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May 30, 2001
@JHF-SK ν workshop

CP sensitivity in the second phase

- Physics of CP violation in neutrino oscillation
- The second phase detector and the beam
- CP sensitivity
- The unitarity triangle
- Comments on other studies (clarification)

What is exciting about neutrino physics?

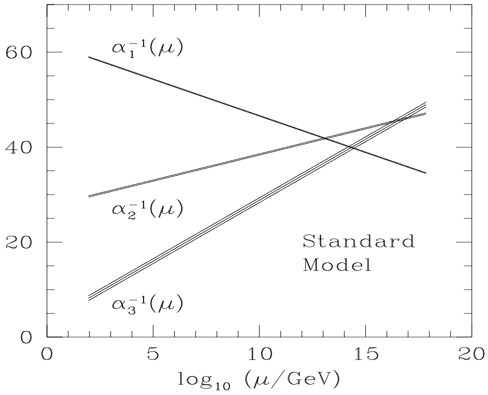
Door is open now for new physics beyond SM

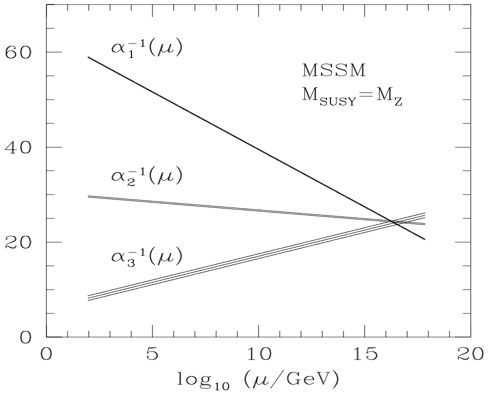
- A new GUT energy scale at ~ 10^{16}GeV

See-saw mechanism

$$\frac{1}{M} = \frac{m_\nu}{v^2} \sim \frac{3\times10^{-3}(eV^2)}{(250GeV)^2} = \frac{1}{6\times10^{15}GeV}$$

Consistent with gauge unification





Flavor texture at GUT scale

Baryon asymmetry of the universe (Leptogenesis)

⇒ Precision measurement of the mixing parameters:
CP violation and the unitarity triangle

- Or beyond neutrino mixing matrix: **Extra Dimension**

Sterile neutrinos (K-K mode)?

Does the unitarity triangle close?

⇒ Oscillation pattern measurement (NC and CC),
⇒ Test of the **leptonic** unitarity triangle

⇒ Next generation long baseline ν experiment

Advantage of $\nu_\mu \to \nu_e$ appearance

- 3 generation senario

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

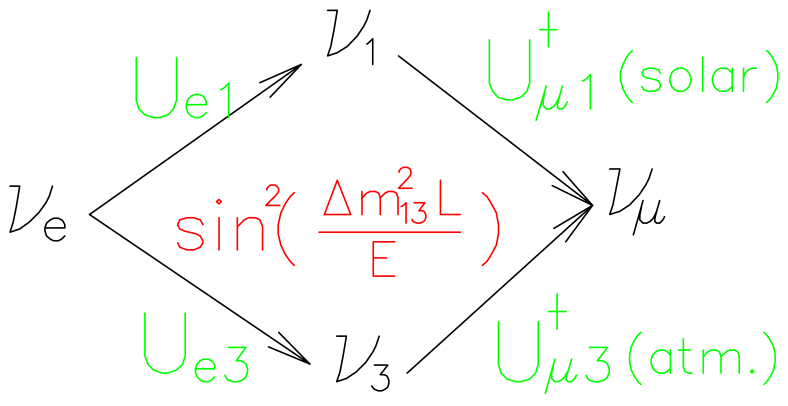
Leptonic CKM
(MNS matrix)

