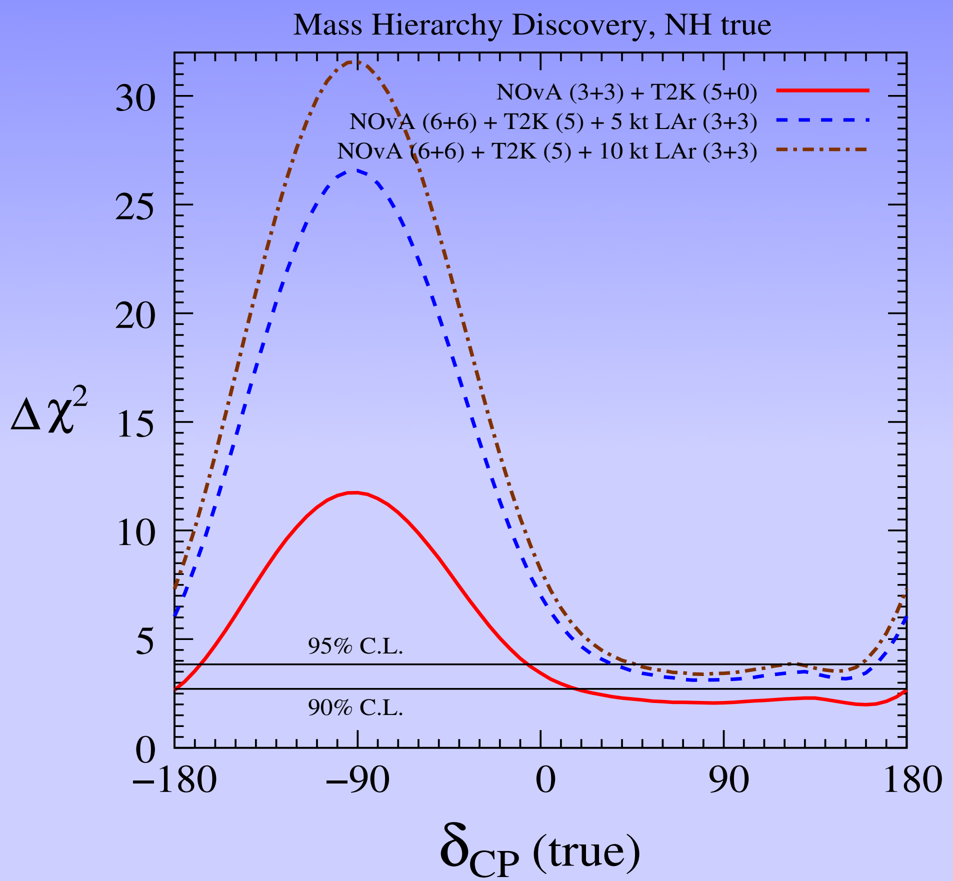


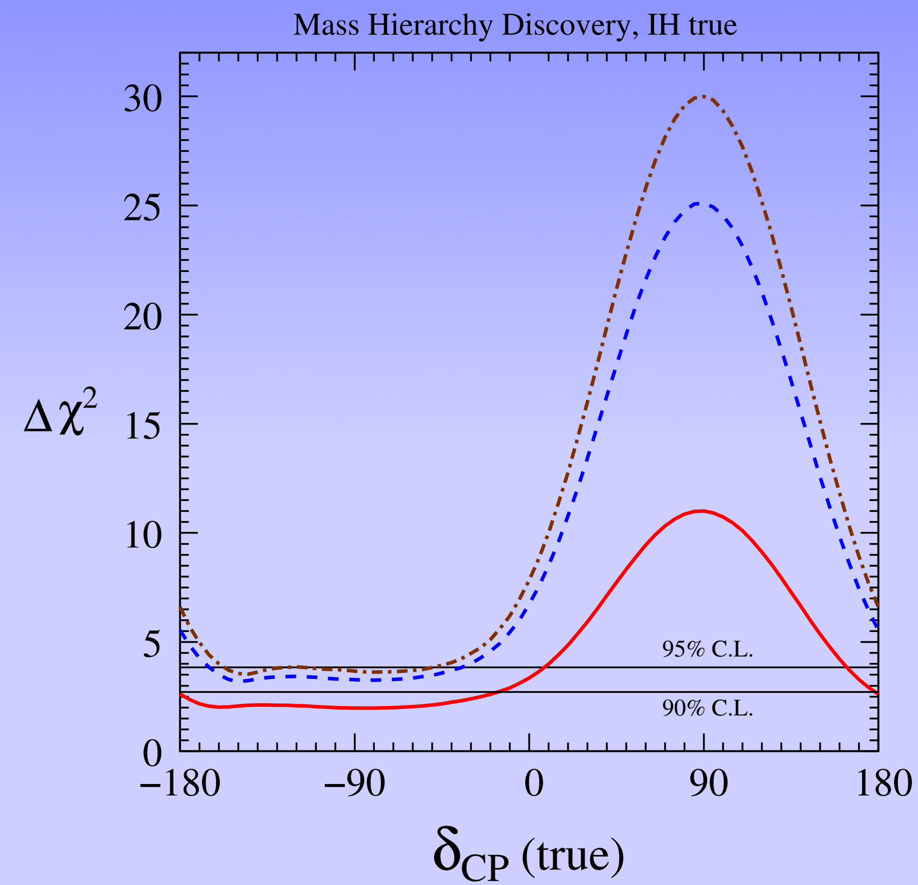
Agarwalla, Prakash, Raut, Uma Sankar, arXiv:1208.3644
See also the talk by S. Prakash in this workshop

Adding data from T2K and NOvA is useful to kill the intrinsic degeneracies

55% CP coverage @ 90% C.L. and 45% CP coverage @ 95% C.L. for MH discovery

Add a small LArTPC in the NOνA Beamline





Agarwalla, Prakash, Raut, Uma Sankar, arXiv:1208.3644

Add a small LArTPC (5 to 10 kt) in the NOνA Beamline taking data simultaneously

100% CP coverage @ 90% C.L. and 64% CP coverage @ 95% C.L. w/ 5 kt LArTPC

What large θ_{13} buys for us?

