Current & Future accelerator-based neutrino experiments

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* Physics goals of accelerator-based neutrino experiments.
* Overview of the strategy of LBL ν Experiments.
* Review of current LBL ν Experiments
    * Latest results from T2K
    * Status of NO ν A
* Next goal of LBL ν Experiments: MH & CPV
    * Method to obtain the hints by current experiments.
* Future prospects

Targets of Accelerator-based ν experiments.

* Understanding the neutrino oscillation
    * Measurement of 3 flavor mixing parameters
* Mass hierarchy
* CP violation in neutrino oscillation
* Sterile neutrino?
* Neutrino-Nucleus interaction

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Coverage of this talk.

3-flavor Neutrino oscillation

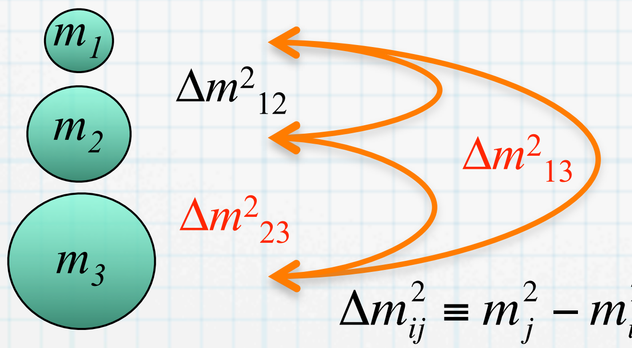
- Neutrino oscillation is well described by 3-flavor neutrino mixing.
  - Long baseline ν experiments mainly measure the "atmospheric" ν oscillation.
    - Long base-line : L ≧ O(100)km

- 6 independent parameters :
  - 3 mixing angle: $\theta_{12}, \theta_{23}, \theta_{13}$
  - 2 mass difference: $\Delta m^2_{12}, \Delta m^2_{23}, \Delta m^2_{13}$
    - $\Delta m^2_{12} + \Delta m^2_{23} + \Delta m^2_{13} = 0$ by definition.
  - 1 complex phase: δ_{CP}

Flavor eigenstates — Mass eigenstates

ν_e, ν_μ, ν_τ

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



$$\Delta m^2_{ij} \equiv m^2_j - m^2_i$$

Neutrino oscillation: $P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j}(U_{\alpha i}U_{\beta i}U_{\alpha j}U_{\beta j})\sin^2\left(\Delta m^2_{ij}L/4E\right)$

$$U_{\text{PNMS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{-i\delta_{CP}} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$\theta_{23} \sim 45°$, $\Delta m^2_{23} \sim 2.5 \times 10^{-3}$ [eV^2]

Atmospheric neutrino, Accelerator neutrino

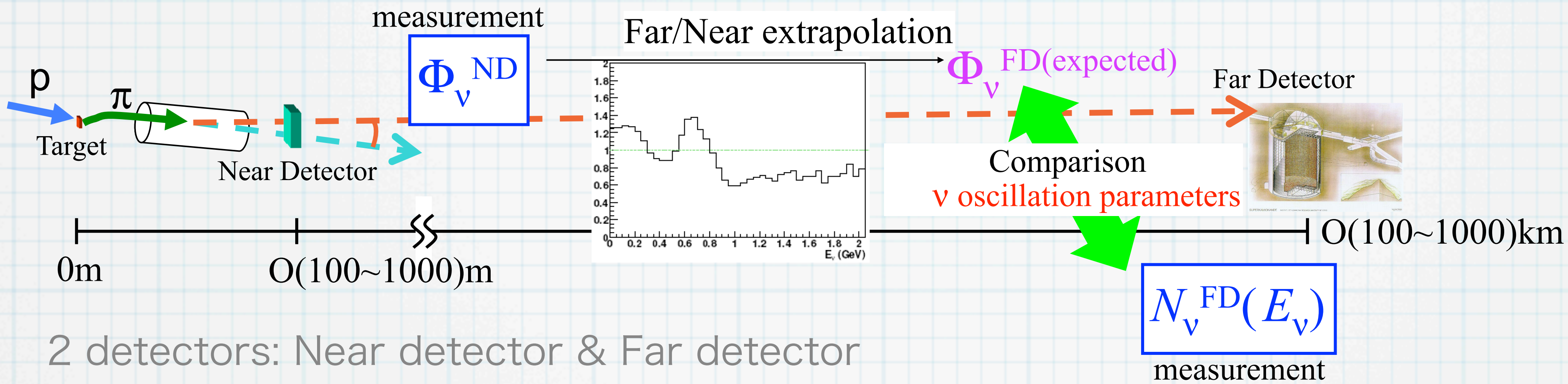
$\theta_{12} \sim 34°$, $\Delta m^2_{12} \sim 8 \times 10^{-5}$ [eV^2]

Solar neutrino, Reactor neutrino

Scope of current & future accelerator-based LBL ν experiments

Observation of the mixing via θ_{13},
Determination of δCP and Mass hierarchy (sign of Δm^2_{13}),
Precise measurement of θ_{23}, θ_{13} and Δm^2_{23}

Basic concept of long base-line ν experiments



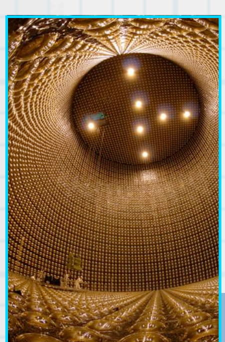
- 2 detectors: Near detector & Far detector
  - Generate the high intensity ν_μ beam using pion decay in flight.
  - Measure the neutrino flux by Near Detector
    - $N_\nu^{ND}(\nu_\mu) = \Phi^{ND}(\nu_\mu) \times \sigma(\nu\text{-N interaction}) \times \varepsilon^{ND}$
  - Extrapolate the flux to Far detector position
    - $\Phi^{FD(expected)}(E^i\nu_\mu) = \Sigma_j R^{FD/ND}(E^i\nu_\mu, E^j\nu_\mu) \times \Phi^{ND}(E^j\nu_\mu)$
      - Energy dependent extrapolation considering the bin-by-bin correlation is obtained based on the hadron-production at the target, horn focusing effect, hadron decay kinematics and beam-line geometry.
  - Calculated the expected the number of the event in Far detector assuming null-oscillation.
    - $N_\nu^{FD,null(expected)}(\nu_\mu) = \Phi^{FD(expected)}(\nu_\mu) \times \sigma(\nu\text{-N interaction}) \times \varepsilon^{FD}$
  - Determine the oscillation probability by comparing it with the observation.
    - $N_\nu^{FD}(\nu_x) = P(\nu_\mu \rightarrow \nu_x) \times N_\nu^{FD,null(expected)}(\nu_\mu)$

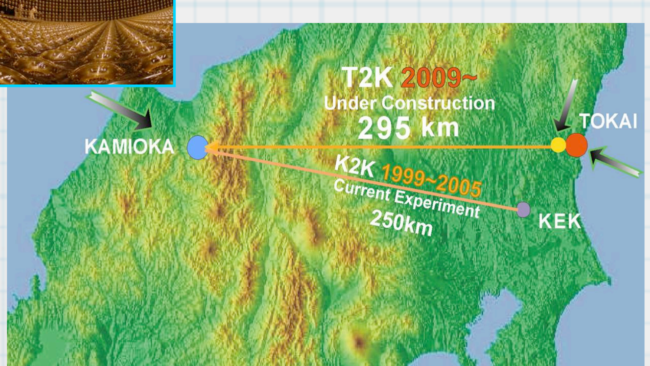
Brief history of LBL ν experiments

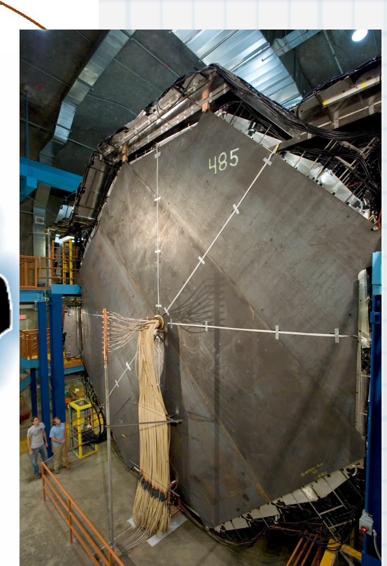
- 1st generation: … Observing dominant mode: $\nu_\mu \rightarrow \nu_\tau$ oscillation
  - K2K / KEK-PS(1999~2005), MINOS/ FNAL-NuMI(2005~2012): $\nu_\mu \rightarrow \nu_\mu$ disappearance
  - OPERA, ICURUS / CERN-CNGS(2006~2012): $\nu_\mu \rightarrow \nu_\tau$ appearance
- 2nd generation:(Current & Future)

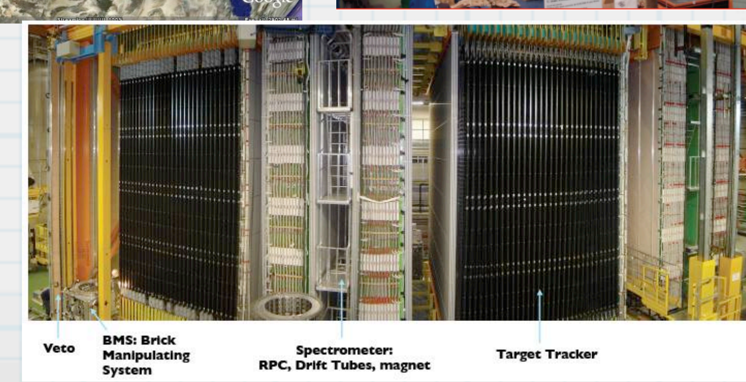
  … Search for **sub-dominant** mode: $\nu_\mu \rightarrow \nu_e$ oscillation mode

  using high intensity ν_μ beam (proton beam power ~700kW)
  - T2K / J-PARC (2009~)
  - NOνA / FNAL-NuMI upgraded (2013~)



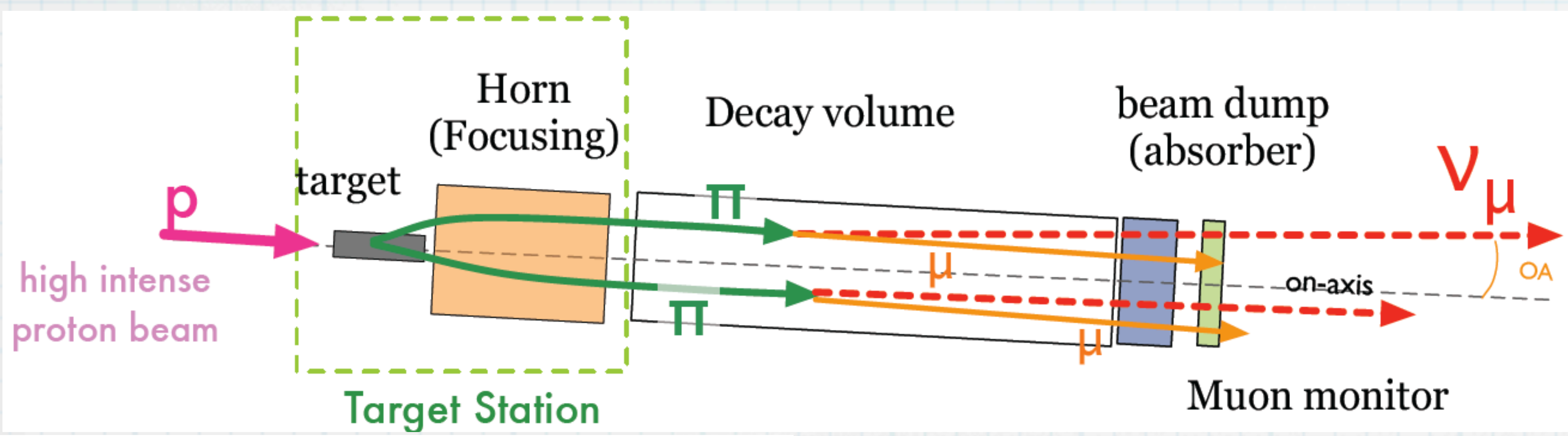


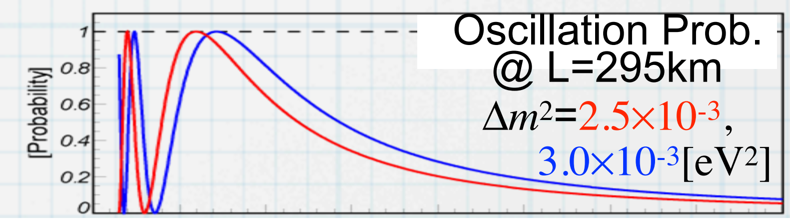


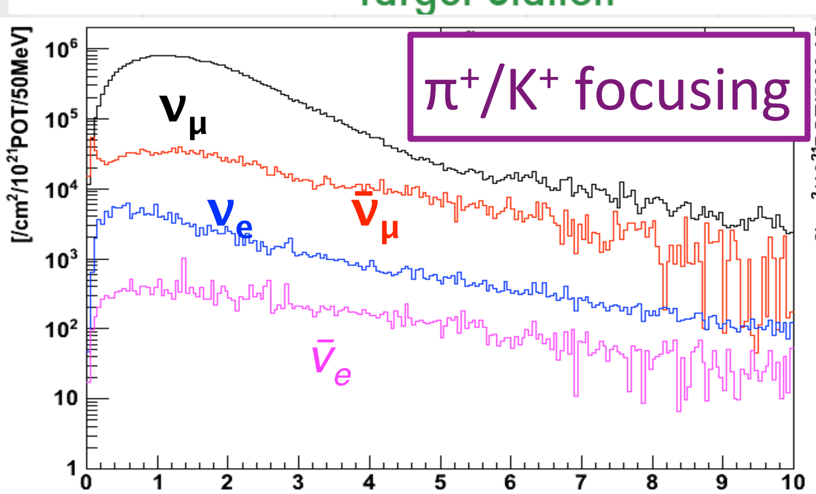


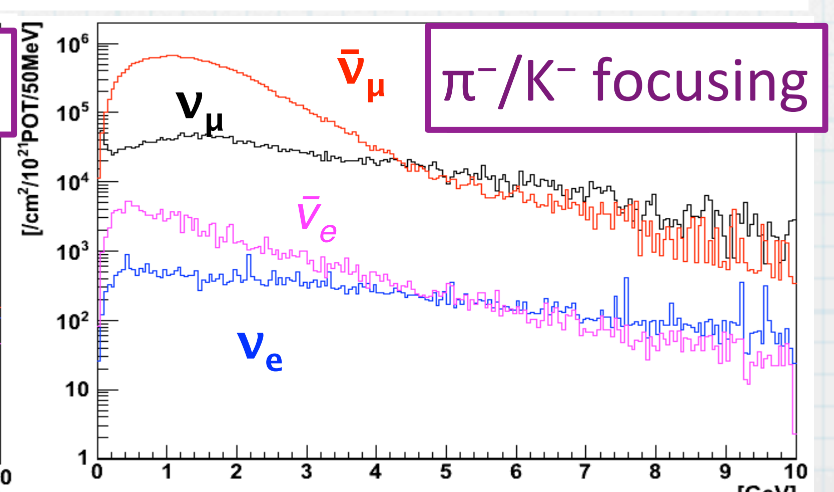
Tool for current LBL: "Super-beam"

- High intensity (~MW class) neutrino beam is essential for current & future LBL.
- "Super beam"
  = conventional horn focused ν_μ-beam using high intensity proton accelerator.
  - ν energy spectrum can be optimized by changing the beam direction from Far Detector.
    - ON-axis = Wide Band Beam
    - OFF-axis = Pseudo-Narrow Band Beam
  - ν-beam and $\bar{\nu}$ -beam can be produced by changing horn polarity.

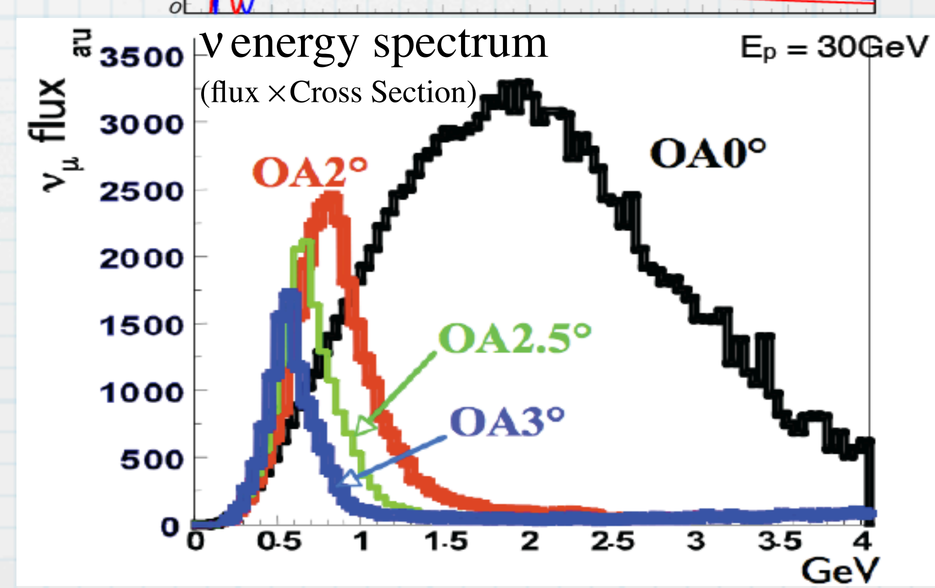




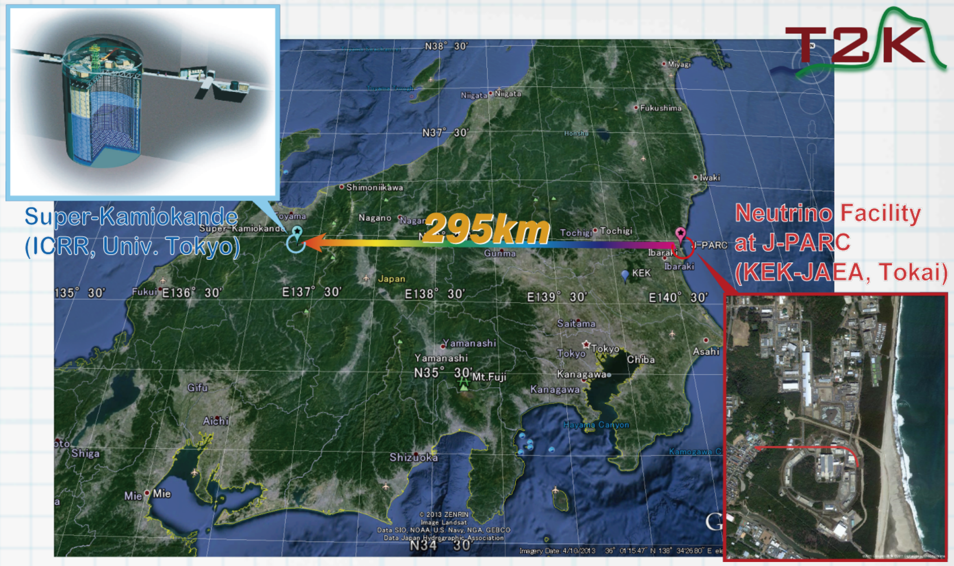




Ex. J-PARC ν –beam Horn(250kA) On-axis @ 295km



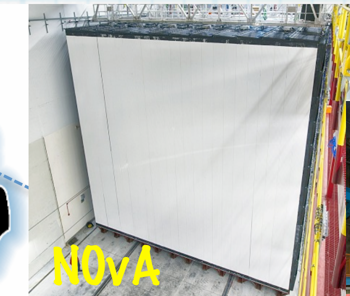
T2K

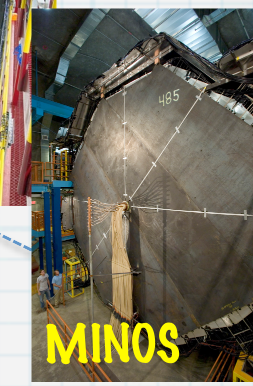


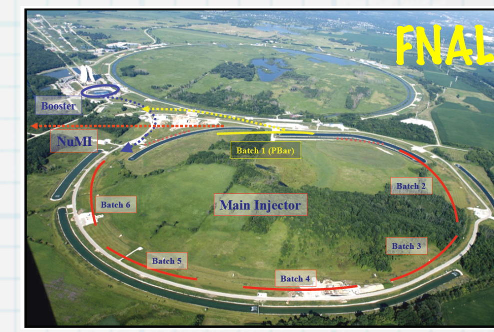
- J-PARC Neutrino beam
  + Super Kamiokande @ L=295km, 2.5°
  (Water cherenkov : fiducial mass = 22.5kt)
  - Start at 2009. Physics data taking from 2010.
  - Beam power: 220kW(now)→750kW(design)
    - Expected # of $\nu_\mu \rightarrow \nu_e$ oscillation assuming $\sin^2 2\theta_{13}=0.1, \delta_{CP}=0$ is 16.4 for 6.39×10^{20} POT
      → ~193 events for T2K proposed POT
      ($750kW\times5$ 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: $\delta(\sin^2 2\theta_{23})$~0.01

NOνA & MINOS+

- NOνA: Upgraded FNAL-NuMI (700kW)
  + 14kt liquid scintillator
  @ Ash Liver: L=810km, 14mrad (0.8°)
  - 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)



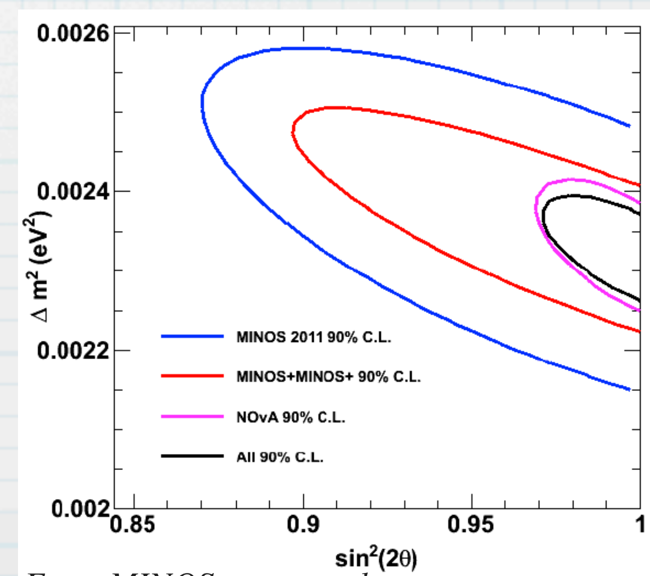




by NOνA collaboration *3 yr + 3 yr*

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

Physics Motivation of "current" LBL ν experiments

* Current LBL ν experiments search for $\nu_\mu \rightarrow \nu_e$ oscillation to find the oscillation via θ_{13}.

$$P(\nu_\mu \rightarrow \nu_e) \simeq \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2\left(\Delta m^2_{13} L/4E\right) \pm 4J_r \sin\delta_{CP} \sin\left(\Delta m^2_{12} L/4E\right) \sin^2\left(\Delta m^2_{13} L/4E\right) + \cdots$$

$$J_r \equiv \cos\theta_{12} \sin\theta_{12} \cos\theta_{23} \sin\theta_{23} \cos^2\theta_{13} \sin\theta_{13}$$

+ for ν
− for $\bar{\nu}$

  * If $\nu_\mu \rightarrow \nu_e$ oscillation is found, it is the signal of $\theta_{13} \neq 0$.
  * Reactor experiments with O(1)km baseline can also measure θ_{13}.

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \simeq 1 - \sin^2 2\theta_{13} \sin^2\left(\Delta m^2_{31} L/4E\right)$$

* If $\theta_{13} \neq 0$ is found, the CP violation term also can be non-zero.
  * $\nu_\mu \rightarrow \nu_e$ channel is also the prove for CP violation term.
  * The combination of independent θ_{13} measurement by reactor experiments can enlarge the sensitivity for δ_{CP} measurement by LBL experiments.

Big breakthrough in 2011~2013

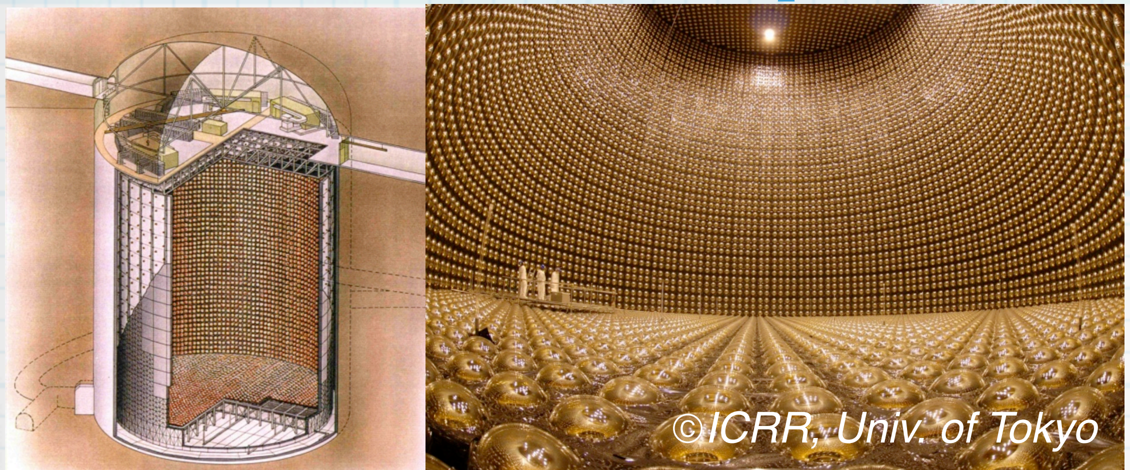
* Jun. 2011: T2K: 6 ν_e events for BG 1.5 ... 2.4σ
  * Fist indication of ν_e appearance
* Nov. 2011: Double Chooz : $\sin^2 2\theta_{13} = 0.085 \pm 0.029$(stat) $\pm\, 0.042$ (syst.)
* Mar. 2012: Daya Bay: $\sin^2 2\theta_{13} = 0.092 \pm 0.016$(stat) $\pm\, 0.005$ (syst.) ... 5.2σ
  * Fist observation of ν_e disappearance via θ_{13}
* Apr. 2012: RENO: $\sin^2 2\theta_{13} = 0.113 \pm 0.013$(stat) $\pm\, 0.019$ (syst.)... 4.9σ
* Jul. 2013: T2K: 28 ν_e events for BG 4.6 ... 7.5σ
  * Observation of ν_e appearance

$\nu_\mu \rightarrow \nu_e$ oscillation is observed by Reactor & LBL experiments.