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

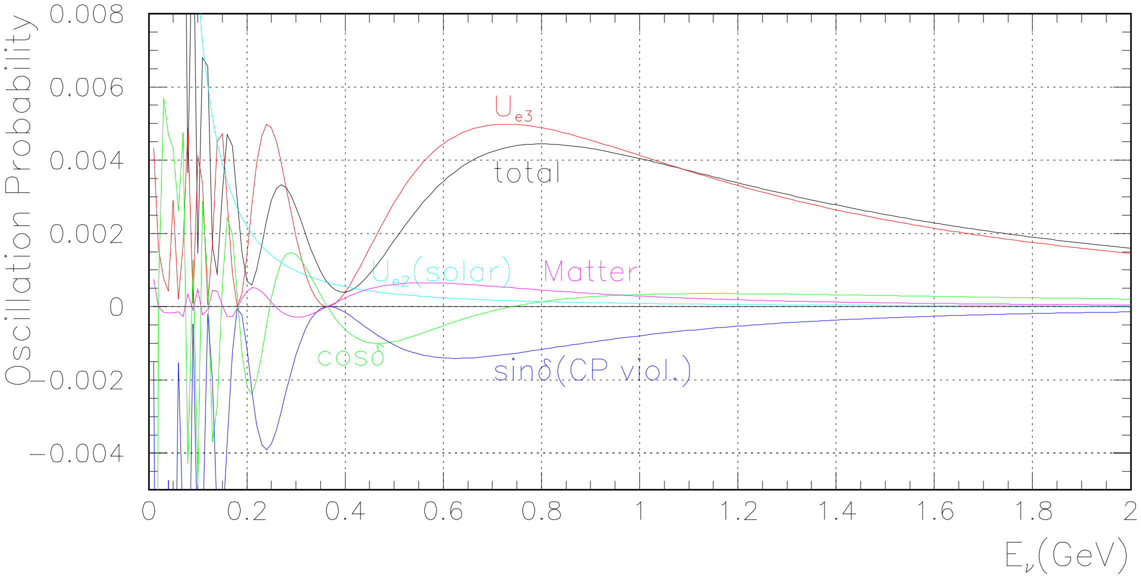
- $\nu_e \leftrightarrow \nu_\mu$ is suppressed due to small Δm^2_{12}

$$P(\nu_e \leftrightarrow \nu_\mu)_{12} \sim sin^2 2\theta_{12} cos^2\theta_{23} sin^2 \frac{1.27\Delta m^2_{12} L(km)}{E(GeV)}$$

- Leading contributions from θ_{13} and δ_{CP}:



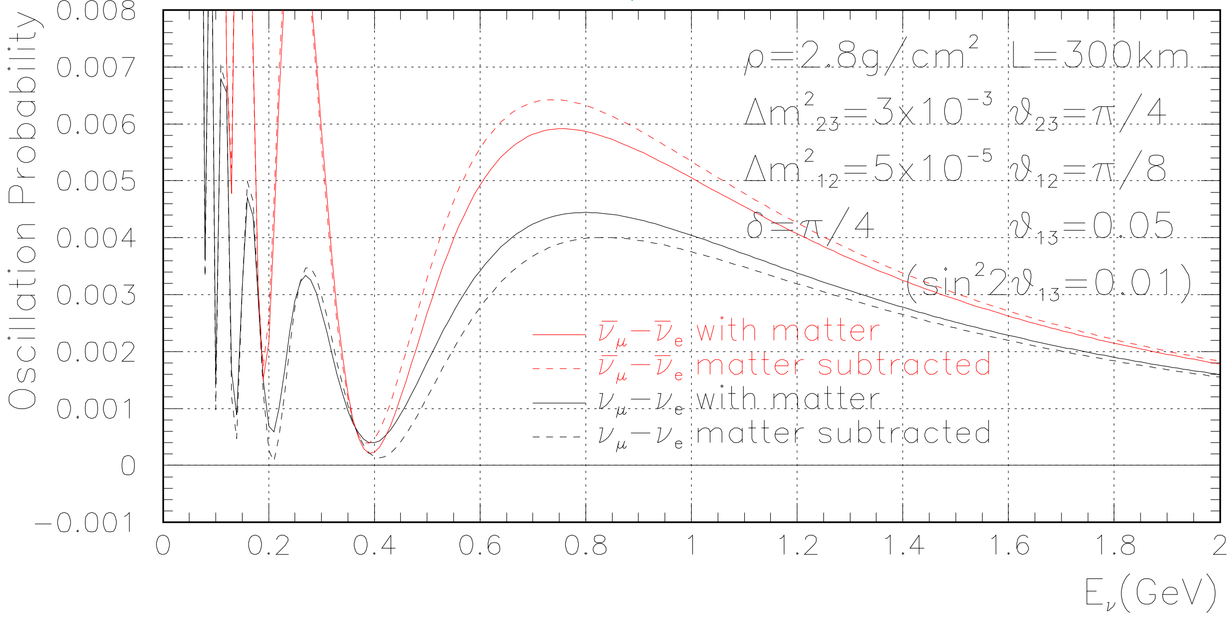
$$\begin{aligned}
P(\nu_\mu \to \nu_e) &= 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2 \frac{\Delta m_{31}^2 L}{4E} \times \left(1 + \frac{2a}{\Delta m_{31}^2}\ (1 - 2S_{13}^2)\right) \\
&+8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta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