- Newly discovered large value of θ_{13} enhanced the chances of present generation experiments to provide a strong hint of mass hierarchy discovery around 2σ

- Combining data from T2K and NOνA will be very useful to kill the clones

- To have a $> 5\sigma$ direct determination of MH for all values of δ_{CP}, we need next generation LBL expts (> 1000 km) enriched with Earth Matter effects

- Thanks to large θ_{13}, we do not need β-beam or ν-Factory for MH discovery

- A reasonably upgraded Superbeam with a power of around 1 MW coupled with a small 10 to 20 kt LArTPC detector can do it provided the baseline is > 1000 km

- Large θ_{13} allowed to adopt an incremental approach for next generation expts

- The determination of MH can be considered as a first step towards the Leptonic CP violation discovery which is quite tough even for large value of θ_{13}

Option for Next Generation LBL Expts (Baselines < 1000 km)

1) CERN to Frejus : 130 km (1st Osc. Max = 0.26 GeV)
   Beam: 4.5 GeV, 4 MW, 56 × 10^{21} POT/yr, 2 yrs ν + 8 yrs $\bar{\nu}$
   Detector: 500 kton Water Cherenkov (MEMPHYS)

See the talk by Thomas Patzak

2) J-PARC to Kamioka : 295 km (1st Osc. Max = 0.6 GeV)
   Beam: 30 GeV, 1.66 MW, 5 × 10^{21} POT/yr, 1.5 yrs ν + 3.5 yrs $\bar{\nu}$
   Detector: 560 kton Water Cherenkov (Hyper-Kamiokande)

See the talk by Masato Shiozawa

3) CERN to Canfranc : 630 km (1st Osc. Max = 1.27 GeV)
   Beam: 50 GeV, 1.6 MW, 3 × 10^{21} POT/yr, 5 yrs ν + 5 yrs $\bar{\nu}$
   Detector: 500 kton Water Cherenkov

4) CERN to Gran Sasso : 730 km (1st Osc. Max= 1.47 GeV)
   Beam: 50 GeV, 1.6 MW, 3 × 10^{21} POT/yr, 5 yrs ν + 5 yrs $\bar{\nu}$
   Detector: 500 kton Water Cherenkov

See the talk by Lucia Votano

Earth Matter effect is not enough at these baselines to provide > 5σ discovery of MH for 100% values of δ_{CP} even with high power beam and very large detector

See the talk by Silvia Pascoli

Option for Next Generation LBL Expts (Baselines > 1000 km)

1) FNAL to Homestake : 1300 km (1st Osc. Max = 2.52 GeV)

Beam: 120 GeV, 0.7 MW, 6×10^{20} POT/yr, 5 yrs ν + 5 yrs $\bar{\nu}$
Detector: 10 kton LArTPC (on surface)

LBNE proposal: See the talk by Kate Scholberg

2) CERN to Phyasalmi : 2300 km (1st Osc. Max = 4.54 GeV)

Beam: 400 GeV, 0.77 MW, 1.5×10^{20} POT/yr, 5 yrs ν + 5 yrs $\bar{\nu}$
Detector: 20 kton LArTPC (deep underground, 4000 m.w.e)

LBNO proposal: See the talk by Andre Rubbia

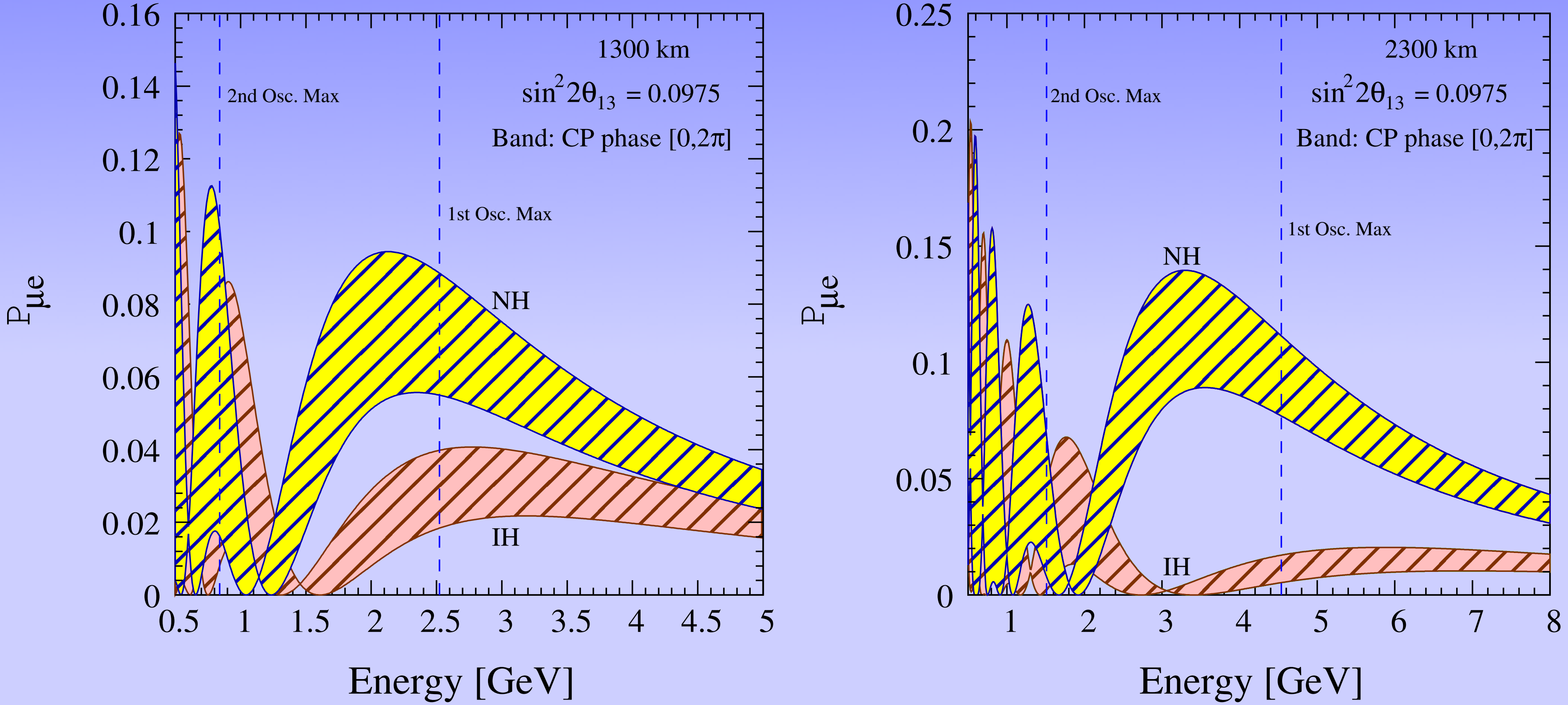
3) CERN to Kamioka : 8770 km (Probability Max = 6.5 GeV)

