Performance on CPV and MH of near future accelerator projects

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Many material in this talk is produced by MINOS+, NOvA and T2K collaboration.

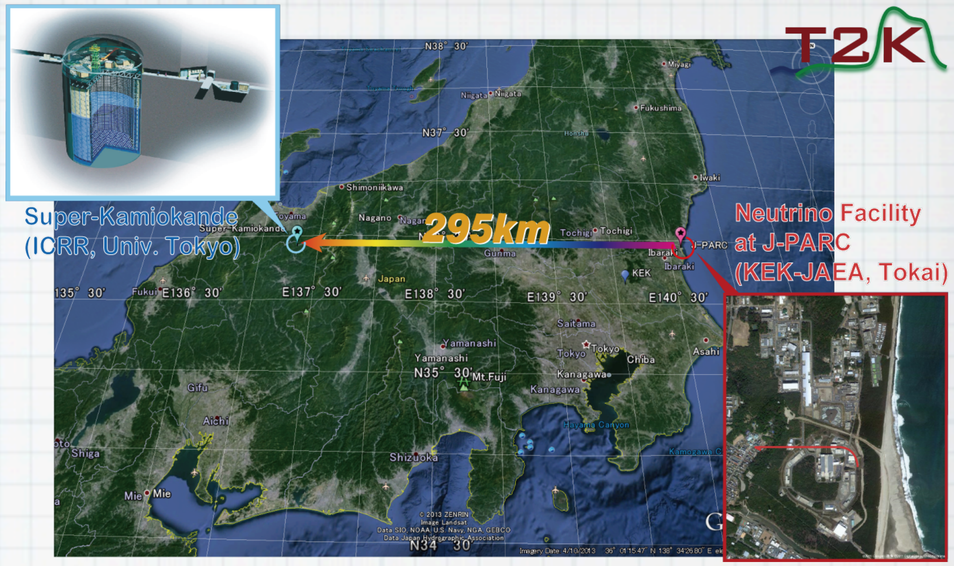
Outline

* Current situation on ν oscillation parameter measurements.
* Overview of current and near future LBL ν-experiments by "super-beam".
* How to address MH & CPV by "running" LBL experiments?
* Prospects for MH & CPV.

Current situation

* T2K: Electron neutrino appearance is "discovered".
* θ_{13} is well measured by Reactor experiments: Daya Bay, Double CHOOZ, RENO.
* Precision measurement of θ_{13} is on-going.
* NOνA and MINOS+ are about to start.
  * Further precise measurements of $P(\nu_\mu \rightarrow \nu_\mu)$ & $P(\nu_\mu \rightarrow \nu_e)$ are expected.
* Next target: Mass Hierarchy and CPV in neutrino

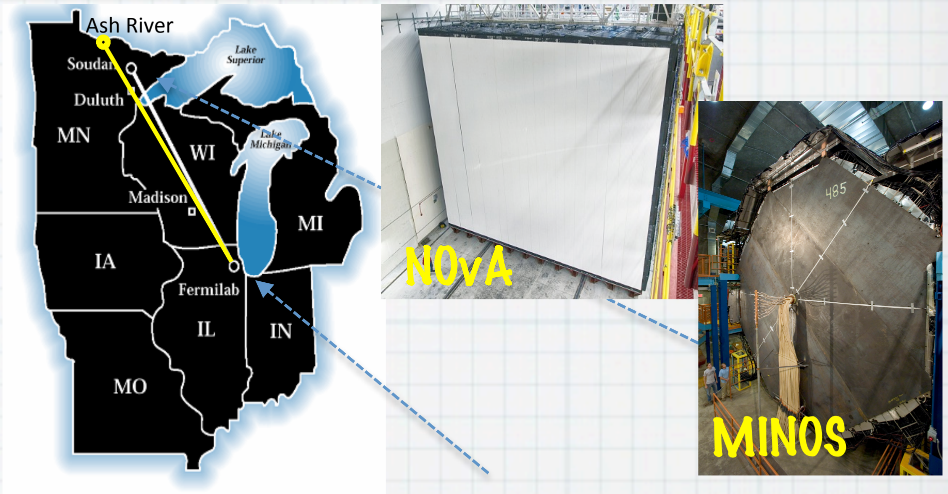
T2K

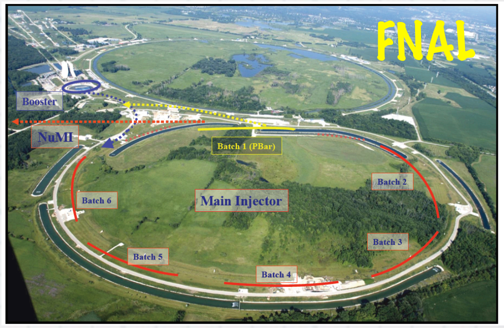


- J-PARC Neutrino beam
  + Super Kamiokande
  (Water cherenkov : fiducial mass = 22.5kt) : L=295km
  - Beam power: 220kW(now)→750kW(design)
  - Latest report : Observation of ν_e appearance (7.5σ).
    - Expected # of $\nu_\mu \to \nu_e$ oscillation assuming $\sin^2 2\theta_{13}=0.1, \delta_{CP}=0$ is 16.4 for 6.39×10^{20} POT
      → ~193 events for T2K proposed POT
      (750kW×5 years ~7.8×10^{21})
      => Statistical error is ~14% at full POT.
    - Systematic uncertainty in current analysis is ~10%.
  - Expected precision of θ_{23} measurement: $\delta(\sin^2 2\theta_{23})\sim0.01$

NOνA & MINOS+

* NOνA: Upgraded FNAL-NuMI (700kW)
  + 14kt liquid scintillator
  @ Ash Liver: L=810km
    * Expected # of events assuming
      $\sin^2 2\theta_{13}=0.095, \delta_{CP}=0$ for
      6.39×10^{20} POT
      (3 years for ν beam
      and 3 years for $\bar{\nu}$ beam)

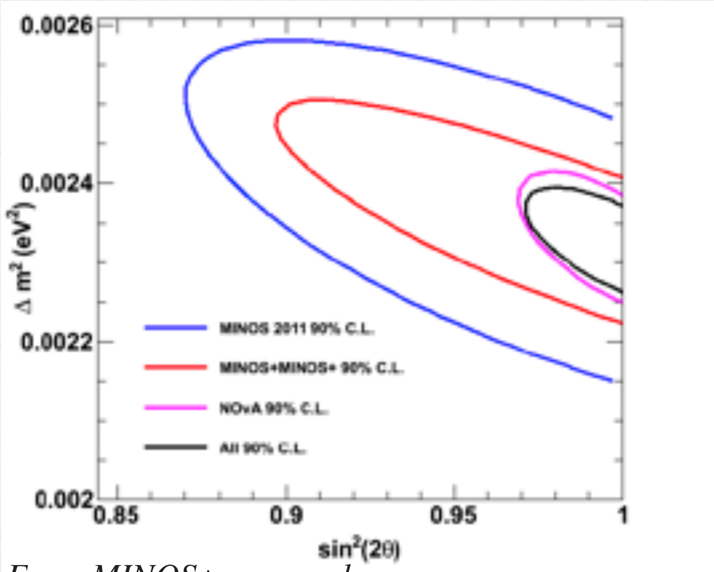




by NOvA collaboration *3 yr + 3 yr*

beam = ν		$\bar{\nu}$
NC	19	10
ν_μ CC	5	<1
ν_e CC	8	5
tot. BG	32	15
$\nu_\mu \to \nu_e$	68	32

* MINOS+: MINOS with upgraded FNAL-NuMI (700kW): L=735km
    * Improved θ_{23} measurement
* NOνA and MINOS+ are about to start operation in 2013.



From MINOS+ proposal

Key observables in “current” LBL experiments

* Possible observable oscillation-mode by “super-beam”.
  * $P(\nu_\mu \to \nu_\mu)$ & $P(\nu_\mu \to \nu_e)$: Includes CPV term + matter effect

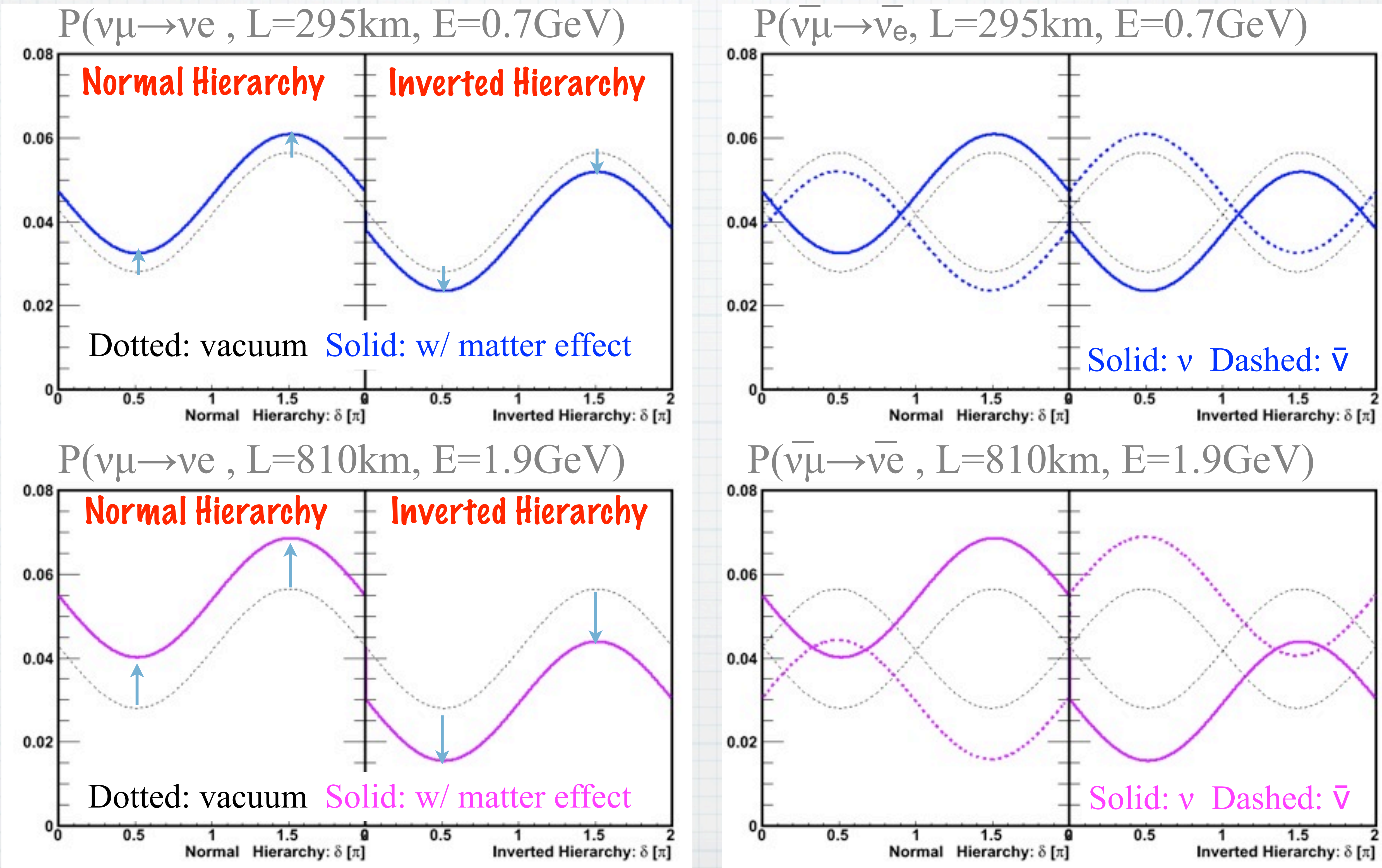
$$P(\nu_\mu \to \nu_\mu) \simeq 1 - (\underbrace{\cos^2\theta_{13}\sin^2 2\theta_{23}}_{\text{Leading}} + \underbrace{\sin^2\theta_{23}\sin^2 2\theta_{13}}_{\text{Next-to-leading}})\left(\sin^2\frac{\Delta m^2_{31}L}{4E}\right) + \dots$$