CP violation in the neutrino oscillation

$$A_{CP} = \frac{Prob(\nu_\mu \rightarrow \nu_e) - Prob(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{Prob(\nu_\mu \rightarrow \nu_e) + Prob(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}$$
$$= \frac{1.27\Delta m^2_{12} L}{E} \cdot \frac{\sin 2\theta_{12}}{\sin \theta_{13}} \cdot sin\delta$$

Central values of LMA and 1/10 of reactor limit in $\sin^2 2\theta_{13}$



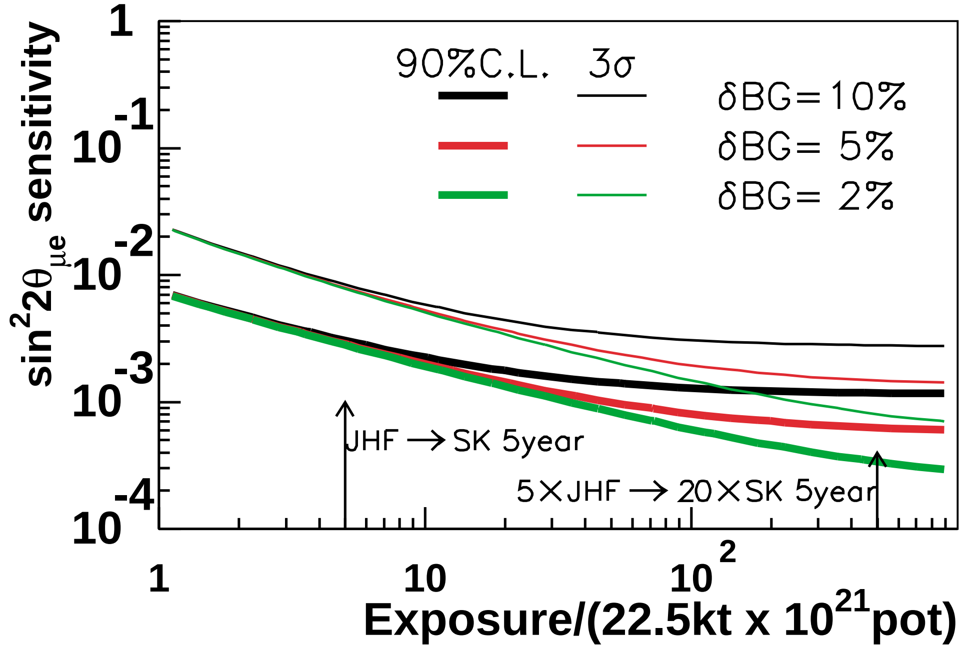
- Large A_{CP} (25%) for a typical LMA parameter.
- Fake asymmetry due to matter effect is small because of small E and L for JHF-SK experiment.

$$A_{matter} = \frac{2a}{\Delta m^2_{31}} + 2\frac{aL}{4E} \frac{< cos\frac{\Delta m^2_{32} L}{4E} >}{< sin\frac{\Delta m^2_{31} L}{4E} >}$$
$$\sim 0.07E(GeV) + 5.3 \times 10^{-4} L(km) \frac{< cos\frac{\Delta m^2_{32} L}{4E} >}{< sin\frac{\Delta m^2_{31} L}{4E} >}$$

The 2nd phase of JHF-Kamioka project

- Hyper-K and JHF upgrade
  - $\times 200$ ν statistics: 1Mt detector and 4MW beam
  - Goal of the 2nd phase:
    - $sin^2 2\theta_{13}$ sensitivity below 10^{-3}
    - CP phase δ to 10-20 degrees
    - Test of the lepton unitarity triangle
    - Proton decay ($p \to K\nu, e^+\pi^0$)

