Complementarity of T2K/HK with Other Longer Baseline Experiments

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The purpose of this talk is to motivate to enforce the synergetic activities among the future long baseline (LBL) experiments.

The speaker is not a member of LBL experiments. Therefore, an objective view may be provided as a bystander.

The discussion is conceptual one and the used parameter values are rough. There might be errors or misunderstandings.

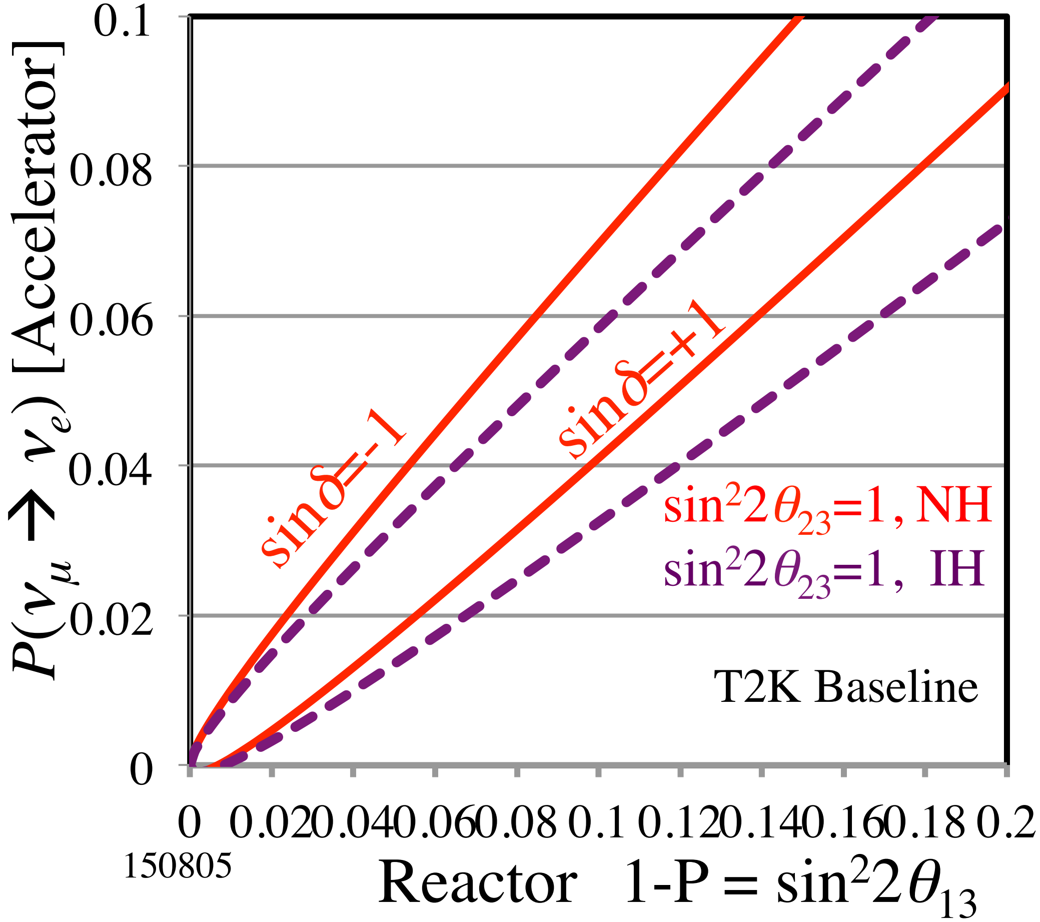
Flow of this talk

* ~~Purpose of this talk~~
* Example of a successful synergy
* $P(\nu_\mu \rightarrow \nu_e)$ and A_{CP} with matter effect
* Possible synergies
* Conclusion

An example of successful synergy:

The complementarity between Accelerator and Reactor

$$P\left(\nu_\mu \to \nu_e; \Phi_{31} = \pi/2\right) \sim \frac{\sin^2 2\theta_{13}}{2\left(1-\left(L/L_0\right)\right)^2} - 0.043\frac{\sin 2\theta_{13}}{1-\left(L/L_0\right)}\sin\delta$$



An example of successful synergy:

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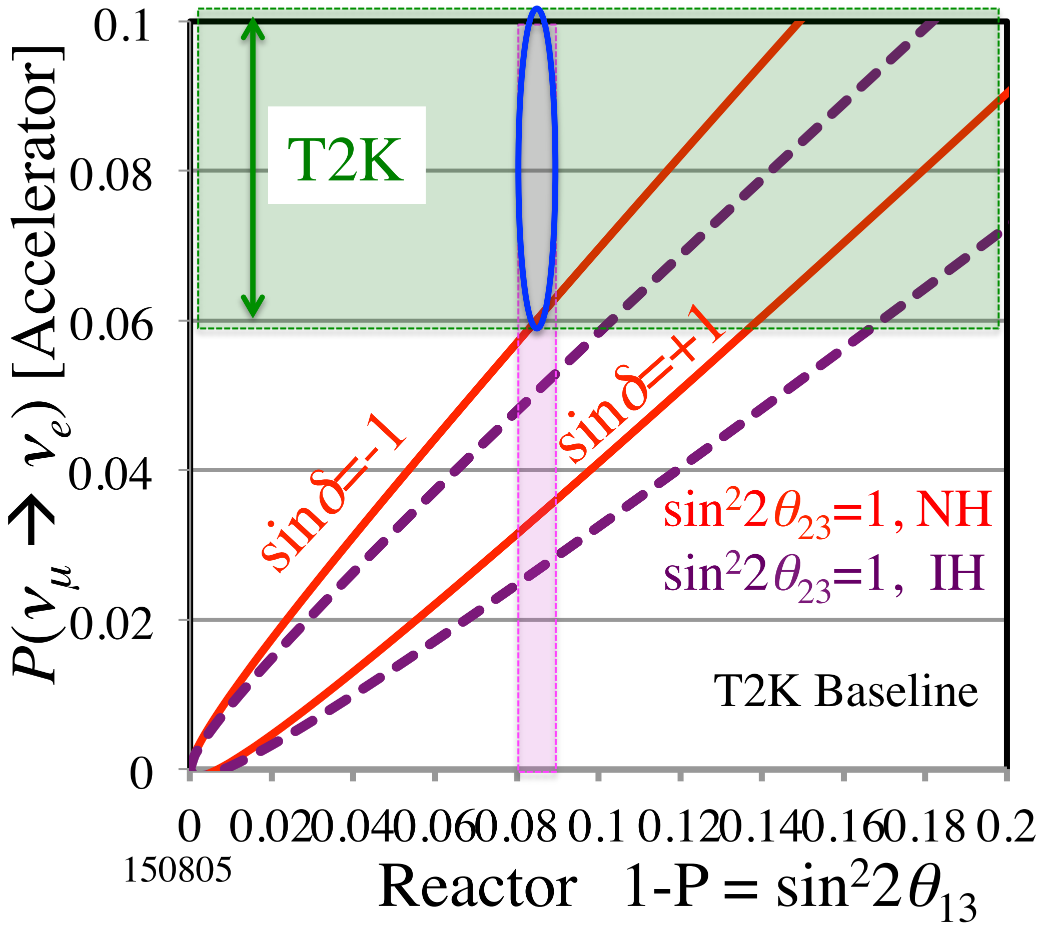
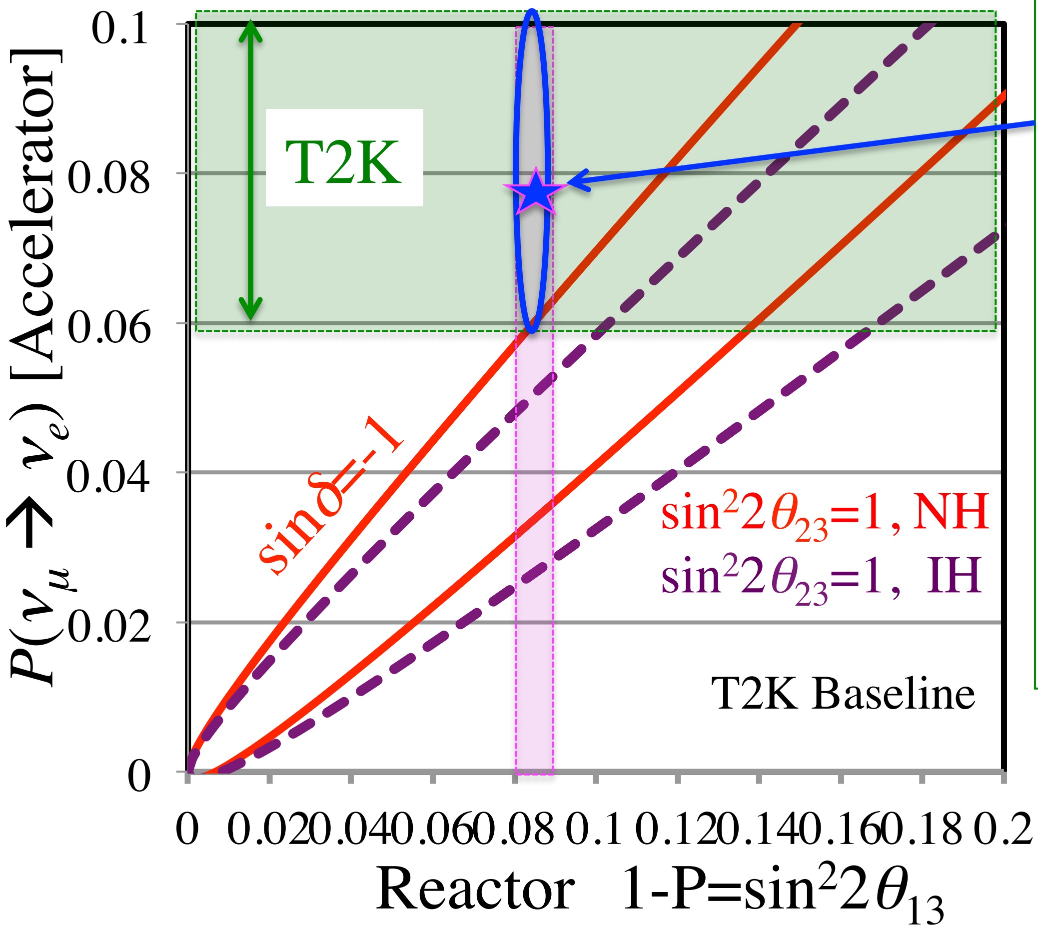


The synergy of Reactor and Accelerator has given us hints of large sinδ & Normal hierarchy,

An example of successful synergy:

The complementarity between Accelerator and Reactor

$$P_{31}\left(\nu_\mu \to \nu_e; \Phi_{31} = \pi/2\right) \sim \frac{\sin^2 2\theta_{13}}{2\left(1-\left(L/L_0\right)\right)^2} - 0.043\frac{\sin 2\theta_{13}}{1-\left(L/L_0\right)}\sin\delta$$



By the way ...
The center value is in the unphysical region now.
T2K: Please shrink the error.
Nova: What is your result?
Double Chooz will check the DB & RENO results soon with the near detector.

