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宇宙v研究会@柏ICRR

CP非保存探索 in JHF-HyperK ν

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All numbers are preliminary

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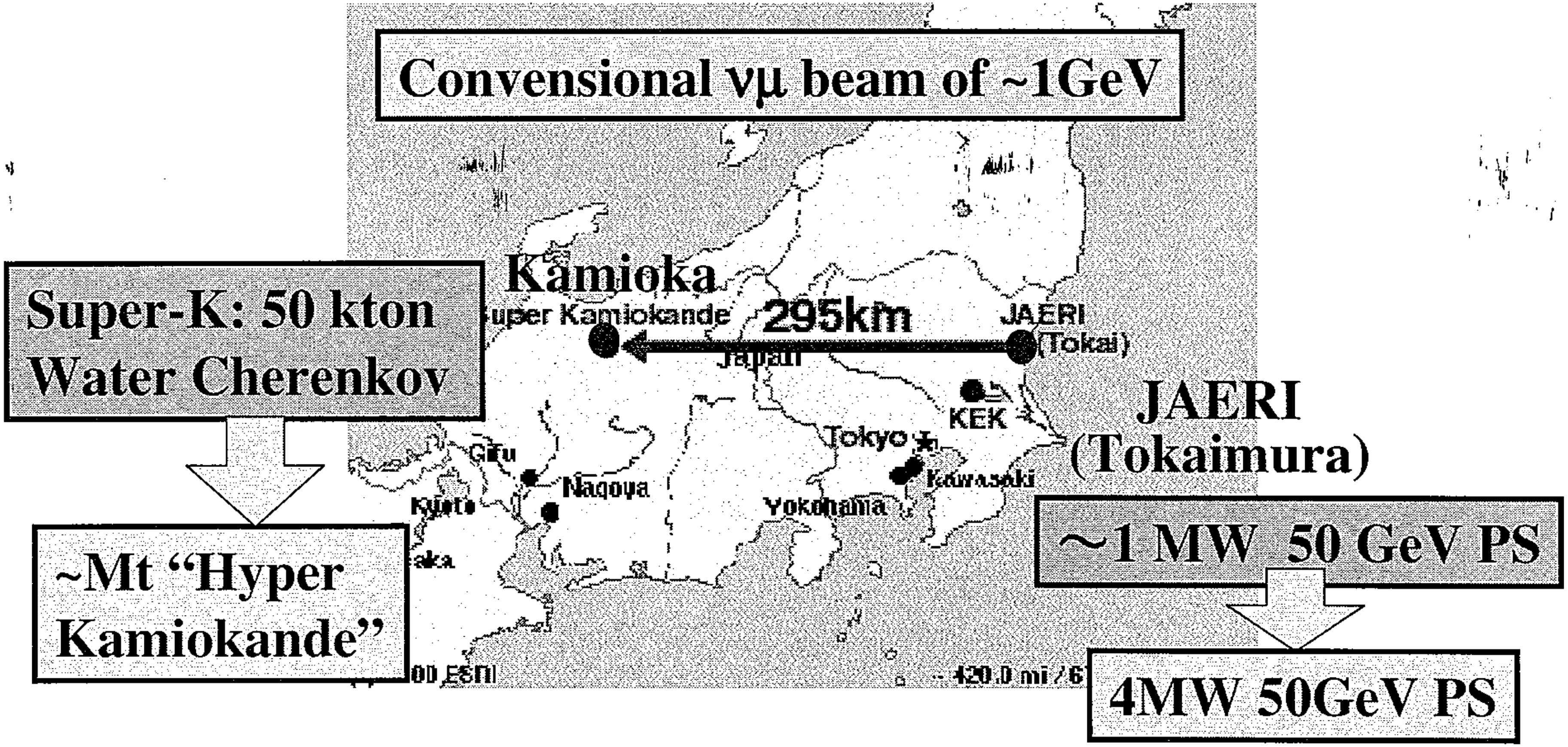
序

JHF-SK(HK) ν Experiment



Convensional νμ beam of ~1GeV

Super-K: 50 kton Water Cherenkov

~Mt "Hyper Kamiokande"

JAERI (Tokaimura)