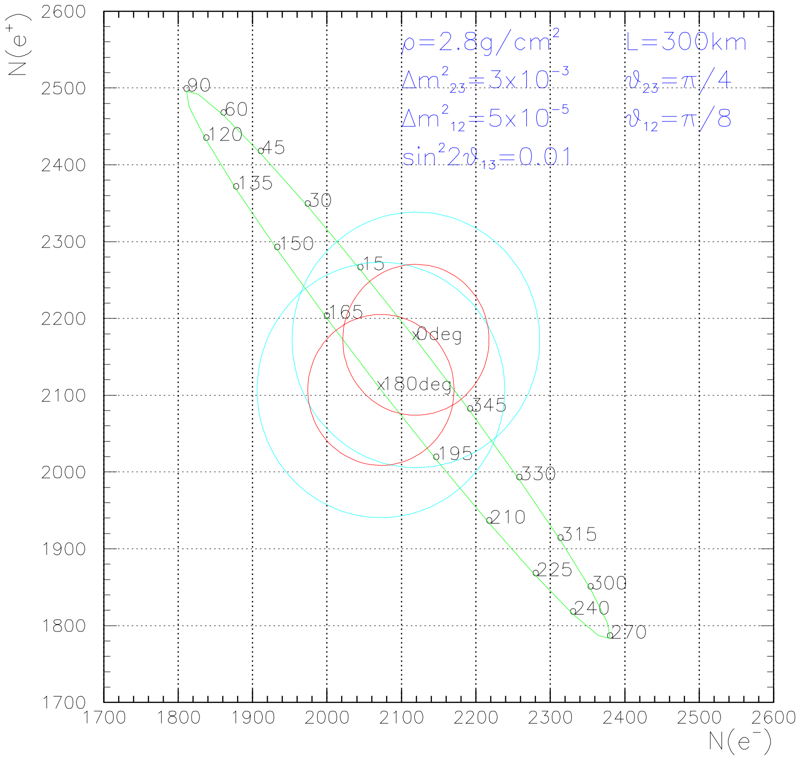
- If θ_{13} not discovered in the 1st phase



  - A factor of $\sqrt{200} = 14$ improvement in statistical uncert.
    $\Rightarrow 2 \times 10^{-4}$ in $sin^2 2\theta_{\mu e}$
  - Systematic uncertainty becomes important.
  - "Peak search" in the oscillation pattern
    $\Rightarrow$ hope to get around the limit due to systematics.

- If θ_{13} discovered $\Rightarrow$ CP study

CP sensitivity



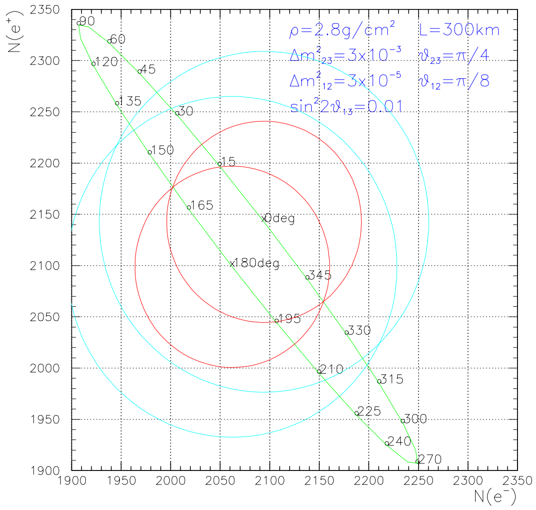
- Ocillation maximum and low neutrino energy
  Signal enhancement relative to the backgrounds.
- Double ratio: **cancellation of systematic errors**

$$\frac{P_{\nu_\mu\to\nu_e}(far)}{P_{\nu_\mu}(near)} \Big/ \frac{P_{\bar{\nu}_\mu\to\bar{\nu}_e}(far)}{P_{\bar{\nu}_\mu}(near)}$$