$$\begin{aligned}P(\nu_\mu \to \nu_e) = & \; 4\cos^2\theta_{13}\sin^2\theta_{13}\sin^2\theta_{23}\sin^2\frac{\Delta m^2_{31}L}{4E} \times \left[1 + \frac{2a}{\Delta m^2_{31}}(1 - 2\sin^2\theta_{13})\right] \\ & + 8\cos^2\theta_{13}\sin\theta_{12}\sin\theta_{13}\sin\theta_{23}(\cos\theta_{12}\cos\theta_{23}\cos\delta - \sin\theta_{12}\sin\theta_{13}\sin\theta_{23}) \\ & \qquad \times \cos\frac{\Delta m^2_{32}L}{4E}\sin\frac{\Delta m^2_{31}L}{4E}\sin\frac{\Delta m^2_{21}L}{4E} \\ & - 8\cos^2\theta_{13}\sin^2\theta_{13}\sin^2\theta_{23}\cos\frac{\Delta m^2_{32}L}{4E}\sin\frac{\Delta m^2_{31}L}{4E}\frac{aL}{4E}(1 - 2\sin^2\theta_{13}) \\ & - 8\cos^2\theta_{13}\cos\theta_{12}\cos\theta_{23}\sin\theta_{12}\sin\theta_{13}\sin\theta_{23}\sin\delta\sin\frac{\Delta m^2_{32}L}{4E}\sin\frac{\Delta m^2_{31}L}{4E}\sin\frac{\Delta m^2_{21}L}{4E} \\ & + 4\sin^2\theta_{12}\cos^2\theta_{13}\{\cos^2\theta_{12}\cos^2\theta_{23} + \sin^2\theta_{12}\sin^2\theta_{23}\sin^2\theta_{13} \\ & \qquad - 2\cos\theta_{12}\cos^2\theta_{23}\sin\theta_{12}\sin\theta_{23}\sin^2\theta_{13}\cos\delta\}\sin^2\frac{\Delta m^2_{21}L}{4E}\end{aligned}$$

  * $P(\bar{\nu}_\mu \to \bar{\nu}_\mu)$ & $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ if the data accumulated with $\bar{\nu}$-mode beam.
    * There are two experiments with different base-line length. (T2K & NOνA, MINOS+)

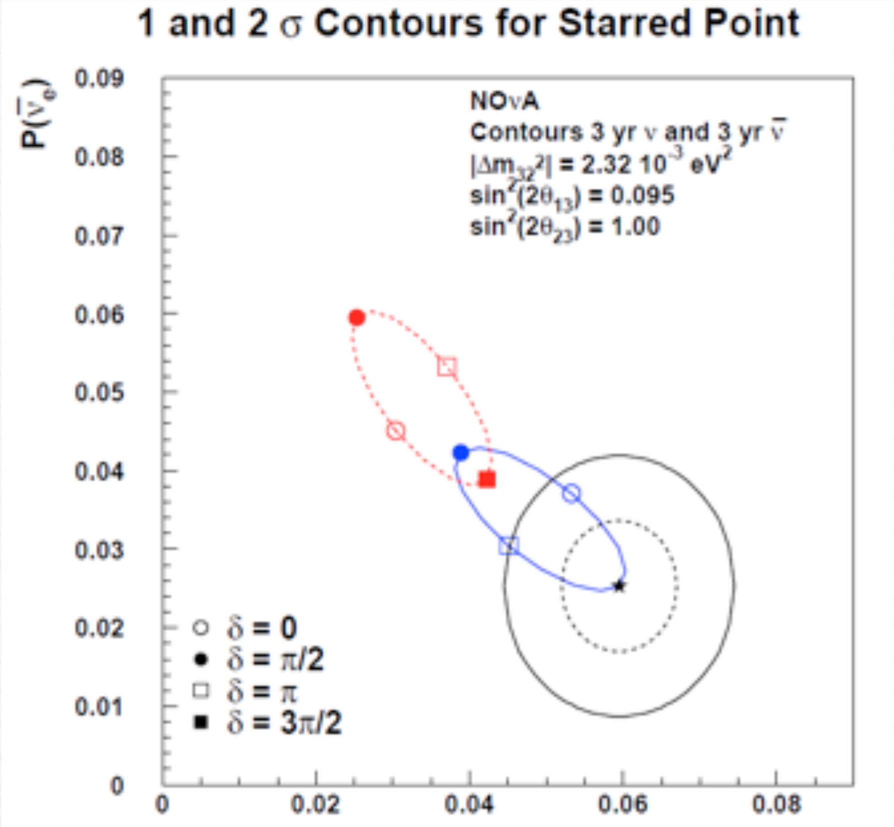
MH & CPV in P($\nu_\mu \rightarrow \nu_e$)

* Only picking up the maximum oscillation probability for demo.



How to obtain CPV in current LBL experiments

- **Direct comparison between $P(\nu_\mu \to \nu_e)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_e)$.**
  - Independent from the model of oscillation mechanism.
  - Expected asymmetry is ~27%.
  - Size of CPV ~ Measurement precision.

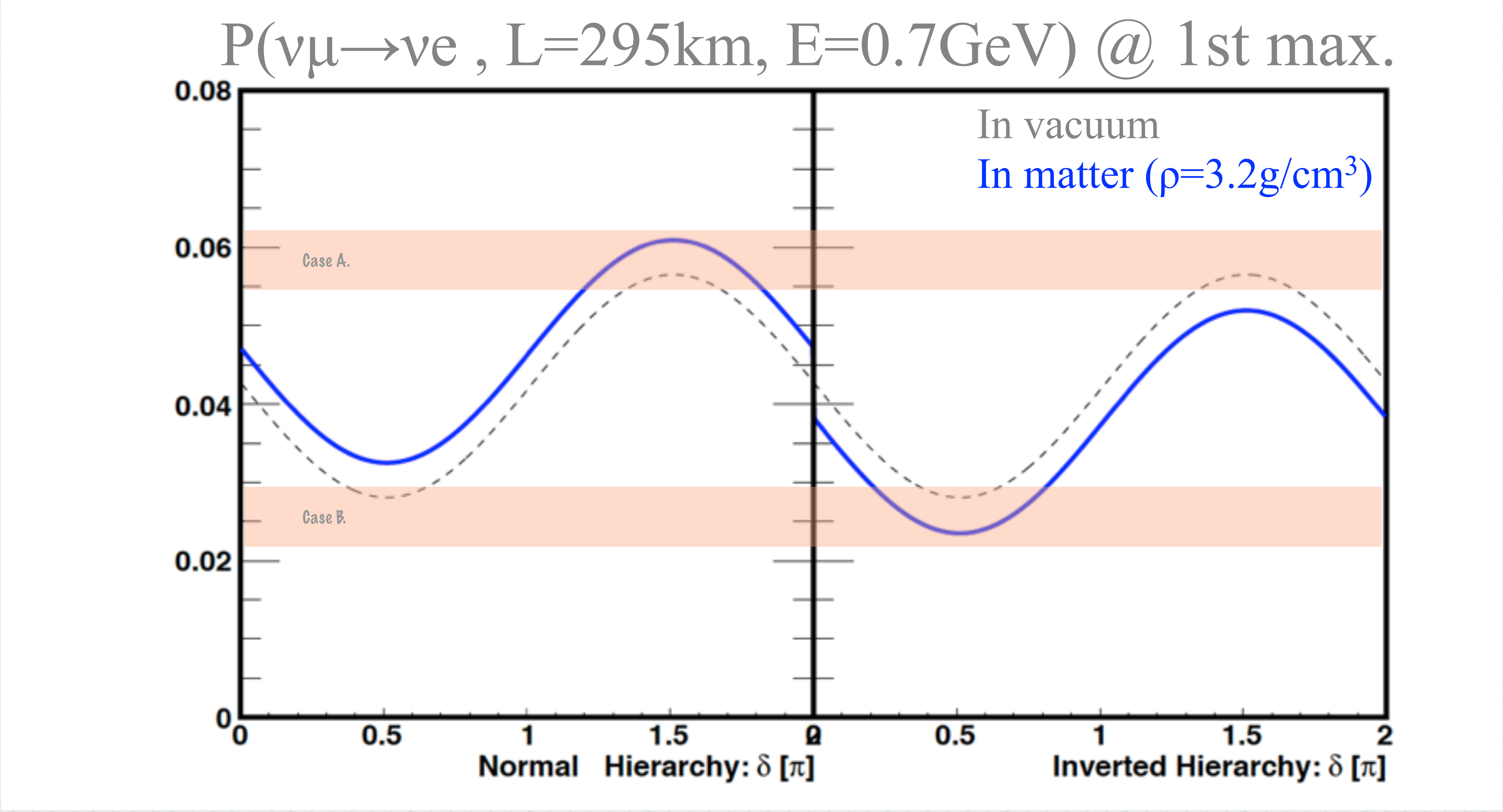


by NOνA collaboration

- **Comparison with the expectation based on the 3-flavor PNMS mixing framework and the obtain the allowed parameter region of δ and sign of Δm^2_{13}.**
  - θ_{13} obtained by reactor experiments can be treated as "known parameter".
  - Although this method is model-dependent CPV search, it is useful to address MH & CPV in current LBL experiment.

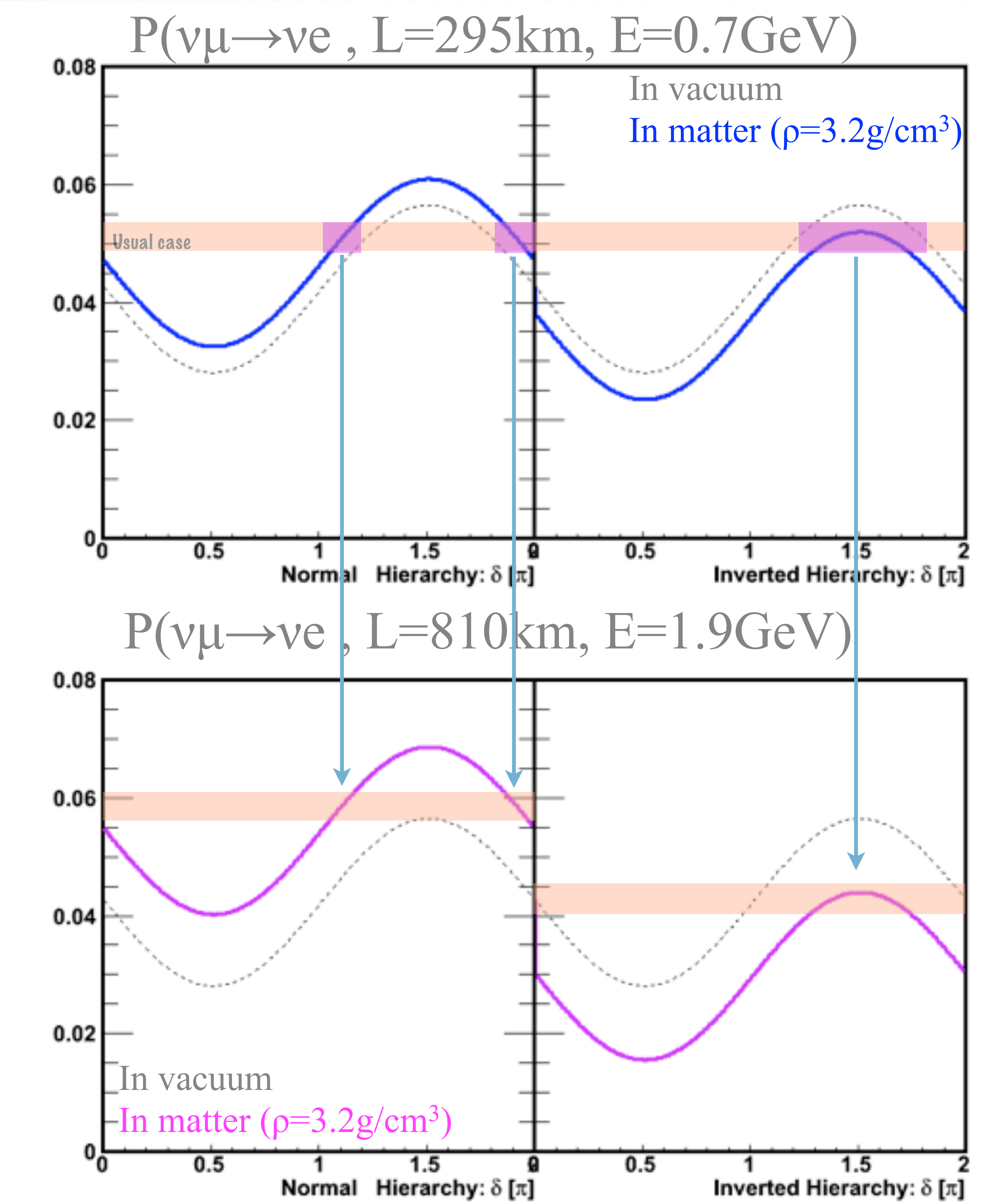
How to obtain the hint of CPV/MH

- Very lucky case: Hint may be obtained by single LBL experiment (+Reactor).
  - Case A: $P(\nu_\mu \to \nu_e)$ is large : NH & ($\pi < \delta < 2\pi$)
  - Case B: $P(\nu_\mu \to \nu_e)$ is small : IH & ($0 < \delta < \pi$)



How to obtain the hint of CPV/MH

* Usual case: The combination of LBL with different baseline may give the hint.