~1 MW 50 GeV PS

4MW 50GeV PS

First Phase

- •νμ→ νx disappearance
- •νμ→ νe appearance
- •NC measurement

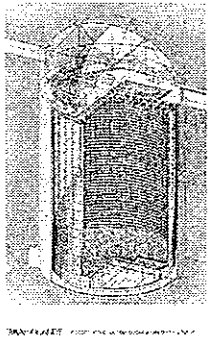
Second Phase

- •CPV
- •proton decay

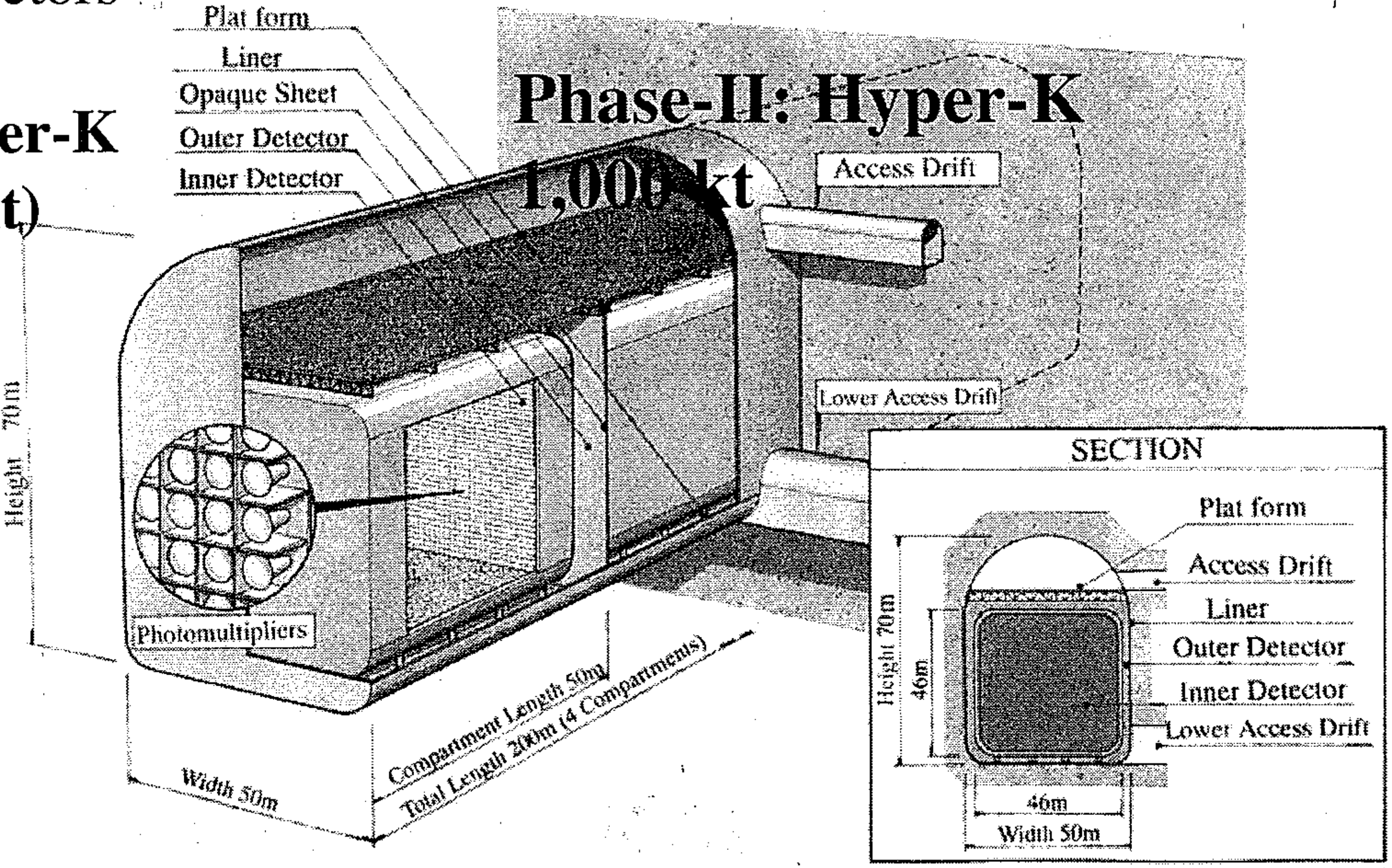
Far ν detector

- Far ν detectors

Phase-I: Suker-K
22.5kt (50kt)



Phase-II: Hyper-K
1,000kt



Neutrino Oscillation

Neutrino Mixing $|\nu_l\rangle = \Sigma U_{li}|\nu_i\rangle$

Weak eigenstates

Mass eigenstates

Maki-**N**akagawa-**S**akata **Matrix**

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i\delta} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix}$$

$s_{ij}=\sin\theta_{ij}$, $c_{ij}=\cos\theta_{ij}$

Oscillation Probability

$$P_{l\to m} = \left|\langle\nu_m(t)|\nu_l(0)\rangle\right|^2 = \delta_{ml} - 2\sum_{i<j}\mathrm{Re}\left[\left(U^*_{mi}U_{li}\right)\cdot\left(U_{mj}U^*_{lj}\right)\cdot\left\{1-\exp\left(-i\frac{\Delta m^2_{ij}}{2E}L\right)\right\}\right]$$

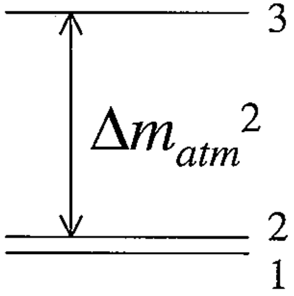
L : flight length, E : neutrino energy, $\Delta m^2_{ij} \equiv m^2_i - m^2_j$, m_i : mass eigenvalues

$$P_{l\to m} \neq \delta_{ml} \Leftrightarrow \Delta m_{ij} \neq 0$$

LFV

Oscillation probabilities

when $\begin{cases} \Delta m_{12}^2 << \Delta m_{23}^2 \approx \Delta m_{13}^2 \equiv \Delta m_{atm}^2 & \text{contribution from } \Delta m_{12} \text{ is small} \\ E_\nu \approx \Delta m_{atm}^2 \cdot L \end{cases}$



ν_e appearance

$$P_{\mu\to e} \approx \underbrace{\boxed{\underbrace{\sin^2\theta_{23}}_{\sim 0.5} \cdot \sin^2 2\theta_{13}}}_{\sin^2 2\theta_{\mu e}} \cdot \sin^2\left(1.27\Delta m_{atm}^2 / E_\nu\right)$$

ν_μ disappearance

$$P_{\mu\to x} = 1 - (P_{\mu\to e} + P_{\mu\to\tau} + P_{\mu\to sterile}) \approx P_{\mu\to\tau}$$

$$P_{\mu\to\tau} \approx \underbrace{\cos^4\theta_{13}}_{\sim 1} \cdot \sin^2 2\theta_{23} \cdot \sin^2\left(1.27\Delta m_{atm}^2 / E_\nu\right)$$

Neutral Current (NC) measurement

$$N_{NC} \propto P_{\mu\to active} = 1 - P_{\mu\to sterile}$$

Cf. Chooz (ν_e disappearance)

$$P_{e\to x} \approx 1 - \sin^2 2\theta_{13} \cdot \sin^2\left(1.27\Delta m_{atm}^2 / E_\nu\right)$$

$\nu_\mu \rightarrow \nu_e$ oscillation probability(1)

大きさを支配 **物質非対称を支配**

$$P(\nu_\mu \to \nu_e) = \boxed{4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2 \frac{\Delta m_{31}^2 L}{4E} \times \left(1 + \frac{2a}{\Delta m_{31}^2} \ (1 - 2S_{13}^2)\right)}$$

$$+8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E}$$

$$\boxed{-8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E}} \quad \textbf{CPV}$$

$$+4S_{12}^2 C_{13}^2 \left\{C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta\right\} \sin^2 \frac{\Delta m_{21}^2 L}{4E}$$

$$-8C_{13}^2 S_{13}^2 S_{23}^2 \cos \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \frac{aL}{4E} \ (1 - 2S_{13}^2)$$

