Sensitivity of Future Long Baseline Experiments and Octant Degeneracy

Osamu Yasuda
Tokyo Metropolitan University

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1. Introduction

- Framework of 3 flavor ν oscillation
- Status of 3ν fit

2. Sensitivity of T2HK & DUNE to N_ν=3 oscillation parameters

Ghosh-OY, NPB 989 ('23) 116142

- Precision of Δm^2_{31} & θ_{23}
- Mass ordering
- Octant degeneracy
- CP

3. Octant parameter degeneracy

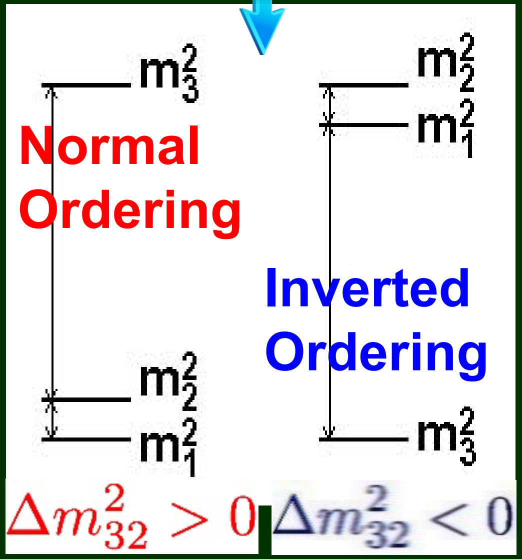
Sugama-OY, arXiv:2308.15071

- Situation before and after 2012
- Octant degeneracy in T2HK, DUNE, T2HKK, ESSνSB

4. Conclusions

1. Introduction

Both **Mass Orderings** are still allowed



Framework of 3 flavor ν oscillation

Mixing matrix $U_{\alpha j}$ depends on θ_{12}, θ_{23}, θ_{13}, and CP phase δ

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

All 3 mixing angles have been measured:

1998- ν_{atm}+T2K +MINOS+NOvA (accelerators)

$P(\nu_\mu \to \nu_\mu)$ → $\theta_{23} \cong \frac{\pi}{4}, |\Delta m_{32}^2| \cong 2.5 \times 10^{-3}\,\mathrm{eV}^2$

2002 ν_{solar}+KamLAND (reactor)

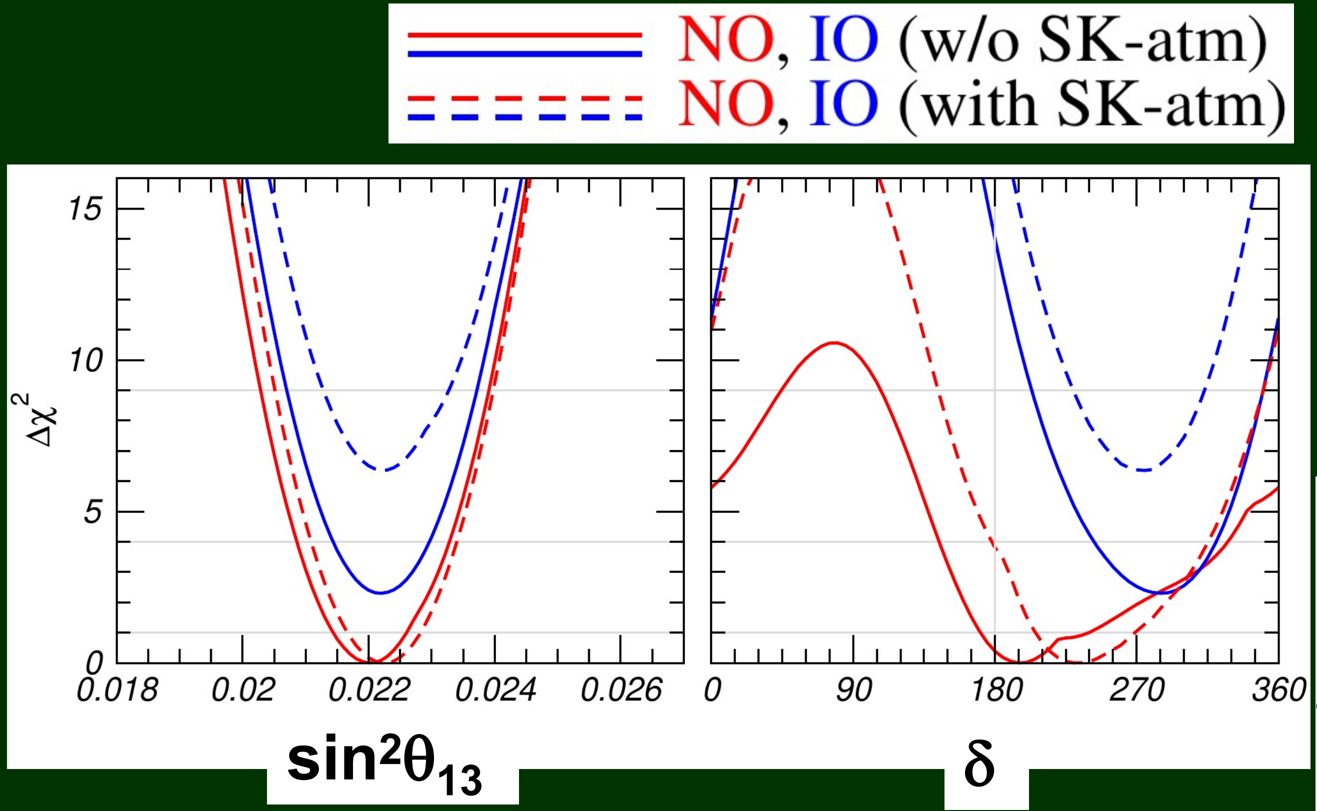
$P(\bar{\nu}_e \to \bar{\nu}_e)$ → $\theta_{12} \cong \frac{\pi}{6}, \Delta m_{21}^2 \cong 8 \times 10^{-5}\,\mathrm{eV}^2$

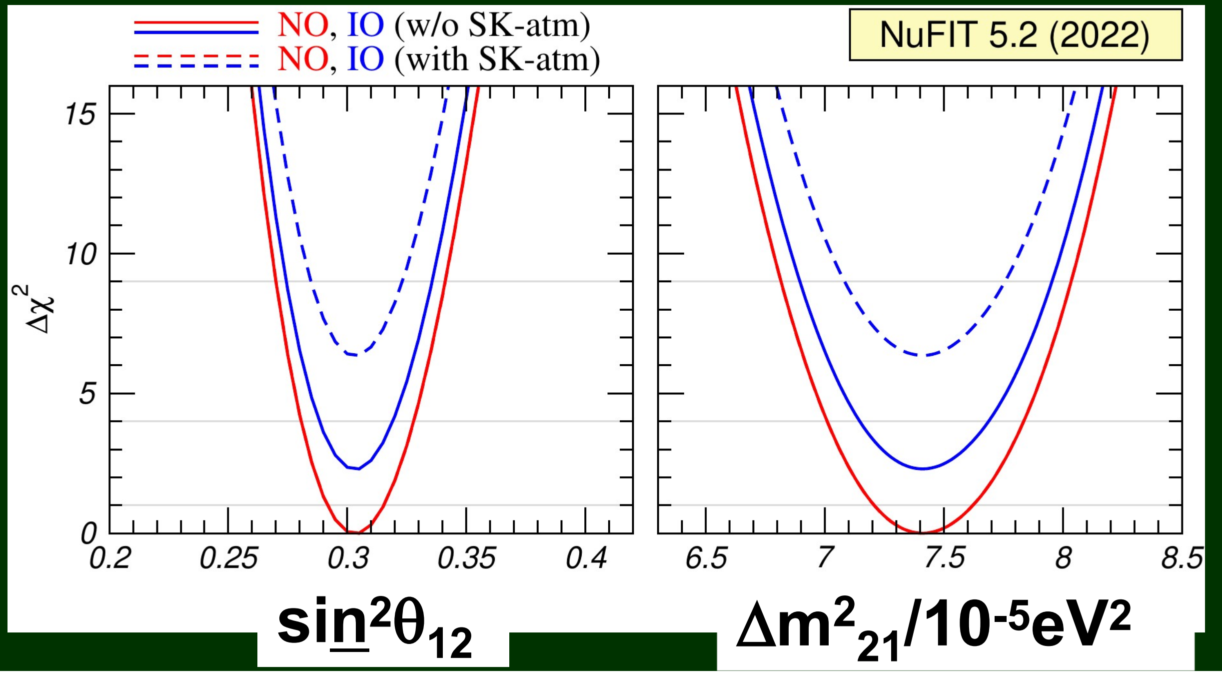
2012 DCHOOZ+Daya Bay+Reno (reactors)

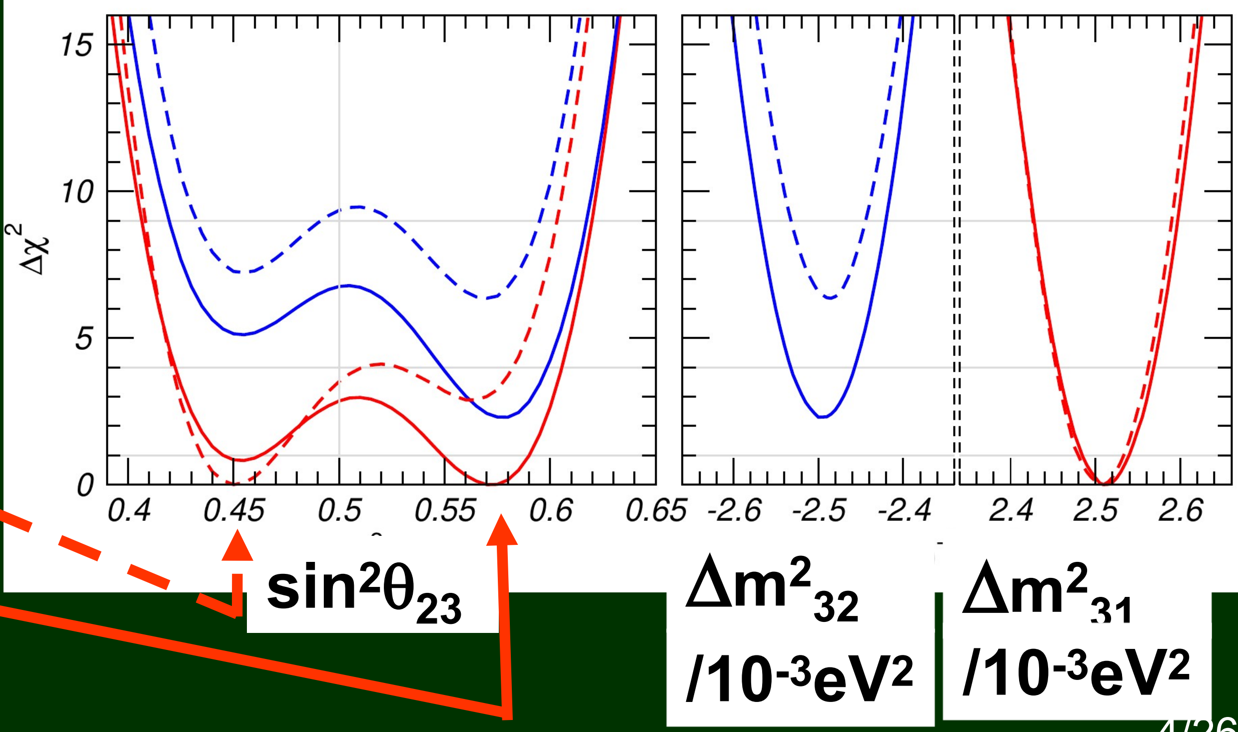
$P(\bar{\nu}_e \to \bar{\nu}_e)$ → $\theta_{13} \cong \pi / 20$

Status of 3ν fit (1)

www.nu-fit.org
v5.2 (Nov. 2022)







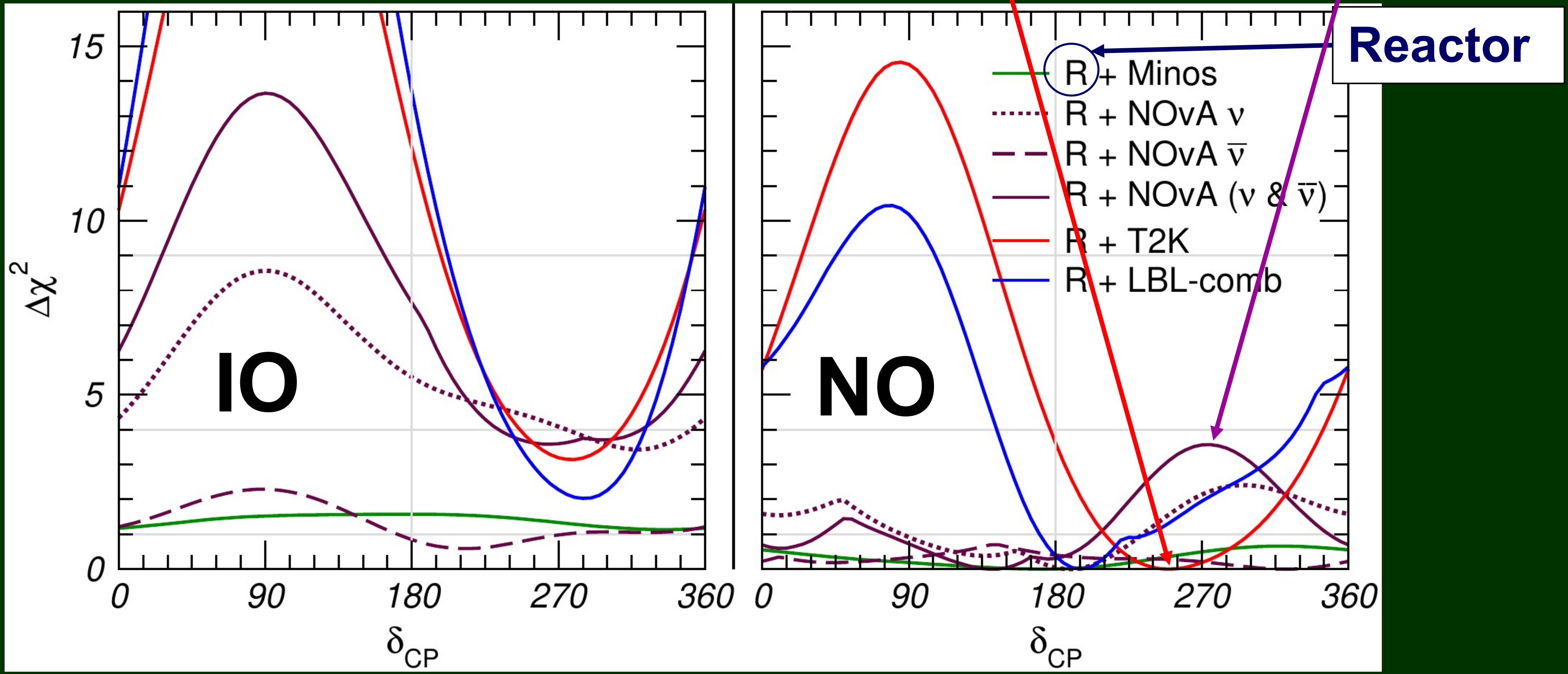
- **NO seems to be preferred over IO**
- **SK-atm seems to prefer Lower Octant, while others prefer Higher Octant**

⇒ Situation of θ_{23} is still confusing.

Status of 3ν fit (2)

● Appearance data of LBL show us potential tension for NO, although T2K dominates over NOvA in statistics. ⇒ Situation of δ is still confusing.

www.nu-fit.org v5.2 (Nov. 2022)



Next things to do are to determine the following by long baseline experiments:

- $\mathrm{sign}(\Delta m^2_{31})$
- $\pi/4-\theta_{23}$
- δ

$$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu + \overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$$

Long baseline experiments under construction

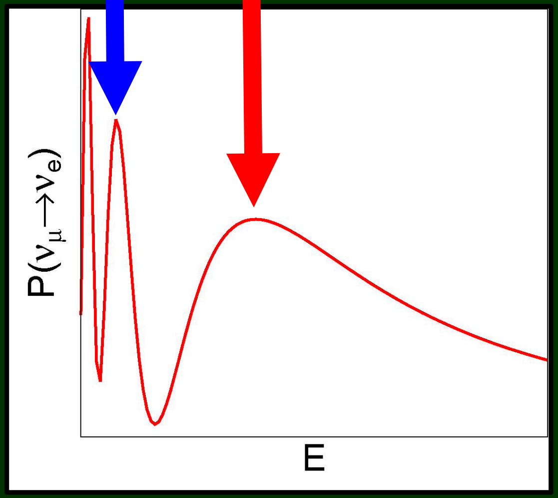
- T2HK(JP, JPARC-->HK) L=295km, E~0.6GeV
- DUNE (US, FNAL-->Homestake, SD) , L=1300km, E~2GeV

Explores 1st oscillation maximum

Proposed long baseline experiments

- T2HKK(JP, JPARC-->1st in Japan+2nd detector in Korea) L=1100km, E~0.8GeV
- ESSνSB (Sweden, ESS-->Zinkgruvan mine) , L=360km, E~0.3GeV

Explores 2nd oscillation maximum



These experiments are expected to measure $\mathrm{sign}(\Delta m^2_{31})$, $\pi/4-\theta_{23}$ and δ

Matter effect in T2HK and DUNE

T2HK: L=295km

DUNE: L=1300km

In a toy 2 flavor case:

To know the sign of $\Delta E = \Delta m^2/2E$, large matter effect is necessary.