➔ Redundancy is important

CP Asymmetry

* Difference between $P\left(\nu_\alpha \to \nu_\beta\right)$ and $P\left(\bar{\nu}_\alpha \to \bar{\nu}_\beta\right)$

* Experimentally:

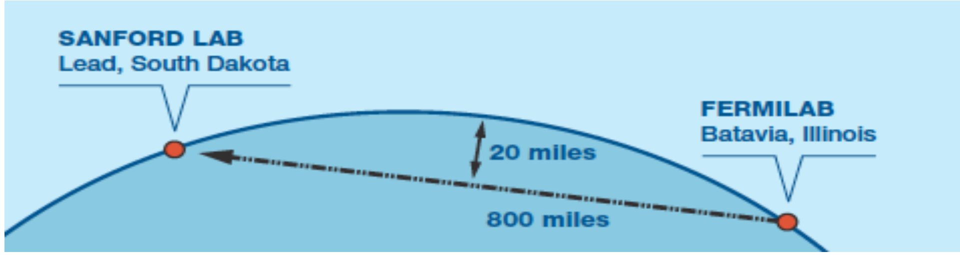
$$A_{CP}\left(@\Phi_{31} = \pi/2\right) = \frac{P\left(\nu_\mu \to \nu_e\right) - P\left(\bar{\nu}_\mu \to \bar{\nu}_e\right)}{P\left(\nu_\mu \to \nu_e\right) + P\left(\bar{\nu}_\mu \to \bar{\nu}_e\right)}$$

$$\sim -\left|\frac{\Delta m_{12}^2}{\Delta m_{31}^2}\right| \frac{\pi \sin 2\theta_{12}}{\tan\theta_{23} \sin 2\theta_{13}} \sin\delta \sim \underline{-0.29} \sin\delta$$

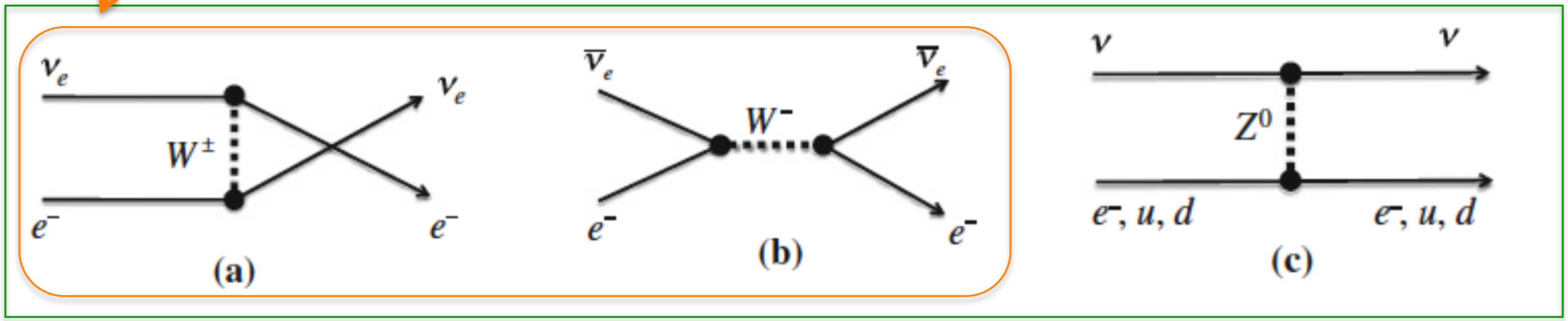
Thanks to the all experiments, this coefficients can be calculated now. (synergies!)

* However, the matter effect introduces a fake A_{CP}

Matter (MSW) Effect



Only ν_e and $\overline{\nu}_e$



Effective Weak Potential

$$V_W = 2\sqrt{2}E_\nu \frac{n_e G_F}{m_3^2 - m_1^2}$$

changes the coupling sign depending on ν or $\overline{\nu}$

changes sign depending on the mass hierarchy

Energy dependent

Baseline Dependence of the Matter Effect

At the oscillation maximum;

$$\Phi_{31} = \frac{|\Delta m_{31}^2| L}{4E_\nu} = \frac{\pi}{2}$$

the weak potential can be expressed by using the baseline *L*,

M.H.

$$V_W = \frac{2\sqrt{2}E_\nu G_F \bar{n}_e}{m_3^2 - m_1^2} = \pm \frac{L}{\pi / \sqrt{2}\, G_F \bar{n}_e} = \pm \frac{L}{L_0} \quad \nu / \bar{\nu}$$

Reference Baseline: $L_0 = \frac{\pi G_F}{\sqrt{2}} \frac{1}{L} \int_0^L n_e\, dl \sim \pm 5{,}500 km$

(ρ=3[g/cm^3])

	L[km]	V_W (=L/L_0)
T2K/HK	295	**±0.055**
NOVA	810	**±0.15**
LBNF	1,300	**±0.24**

Weak Potential & Oscillation Probability

Main effect of the weak potential on the oscillaion:

$$\sin\Phi_{31} \rightarrow \frac{\sin\left(1-V_W\right)\Phi_{31}}{1-V_W}$$

At oscillation maximum $\quad \sin\left(1-V_W\right)\frac{\pi}{2} \sim 1-\frac{\pi^2}{8}V_W^2 \sim 1$

Then, the appearance probability with the matter effect is,

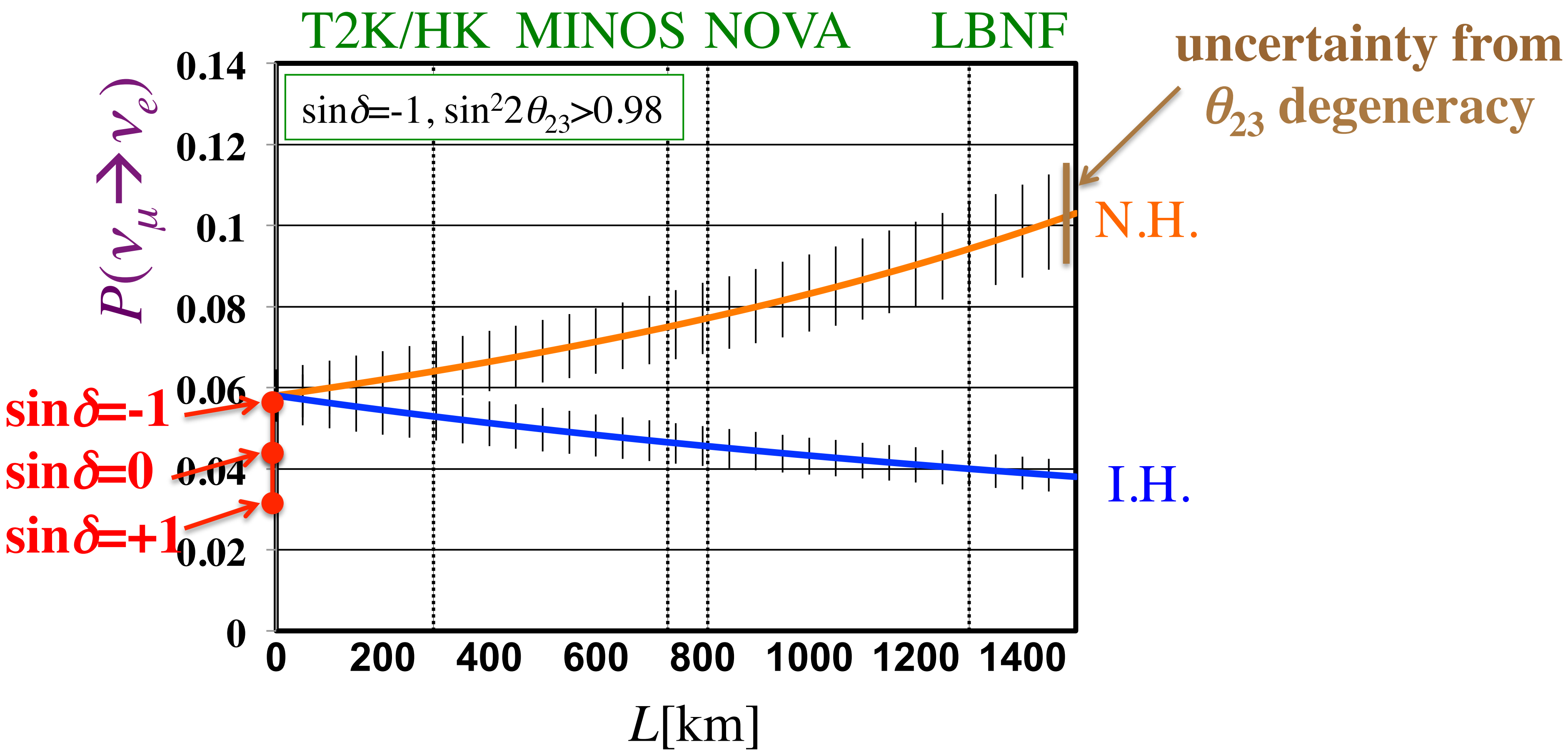
$$P\left(\nu_\mu \rightarrow \nu_e;@\Phi_{31}\right) \sim \frac{s_{23}^2\sin^2 2\theta_{13}}{\left(1-V_W\right)^2} \pm \frac{\pi}{2}\frac{\Delta m_{21}^2}{\Delta m_{31}^2}\frac{\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}}{\left(1-V_W\right)}\sin\delta$$

