Parameter degeneracy and strategies of future long baseline ν experiments

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Contents

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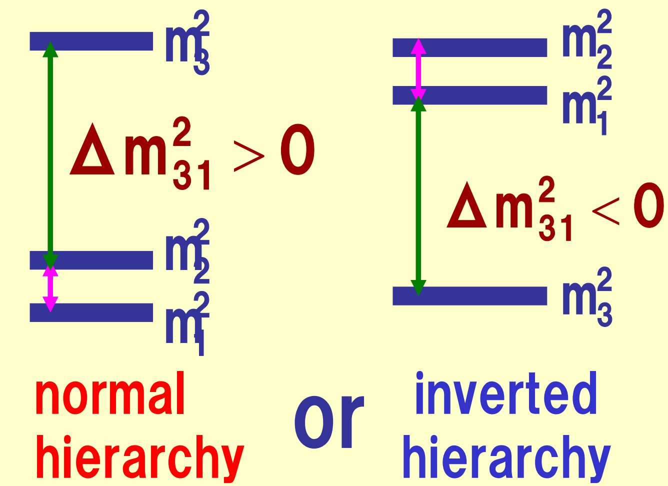
1. Introduction

ν oscillation

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$



- solar ν・KamLAND (reactor)

  ⇒ $\Delta m_{21}^2 \cong 8\times10^{-5}\,\mathrm{eV}$, $\sin^2 2\theta_{12} \cong 0.8$
- atmospheric ν・K2K (accelerator)

  ⇒ $|\Delta m_{32}^2| \cong 2\times10^{-3}\,\mathrm{eV}^2$, $\sin^2 2\theta_{23} \cong 1.0$
- CHOOZ (reactor)

  ⇒ $\sin^2 2\theta_{13} < 0.2$

Next things to determine: θ_{13}, δ (CP phase) and $\mathrm{sgn}(\Delta m_{31}^2)$ (hierarchy pattern)

Ongoing/planned long baseline accelerator experiments

(not exhaustive)

1st generation

$\nu_\mu \to \nu_\mu$

In red: approved

1999-	K2K	KEK→SK	L=250km	E～1GeV
2004-	MINOS	FNAL→Soudan	L=730km	E～10GeV
2006-	CNGS (ICARUS, OPERA ($\nu_\mu \to \nu_\tau$))	CERN→Grand Sasso	L=730km	E～20GeV

Mainly for determination of $|\Delta m^2_{31}|$

2nd generation

$\nu_\mu \to \nu_e + \bar{\nu}_\mu \to \bar{\nu}_e$

In green: not approved yet

2009- JPARC I JAERI→SK (0.75MW,22.5kt) L=295km E～1GeV

discovery of $\theta_{13} \neq 0$? ↰($\nu_\mu \to \nu_e$ for 5 yrs)

20??- NOva FNAL→near Soudan L～800km E～?GeV

identification of $\mathrm{sgn}(\Delta m^2_{31})$???

20??- SPL CERN→Frejus (4MW,0.4Mt) L=130km E～0.1GeV

20??- JPARC II JAERI→HK (4MW,1Mt) L=295km E～1GeV

discovery of $\delta \neq 0$? ↰($\nu_\mu \to \nu_e$ for 2 yrs $\bar{\nu}_\mu \to \bar{\nu}_e$ for 6 yrs)

Proposed Reactor experiments

$\bar{\nu}_e \rightarrow \bar{\nu}_e$

2008?-	**Double CHOOZ**	France
2008?-	**Kaska**	Japan
20??-	**Braidwood**	US
20??-	**Diablo Canyon**	US
20??-	**Daya Bay**	China
20??-	**Angra**	Brazil

discovery of $\theta_{13} \neq 0$?

- (stage I) Measurement of θ_{23}

$$P(\nu_\mu \to \nu_\mu) \cong 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

- (stage I&II) Naïve argument on measurement of θ_{13}

$$P(\nu_\mu \to \nu_e) \cong s^2_{23} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) + \text{corrections}$$

θ_{13} can be deduced

- (stage II) Naïve argument on measurement of δ

$$P(\nu_\mu \to \nu_e) - P(\overline{\nu_\mu} \to \overline{\nu_e}) = 2J \sin\left(\frac{\Delta m^2_{21} L}{4E}\right) \sin\left(\frac{\Delta m^2_{32} L}{4E}\right) \sin\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

$$J \equiv \sin\delta\, c_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23}$$

δ can be deduced

(stage II) Naïve argument on identification of $\mathrm{sgn}(\Delta m^2_{31})$

$$P(\nu_\mu \to \nu_e) \simeq s^2_{23}\sin^2 2\theta_{13}\frac{\Delta E^2_{31}}{\Delta \tilde{E}^2_{31}}\sin^2\left(\frac{\Delta \tilde{E}_{31}L}{2}\right)$$

$\mathrm{sgn}(\Delta m^2_{31})$ **can be deduced**

$$\Delta \tilde{E}_{31} \equiv \left[(\Delta E_{31}\cos 2\theta_{13} - A)^2 + (\Delta E_{31}\sin 2\theta_{13})^2\right]^{1/2}$$

$$\Delta E_{31} \equiv \Delta m^2_{31}/2E, \quad A \equiv \sqrt{2}G_F N_e \simeq 1/2000\mathrm{km} > 0$$

To identify $\mathrm{sgn}(\Delta m^2_{31})$, a longer baseline will be necessary, because AL～O (1) is necessary.