Matter effect becomes most conspicuous if $\Delta E \cos 2\theta = A$ is satisfied.

$$P(\nu_\mu \to \nu_e) = \left(\frac{\Delta E \sin 2\theta}{\Delta \tilde{E}}\right)^2 \sin^2\left(\frac{\Delta \tilde{E} L}{2}\right)$$

$$\tan 2\tilde{\theta} \equiv \frac{\Delta E \sin 2\theta}{\Delta E \cos 2\theta - A}$$

$$\Delta \tilde{E} \equiv \left\{(\Delta E \cos 2\theta - A)^2 + (\Delta E \sin 2\theta)^2\right\}^{1/2}$$

$$A \equiv \sqrt{2}\, G_F\, N_e \sim 1/2000\text{km}$$

In this case, the baseline length L has to be large

→L>π/A∼O(1000km) → It is satisfied by DUNE but not by T2HK.

2. Sensitivity of T2HK & DUNE to $N_\nu=3$ oscillation parameters

Uncertainty in matter density taken into account

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The parameters assumed here:

T2HK

187 kton fiducial volume

$\nu:\bar{\nu} = 1:1$

Total exposure: 2.7×10^{22} POT

DUNE

40 kt LiAr detector,

$\nu:\bar{\nu} = 1:1$

Total exposure: 1.1×10^{21} POT

Reference value:

$\theta_{23} = 42^o$ or 48^o,

$\delta = -90^o$,

$\Delta m^2_{31} = 2.51\times10^{-3}\mathrm{eV}^2$,

$\Delta\rho/\rho = 0$, 5%, 10%

Recommended by Geller-Hara, hep-ph/0111342

2.1 Precision to oscillation parameters

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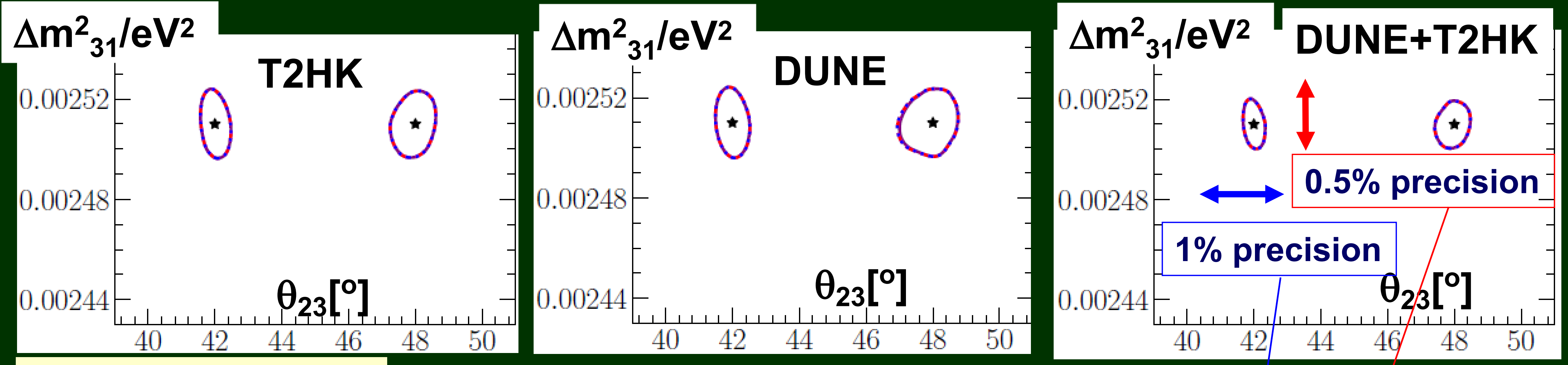
Uncertainty in matter density taken into account

Precision of DUNE is slightly better than that of T2HK.
-> Combined precision is excellent.

Uncertainty in matter density has little effect
<- Major contribution comes from disappearance channel.

$\Delta\rho/\rho=0\%$
$\Delta\rho/\rho=5\%$
$\Delta\rho/\rho=10\%$



T2HK: $\Delta m^2_{31}/10^{-3}eV^2 = (2.51+0.013-0.014)$, $\theta_{23} = (42\pm0.5)°$

DUNE: $(2.51+0.015-0.014)$, $(42\pm0.5)°$

DUNE+T2HK: (2.51 ± 0.01), $(42+0.4-0.3)°$

DUNE&T2HK vs Present status of global fit

	Ref	$\Delta m^2_{31}/10^{-3}eV^2$	$\theta_{23}[^\circ]$
Global fit	www.nu-fit.org v5.2 (Nov. 2022)	$2.507^{+0.026}_{-0.027}$	$42.2^{+1.1}_{-0.9}$
Future exp	T2HK Ghosh-OY('23)	$2.510^{+0.013}_{-0.014}$	42.0 ± 0.5
	DUNE Ghosh-OY('23)	$2.510^{+0.015}_{-0.014}$	42.0 ± 0.5
	DUNE+T2HK Ghosh-OY('23)	2.510 ± 0.010	$42.0^{+0.4}_{-0.3}$

2.2 Sensitivity to Mass Ordering

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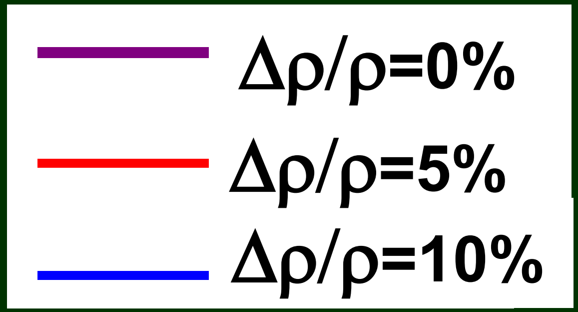
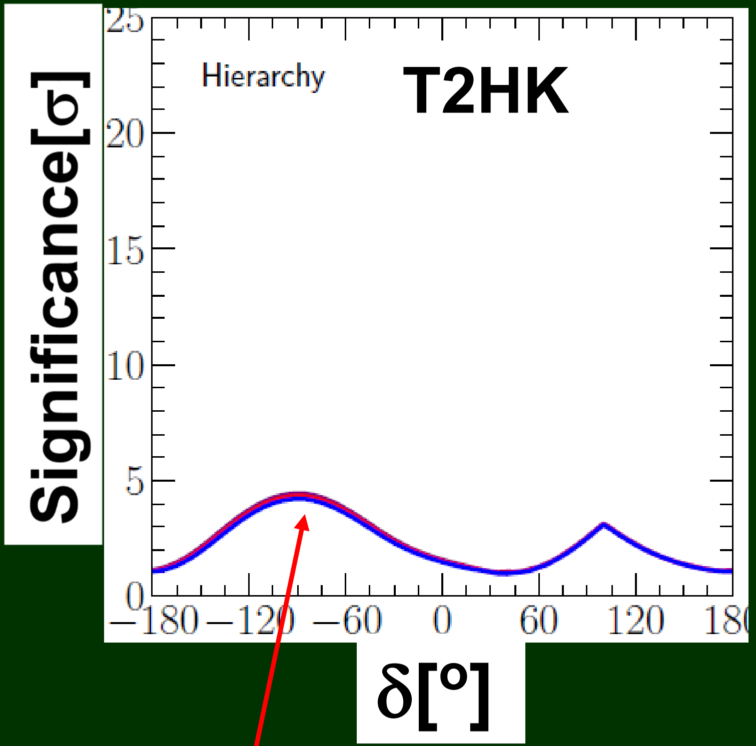
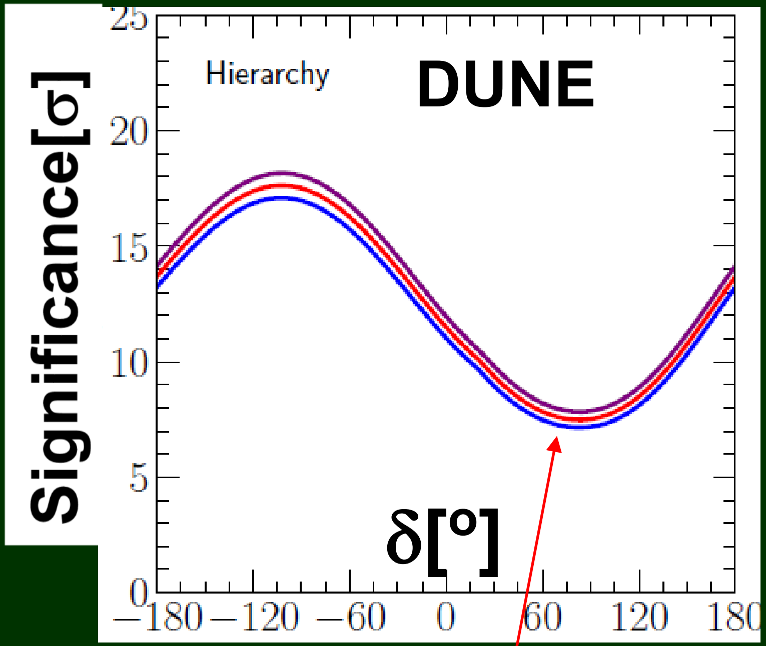
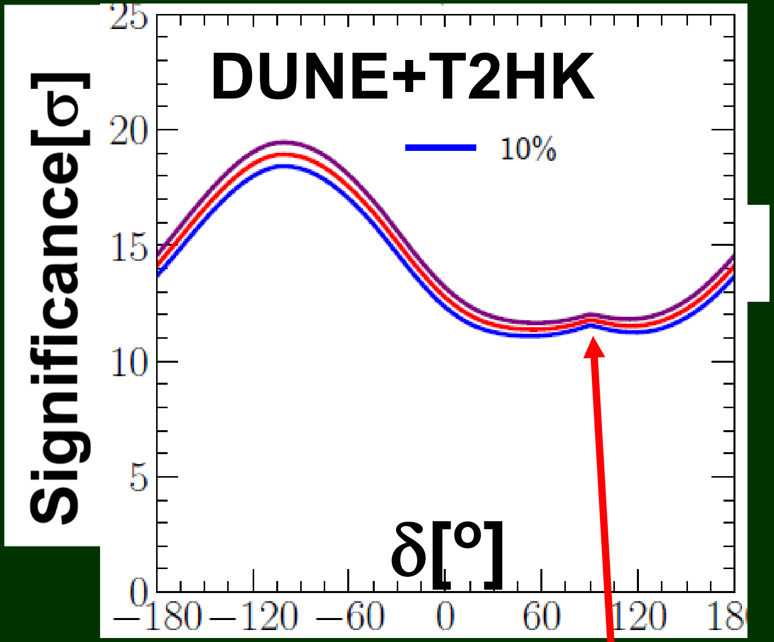


Uncertainty in matter density has some effect on DUNE
<- DUNE has longer baseline L=1300km







Sensitivity of T2HK is poor except for $\delta \sim -\pi/2$

Sensitivity of DUNE is excellent for any δ

Synergy of T2HK+DUNE at $\delta = \pi/2$: If MO is known from DUNE → Sensitivity of T2HK is improved

2.3 Sensitivity to Octant degeneracy

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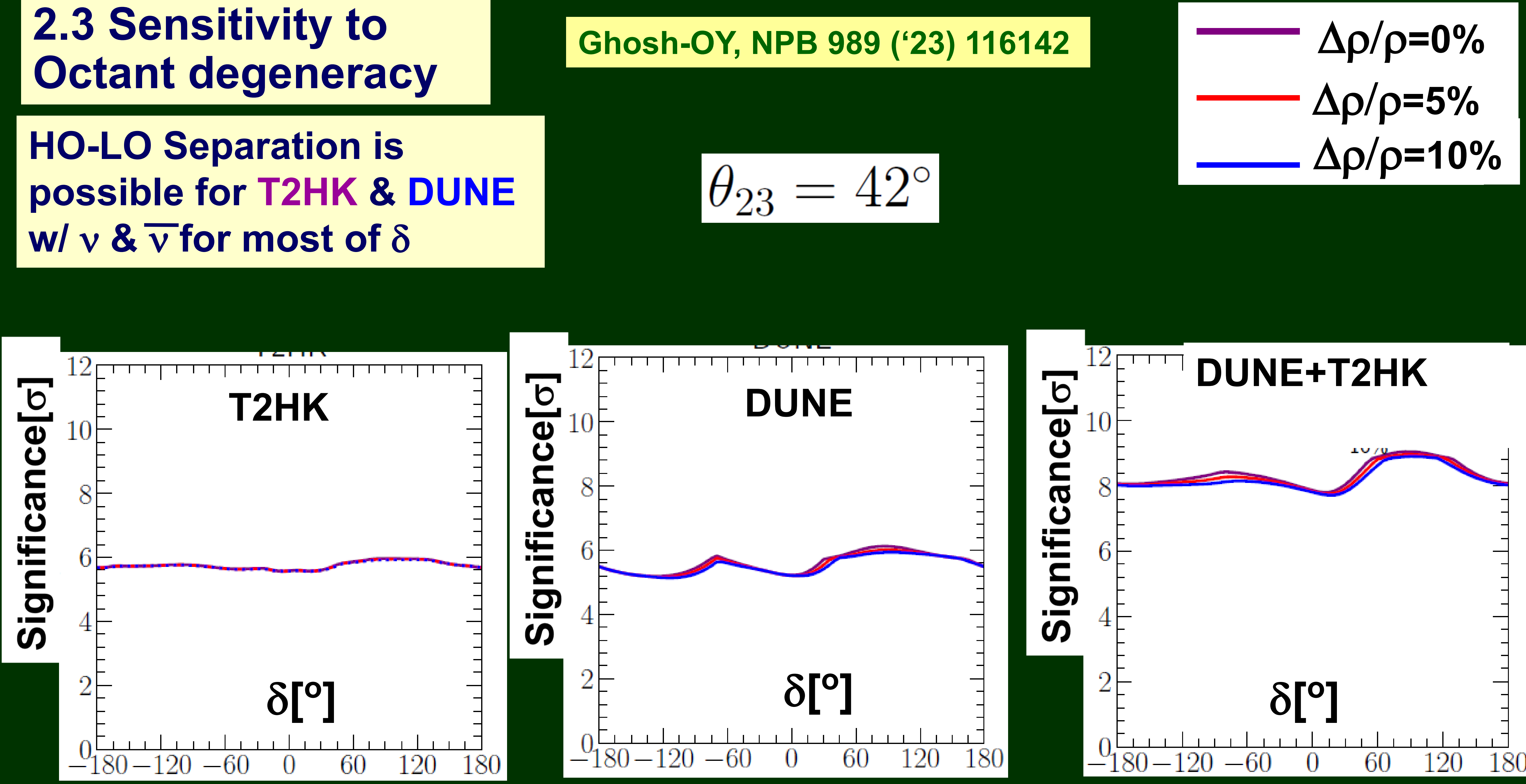
HO-LO Separation is possible for T2HK & DUNE w/ ν & $\overline{\nu}$ for most of δ

$$\theta_{23} = 42^\circ$$



2.4 Sensitivity to CP(1)

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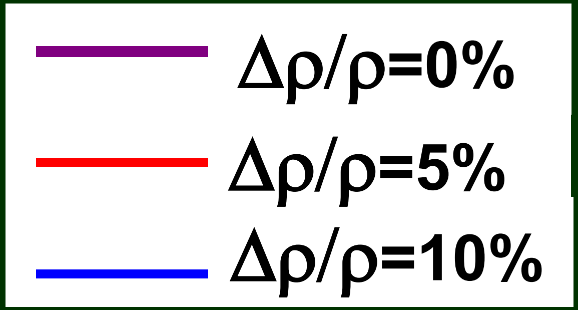
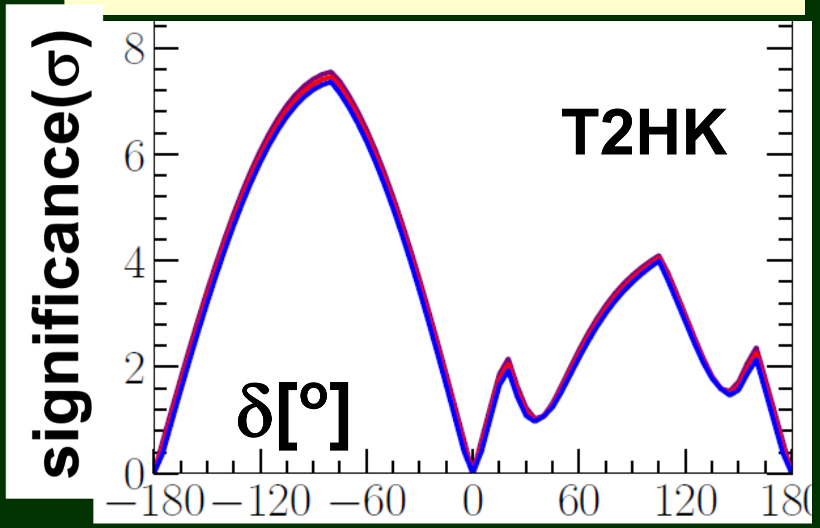
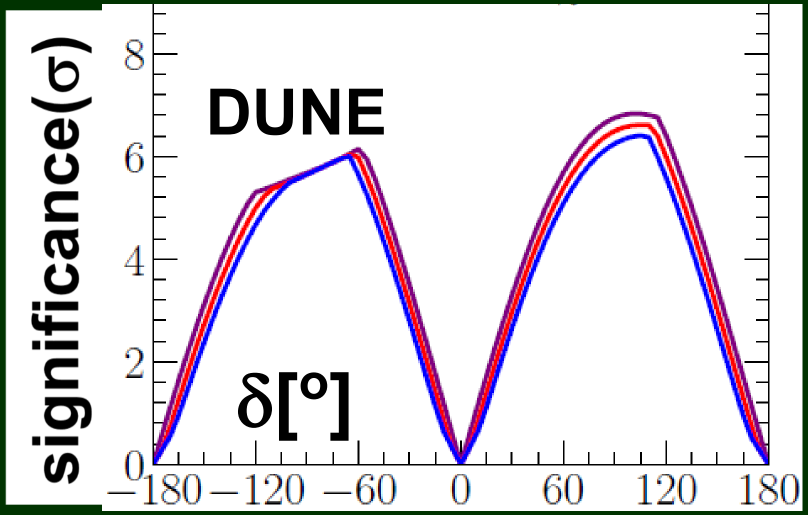