Oscillation probabilities for various cases

$$
\begin{cases}
P_{NH}\left(\nu_\mu \to \nu_e; @\Phi_{31}\right) \sim s_{23}^2 \dfrac{0.09}{\left(1 - L/|L_0|\right)^2} - \dfrac{0.013}{\left(1 - L/|L_0|\right)} \sin\delta \\
P_{IH}\left(\nu_\mu \to \nu_e; @\Phi_{31}\right) \sim s_{23}^2 \dfrac{0.09}{\left(1 + L/|L_0|\right)^2} - \dfrac{0.013}{\left(1 + L/|L_0|\right)} \sin\delta \\
P_{NH}\left(\bar{\nu}_\mu \to \bar{\nu}_e; @\Phi_{31}\right) \sim s_{23}^2 \dfrac{0.09}{\left(1 + L/|L_0|\right)^2} + \dfrac{0.013}{\left(1 + L/|L_0|\right)} \sin\delta \\
P_{IH}\left(\bar{\nu}_\mu \to \bar{\nu}_e; @\Phi_{31}\right) \sim s_{23}^2 \dfrac{0.09}{\left(1 - L/|L_0|\right)^2} + \dfrac{0.013}{\left(1 - L/|L_0|\right)} \sin\delta
\end{cases}
$$

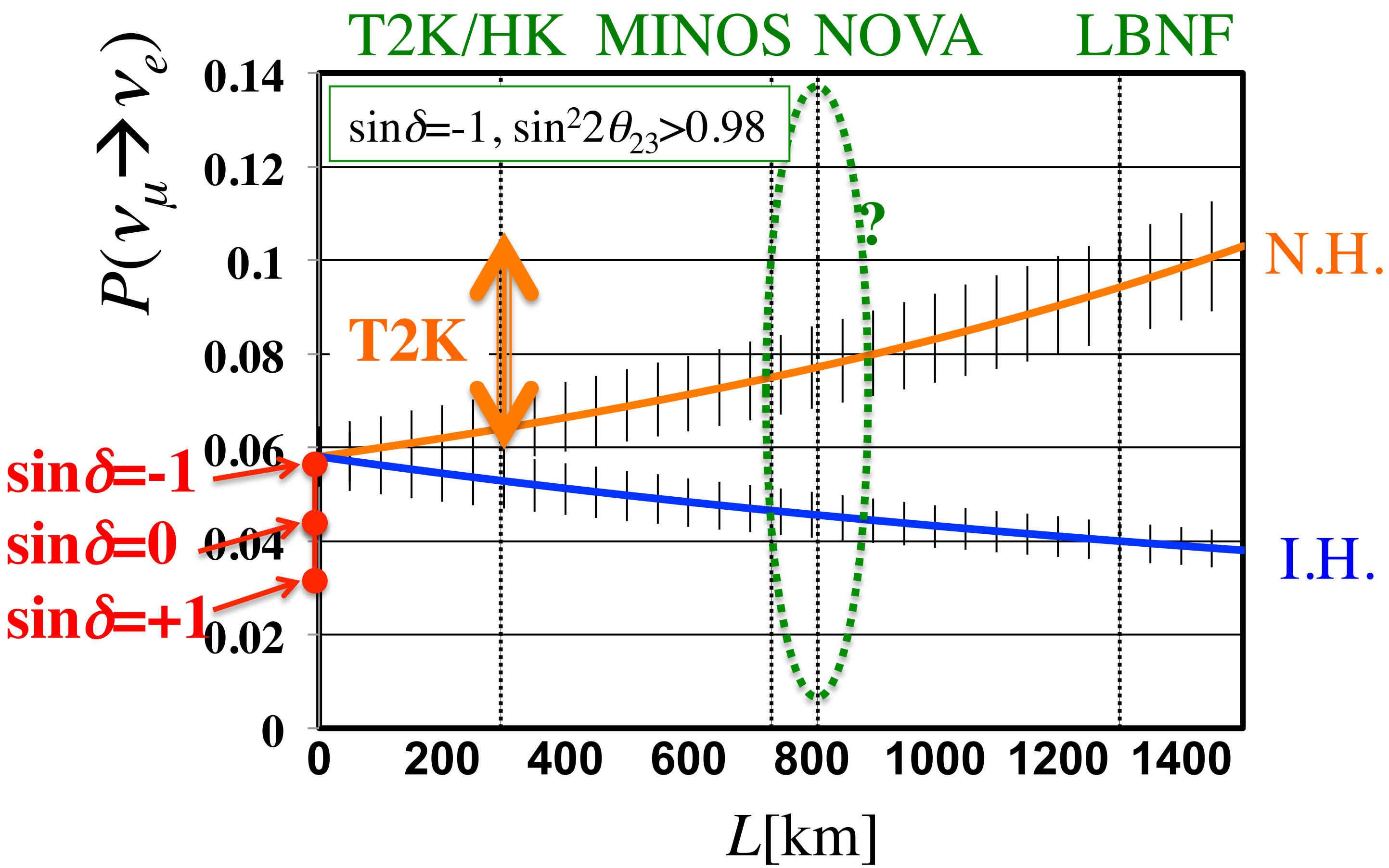
Baseline Dependence of ν_e Appearance Prob.

$$P\left(\nu_\mu \to \nu_e;@\Phi_{31}\right) \sim s_{23}^2 \frac{0.09}{\left(1 \pm L/\left|L_0\right|\right)^2} - \frac{0.013}{\left(1 \pm L/\left|L_0\right|\right)} \sin\delta$$



Baseline Dependence of ν_e Appearance Prob.

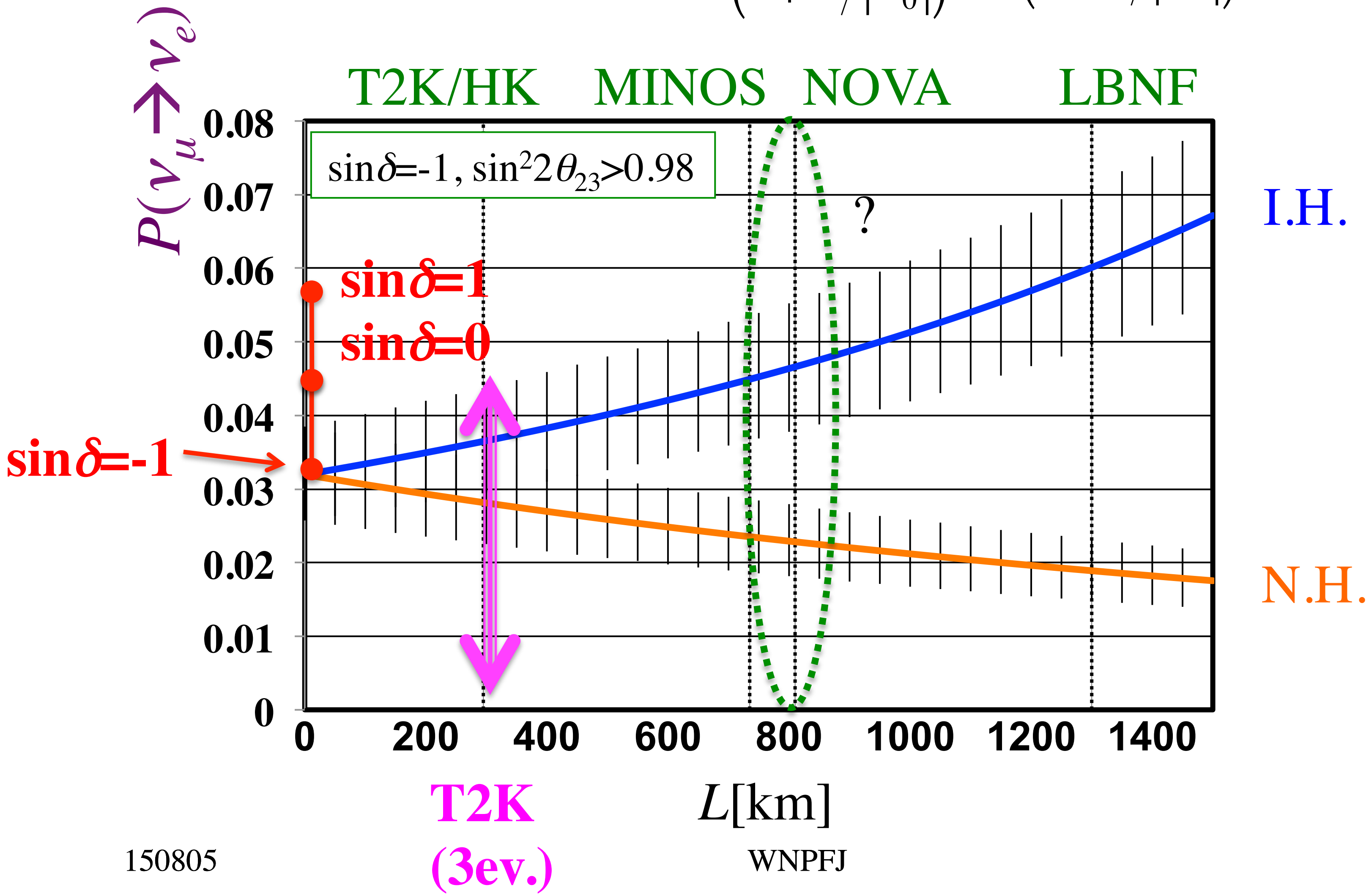
$$P\left(\nu_\mu \to \nu_e;@\Phi_{31}\right) \sim s_{23}^2 \frac{0.09}{\left(1 \pm L/|L_0|\right)^2} - \frac{0.013}{\left(1 \pm L/|L_0|\right)} \sin\delta$$



T2K+NOVA may enforce the hint on M.H. and sinδ or may give us tension.

