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Neutrino and Anti-Neutrino Cross Sections and CP Phase Measurement

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Introduction

- MNS Matrix:

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{m1} & U_{m2} & U_{m3} \\ U_{t1} & U_{t2} & U_{t3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-id} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- WHY CP ?
  - In the Quark Sector, CP is violated.
  - Then, also in the Lepton Sector? $\rightarrow$ Leptogenesys
  - CP Measurement is a final goal of flavor physics

CP Phase Measurement

- In the case of conventional (super) beam,
  - $CPV \Leftrightarrow P(n_m \rightarrow n_e) \neq P(\bar{n}_m \rightarrow \bar{n}_e)$
  - cf: NuFact: $CPV \Leftrightarrow P(n_e \rightarrow n_m) \neq P(\bar{n}_e \rightarrow \bar{n}_m)$
- Oscillation Probability P($\nu_\mu \rightarrow \nu_e$):

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

$$d \rightarrow -d, a \rightarrow -a \quad for\ \bar{n}$$

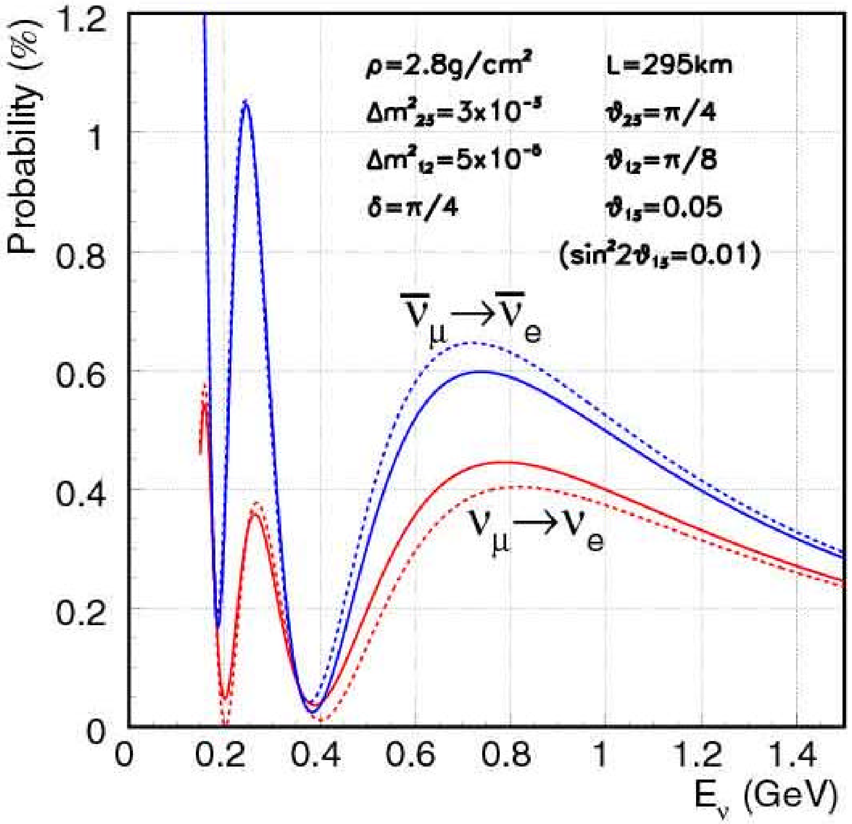
- $A_{CP} \equiv \dfrac{P - \bar{P}}{P + \bar{P}} \approx \dfrac{\Delta m_{12}^2 L}{E} \cdot \dfrac{\sin 2q_{12}}{\sin q_{13}} \cdot \sin d$

Assumed Scenario on ν physics ~2010

- $\nu_\mu \rightarrow \nu_\tau$ oscillation is established by Atmν, LBLν
  - $\sin^2 2\theta_{23} \sim 1.0$
  - $\Delta m^2_{23} \sim 3 \times 10^{-3} eV^2$
- LMA solution is established by Solν, KamLAND
  - $\sin^2 2\theta_{12} \sim 0.8$
  - $\Delta m^2_{12} \sim 5 \times 10^{-5} eV^2$
- Finite θ_{13} is found by JHF1 (, Atmν)
  - $\sin^2 2\theta_{13} \sim 0.03$
- MiniBooNE excluded LSND result
- (Still) Unknown parameters:
  - CP phase δ and sign of Δm^2