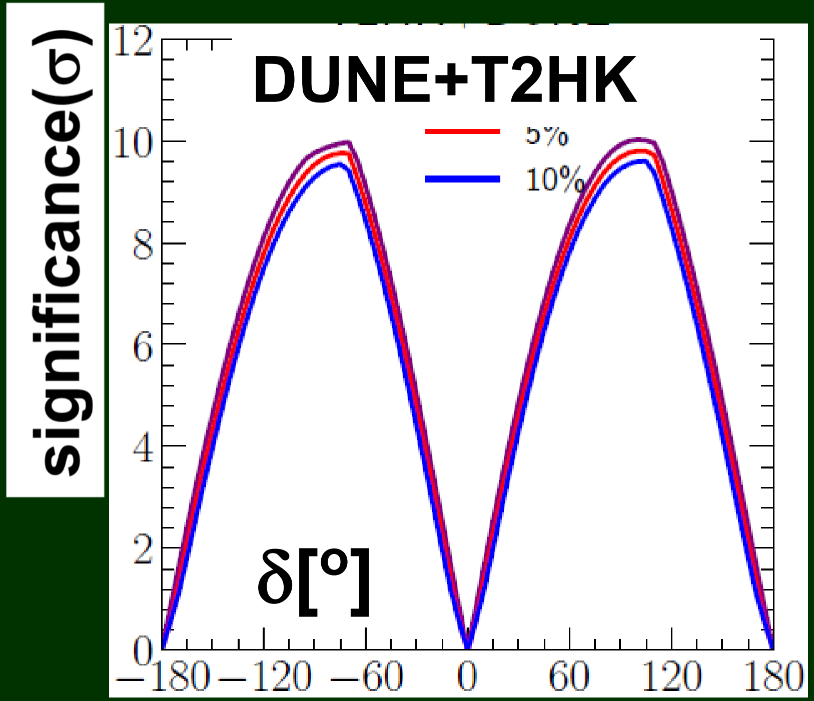
Uncertainty in matter density has some effect on DUNE.
<- DUNE has longer baseline L=1300km
However even with Δρ/ρ=10%, the sensitivity is excellent.

Sensitivity of **T2HK** is poor for (NO, $\delta = +\pi/2$) & (IO, $\delta = -\pi/2$)



Sensitivity of **DUNE** is excellent for $|\sin\delta|=1$ for both mass hierarchy





2.4 Sensitivity to CP(2)

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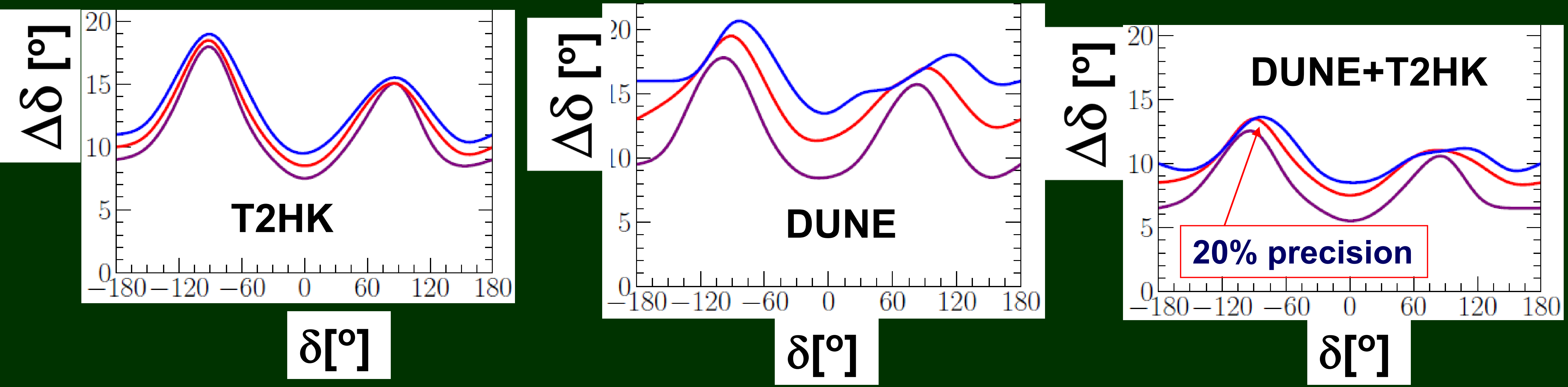
Uncertainty in matter density has some effect on the precision $\Delta\delta$ both for T2HK & DUNE.

$\Delta\delta/\delta$ has mild dependence on δ but not much.



3. Octant parameter degeneracy

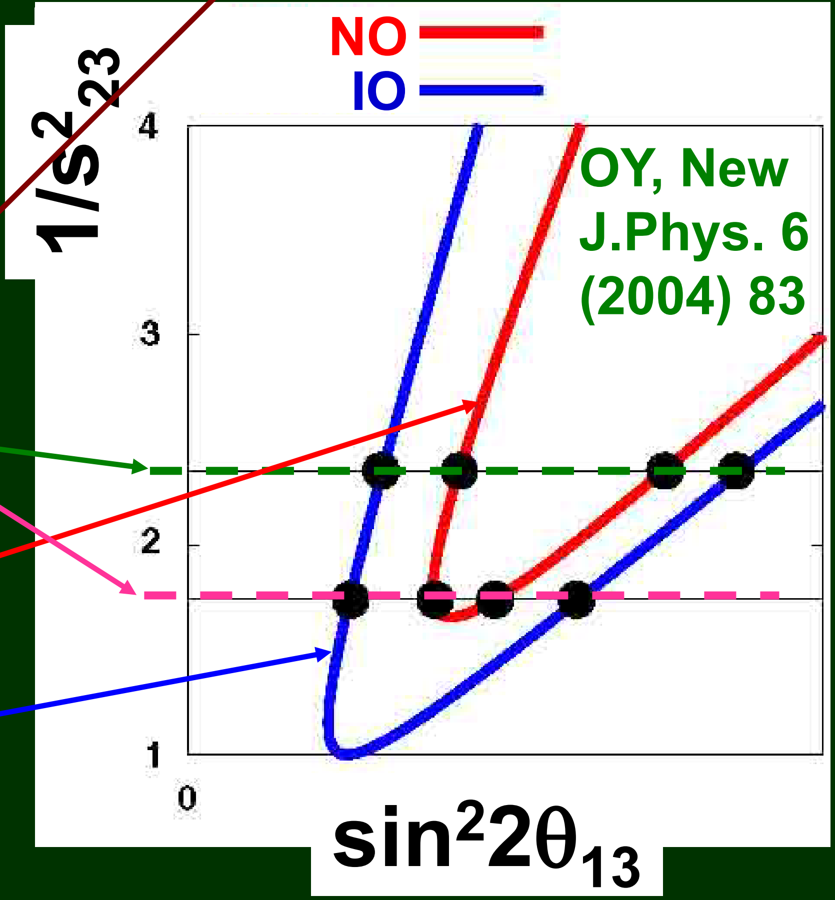
Sugama - OY, arXiv:2308.15071

- **Parameter degeneracy**

Even if we know $P \equiv P(\nu_\mu \to \nu_e)$ and $\bar{P} \equiv P(\bar{\nu}_\mu \to \bar{\nu}_e)$ in LBL experiments with energy E and baseline L, δ cannot be uniquely determined because of the 8-fold parameter degeneracy.

- **octant degeneracy** $\theta_{23} \Leftrightarrow \pi/2 - \theta_{23}$ (Fogli-Lisi, '96)
- **intrinsic degeneracy** (δ, θ_{13}) (Burguet-Castell et al, '01)
- **sign degeneracy** $\Delta m^2_{31} \Leftrightarrow -\Delta m^2_{31}$ (Minakata-Nunokawa, '01)

$(\sin^2 2\theta_{13}, 1/s^2_{23})$ plane (P=const & $\bar{P}$=const gives a quadratic curve)



Appearance oscillation probability

$$A \equiv \sqrt{2} G_F N_e$$

$$P(\nu_\mu \to \nu_e, E) = x^2 F^2 + 2\,\mathrm{sign}(\Delta m^2_{31})\, xyFg \cos\left[\delta + \mathrm{sign}(\Delta m^2_{31})\,\Delta\right] + y^2 g^2$$

$$P(\bar\nu_\mu \to \bar\nu_e, E) = x^2 \bar F^2 + 2\,\mathrm{sign}(\Delta m^2_{31})\, xy\bar F g \cos\left[\delta - \mathrm{sign}(\Delta m^2_{31})\,\Delta\right] + y^2 g^2$$

$$x \equiv s_{23} \sin 2\theta_{13}$$

$$y \equiv \left|\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\right| \cos\theta_{23} \sin 2\theta_{12}$$

$$(F, \bar F) \equiv \left\{ \begin{array}{ll} (f, \bar f) & \text{for NO} \\ (\bar f, f) & \text{for IO} \end{array} \right\}$$

$$\Delta \equiv \frac{|\Delta m^2_{31}| L}{4E}$$

$$g \equiv \frac{\sin(AL/2)}{AL/2\Delta}$$

$$\left\{ \begin{array}{c} f \\ \bar f \end{array} \right\} \equiv \frac{\sin(\Delta \mp AL/2)}{(1 \mp AL/2\Delta)}$$

Change of variables

$$X \equiv \sin^2 2\theta_{13}$$

$$Y \equiv \frac{1}{s^2_{23}}$$

Eliminate δ → **For sinΔ≠0: a quadratic curve in (X,Y)-plane**

$$C \equiv \left(\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\right)^2 \left[\frac{\sin(AL/2)}{AL/2\Delta}\right]^2 \sin^2 2\theta_{12}$$

$$16CX(Y-1)$$
$$= \frac{1}{\cos^2\Delta}\left[\left(\frac{P(E)-C}{F} + \frac{\bar P(E)-C}{\bar F}\right)(Y-1) - (F+\bar F)X + \frac{P(E)}{F} + \frac{\bar P(E)}{\bar F}\right]^2$$
$$+ \frac{1}{\sin^2\Delta}\left[\left(\frac{P(E)-C}{F} - \frac{\bar P(E)-C}{\bar F}\right)(Y-1) - (F-\bar F)X + \frac{P(E)}{F} - \frac{\bar P(E)}{\bar F}\right]^2$$

$$X \equiv \sin^2 2\theta_{13} \quad Y \equiv \frac{1}{s_{23}^2} \quad C \equiv \left(\frac{\Delta m_{21}^2}{\Delta m_{31}^2}\right)^2 \left[\frac{\sin(AL/2)}{AL/2\Delta}\right]^2 \sin^2 2\theta_{12}$$

For sinΔ≠0 → **A quadratic curve in (X,Y)-plane**

$$\begin{aligned} &16CX(Y-1) \\ &= \frac{1}{\cos^2\Delta}\left[\left(\frac{P(E)-C}{F}+\frac{\bar{P}(E)-C}{\bar{F}}\right)(Y-1)-(F+\bar{F})X+\frac{P(E)}{F}+\frac{\bar{P}(E)}{\bar{F}}\right]^2 \\ &+\frac{1}{\sin^2\Delta}\left[\left(\frac{P(E)-C}{F}-\frac{\bar{P}(E)-C}{\bar{F}}\right)(Y-1)-(F-\bar{F})X+\frac{P(E)}{F}-\frac{\bar{P}(E)}{\bar{F}}\right]^2 \end{aligned}$$

For sinΔ=0 (Oscillation Maximum $\Delta \equiv \frac{|\Delta m_{31}^2|L}{4E} = \frac{\pi}{2}$)

→ **A straight line in (X,Y)-plane**

$$\left(\frac{P(E)-C}{F}+\frac{\bar{P}(E)-C}{\bar{F}}\right)(Y-1)-(F+\bar{F})X+\frac{P(E)}{F}+\frac{\bar{P}(E)}{\bar{F}}=0$$

Fit of test oscillation parameters to true ones

From the values of P and $\bar{P}$ given by the true oscillation parameters, can we determine uniquely the test oscillation parameters?

$$P(\nu_\mu \to \nu_e, E; \theta_{jk}^{\text{test}}, \Delta m_{jk}^{2\ \text{test}}, \delta^{\text{test}}) = P(\nu_\mu \to \nu_e, E; \theta_{jk}^{\text{true}}, \Delta m_{jk}^{2\ \text{true}}, \delta^{\text{true}}) \equiv P(E)$$

$$P(\bar{\nu}_\mu \to \bar{\nu}_e, E; \theta_{jk}^{\text{test}}, \Delta m_{jk}^{2\ \text{test}}, \delta^{\text{test}}) = P(\bar{\nu}_\mu \to \bar{\nu}_e, E; \theta_{jk}^{\text{true}}, \Delta m_{jk}^{2\ \text{true}}, \delta^{\text{true}}) \equiv \bar{P}(E)$$

Test oscillation parameters (θ_{13}, θ_{23}, δ): varied (δ is expressed by θ_{13} and θ_{23})
→ 2 independent parameters are: $X \equiv \sin^2 2\theta_{13}$ $Y \equiv \frac{1}{s^2_{23}}$

True oscillation parameters: fixed

NB Other test oscillation parameters (Δm^2_{31}, θ_{12}, Δm^2_{21}) are fixed

3.1 Situation before 2012

2012 Reactor ν: $P(\bar{\nu}_e \to \bar{\nu}_e)$ ⇨ $\sin^2 2\theta_{13}$

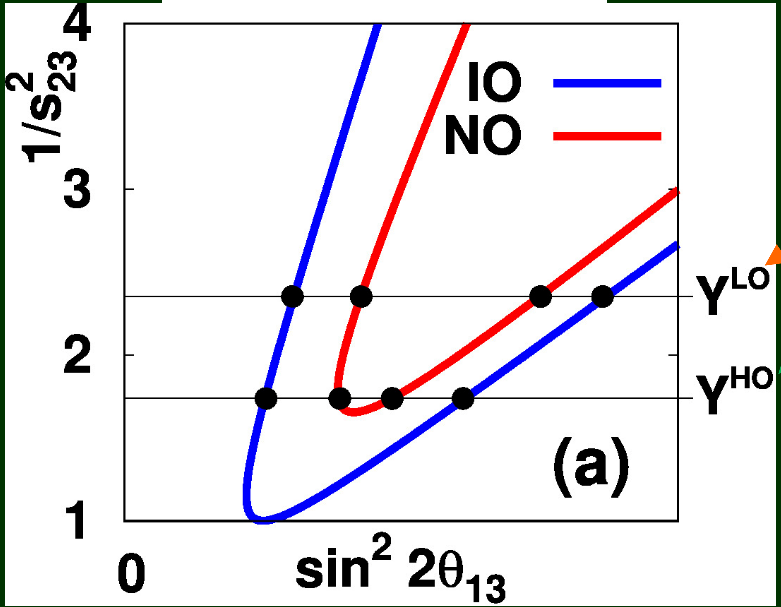
(1) No information on $\sin^2 2\theta_{13}$ was available

(2) From $P(\nu_\mu \to \nu_\mu)$ only $\sin^2 2\theta_{23}$ is known

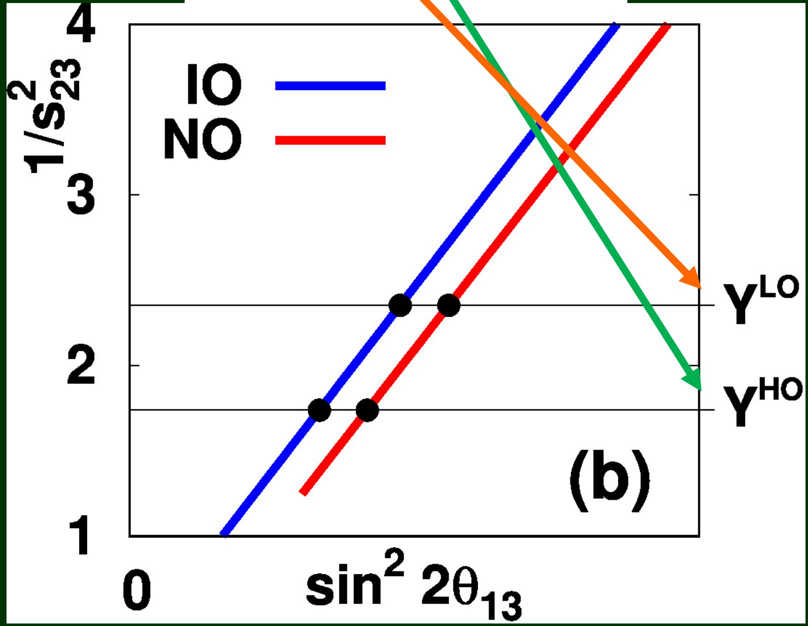
⇨ **2 possibilities for $Y=1/s^2_{23}$ remain:**

$$Y = \left\{ \begin{array}{c} Y^{\rm HO} \\ Y^{\rm LO} \end{array} \right\} \equiv \frac{2}{1 \pm \sqrt{1-\sin^2 2\theta_{23}^{\rm true}}}$$