$\boldsymbol{\delta \rightarrow -\delta}$, $\boldsymbol{a \rightarrow -a}$ for $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$

Matter eff.:

$$a = 7.56 \times 10^{-5} [\mathrm{eV}^2] \cdot \left(\frac{\rho}{[\mathrm{g/cm^3}]}\right) \cdot \left(\frac{E}{[\mathrm{GeV}]}\right)$$

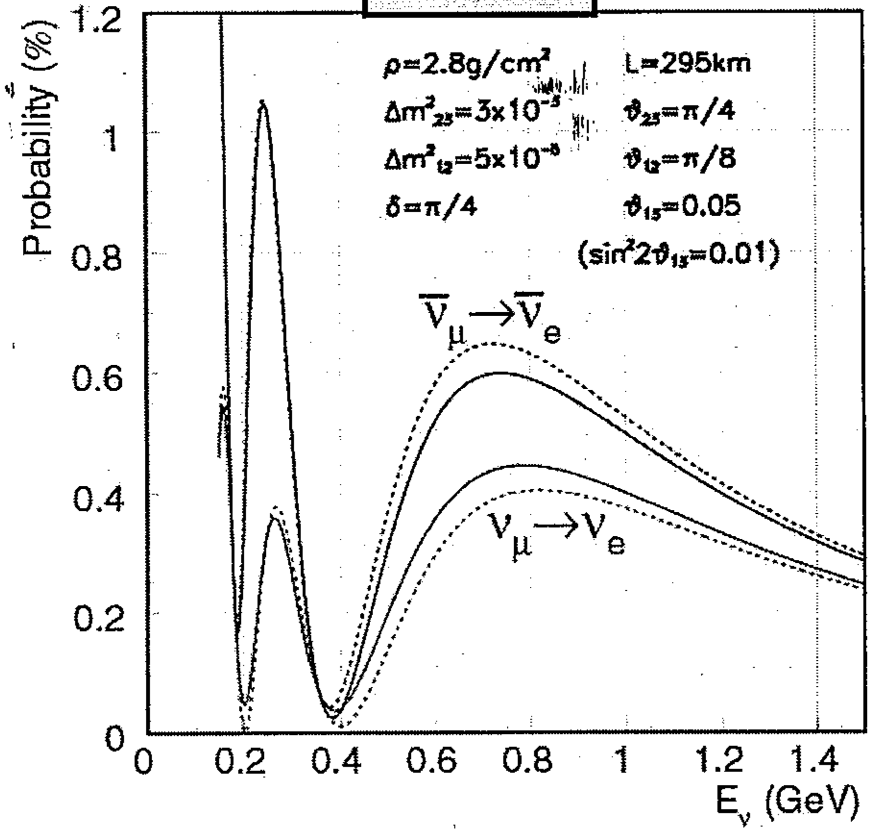
$$\boxed{A_{CP} \equiv \frac{P - \overline{P}}{P + \overline{P}} \approx \frac{\Delta m_{12}^2 L}{E} \cdot \frac{\sin 2\theta_{12}}{\sin \theta_{13}} \cdot \sin\delta}$$

CPV measurement in JHF-HK exp.

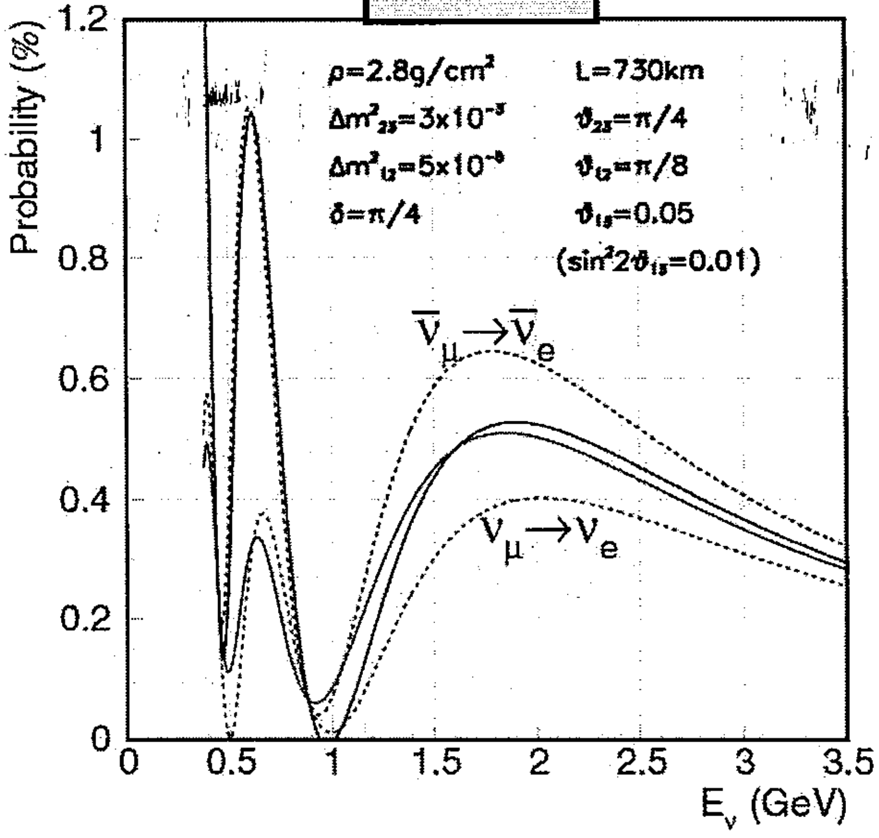
$\nu_\mu \rightarrow \nu_e$ appearance
  - leading CP conserving term strongly suppresed by small θ_{13} → expect large effect.
- CP effect enhanced at low energy
- Matter effect suppressed at low energy
- Background p0 less at low energy
- Gigantic water Cherenkov detector
  - good electron ID @ low E (~GeV)

$\nu_\mu \rightarrow \nu_e$ oscillation probability(2)

295km



730km



Solid line: w/ matter
Dashed line: w/o matter

Small Matter Effect at 295km.