$\nu_\mu \rightarrow \nu_e$ oscillation probability

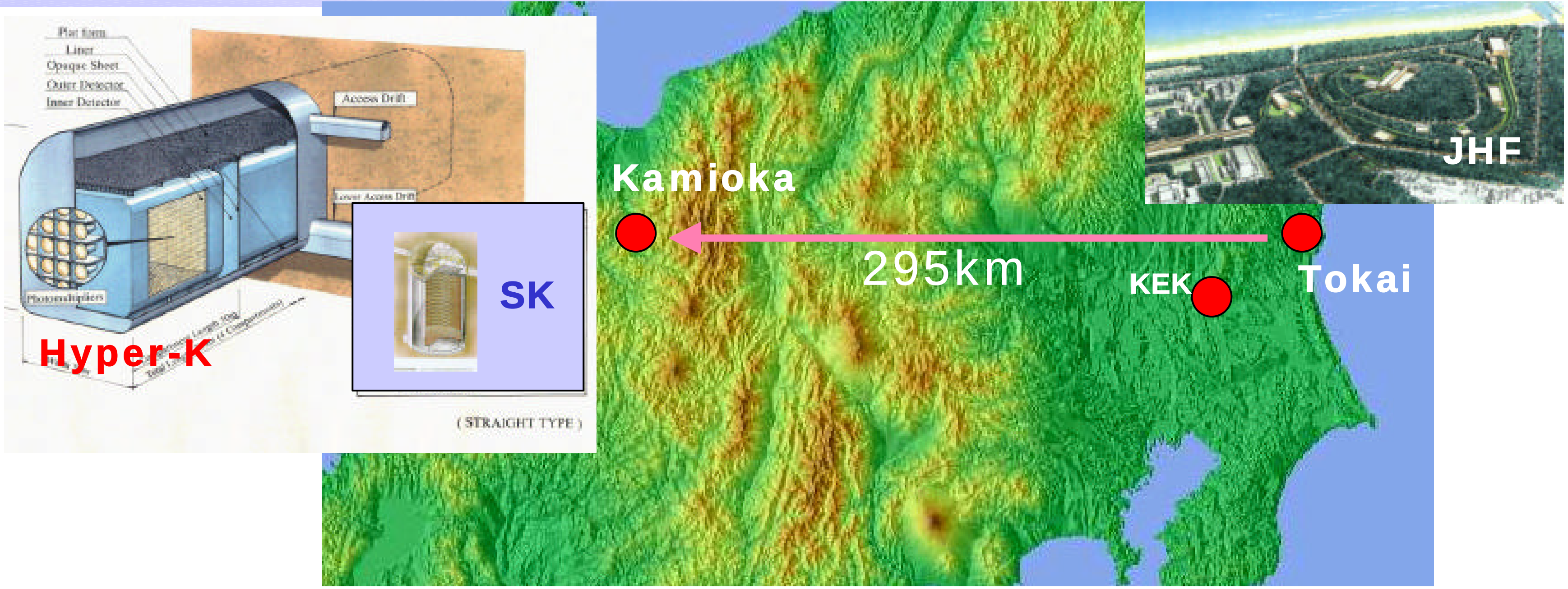
295km



Solid lines: w/ matter, Dashed lines: w/o matter

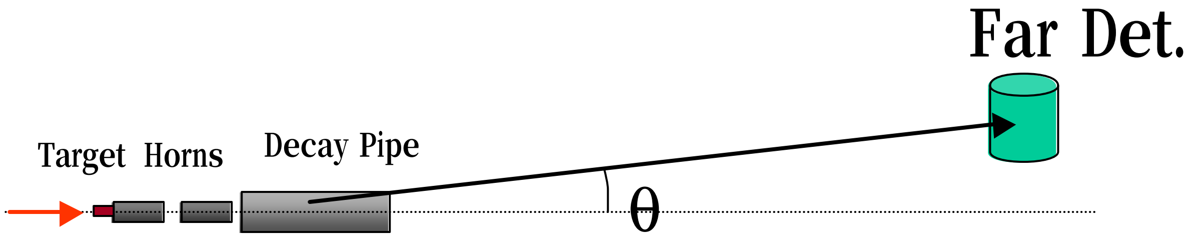
- Asymmetry can be seen at oscillation maximum ~0.7GeV