Baseline Dependence of $\bar{\nu}_e$ Appearance Prob.

$$P\left(\bar{\nu}_\mu \to \bar{\nu}_e;@\Phi_{31}\right) \sim s_{23}^2 \frac{0.09}{\left(1 \mp L/|L_0|\right)^2} + \frac{0.013}{\left(1 \mp L/|L_0|\right)} \sin\delta$$



CP asymmetry with the matter effect

$$A_{CP}(@\Phi_{13}) = \frac{P-\overline{P}}{P+\overline{P}} \sim -\pi \left|\frac{\Delta m_{21}^2}{\Delta m_{31}^2}\right| \frac{\sin 2\theta_{12}}{t_{23}\sin 2\theta_{13}} \sin\delta_{CP} \pm 2\left(\frac{L}{L_0}\right)$$

$$\sim -0.29\sin\delta_{CP} \pm A_{FK}$$

fake CP asymmetry

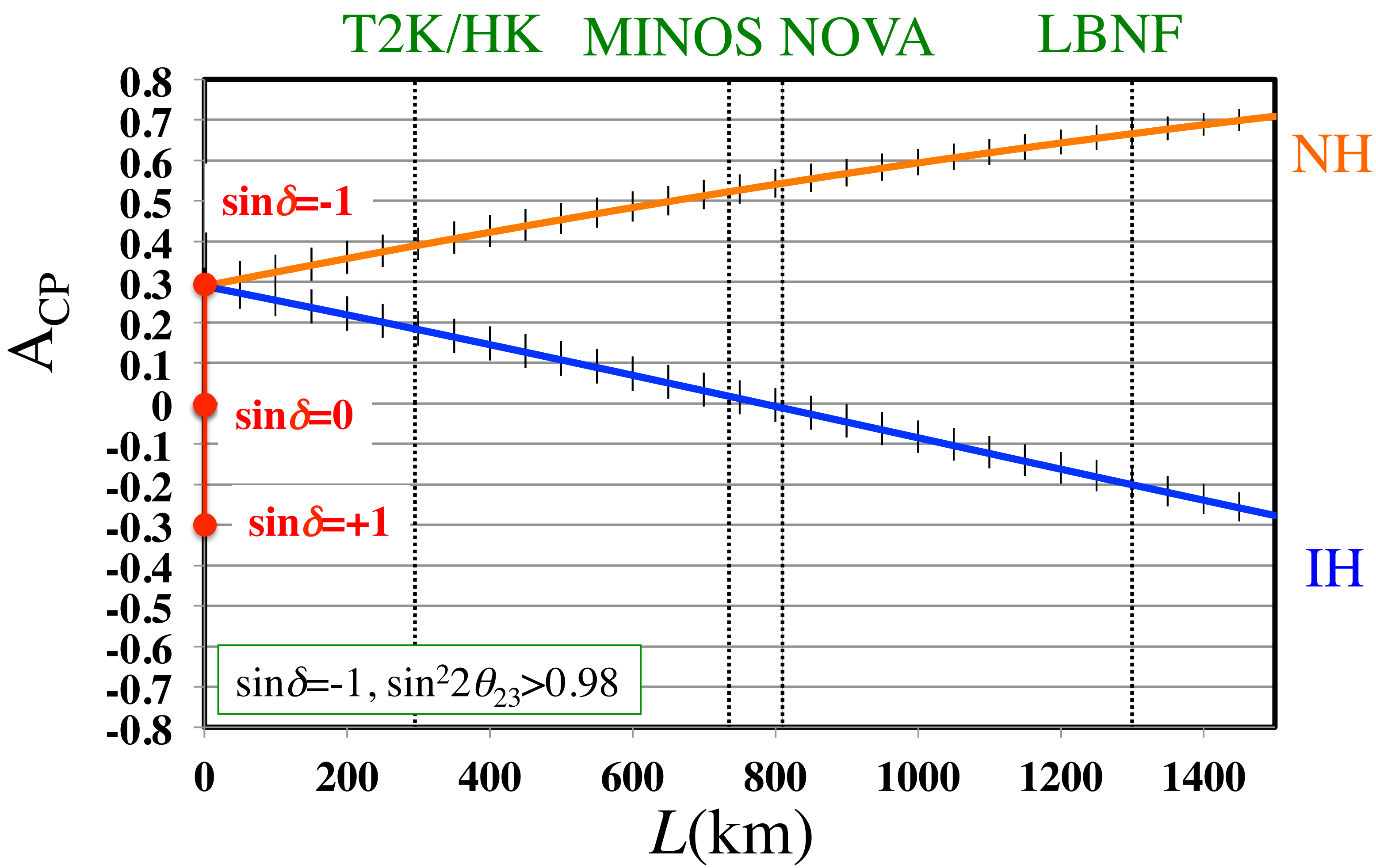
	L[km]	V_W	$A_{FK}=2(L/L_0)$
T2K/HK	295	±0.055	**±0.11**
Nova	810	±0.15	**±0.30**
LBNF	1,300	±0.24	**±0.48**

Error of the sinδ measurement

$$\delta(\sin\delta_{CP}) = 3.4\sqrt{(\delta A_{CP})^2 + \left(A_{FK}\left(\delta\overline{n}_e/\overline{n}_e\right)\right)^2}$$

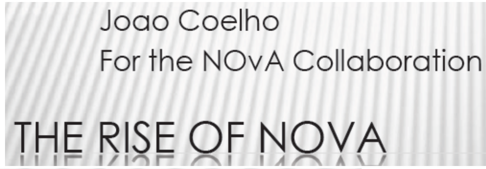
Baseline Dependence of CP asymmetry

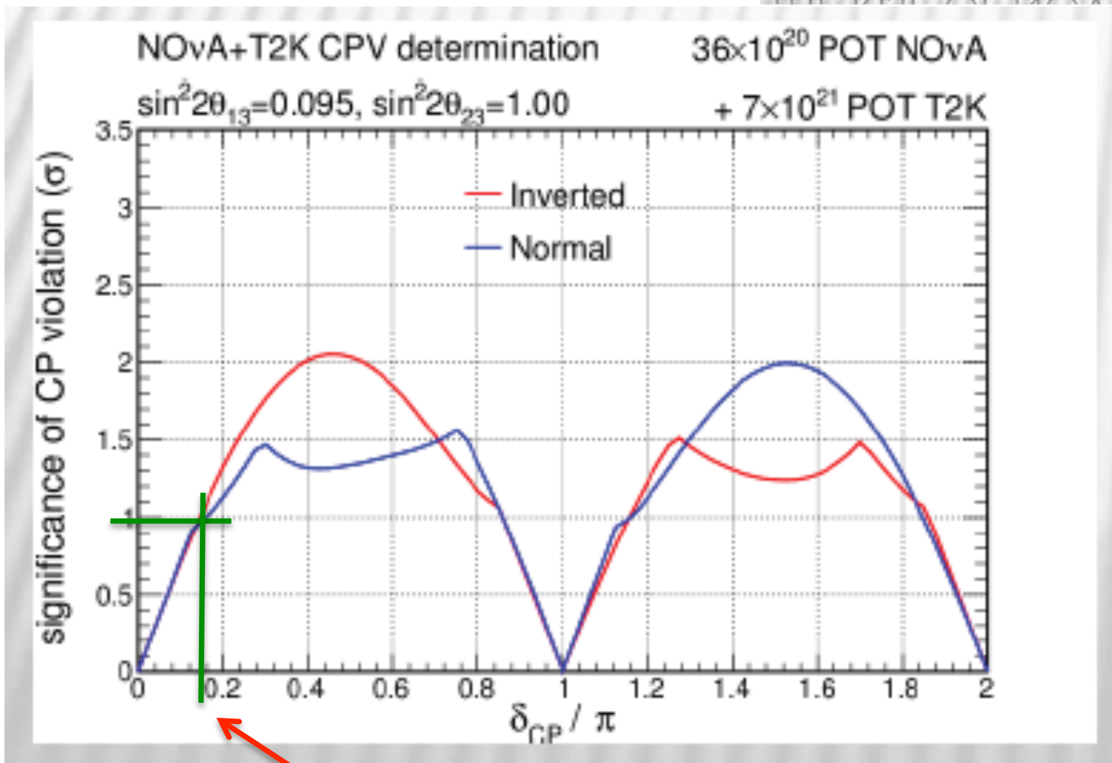
$$A_{CP} \sim -0.29 \sin\delta \pm 2\left(\frac{L}{L_0}\right)$$



Will evaluate the sensitivity by 3σ error of $\sin\delta_{CP}$ assuming $\delta_{CP}=0$.