Beam: 400 GeV, 0.77 MW, 1.5×10^{20} POT/yr, 5 yrs ν (only rate)
Detector: 22.5 kton Water Cherenkov (existing & well understood Super-K)

Agarwalla and Hernandez, arXiv:1204.4217 [hep-ph]

These baselines are long enough to provide > 5σ discovery of MH for 100% values of δ_{CP} even with modest power beam and small detector

FNAL-Homestake .vs. CERN-Phyasalmi

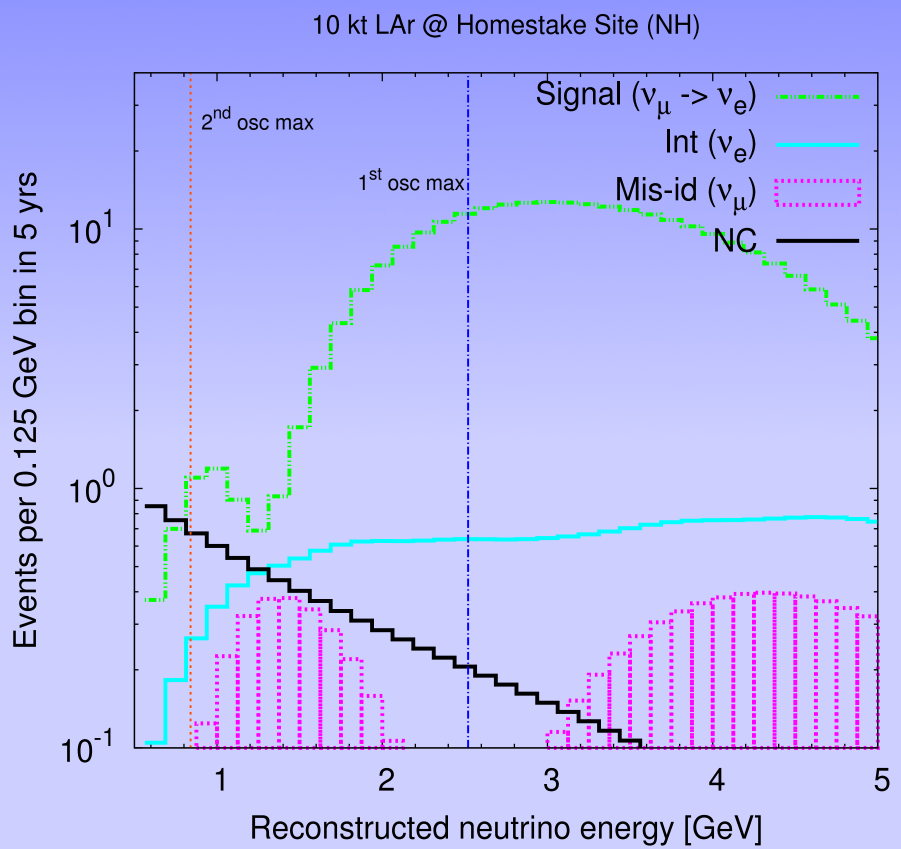


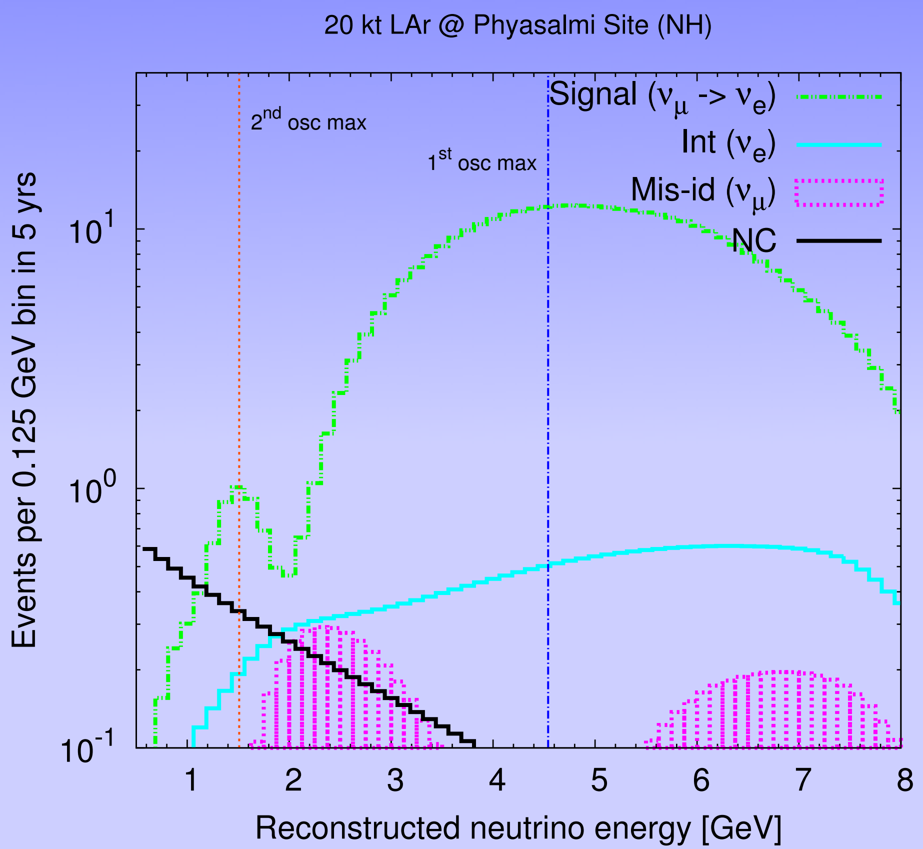
MH is a discrete measurement, both 1st and 2nd Oscillation maxima are useful