どうやって
測るのか？

手順

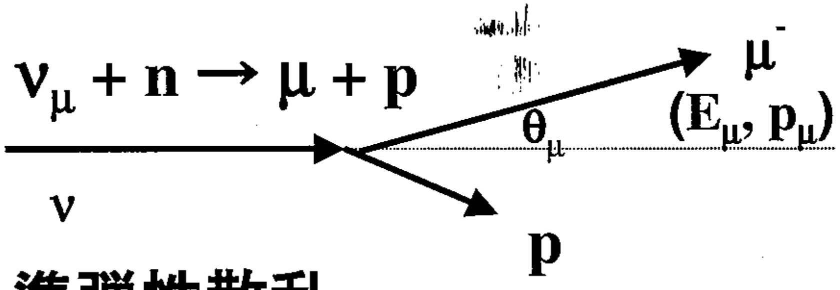
- Detect electron like events
- Energy reconstruction
- BG subtraction
  - Beam ν_e
    ν_μ NC π^0 production (incl. BG from wrong sign ν_μ)
- Fake asymmetry correction
  - spectrum
  - cross section
  - efficiency
  - matter effect
- Asymmetry

Neutrino Energy E_ν の再構成

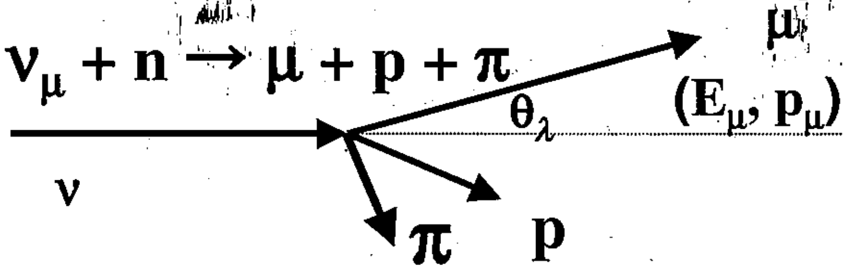
CC quasi elastic reaction
(準弾性散乱)

$$\Leftrightarrow \quad E_\nu = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + p_\mu \cos\theta_\mu}$$

$\nu_\mu + n \rightarrow \mu + p$

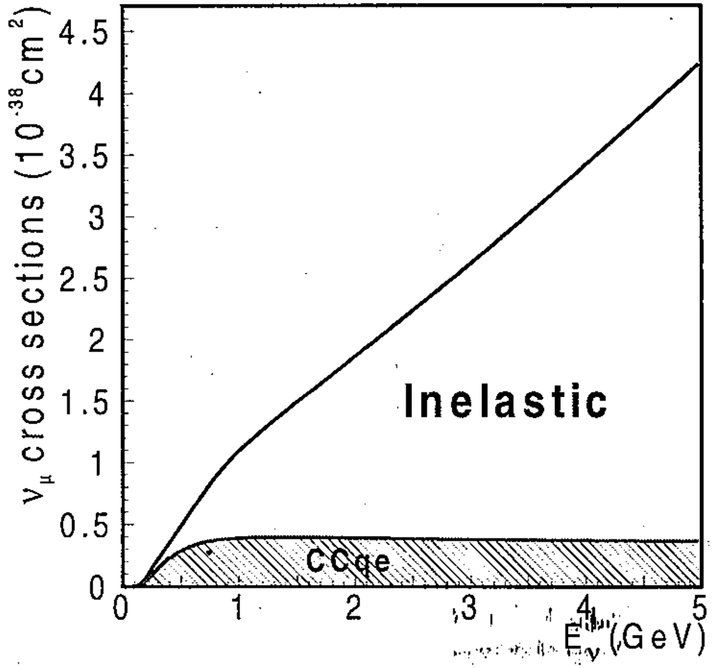


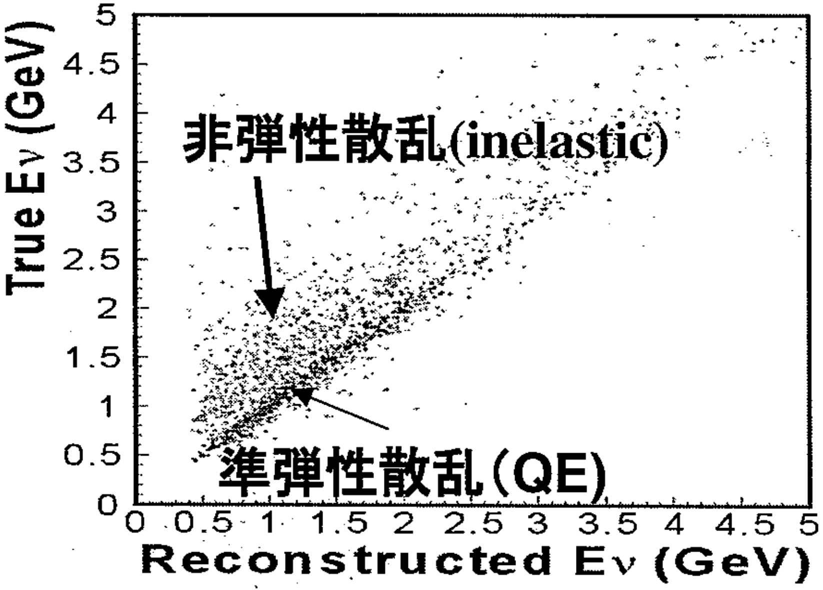
$\nu_\mu + n \rightarrow \mu + p + \pi$



準弾性散乱

非弾性散乱





CP measurement (II)

Observables

$$N_e(E_{rec}) = N_{obs}(E_{rec}) - N_{BG}(E_{true})$$

$$= \int dE_{true} \underbrace{\Phi_\mu(E_{true})}_{\mu\ \text{flux}} \cdot P_{\mu\to e}(E_{true}) \cdot \underbrace{\sigma_e(E_{true})}_{\text{cross sec.}} \cdot \underbrace{\varepsilon_e(E_{true})}_{\text{det.eff}} \cdot \underbrace{r_e(E_{true} - E_{rec})}_{\text{det.responce}}$$

unfold det. responce

$$N_e(E_{true}) = \Phi_\mu(E_{true}) \cdot \underline{P_{\mu\to e}(E_{true})} \cdot \sigma_e(E_{true}) \cdot \varepsilon_e(E_{true})$$