NOVA + T2K

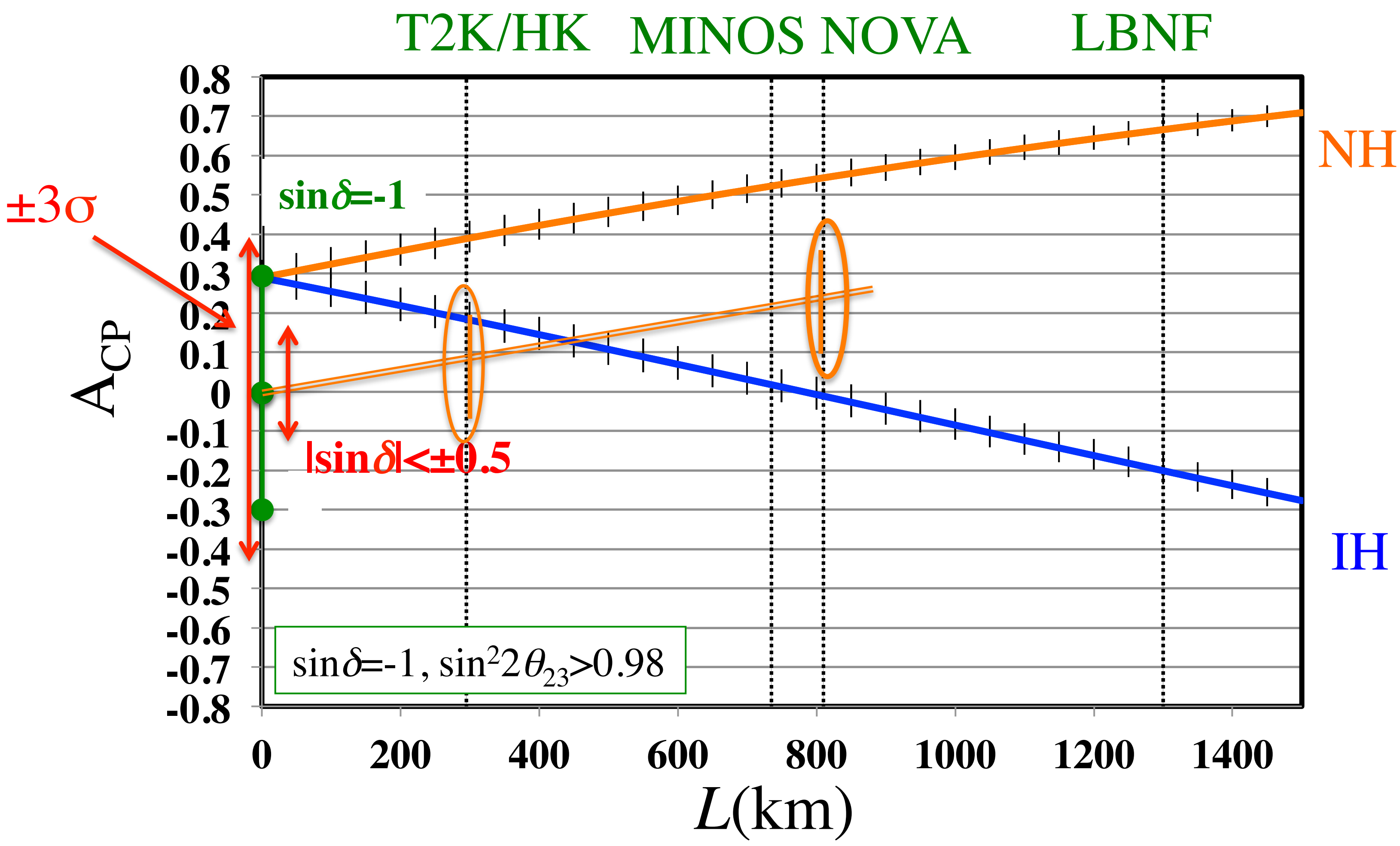




$\sigma_{\sin\delta} \sim 0.5$

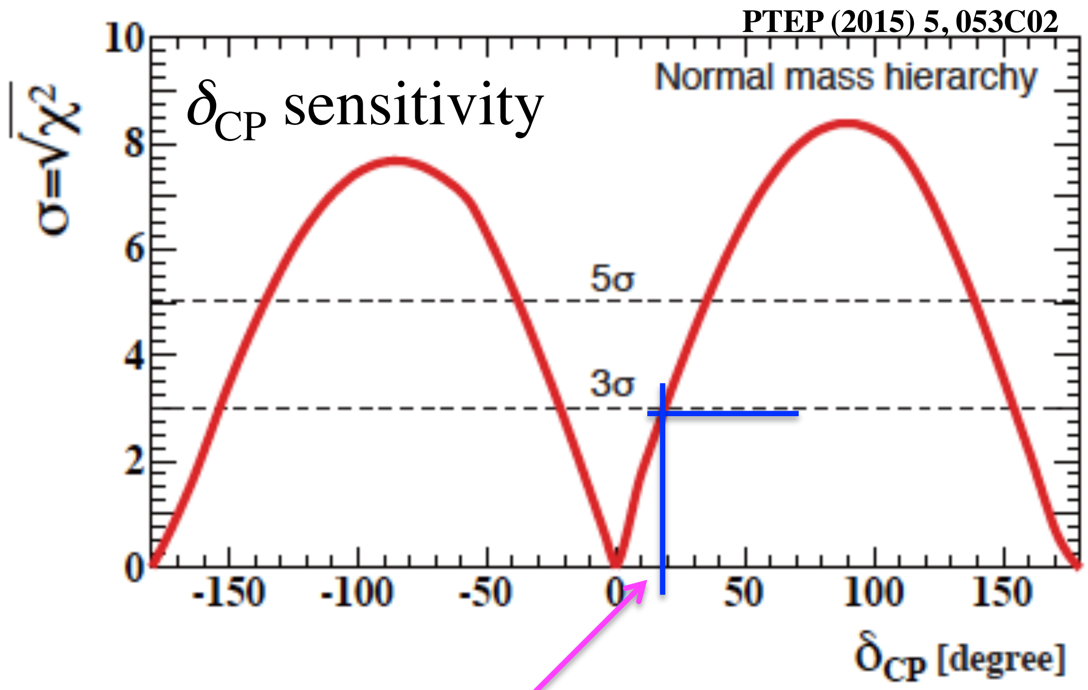
NOVA + T2K

$$A_{CP} \sim -0.29 \sin\delta \pm 2\left(L/L_0\right)$$



May be possible to limit δ_{CP} by 2σ but not 3σ.