CERN-Phyasalmi distance is also close to the Bimagic baseline of 2540 km

Raut, Singh, Uma Sankar, arXiv:0908.3741, Dighe, Goswami, Ray, arXiv:1009.1093

Event Spectrum at LBNE and LBNO



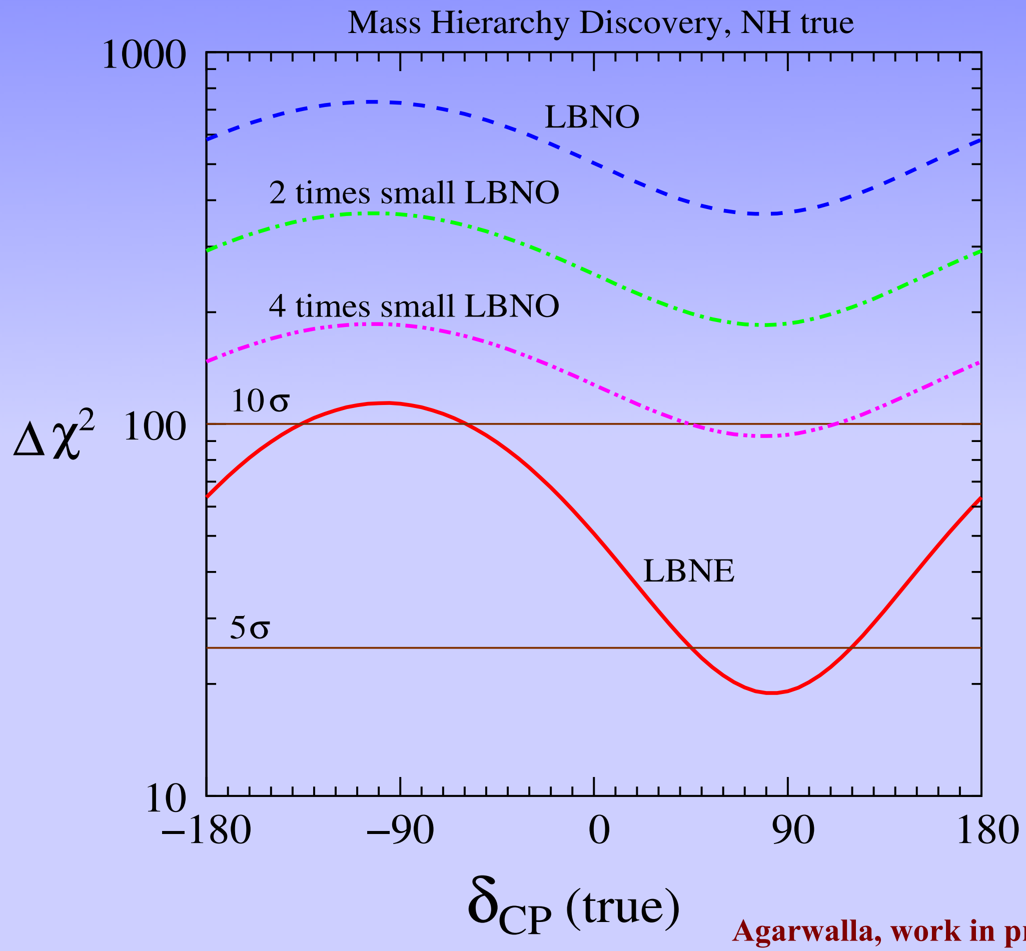


Wide Band Beam ➔ Higher statistics ➔ cover several L/E values ➔kill clone solutions

LAr Detector ➔ Excellent Detection efficiency at 1st and 2nd Oscillation maxima

High L ➔ High E ➔ High cross-section ➔ Less uncertainties in cross-section at high E