For sinΔ≠0



For sinΔ=0



3.2 Situation after 2012

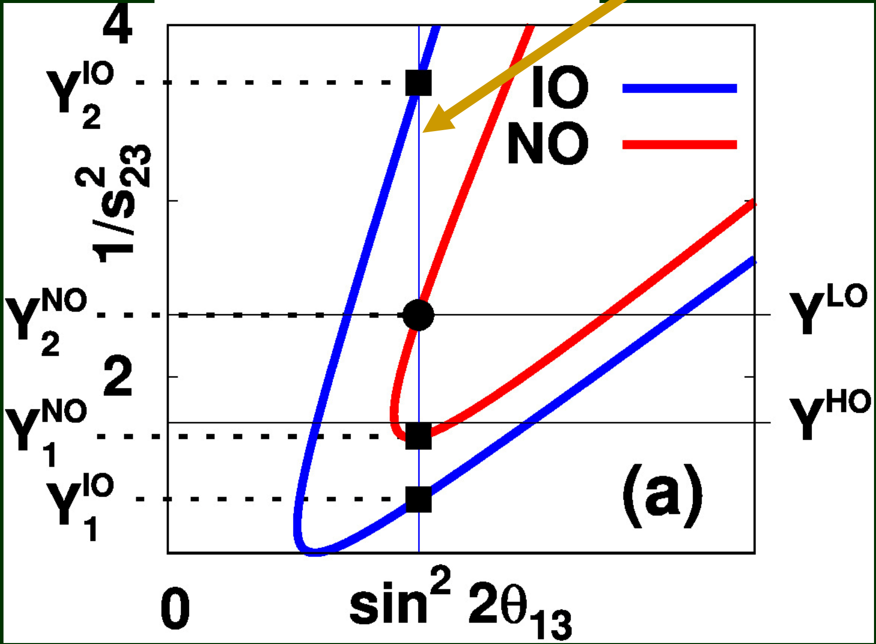
2012 Reactor ν: $P(\bar{\nu}_e \to \bar{\nu}_e)$ ⇨ $\sin^2 2\theta_{13}$

(1) From $P(\nu_\mu \to \nu_\mu)$ only $\sin^2 2\theta_{23}$ is known

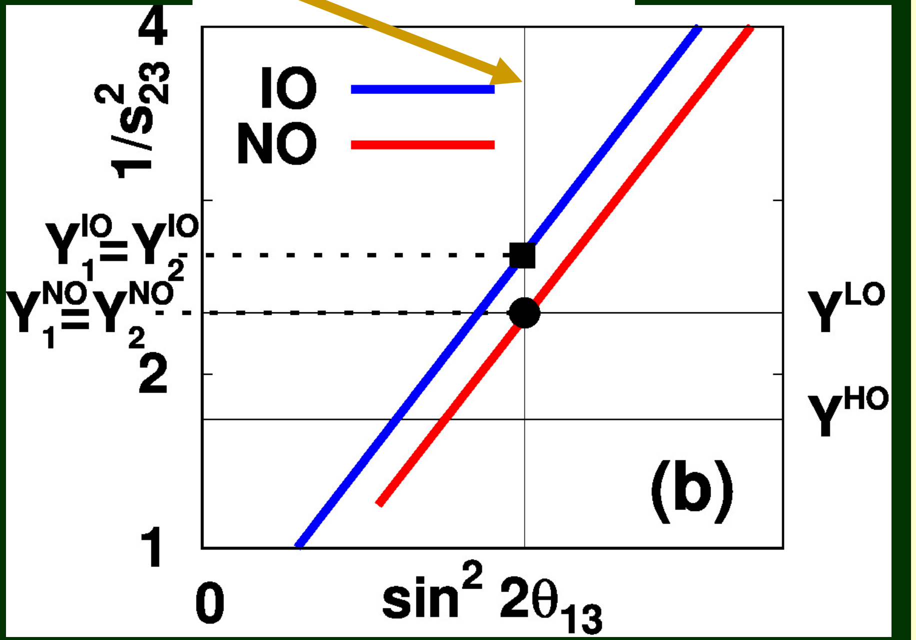
(2) Information on $\sin^2 2\theta_{13}$ is available

From these two, θ_{23} should be determined!?

For sinΔ≠0



For sinΔ=0



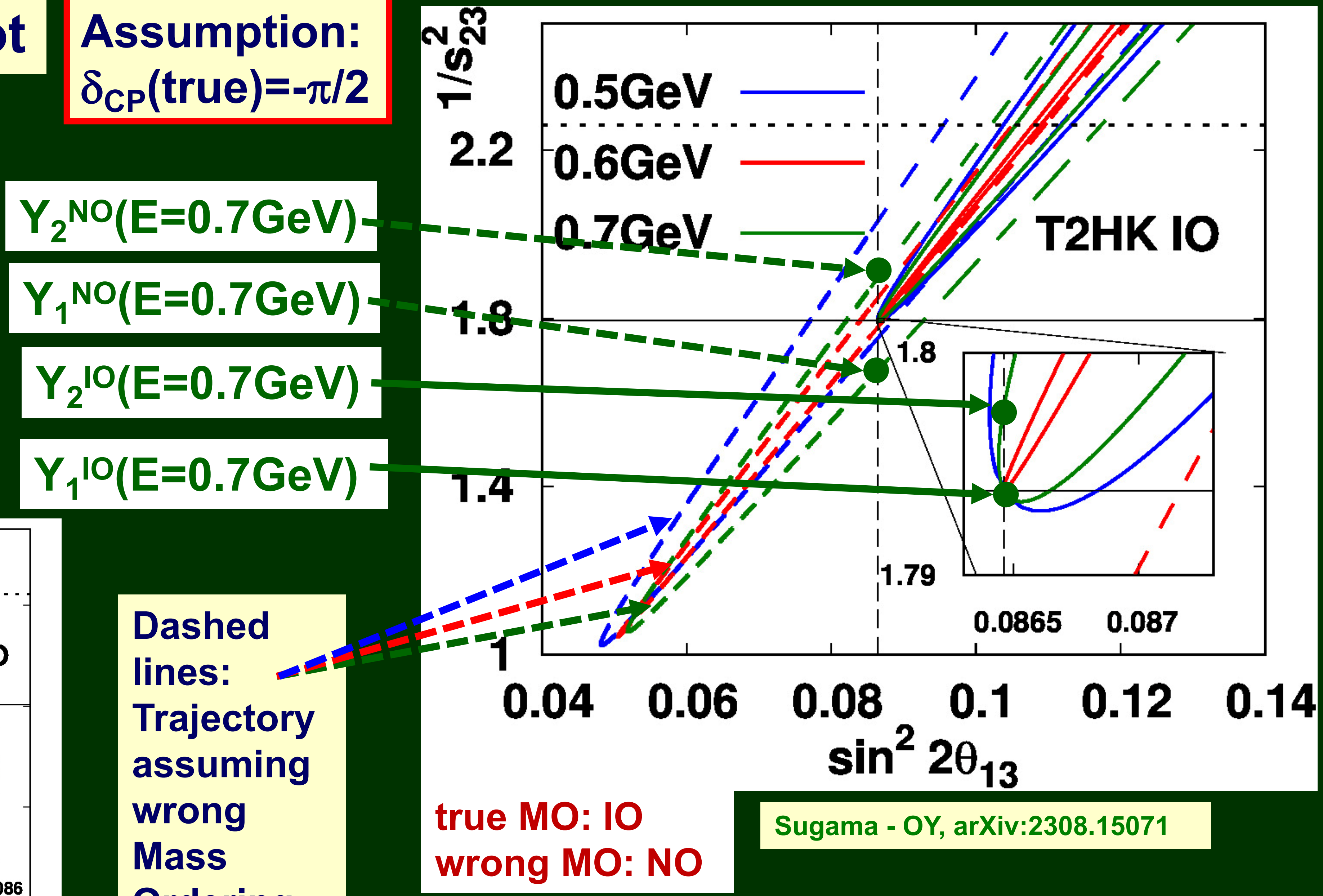
These figures are for a fixed energy. → Later we will see the behavior of Y_j^{MO} over the whole energy spectrum.

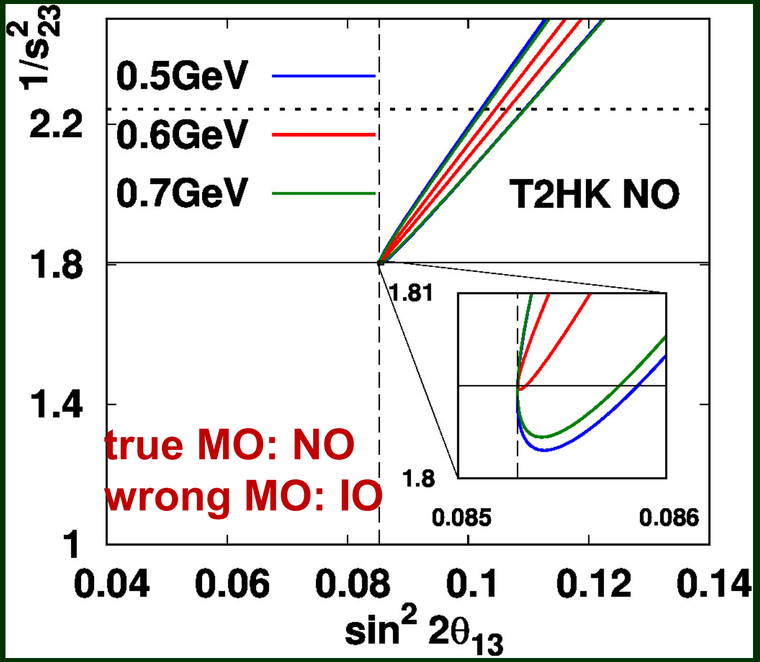
3.3 T2HK: (X,Y) plot

Assumption: δ_{CP}(true)=-π/2

L=295km
E∼0.6GeV

If true Mass Ordering is NO and true δ_{CP} is -π/2, then T2HK can exclude IO.





Sugama - OY, arXiv:2308.15071

3.3 T2HK: $(E, Y_j^{MO}(E))$ plot

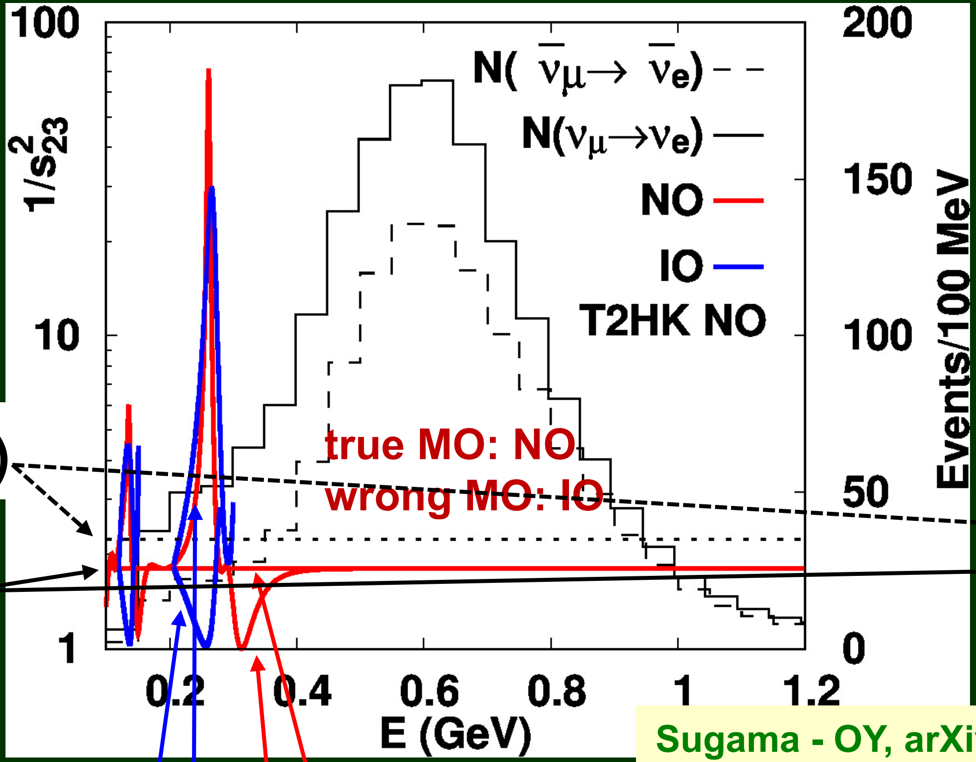
Assumption: True Octant=Higher Octant

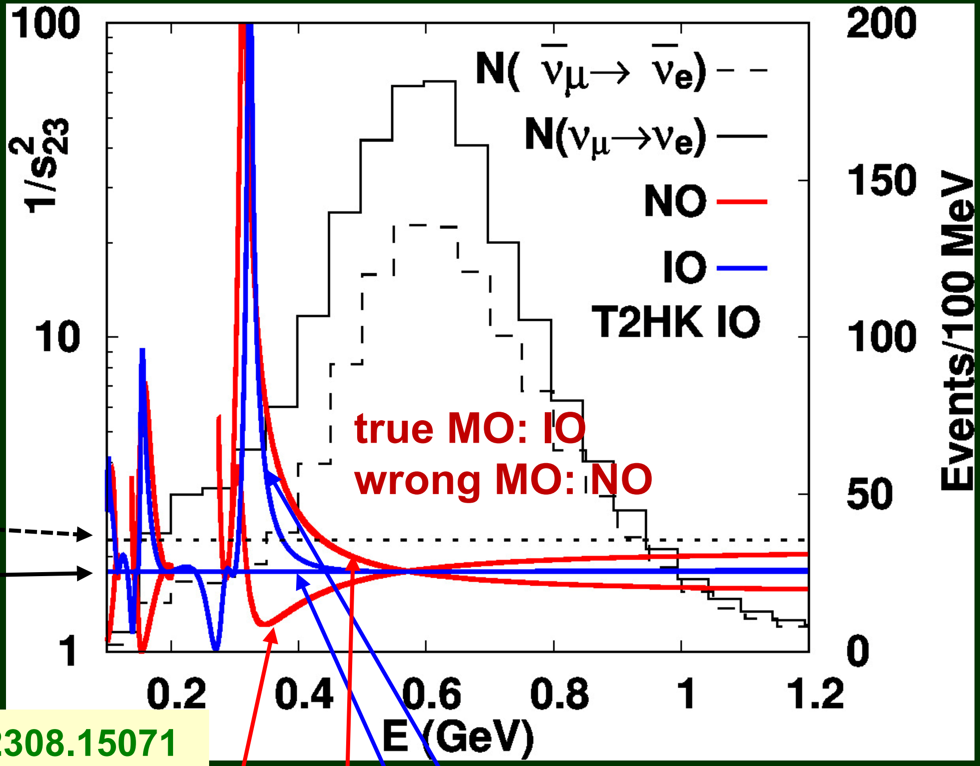
L=295km
E∼0.6GeV

Sugama - OY, arXiv:2308.15071

Y^{LO} (wrong octant)

Y^{HO} (true octant)





Sugama - OY, arXiv:2308.15071

For dominant energy bins, Y_j^{MO} agree with Y^{HO} → Octant degeneracy can be resolved.