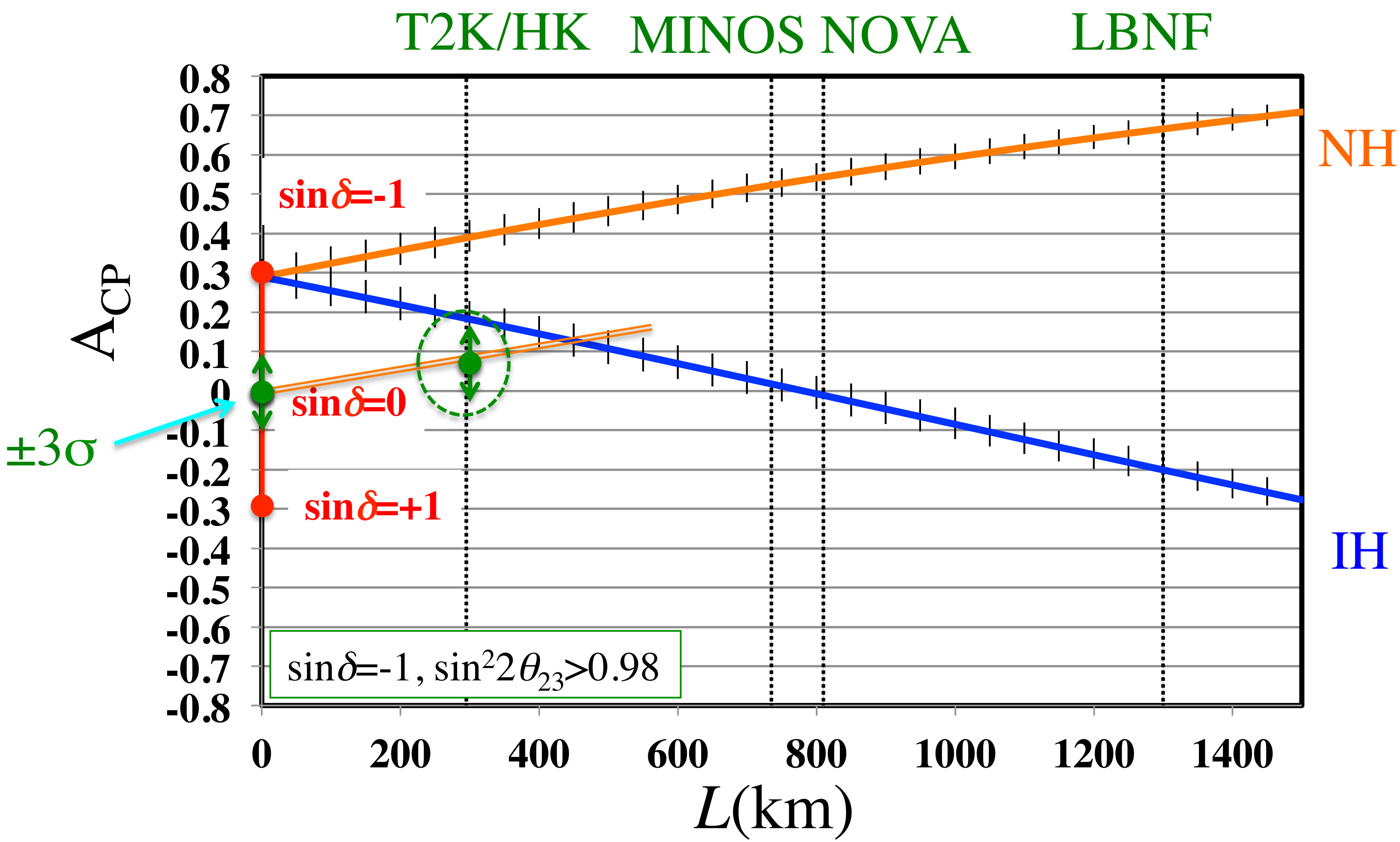
HK case



$3\sigma_{\sin\delta} \sim 0.33$

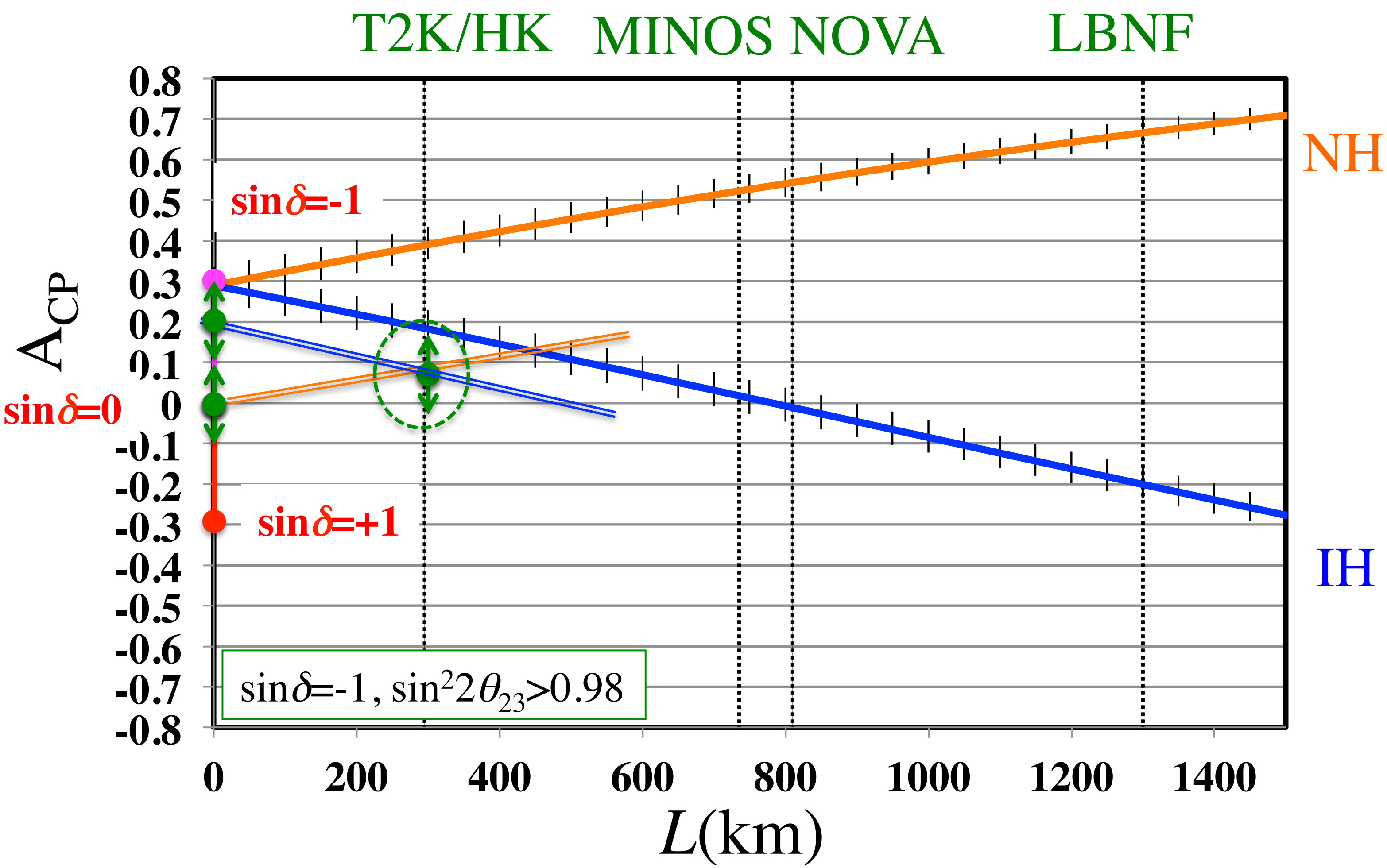
HK case

If sinδ=0 & N.H. and HK measured the expected value.



If M.H. is known, |sinδ|<0.33(3σ) can be obtained.

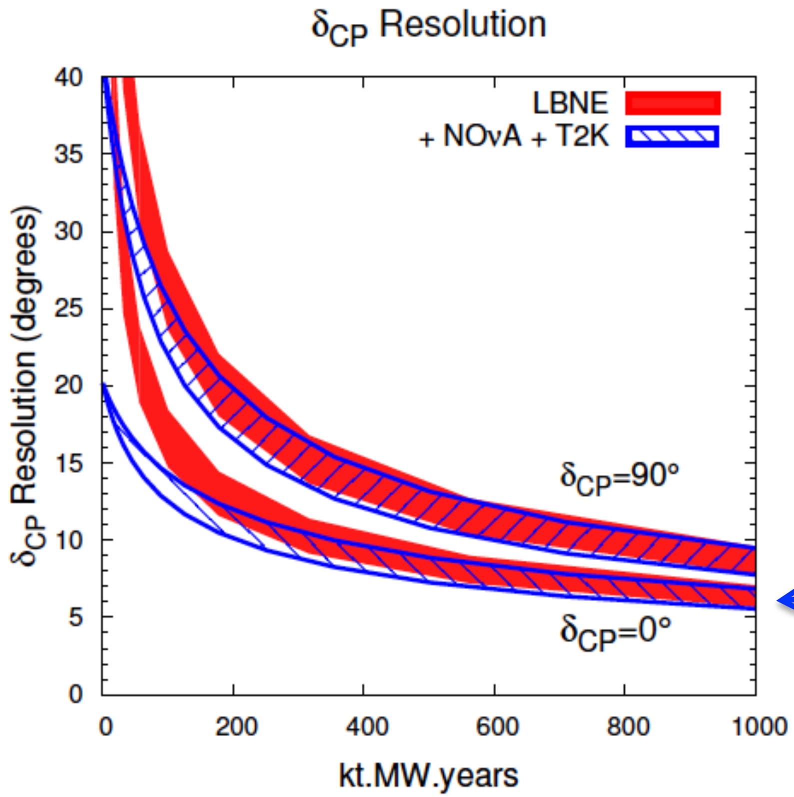
HK case



If M.H. is not known, there are two solutions.
sinδ=0 can not be confirmed. ➔ M.H. is necessary.