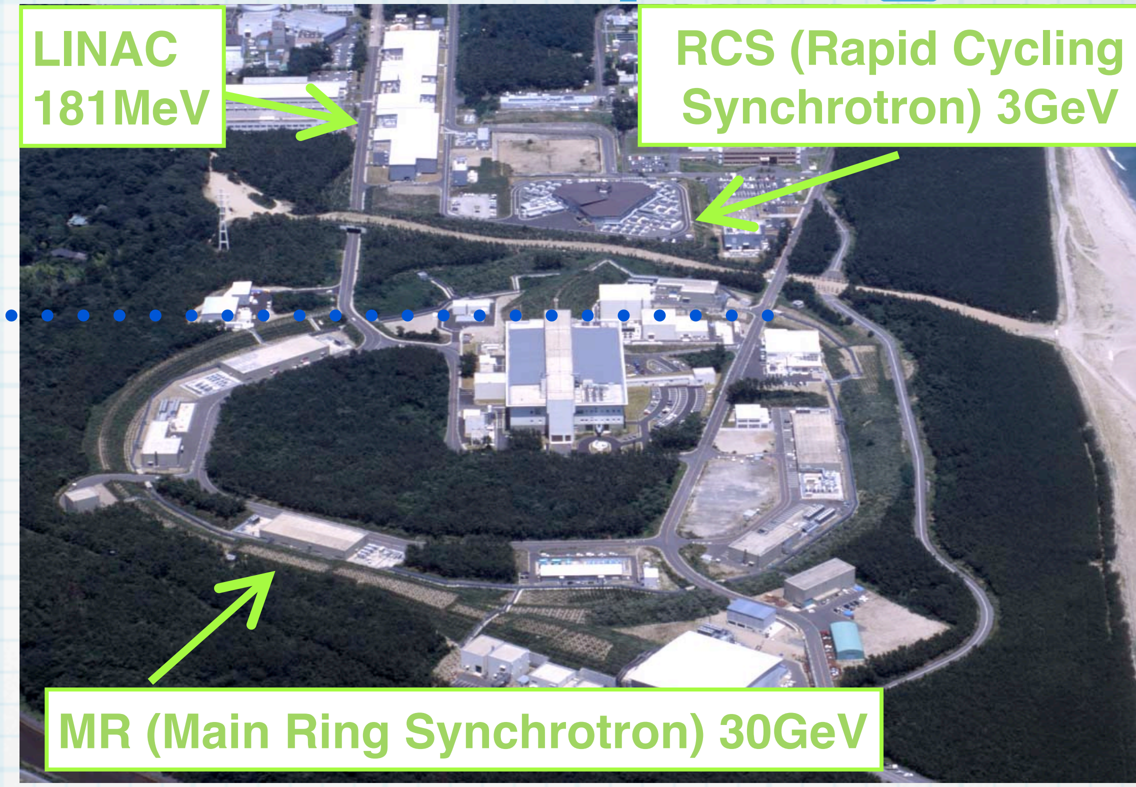
All mixing angles are determined.
θ_{13} is measured precisely!!

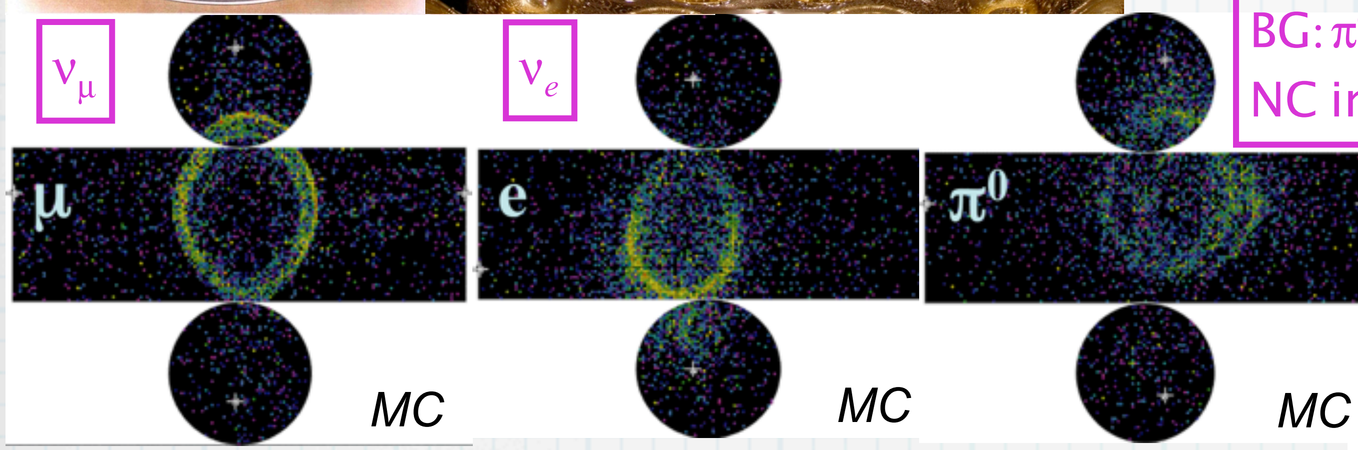
Reactor combined (PDG2012) : $\theta_{13} = 9.1° \pm 0.6°$
cf. world average for $\theta_{23} = 40.4°^{+4.6°}_{-1.8°}$

T2K experiment in 1-page

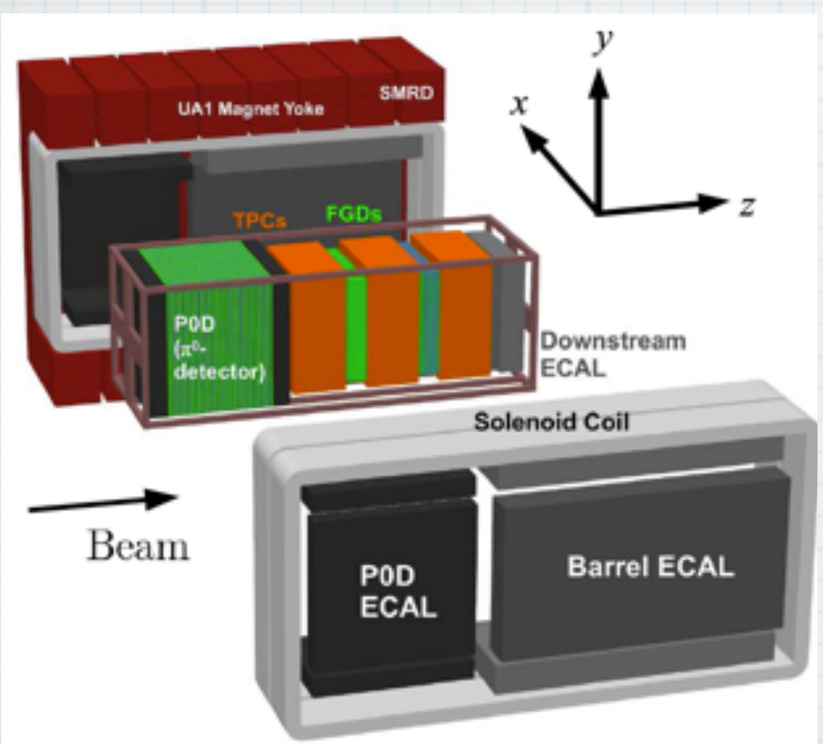


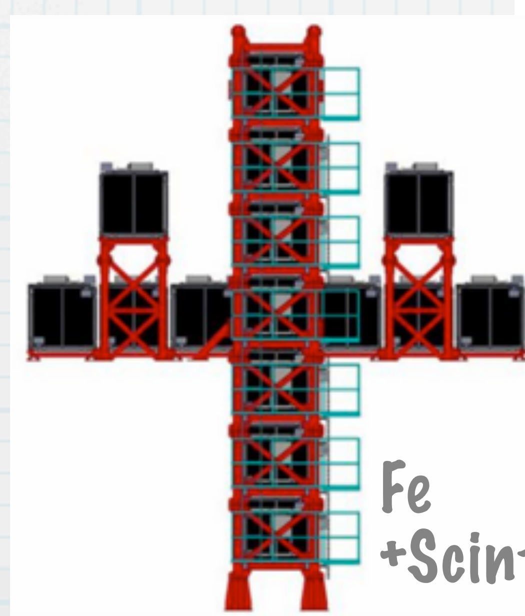
Far Detector
Synchronized
using GPS
timing info.

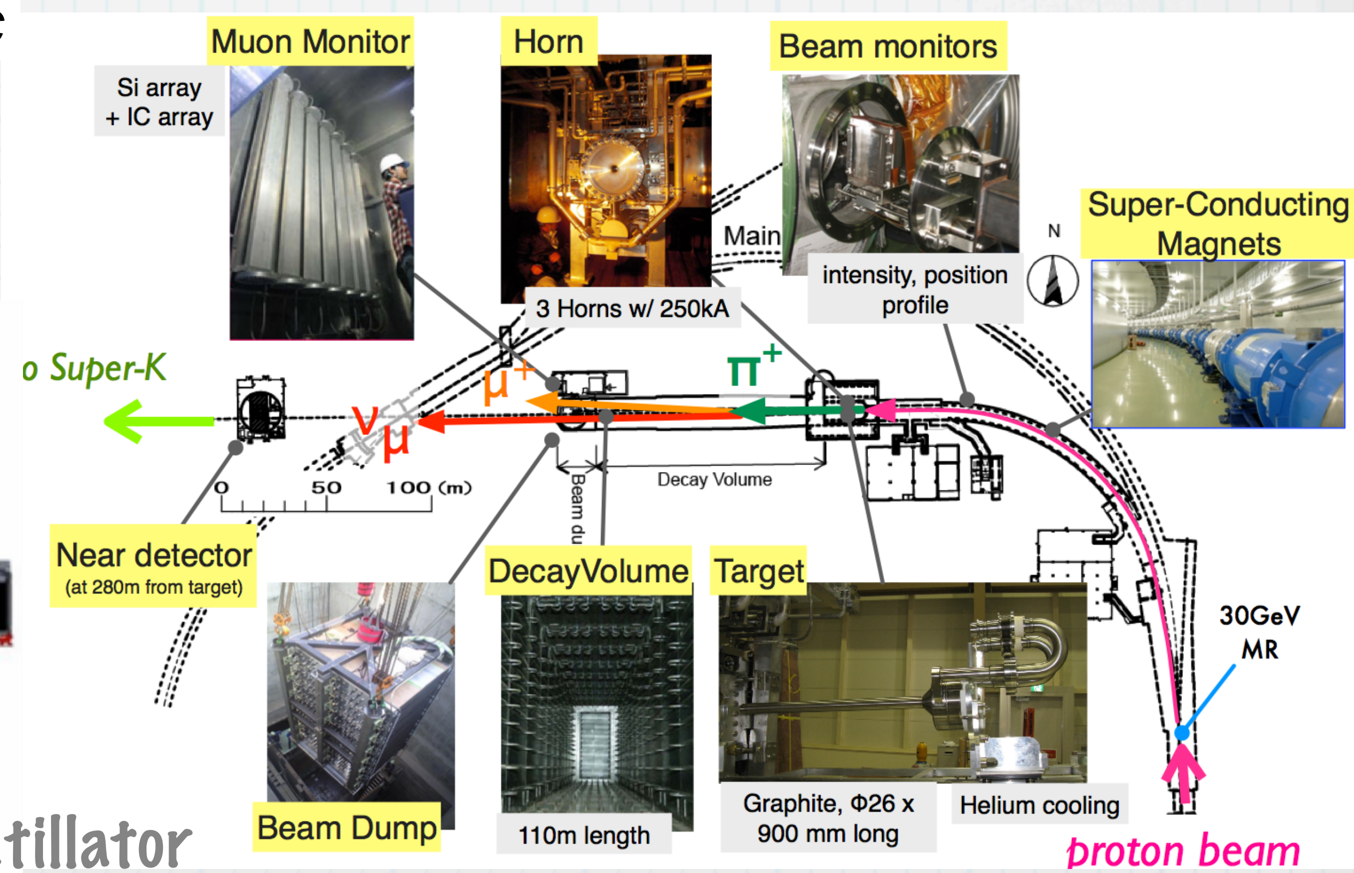




Two near detector
* On-axis (INGRID)
* Off-axis (ND280)

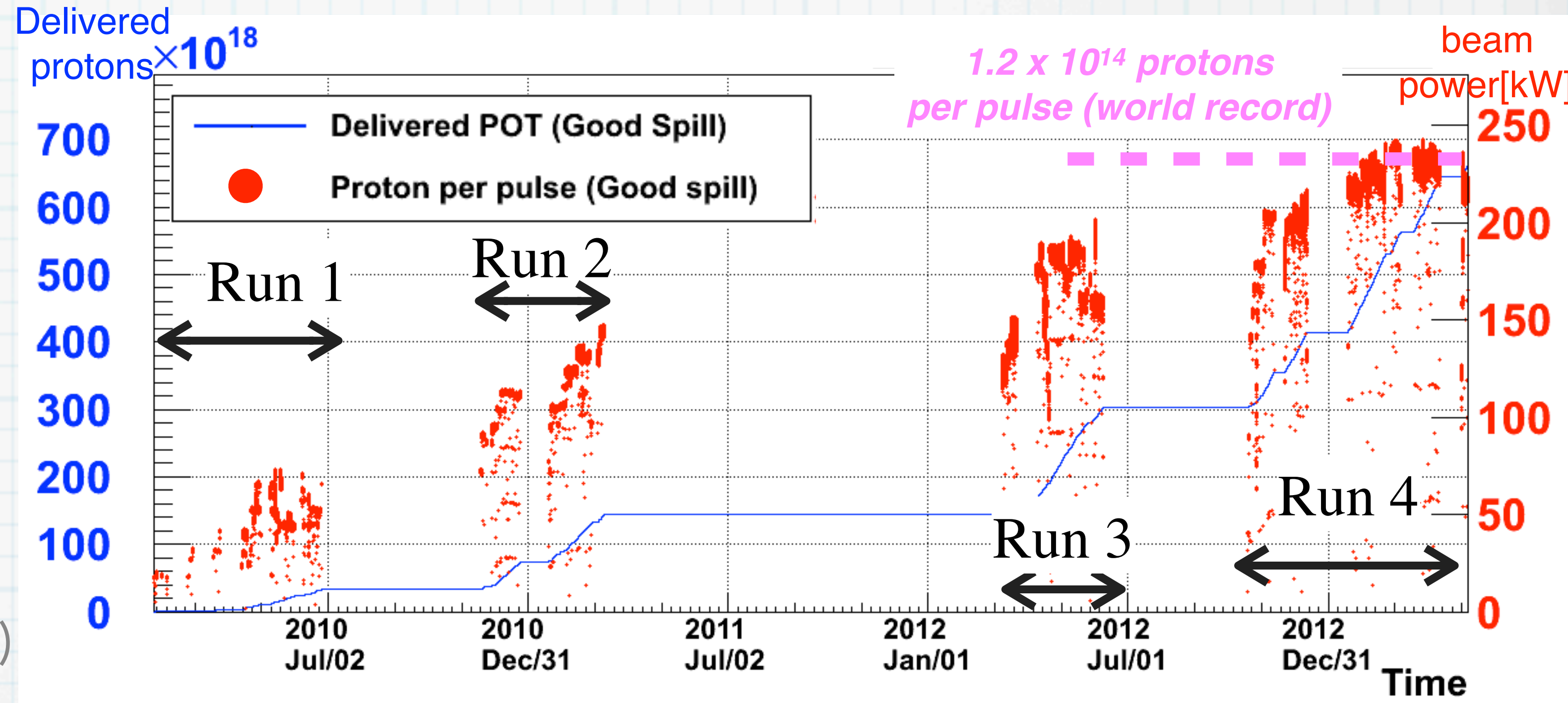




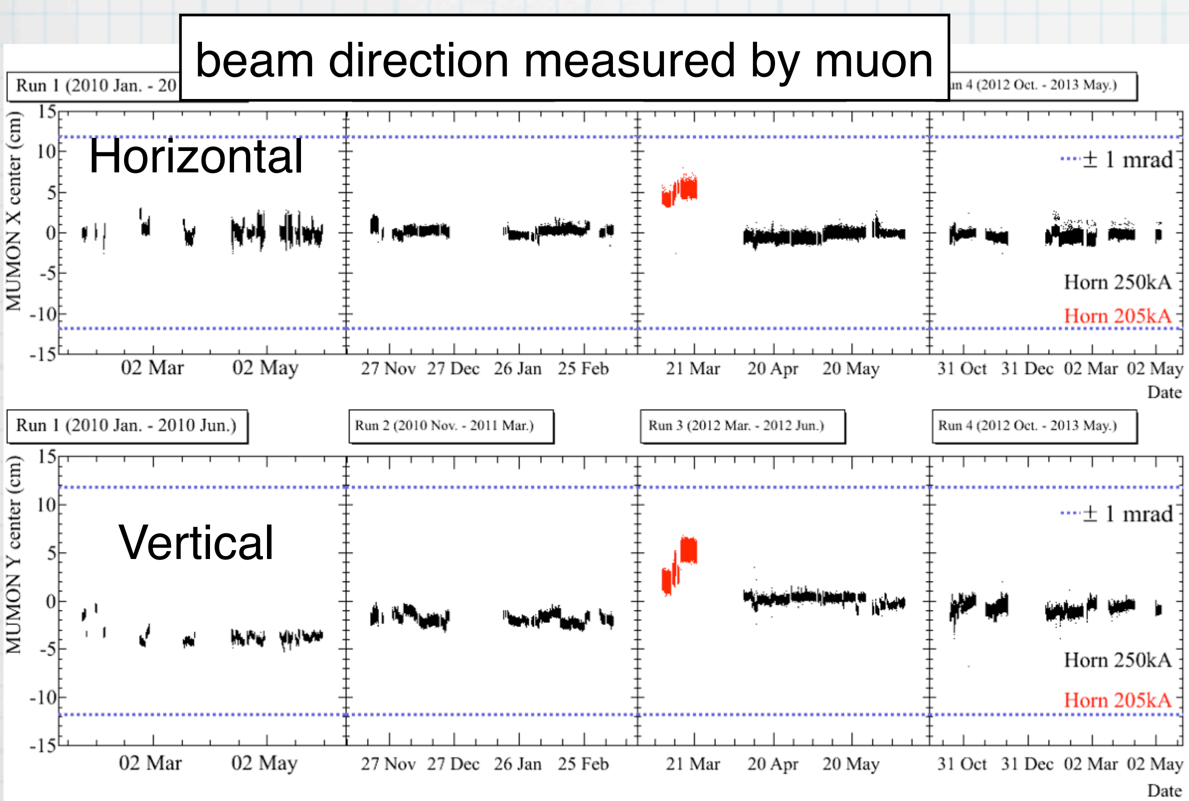


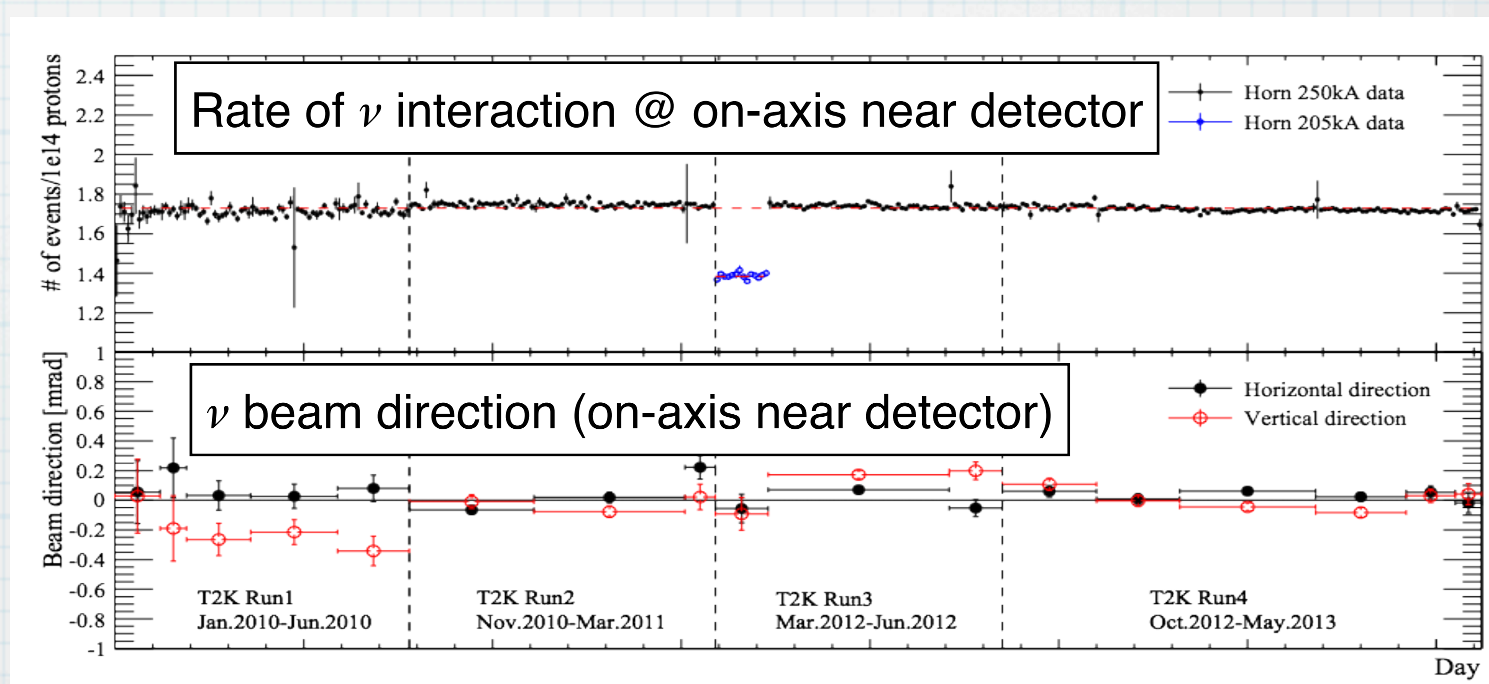
Latest results of T2K

* Total delivered beam so far: 6.63×10^{20} POT
    * 6.57×10^{20} POT used for ν_e appearance analysis (arXiv:1311.4750 [hep-ex])
    * 3.01×10^{20} POT used for ν_μ disappearance analysis (Phys. Rev. Lett. 111, 211803 (2013))



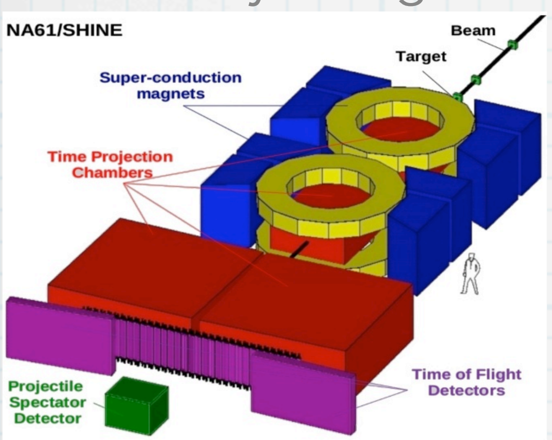
* Stability of beam is very stable
    * Neutrino event rate stability at on-axis neutrino detector = 0.7%
    * Direction stability <<1 mrad (1 mrad shift corresponds to ~20MeV beam energy shift)

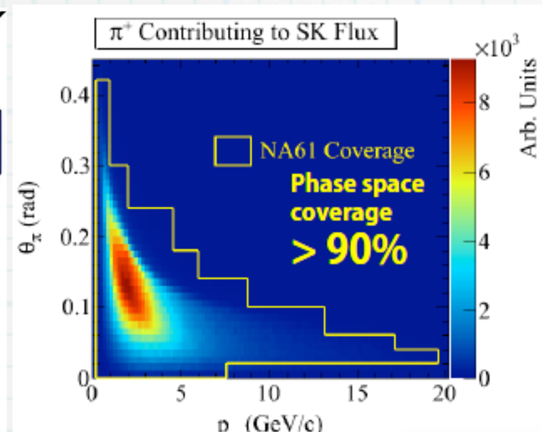


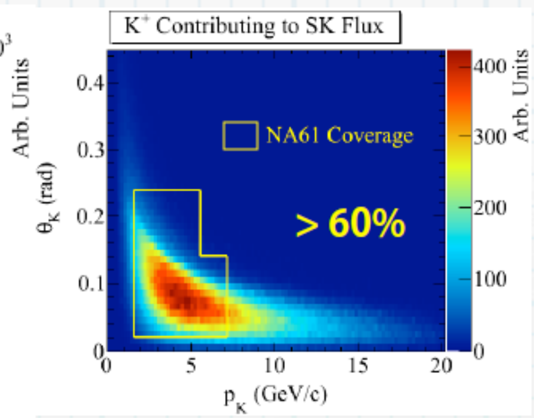


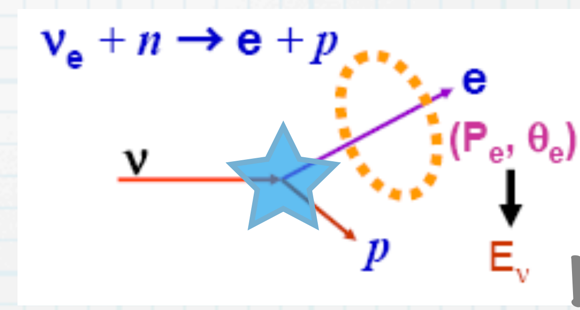
T2K Far detector flux prediction

- The neutrino flux is estimated based on the dedicated experimental data of p+C hadron production by the SHINE (CERN NA61) experiment.
  - Uncertainty of the flux at Far detector / Near detector around Oscillation Max. is 10~15%.
  - The energy dependent correlation between ND and FD also used.
- By using the ND measurement, flux at FD is estimated with 3~5% uncertainty.