correct Mass Ordering: Larger: $Y_2^{NO}(E)$, Smaller: $Y_1^{NO}(E)$

wrong Mass Ordering: Larger: $Y_2^{IO}(E)$, Smaller: $Y_1^{IO}(E)$

correct Mass Ordering: Larger: $Y_2^{IO}(E)$, Smaller: $Y_1^{IO}(E)$

wrong Mass Ordering: Larger: $Y_2^{NO}(E)$, Smaller: $Y_1^{NO}(E)$

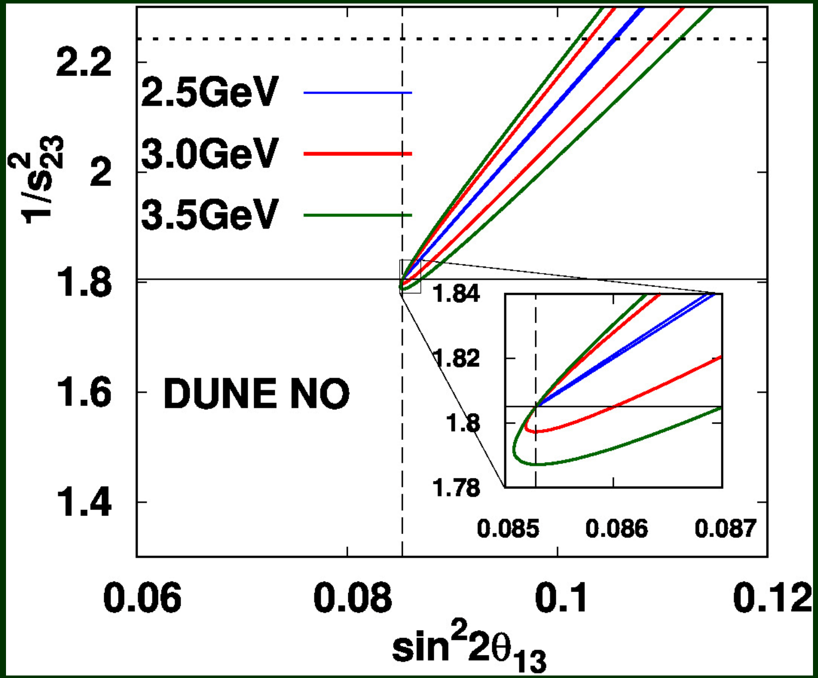
3.4 DUNE

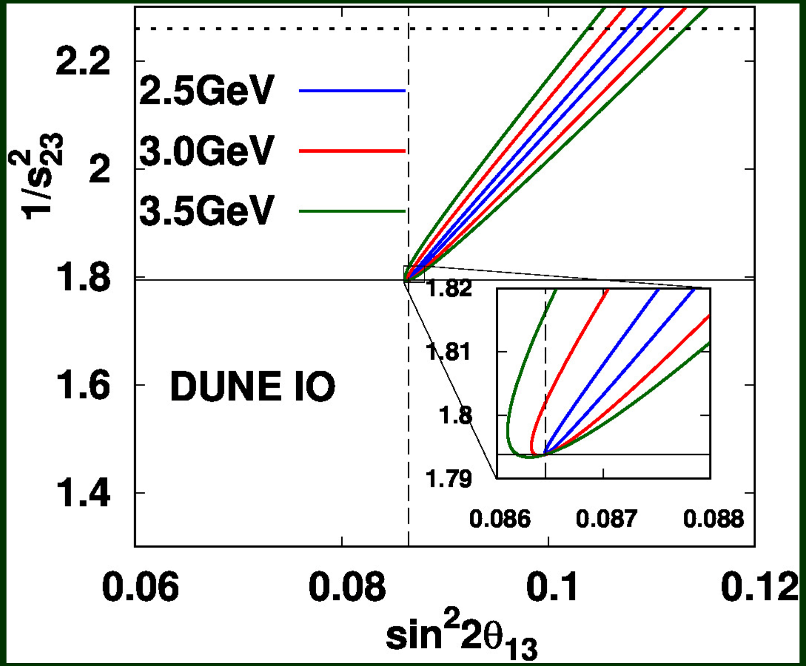
Sugama - OY, arXiv:2308.15071

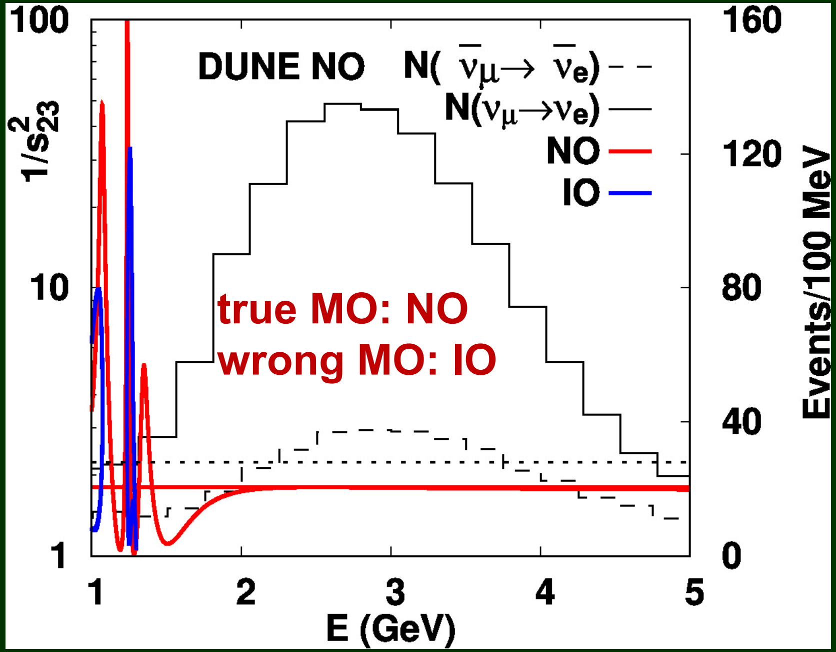
L=1300km
E=2GeV - 4GeV

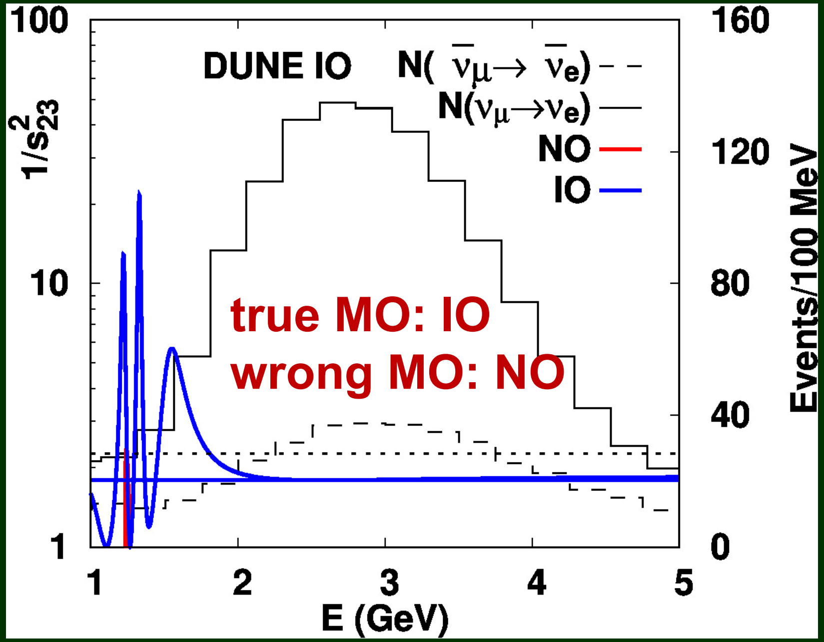
Because of the long baseline, wrong Mass Ordering can be always excluded.

→ Octant degeneracy can be resolved, as in T2HK.





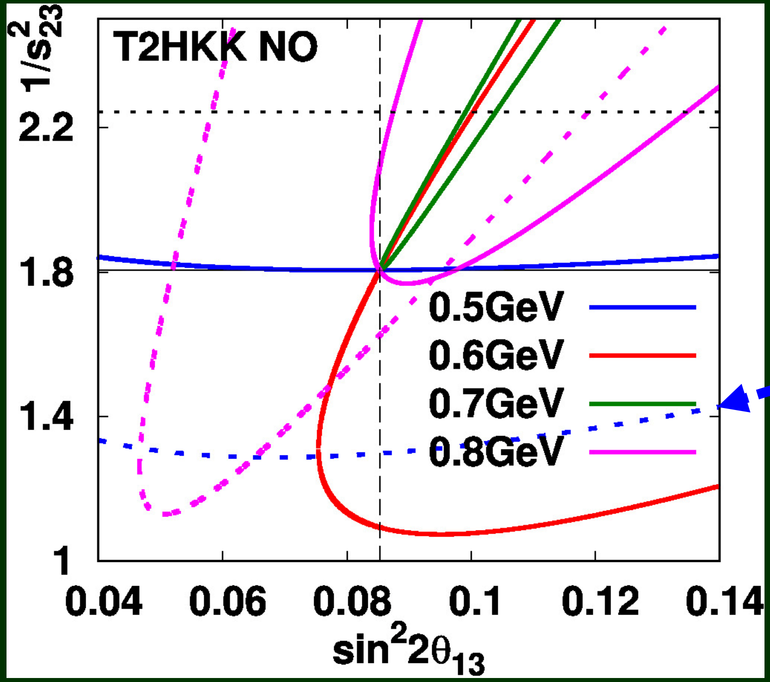


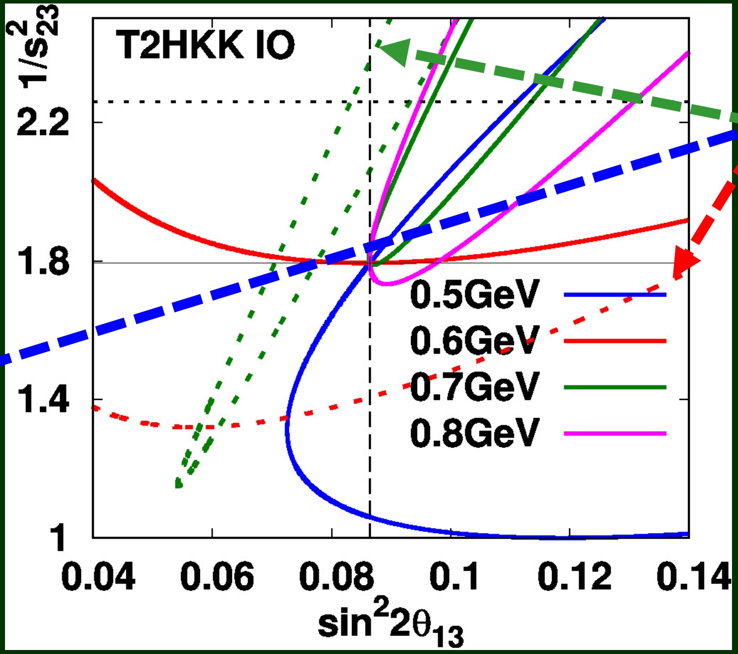


3.5 T2HKK

L=1100km
E=0.5GeV – 0.8GeV

1st Oscillation Maximum ($\Delta=\pi/2$, E=2.2GeV) is missed, but 2nd Oscillation Maximum ($\Delta=3\pi/2$, E=0.75GeV) is covered.

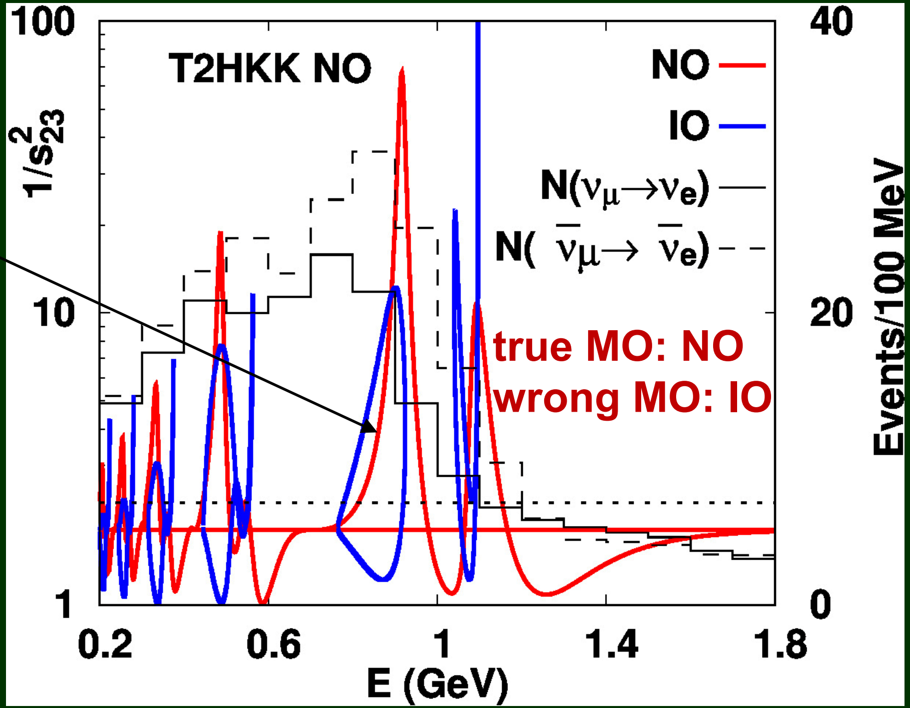


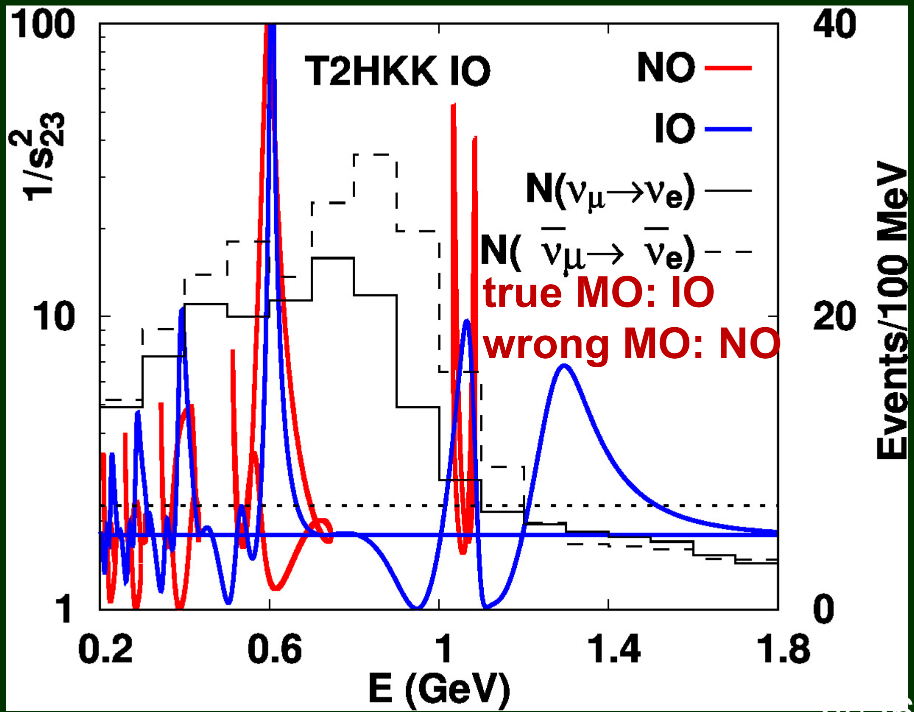


Dashed lines: Trajectory assuming wrong Mass Ordering

Sugama - OY, arXiv:2308.15071

→ Because of large deviation and rapid oscillations near 2nd oscillation maximum, it is difficult to resolve octant degeneracy. [← already known by numerical simulations in P. Panda et al. (arXiv:2206.10320)]



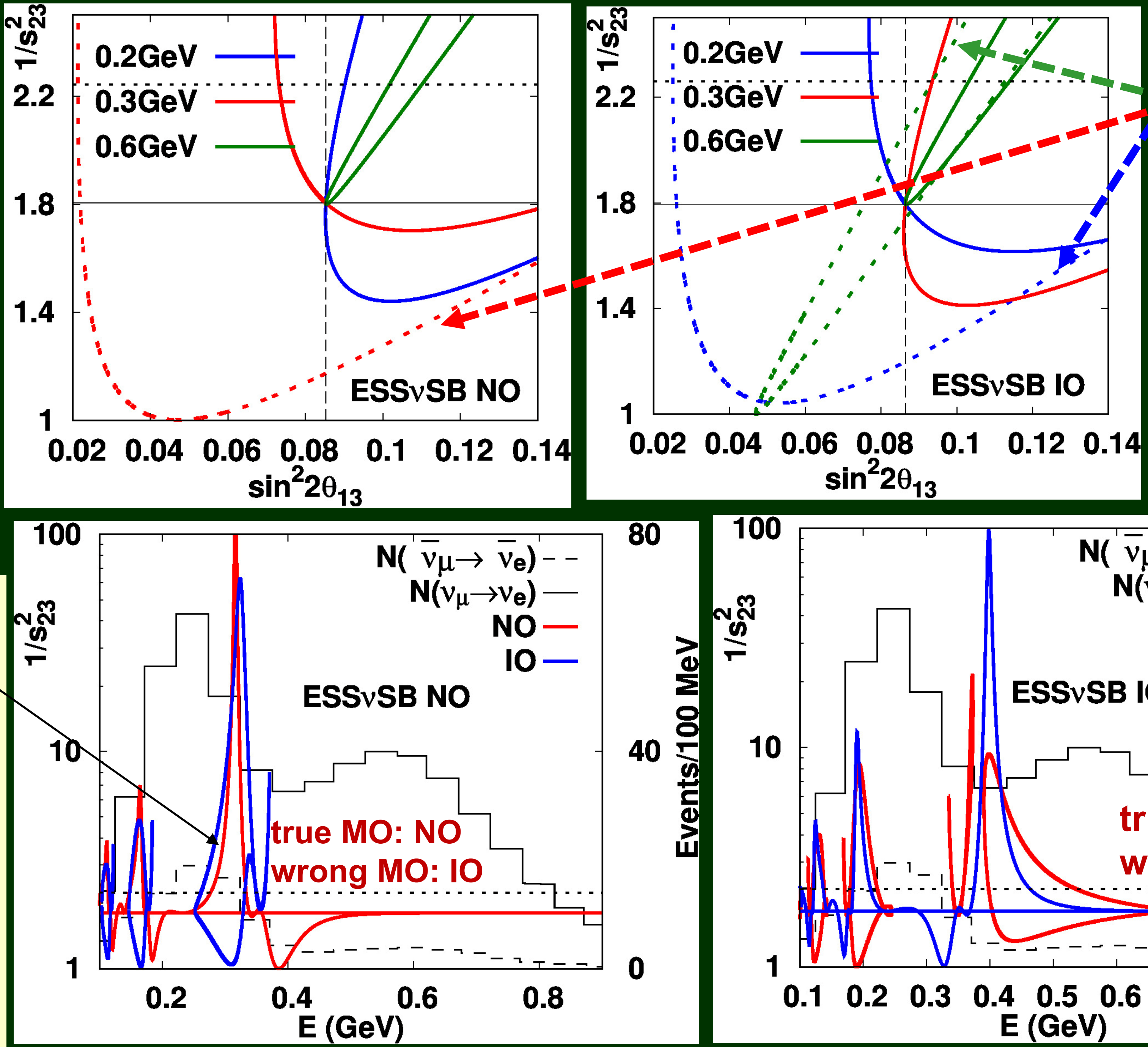


3.6 ESSνSB

L=530km
E=0.2GeV – 0.4GeV

1st Oscillation Maximum ($\Delta=\pi/2$, E=0.73GeV) is missed for $\bar{\nu}$ mode, but 2nd Oscillation Maximum ($\Delta=3\pi/2$, E=0.24GeV) is covered.