Mass Hierarchy Discovery: LBNE .vs. LBNO

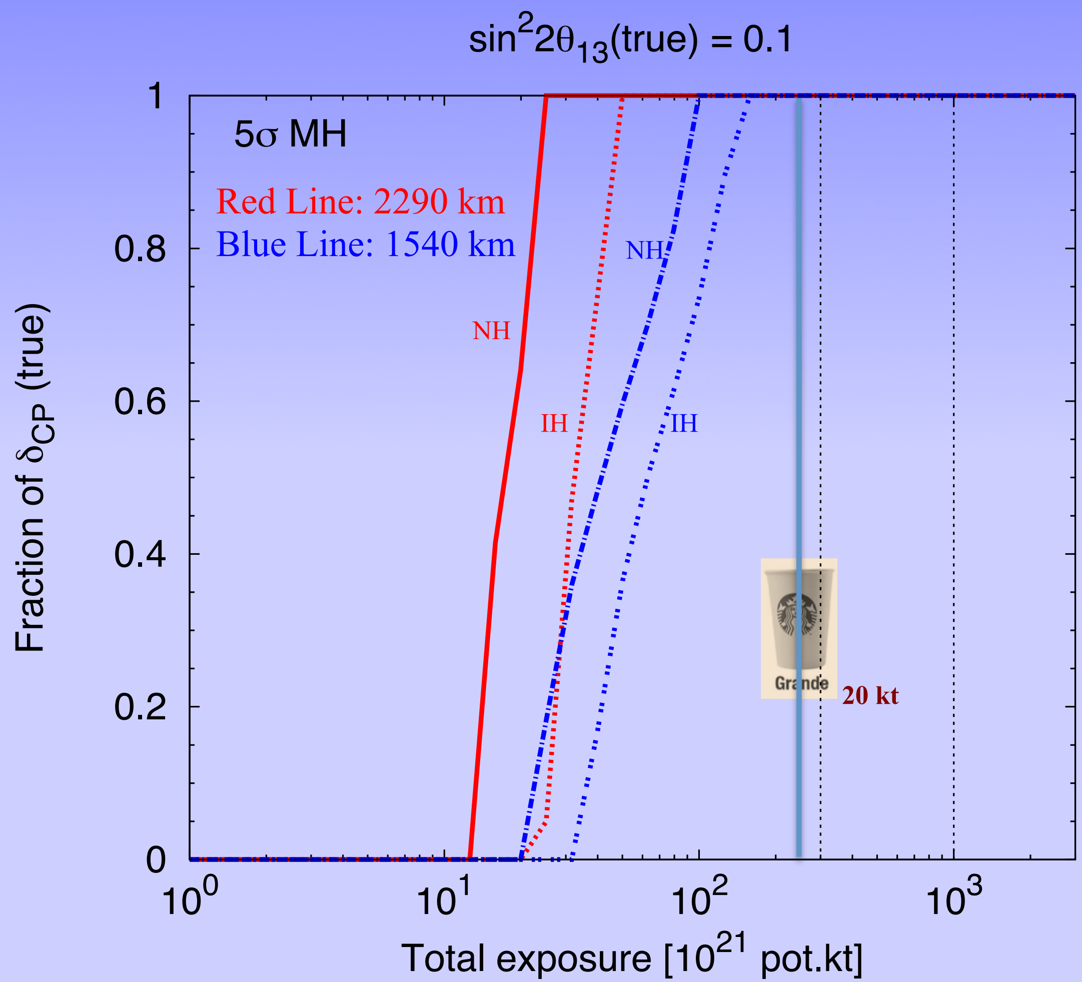


Agarwalla, work in progress

A four times small LBNO can give 10σ MH discovery for 100% values of δ_{CP}

LBNE as it stands now can give 5σ MH discovery for 85% values of δ_{CP}

Incremental Approach: Well suited for CERN-Phyasalmi



1540 km: CERN-Slanic (Romania)
Similar to FNAL-Homestake (1290 km)

	Total exposure ($\times 10^{21}$pot·kt)	
	NH true	IH true
2290 km	32 (80)	50 (158)
1540 km	158 (502)	250 (627)
	3σ 5σ	3σ 5σ

Exposure needed to achieve MH discovery with 100% coverage in δ_{CP}

240×10^{21} pot.kt with 50 GeV HPPS2

=

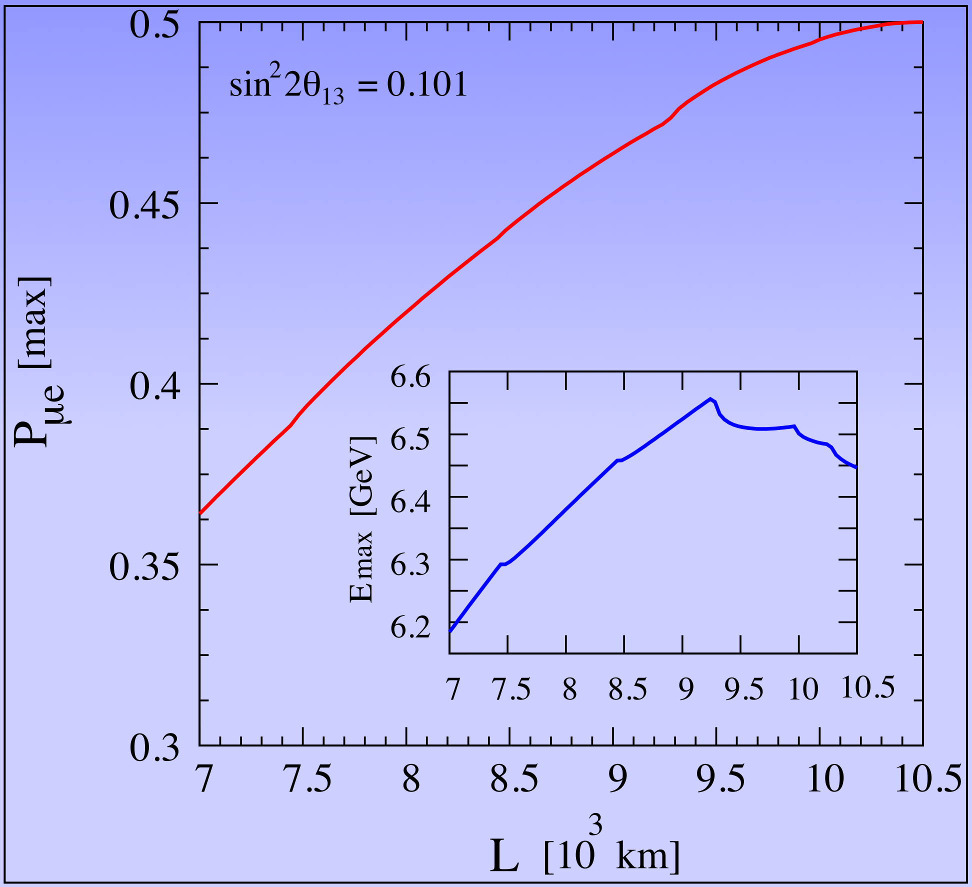
30×10^{21} pot.kt with 400 GeV SPS

Agarwalla, Li, Rubbia, arXiv:1109.6526 [hep-ph]

Equal sharing of neutrino & anti-neutrino running. NH requires less exposure than IH

Mass hierarchy will be discovered at > 5σ with small exposure at 2300 km

Near Resonant Matter Effect: Optimal E and L



Agarwalla and Hernandez, arXiv:1204.4217 [hep-ph]

One Mass Scale Dominance (neglect solar term)

$$P_{\mu e} = \sin^2\theta_{23}\sin^2 2\tilde{\theta}_{13}\sin^2\left(\frac{\Delta\tilde{m}^2_{31}L}{4E}\right)$$

$$\Delta\tilde{m}^2_{31} \equiv \sqrt{(\Delta m^2_{31}\cos 2\theta_{13} - A)^2 + (\Delta m^2_{31}\sin 2\theta_{13})^2}$$

$$\sin^2 2\tilde{\theta}_{13} \equiv \sin^2 2\theta_{13}\left(\frac{\Delta m^2_{31}}{\Delta\tilde{m}^2_{31}}\right)^2$$

Constant line-averaged Earth matter potential

$$A \equiv 2\sqrt{2}G_F n_e(L)E$$

First maximize the 1-3 mixing in matter:

$$\sin^2 2\tilde{\theta}_{13}|_{E=E_{\rm res}} = 1, \quad E_{\rm res} \equiv \frac{\Delta m^2_{31}\cos 2\theta_{13}}{2\sqrt{2}G_F n_e}$$