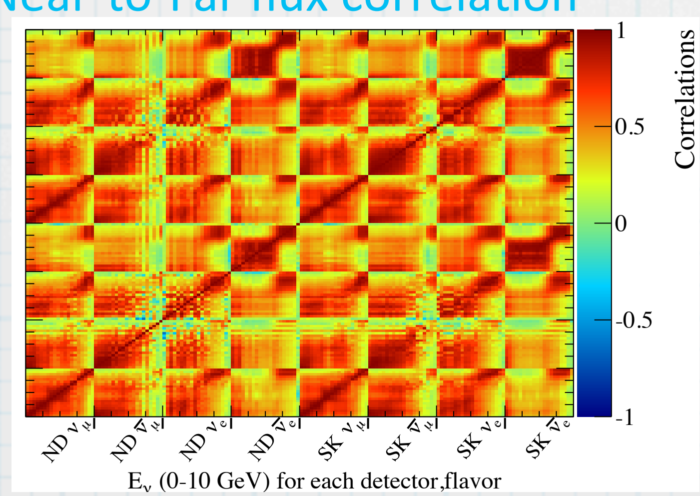








π, K (p,θ) distribution by external measurements (NA61+etc)
+ FLUKA/GEANT+GCALOR simulation
(Horn focusing, etc)
→ Near-to-Far flux correlation



ν flux

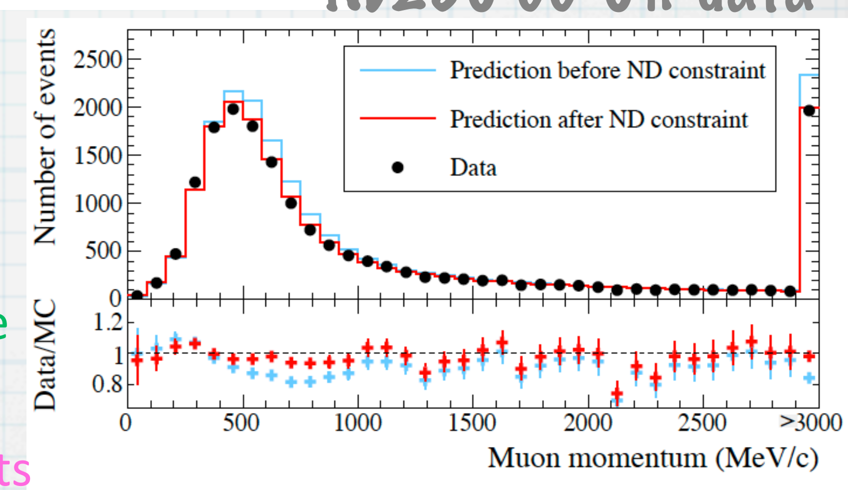
ν-N int. cross section

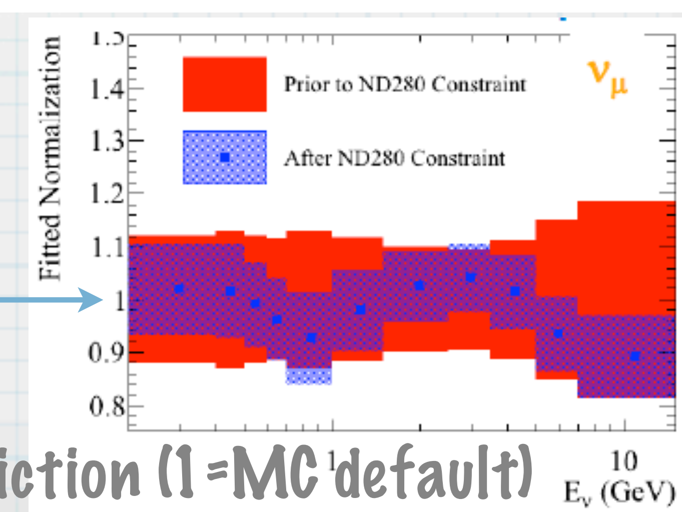
NEUT (model)
+ uncertainties from the external data

Near detector constraints (except for Near-Far uncorrelated parameters)

Far detector (flux × Int. cross section) prediction

ND280 CC-0π data

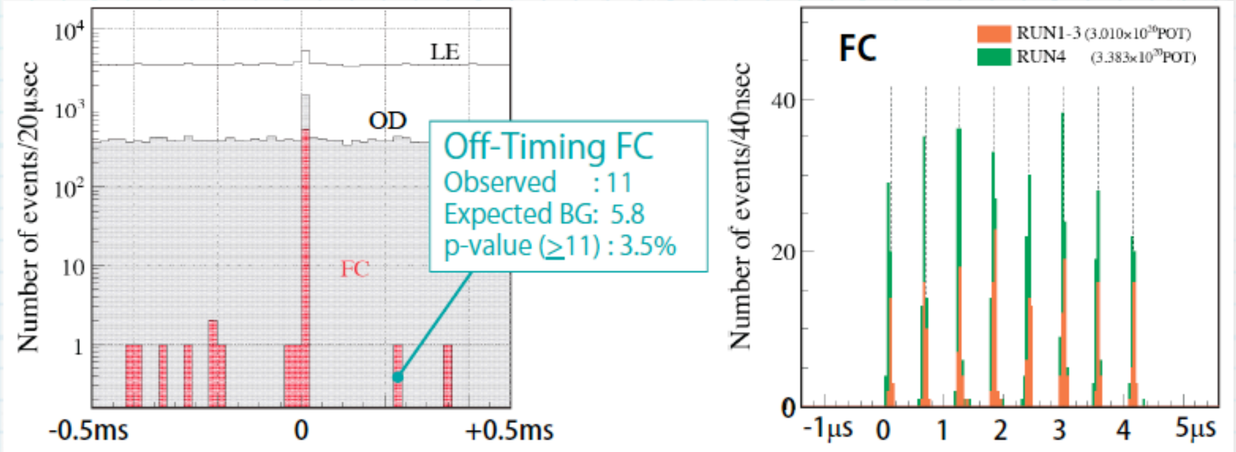




Flux × Int. cross-section prediction (1=MC default)

T2K event selection for oscillation analysis

* Find the on-timing "fully contained" (FC) event in Fiducial Volume (FC).
    * 377 events in 6.57×10^{20} POT (Expected non-accelerator-origin BG is 0.0085.)

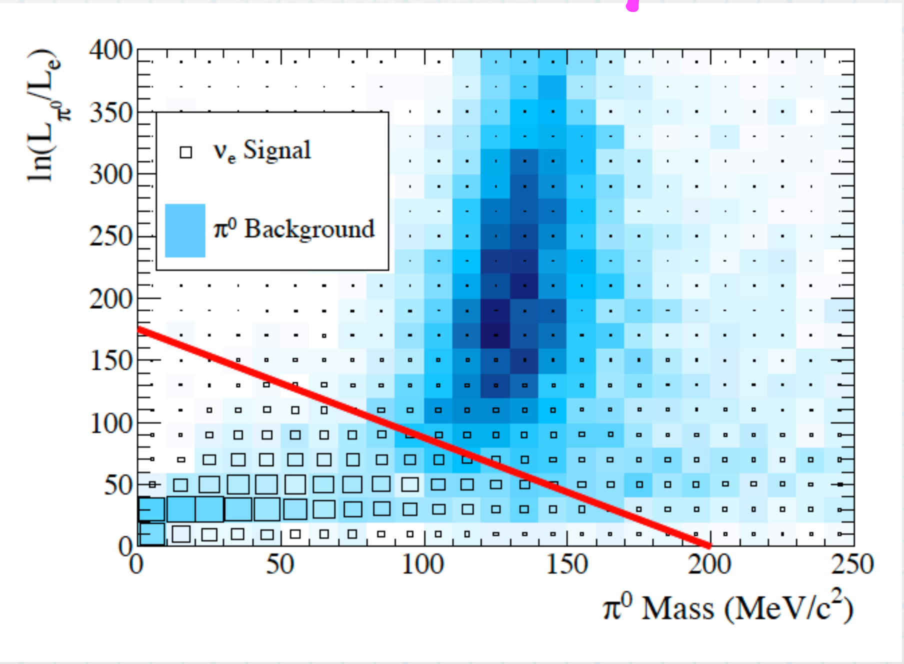


On-timing FCFV 1-Ring

Particle ID

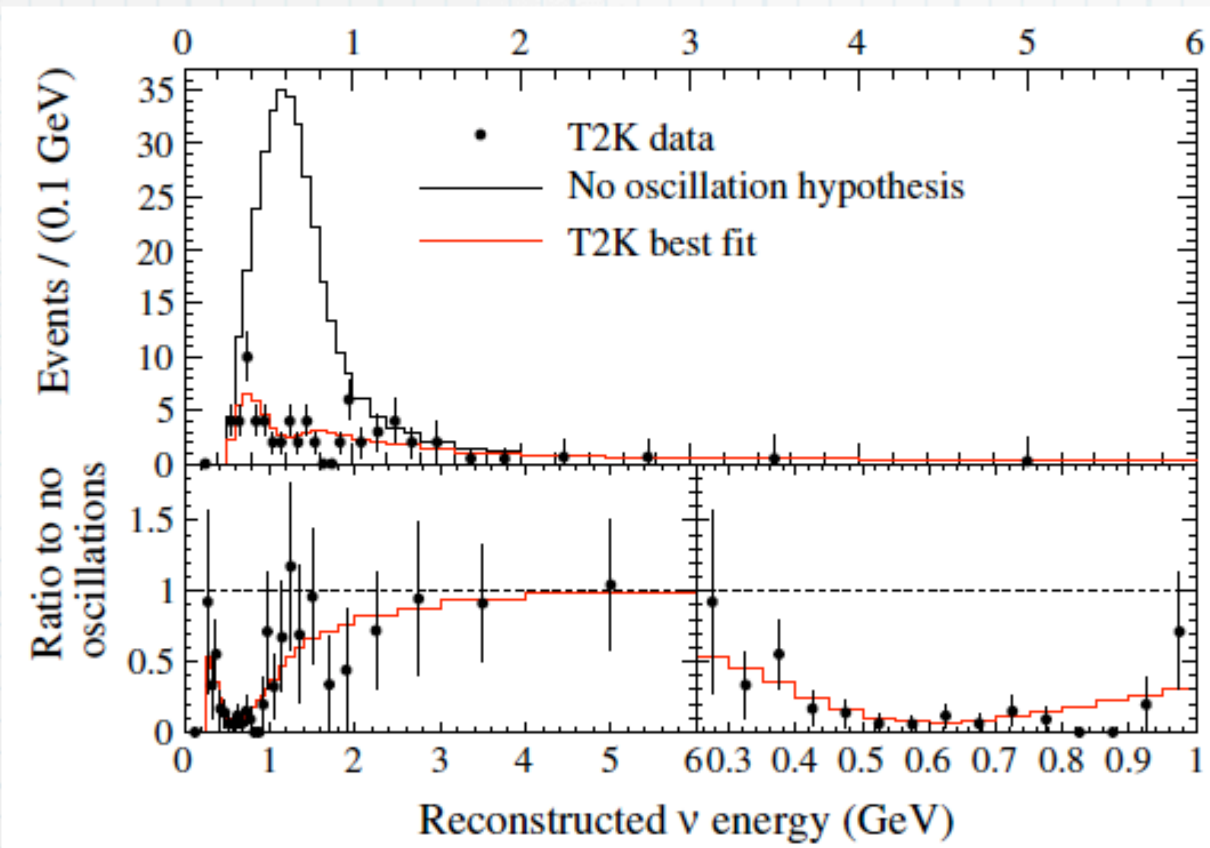
μ - like	e - like
$E_{visible}$ > 30MeV	$E_{visible}$ > 100MeV
# of Michel-e ≦ 1	w/o Michel-e
$p_\mu(rec)$ > 200MeV	π^0 rejection
ν_μ candidate	$E_\nu(rec)$ < 1.25GeV
	ν_e candidate

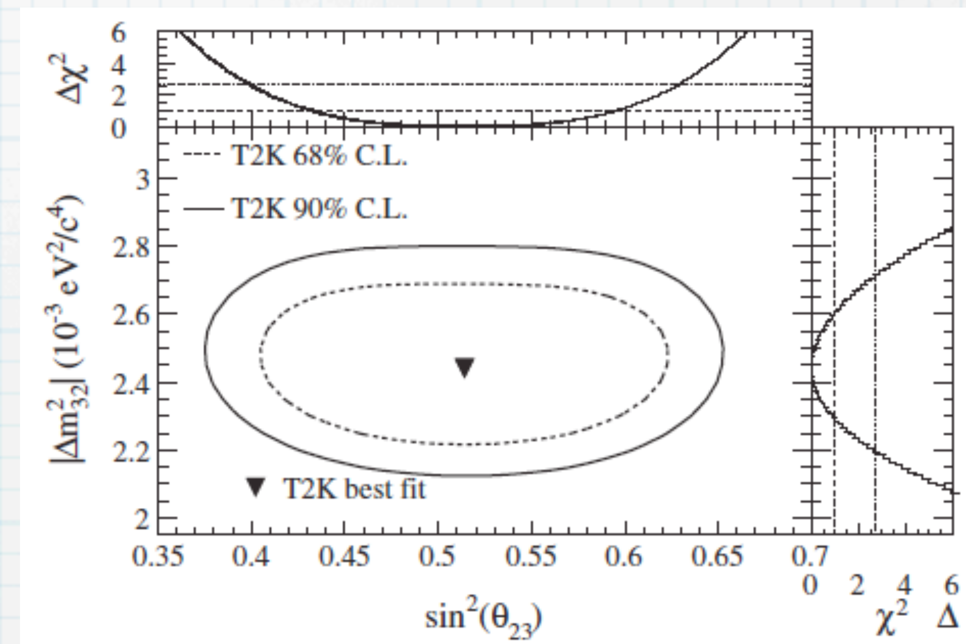
NC-π^0 rejection is significantly improved in 2013 analysis.



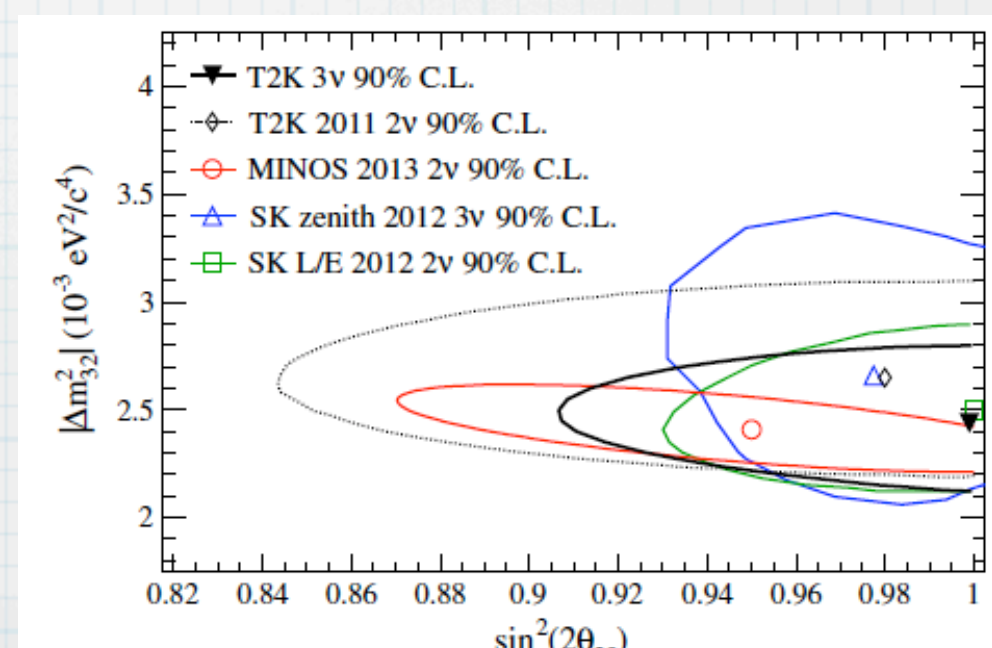
T2K ν_μ disappearance

- 58ν_μ candidates in 3.01×10^{20} POT data
  - Expected = 205±17 (syst.) for Null-oscillation assumption
  - Oscillation parameters is obtained from the reconstructed energy distribution.





$$P(\nu_\mu \to \nu_\mu) \simeq 1 - 4\cos^2(\theta_{13})\sin^2(\theta_{23})[1-\cos^2(\theta_{13}) \times \sin^2(\theta_{23})]\sin^2(1.27\Delta m^2_{32}L/E_\nu),$$



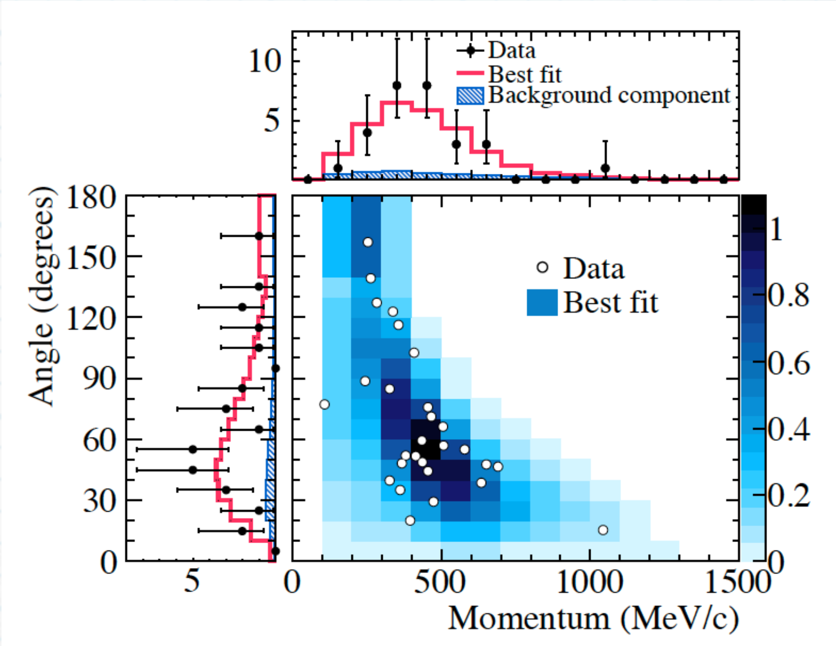
$|\Delta m^2_{23}| = 2.44^{+0.17}_{-0.15} \times 10^{-3}$ [eV^2]

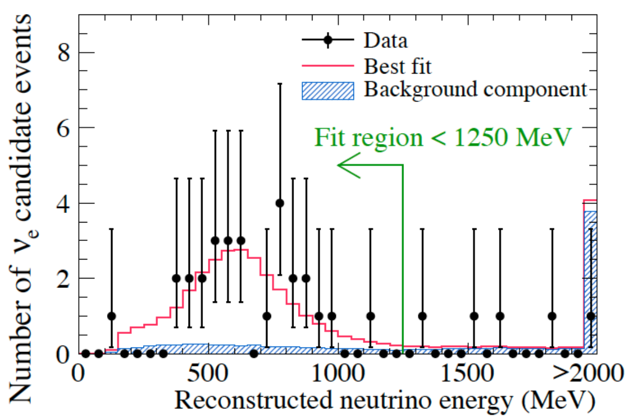
$\sin^2\theta_{23} = 0.054 \pm 0.082$

T2K ν_e appearance

* 28 ν_e candidates in 6.57×10^{20} POT data
  * Expected : 4.92±0.55 for $\sin^2\theta_{13}=0$

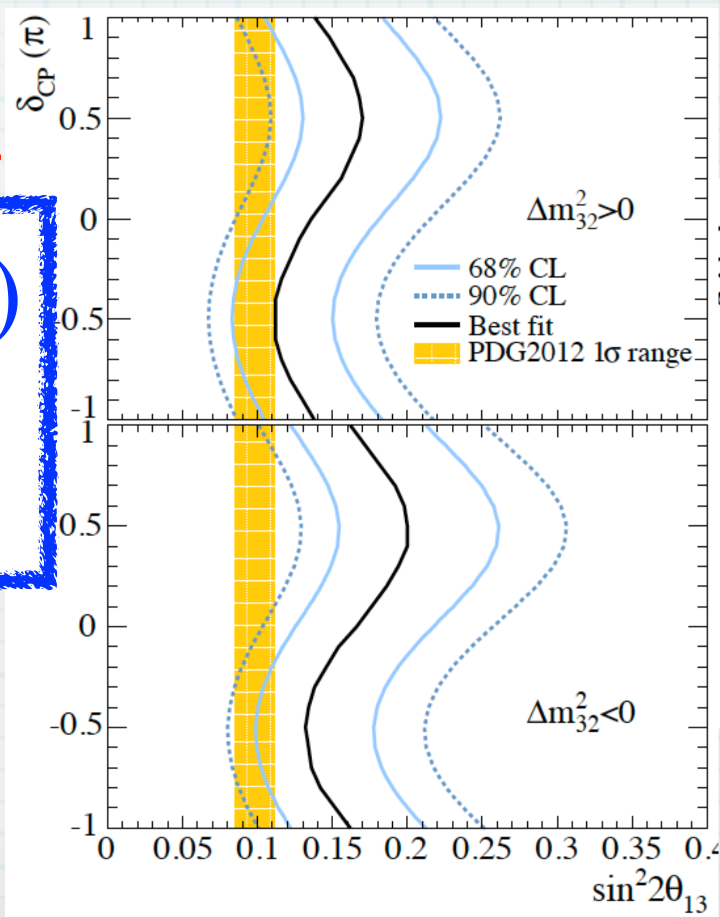
    (c.f 21.6 for $\sin^2\theta_{13}=0.1$)
* θ_{13} is estimated as the function of the δ_{CP} phase for each mass-hierarchy assumptions.
  * Two independent analysis gives consistent results.
    * Reconstructed electron-momentum and direction.
    * Reconstructed neutrino energy.
* First constraint on δ_{CP} by combining the reactor measurement.

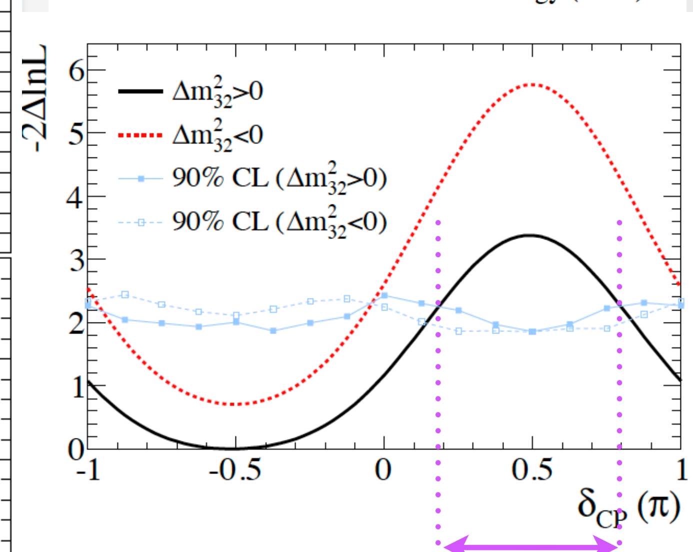




$$\sin^2 2\theta_{13} = 0.136^{+0.044}_{-0.033}(\text{NH})$$
$$= 0.166^{+0.051}_{-0.042}(\text{IH})$$

for $|\Delta m^2_{32}|=2.44\times10^{-3}[\text{eV}^2]$, $\sin^2\theta_{23}=0.5$, $\delta_{CP}=0$



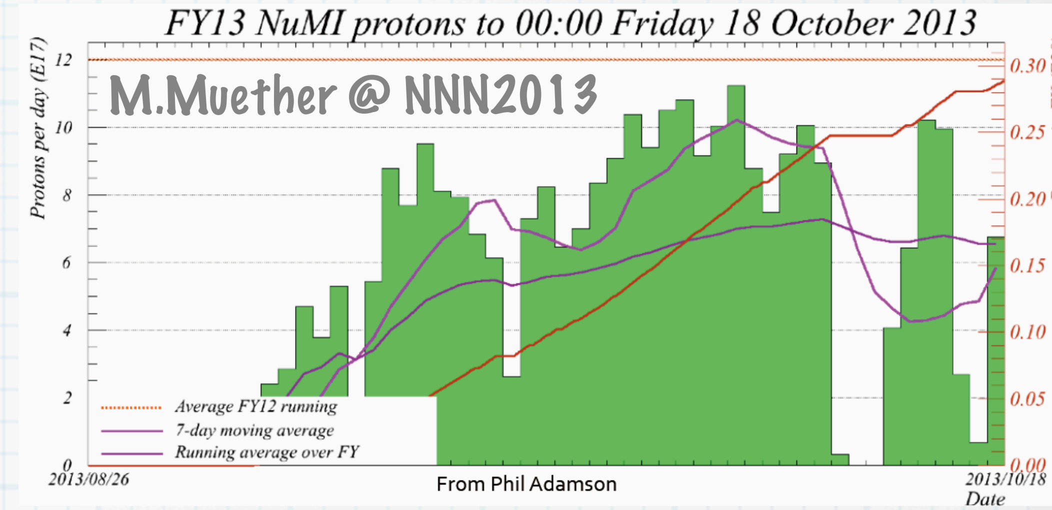


This region is disfavored.

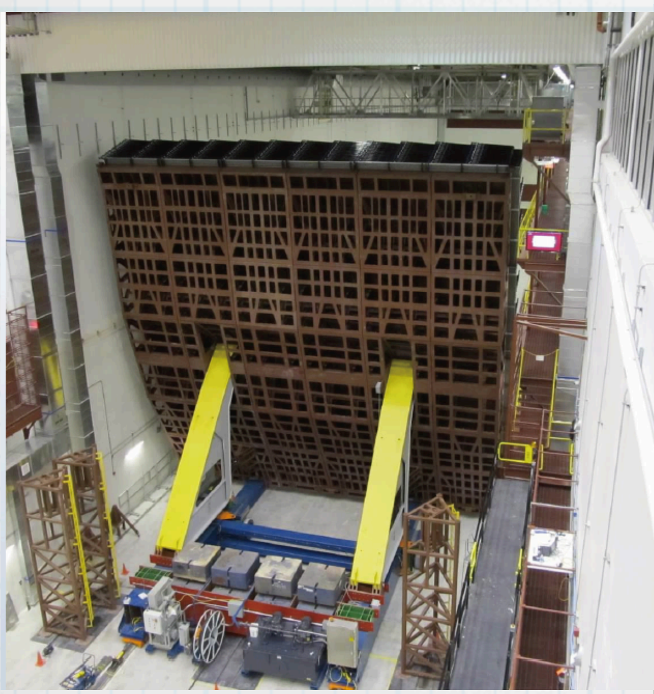
7.3σ significance to reject $\theta_{13}=0$.