→ Because of large deviation and rapid oscillations near 2nd oscillation maximum, it is difficult to resolve octant degeneracy.
[← already known by numerical simulations in S. K. Agarwalla et al., (arXiv:1406.2219)]



Dashed lines: Trajectory assuming wrong Mass Ordering

Sugama - OY, arXiv:2308.15071

4. Conclusions

- T2HK+DUNE gives us excellent precision in θ_{23} (1%), Δm_{32}^2 (0.5%), δ (20%), although DUNE suffers from uncertainty in the density (20%).
- T2HK and DUNE are expected to resolve octant degeneracy, while it seems difficult to resolve octant degeneracy for far future long baseline experiments, T2HKK and ESSνSB, which focus on 2nd oscillation maximum.

Backup slides

Historical background of ν oscillation studies:

1998- Atmospheric ν / Long baseline ν: $P(\nu_\mu \to \nu_\mu)$ ➡ **$\sin^2 2\theta_{23}$**

2000- Phenomenology of Long baseline ν:

How to determine δ_{CP} from $P(\nu_\mu \to \nu_e)$ **and** $P(\bar{\nu}_\mu \to \bar{\nu}_e)$

2001- Parameter degeneracy was pointed out.

2004 Plot of 8-fold parameter degeneracy was proposed.

2012 Reactor ν: $P(\bar{\nu}_e \to \bar{\nu}_e)$ ➡ **$\sin^2 2\theta_{13}$**

2023 Plot of 8-fold parameter degeneracy is revisited, taking into account the measured values of $\sin^2 2\theta_{13}$ and $\sin^2 2\theta_{23}$ (this talk).

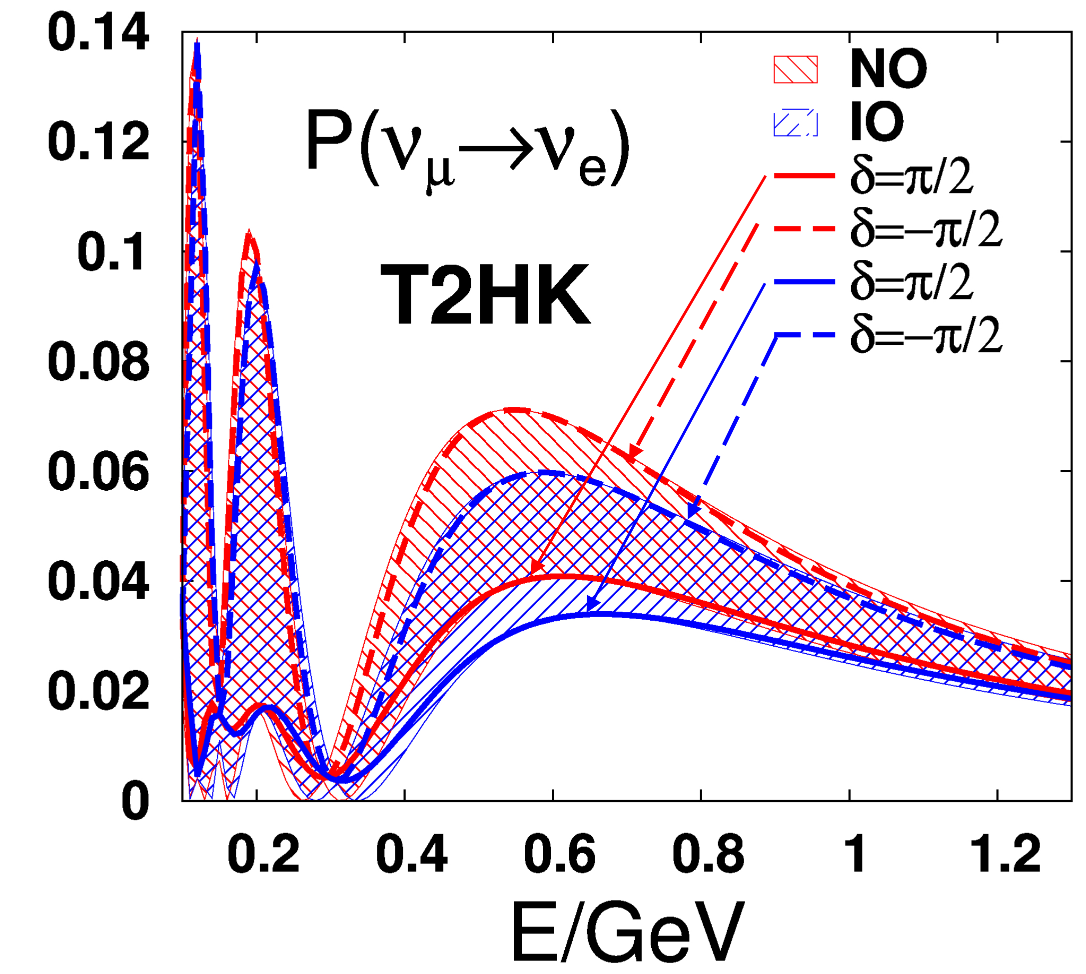
Understanding degeneracy by appearance probabilities

hierarchy - δ

Prakash, Raut, Sankar, PRD 86, 033012 (2012)

octant - δ

Agarwalla, Prakash, Sankar, JHEP 1307, 131 (2013)



Due to uncertainty in δ, the appearance probabilities has finite width.

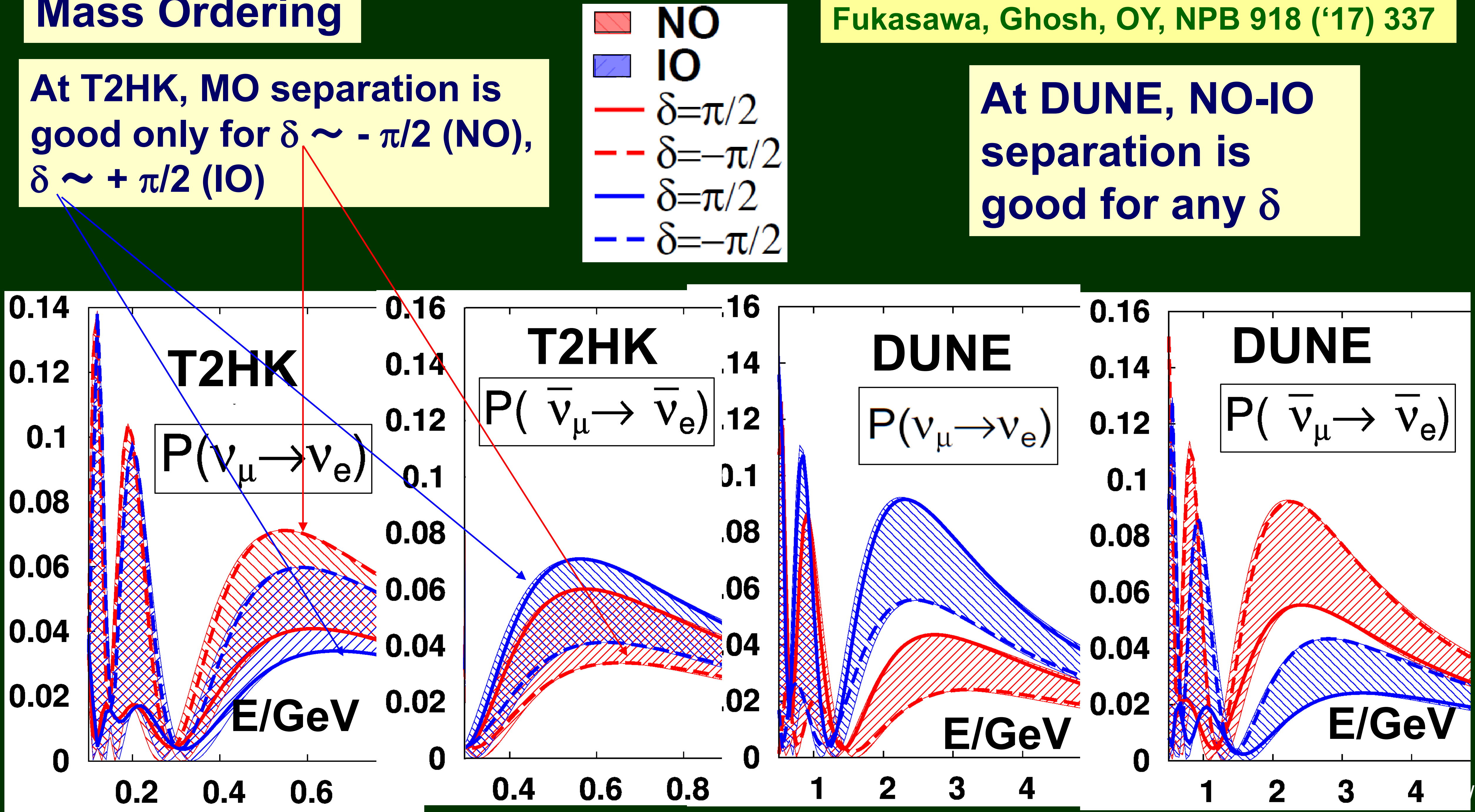
-> Each border is approximately realized for $\delta = +\pi/2$ or $-\pi/2$

Mass Ordering

Fukasawa, Ghosh, OY, NPB 918 ('17) 337

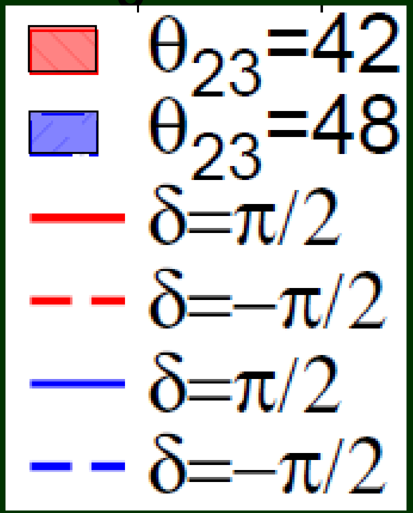
At T2HK, MO separation is good only for δ ~ - π/2 (NO), δ ~ + π/2 (IO)

At DUNE, NO-IO separation is good for any δ



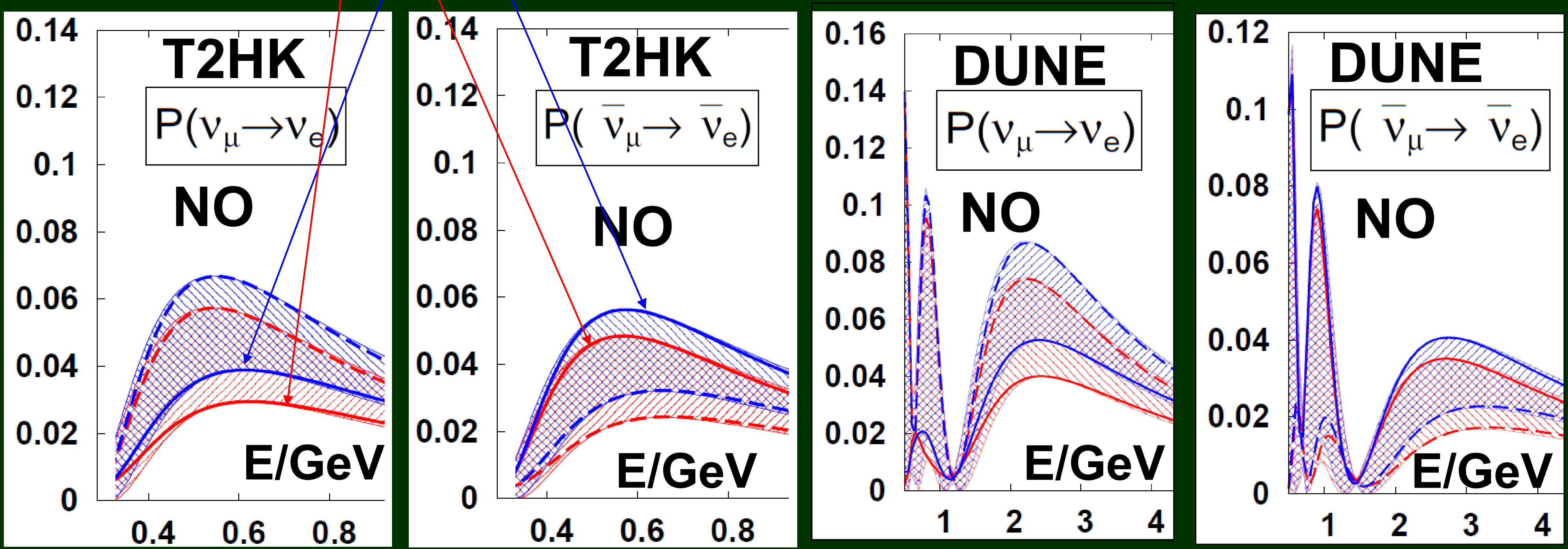
Octant

Fukasawa, Ghosh, OY, NPB 918 ('17) 337

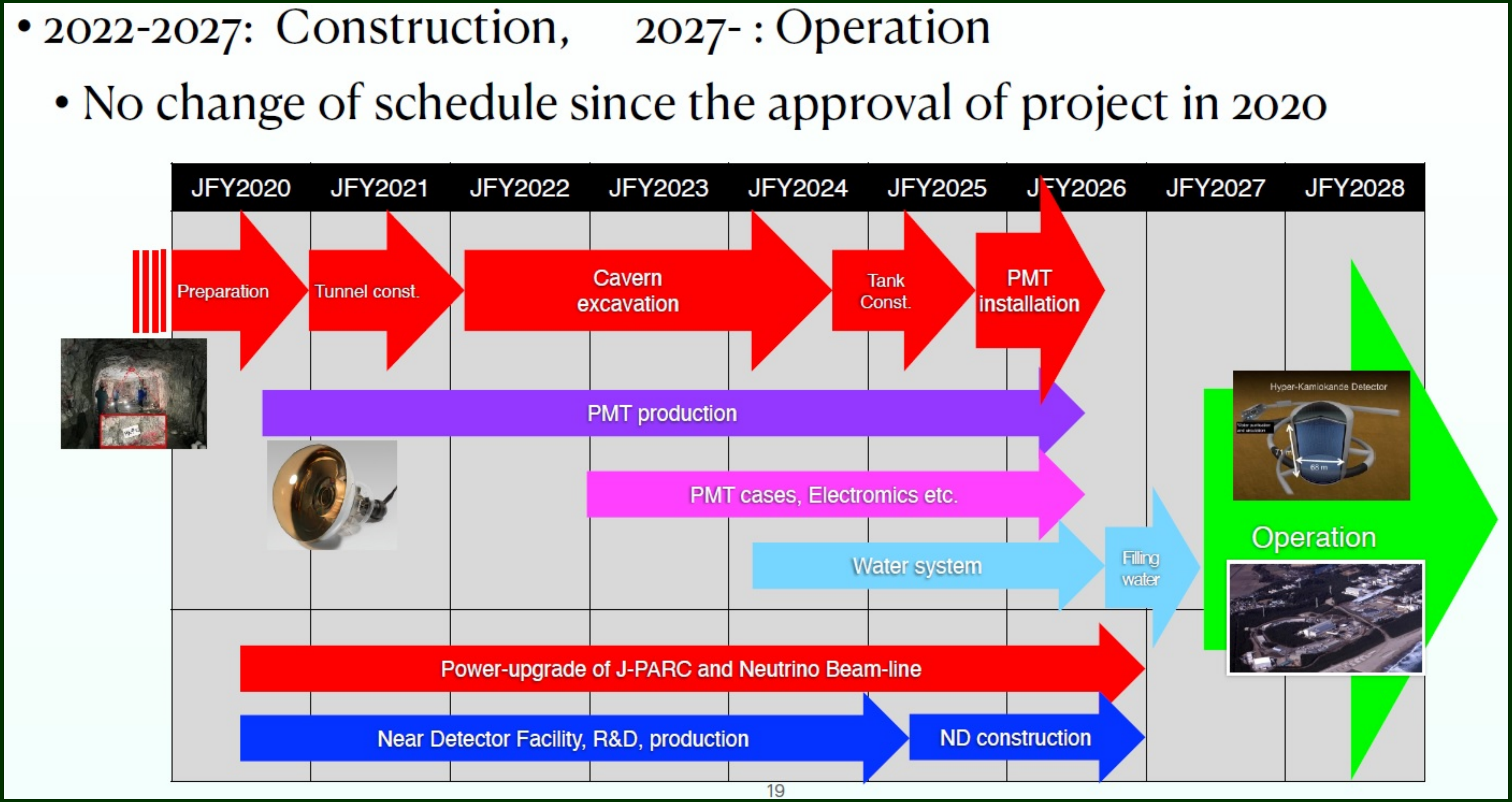


At both T2HK & DUNE, HO-LO separation is possible w/ ν & $\bar{\nu}$ for most of δ

Unlike hierarchy degeneracy, $\delta=-\pi/2$ lies on the same side for ν & $\bar{\nu}$