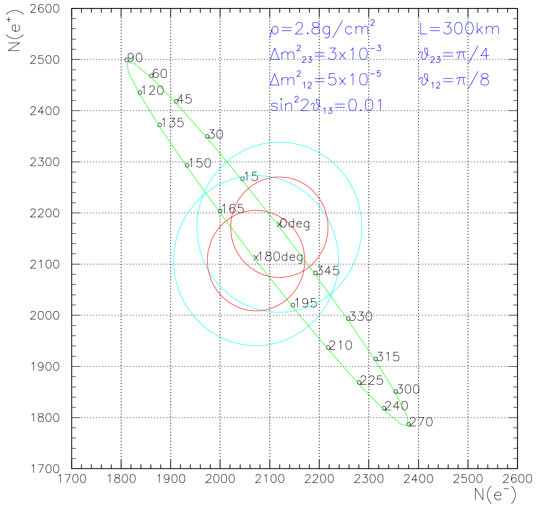
- CP phase δ can be measured down to 10-20 degrees.

CP sensitivity goes up linearly with Δm^2_{12}

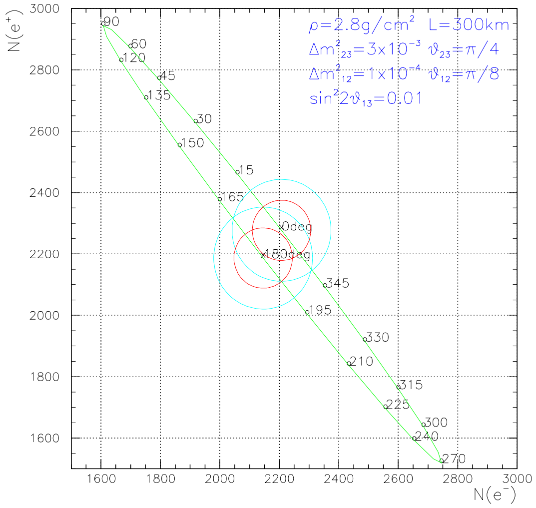
$$\Delta m^2_{12} = 3 \times 10^{-5}$$



$$\Delta m^2_{12} = 5 \times 10^{-5}$$

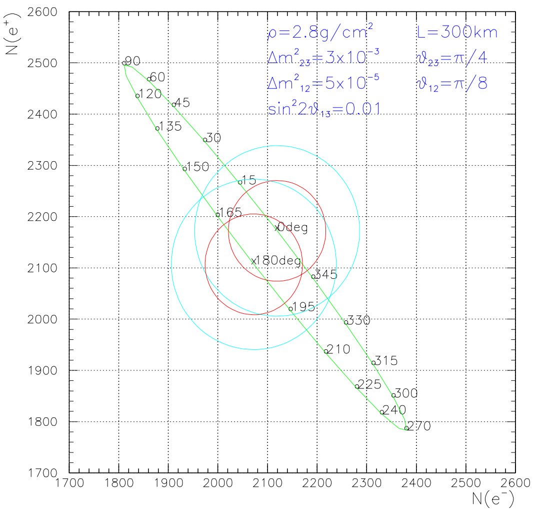


$$\Delta m^2_{12} = 10 \times 10^{-5}$$

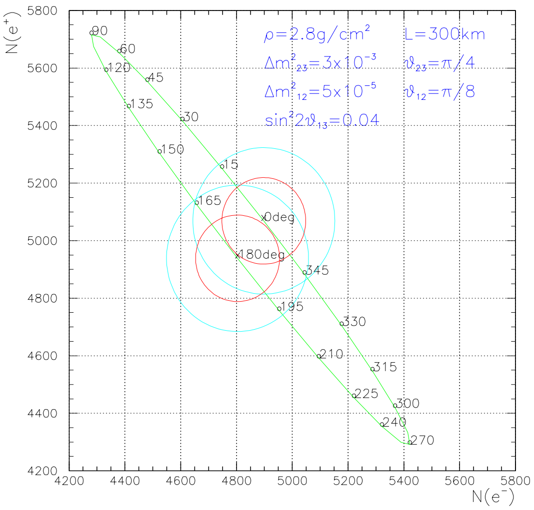


CP sensitivity does not depend much on $sin^2 2\theta_{13}$

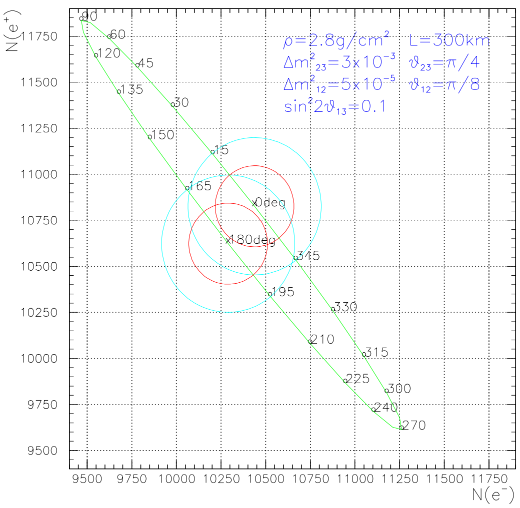
$sin^2 2\theta_{13} = 0.01$



$sin^2 2\theta_{13} = 0.04$

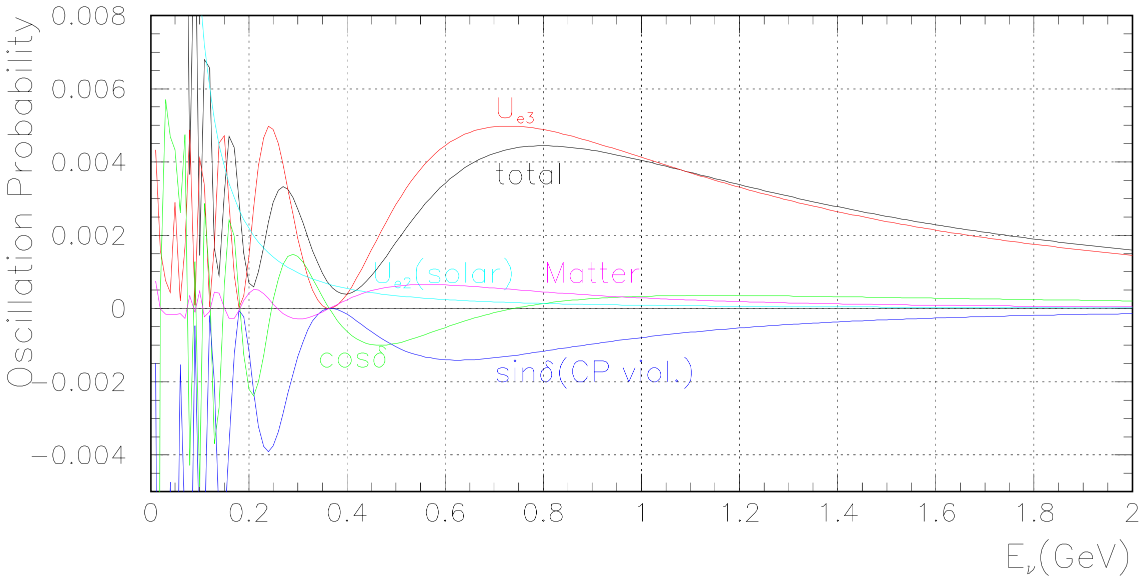


$sin^2 2\theta_{13} = 0.1$

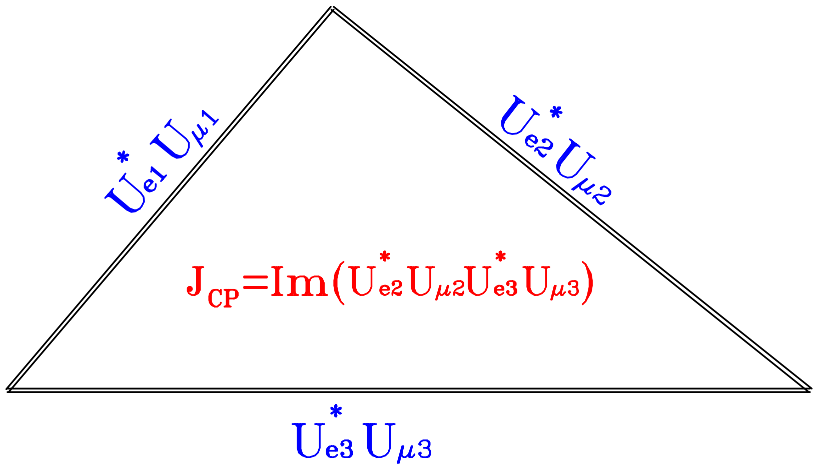


Overconstrain the Unitarity Triangle

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) \;=\; & 4|U_{e3}U^*_{\mu 3}|^2 \sin^2 \frac{\Delta m^2_{31} L}{4E} \;\; [U_{e3}] \\