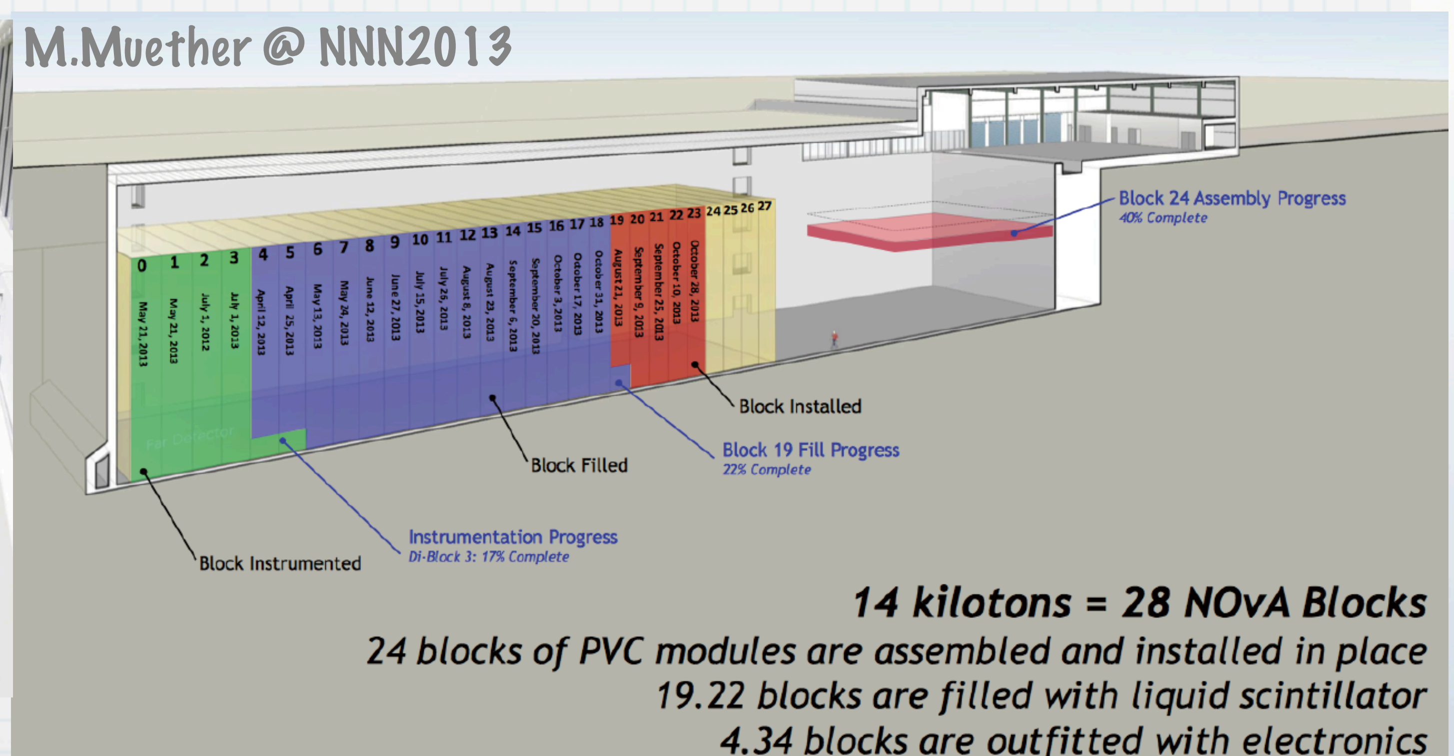
Status of NOνA

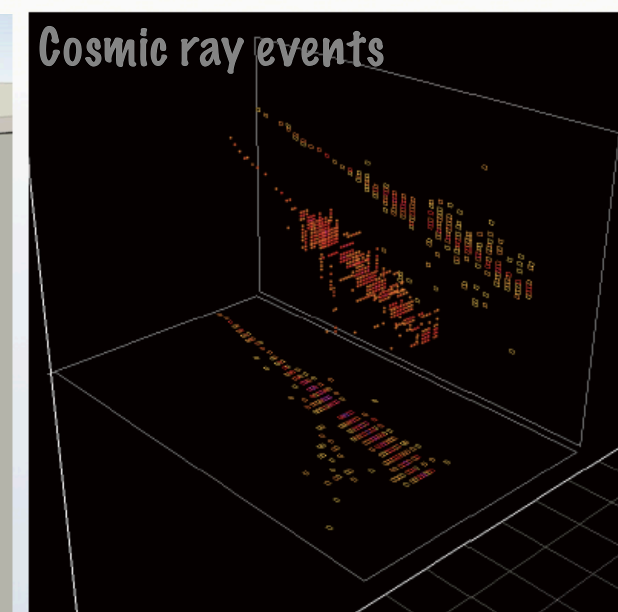
* Beam commissioning has been started.
  * Accelerator: Upgrade to 500kW is done.
    * Upgrade to ~700kW in 2014



* Far detector: Construction is in progress.
  * The data taking with installed part has been already started.
* Near-detector: installation will be done in early 2014.







First 3D track recorded in the detector. Event was recorded on 21 May 2013.

Next step: MH & CP Violation

* Next questions which LBL ν experiment can address.
  * CP violation:

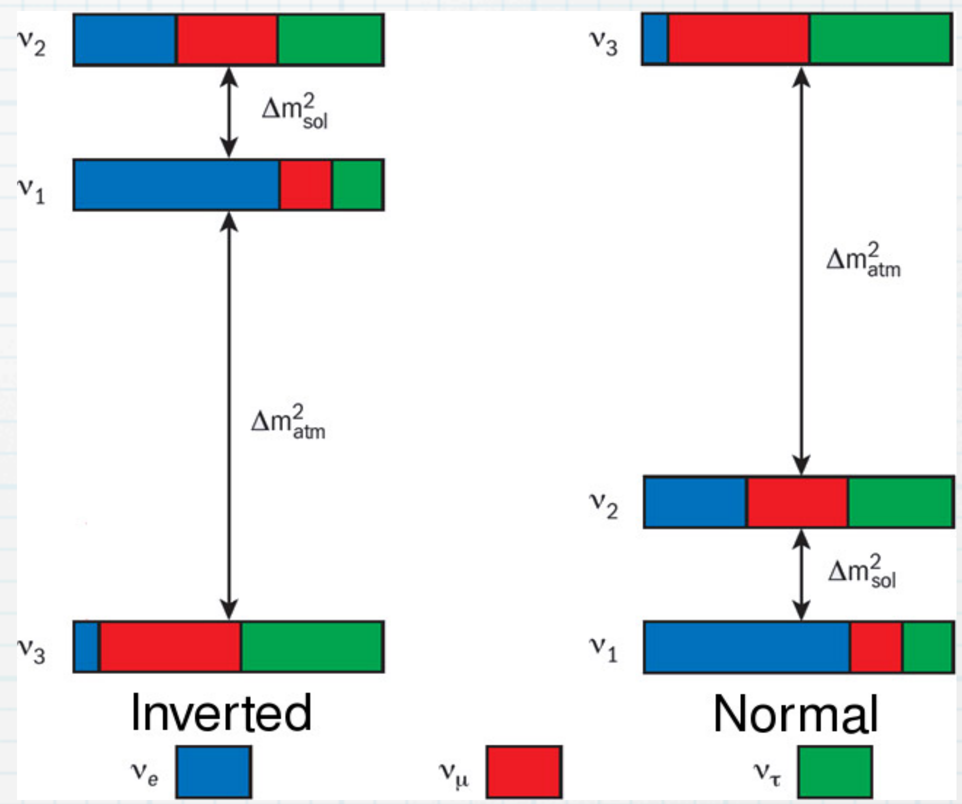
    $P(\nu_\alpha \rightarrow \nu_\beta) = P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta)$

    or $P(\nu_\alpha \rightarrow \nu_\beta) \neq P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta)$

  * Mass hierarchy:

    $\Delta m^2{}_{13}$<0(Normal)

    or $\Delta m^2{}_{13}$>0(inverted)



  * Maximal "atmospheric" mixing? : $\sin^2 2\theta_{23}=1$ (i.e. $\sin^2\theta_{23}=0.5$)

    If not, $\sin^2\theta_{23}<0.5$ ($\theta_{23}<45°$) or $\sin^2\theta_{23}>0.5$ (i.e. $\theta_{23}>45°$)

    [Octant degeneracy]

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

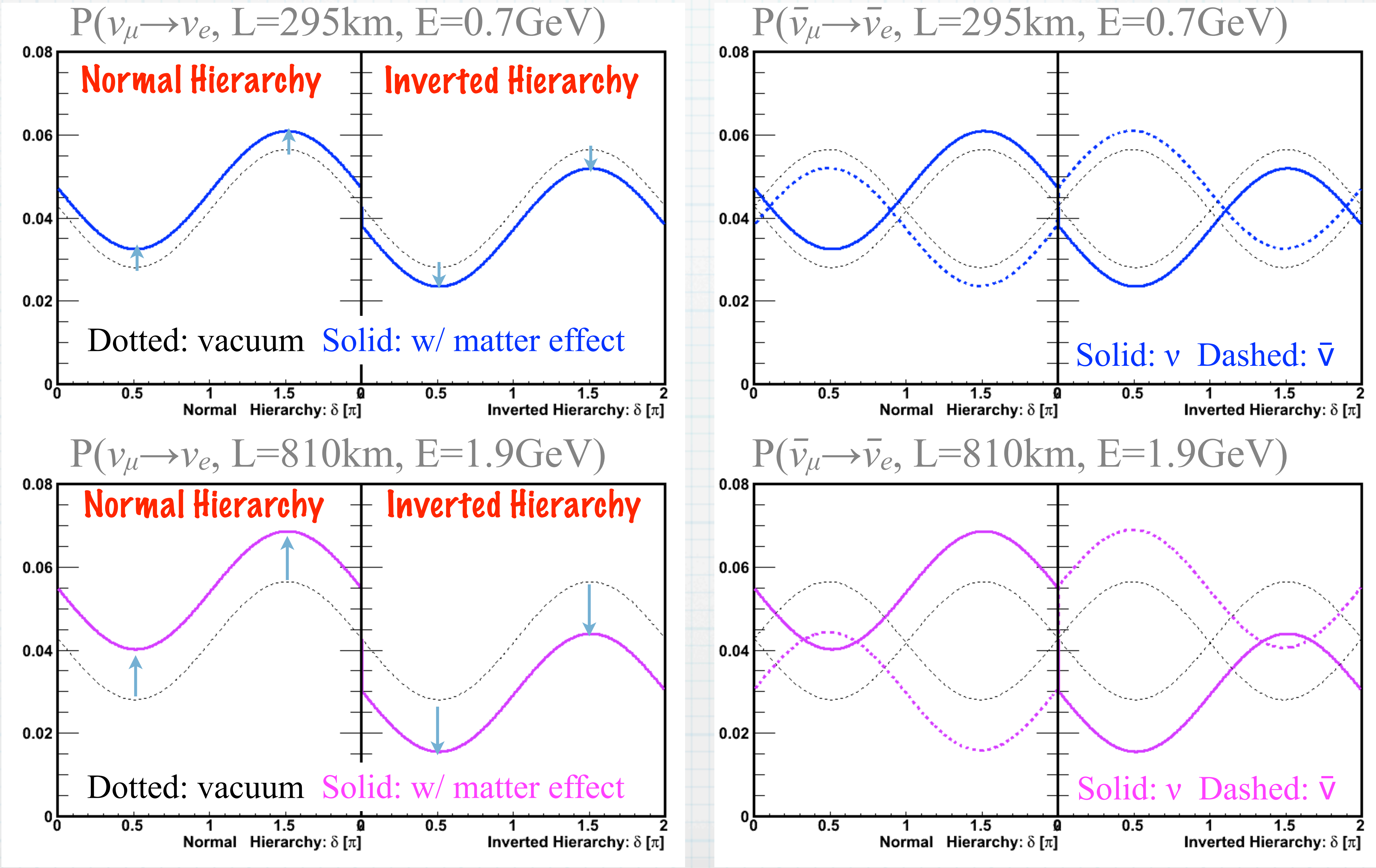
$$P(\nu_\mu \to \nu_\mu) \simeq 1 - (\underbrace{\cos^2\theta_{13}\sin^2 2\theta_{23}}_{\text{Leading}} + \underbrace{\sin^2\theta_{23}\sin^2 2\theta_{13}}_{\text{Next-to-leading}})\left(\sin^2\frac{\Delta m_{31}^2 L}{4E}\right) + \ldots$$

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

  - 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 <u>different base-line length</u>. (T2K & NOνA, MINOS+)

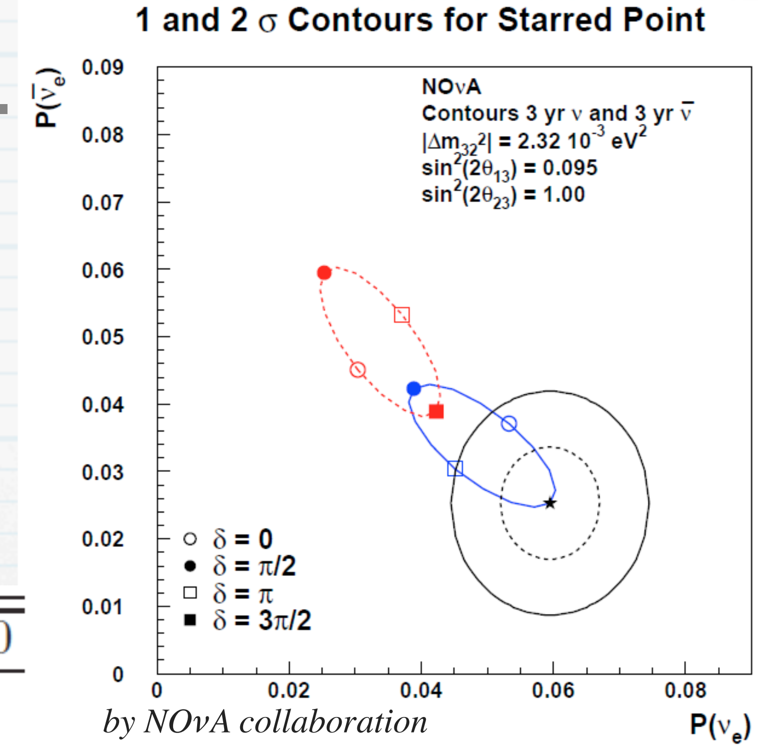
MH & CPV in $P(\nu_\mu \to \nu_e)$

* For demo., the maximum oscillation probability is shown here.



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 oscillation mechanism.
  - Expected asymmetry is ~27% (max).
  - Size of CPV ~ Measurement precision.



by NOvA collaboration

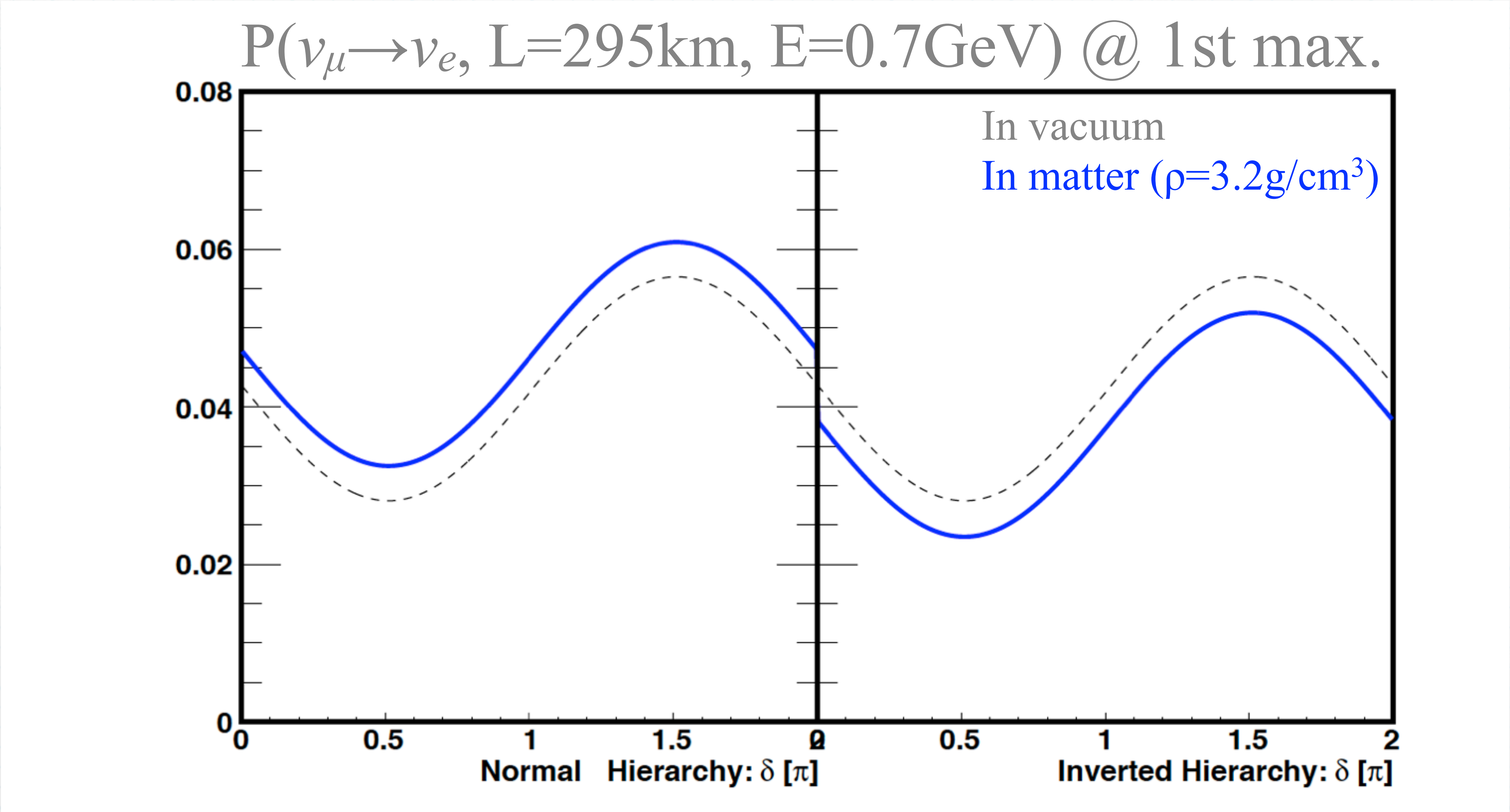
Systematic uncertainty of ν_e event rate prediction in T2K [%]

Error source [%]	$\sin^2 2\theta_{13} = 0.1$	$\sin^2 2\theta_{13} = 0$
Beam flux and near detector	2.9	4.8
(w/o ND280 constraint)	(25.9)	(21.7)
ν interaction (external data)	7.5	6.8
Far detector and FSI+SI+PN	3.5	7.3
Total	8.8	11.1

- **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 & ($0 < \delta < \pi$)



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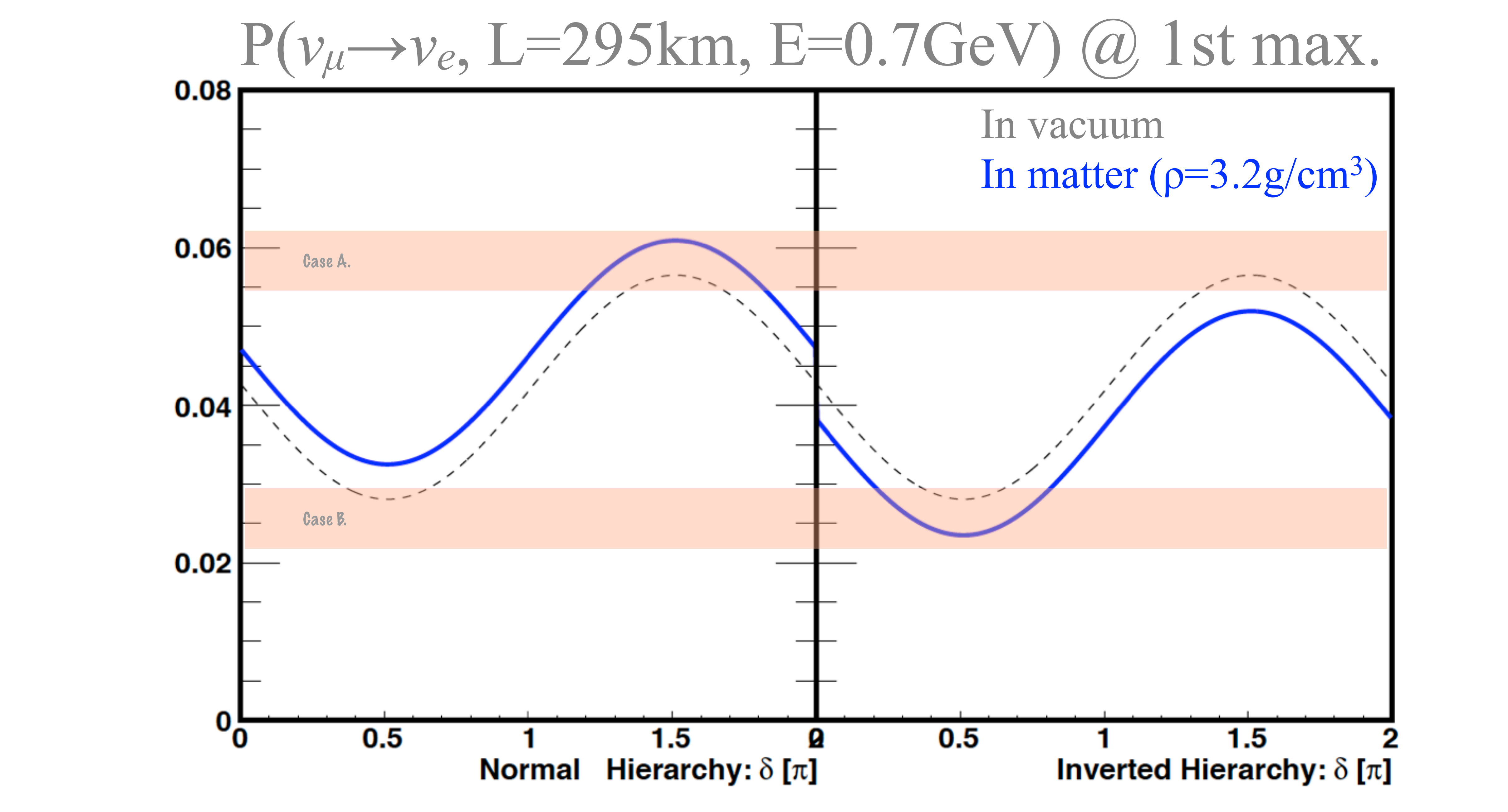
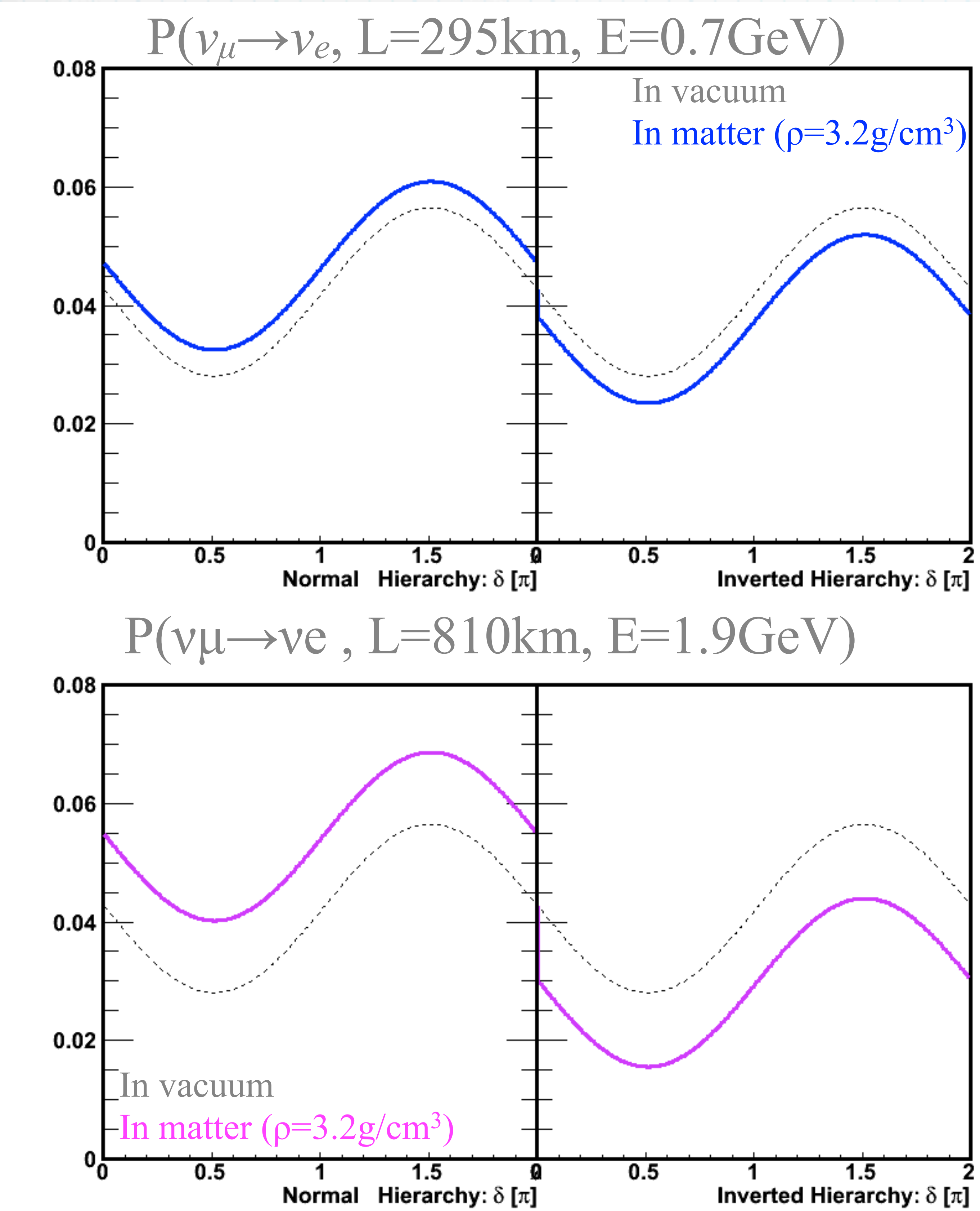


How to obtain the hint of CPV/MH

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



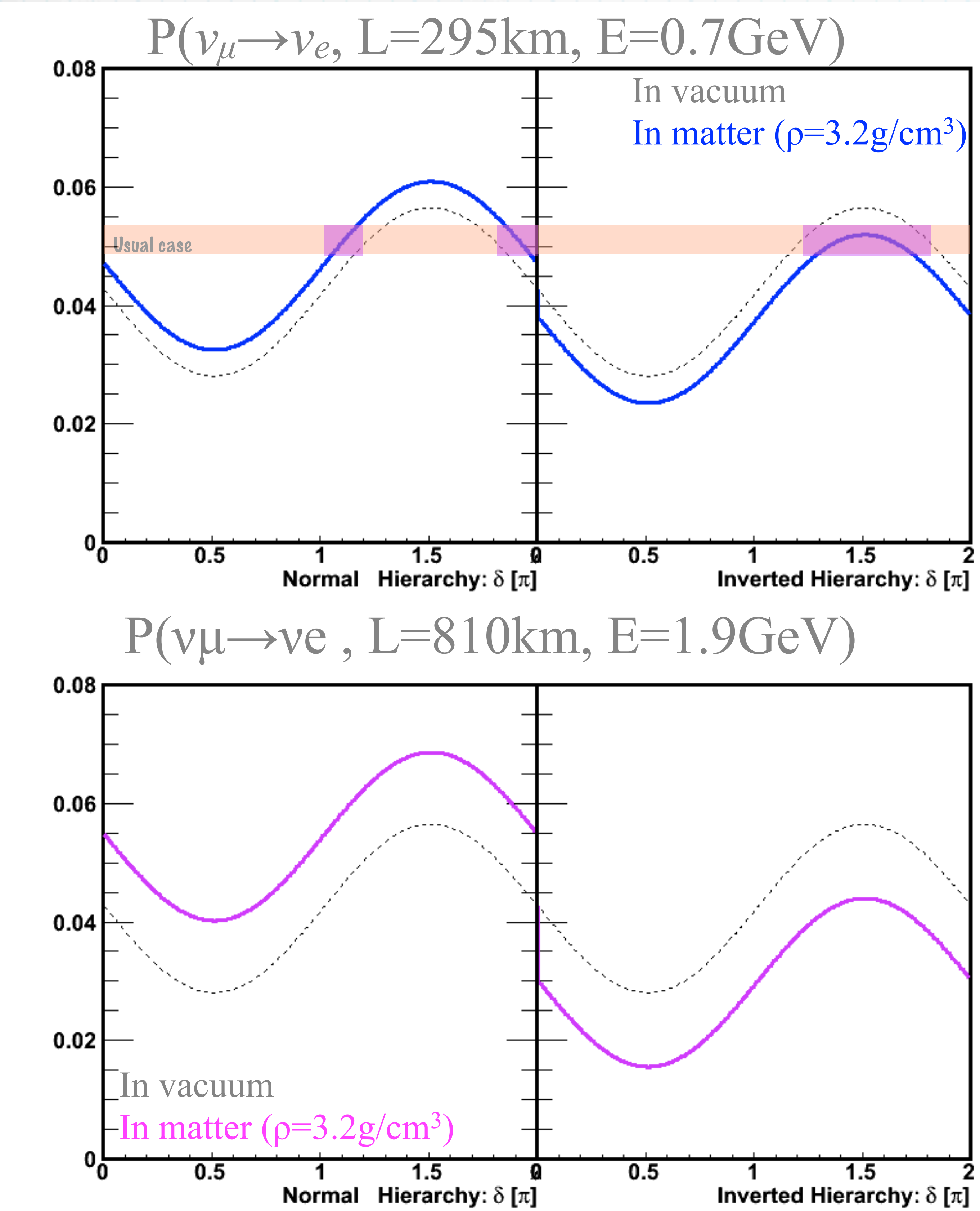
Allowed region of MH and CPV is not determined uniquely from single experiment.