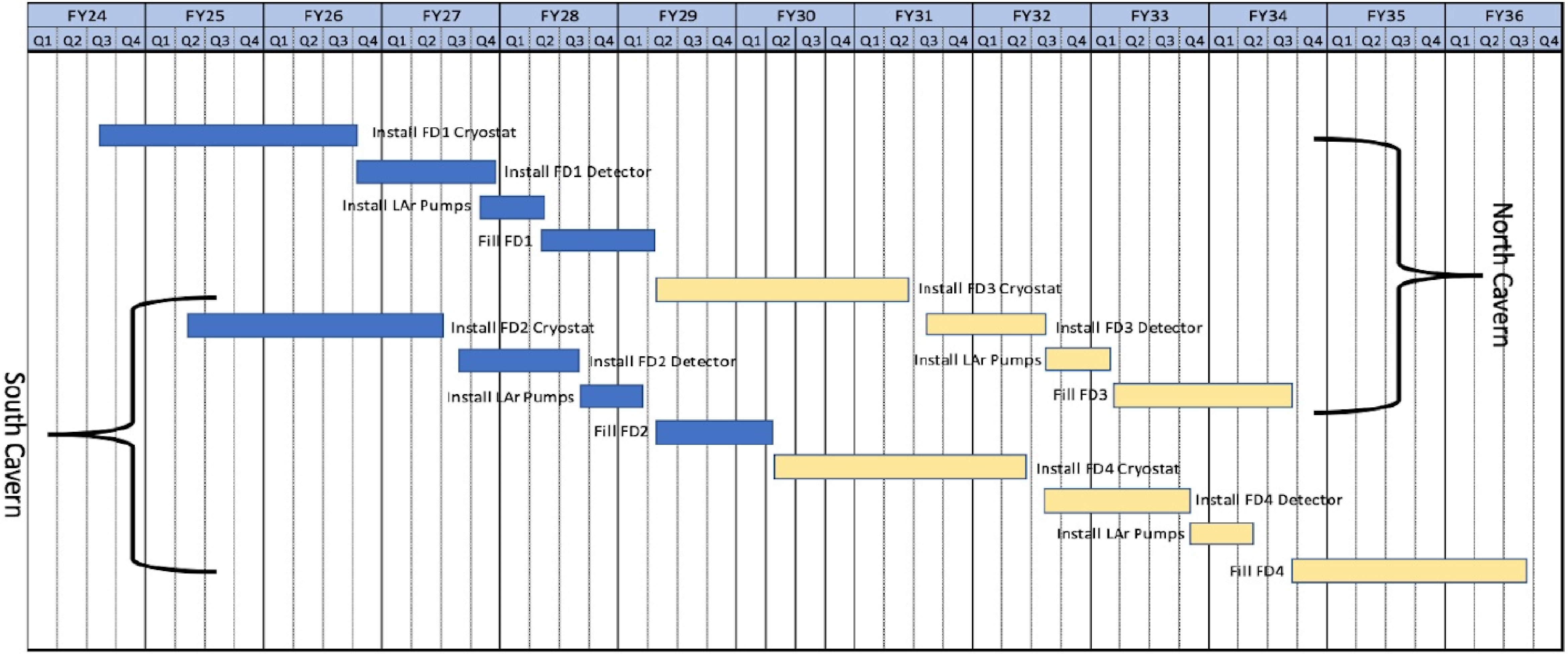


Timeline of Hyperkamiokande



Nakaya@Neutrino Workshop at IFIRSE, 2023.7.17

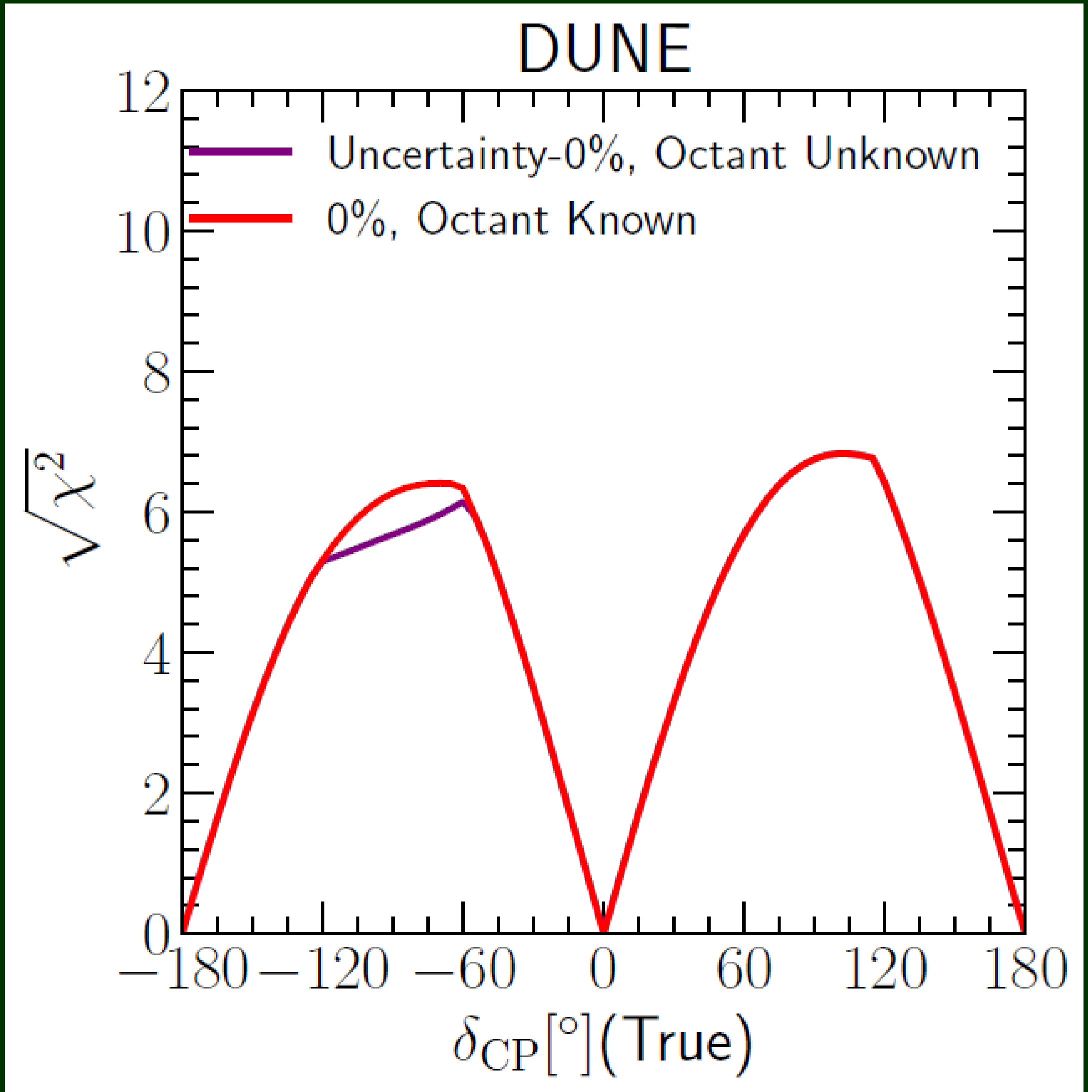
Timeline of DUNE（2029(?)-)



Earliest installation start in 2029 with FD3 completed in Q4,2034 and FD4 in Q4,2036

Bishai@ P5 Townhall Meeting, Fermilab, March 21, 2023

Ghosh-OY, NPB 989 ('23) 116142



octant degeneracy at DUNE

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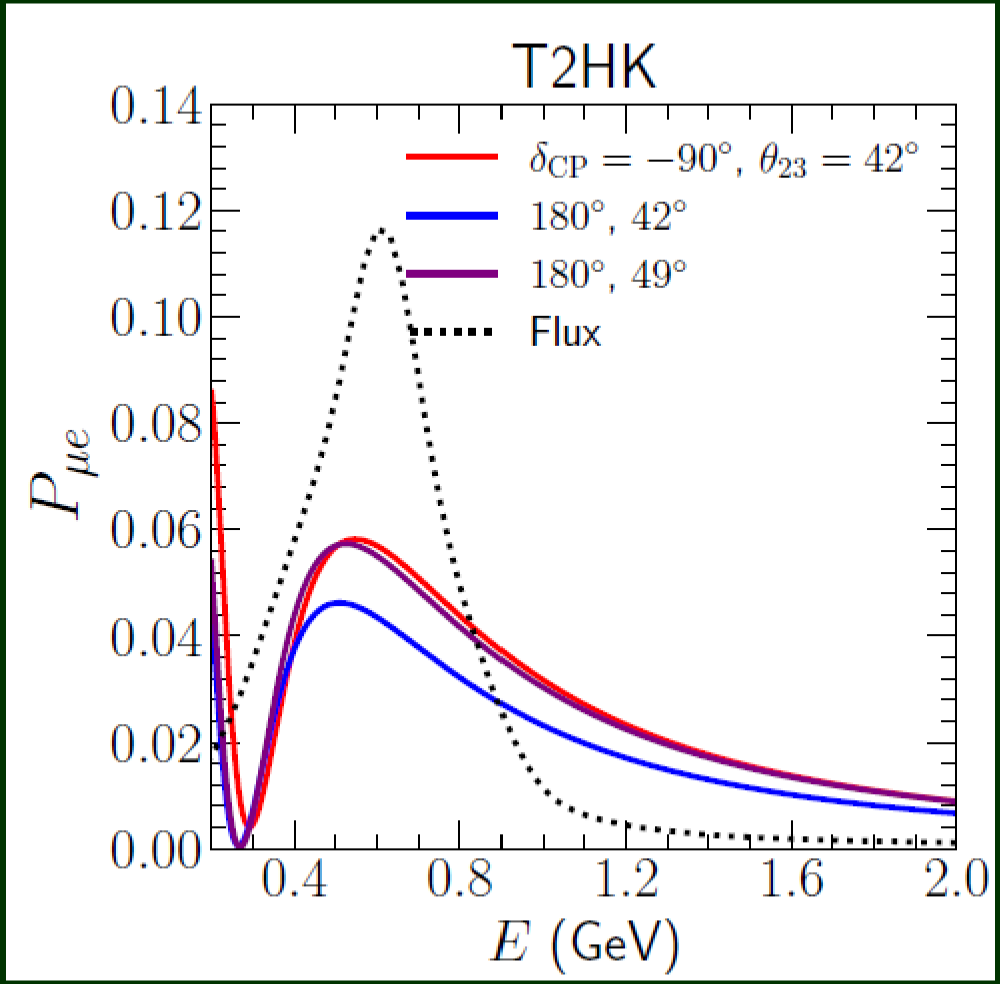