Divide by exp'ed # of ν_μ events w/o oscillation

$$P'_{\mu\to e}(E_{true}) \equiv \frac{N_e(E_{true})}{N_\mu^{\exp}(E_{true})} = \frac{N_e(E_{true})}{\Phi_\mu^{\exp} \cdot \sigma_\mu \cdot \varepsilon_\mu} = \frac{N_e(E_{true})}{\Phi_\mu^{\exp} \cdot \sigma_e \cdot \varepsilon_e} \times \overset{r_\sigma}{\frac{\sigma_e}{\sigma_\mu}} \cdot \overset{r_\varepsilon}{\frac{\varepsilon_e}{\varepsilon_\mu}}$$

$$= P_{\mu\to e}(E_{true}) \cdot r_\sigma(E_{true}) \cdot r_\varepsilon(E_{true})$$

CP Asymmetry

$$A_{CP} \equiv \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} = \frac{P'\big/ r_\sigma r_\varepsilon - \bar{P}'\big/ \bar{r}_\sigma \bar{r}_\varepsilon}{P'\big/ r_\sigma r_\varepsilon + \bar{P}'\big/ \bar{r}_\sigma \bar{r}_\varepsilon}$$

$$= A'\left\{1 + \frac{2\bar{P}'^2}{P'^2 - \bar{P}'^2}\left(\delta_\sigma + \delta_\varepsilon\right)\right\}$$

断面積、検出効率の
e/μ比の差のみが入る。

where

$$A' \equiv \frac{P' - \bar{P}'}{P' + \bar{P}'}, \quad \delta_\sigma \equiv \frac{\bar{r}_\sigma - r_\sigma}{r_\sigma}, \quad \delta_\varepsilon \equiv \frac{\bar{r}_\varepsilon - r_\varepsilon}{r_\varepsilon} \qquad \left(r_\sigma = \sigma_e\big/\sigma_\mu,\ r_\varepsilon = \varepsilon_e\big/\varepsilon_\mu\right)$$

(上線は反ニュートリノを意味する。)

手持ちの技術でどこまでいけるのか？

- 方法、手順
- Neutrino/Anti neutrino ビーム
- 解析(high performance e/p0 separation)
- 擬非対称性補正(スペクトル、断面積、検出効率、物質効果)

CP測定シナリオ設定(このトークでの)

- JHF-SK 1st phaseでν_e app. >3σ発見。
  - → **$\sin^2 2\theta_{13}$>0.009** **(3σ discovery region studied by Obayashi)**
- 2nd phase 5(10)年以内に決着をつける。

  νbarはνの3.4倍走る必要。
  - 従って、ν 1(2)年、νbar3.4(6.8)年、

    計4.4(8.8)年で勝負
- 手持ちの技術でどこまでいけるか？
- BG除去、系統誤差に対する要求

Present Study

- Full beam MC w/ same algorism as K2K and w/ realistic design → neutrino flux
- Event generation w/ SK/K2K code for all neutrino species
- Full detector (SK)MC simulation fully established by >5yrs of SK operation
- High performance electron selection algorism developed for JHF-SK ν_e app. search

Parameters

- OAB2°
- 4MW, 1Mt F.V. ➔ 231x(JHF1)

ν_μ: 1(2)year, ν_μ: 3.4(6.8)year

$\Delta m_{21}=5\text{x}10^{-5}\text{eV}^2$, $\theta_{12}=\pi/8$

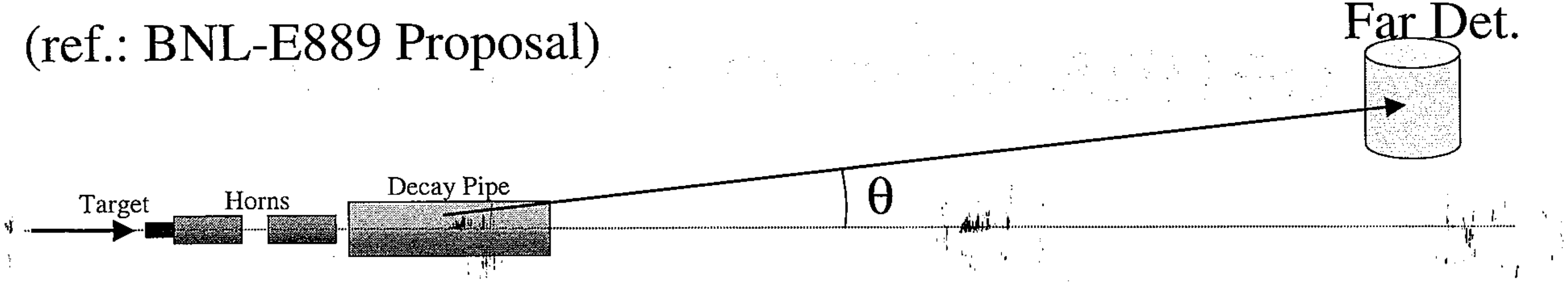
$\Delta m_{32}=\Delta m_{31}=3\text{x}10^{-3}\text{eV}^2$, $\theta_{23}=\pi/4$

$\delta=\pi/4$

unless otherwise stated

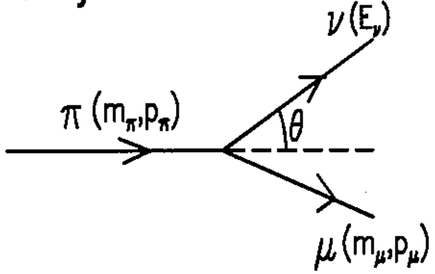
Off Axis Beam (another NBB option)

(ref.: BNL-E889 Proposal)