& +8\mathrm{Re}(U^*_{e3}U_{\mu 3}U_{e2}U^*_{\mu 2}) \cos \frac{\Delta m^2_{32} L}{4E} \sin \frac{\Delta m^2_{31} L}{4E} \sin \frac{\Delta m^2_{21} L}{4E} \;\; [cos\delta] \\
& -8\mathrm{Im}(U^*_{e3}U_{\mu 3}U_{e2}U^*_{\mu 2}) \sin \frac{\Delta m^2_{32} L}{4E} \sin \frac{\Delta m^2_{31} L}{4E} \sin \frac{\Delta m^2_{21} L}{4E} \;\; [sin\delta] \\
& -4\mathrm{Re}(U^*_{e2}U_{\mu 2}U_{e1}U^*_{\mu 1}) \sin^2 \frac{\Delta m^2_{21} L}{4E} \;\; [U_{e2}] \\
& +(Matter\ effect) \qquad (Joe\ Sato,\ hep-ph/0008056)
\end{aligned}
$$



- The 4 coefficients overconstrain the unitarity triangle:
  $U^*_{e1}U_{\mu 1} + U^*_{e2}U_{\mu 2} + U^*_{e3}U_{\mu 3} = 0$



Comments on other studies (clarification)

Different results on the “optimum E_ν/baseline length”:

- Comparing $\delta = 90^\circ$ only with $\delta = 0^\circ$ but not $\delta = 180^\circ$
  $\delta = 180^\circ$ simply corresponds to $\theta_{13} \to -\theta_{13}$:

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

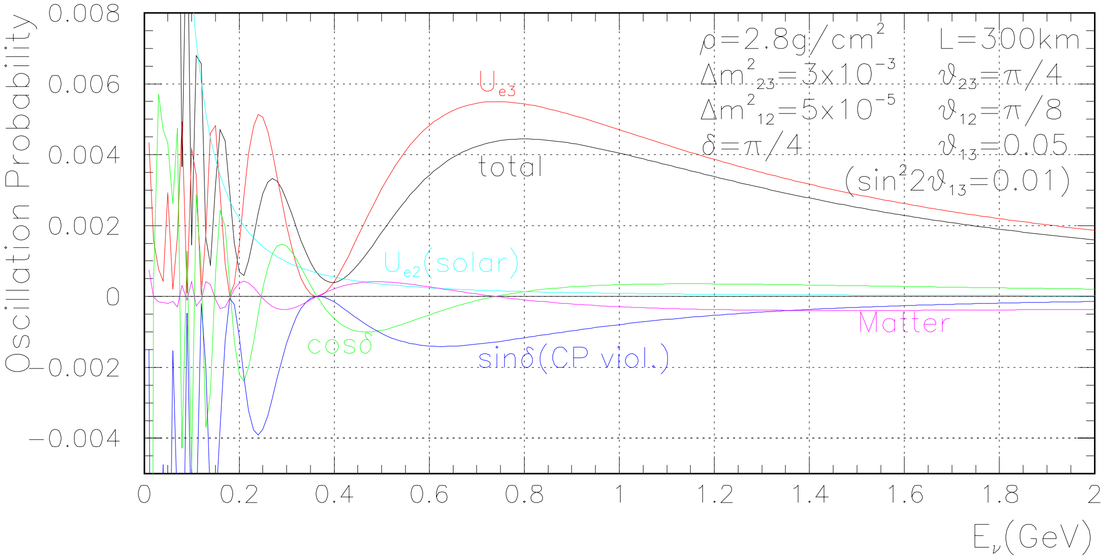
- Comparing $\delta = 90^\circ$ with $\delta = 0^\circ$ and $\delta = 180^\circ$
  Optimization favours CP-conserving $\cos\delta$ term at high E_ν

- Systematic uncertainties are not accounted for:
  - Uncertainties due to other oscillation parameters: e.g.θ_{12},θ_{13}
    Important in comparing $\delta = 90^\circ$ with $\delta = 0^\circ$ and $\delta = 180^\circ$ instead of asymmetry.
  - Uncertainty due to matter effect:
    Fake CP asymm. much larger than signal at high E_ν.
    $\Rightarrow$ Careful study of systematic uncertainty required.