JHF-Kamioka ν Experiments

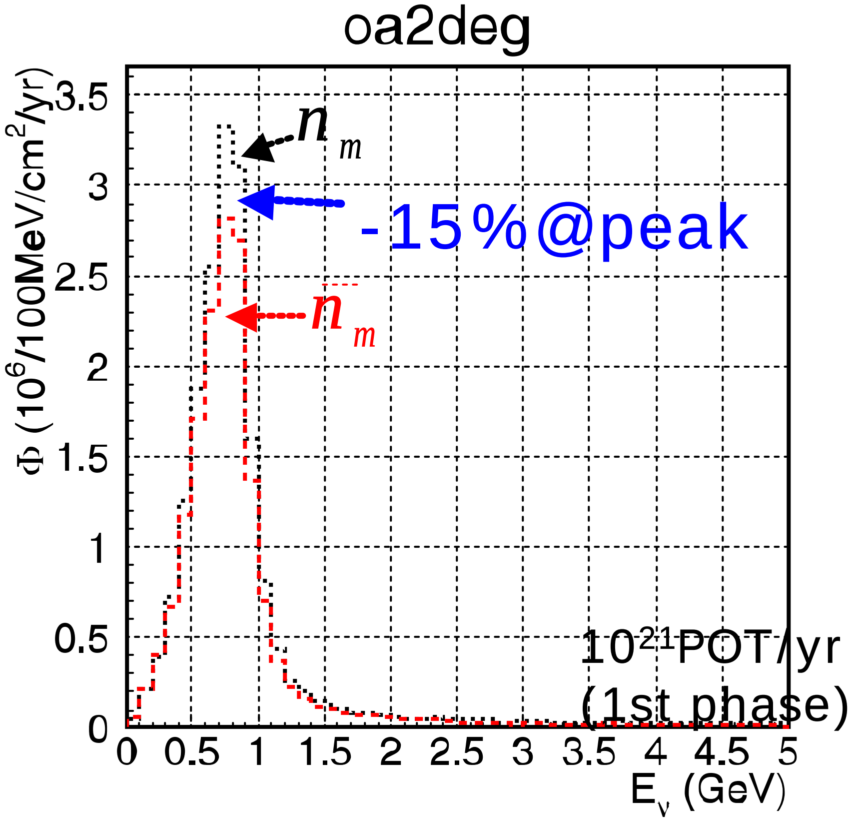


- Phase I: 2007$_{(?)}$~201x
  - ~1MW 50GeV PS → 22.5kt detector (Super-Kamiokande)
    - $\nu_\mu \rightarrow \nu_x$ disapp., $\nu_\mu \rightarrow \nu_e$ app., NC measurement
- Phase II: 201x(?)~202y(??)
  - ~4MW 50GeV PS → ~1Mt detector (Hyper-Kamiokande)
    - CPV search, Proton Decay, . . .