Allowed region of MH and CPV is not determined uniquely from single experiment.

But, the corresponding expectations for another experiment is different between NH and IH assumptions.

The observation by another experiment may reject one of the MH assumptions.

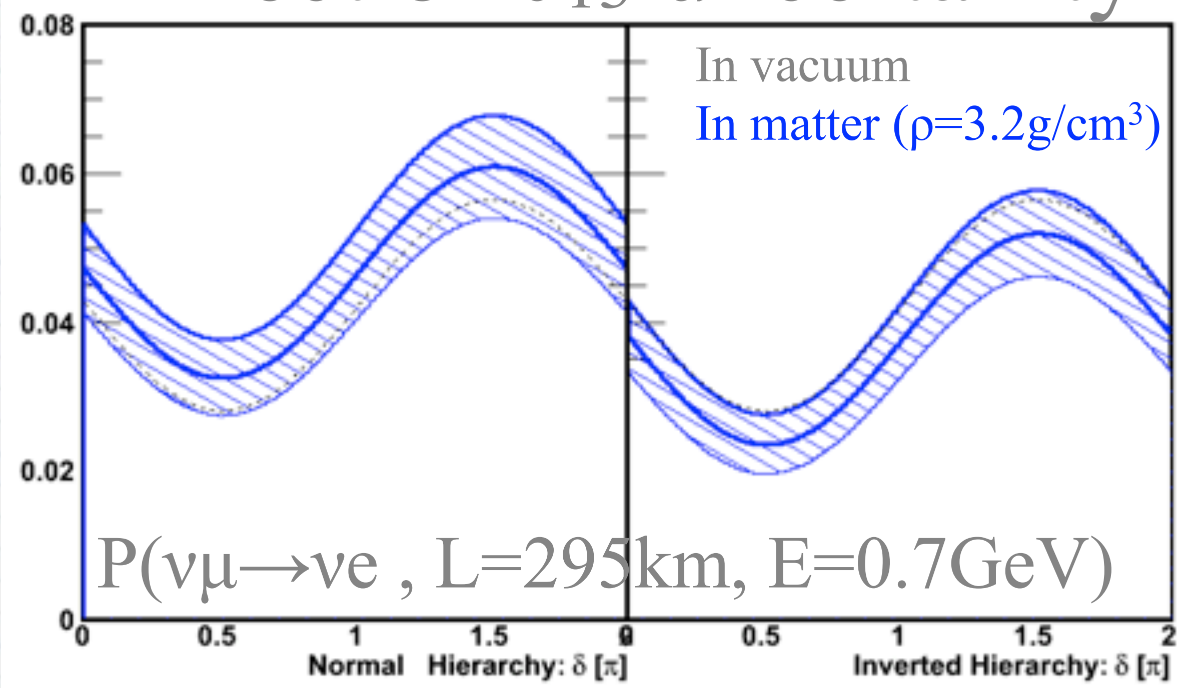
But, in reality.

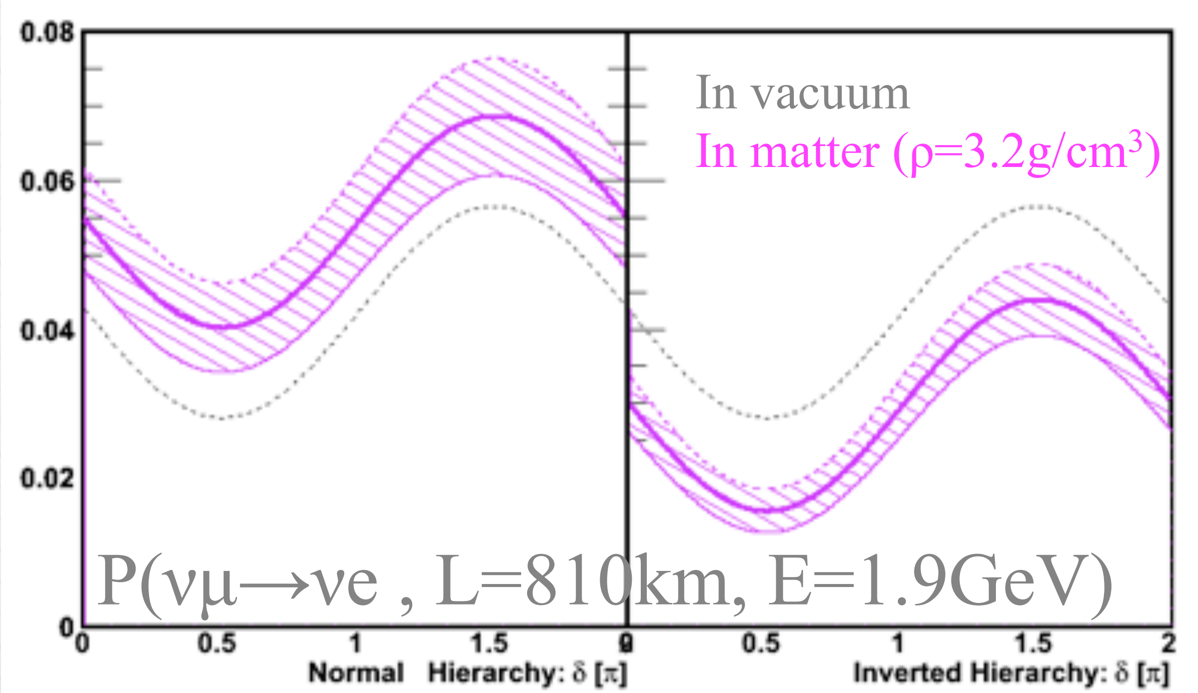
- Precise measurement of the mixing angle is quite important.

Due to "Octant degeneracy"

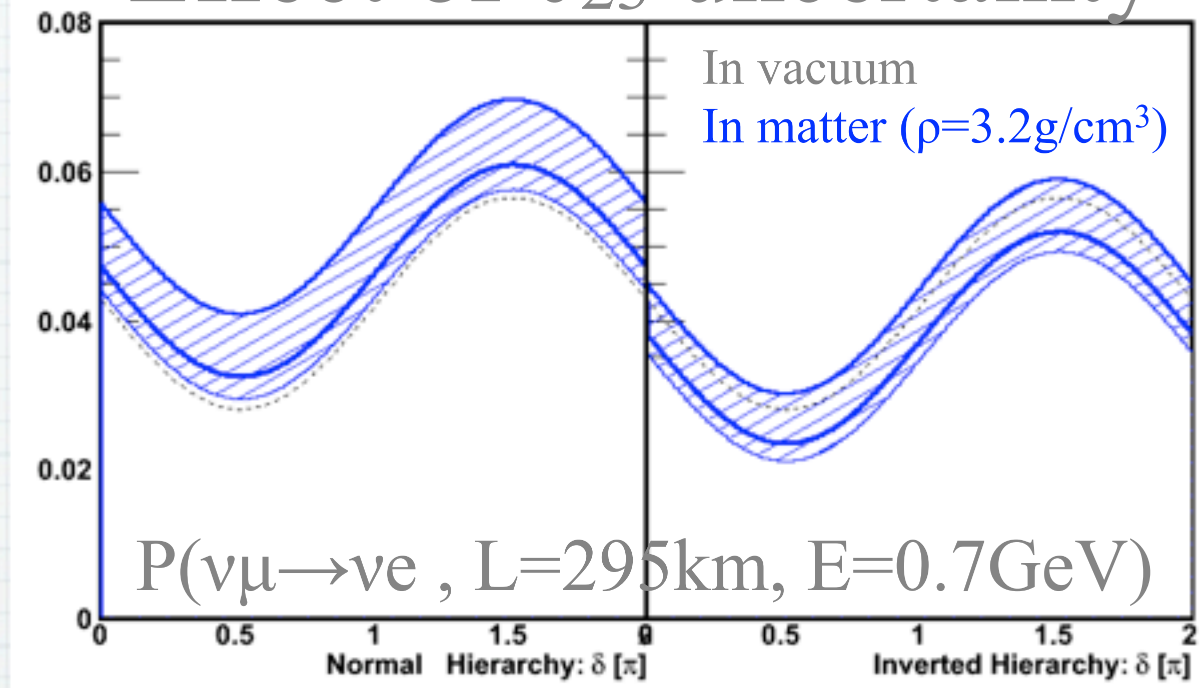
- PDG2013: $\sin^2\theta_{13} = 0.0251 \pm 0.0034$(REACTOR), $\sin^2\theta_{23} = 0.42^{+0.08}_{-0.03}$