Unfortunately, these naïve arguments do not hold due to

Parameter degeneracy

Even if we know $P(\nu_\mu \to \nu_e)$ and $P(\overline{\nu_\mu} \to \overline{\nu_e})$ in a long baseline accelerator experiments with approximately monoenergetic neutrino beam, precise determination of θ_{13}, sign(Δm^2_{31}) and δ is difficult because of the 8-fold parameter degeneracy.

- intrinsic (δ, θ_{13}) degeneracy
- $\Delta m^2_{31} \Leftrightarrow -\Delta m^2_{31}$ degeneracy
- $\theta_{23} \Leftrightarrow \pi/2 - \theta_{23}$ degeneracy

● $\theta_{23} \Leftrightarrow \pi/2 - \theta_{23}$ degeneracy

$(a)\cos 2\theta_{23} = 0 \rightarrow (b)\cos 2\theta_{23} \neq 0$

present bound : $|\cos 2\theta_{23}| < 0.3$

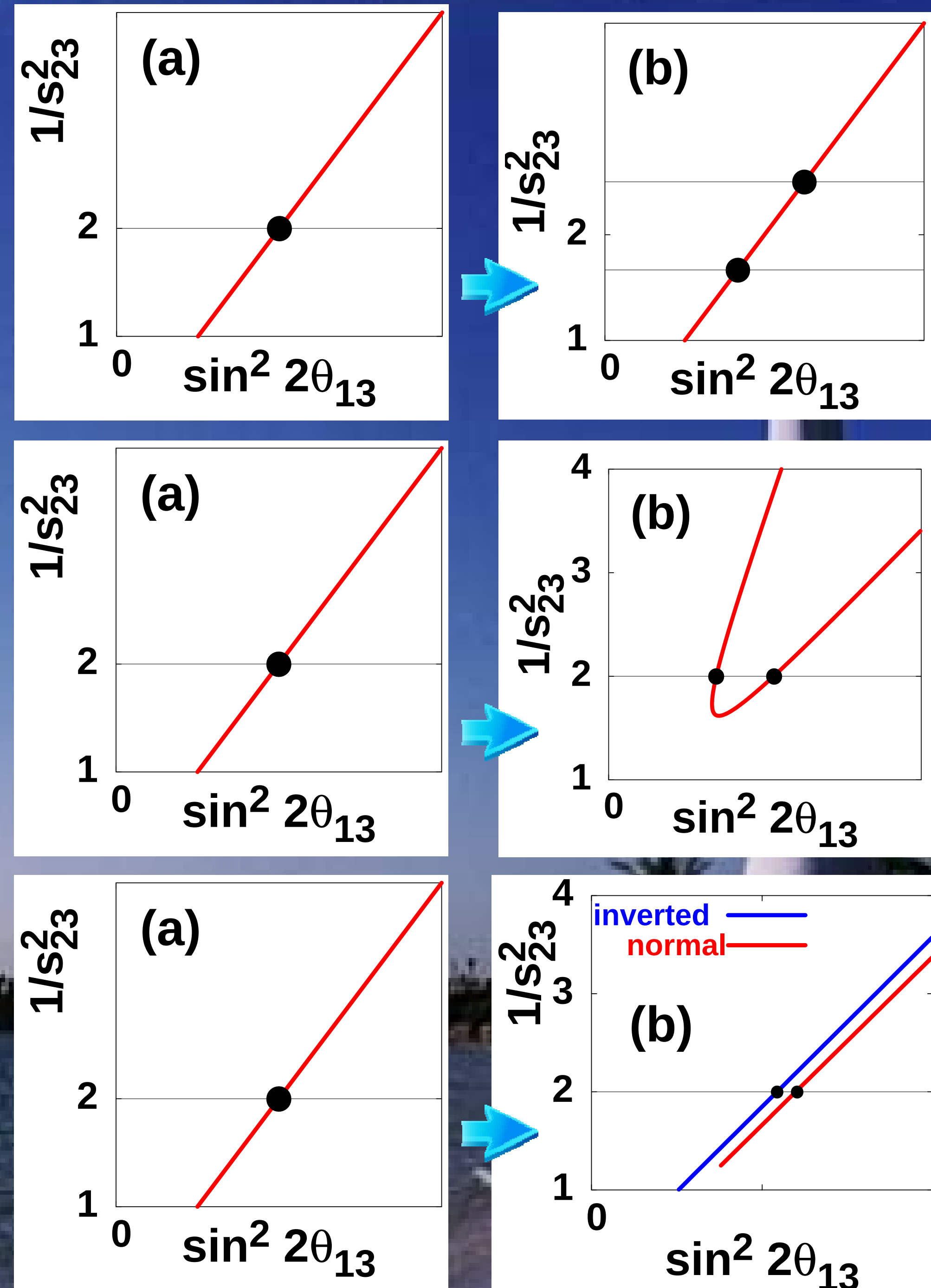
● intrinsic (δ, θ_{13}) degeneracy