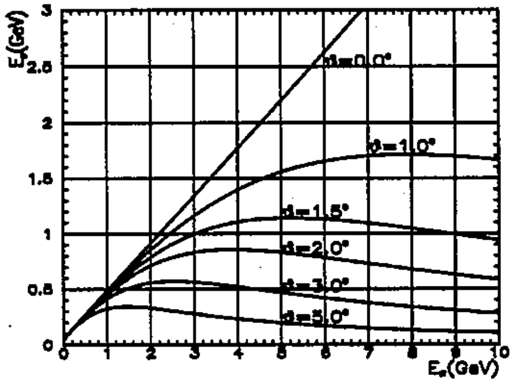


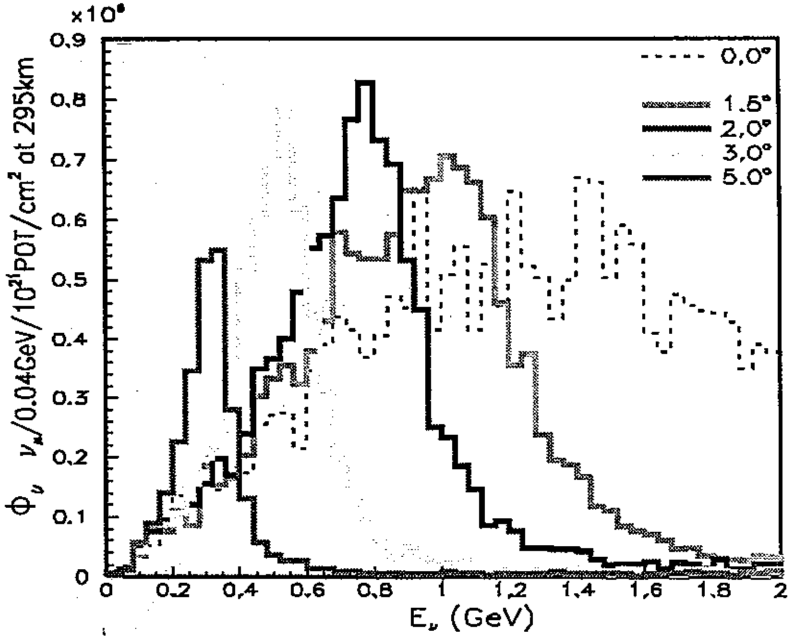
WBB w/ intentionally misaligned beam line from det. axis

Decay Kinematics



$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{2(E_\pi - p_\pi \cos\theta)}$$