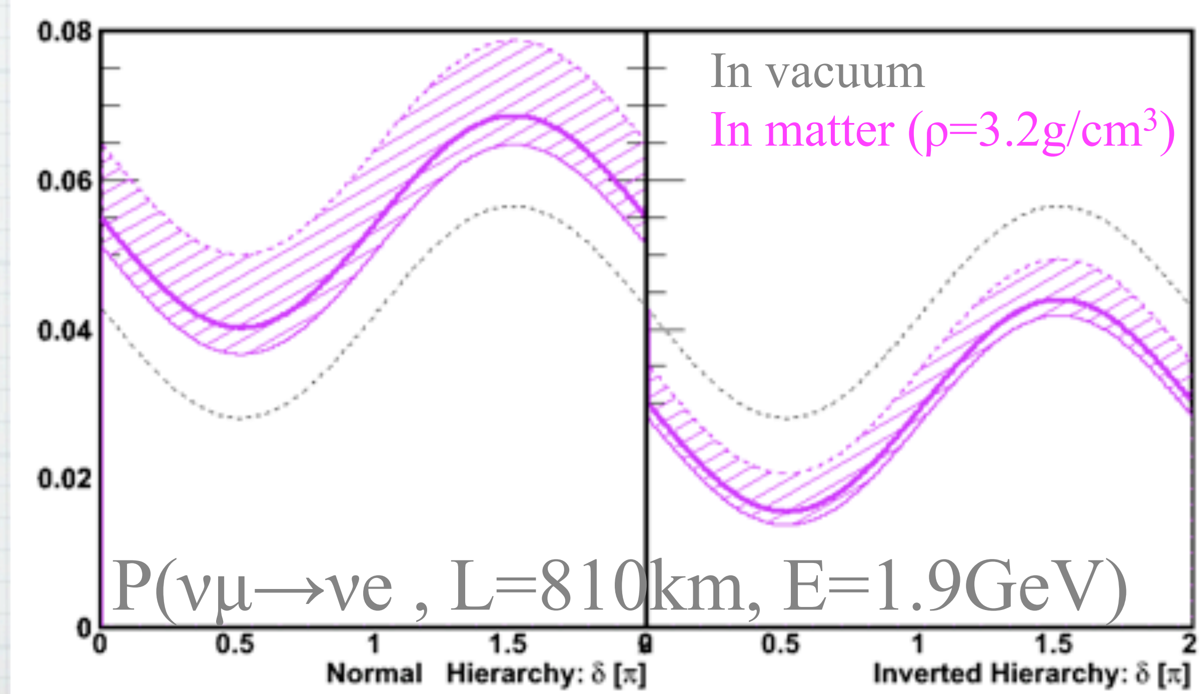
Effect of θ_{13} uncertainty





Effect of θ_{23} uncertainty

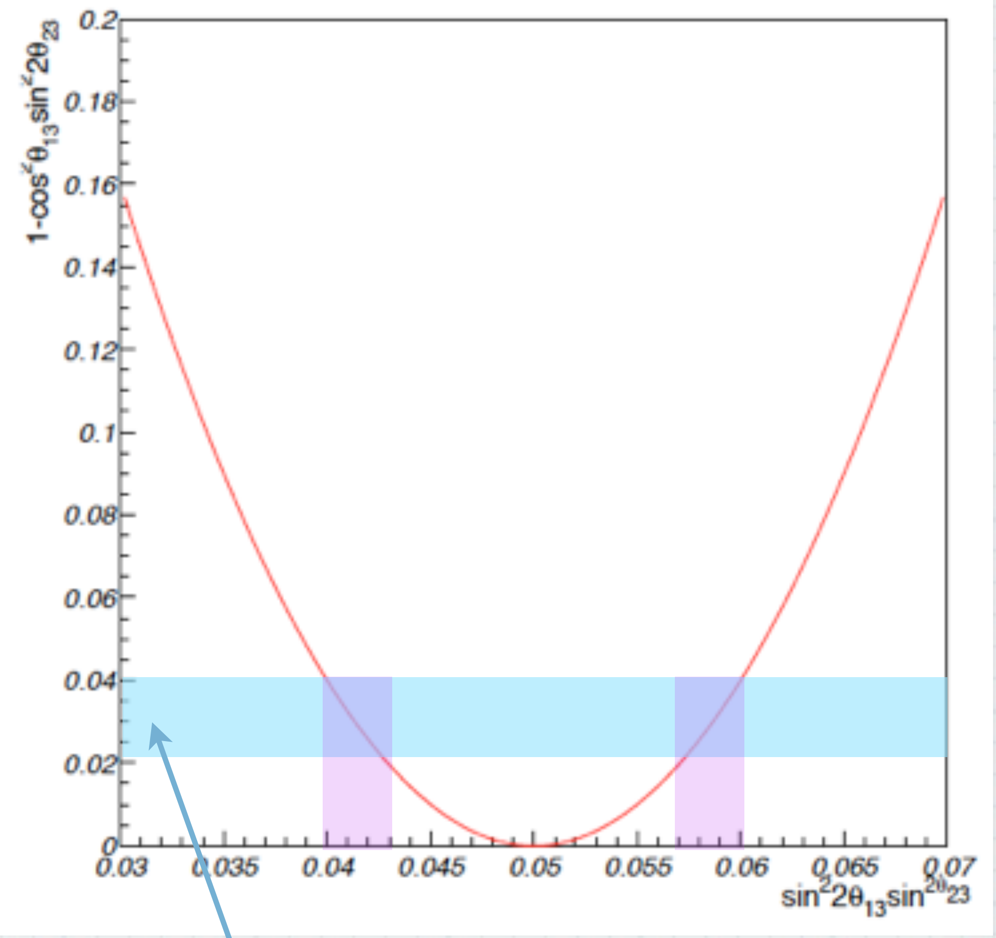




Degeneracy for θ_{23}

- θ_{23} is dominantly determined by the ν_μ disappearance.
  - $P_{min}(\nu_\mu \to \nu_\mu) \sim 1 - \cos^2\theta_{13}\sin^2 2\theta_{23}$
- θ_{23} dependence for ν_e appearance is a function of $\sin^2\theta_{23}$.
  - $P_{max}(\nu_\mu \to \nu_e) \sim \sin^2\theta_{23}\sin^2 2\theta_{13}$
  - If θ_{23} is not 45 degree (= Maximal mixing), there are two solution.
- This effect increases the uncertainty of ν_e appearance expectation.
- Oh the other hand, if ν_e appearance is measured with good precision, the octant degeneracy can be solved.

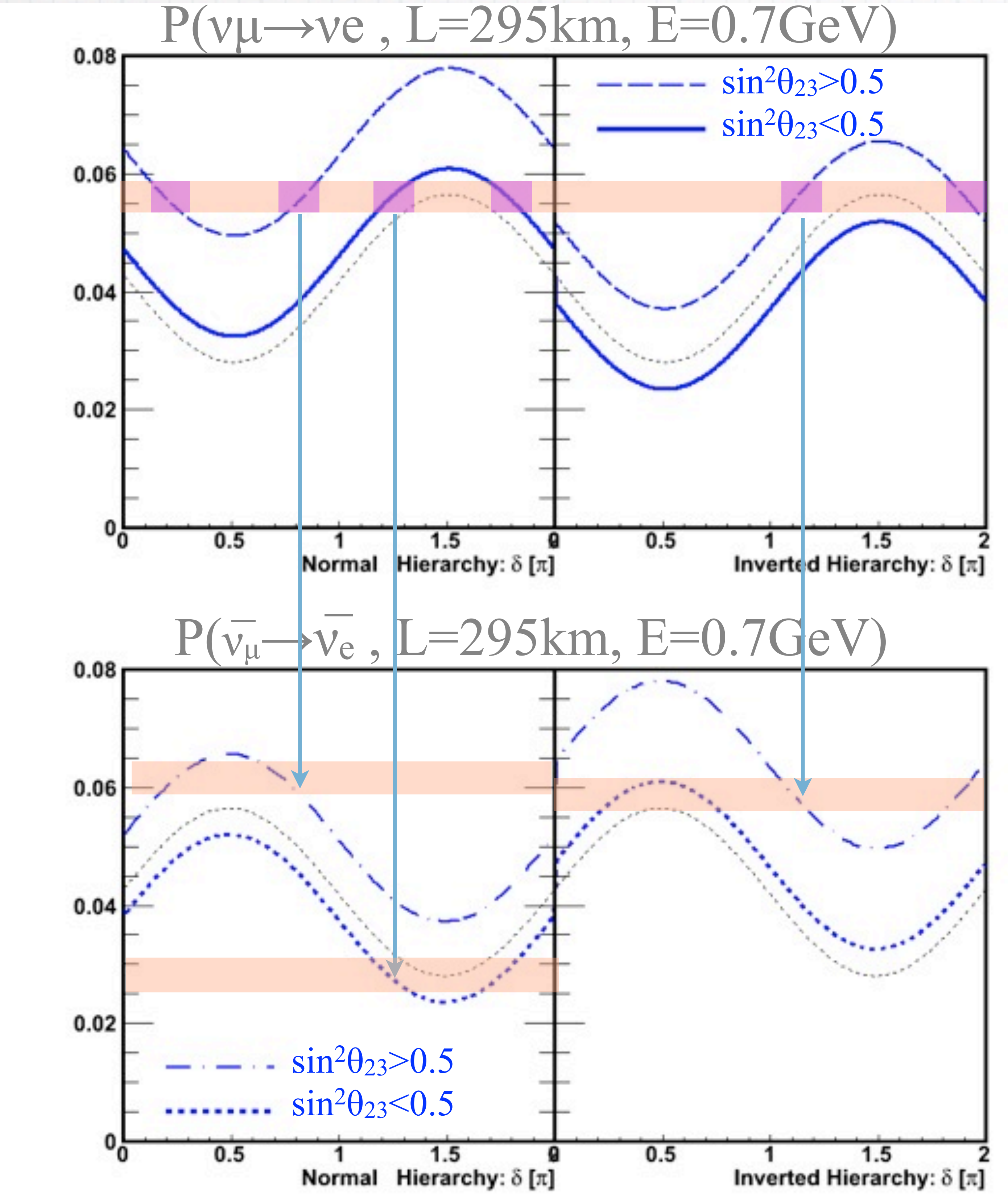
↓ Determined by νμ disappearance



If the νμ disappearance is not maximal, there are two possible νe appearance expectation.

How to address octant degeneracy?

* Using anti-neutrino run is one method.



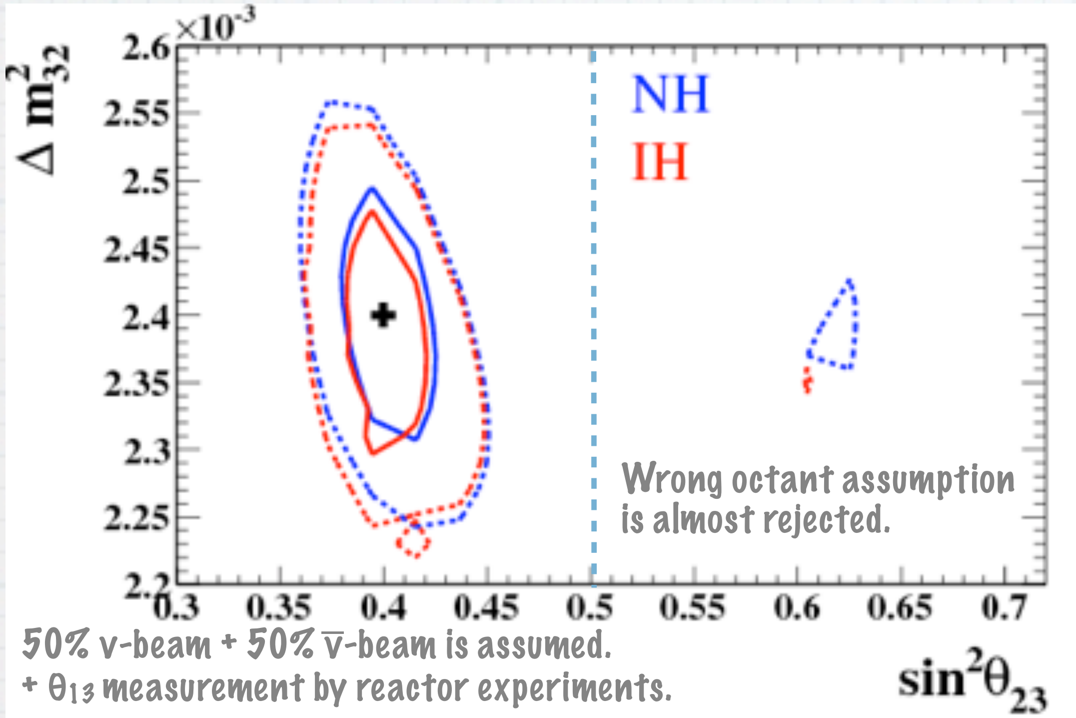
In this case, octant degeneracy is not solved only by ν-mode.