$$(a)\frac{\Delta m^2_{21}}{|\Delta m^2_{31}|} = 0 \rightarrow (b)\frac{\Delta m^2_{21}}{|\Delta m^2_{31}|} \cong \frac{1}{35} \neq 0$$

● $\Delta m^2_{31} \Leftrightarrow -\Delta m^2_{31}$ degeneracy

$(a)AL/2 = 0 \rightarrow (b)AL/2 \neq 0$

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



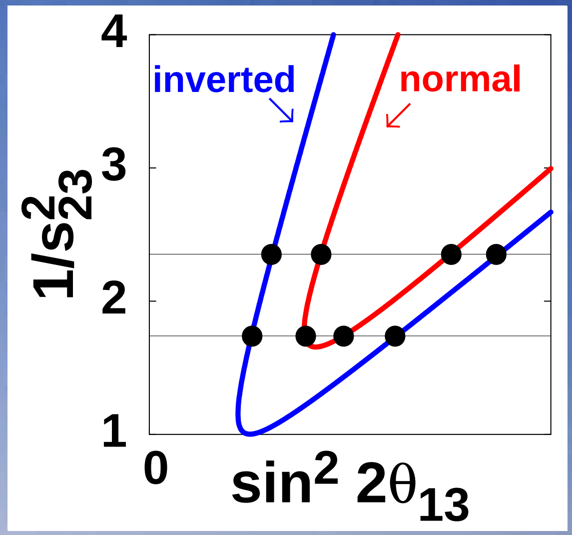
In total we have 8-fold ambiguity

Plot of $P(\nu_\mu \to \nu_e)$, $P(\overline{\nu_\mu} \to \overline{\nu_e})$=const.

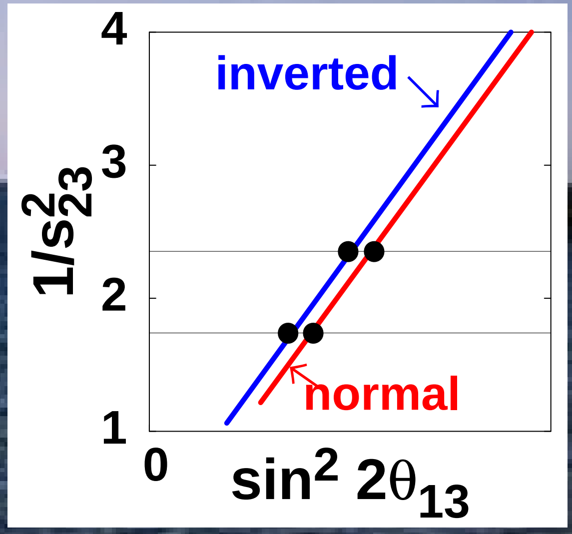
Oscillation Maximum:

$$\left|\frac{\Delta m^2_{31} L}{4E}\right| = \frac{\pi}{2}$$

Off OM



On OM



JPARC experiment is expected to be done on OM

→ intrinsic（δ, θ_{13}）degeneracy is not a problem at JPARC

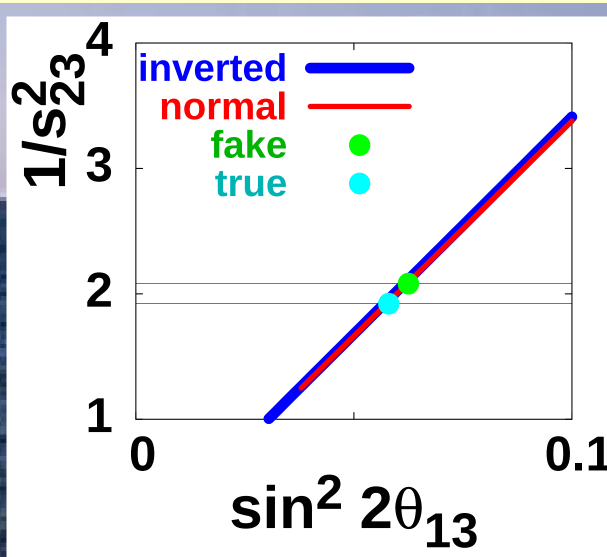
2. Determination of θ_{13}

Assumption: $\nu_\mu \to \nu_e$ and $\overline{\nu_\mu} \to \overline{\nu_e}$ will be measured at JPARC II (@OM, 4MW, HK) .