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.

How to obtain the hint of CPV/MH

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



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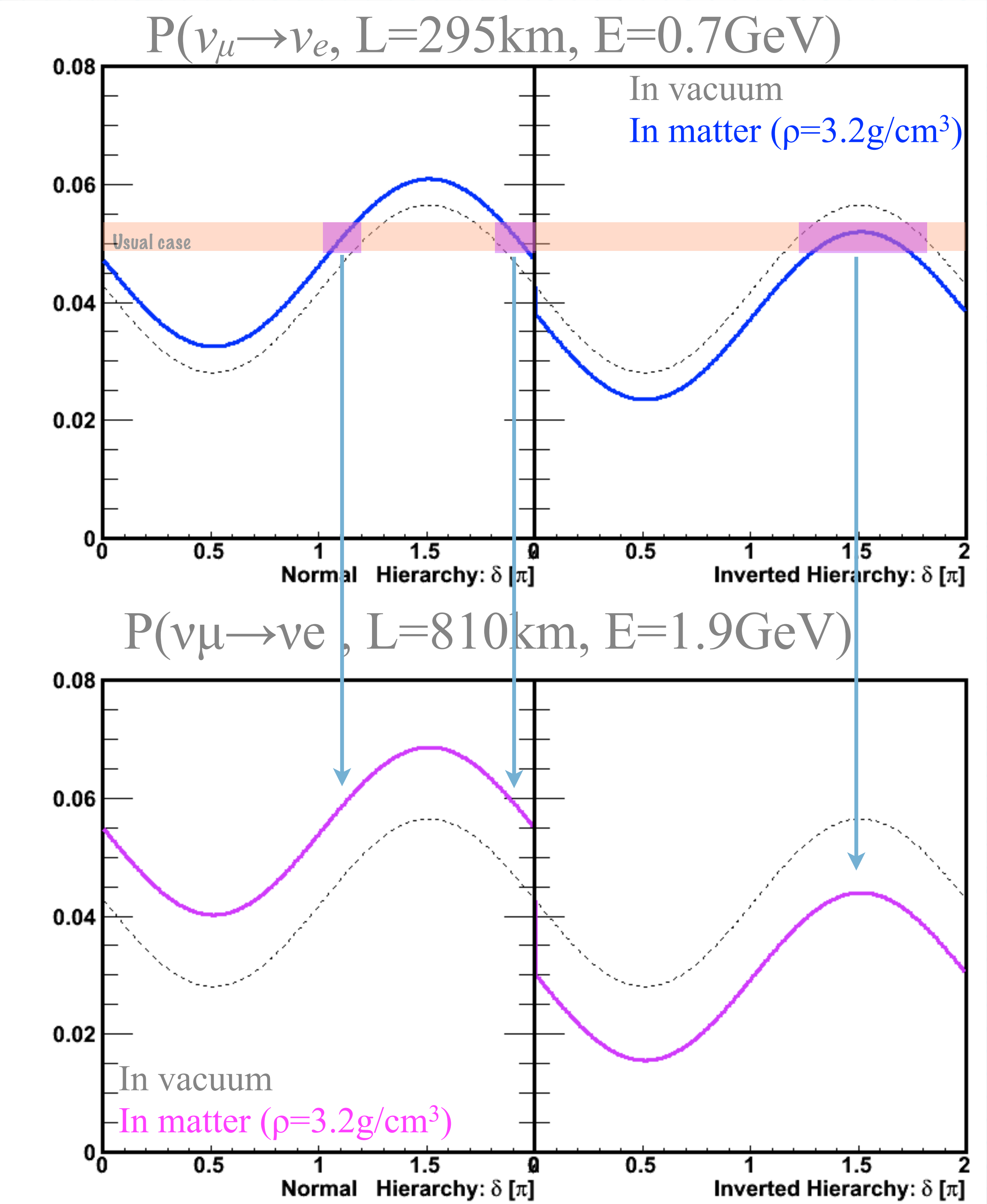

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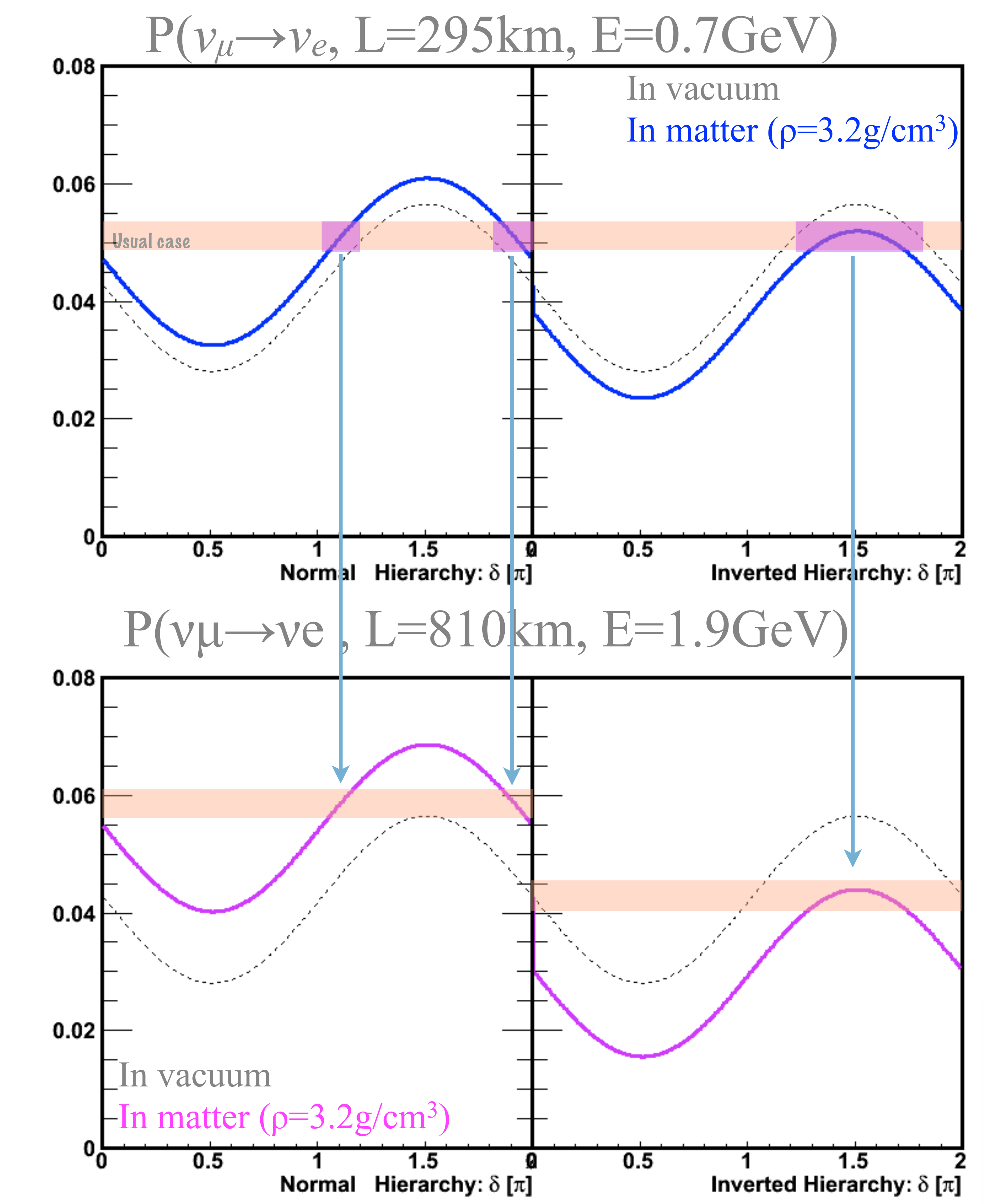


Allowed region of MH and CPV is not determined uniquely from single experiment.

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

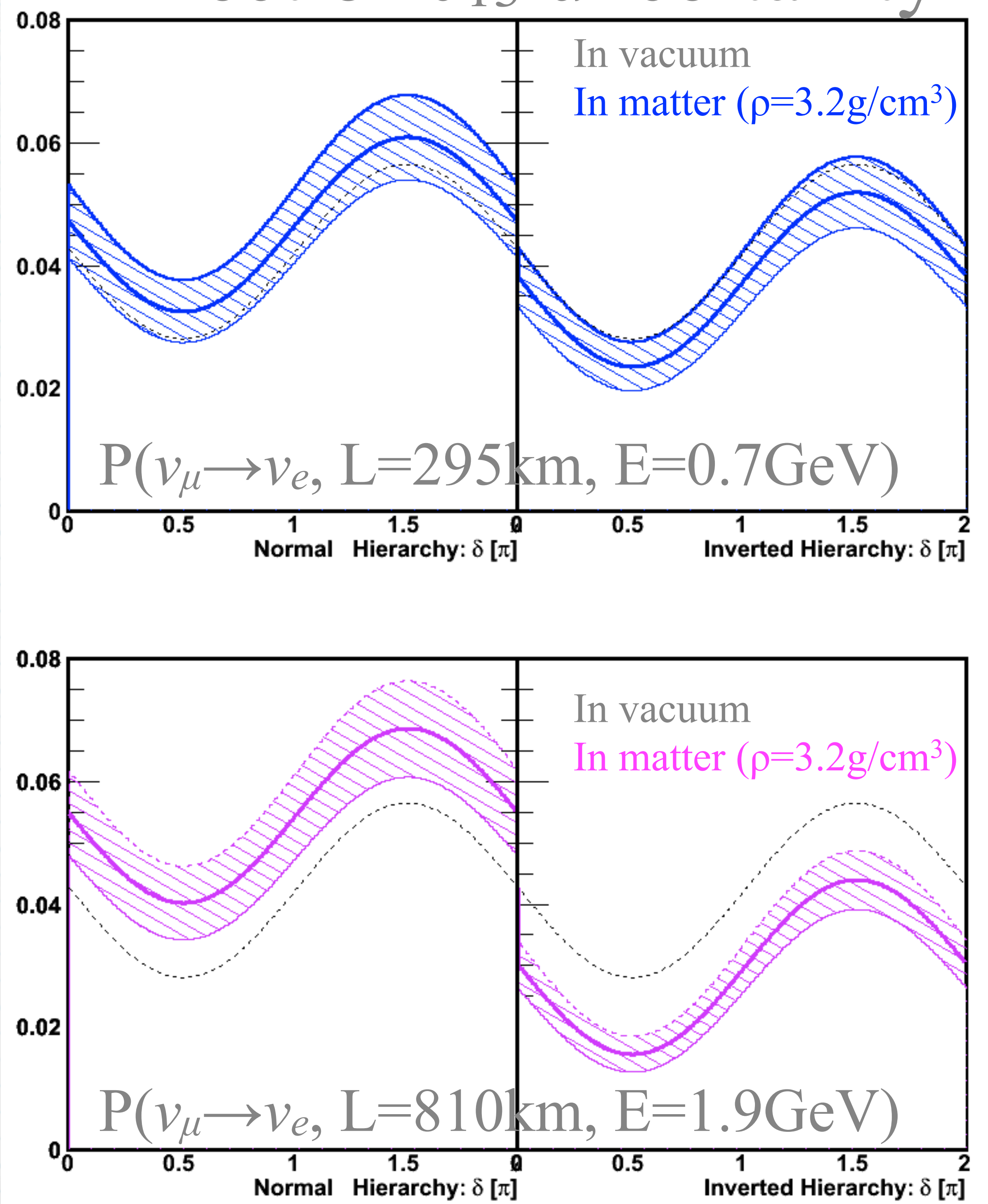
The observation by another experiment may reject one of the MH assumptions.

But, in reality.

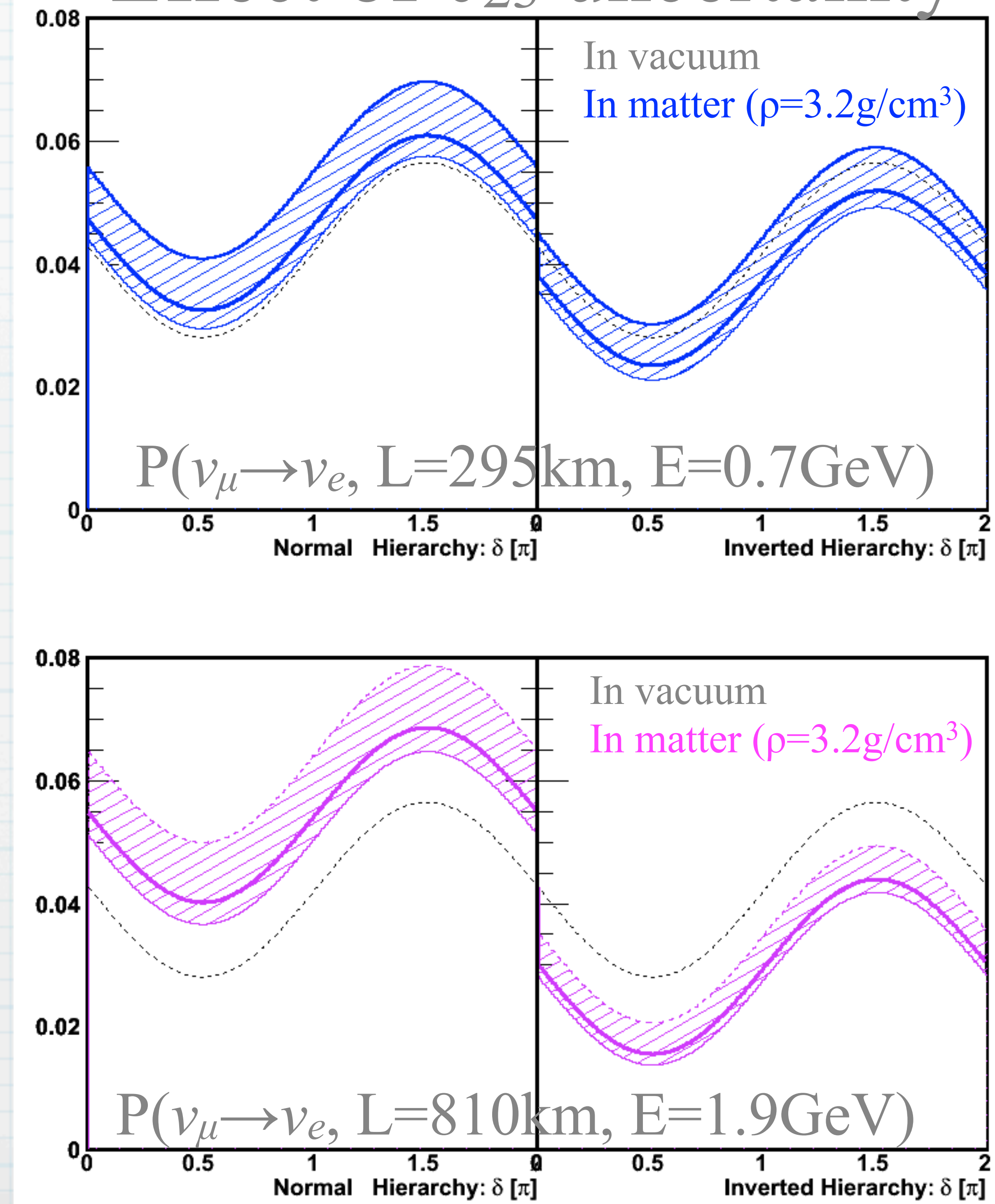
* Precise measurement of the mixing angle is quite important.
* PDG2012: $\sin^2\theta_{13} = 0.0251 \pm 0.0034$(REACTOR), $\sin^2\theta_{23} = 0.42^{+0.08}_{-0.03}$

Due to "Octant degeneracy"

Effect of θ_{13} uncertainty



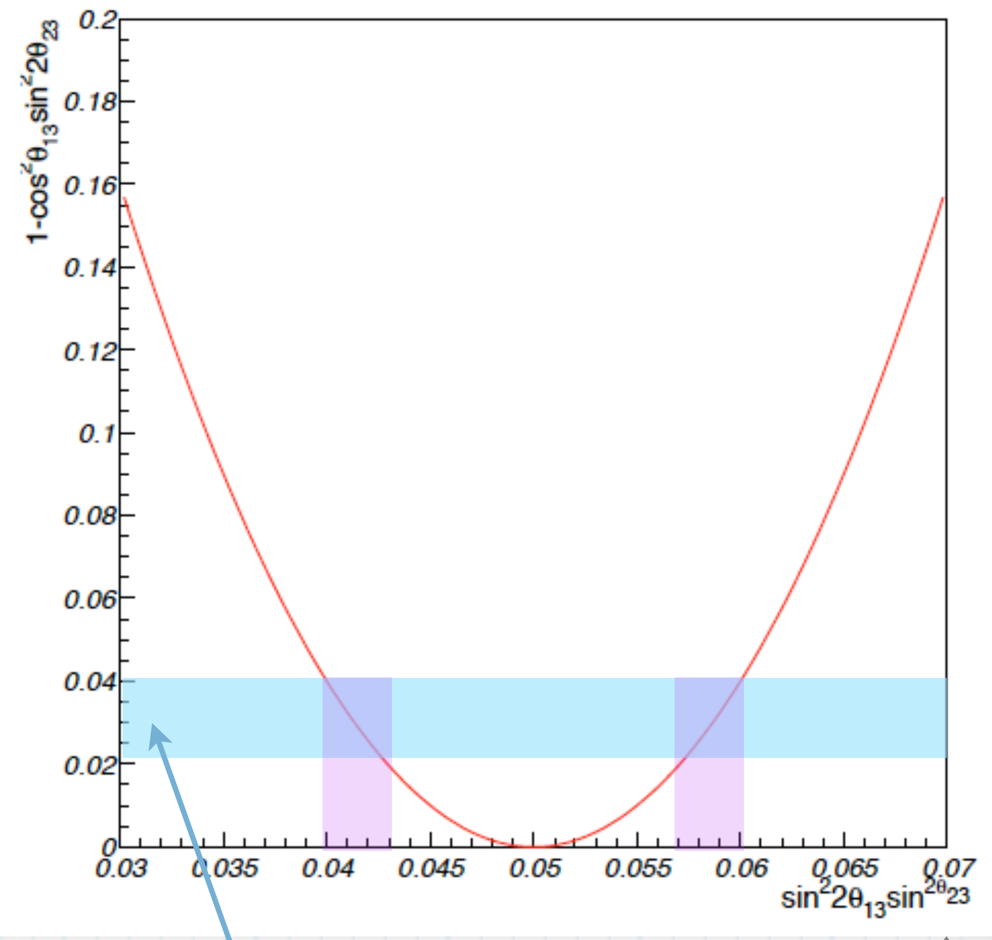
Effect of θ_{23} uncertainty



Degeneracy for θ_{23}

- θ_{23} is dominantly determined by the ν_μ disappearance.
  - $P_{min}(\nu_\mu \to \nu_\mu) \sim 1 - \cos^2\theta_{13}\underline{\sin^2 2\theta_{23}}$
- θ_{23} dependence for ν_e appearance is a function of $\sin^2\theta_{23}$.
  - $P_{max}(\nu_\mu \to \nu_e) \sim \underline{\sin^2\theta_{23}}\sin^2 2\theta_{13}$
  - 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 ν_μ disappearance

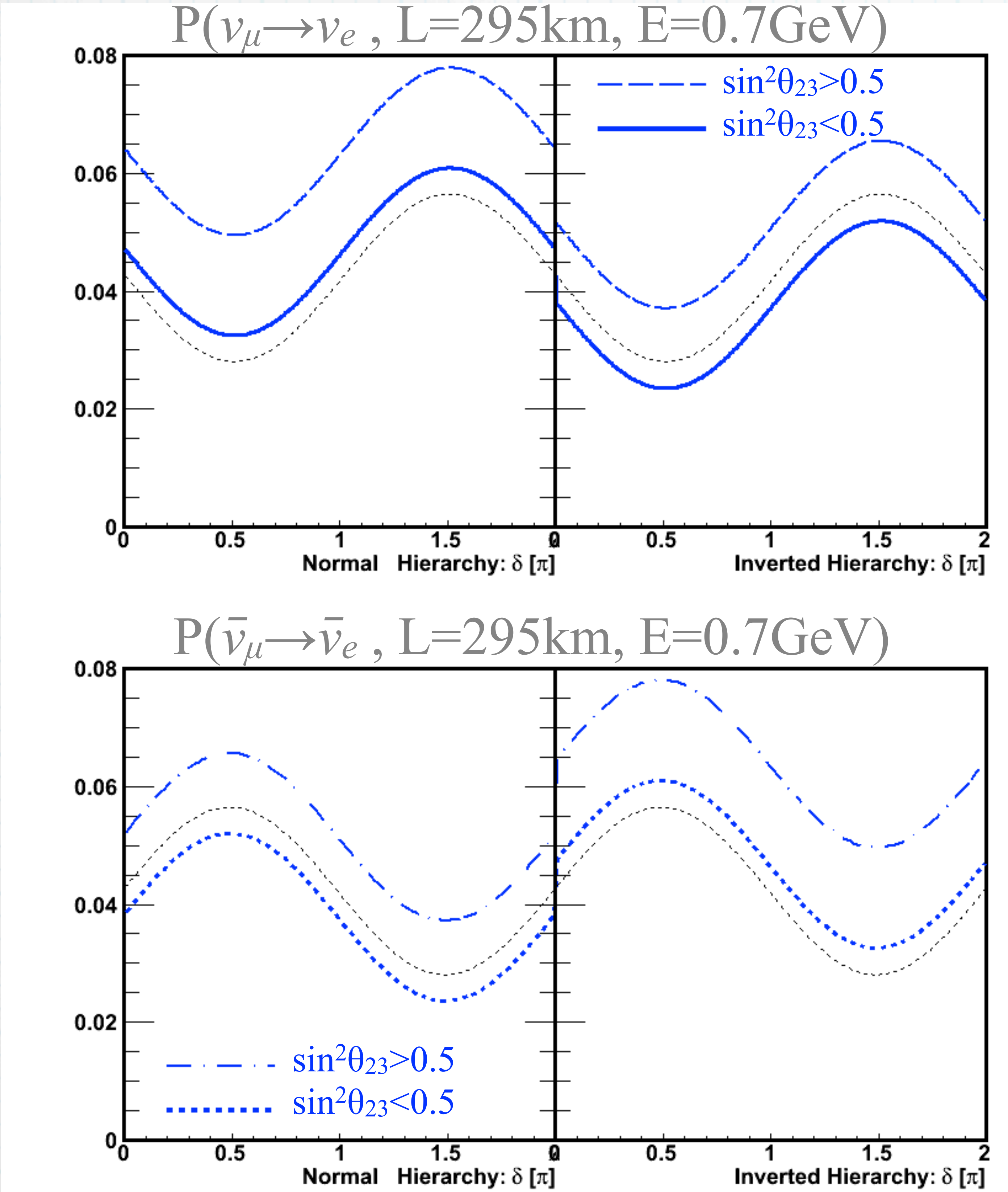


ν_e appearance size ↑

If the ν_μ disappearance is not maximal, there are two possible ve 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.