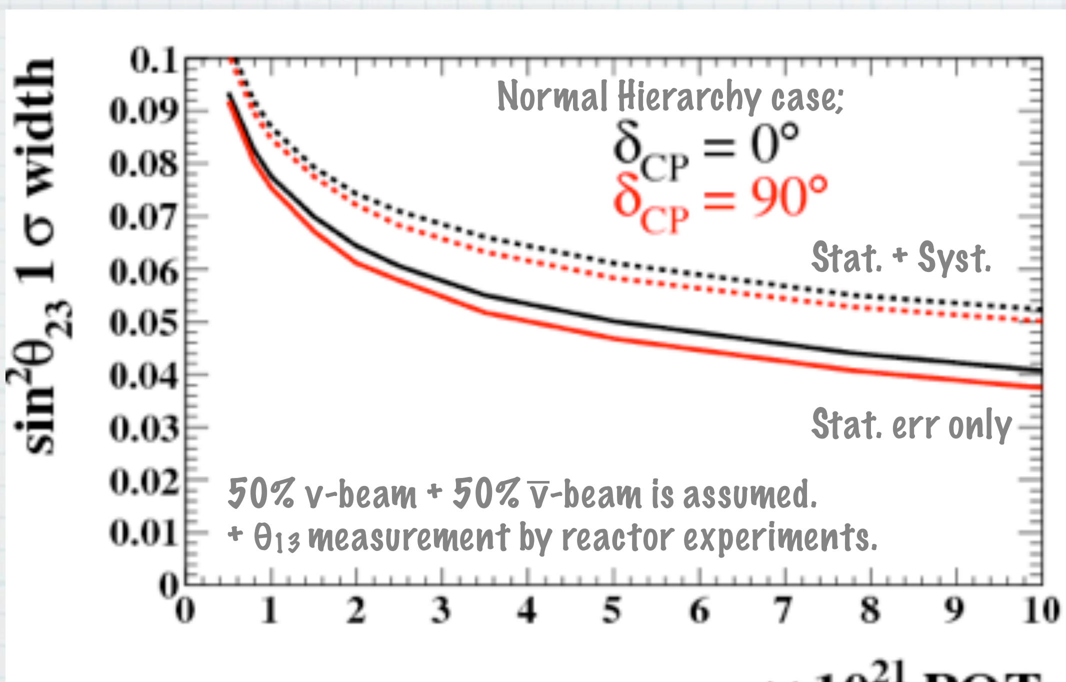
But, the corresponding expectations for $\bar{\nu}$-mode are different between two octant assumptions.

By combining ν-mode and $\bar{\nu}$-mode run, the octant degeneracy may be untangled.