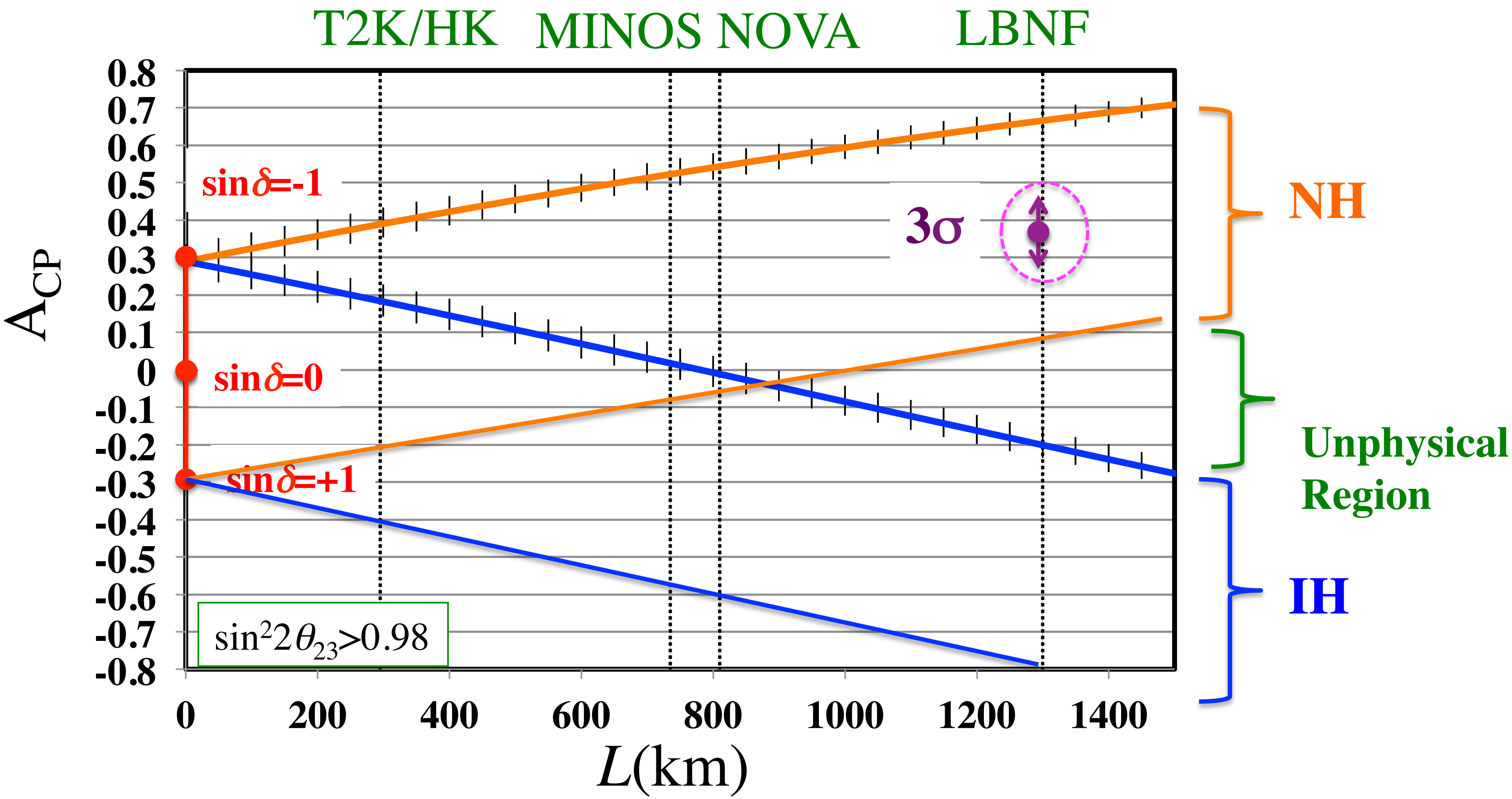
LBNF case

arXive: 1307.7335



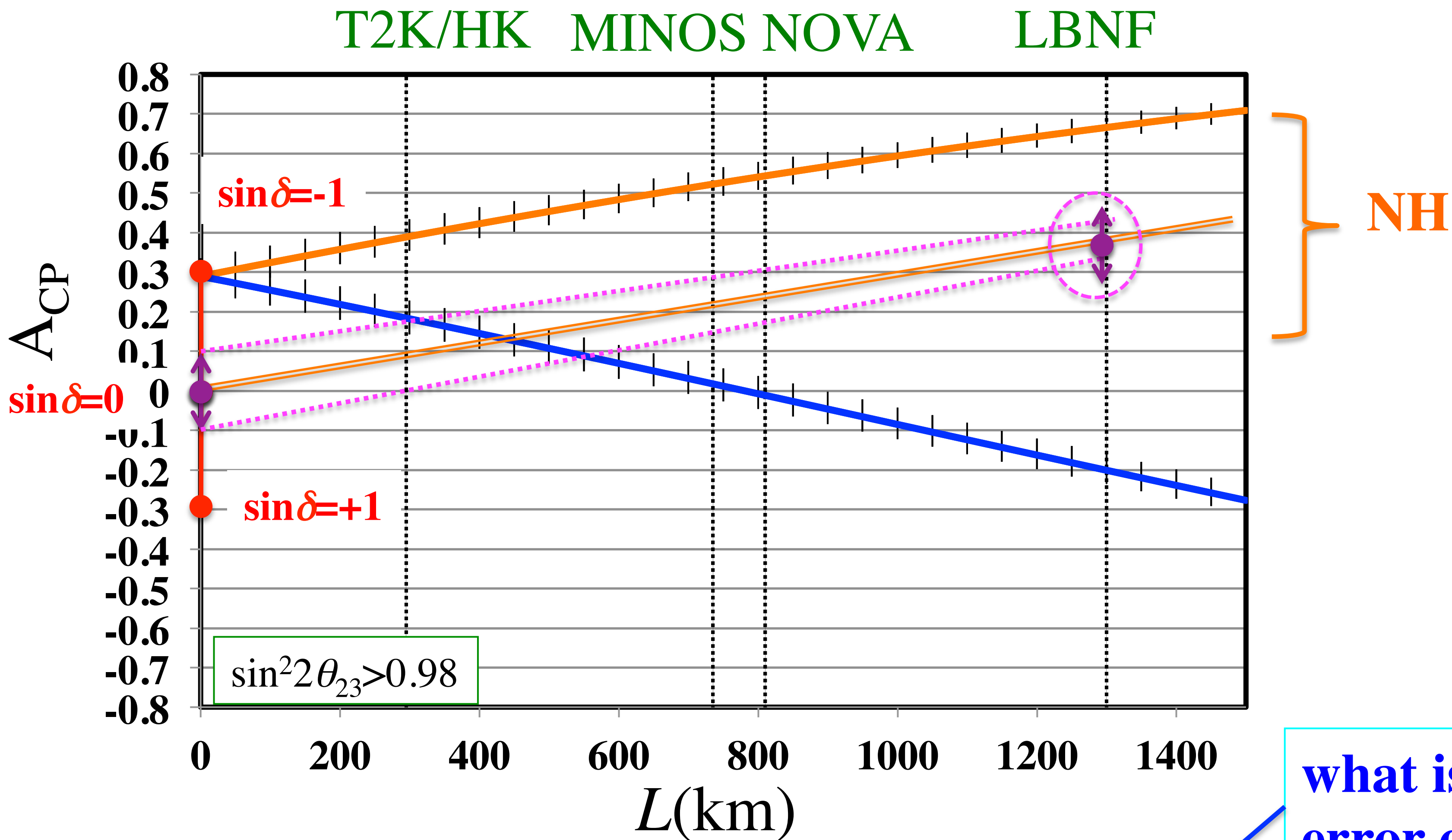
$3\sigma_{\sin\delta} \sim 0.3$

LBNF case



This case, M.H. is determined to be N.H.

LBNF case



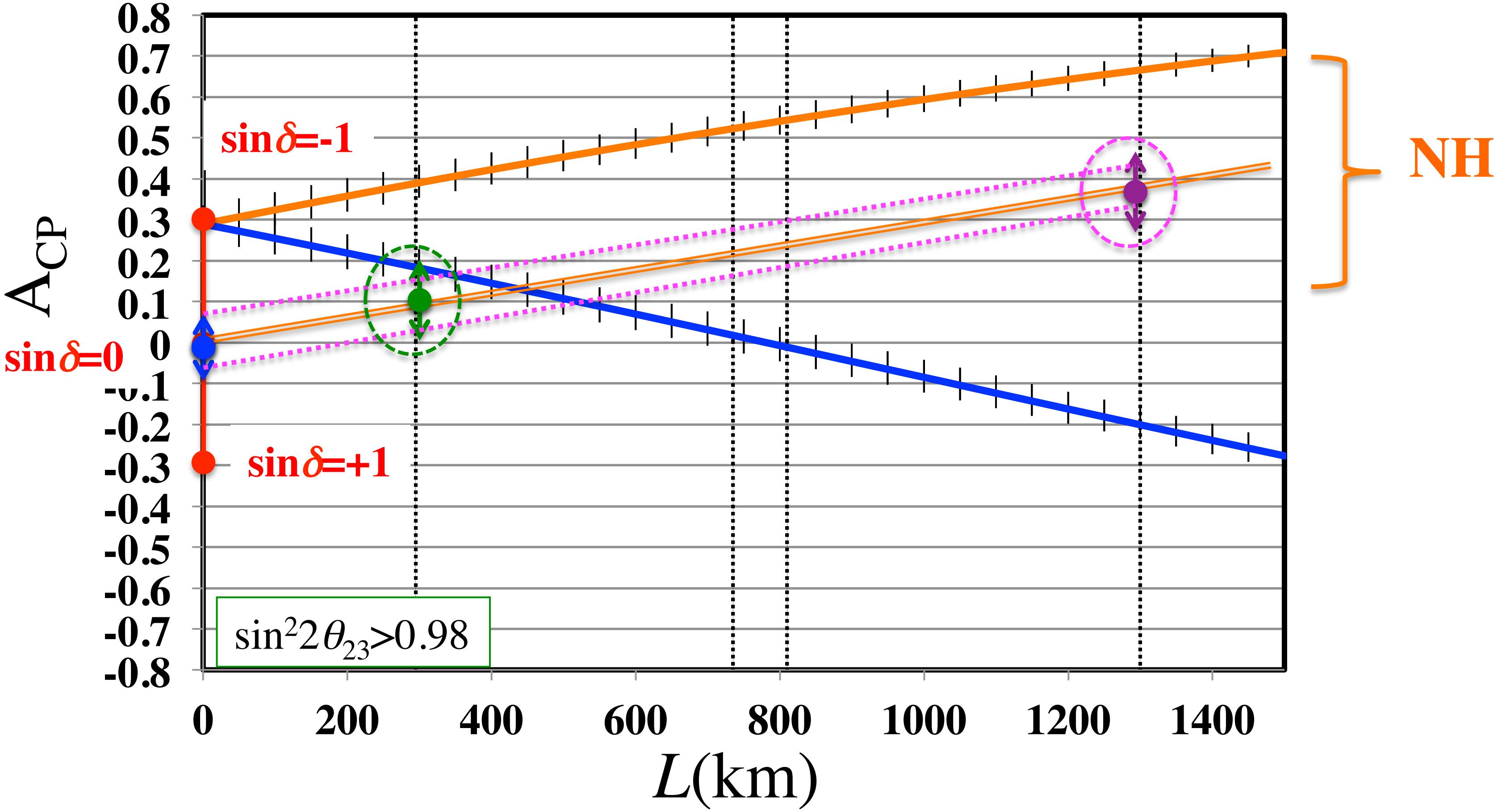
Then extrapolate to *L*=0 to obtain sinδ_{CP}.

$$\delta(\sin\delta_{CP}) = 3.4\sqrt{(\delta A_{CP})^2 + \left(A_{FK}\left(\delta\bar{n}_e/\bar{n}_e\right)\right)^2}$$

what is the error of the average density?

HK+LBNF case

Improvement of sinδ accuracy



* δsinδ_{HK}=0.1 & δsinδ_{LB}=0.1

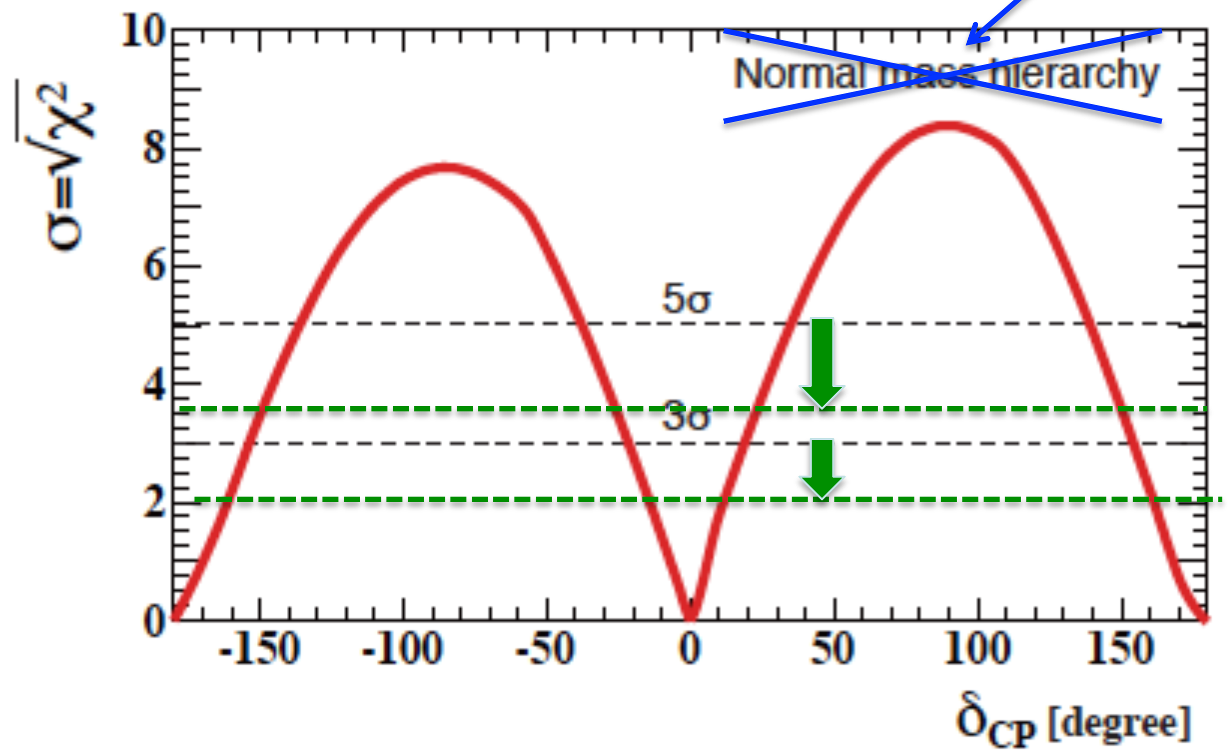
→ δsinδ_{HK+LB}=0.071?? (common error?)