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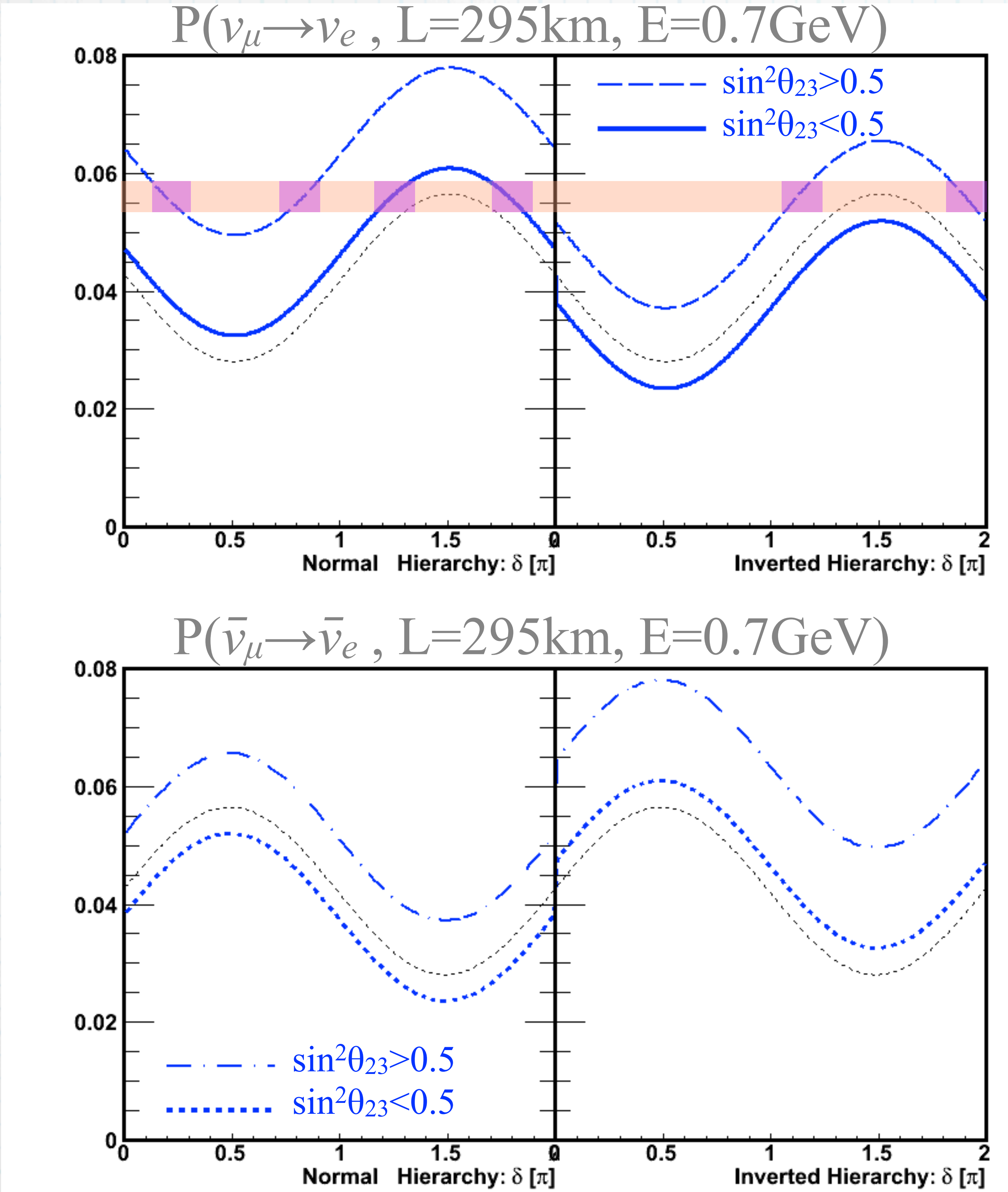

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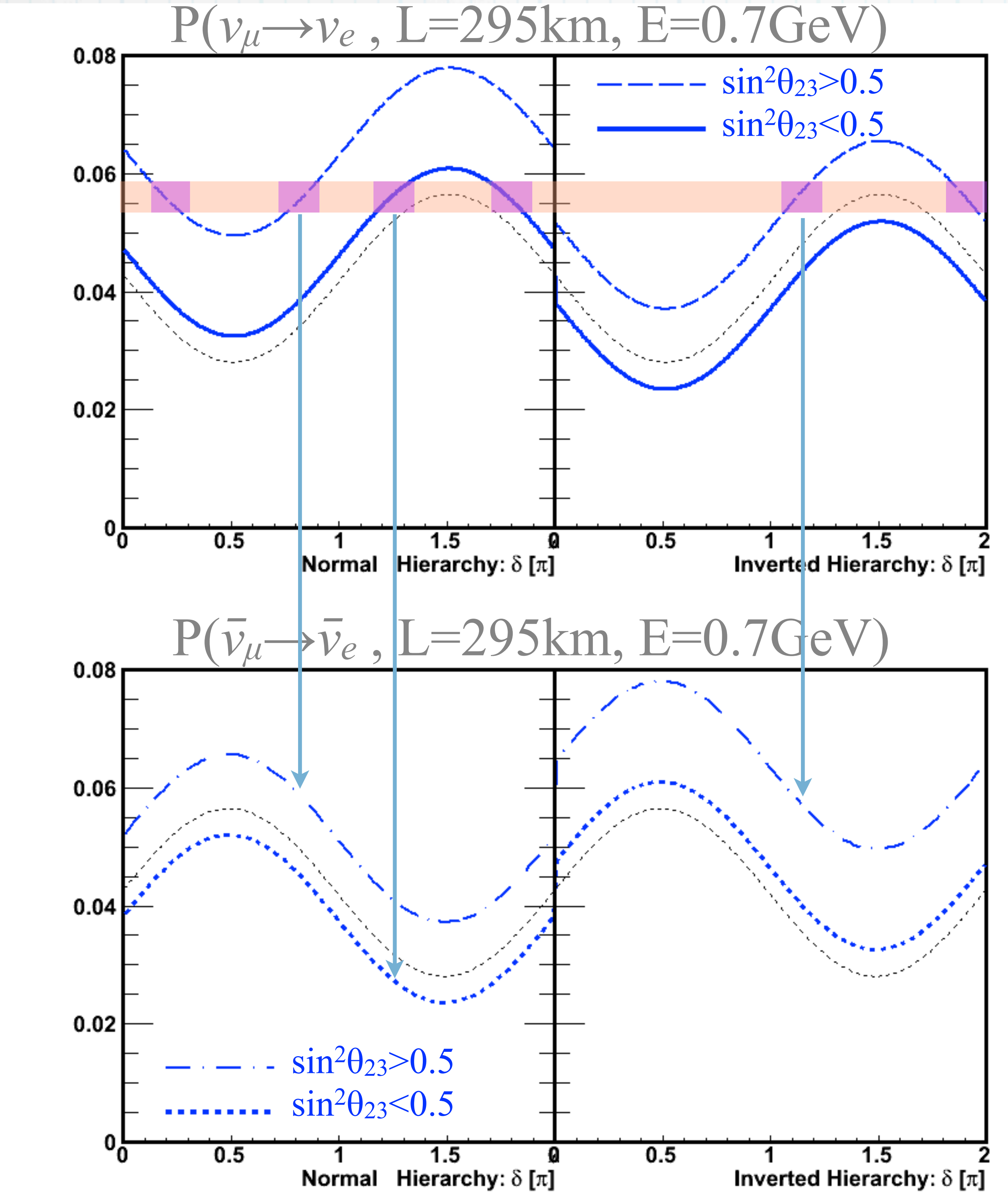

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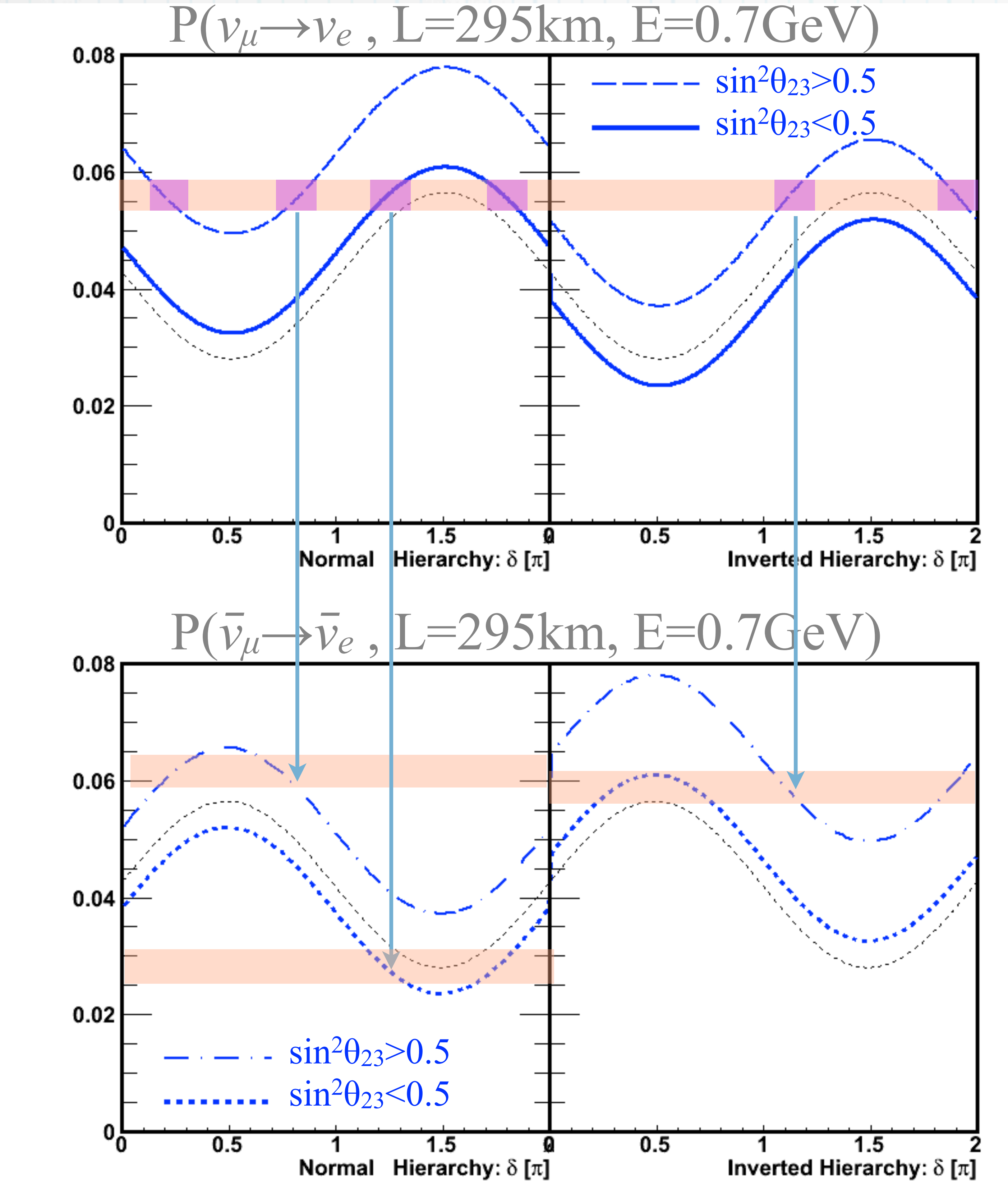

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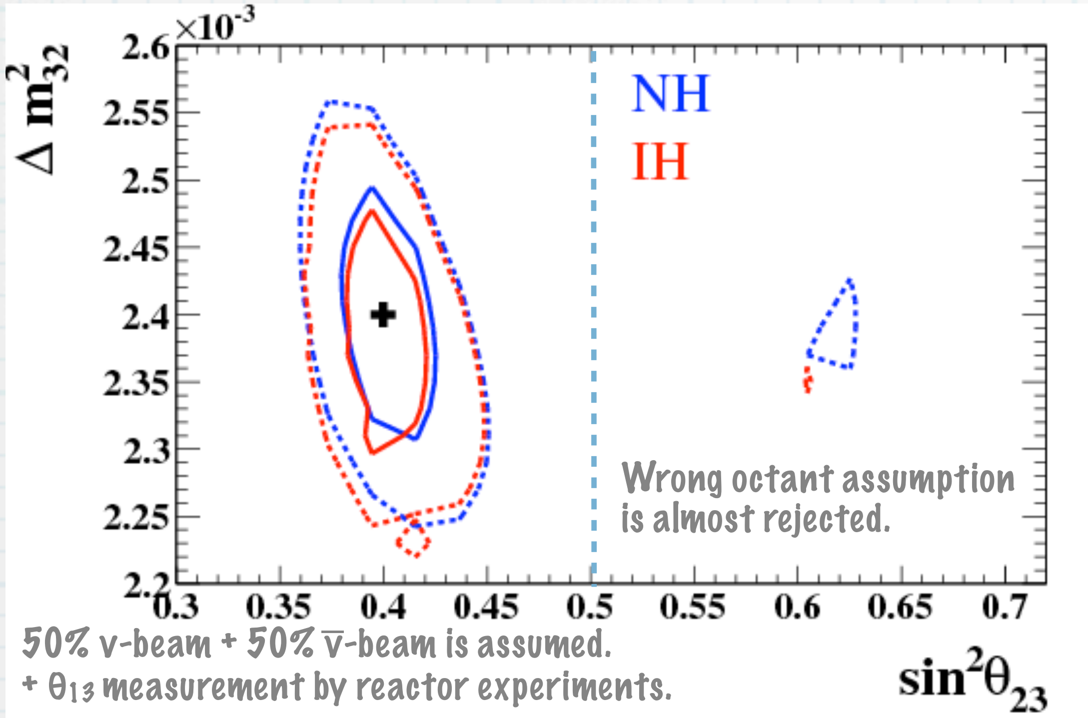
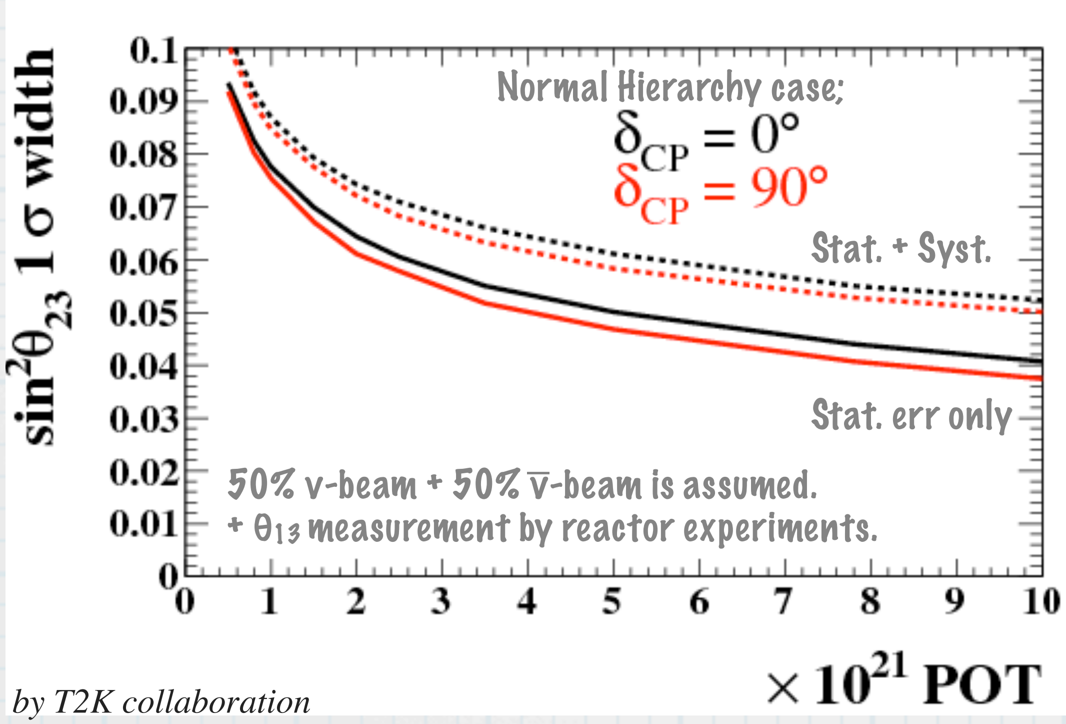
Expected precision of θ_{23} measurement