Expected precision of θ_{23} measurement

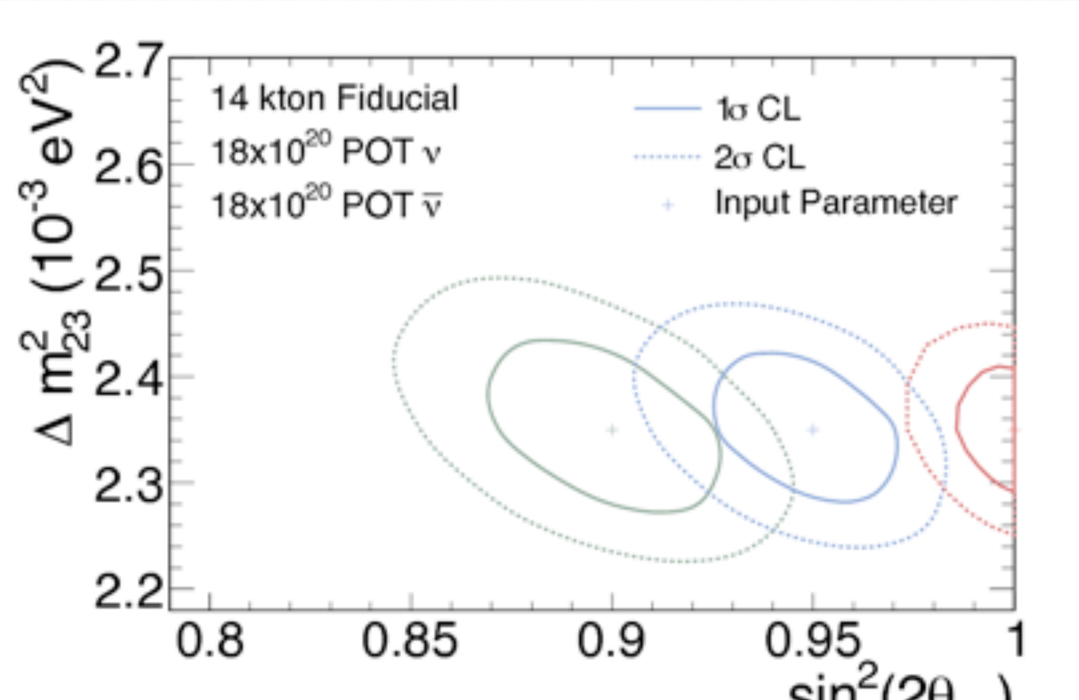
* T2K + Reactor θ_{13}



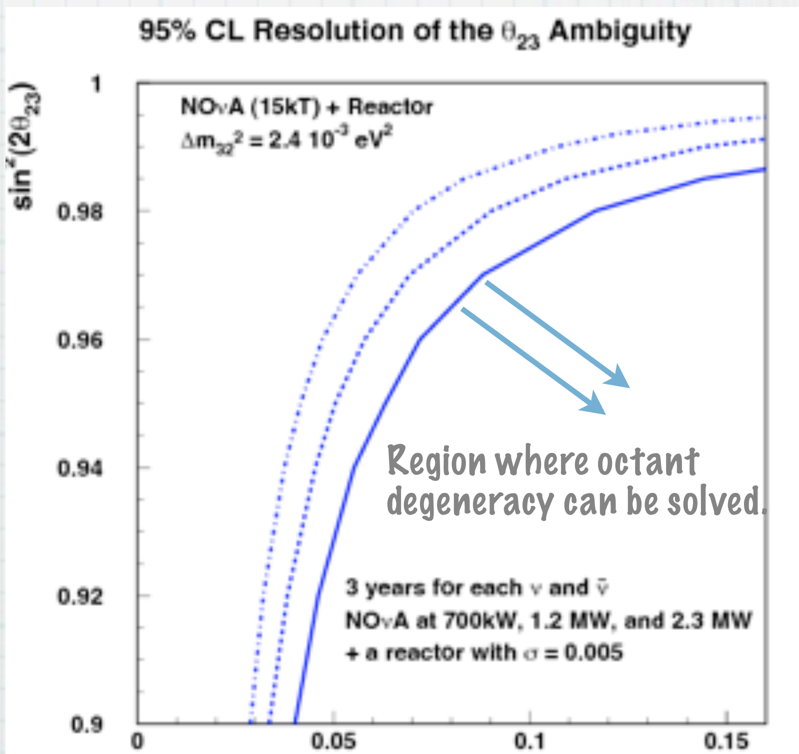


by T2K collaboration

* NOνA



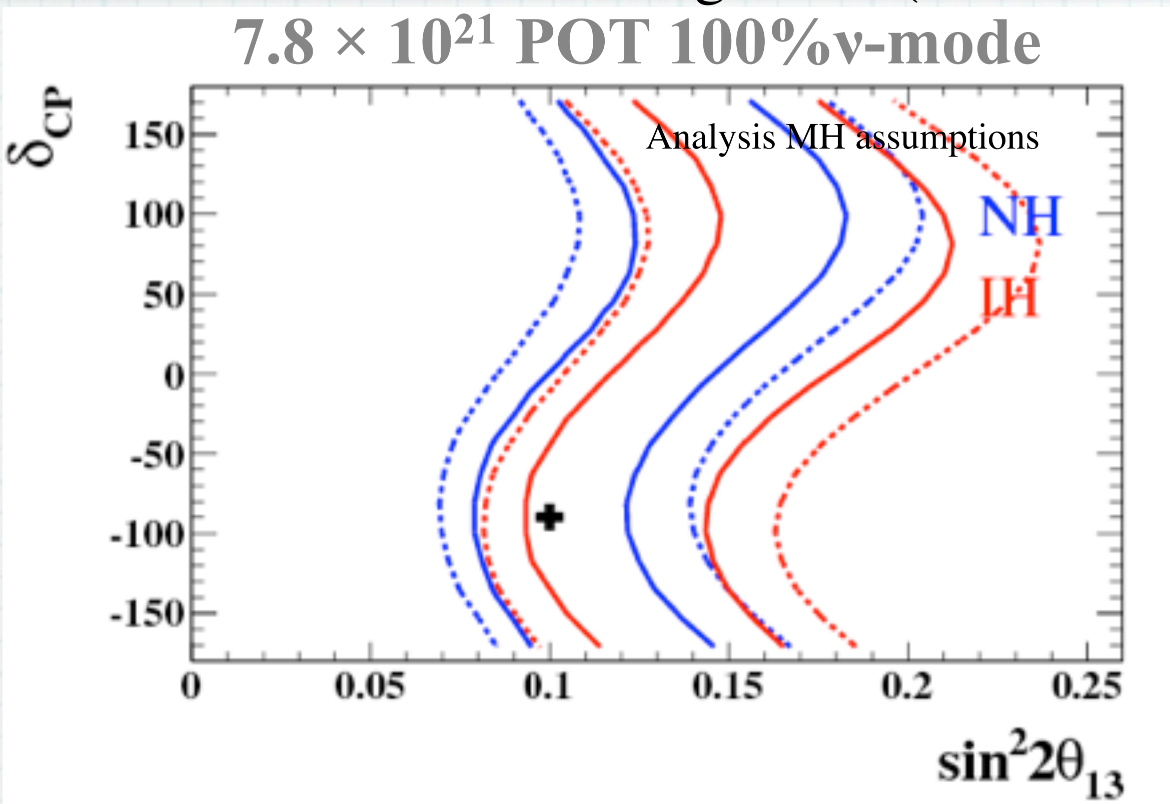
by NOvA collaboration

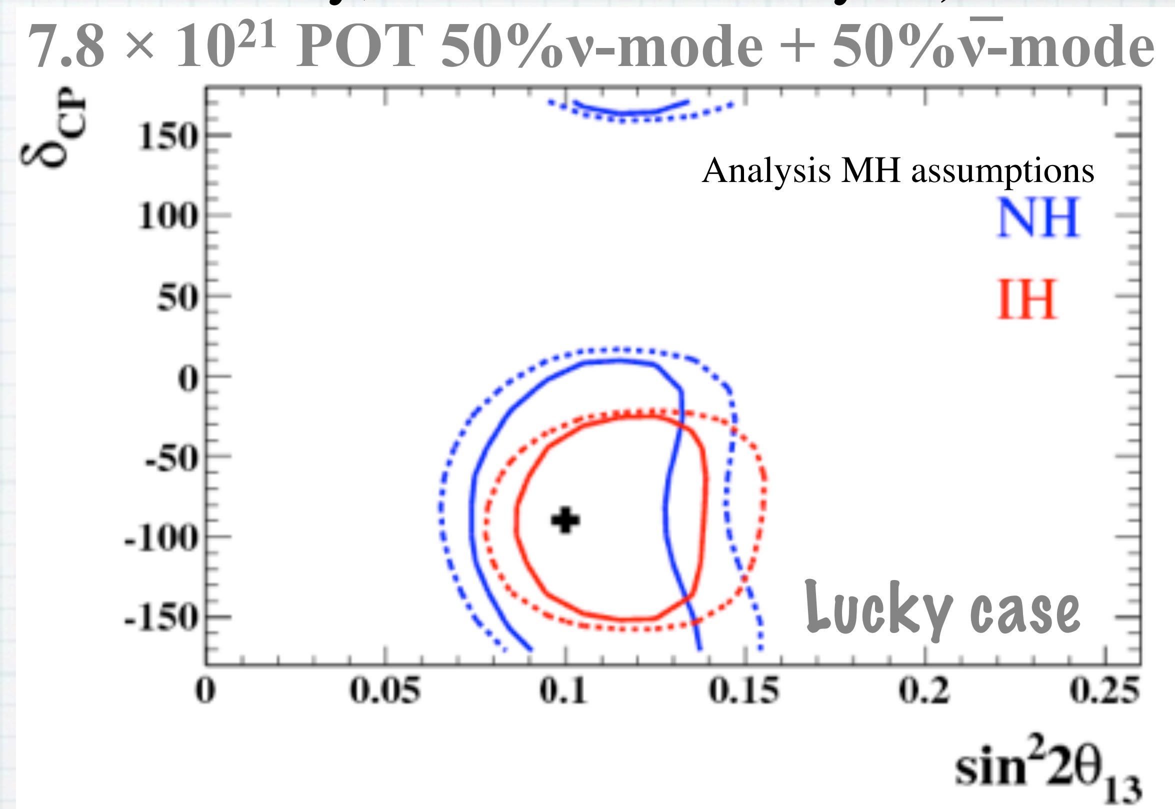


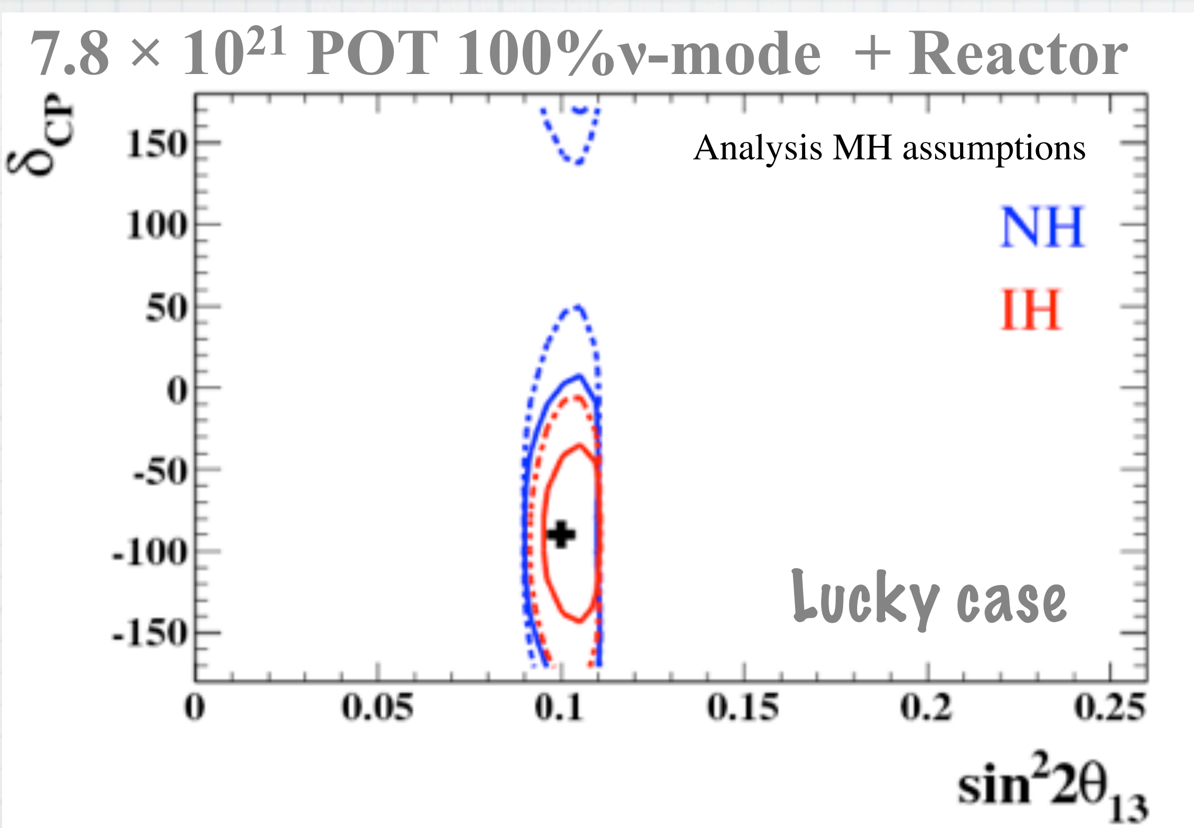
by NOvA collaboration

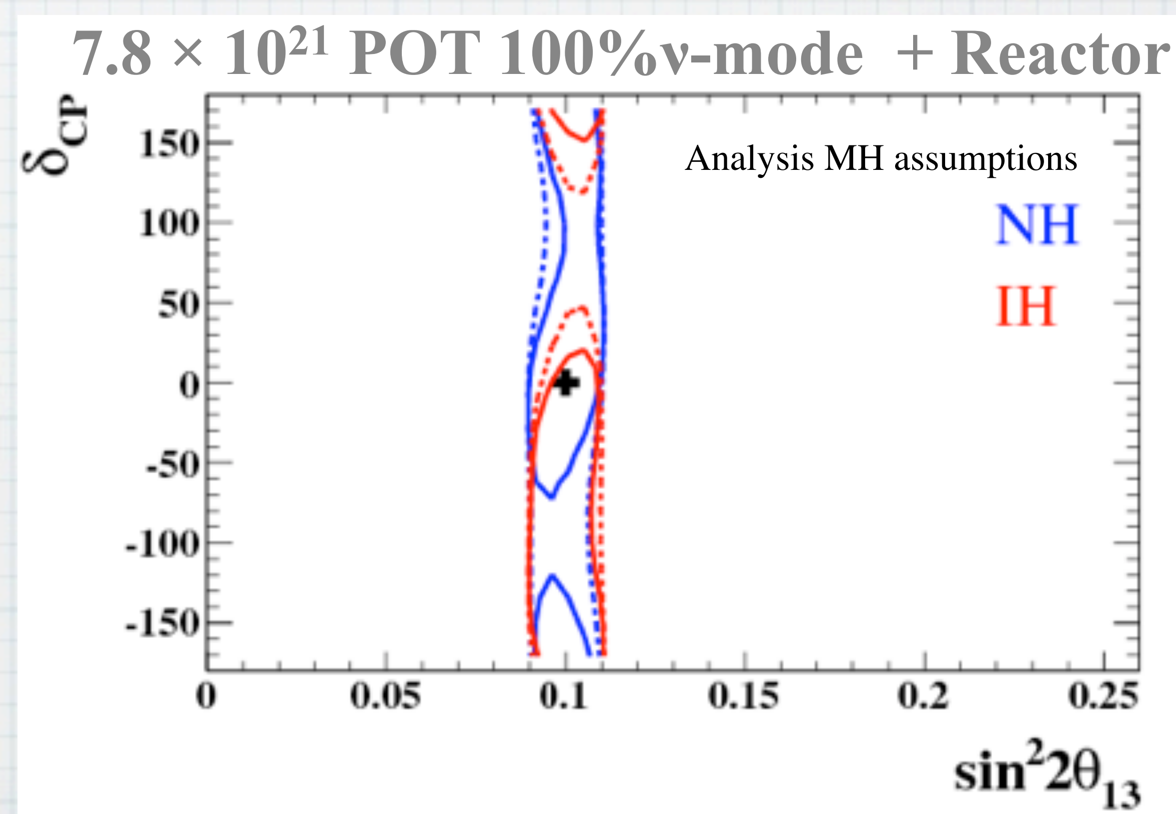
Case studies for MH & CPV : T2K

* 90% C.L. allowed regions (Solid: statistical error only, Dashed: Stat. + Syst.)