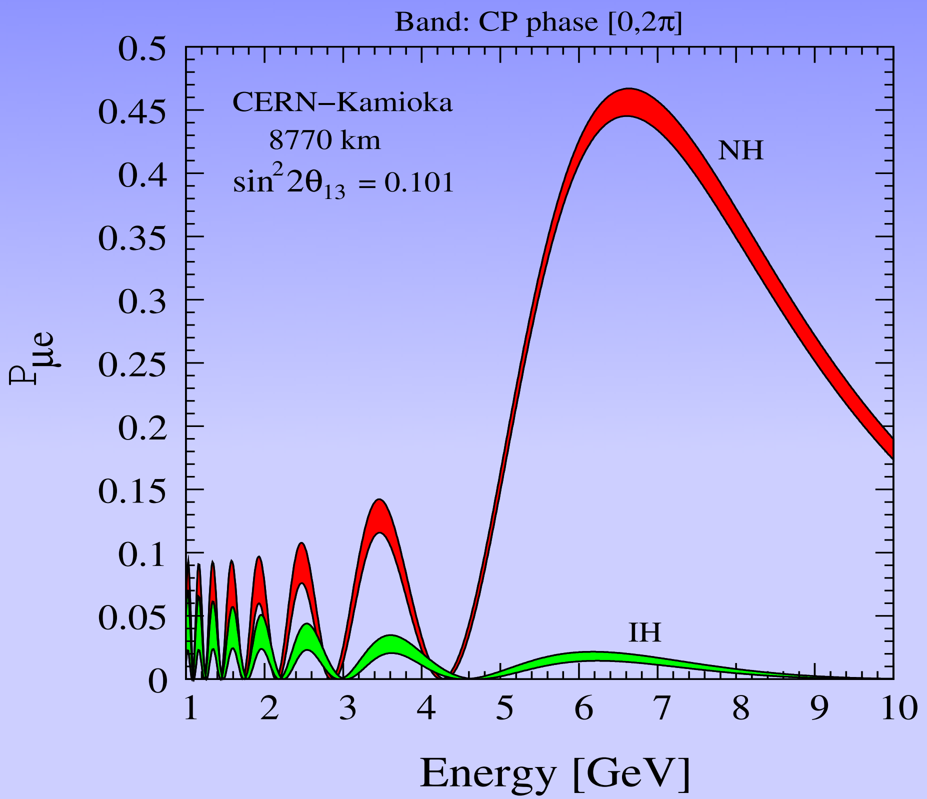
Then maximize the oscillatory term at $L = L_{max}$

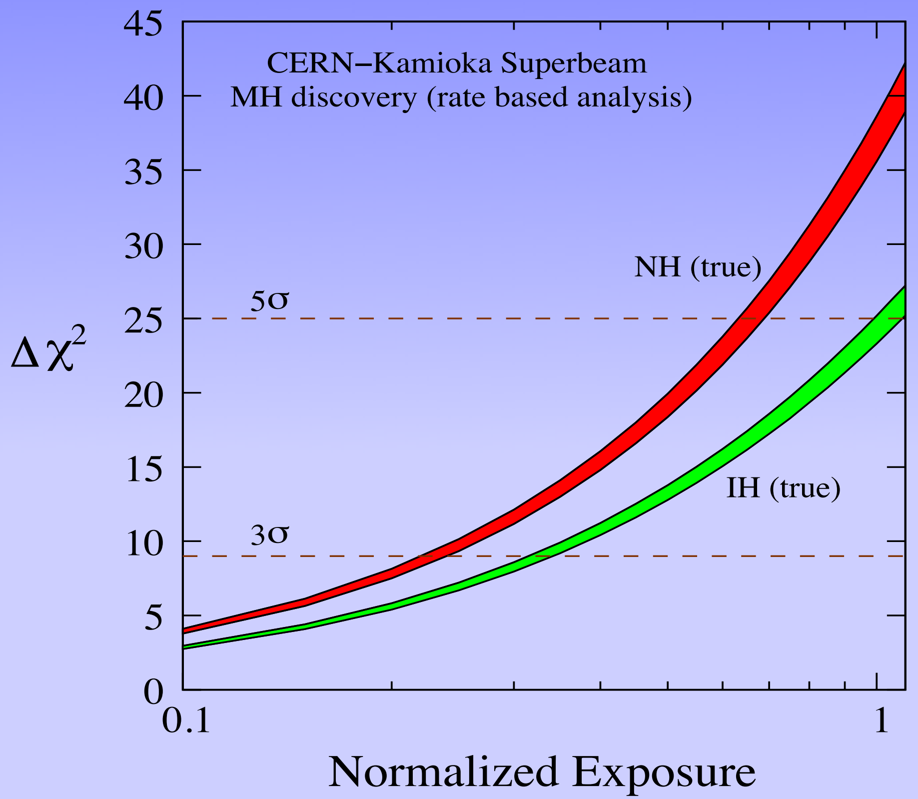
$$n_e(L)L|_{L_{\rm max}} = \frac{\pi}{\sqrt{2}G_F\tan 2\theta_{13}}$$

For $\sin^2 2\theta_{13} = 0.1$: $L_{max} \sim 10^4$ km & $E_{res} \sim 6.6$ GeV

!Maximum probability: only if 1-3 mixing is large!

Mass Hierarchy Discovery with CERN-Kamioka Baseline





Agarwalla and Hernandez, arXiv:1204.4217 [hep-ph]

- Send a Superbeam (average energy of 5 GeV) from CERN towards existing and well-understood Super-Kamiokande detector (L = 8770 km)

- This setup can reveal the neutrino MH at 5σ in 4.5 years irrespective of the true hierarchy and CP phase with only neutrino beam from 400 GeV SPS, counting the total number of appearance events

- This measurement relies on the near resonant matter effect in the ν_μ to ν_e channel

Other Probes of Neutrino Mass Hierarchy

- Large value of θ_{13} allows us to explore MH with atmospheric neutrinos. ICAL@INO experiment, IceCube Deepcore, PINGU are the candidates

See the talk by Srubabati Goswami, Francis Halzen

- Supernova neutrinos can also discriminate between NH and IH

See the talk by Sovan Chakraborty

- Cosmology can weigh neutrinos with precision and future CMB & LSS measurements have a chance to determine the light neutrino spectrum

See the talk by Carmelita Carbone

- Observation of $0\nu\beta\beta$ with the next generation expts would not only imply that neutrinos are Majorana, but also that the hierarchy is inverted

See the talk by Werner Rodejohann

- High Statistics Reactor experiments at a baseline of 60 km with an exposure of $>$ 200 kt GW yr and 2% energy resolution (The proposals of Daya Bay II & RENO II)

See the talk by Seon-Hee Seo and Liang Zhan

Concluding Remarks

- Recent discovery of large value of θ_{13} have taken us one step further in validating the 3-flavor picture of the Standard ν model with a strong footing

- Neutrino mass hierarchy is one of the fundamental unsolved issues that needs to be addressed in the present or next generation LBL expts

- To have a > 5σ direct determination of MH for all values of δ_{CP}, we need next generation LBL expts (> 1000 km) enriched with Earth Matter effects

- An optimized Superbeam using the existing 400 GeV SPS machine pointing towards Phyasalmi mine with a baseline of 2300 km and coupled with a 20 kt LArTPC can provide a 10σ direct determination of MH for all values of δ_{CP} within 2.5 years

- The determination of MH can be considered as a first step towards the Leptonic CP violation discovery!