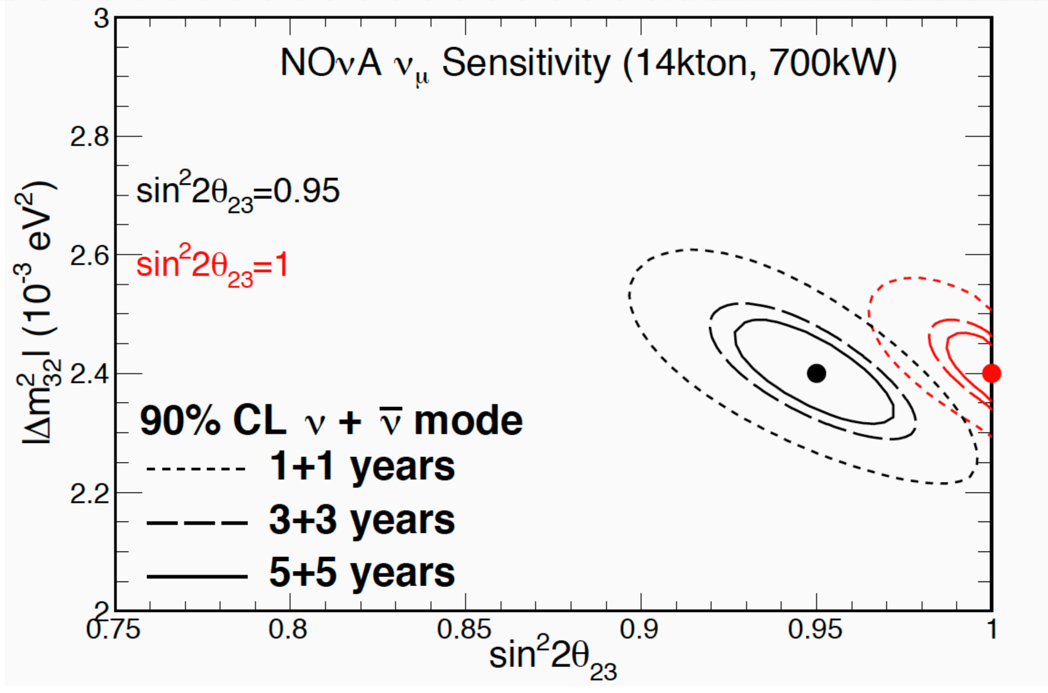
* T2K + Reactor θ_{13}



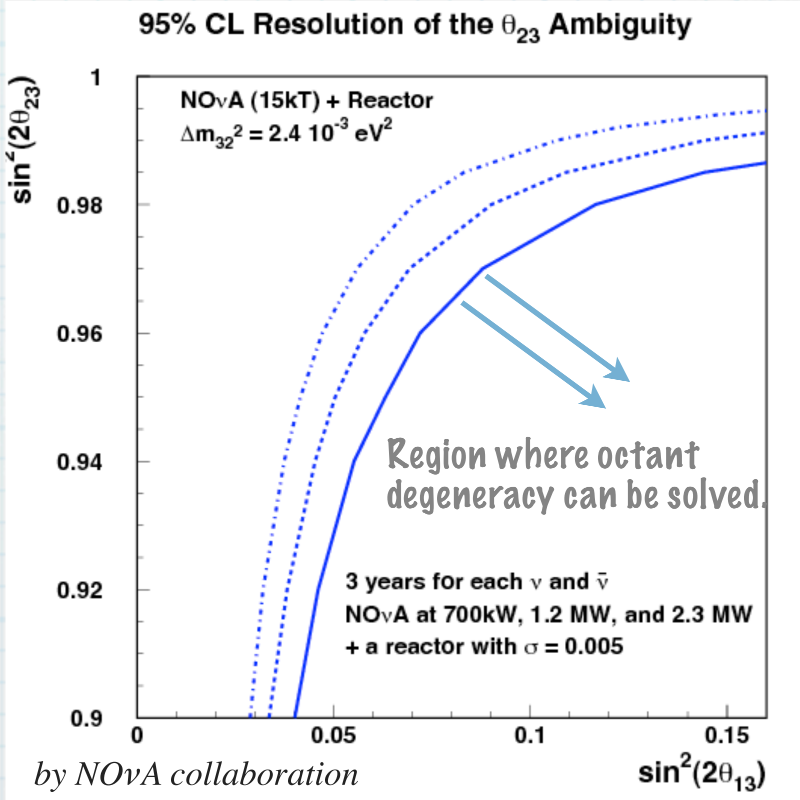


by T2K collaboration

* NOνA



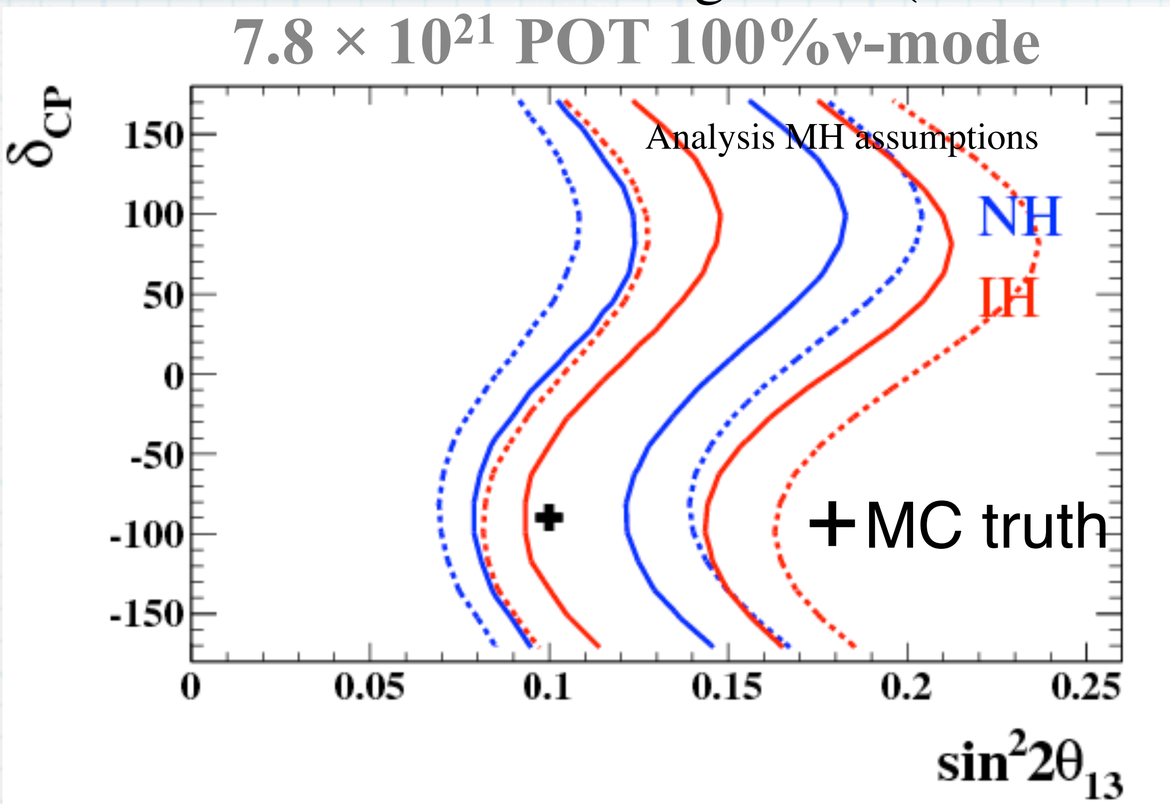
by NOνA collaboration

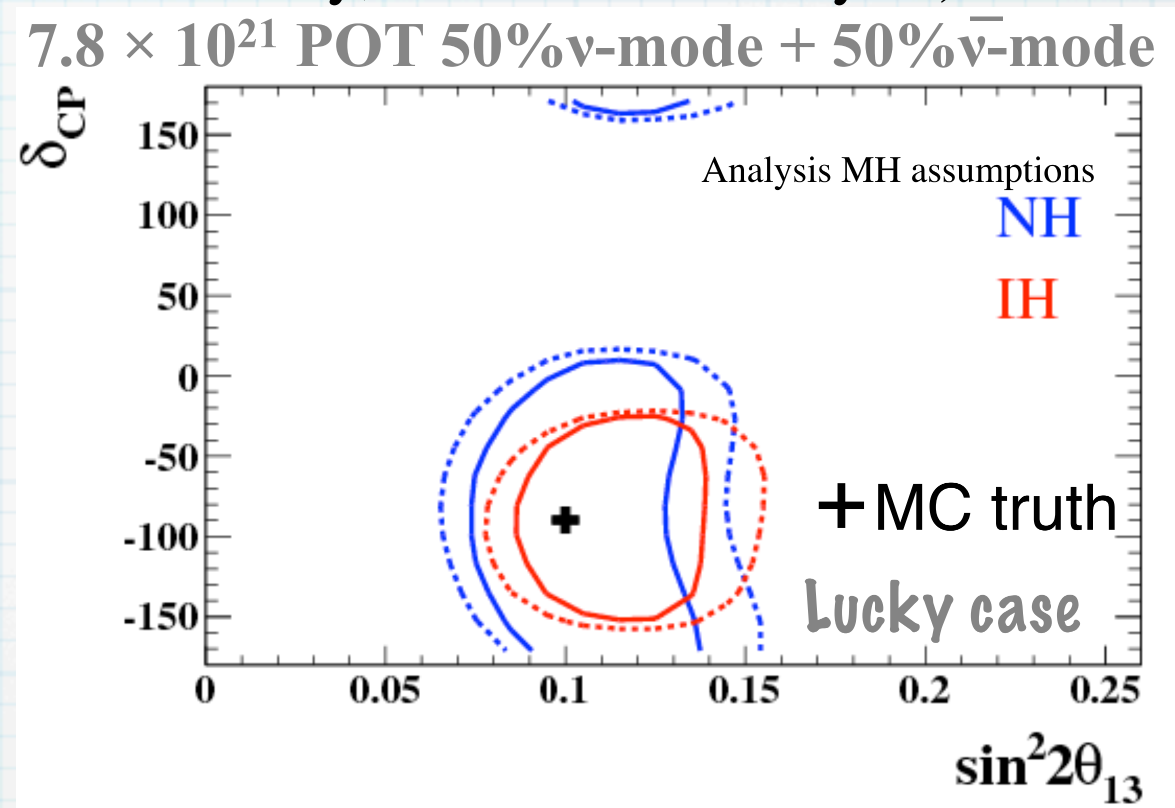


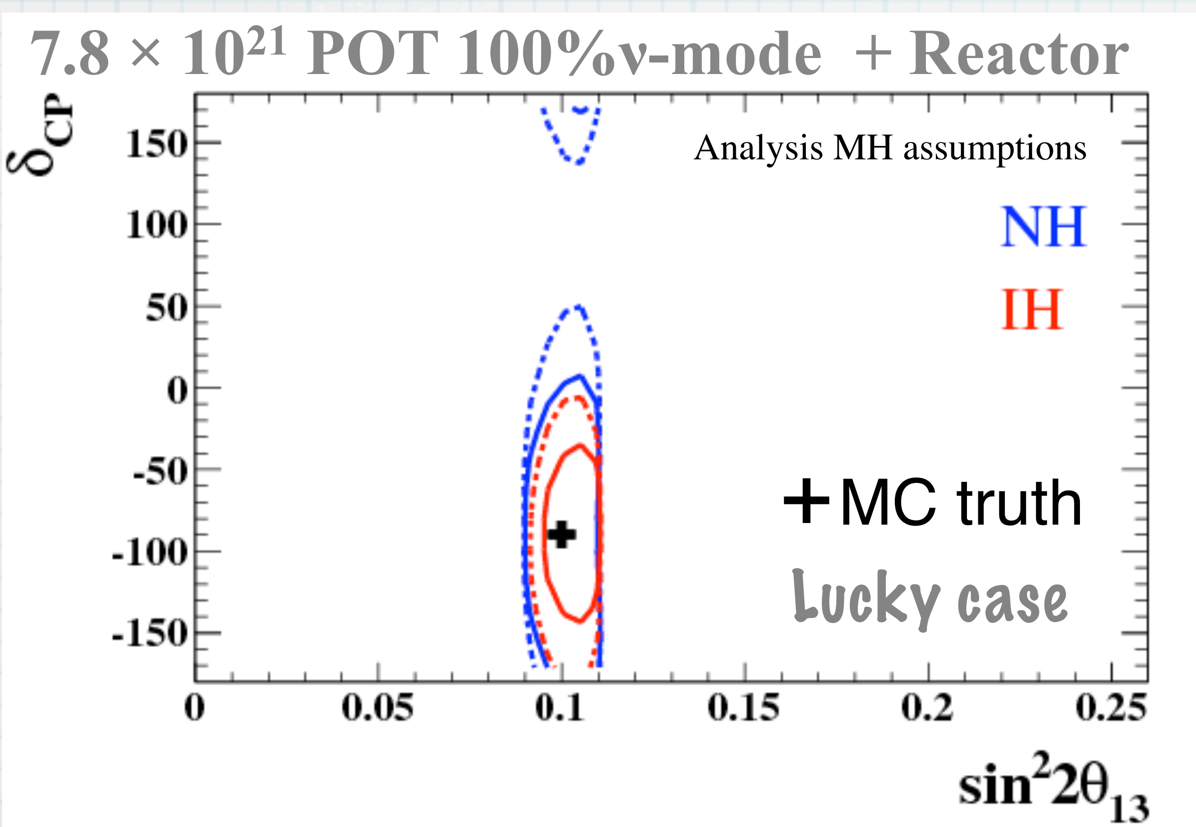
by NOνA collaboration

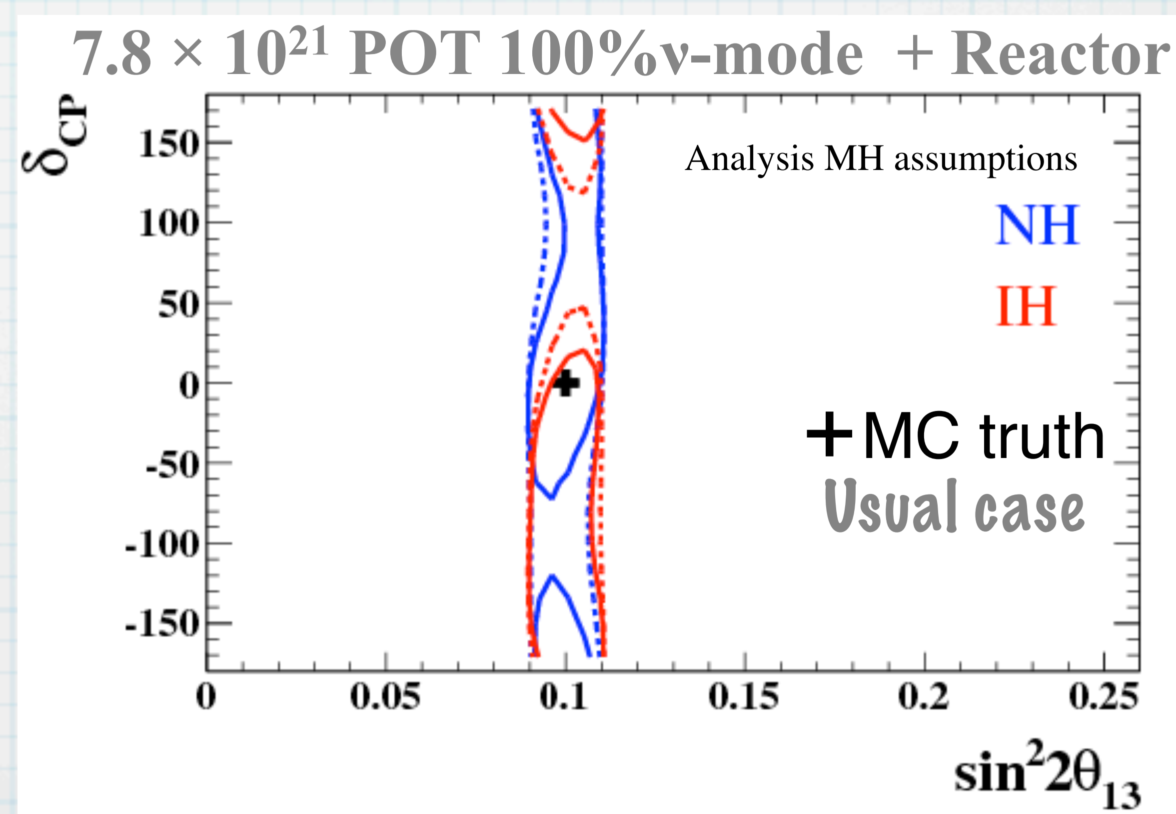
Case studies for MH & CPV : T2K

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



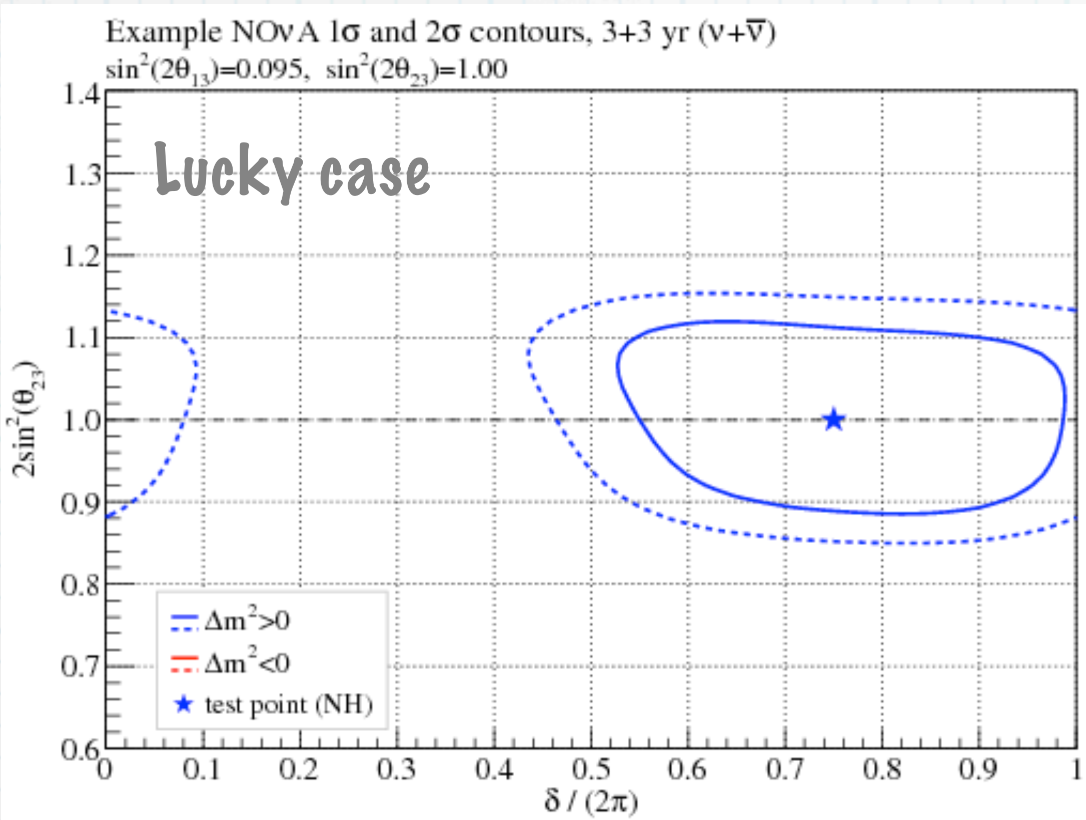


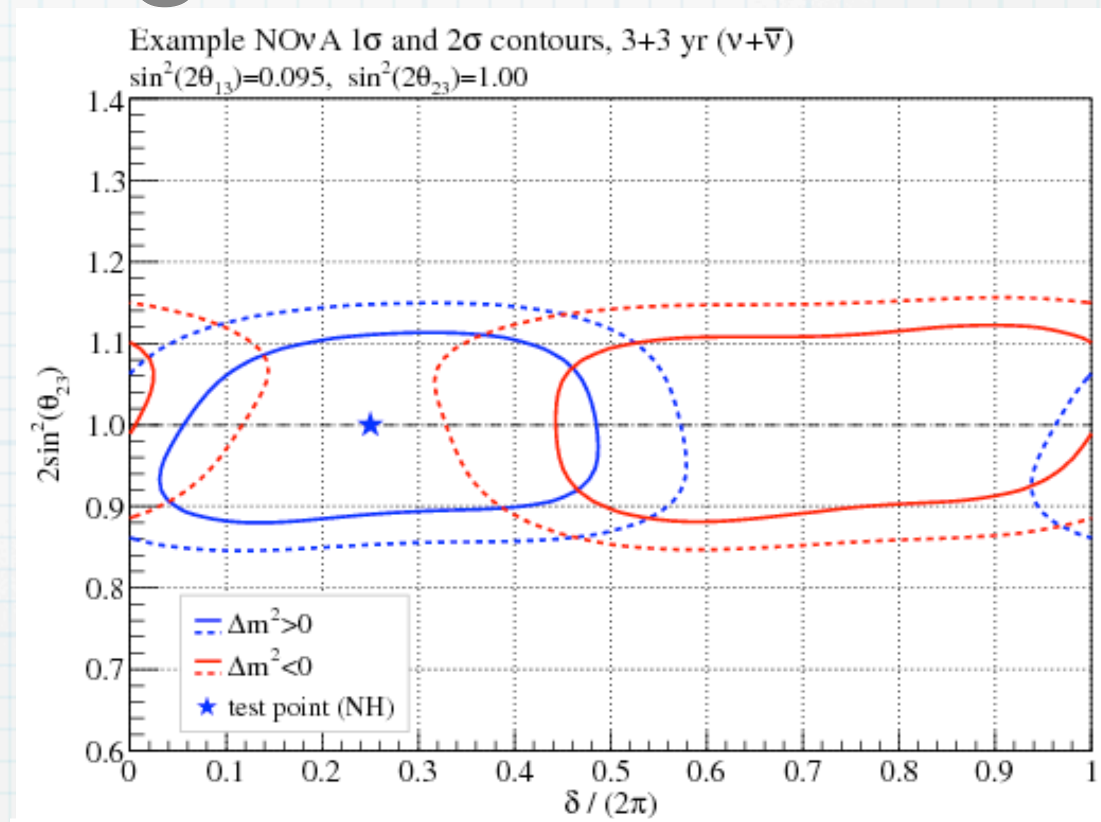


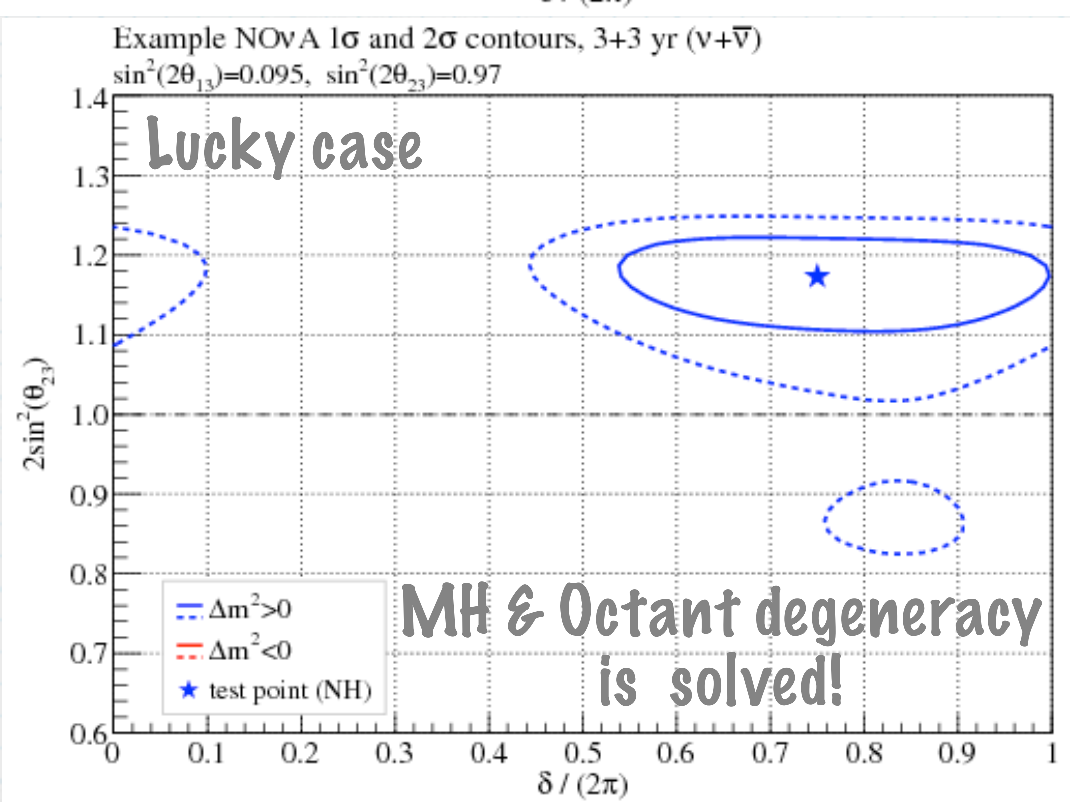


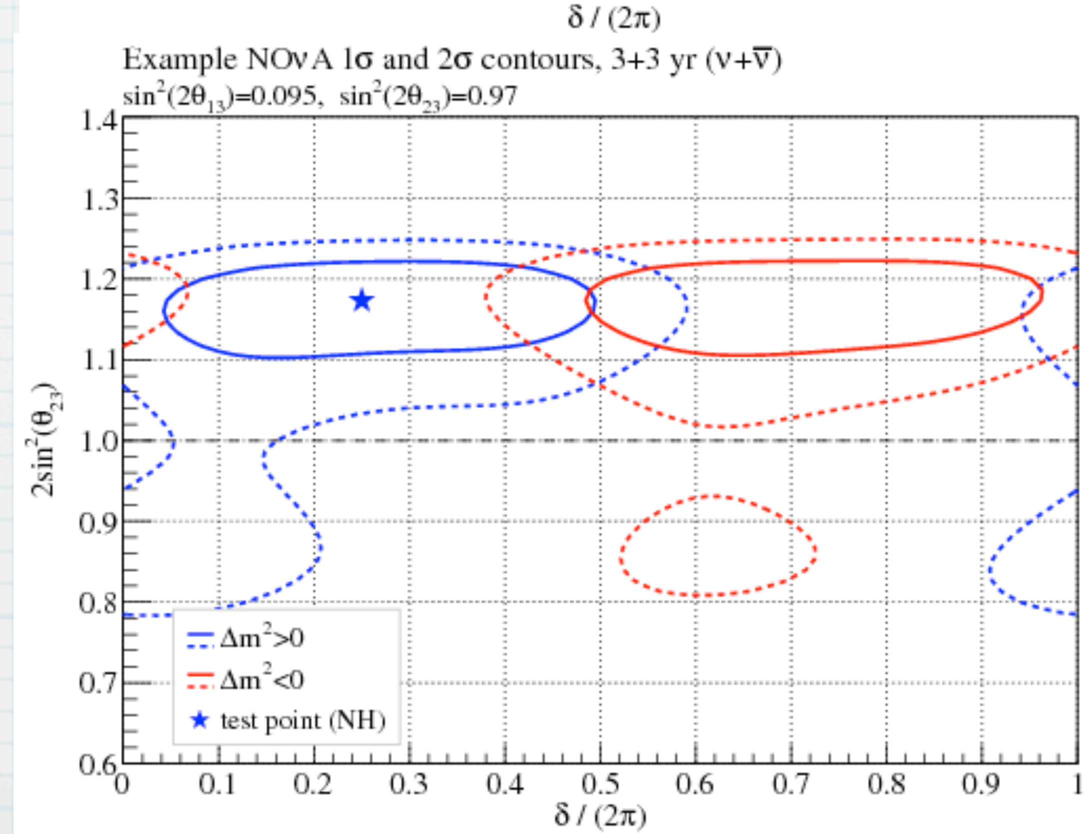
Case studies for MH & CPV: NOνA

- Solid: 1σ allowed region, Dashed 2σ



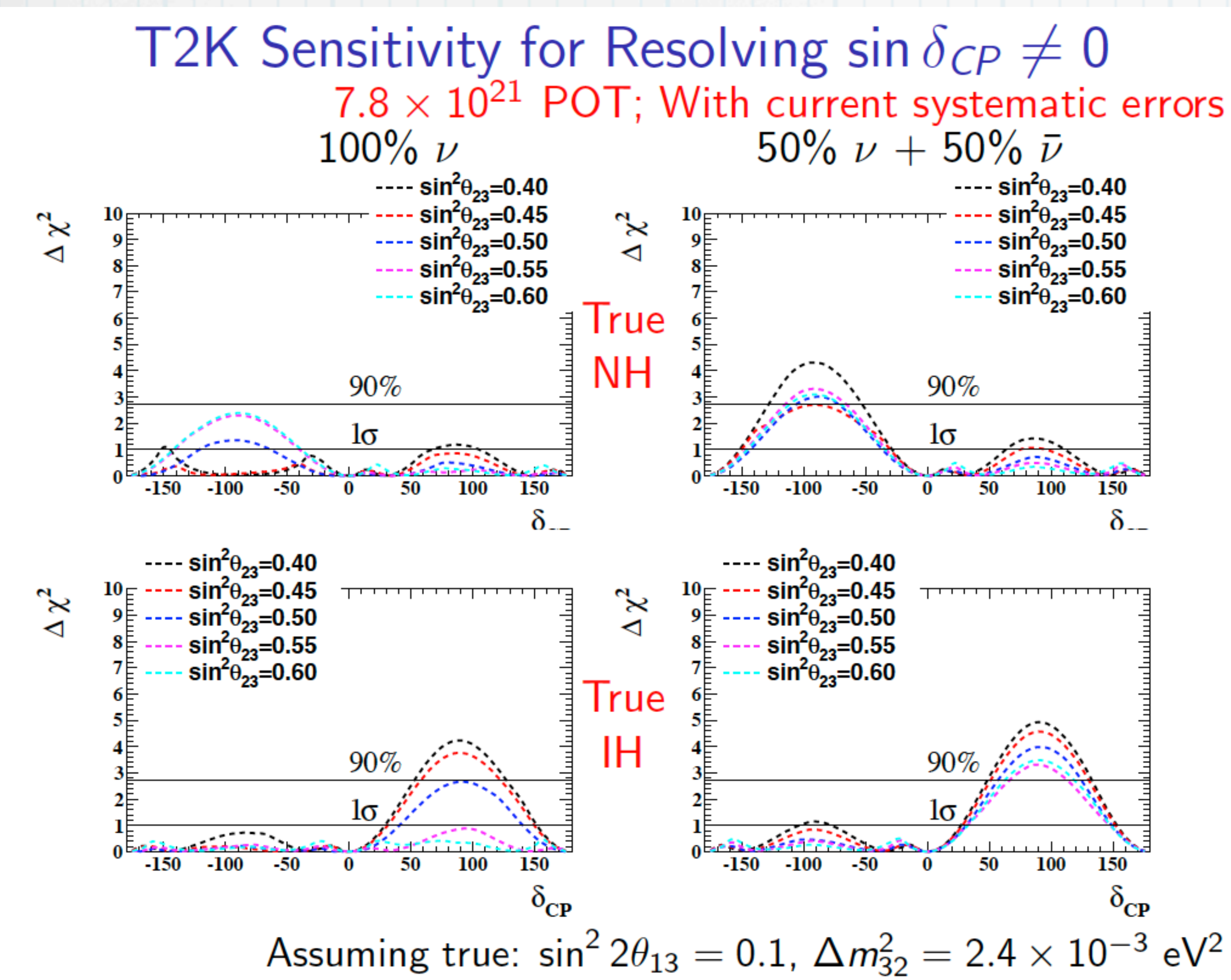






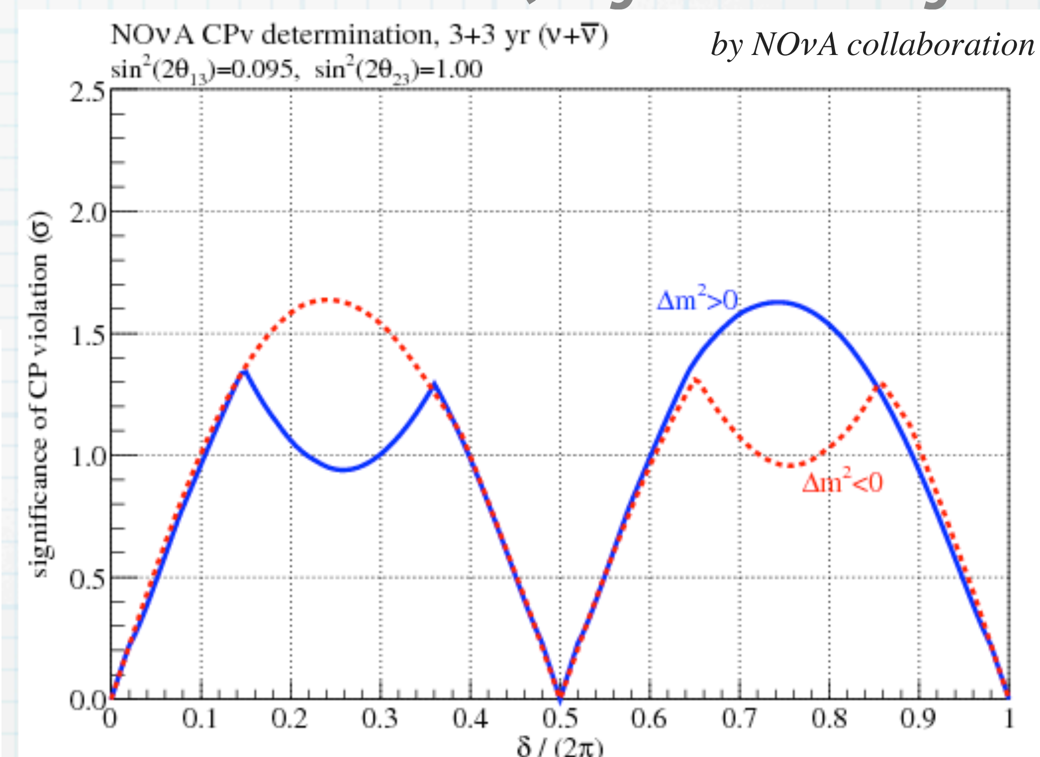
Sensitivity for CPV

- 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.

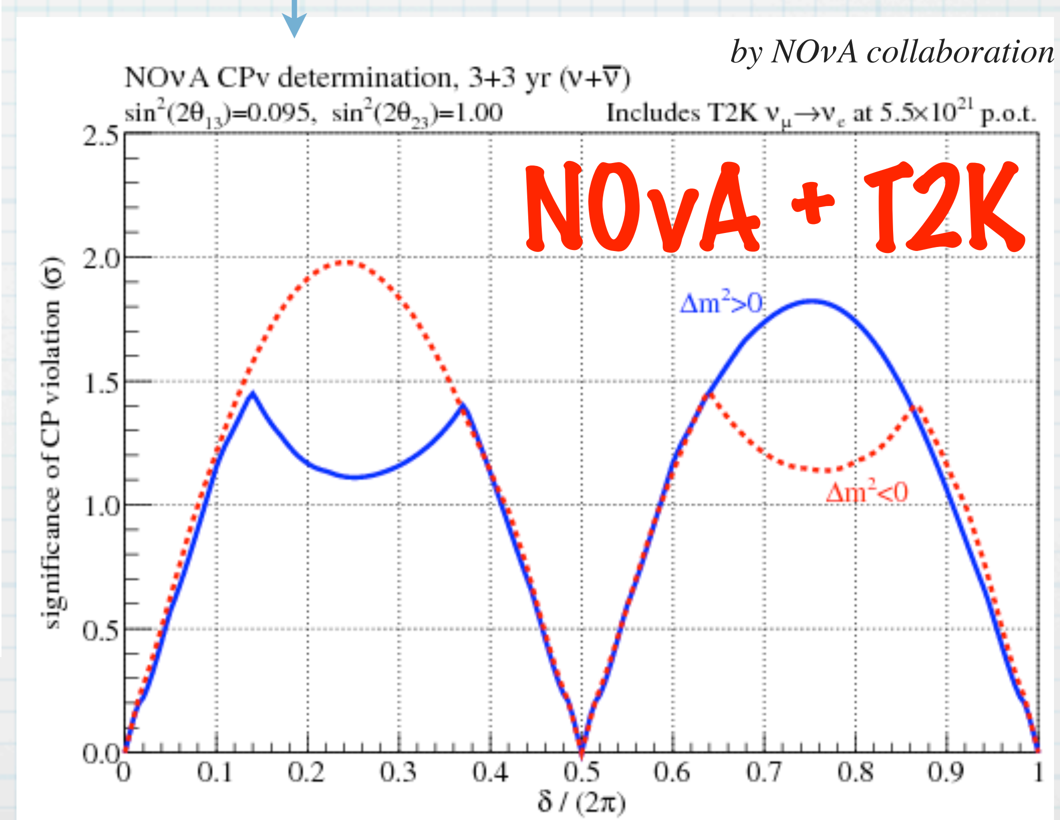


by T2K collaboration

- NOνA (3y ν+3y $\bar{\nu}$)