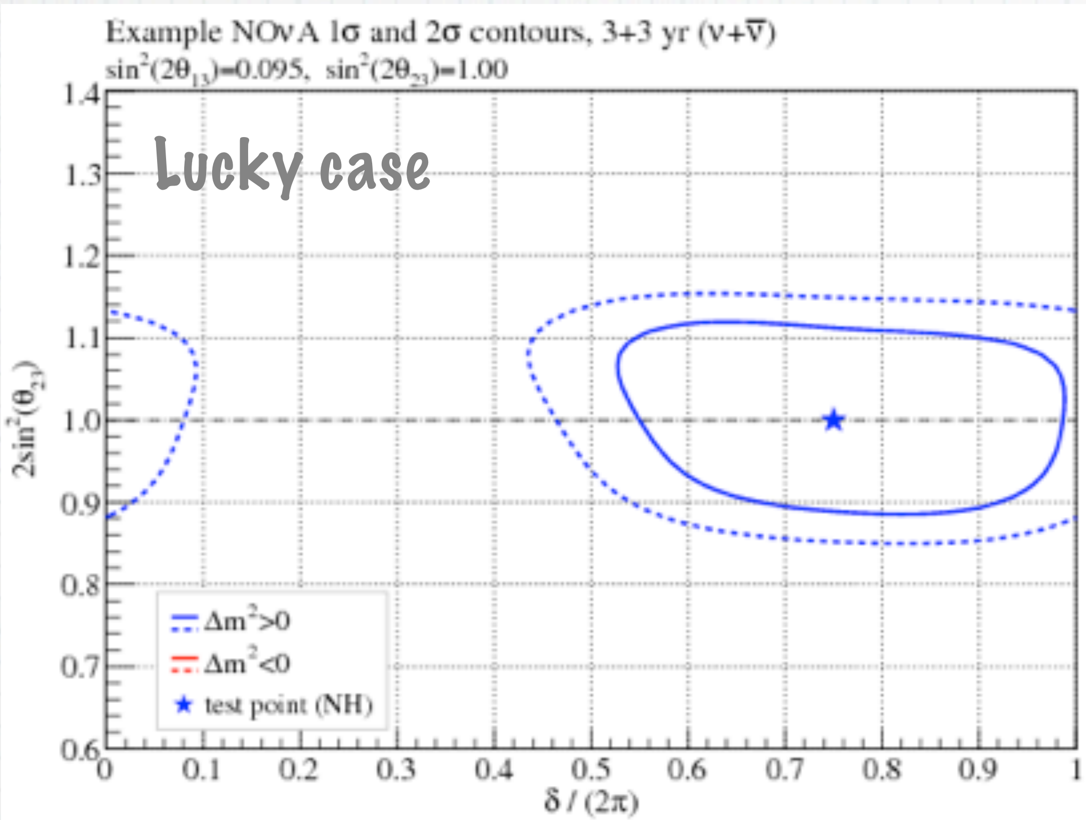


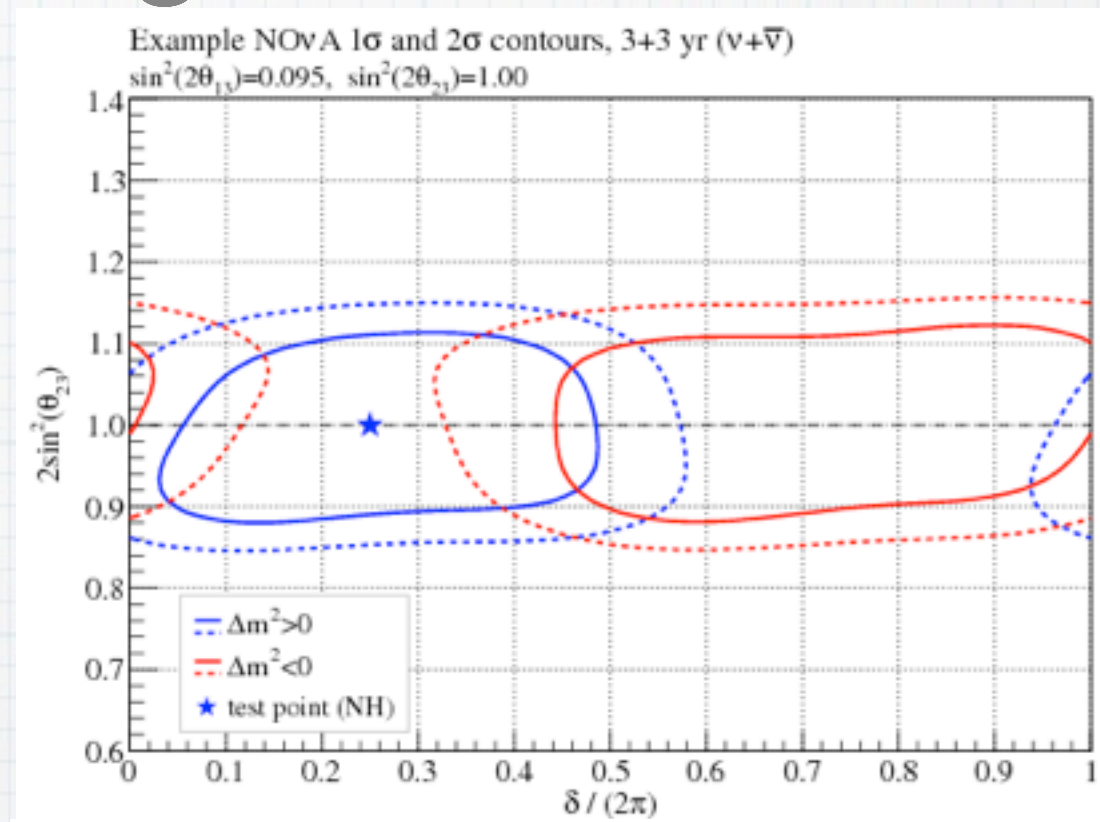


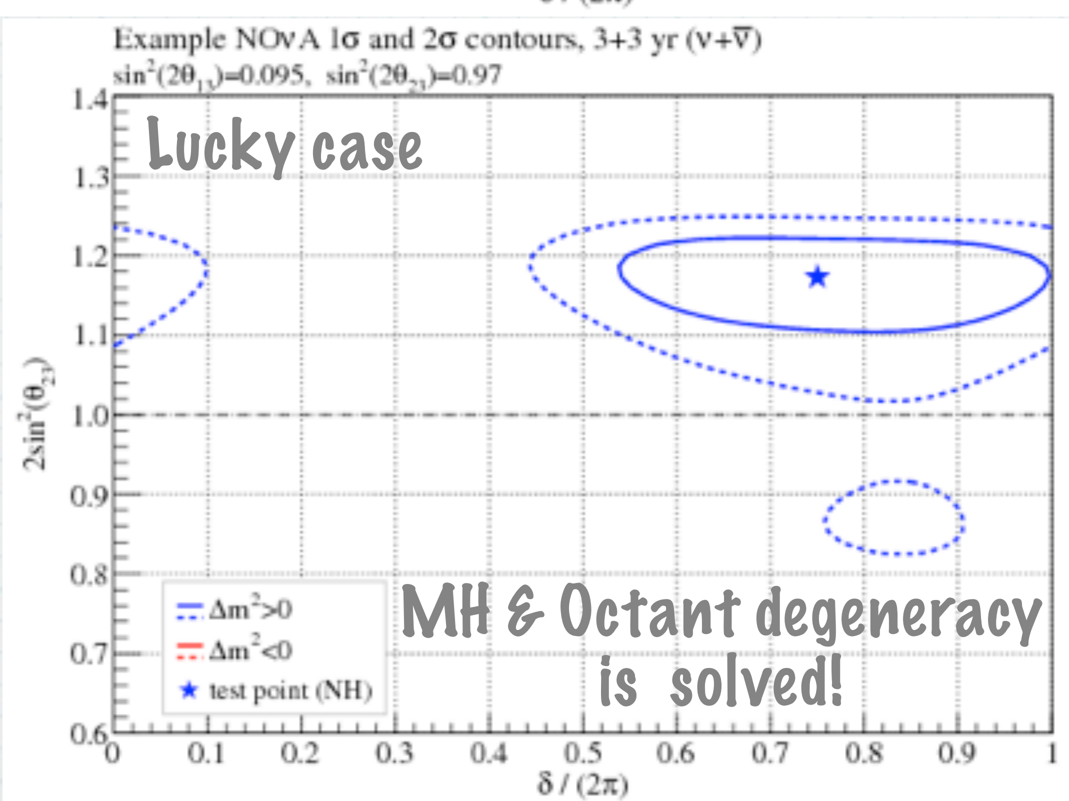


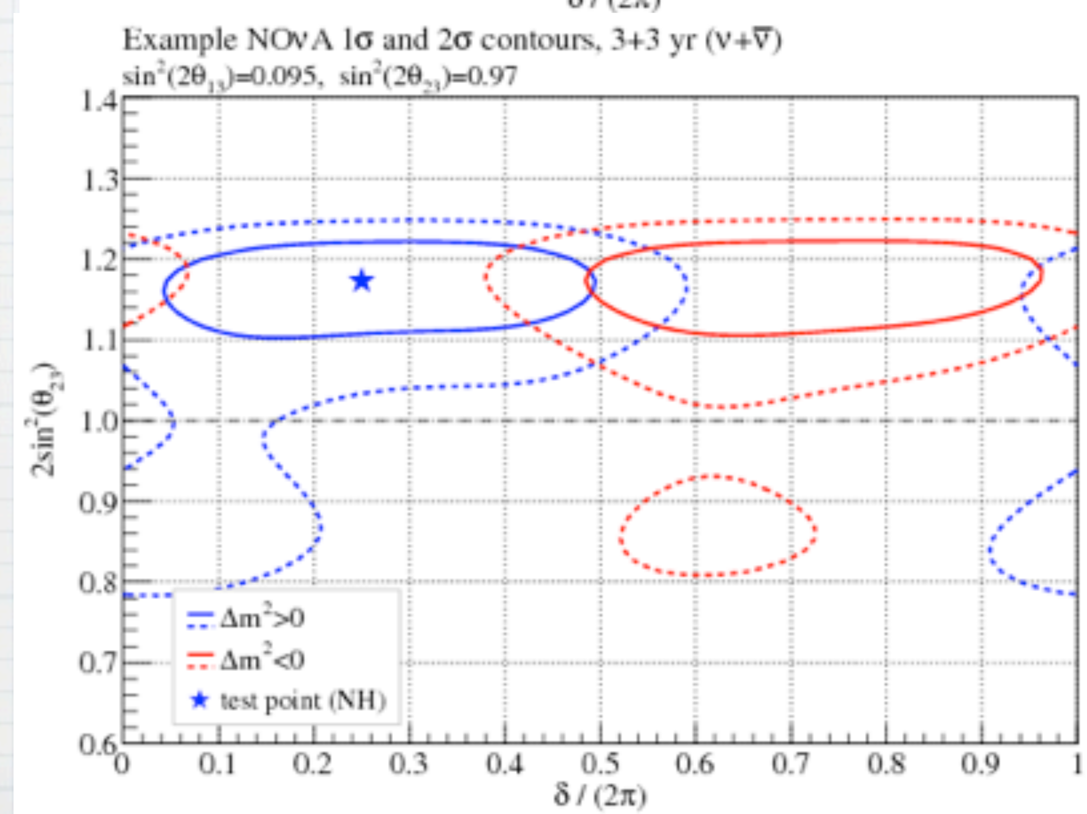
Case studies for MH & CPV: NOνA

* Solid: 1σ allowed region, Dashed 2σ



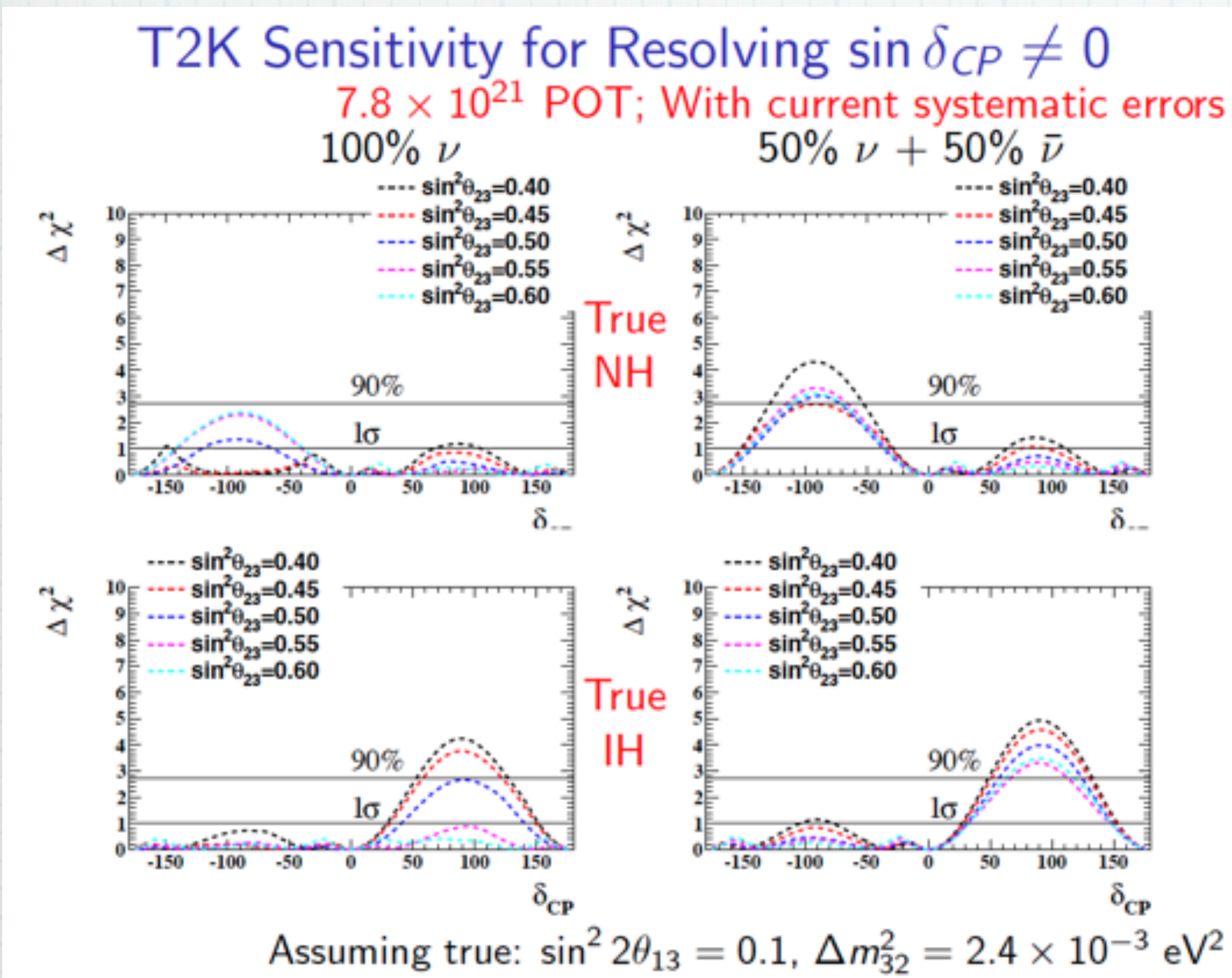






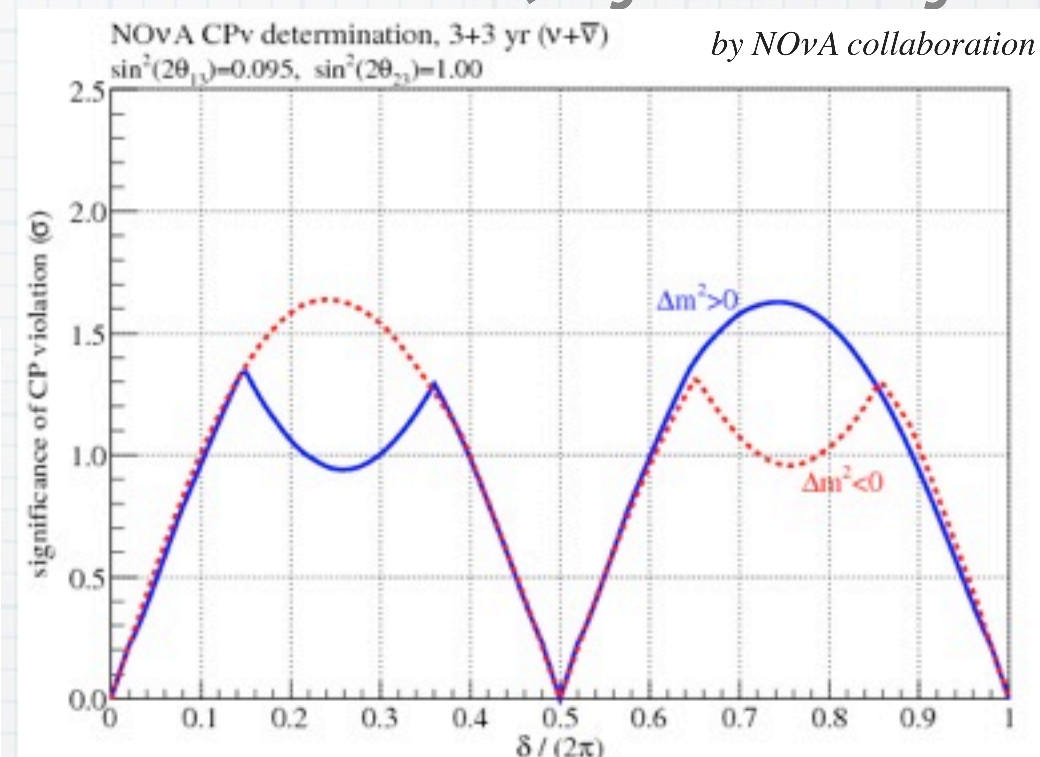
Sensitivity for CPV

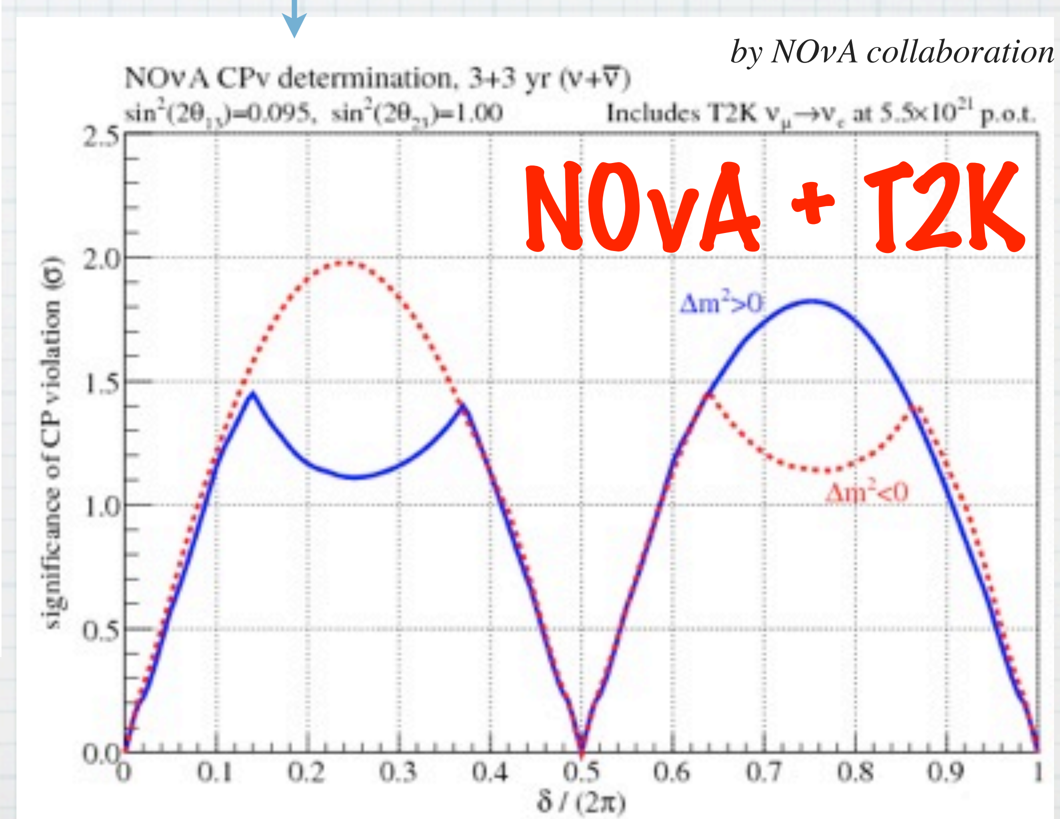
* T2K + Reactor θ_{13}
  * There is 90% CL sensitive region
  * Preliminary: Run plan of T2K (such as $\nu/\bar{\nu}$ ratio) is still under discussion.



by T2K collaboration

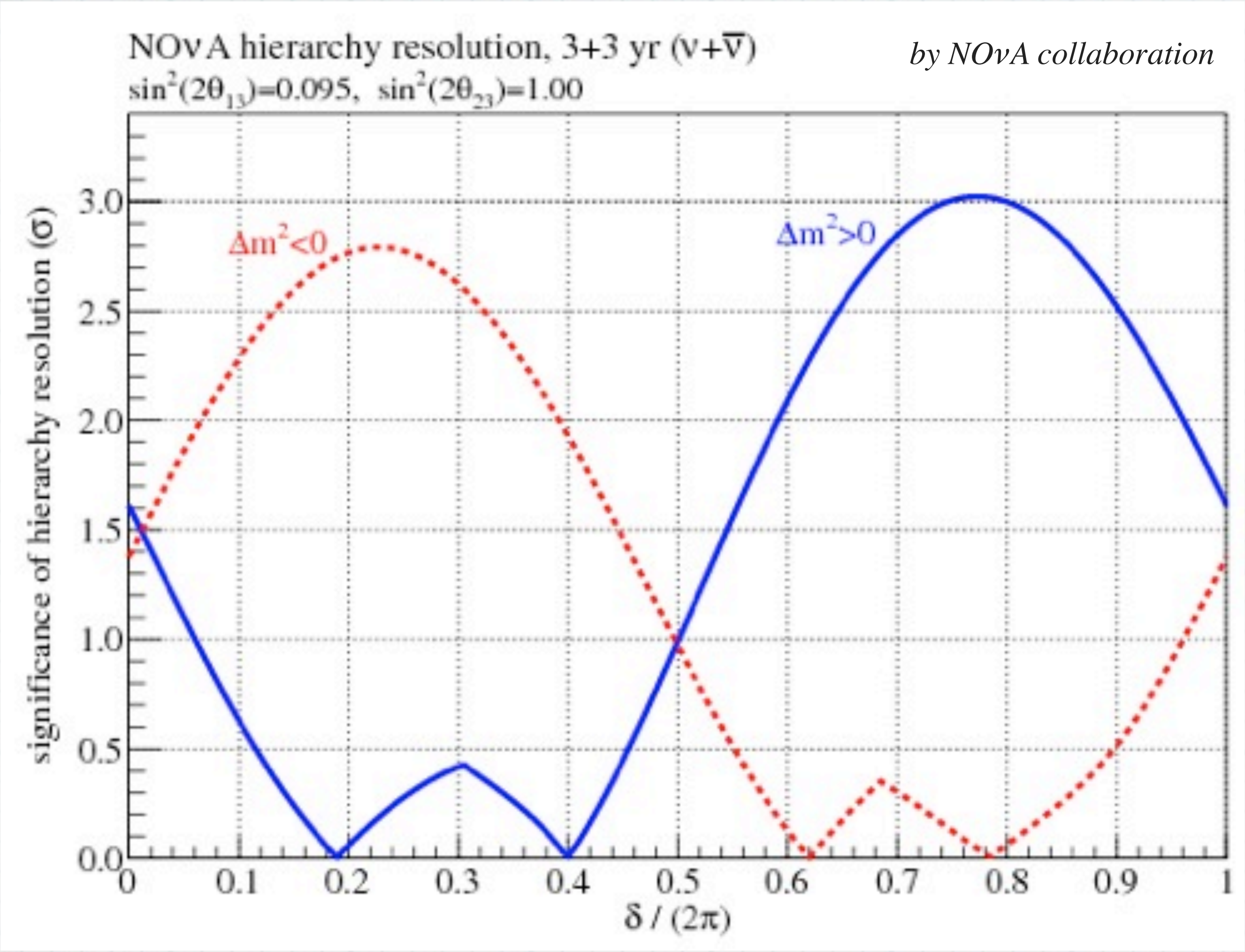
* NOνA (3y ν+3y $\bar{\nu}$)



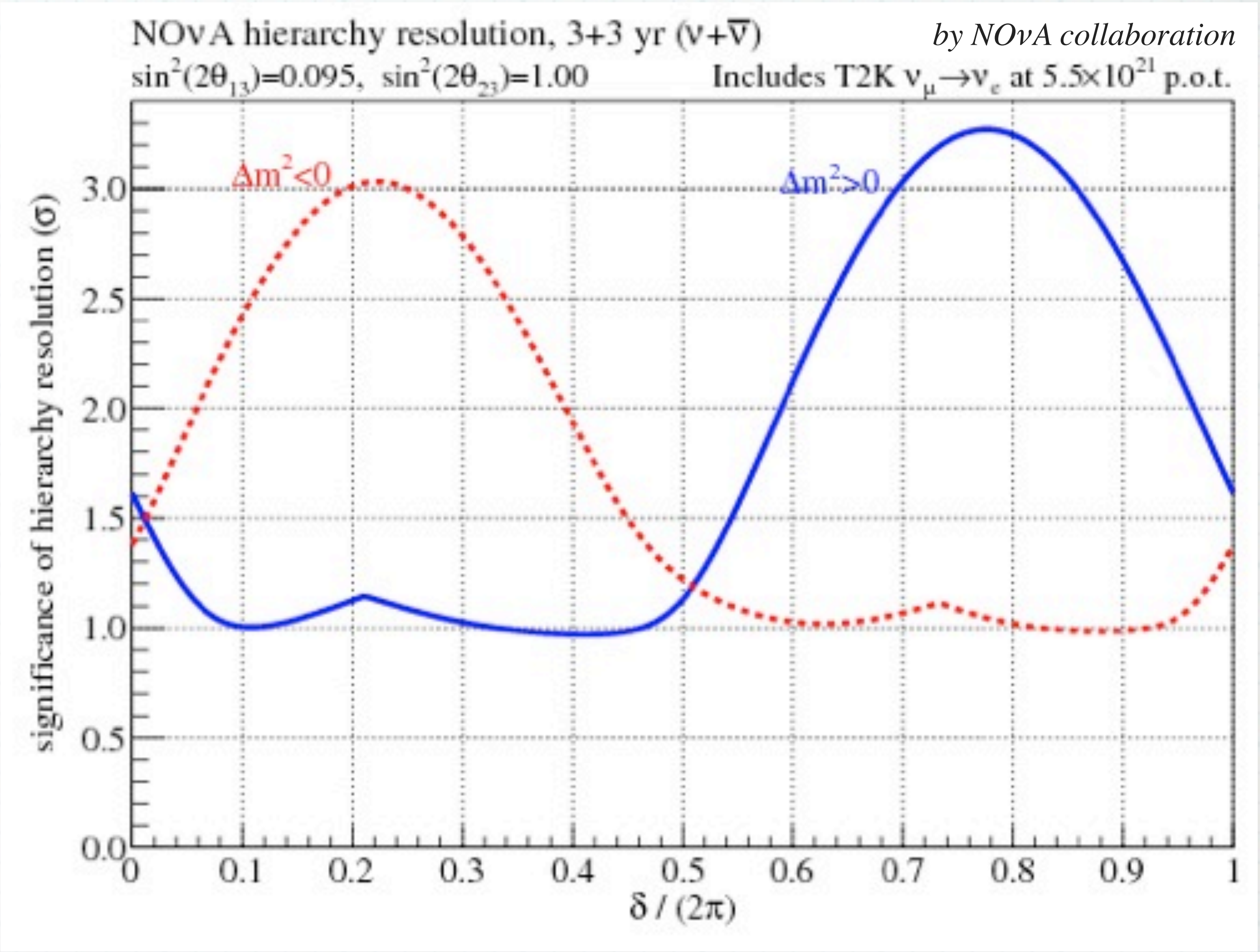


Sensitivity for MH

* NOvA



* NOvA + T2K



Sensitive region (especially for 1σ) is significantly increased by combining NOvA & T2K.

Summary

* Concept of the method to address MH & CPV by “running” LBL experiments is explained.
    * The hints of MH & CPV may be obtained by comparing the measured $P(\nu_\mu \rightarrow \nu_e)$ and the expectation assuming the 3-flavor PNMS mixing.
        * Precise measurements of θ_{13} (by reactor) and θ_{23} by $P(\nu_\mu \rightarrow \nu_\mu)$ is key.
            * If the $P(\nu_\mu \rightarrow \nu_\mu)$ is not maximum, the solving the octant degeneracy is important to reduce the uncertainty of the θ_{23}.
        * Synergy among the experiments are important to expand the sensitive area.
    * T2K and NOνA can address MH and CP phase with >1σ significance.
* Detailed discussion in WG1 parallel session is interesting!