Question: **Will that be enough to determine θ_{13}?**

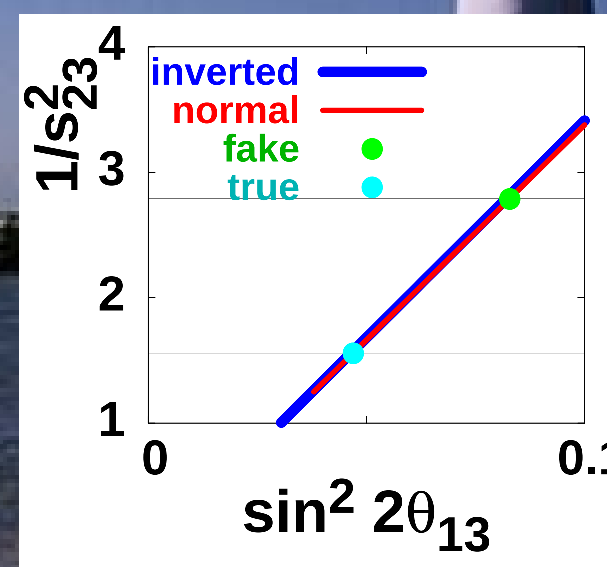
(1) $\sin^2 2\theta_{23} \cong 1$ ⇨ **Yes!**

JPARC $\nu + \bar{\nu}$ is almost enough, since (a) there is no intrinsic (δ, θ_{13}) degeneracy, and (b) sign(Δm^2_{31}) degeneracy is small.



(2) $\sin^2 2\theta_{23} < 1$ ⇨ **No!**

Ambiguity due to $\theta_{23} \Leftrightarrow \pi/2 - \theta_{23}$ degeneracy is significant.



In the case of (1) $\sin^2 2\theta_{23} \cong 1$:

JPARC $\nu_\mu \to \nu_e + \bar{\nu}_\mu \to \bar{\nu}_e$ is enough to determine θ_{13}.

In the case of (2) $\sin^2 2\theta_{23} < 1$:

To resolve θ_{23} ambiguity, possible ways are:

Combine JPARC $\nu_\mu \to \nu_e + \bar{\nu}_\mu \to \bar{\nu}_e$ with:

(A) reactor measurement of θ_{13} $\bar{\nu}_e \to \bar{\nu}_e$

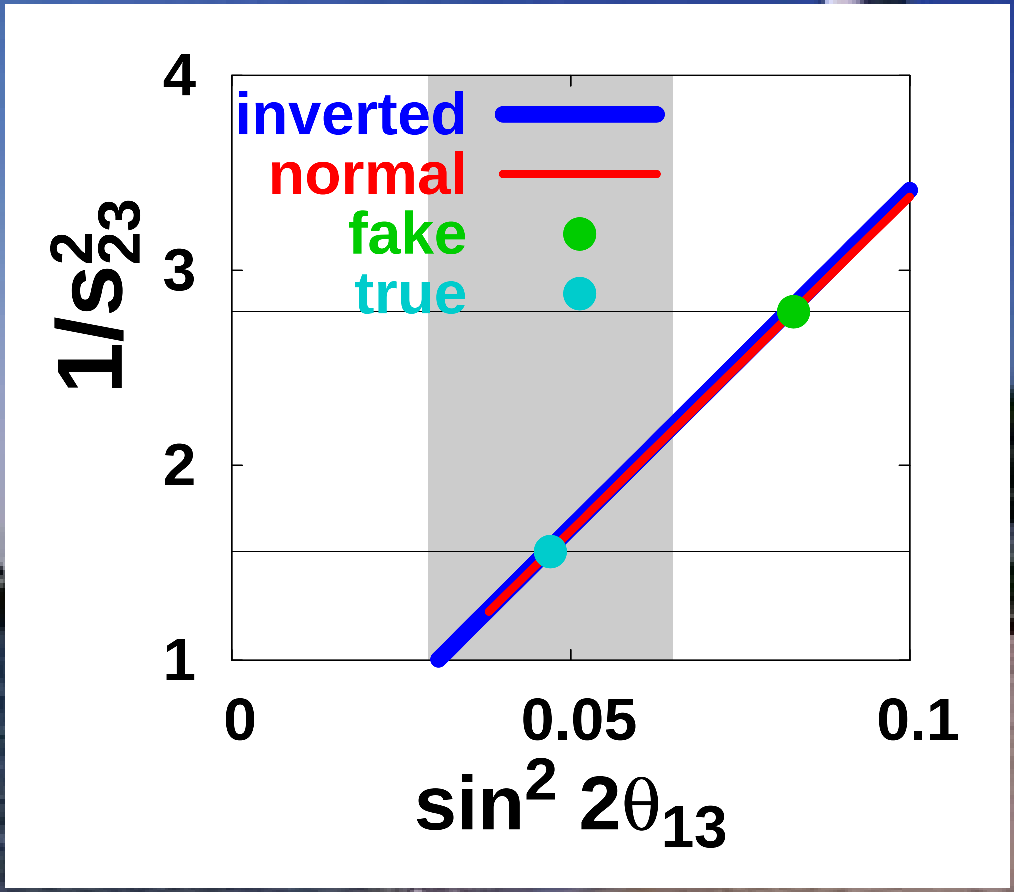
(B) β beam measurement of $\nu_e \to \nu_\tau$