Thank you!

Performance of Super-K at Higher Energies

We consider the existing and well understood Super-K detector with 22.5 kt fiducial

Pre-cut efficiencies for T2KK proposal

	Signal			Background	
True ν energy	ν_e (avg)	QE ν_e	non-QE ν_e	NC	ν_μ mis-ID
0 - 0.35 GeV	95%	94%	53%	0.4%	0.5%
0.35 - 0.85 GeV	87%	96%	49%	3%	0.4%
0.85 GeV - 1.5 GeV	70%	95%	43%	8%	0.3%
1.5 - 2.0 GeV	58%	91%	38%	11%	0.5%
2.0 - 3.0 GeV	51%	91%	35%	11%	0.8%
3.0 - 4.0 GeV	45%	90%	34%	12%	0.9%
4.0 - 5.0 GeV	43%	90%	33%	13%	1.0%
5.0 - 10.0 GeV	37%	86%	29%	10%	1.4%

F. Dufour etal., arXiv: 1001.5165

Estimated based on the criteria:

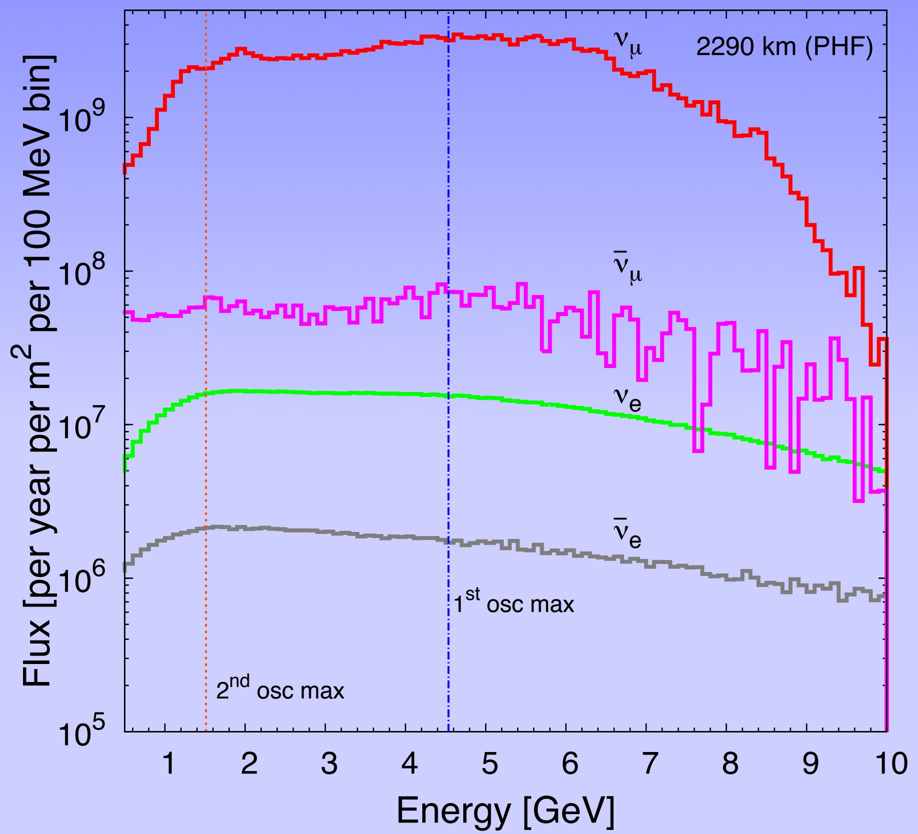
1) Events are fully contained in the fiducial volume!

2) Have a single Cerenkov ring recognized as electron-like!

3) No Michel electron present!

- We only consider charged current single ring events as our signal
- We only rely on total signal and background event rates
- No spectral information has been used
- For ν_e appearance: main NC background comes from Single-π^0 contamination
- We use the true neutrino energy window of 0.5 GeV to 10 GeV
- 90% NC background rejection (5 – 10 GeV)

Superbeam flux



A. Longhin, PoS ICHEP2010, 325 (2010)

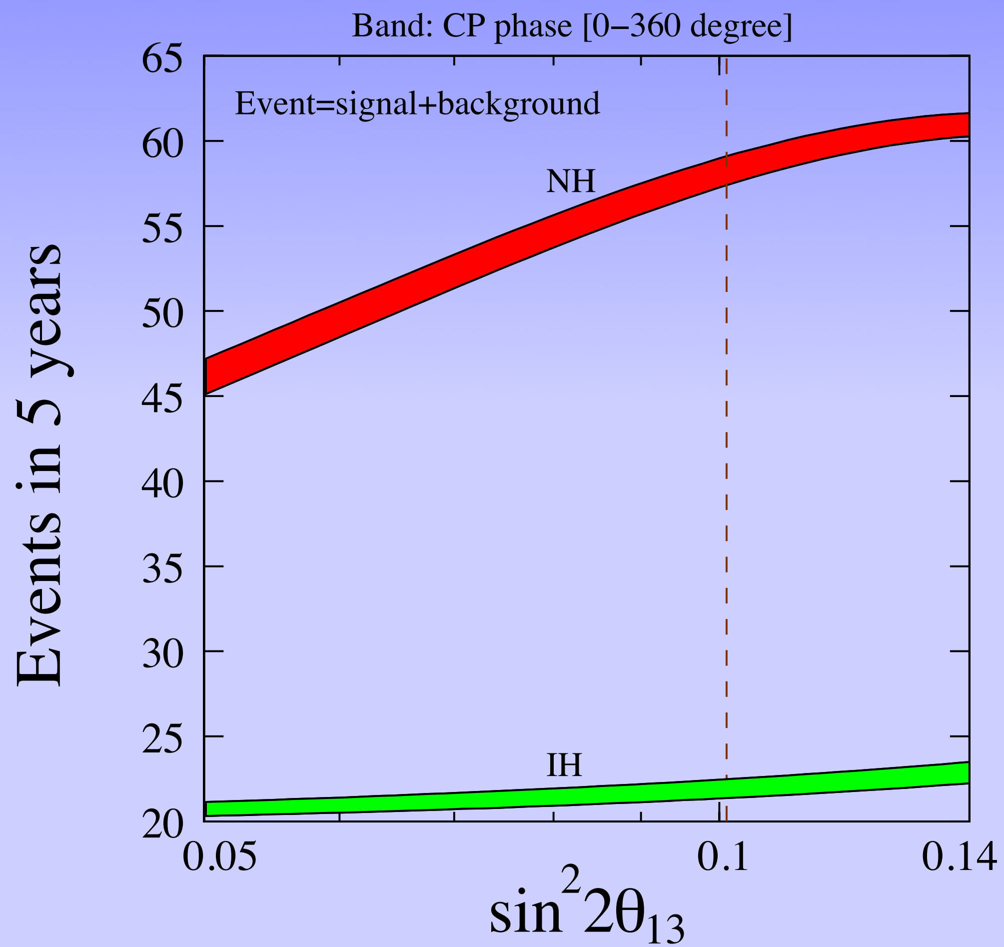
- *New high power accelerator (HP-PS2)*
- *50 GeV proton beam, power 1.6 MW*
- *3 × 10^{21} protons on target/yr (200 days/yr)*
- *@ flux level, 0.62% intrinsic ν_e contamination*