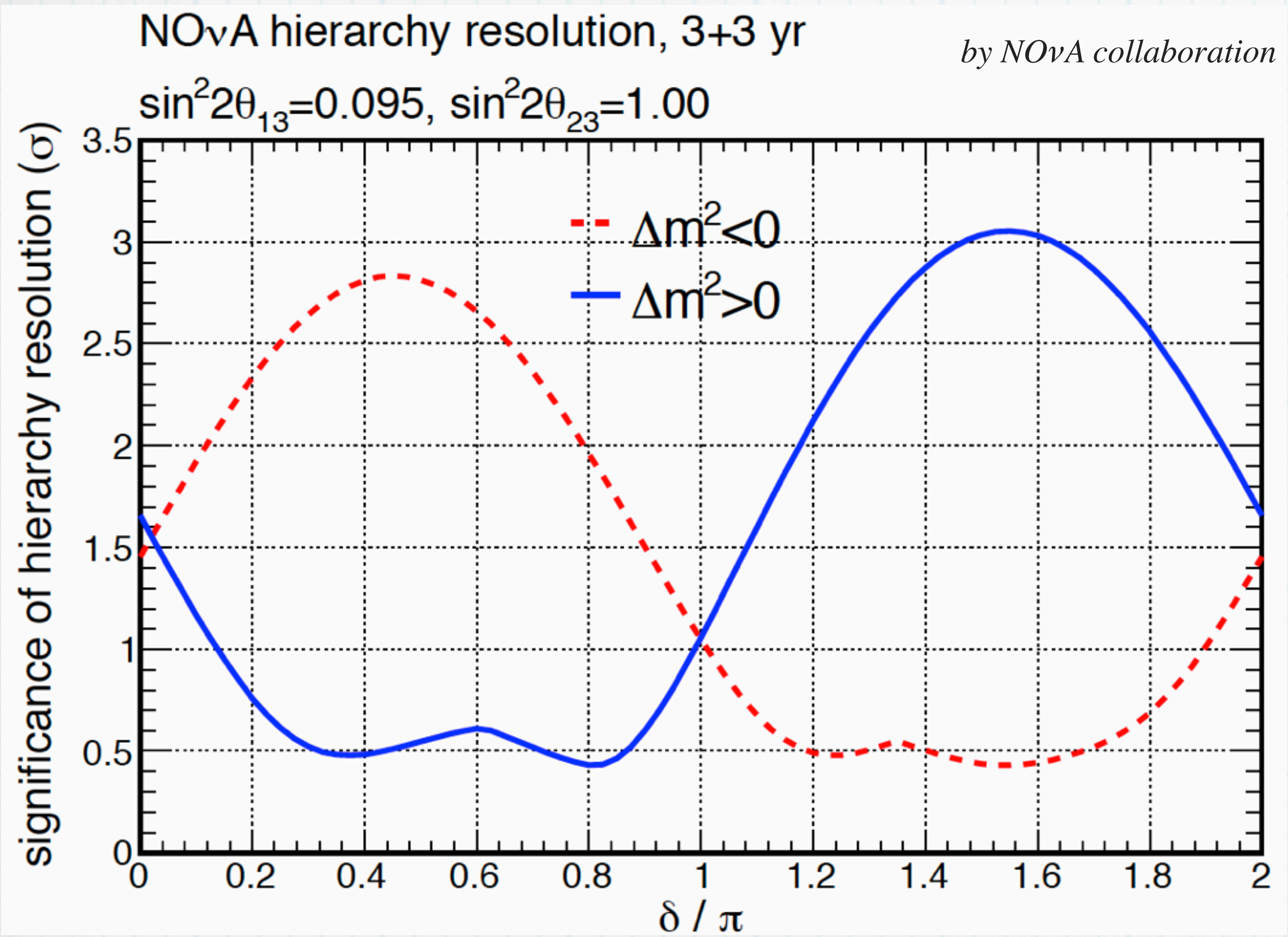
by NOvA collaboration



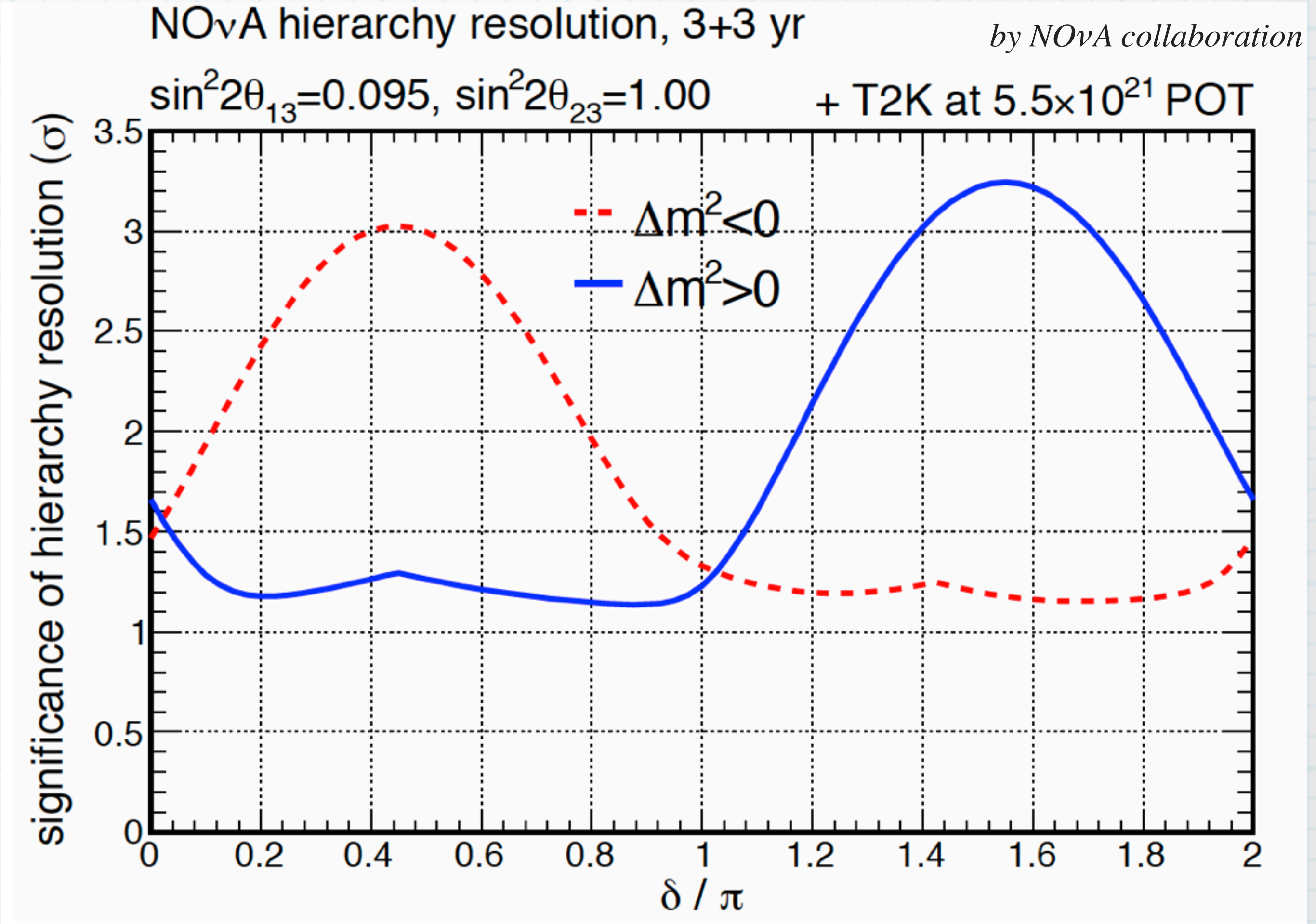
by NOvA collaboration

Sensitivity for MH

* NOvA



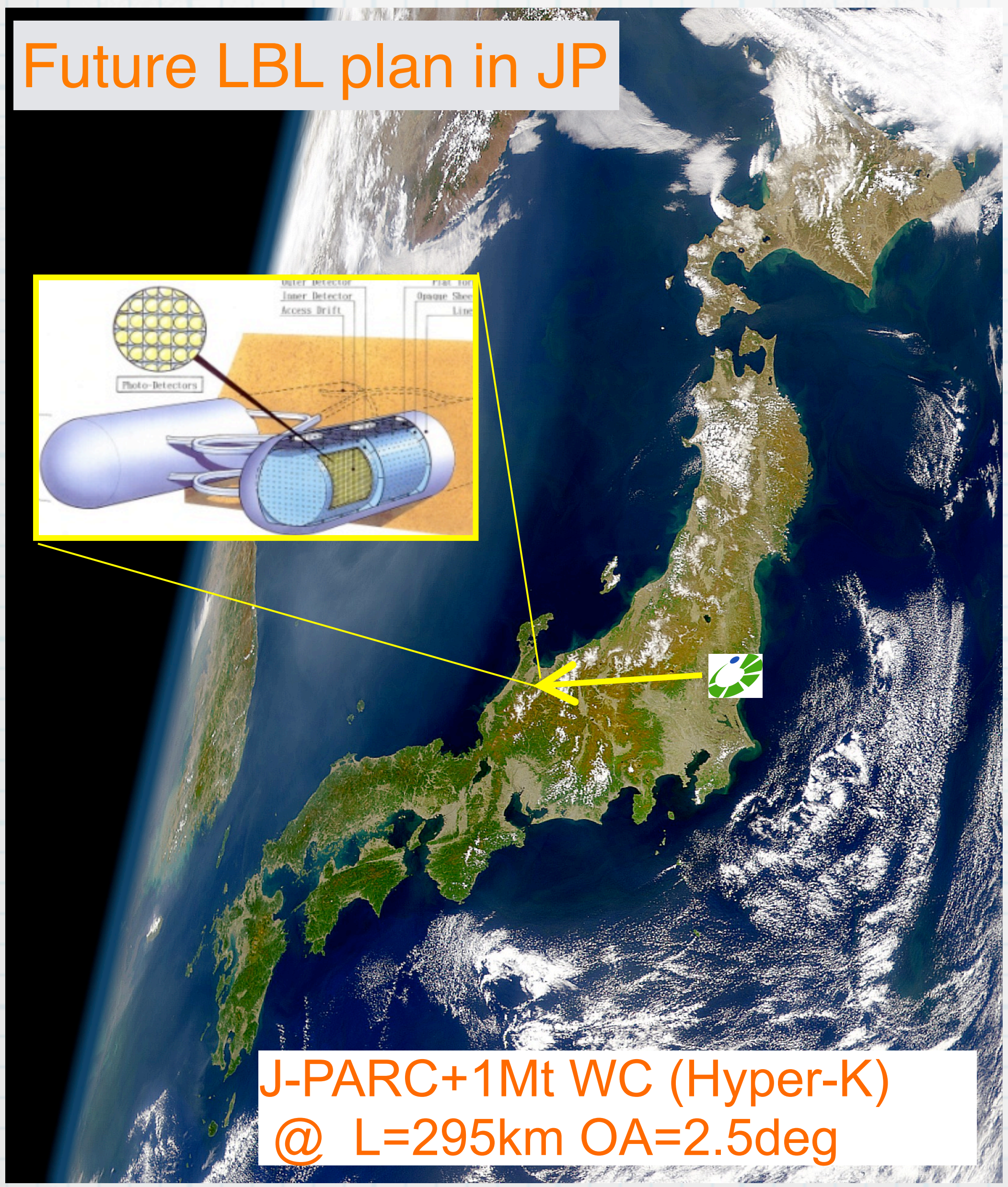
* NOvA + T2K

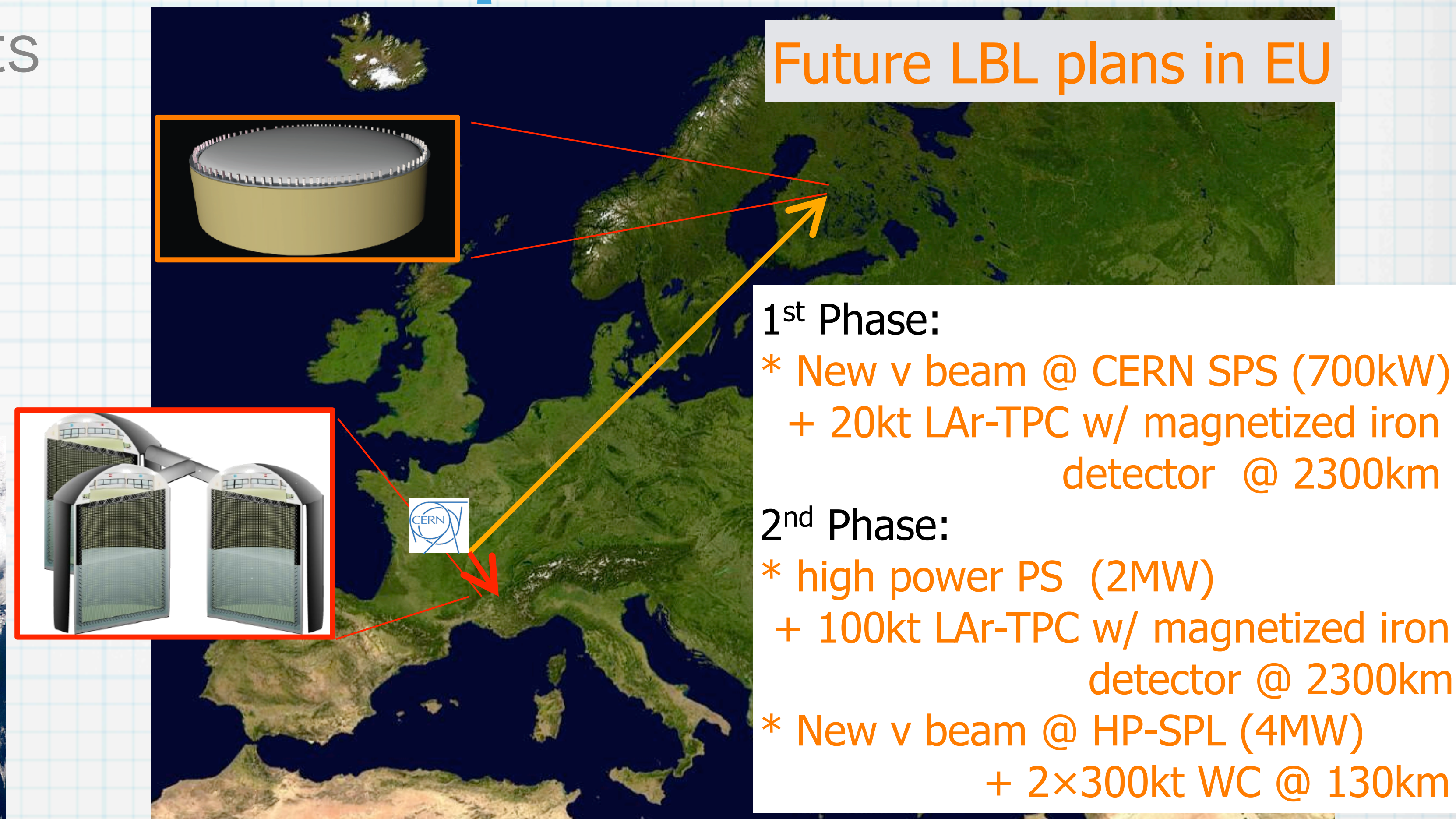


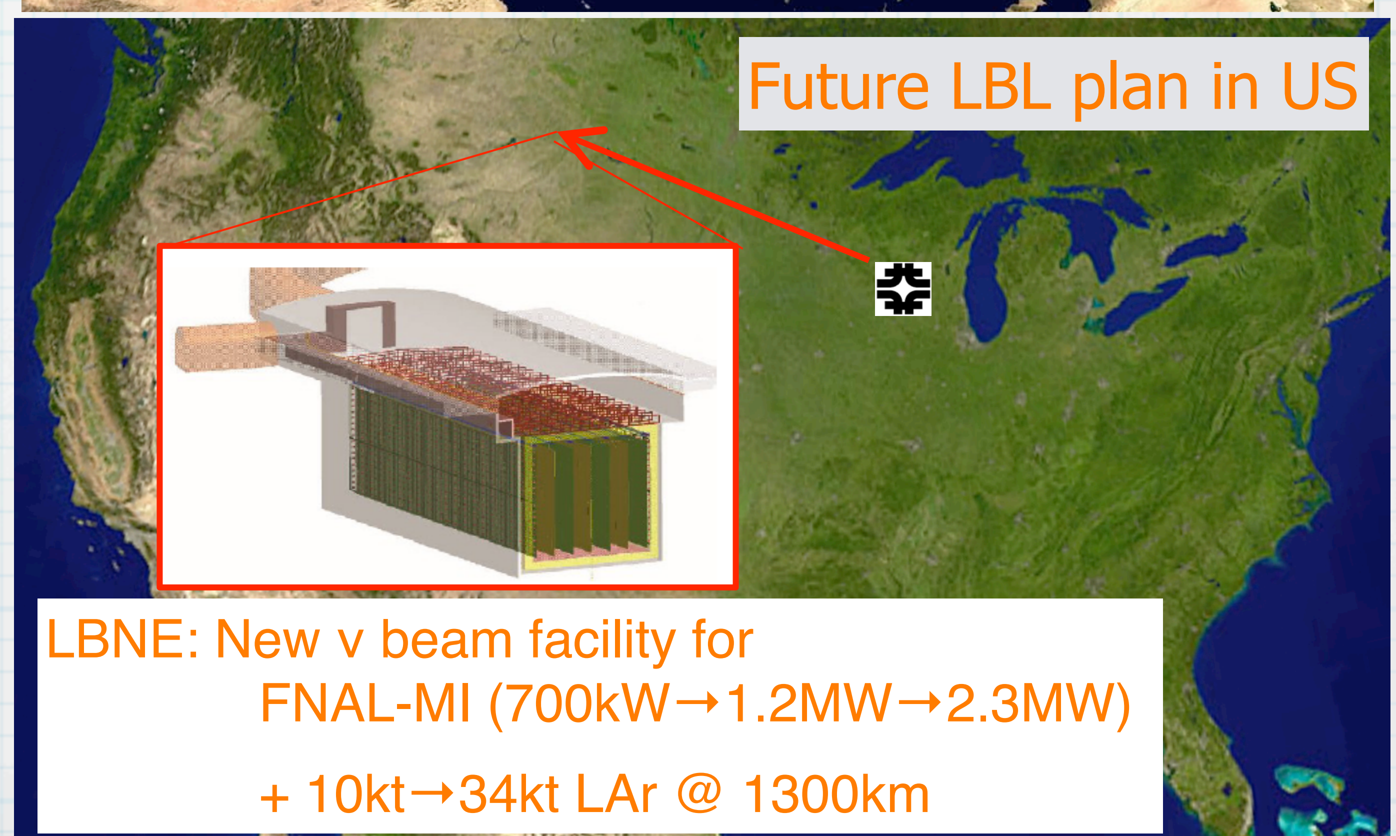
Sensitive region (especially for 1σ) is significantly increased by combining NOvA & T2K.

Future Proposals

* The future experiments to measure CPV and MH conclusively are proposed.



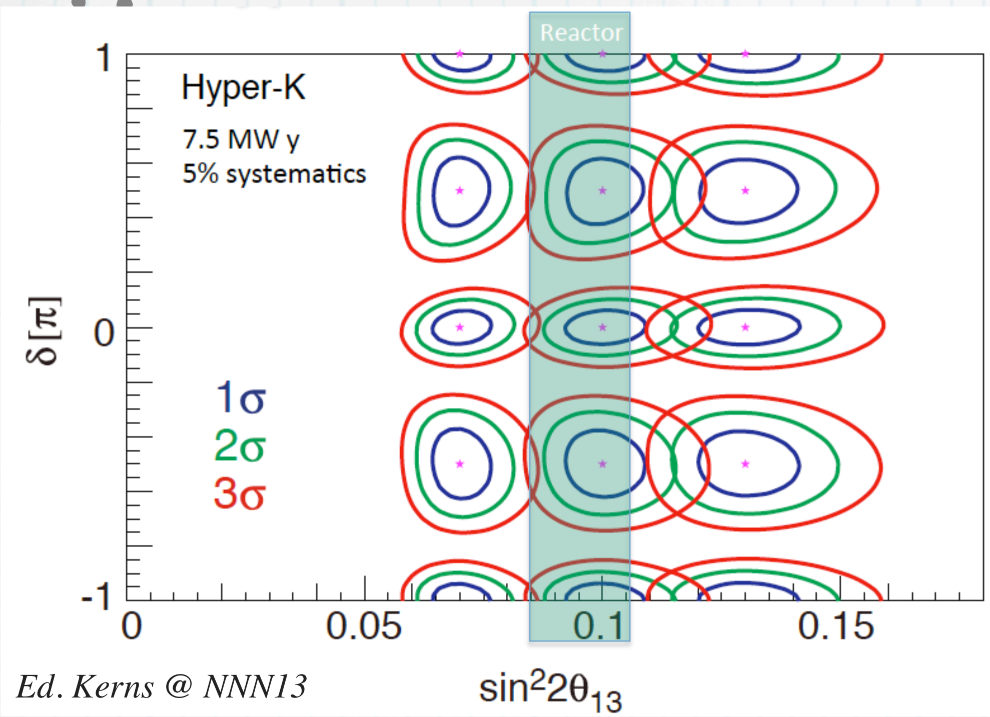




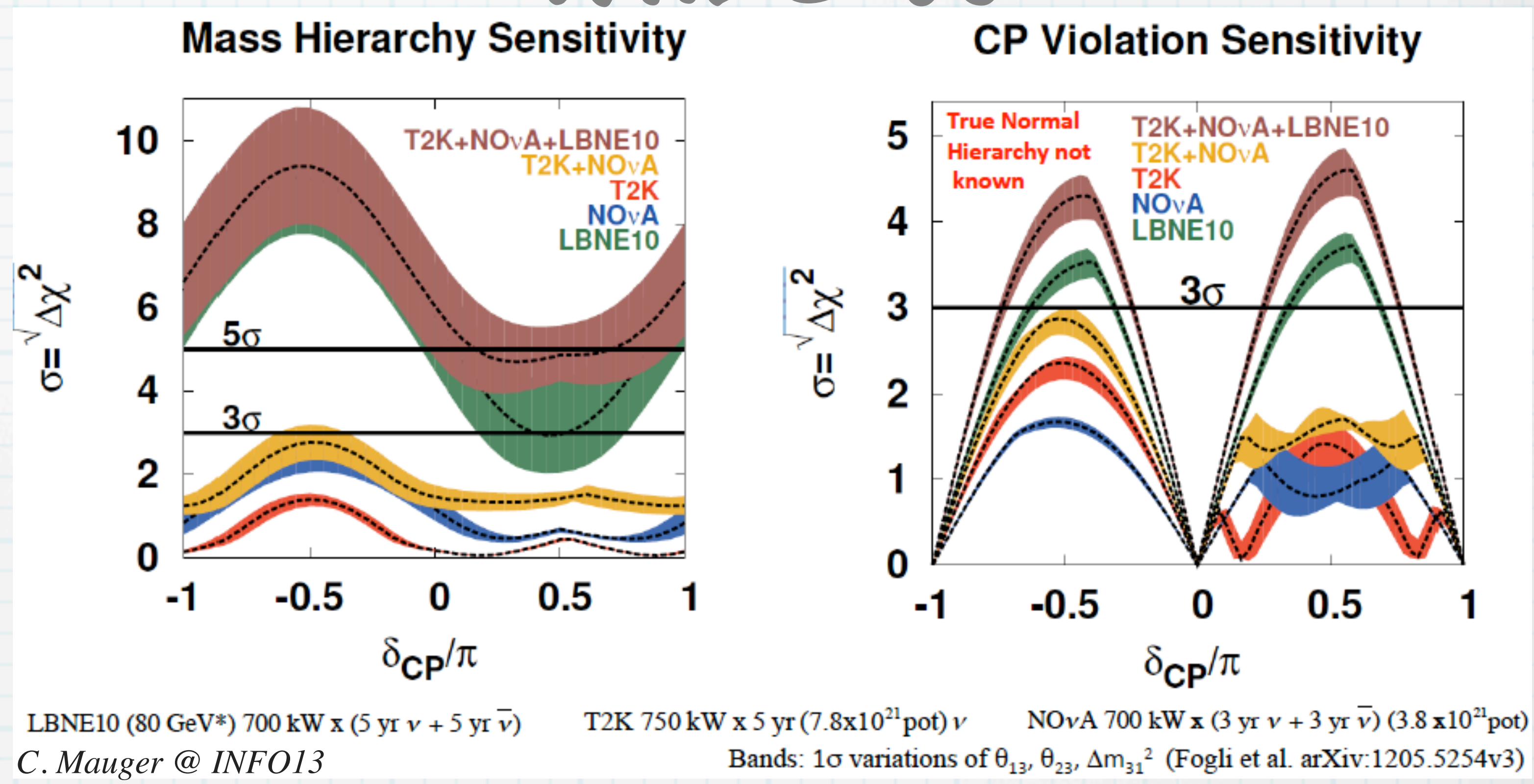
Sensitivity for future proposals

* Aiming to address MH & CPV with 3~5 σ Significance.

Hyper-K + J-PARC



LBNE @ US

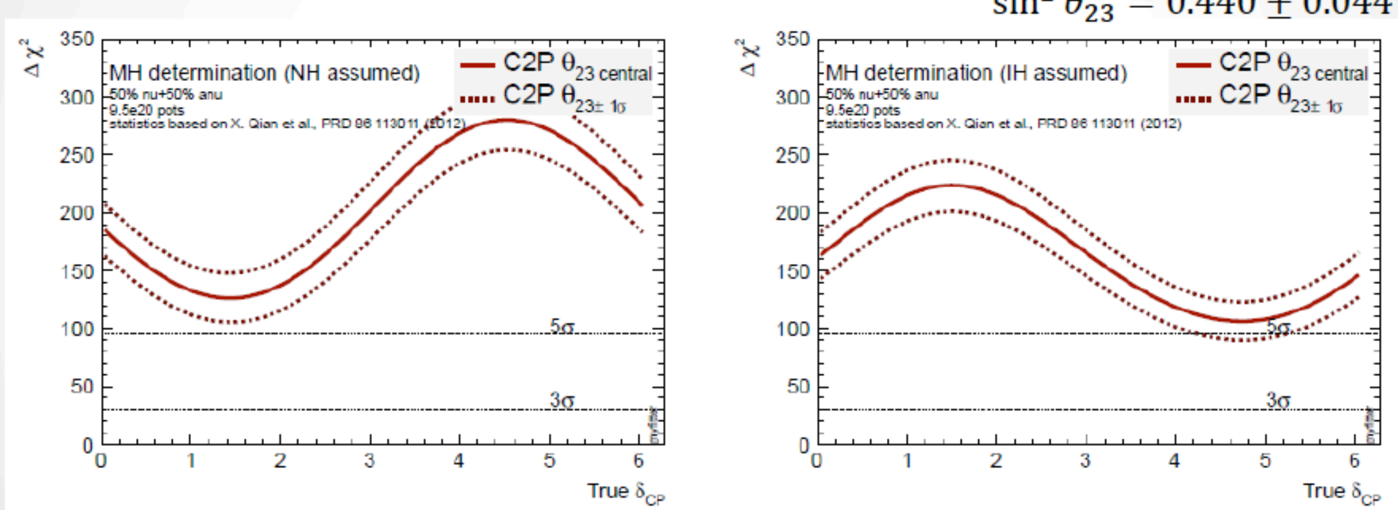


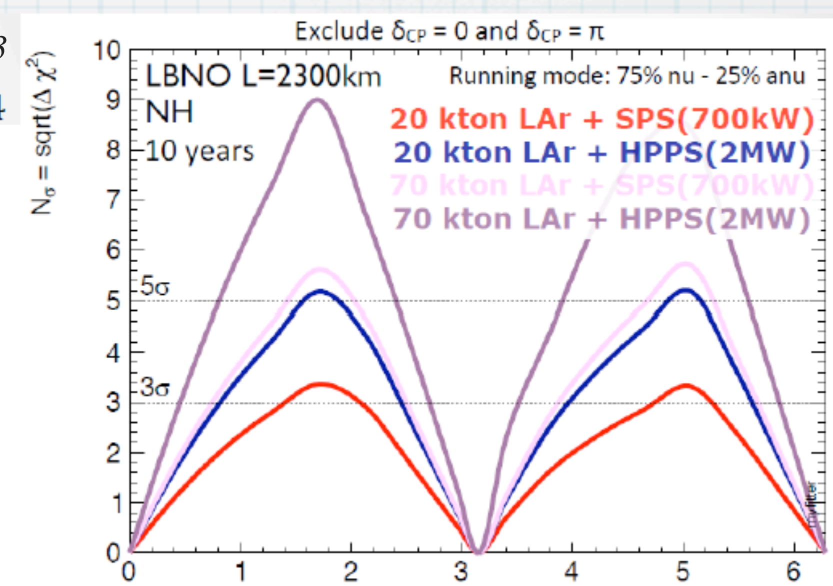
LBNO @ EU (SPSC-EOI-007)

LBNO Phase I: active mass 22.8 kton LAr TPC
with ν beam from 700 kW CERN SPS

V. Galymov @ NNN13

$\sin^2\theta_{23} = 0.440 \pm 0.044$





V. Galymov @ NNN13

Conclusion

* Major breakthrough of neutrino physics in 2011-2013
  * Discovery of $\nu_\mu \rightarrow \nu_e$ Oscillation by T2K.
  * Measurement of θ_{13} by Reactor experiments: Daya Bay, Double chooz and RENO.
* Non-zero θ_{13} opens door to CP violation search.
  * Large θ_{13} ($\sin^2 2\theta_{13} \sim 0.1$) allow the LBL experiment using conventional beam to measure the size of δ_{CP}.
  * Latest T2K & Reactor comparison gives the hints for δ_{CP}.
* T2K & NOvA is doing the precise measurement of the neutrino oscillation to obtain the hint for CPV and MH.
* The future accelerator-based neutrino experiments to conclude on CPV & MH are proposed.