(C) LBL measurement of $\nu_\mu \to \nu_e$ (or $\bar{\nu}_\mu \to \bar{\nu}_e$)??

(A) reactor measurement of θ_{13} $\bar{\nu}_e \to \bar{\nu}_e$

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

One can resolve θ_{23} ambiguity at 90%CL.



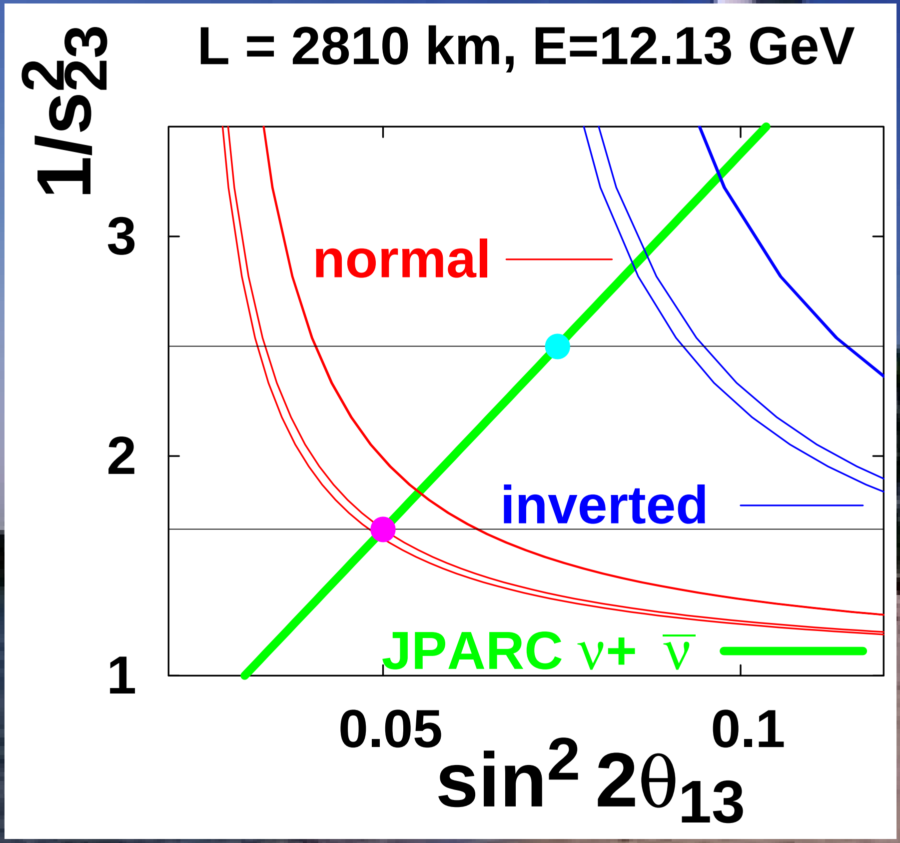
(B) β beam measurement of $\nu_e \to \nu_\tau$

ν_e beam from radioactive nuclei in a storage ring

$$P(\nu_e \to \nu_\tau) \simeq c_{23}^2 \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right)$$

Curves intersect with the JPARC line almost orthogonally.

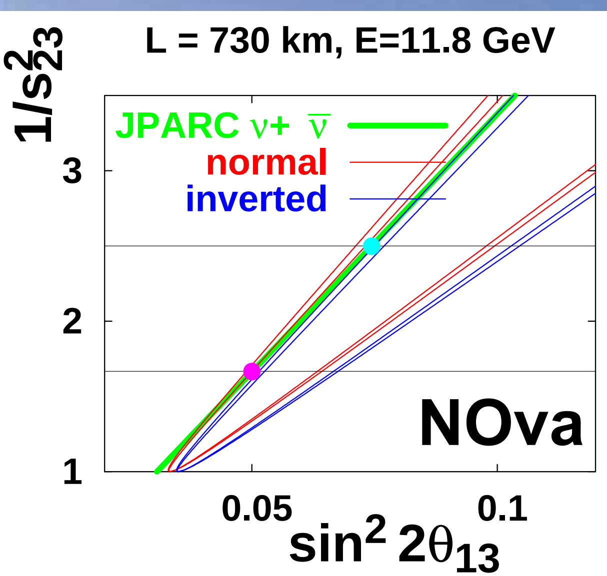
This channel may be interesting to be combined with JPARC in the future.