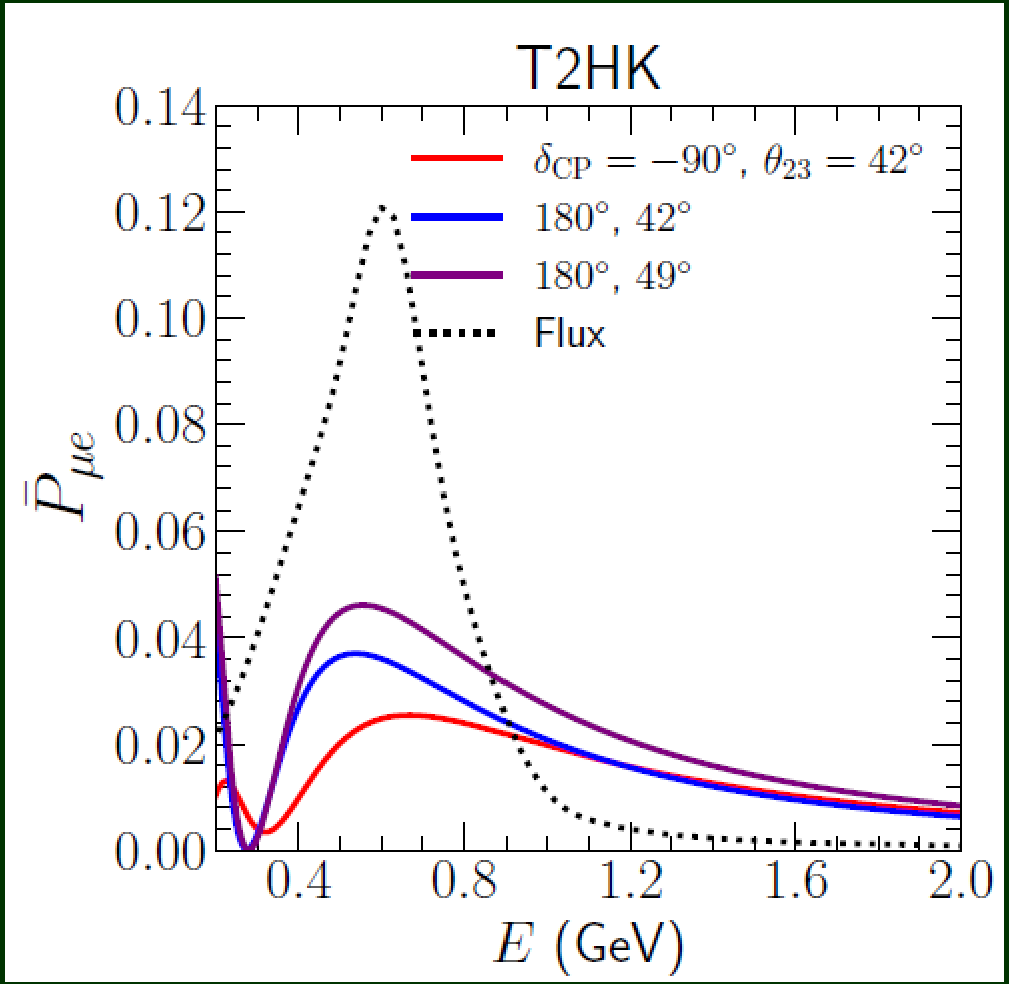

Probability vs octant degeneracy at T2HK

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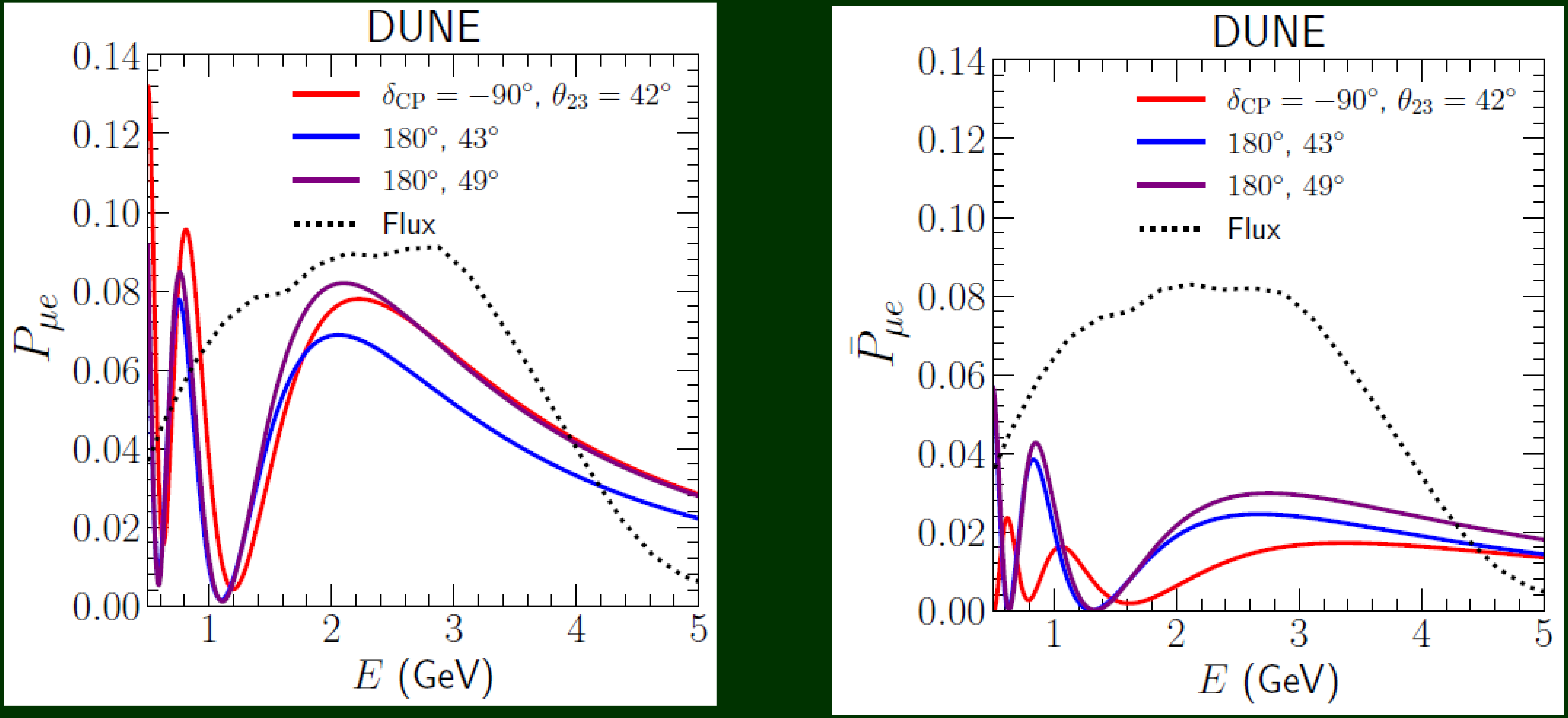
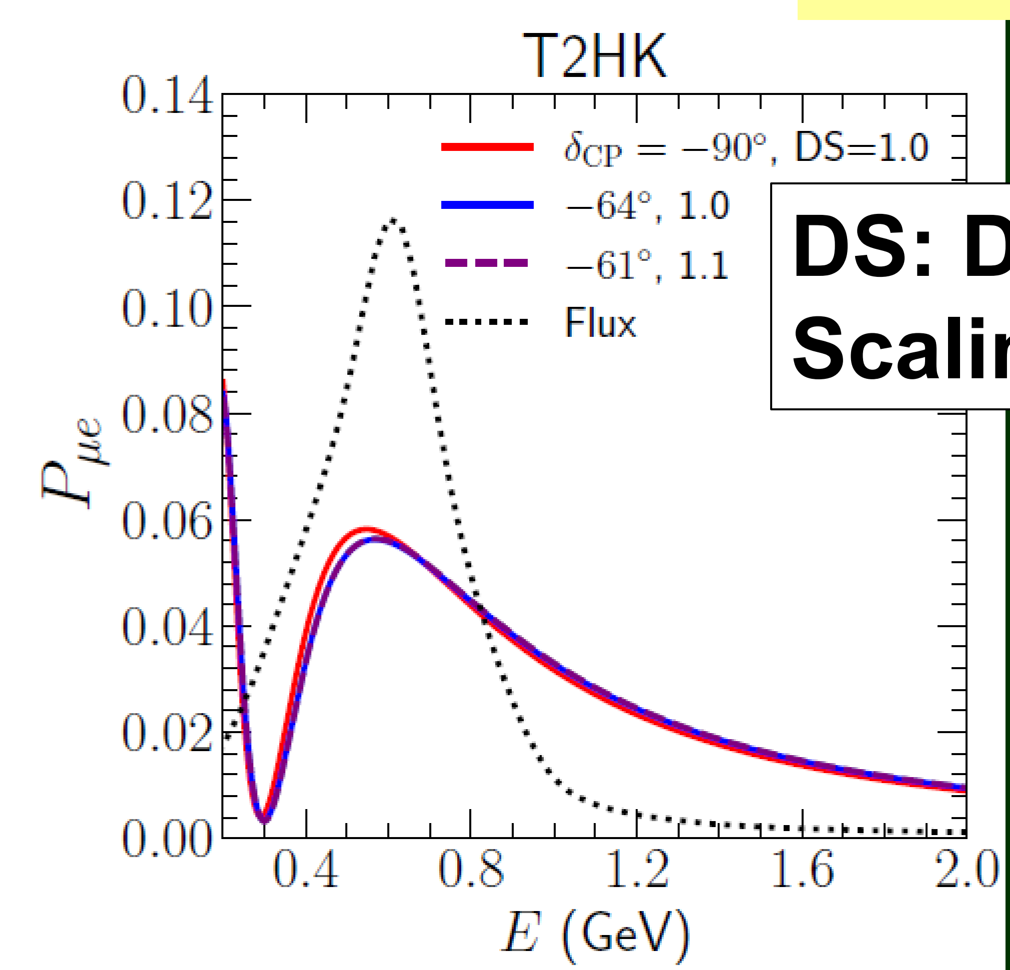
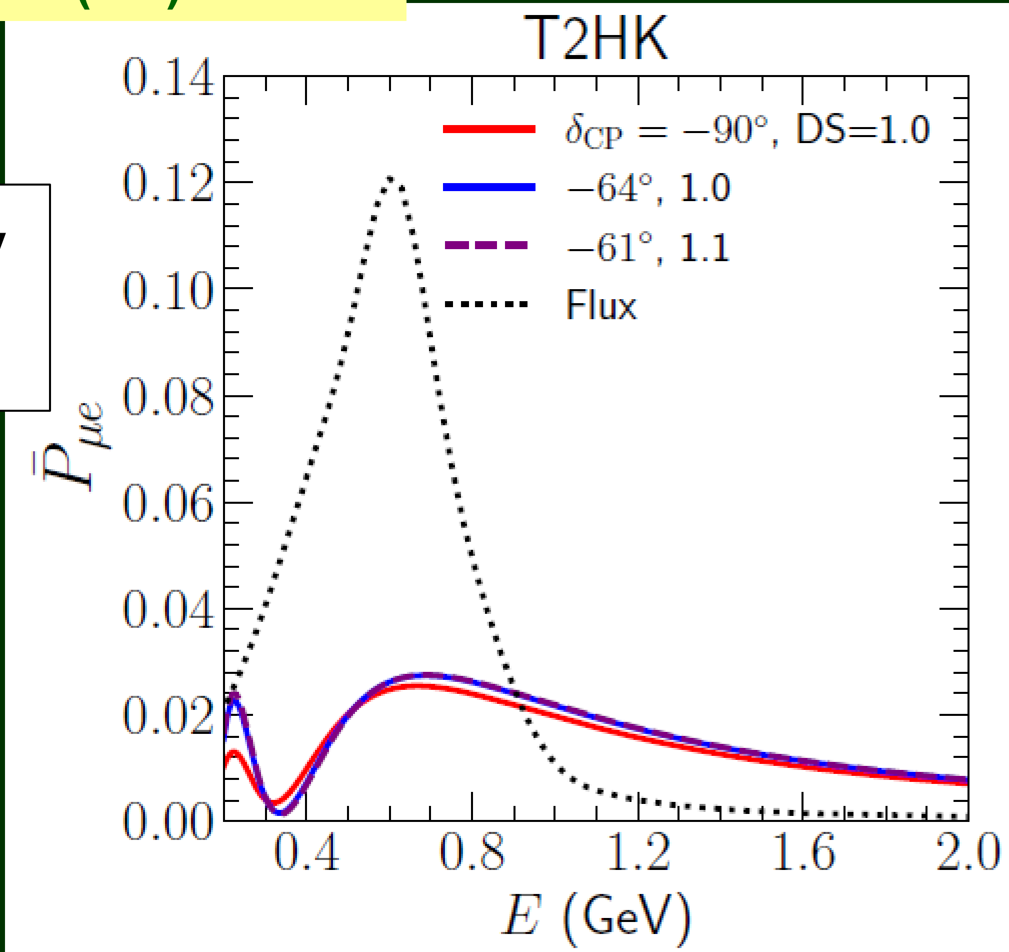


Probability vs octant degeneracy at DUNE

Ghosh-OY, NPB 989 ('23) 116142

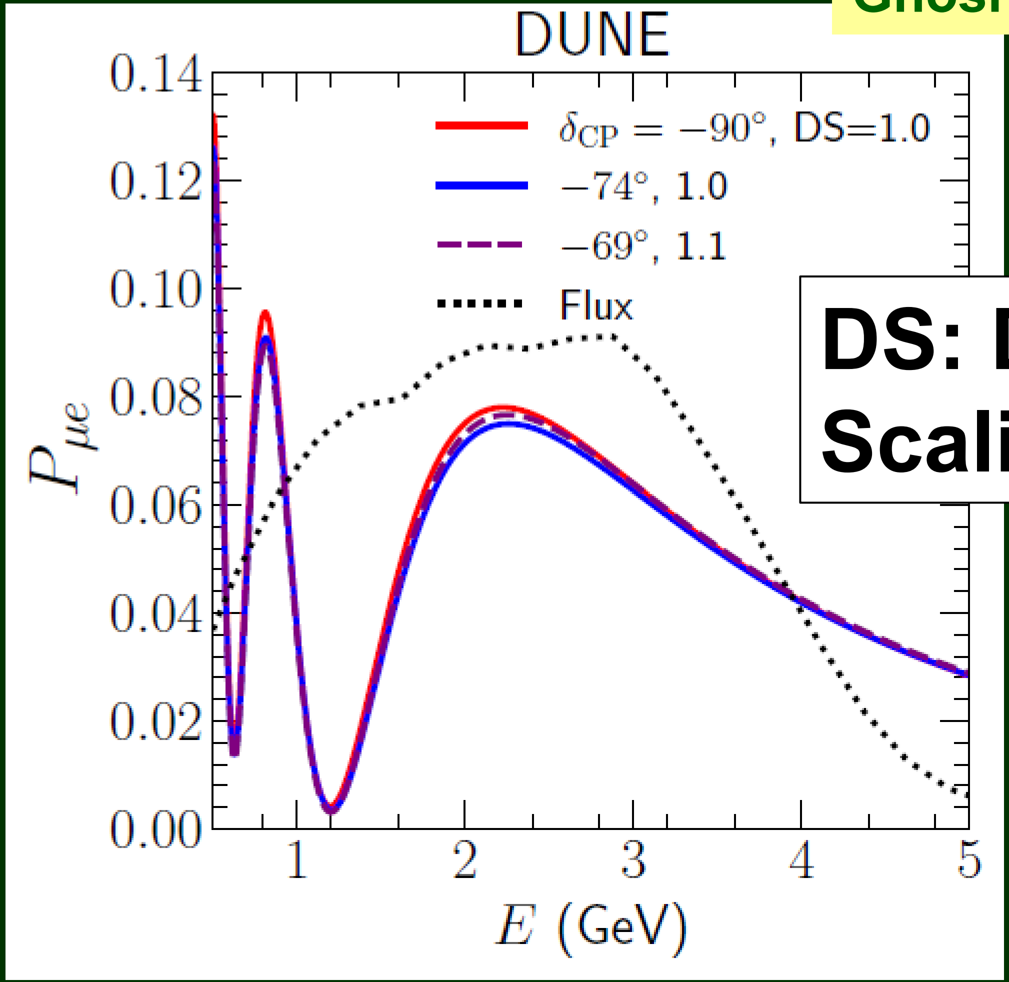


DS: Density Scaling

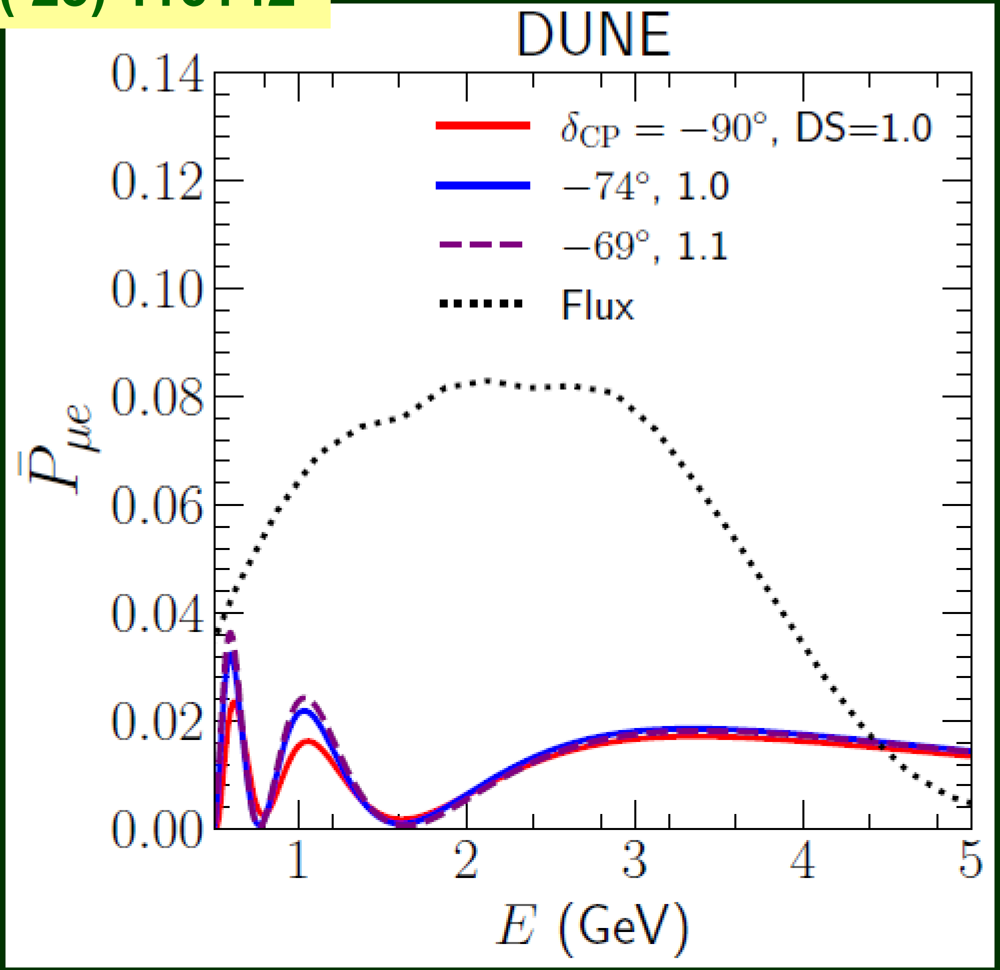


For T2HK, (δ, DS)=(-64°, 1.0) is degenerate with (-61°, 1.1). For δ(true) = -90°, (δ(test),DS(test)) = (-61°, 1.0) is excluded but (δ(test),DS(test)) = (-61°, 1.1) is allowed.

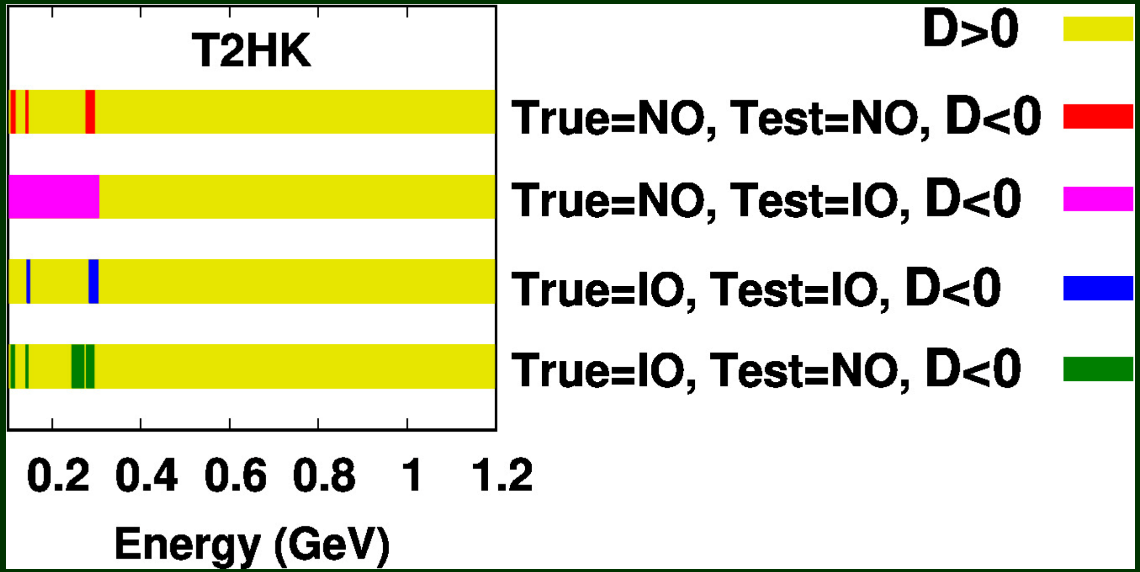
Ghosh-OY, NPB 989 ('23) 116142

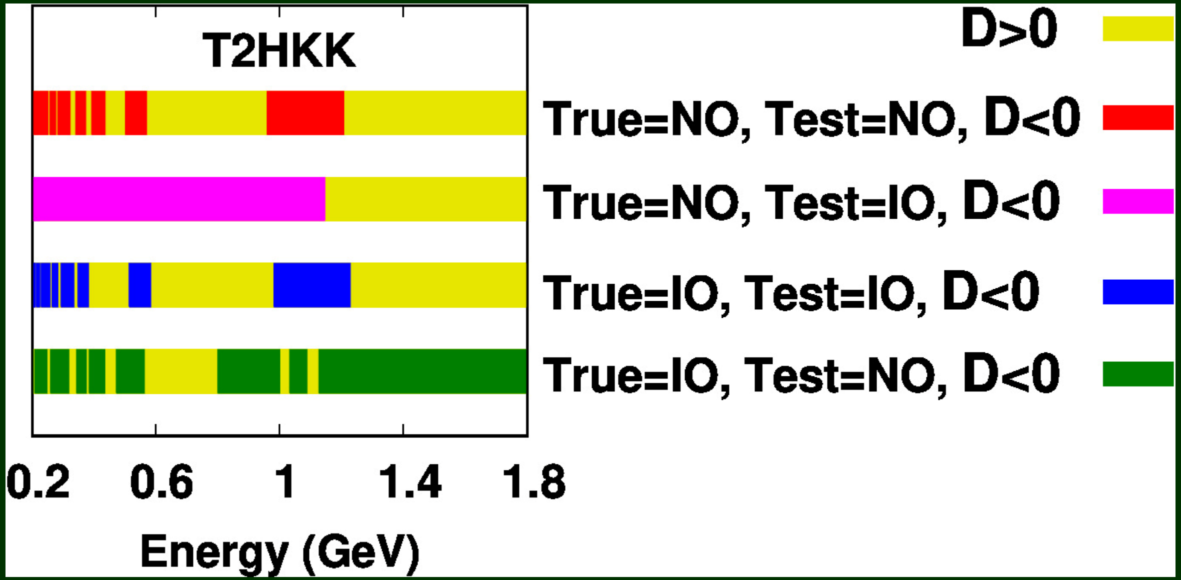


DS: Density Scaling



For DUNE, (δ, DS)=(-74°, 1.0) is degenerate with (-69°, 1.1). For δ(true) = -90°, (δ(test),DS(test)) = (-69°, 1.0) is excluded but (δ(test),DS(test)) = (-69°, 1.1) is allowed.





Sugama-OY, arXiv:2308.15071