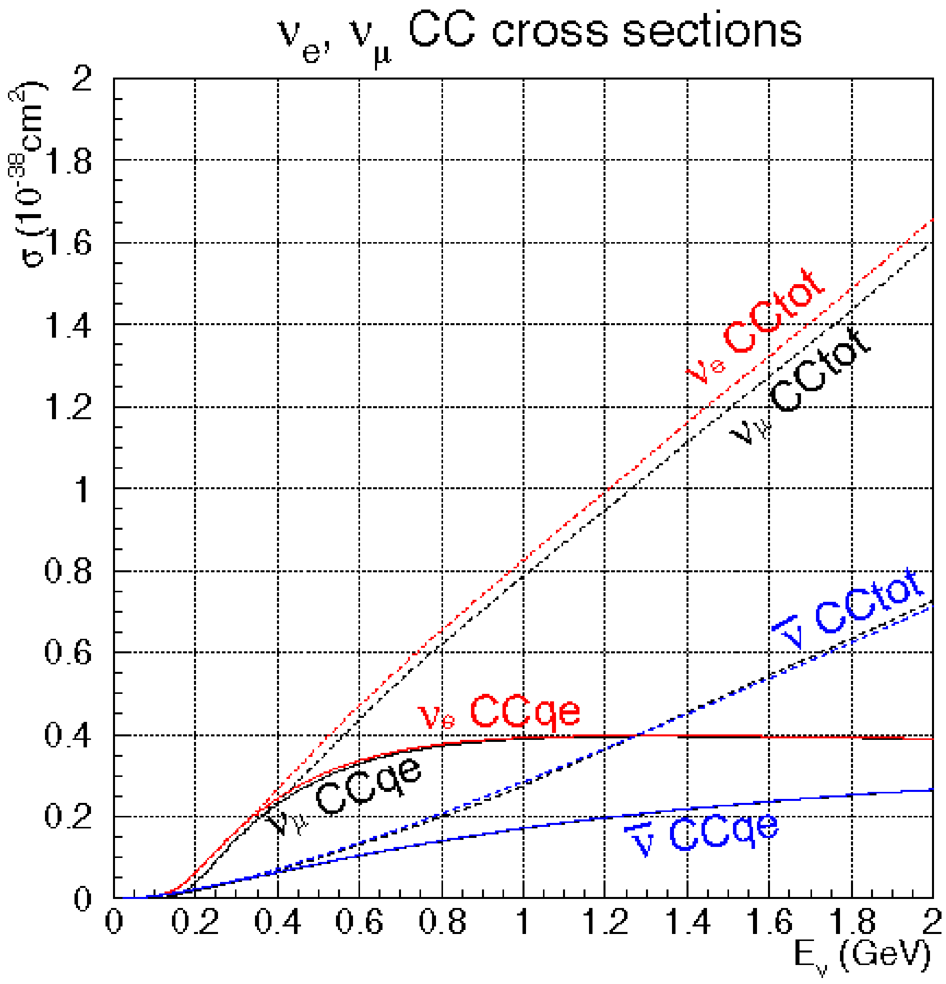
Beams



- Off Axis Beam
- Switch n_m and $\bar{n}_m$ by changing polarity of horn magnets
- Neutrino Flux is almost the same between n_m and $\bar{n}_m$ beams



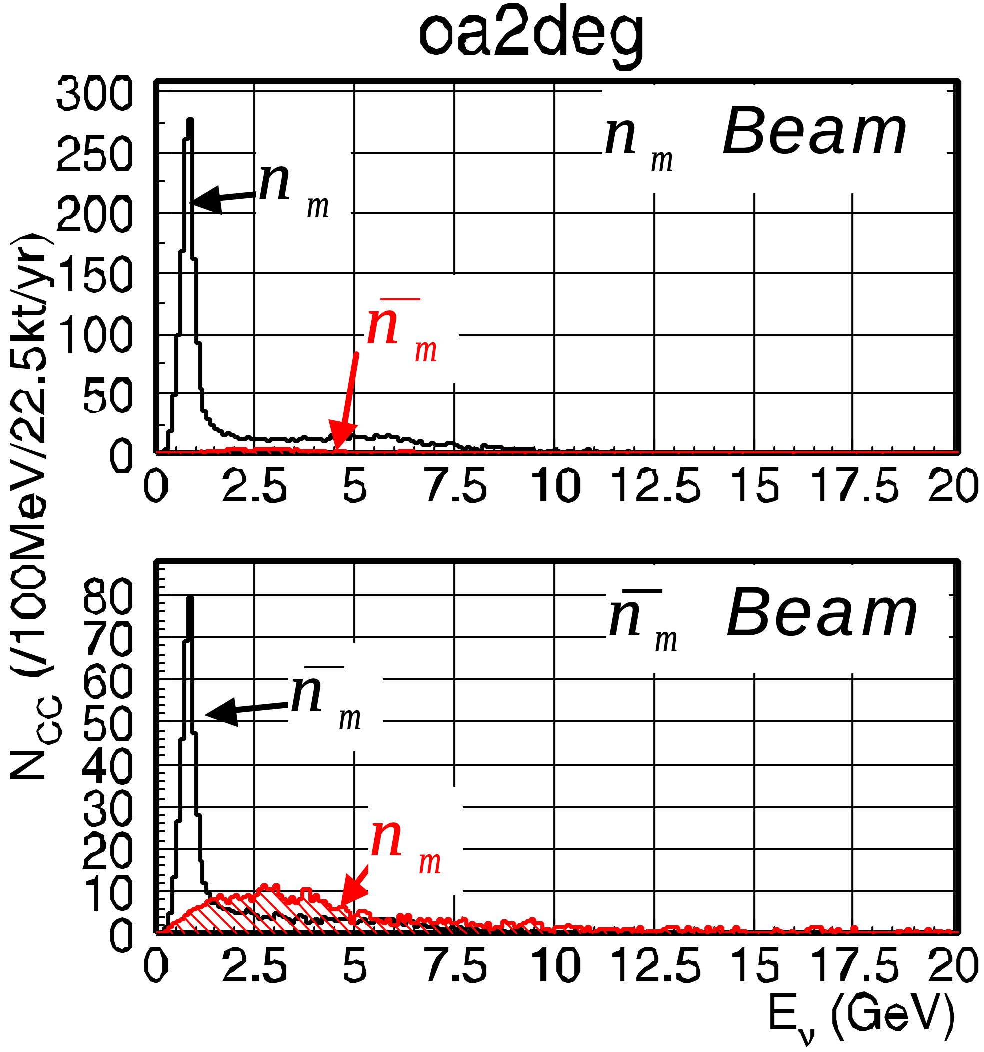
Cross Sections



- $s(\bar{n}) \approx 1/3 \times s(n)$
- Quasi elastic interactions dominate below ~1GeV
- $s(n_m\ CCqe) \approx s(n_e\ CCqe)$
- $s(\bar{n}_m\ CCqe) \approx s(\bar{n}_e\ CCqe)$

Expected Neutrino Events (w/o osc.)