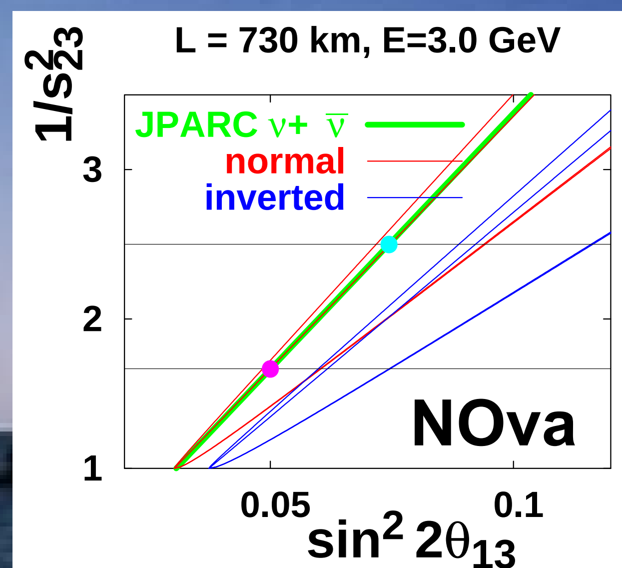


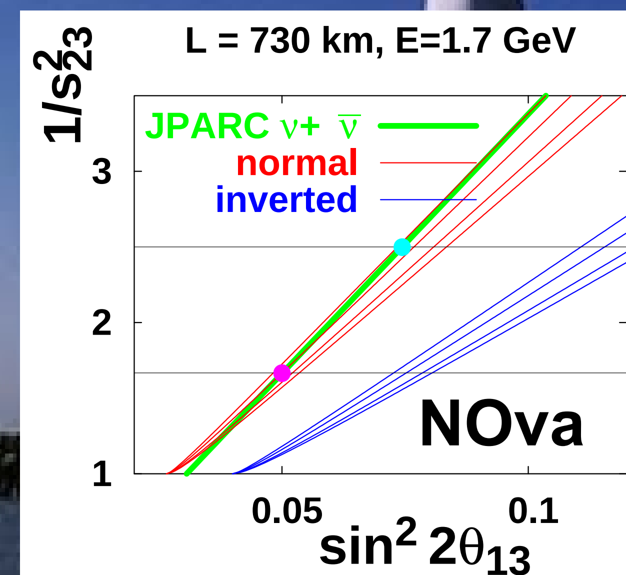
(C) LBL measurement of $\nu_\mu \to \nu_e$ (or $\overline{\nu_\mu} \to \overline{\nu_e}$)

Consider 3rd measurement of $\nu_\mu \to \nu_e$ (e.g. @ NOva) in addition to JPARC $\nu_\mu \to \nu_e + \nu_\mu \to \nu_e$.

In general, the gradient of the hyperbola is almost equal to that of the JPARC line, and this additional curve does not help to resolve θ_{23} ambiguity.

