Measuring CP Violation by Low Energy Neutrino Oscillation Experiments

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Neutrino Oscillation

and

CP Violation

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1. Introduction

o Completely Unknown Parameters for the lepton sector will be:

$$\begin{array}{ll} \sin\phi(\theta_{13}) & : \text{Last Mixing} \\ \sin\delta & : \text{CP Violation} \end{array}$$

How can we see?

o CP Violation is essentially 3 generation phenomenon.

$\Longrightarrow$ We have to see "3 generation".

$\Longrightarrow$ Not too high and Not too low energy region should be used.

o What are "High" and "Low" energies in an oscillation experiment.

$\diamond$ Two energy scales $\quad E \sim \begin{cases} \delta m^2_{31} L \\ \delta m^2_{21} L \end{cases}$

⋆ In high energy the first two lightest states seem "degenerate".

$$\Longleftrightarrow \delta m^2_{21} \sim 0$$

$$\begin{aligned} & \sin\Delta_{21} + \sin\Delta_{32} + \sin\Delta_{13} \\ \sim\ & \sin\Delta_{31} + \sin\Delta_{13} \Longrightarrow 0 \end{aligned}$$

In low energy the heaviest (two) state(s) "decouple(s)".

$$\Longleftrightarrow \Delta m^{2'} s \sim \infty$$

$$\begin{array}{lccccc} & \sin\Delta_{21} & + & \sin\Delta_{32} & + & \sin\Delta_{13} \\ \text{oscillating oute} & \downarrow & & \downarrow & & \downarrow \\ & 0 & & 0 & & 0 \end{array}$$

o $\delta m^2_{21} L \le E \le \delta m^2_{31} L$ will be the best energy range.

o Moreover to avoid the uncertainty due to matter effect, lower energy and shorter baseline length are better.

Konaka

o Experimentally several hundreds MeV region is preferable for neutrino experiment.

2 Oscillation probability $P(\nu_\alpha \to \nu_\beta)$ for $E \sim$ O(100) MeV and $L \sim$ O(100) Km

(Ignoring matter effect)
(subleading)

$$
\begin{aligned}
&P(\nu_\mu \to \nu_e) \\
&= 4|U_{e3}U_{\mu 3}|^2 \sin^2 \frac{\Delta_{31}}{2} \\
&+ 4\mathrm{Re}(U_{e3}^* U_{\mu 3} U_{e2} U_{\mu 2}^*) \left(\frac{\delta m_{21}^2}{\delta m_{31}^2}\Delta_{31}\right) \sin \Delta_{31} \\
\text{CPV!!} \quad &- 4\mathrm{Im}(U_{e3}^* U_{\mu 3} U_{e2} U_{\mu 2}^*) \left(\frac{\delta m_{21}^2}{\delta m_{31}^2}\Delta_{31}\right) \sin^2 \frac{\Delta_{31}}{2} \\
&- 4\mathrm{Re}(U_{e2}^* U_{\mu 2} U_{e1} U_{\mu 1}^*) \left(\frac{\delta m_{21}^2}{\delta m_{31}^2}\right)^2 \left(\frac{\Delta_{31}^2}{2}\right)^2 \\
&\equiv A \sin^2 \frac{\Delta_{31}}{2} \\
&+ \frac{B}{2}\Delta_{31} \sin \Delta_{31} \\
&+ C\Delta_{31} \sin^2 \frac{\Delta_{31}}{2} \\
&+ D \left(\frac{\Delta_{31}^2}{2}\right)^2
\end{aligned}
$$

Up to the leading(second) order of small values,

$$U_{e3} \text{ and } \frac{\delta m_{21}^2}{\delta m_{31}^2}.$$

o Current bounds on coefficients:

$$\begin{aligned} A &\leq 0.05 \\ B &\leq 0.006 \\ C &\leq 0.006 \\ D &\leq 0.001 \end{aligned}$$

with $U_{e3} \leq 0.15$ and $\frac{\delta m^2_{21}}{\delta m^2_{31}} < 3 \times 10^{-2}$.

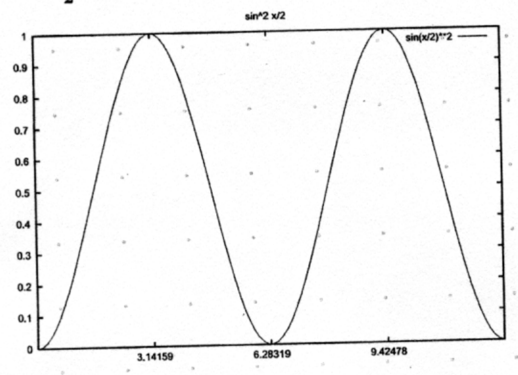
Due to the differnt energy dependence, these four terms can contribute the oscillation probability equibalently!!