- # of events @ far det.



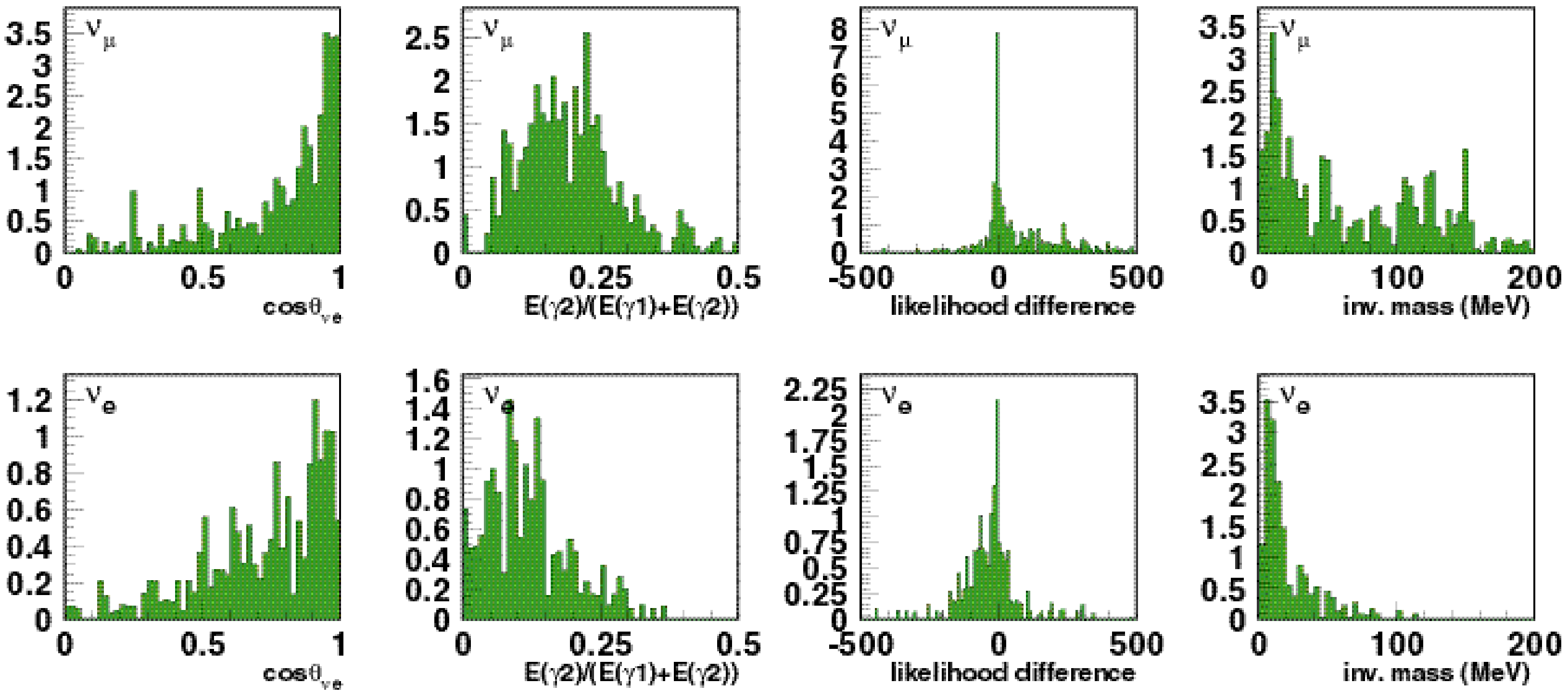
- $\sigma(\bar{\nu}_\mu)$ is factor 3 smaller than $\sigma(\nu_\mu)$
  - Running time of $\bar{\nu}_\mu$ beam need to be longer
- Wrong sign contribution is 3x3~10 times large for $\bar{\nu}_\mu$ beam
  - Cause fake CP asymmetry

Selection for ν_e appearance search

- Select ν_e CCqe interactions
  - Vertex is in the fiducial volume
  - Single EM shower ring
  - No decay electron observed
  - Evis > 100MeV (reject NC elastic)
  - Tight e/π^0 separation
    - see next slide
  - Reconstructed Eν cut
    - $0.4 < E\nu(\mathrm{GeV}) < 1.2$