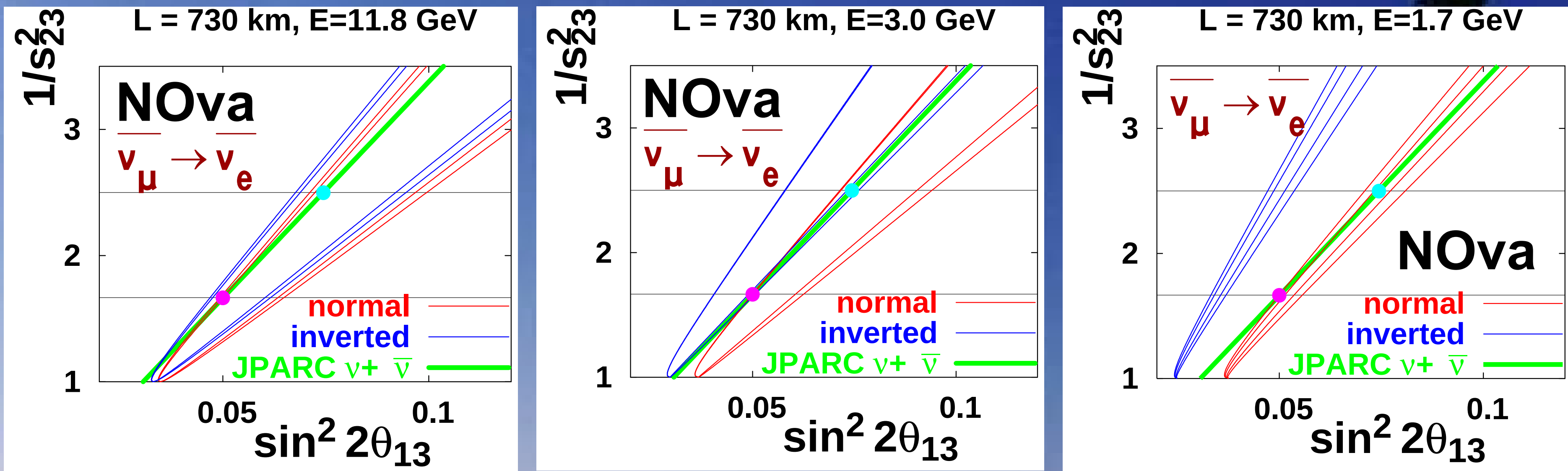






However, with lower E it may be possible to identify sgn (Δm^2_{31}).

The situation doesn't change much for $\overline{\nu_\mu} \to \overline{\nu_e}$.



NOva may be complementary to JPARC only if it runs with low energy to determine $\mathrm{sgn}(\Delta m^2_{31})$.

3. Determination of δ (CP phase)

Assumption: at JPARC (@OM, 4MW, HK)

$\nu_\mu \rightarrow \nu_e$ **and** $\overline{\nu_\mu} \rightarrow \overline{\nu_e}$ **will be measured.**

Question: Will that be enough to determine δ ?

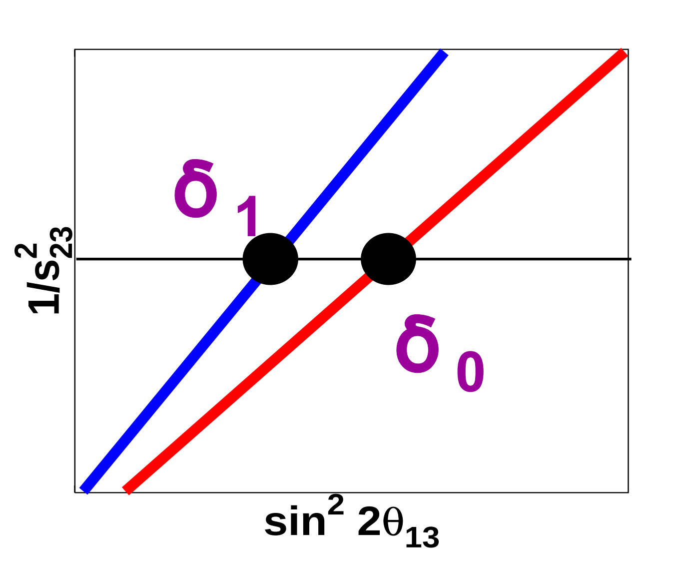
⇒ **Answer: In general no.**

Resolution of sign(Δm^2_{31}) ambiguity is important.

Ambiguity due to sign(Δm^2_{31})

δ_0 : by correct assumption on sign(Δm^2_{31})

δ_1 : by wrong assumption on sign(Δm^2_{31})



Difference between δ_0 & δ_1 turns out to be large.

If $\delta_0 = 0$, then $\sin\delta_1 \cong -2.2 \sin 2\theta_{13}$ at JPARC

$= -0.5$ (if $\sin^2 2\theta_{13} = 0.05$)

i.e., if we made a mistake on sign(Δm^2_{31}), then our prediction on δ would be significantly different!

→ Identification of sign(Δm^2_{31}) is important.

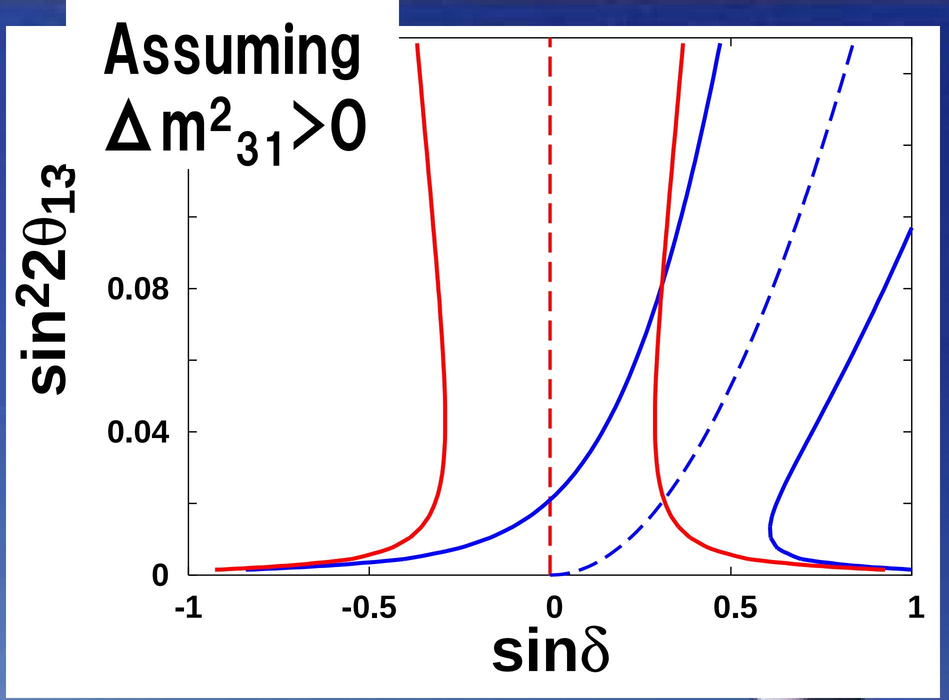
3σ sensitivity to δ (w/ exp. errors included)