∘ Base functions,

$$\sin^2\frac{\Delta_{31}}{2},\ \ \Delta_{31}\sin\Delta_{31},\ \ \Delta_{31}\sin^2\frac{\Delta_{31}}{2},\ \ \Delta_{31}^2$$

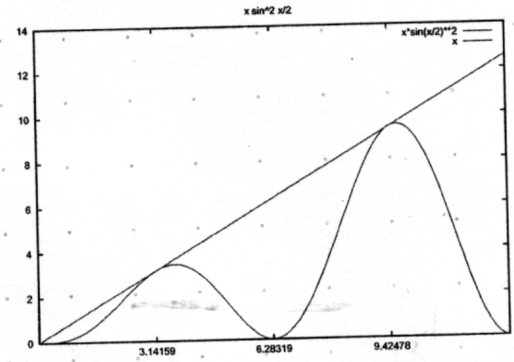
are independent!

$\sin^2\frac{\Delta_{31}}{2}$



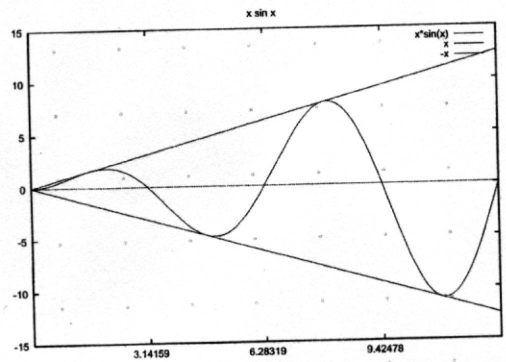
Δ_{31}

$\Delta_{31}\sin^2\frac{\Delta_{31}}{2}$



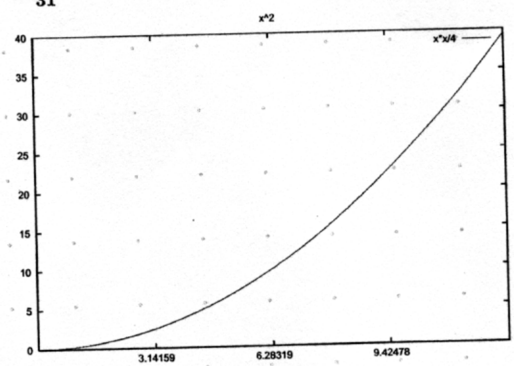
Δ_{31}

$\sin^2\Delta_{31}$



Δ_{31}

Δ_{31}^2



Δ_{31}

$$\begin{cases} L &= 300\text{km} \\ \delta m_{31}^2 &= 3\times 10^{-3} \end{cases} \Longleftrightarrow \frac{\Delta_{31}}{2} = \begin{cases} \frac{\pi}{2} \text{ at } E \sim 700\text{MeV} \\ \frac{\pi}{2} \text{ at } E \sim 250\text{MeV} \end{cases}$$

- For much higher energy

$$P(\nu_\mu \to \nu_e) = (A + B + D)\Delta_{31}^2 + C\Delta_{31}^3 + \cdots$$

$\Longrightarrow$ less infomation in higher energy.

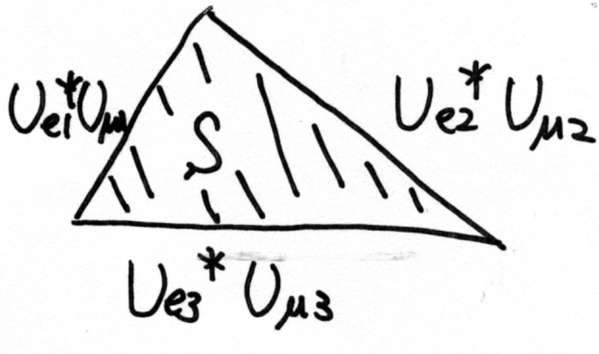
3 High Energy vs Low Energy

CP ? Unitarity Relation ?