Tight e/π^0 separation

- $\cos\theta_{\nu e}$: γ from π^0 tend to have a forward peak
- $E(\gamma_2)/E(\gamma_1+\gamma_2)$: Large for BG
- Likelihood diff. between 1-ring and 2-rings
- Invariant mass: Small for ν_e



Expected Signal & Backgrounds

Beam	ν_e app. Signal w/o CP	Effect of CP	Background in Hyper-K				
			n_m	n_e	$\bar{n}_m$	$\bar{n}_e$	total
n_m	699	-123	241	225	34	11	510
	w/π^0		223	13	28	1	264
$\bar{n}_m$	699	+120	238	164	342	210	953
	w/π^0		213	16	302	8	540

- By the present tools,
  - BG level is ~5x larger than expected CP asymmetry.
  - We need to achieve ~5% precision of BG subtraction if we want to see 3σ effect.
- ~90% of ν_μ BG (50~60% of total BG) are from π^0

- Δm_{12}^2 = 5×10^{-5}eV^2
- Δm_{23}^2 = 3×10^{-3}eV^2
- $\sin^2 2\theta_{13}$ = 0.03
- $\sin^2 2\theta_{23}$ = 1
- $\sin^2 2\theta_{12}$ = 0.8
- δ = 45 deg
- 5 x 10^{21} pot x 450 kt (ν_μ)
- 1.83 x 10^{22} x 450 kt pot ($\bar{n}_m$)
- **Off axis 2deg beam**
- **No matter effect considered**

Cross Section (& Efficiency) Difference

- We want to know

$$P_{m\to e} \equiv \frac{N_e^{obs}}{\Phi_m^{\exp}\cdot s_e \cdot e_e}$$

- Observable

$$P'_{m\to e} \equiv \frac{N_e^{obs}}{N_m^{\exp}} = P_{m\to e}\cdot\frac{s_e}{s_m}\cdot\frac{e_e}{e_m} = P_{m\to e}\cdot r_s \cdot r_e$$