We can also use 400 GeV proton line from SPS towards a 0.7 - 1 MW target region!

Recent optimization suggests that we can have 1.5 × 10^{20} protons on target/year with 200 days/year!

We scale these fluxes to the longer L = 8770 km baseline, as L^{-2}

Signal and Background Event rates for CERN-Kamioka

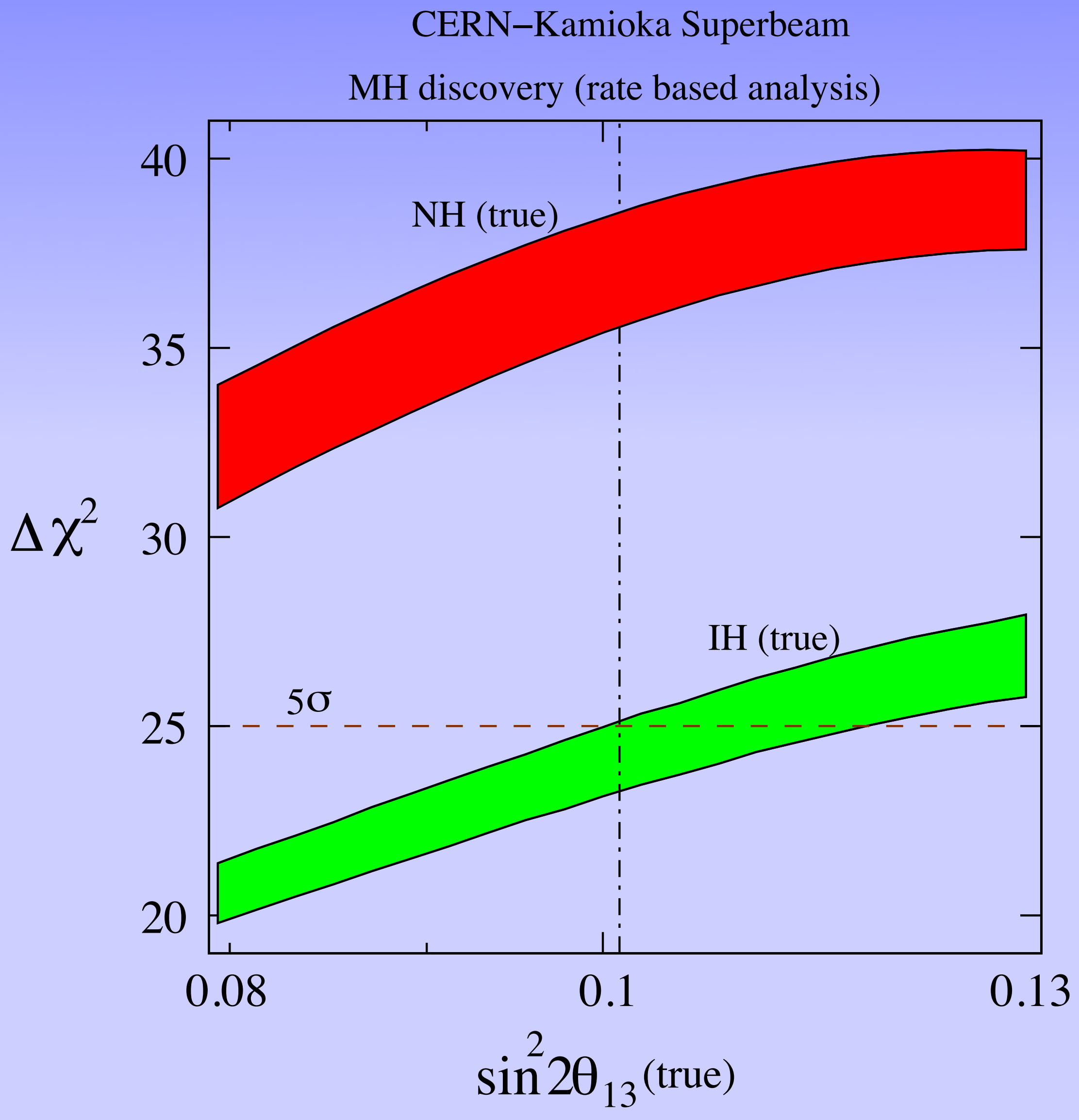


Channel	CERN-Kamioka (8870 km)	
	Signal	Background
	CC-1 ring	Int+Mis-id+NC = Total
$\nu_\mu \to \nu_e$ (NH)	**40**	1+2+16=**19**
$\nu_\mu \to \nu_e$ (IH)	**2**	1+3+16=**20**
$\nu_\mu \to \nu_\mu$ (NH)	**84**	**2**
$\nu_\mu \to \nu_\mu$ (IH)	**89**	**2**

Total exposure 5×10^{21} protons on target

This is for appearance channel!

Mass Hierarchy Discovery for different 1-3 mixing angle



Here we take total 5×10^{21} pot!