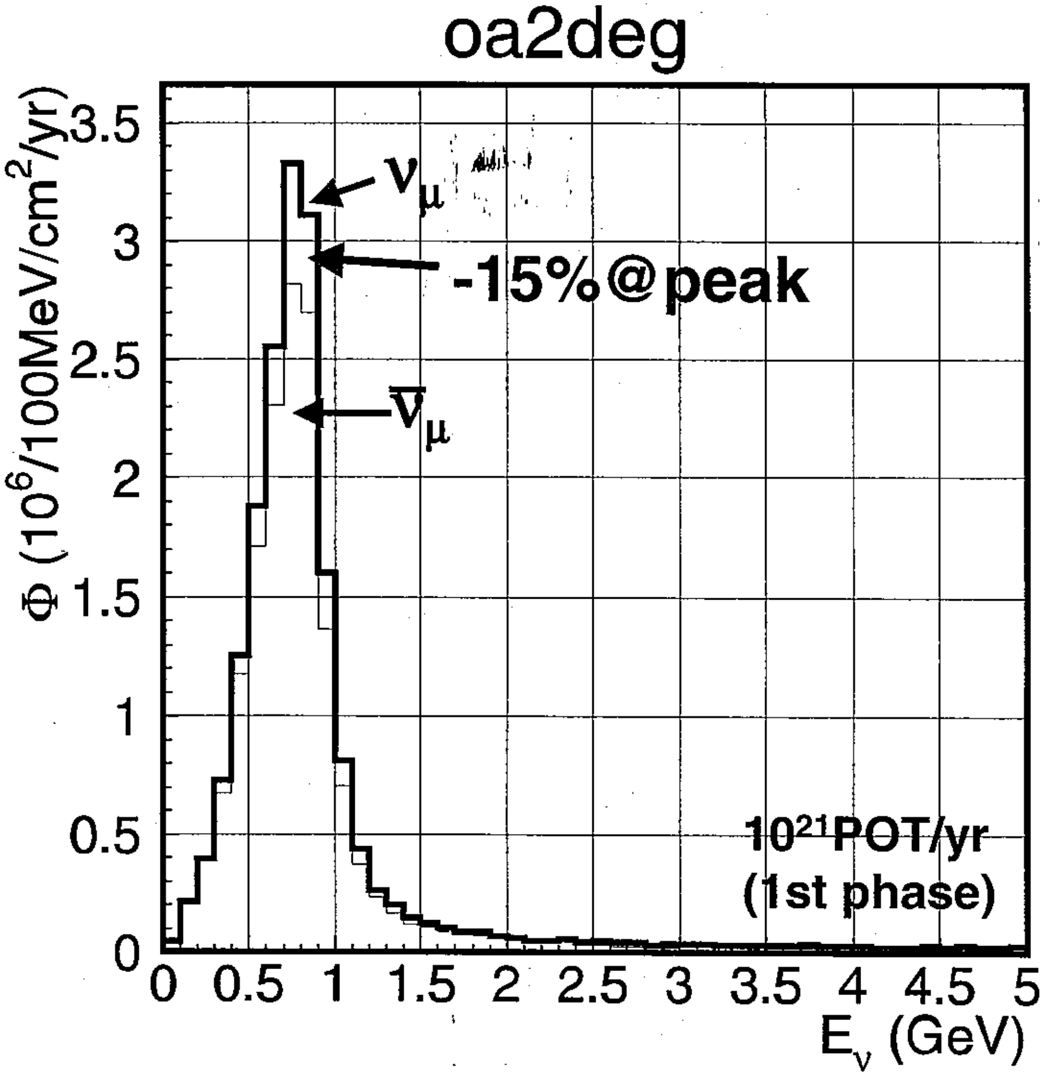




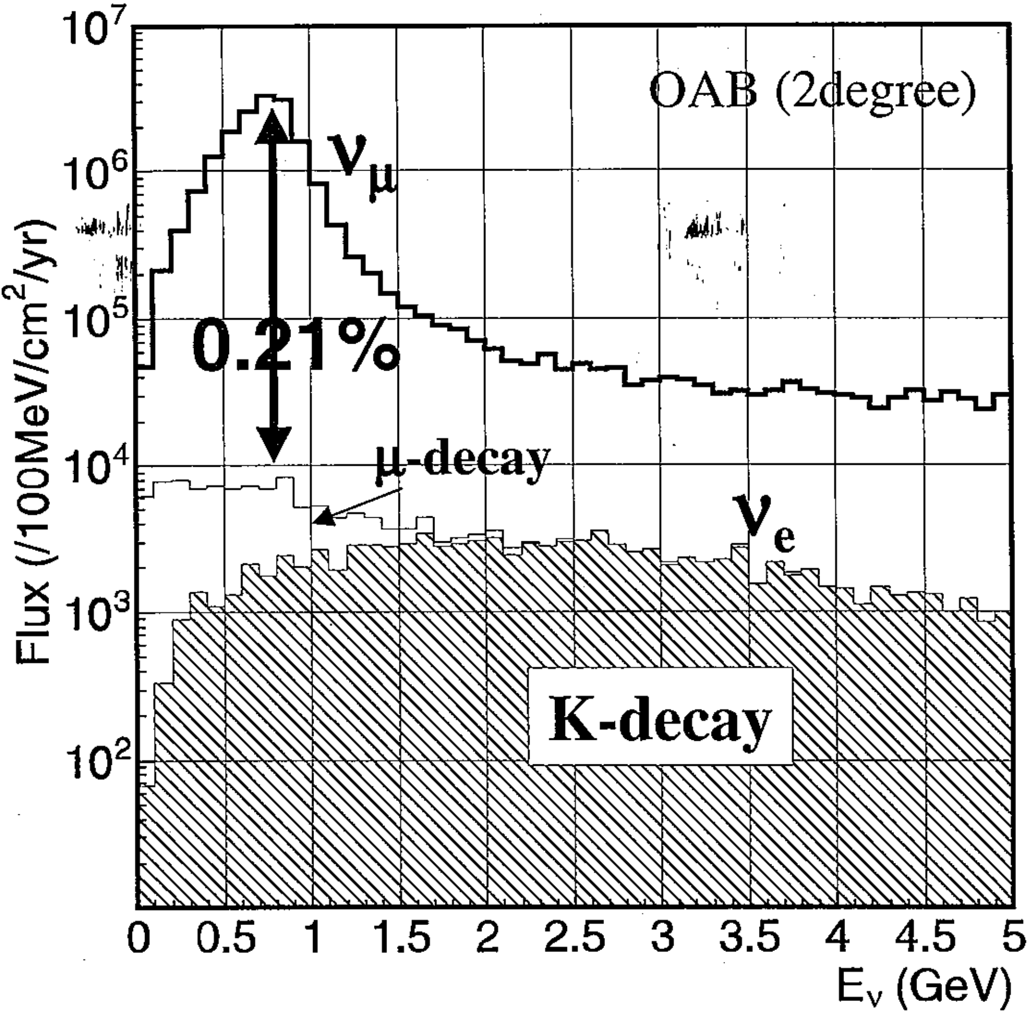
Quasi Monochromatic Beam

$\nu_\mu/\overline{\nu_\mu}$ flux for CPV meas.

Sign flip by just changing horn plarity

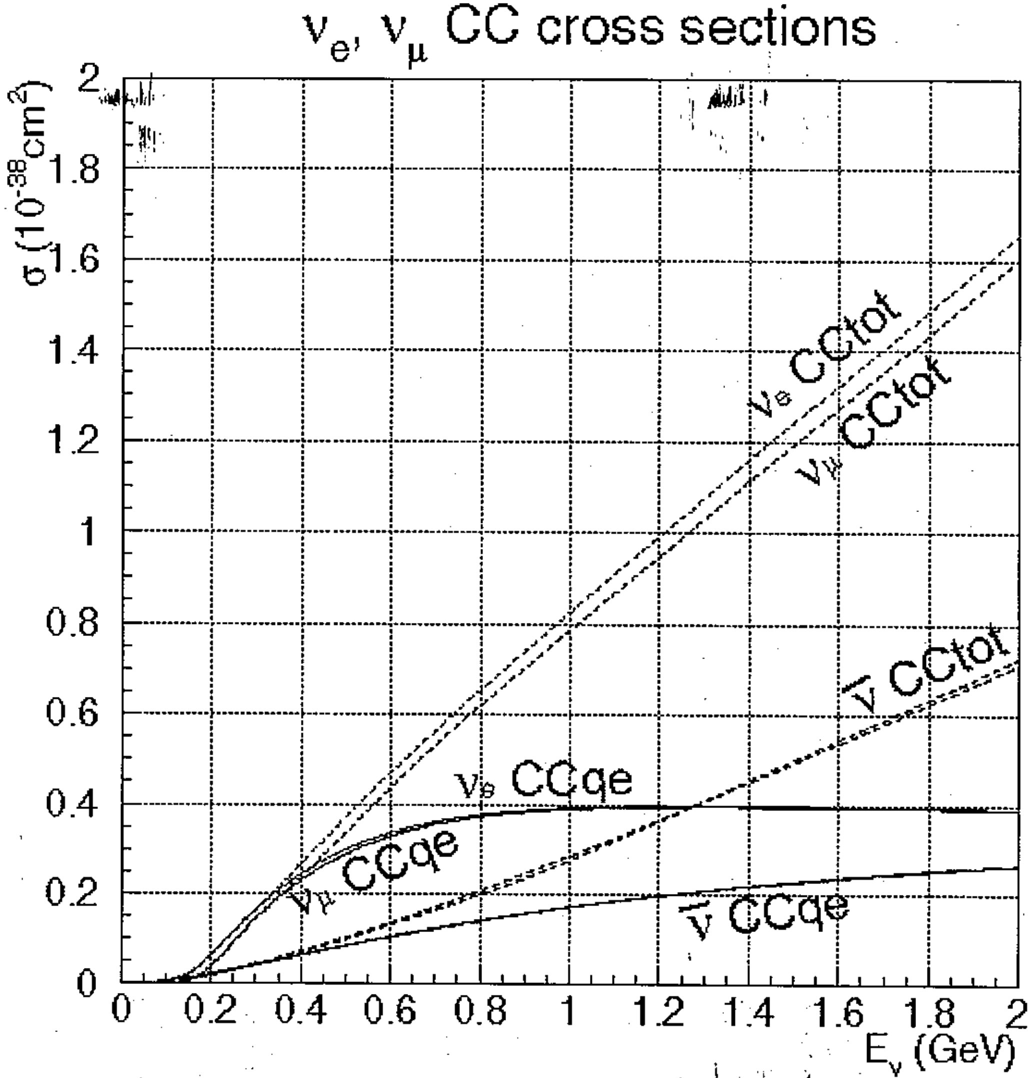


ν_e components



Very small ν_e/ν_μ ratio at ν_μ spectrum peak.