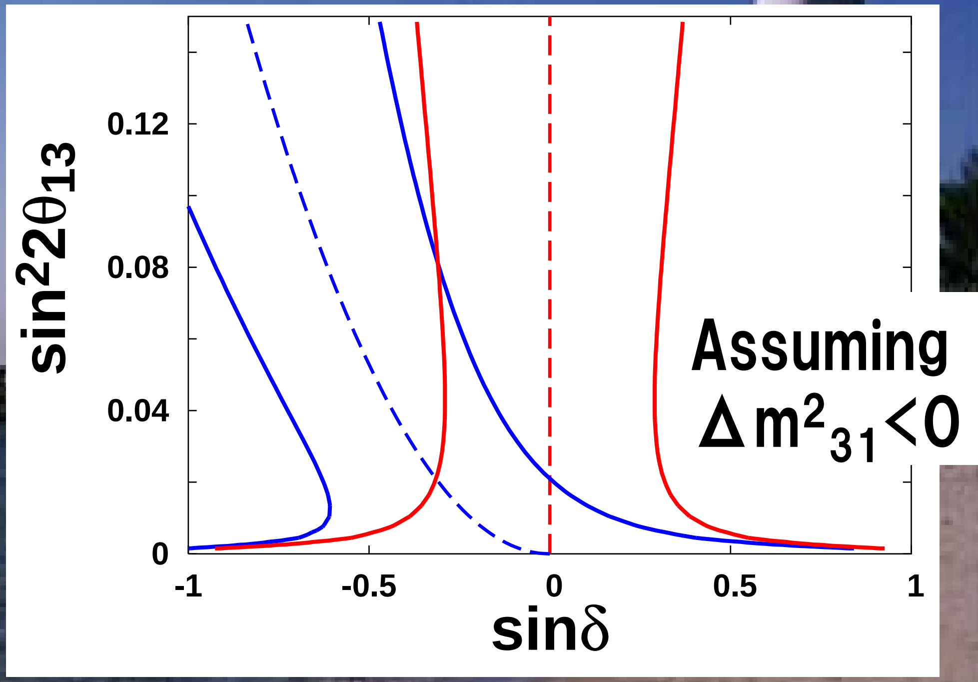
correct assumption on sign(Δm^2_{31}) ——

wrong assumption on sign(Δm^2_{31}) ——

δ ≠ 0 can be claimed outside of red or blue solid lines.

⇨ If we don't know sign(Δm^2_{31}), the region in which δ ≠ 0 can be claimed becomes smaller.





4.Summary

It is important

- for determination of θ_{13}

  to resolve θ_{23} ambiguity

  if $\sin^2 2\theta_{23} < 1$.

- for determination of δ

  to resolve $\mathrm{sign}(\Delta m^2_{31})$ ambiguity.

If NOva runs with lower E, then it will become complementary to JPARC, and only in this case it will play an important role.

Otherwise, another LBL exp. with a longer baseline will be necessary.

Stage \ θ_{23}	$\sin^2 2\theta_{23} \simeq 1$	$\sin^2 2\theta_{23} < 1$
Stage I — θ_{13}	JPARC@OM $\nu_\mu \to \nu_e$ & $\bar{\nu}_\mu \to \bar{\nu}_e$ is almost enough.	In addition to JPARC ν & $\bar{\nu}$ @OM, $\bar{\nu}_e \to \bar{\nu}_e$ (reactor) or $\nu_e \to \nu_\tau$ (β beam) is necessary to resolve θ_{23} ambiguity.
Stage II — δ	In addition to JPARC ν & $\bar{\nu}$@OM, LBL w/ L>～1000km is necessary to resolve sign(Δm^2_{31}) ambiguity (NOva w/ low E may work).	In addition to JPARC ν & $\bar{\nu}$ @OM, (A) $\nu_e \to \nu_e$ (reactor) or $\nu_e \to \nu_\tau$ (β beam) is necessary to resolve θ_{23} ambiguity. (B) LBL w/ L>～1000km is necessary to resolve sign(Δm^2_{31}) ambiguity.