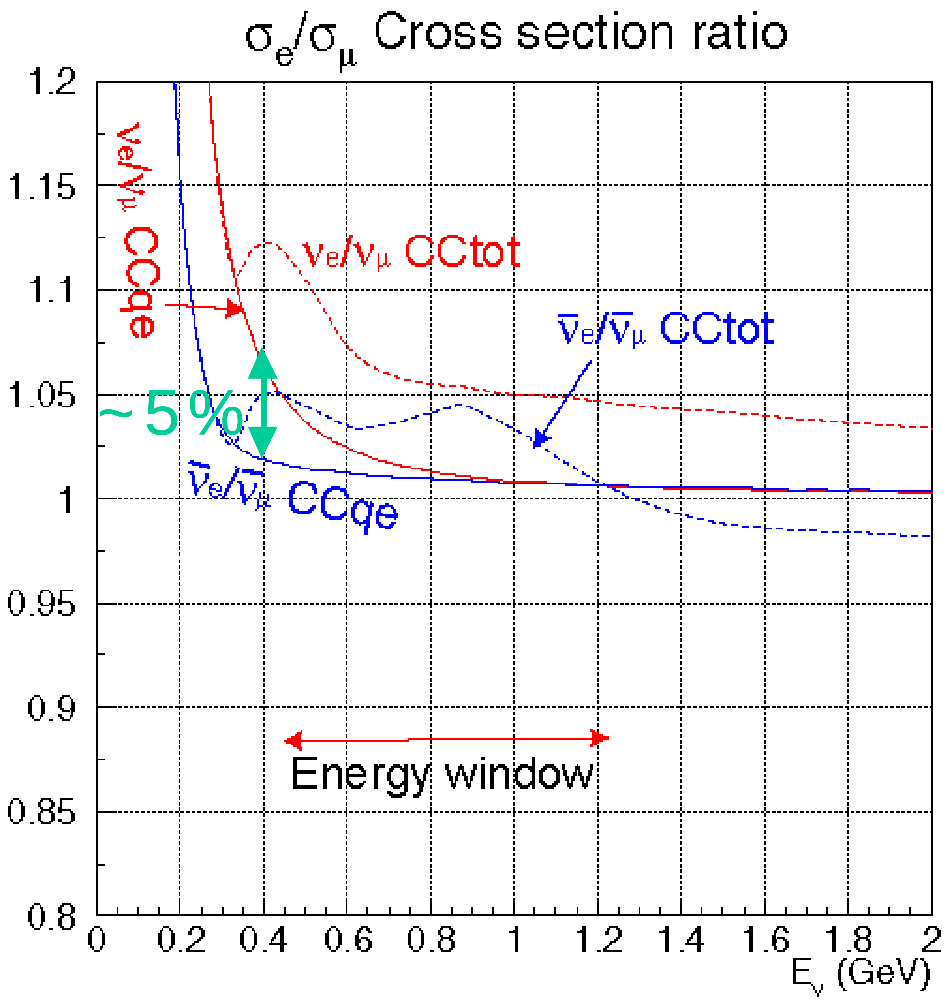
- Then Asymmetry Parameter

$$A_{CP} \equiv \frac{P(n_m \to n_e) - P(\bar{n}_m \to \bar{n}_e)}{P(n_m \to n_e) + P(\bar{n}_m \to \bar{n}_e)} = \frac{P'/r_s r_e - \bar{P}'/\bar{r}_s \bar{r}_e}{P'/r_s r_e + \bar{P}'/\bar{r}_s \bar{r}_e}$$

$$= \frac{P'-\bar{P}'}{P'+\bar{P}'}\left\{1 + \frac{2\bar{P}'^2}{P'^2-\bar{P}'^2}\left(\boxed{\frac{\bar{r}_s - r_s}{r_s} + \frac{\bar{r}_e - r_e}{r_e}}\right)\right\}$$

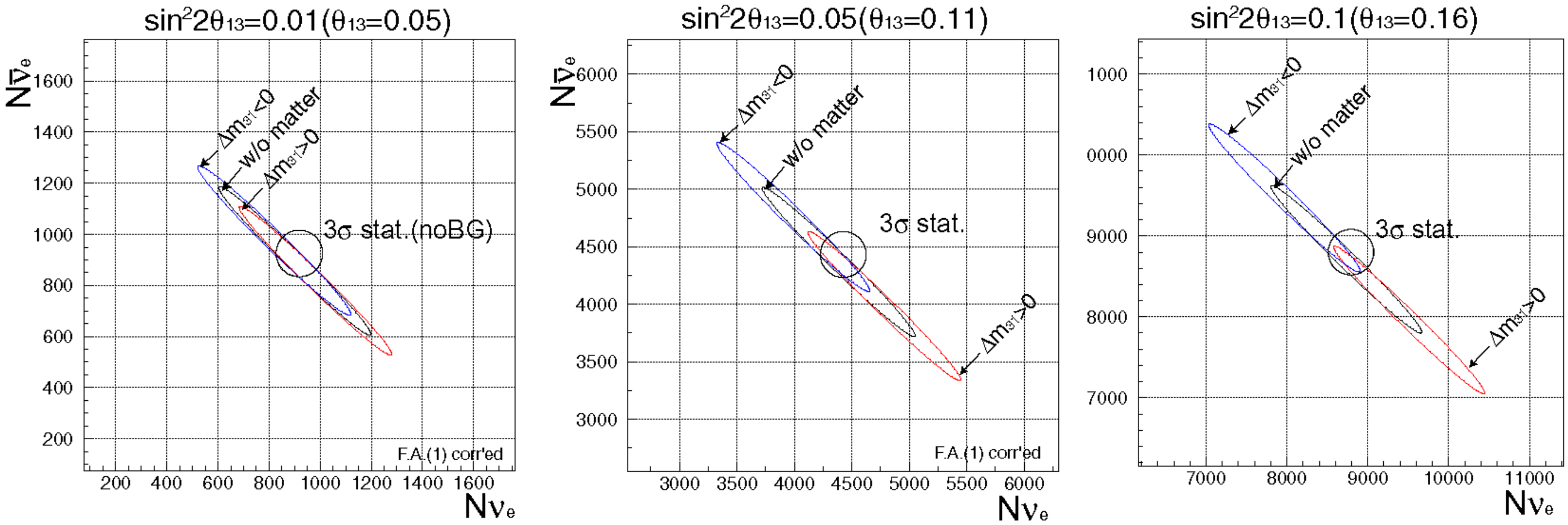
- Only the difference of rσ,rε between neutrino and anti neutrino appear in the asymmetry