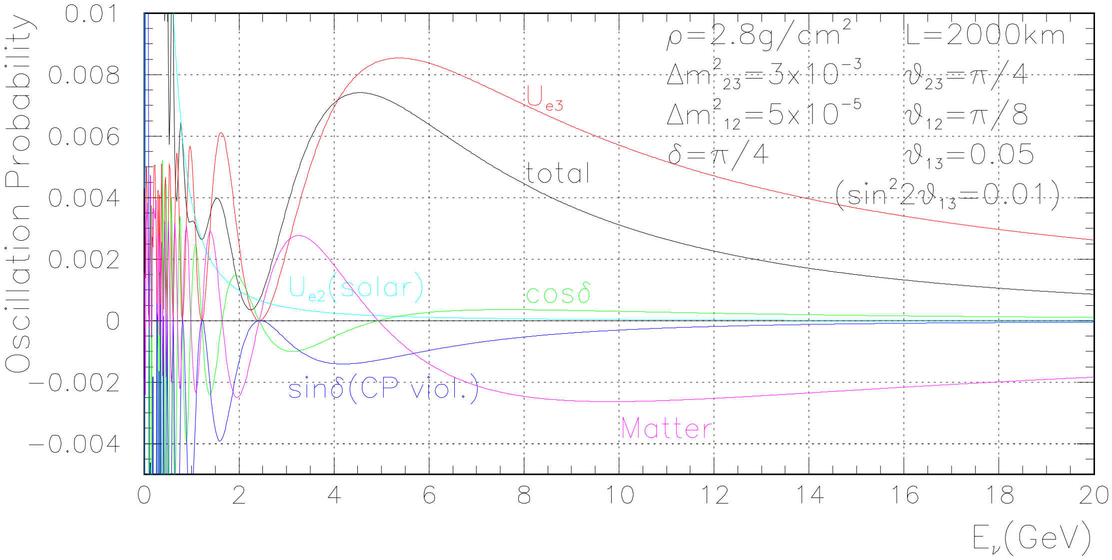
- E_ν dependence of backgrounds are not accounted for:
  - Suppressed ν_e contamination at low E_ν (less Kaon)
  - NC(π^0) rejection is higher at low E_ν due to
    lower cross section & larger opening angle for $\pi^0 \to \gamma\gamma$.

- E_ν dependence of the detector mass is not accounted for:
  Large mass water Čerenkov is good at low E_ν

- ∼1GeV neutrino beam



- ∼10GeV neutrino beam



- Good for studying the matter effect
- Matter effect dominates the ν-$\bar{\nu}$ asymmetry (A_{fake})
- $\cos\delta$ term becomes larger than $\sin\delta$ term
  $\Rightarrow$ δ measurement through $\cos\delta$ term?

Summary

- High sensitivity CP search by 4MW-JHF and Hyper-K.

$$A_{CP} = \frac{Prob(\nu_\mu \to \nu_e) - Prob(\bar{\nu}_\mu \to \bar{\nu}_e)}{Prob(\nu_\mu \to \nu_e) + Prob(\bar{\nu}_\mu \to \bar{\nu}_e)} = \frac{1.27\Delta m^2_{12} L}{E} \cdot \frac{\sin 2\theta_{12}}{\sin \theta_{13}} \cdot sin\delta$$

- Large CP asymmetry using the oscillation maximum: Central LMA, $\sin^2 2\theta_{13}$=0.01 $\Rightarrow$ A_{CP}=25%
- Fake asymmetry due to matter effect is small
- Cancellation of systematic uncertainty by the double ratio:

$$\frac{P_{\nu_\mu \to \nu_e}(far)}{P_{\nu_\mu}(near)} / \frac{P_{\bar{\nu}_\mu \to \bar{\nu}_e}(far)}{P_{\bar{\nu}_\mu}(near)}$$

- CP phase δ down to $10^\circ - 20^\circ$ for LMA& $\sin^2 2\theta_{13} > 0.01$.
- Possibility of overconstrain the unitarity triangle