HK+LBNF case

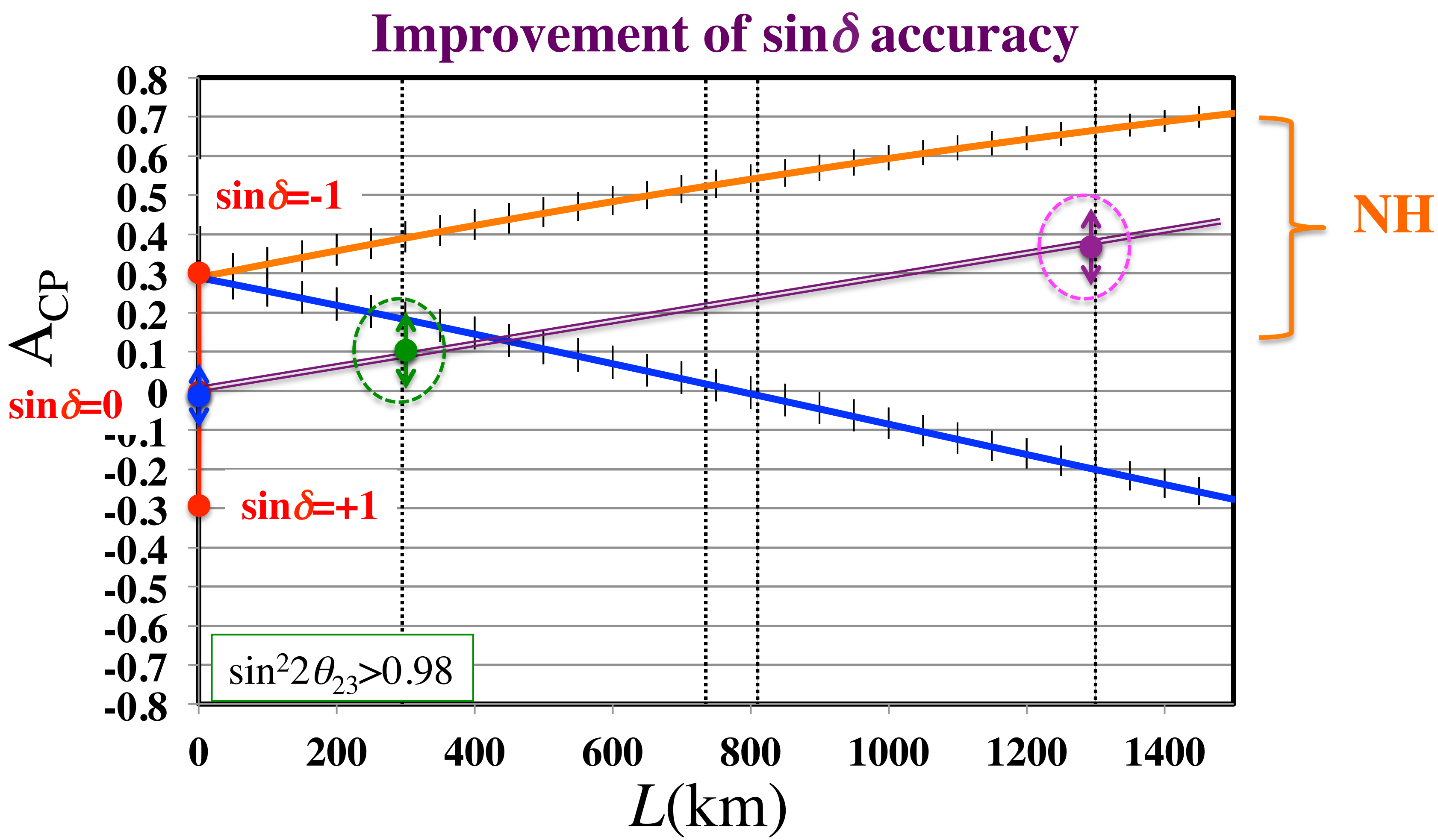
If $\delta\sin\delta_{CP}$~0.1 ➔ $\delta\sin\delta_{CP}$~0.1/√2 by combining with LBNF

Need not this proviso

δ_{CP} sensitivity



HK+LBNF case

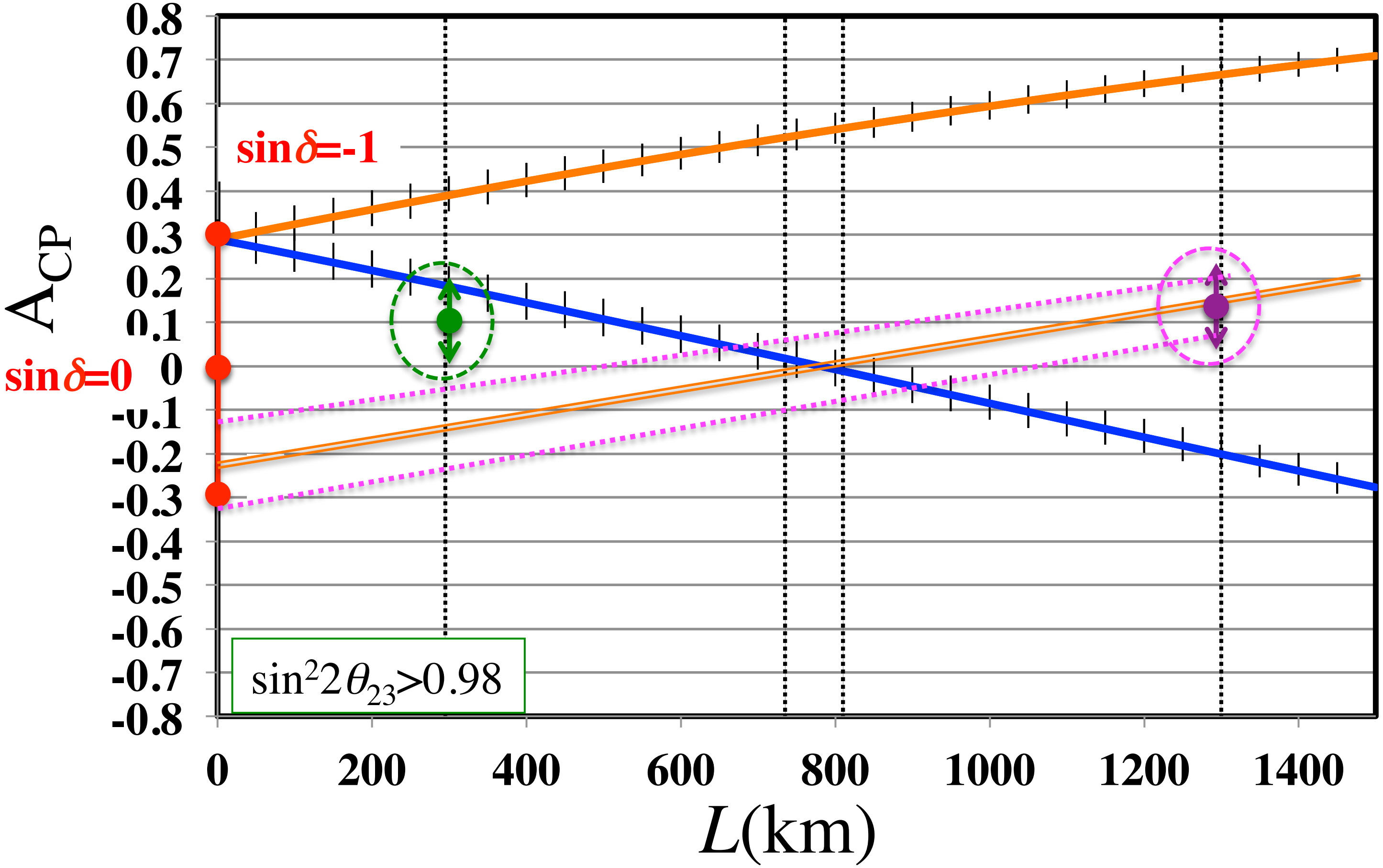


* **MSW error independent analysis is possible.**

$$\sin\delta = 3.4\,\frac{L_{HK}A_{LB} - L_{LB}A_{HK}}{L_{LB} - L_{HK}}$$

HK+LBNF case

Strict test of the standard neutrino scheme and MSW effect.



This indicates a new physics or failure of the standard MSW

Energy dependence of the oscillation

$$\sin\left(1 - V_W\right)\Phi_{31} = \sin\left(\Phi_{31} - \frac{n_e G_F}{\sqrt{2}} L\right)$$

Constant phase shift ($\Delta\Phi$) at given L

	L[km]	V_W	$2(L/L_0)$	**$\Delta\Phi$[rad]**
T2K/HK	295	±0.055	±0.11	**±0.086**
NOVA	810	±0.15	±0.30	**±0.24**
LBNF	1300	±0.24	±0.48	**±0.38**

$$\Delta\Phi_{LB} - \Delta\Phi_{HK} = \frac{G_F}{\sqrt{2}}\left(\bar{n}_e^{LB} L_{LB} - \bar{n}_e^{HK} L_{HK}\right) \sim 0.29?$$

Strong test of MSW with the same osc. mode.

Any merit compared with using Φ_{31} from the ν_μ disappearance?

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On the complementarity of Hyper-K and LBNF

- **Enhance the sensitivity of CPV**
- **Solving θ_{23} degeneracy**
- **Improve precision of oscillation parameters. (not only δ_{CP} ..)**
- **Search for non standard phenomena: different L and E**
- **Nucleon decay: different channel**
- **Supernova: flavor separated measurements**

:

The last sentence of this report.

> The benefit that will accrue from the parallel implementation of these complementary experiments should be quantified at an early stage.

➔ **A concrete benifit: Proposals will become stronger ....**

Conclusion

Be Bosons;

$$|1+1|^2=4,$$

Rather Incoherence;

$$|1|^2+|1|^2=2,$$

No Fermions;

$$|1-1|^2 = 0.$$