Cross Section Difference



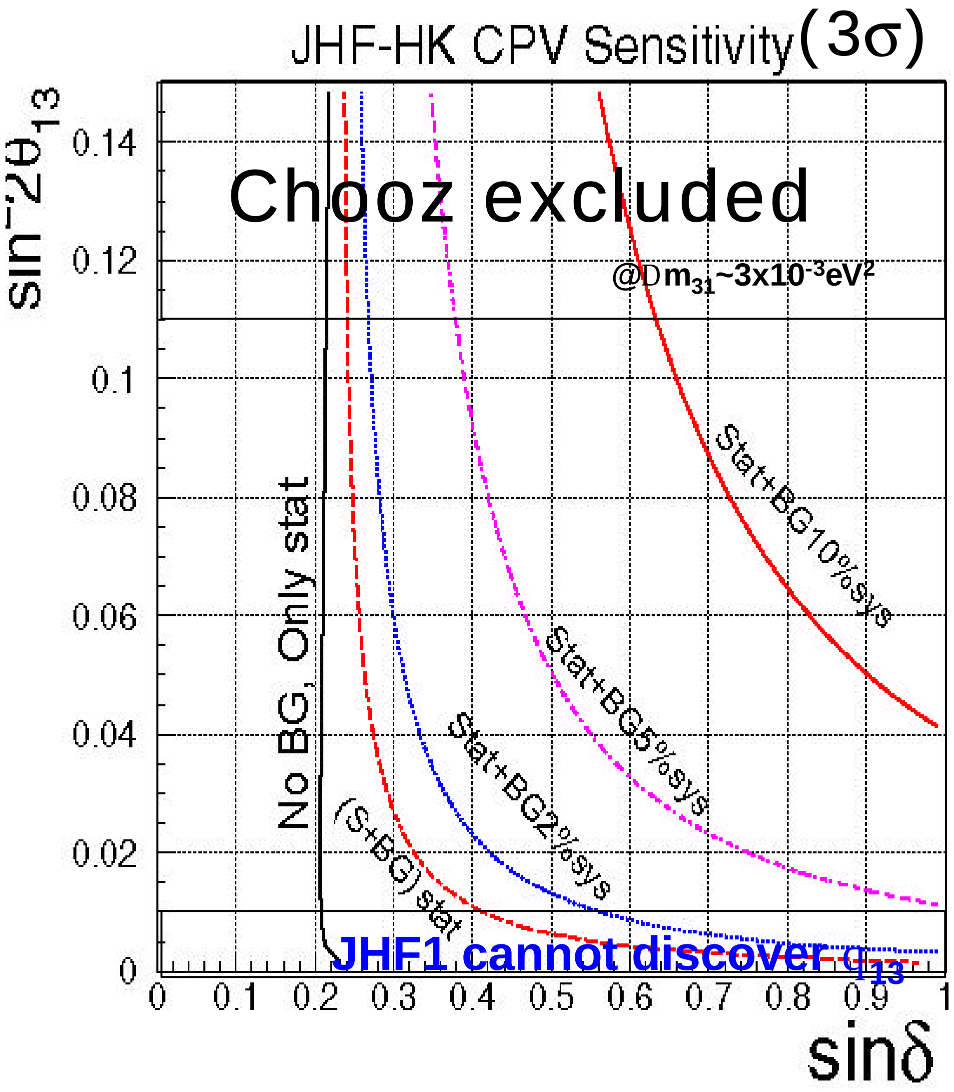
- CCqe cross section ratio of ν_e/ν_μ
  - Difference between neutrino and anti-neutrino is at most 5% within the energy window

CP Measurement



- Matter effect becomes larger for large θ_{13}
- Black circles represent 3σ contour for phase 2 of JHF running

BG subtraction vs Sensitivity



- Sensitivity strongly depends on systematic uncertainty of BG subtraction.
- If BG sys. = 2%:
  - $\sin^2 2\theta_{13}=0.01 \rightarrow \sin\delta>0.55(33^o)$
  - large $\theta_{13} \rightarrow \sin\delta>0.25(14^o)$
- Sensitivity improves with better BG rejection

➔ Better BG rejection and smaller uncertainty in BG subtraction are strongly preferred in the CP measurement

Items for the Improvement of Sensitivity

- ~90% of ν_μ BG are from π^0
  - Improve the hardware (Hyper-K)
    - Timing resolution, Light scattering and reflection, Segment . . .
  - Improve the software
    - Reconstruction algorithm, . . .
  - Measure NC π^0 rate@ Front detector
    - Energy scan with Narrow Band Beam
- ~50% of BG are from ν_e
  - Measure ν_e/ν_μ ratio @ Front detector
  - Narrower energy window
    - Improvement of energy resolution
- ~50% of BG are from high energy tail of beam
  - Tune the beam line and reduce HE tail
- Measurement of wrong sign contamination
  - Magnetized detector?
  - Recoiled neutron detector?

Conclusion

- Phase 2 of JHF-Kamioka experiment aims at measuring CP violation
- Better BG rejection and smaller uncertainty in BG subtraction are strongly preferred in the CP measurement
- Let's Complete MNS matrix!