- To observe $\cancel{CP}$

$$\Updownarrow$$

To mesure



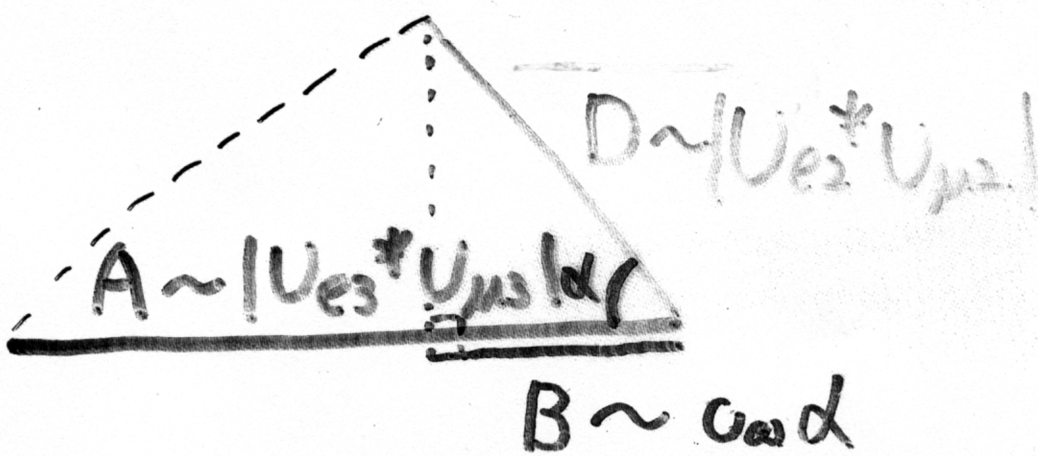
$$S = J_{\cancel{CP}}$$

∘ How to measure ?

☆ $A \propto |U_{e3}^* U_{\mu 3}|^2$

$B \propto \mathrm{Re}\, U_{e3}^* U_{\mu 3} U_{e2} U_{\mu 2}^*$

$D \propto |U_{e2}^* U_{\mu 2}|^2$



☆ $\Longrightarrow S = J_{\cancel{\phi}}$

$C \propto S = J_{\cancel{\phi}}$!!

$\propto \mathrm{Im}\, U_{e3}^* U_{\mu 3} U_{e2} U_{\mu 2}^*$

- Which determines $J_{\not{C}P}$?

$$\left\{ \begin{matrix} \text{Unitarity} \\ CP \end{matrix} \right\}$$

★ In high energy

$$P(\nu_e \to \nu_\mu) = (A + B + D)\,\Delta_{31}^2 + C\Delta_{31}^3$$

$$+ \cdots \text{ (matter, higher)}$$

Sensitive to $A + B + D$

$$\begin{array}{cccc} & A & + B & + D \\ \text{with matter} & \downarrow & \downarrow & \downarrow \\ & A & B & D \end{array}$$

while C is hidden

$$\Rightarrow C^2 \sim AD - B^2$$

Current Analysis assumes

D is completely know

$\Rightarrow$ C is determined rather well

☆ In low energy

C is directly measured !!!

Conventional horn beam vs. neutrino factory

E_ν	0.02-0.2GeV	0.2-1.5GeV	1.5-5GeV	>5GeV
σ_ν	Nuclear resonances	Quasi-Elastic $\sigma \sim const.$	Nucleon resonances	Deep Inelastic $\sigma \sim E_\nu$
E_ν meas.		2 body kinematics $(\nu_e n \to e^- p)$		hadron shower hadron calorimeter
Beam		horn beam $\nu_\mu \to \nu_e$ ν_e appearance		neutrino factory $\nu_e \to \nu_\mu$ wrong sign μ
Detector		e/π^0 separation		magnetic field

* Horn beam catches 20-30% of the entire π's:
  $\Rightarrow$ Horn beam is better at lower energy

* ν_e contamination is 0.5-1.0%
  $\Rightarrow$ Horn beam is good down to $sin^2 2\theta_{13} \geq 0.01$

* Detection efficiency (σ_ν) stays constant
  $\Rightarrow$ Advantage as $A_{CP} \propto \frac{L}{E}$

* Narrow band beam available:
  Off axis beam (BNL-E889) or Dichromatic beam

An example of sensitivity

- Assumptions:
  * JHF (50GeV, 1MW, 10^{21}POT/year)
  * Super-K detector 300km from JHF
  * 2 degree off axis neutrino flux ala BNL-E889:
    $3 \times 10^{-14} \nu_\mu / POT / cm^2$ at 300km for E_p=50GeV

- $N_{QE} = \phi_\nu \cdot N_{POT} \cdot N_{detector} \cdot \sigma$
  $= 1000$ Quasi-Elastic events/year

- Sensitivity to θ_{13} and CP violation

$sin^2 2\theta_{13}$	$\nu_\mu \to \nu_e$	5years&100kton	A_{CP}
0.04	20 events/year	500 events	25%(10%)
0.01	5 events/year	125 events	50%(20%)

$\Delta m^2_{23} = 3 \times 10^{-3}, \theta_{23} = \pi/4$ (Atmospheric)
$\Delta m^2_{12} = 3 \times 10^{-5}, \theta_{23} = \pi/8$ (Solar-LMA)
$\delta_{CP} = \pi/4$

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