Cross sections



Summary of beam @ SK

0.77MW

ν_μ Beam

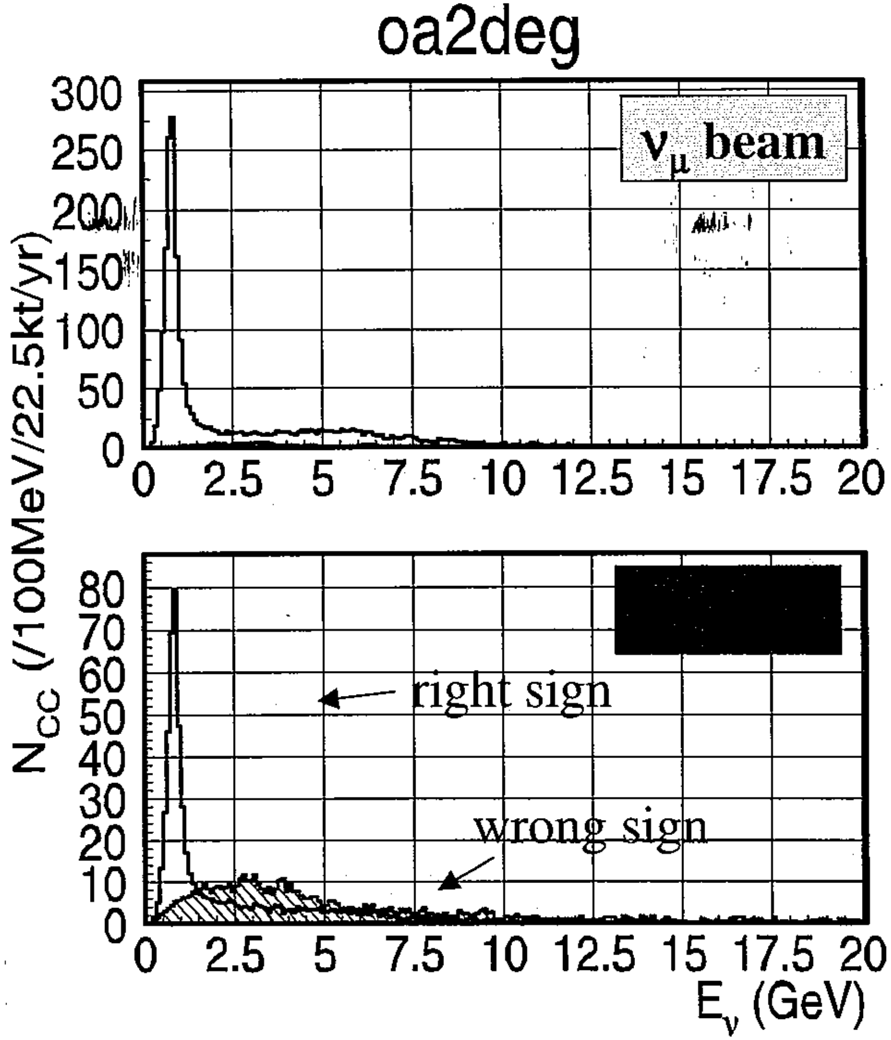
		Flux (/cm²/yr)			# of interactions (/22.5kt/yr)			
Beam	$\langle E_\nu \rangle$	(10^6) ν_μ	(10^4) ν_e	$\nu_e/\nu_\mu(\%)$	ν_μ	ν_e	$\bar{\nu}_\mu$	$\bar{\nu}_e$
WIDE	1.95	25.5	18.8	0.74(0.34)	7000(5200)	78(59)	420(300)	13((9.6)
LE1.5π	0.69	5.3	5.3	1.00(0.39)	510(360)	5.7(4.2)	5.9(4.1)	0.41(0.29)
LE1.8π	0.79	6.5	4.6	0.71(0.19)	740(530)	5.7(4.2)	6.3(4.4)	0.33(0.23)
LE2π	0.86	7.0	5.1	0.73(0.15)	870(620)	6.8(5.0)	6.1(4.3)	0.41(0.29)
LE3π	1.19	8.0	5.2	0.65(0.16)	1400(1000)	9.3(6.9)	6.4(4.5)	0.48(0.34)
OA1°	1.75	37.7	27.5	0.73(0.20)	9400(6900)	120(88)	370(270)	16(12)
OA2°	1.13	19.2	19.2	1.00(0.21)	3100(2200)	60(45)	250(180)	11(7.6)
OA3°	0.77	10.6	12.8	1.21(0.20)	1100(800)	29(22)	96(69)	5.2(3.7)

(@peak) total(CC)

$\bar{\nu}_\mu$ Beam

		Flux			# of interactions			
Beam	$\langle E_{\bar{\nu}} \rangle$	$\bar{\nu}_\mu$	$\bar{\nu}_e$	$\bar{\nu}_e/\bar{\nu}_\mu$	ν_μ	ν_e	$\bar{\nu}_\mu$	$\bar{\nu}_e$
WIDE	1.63	21.6	14.3	0.66(0.21)	1700(1300)	42(32)	2300(1600)	22((16)
LE1.5π	0.66	5.0	3.7	0.74(0.27)	24(17)	1.4(1.0)	160(110)	1.4(0.98)
LE2π	0.83	6.5	4.4	0.68(0.24)	24(17)	1.4(1.0)	280(200)	1.9(1.4)
OA2°	0.96	16.4	14.5	0.88(0.19)	780(590)	28(21)	870(610)	19(14)
OA3°	0.67	9.3	8.8	0.94(0.14)	340(250)	15(11)	310(220)	9.2(6.6)

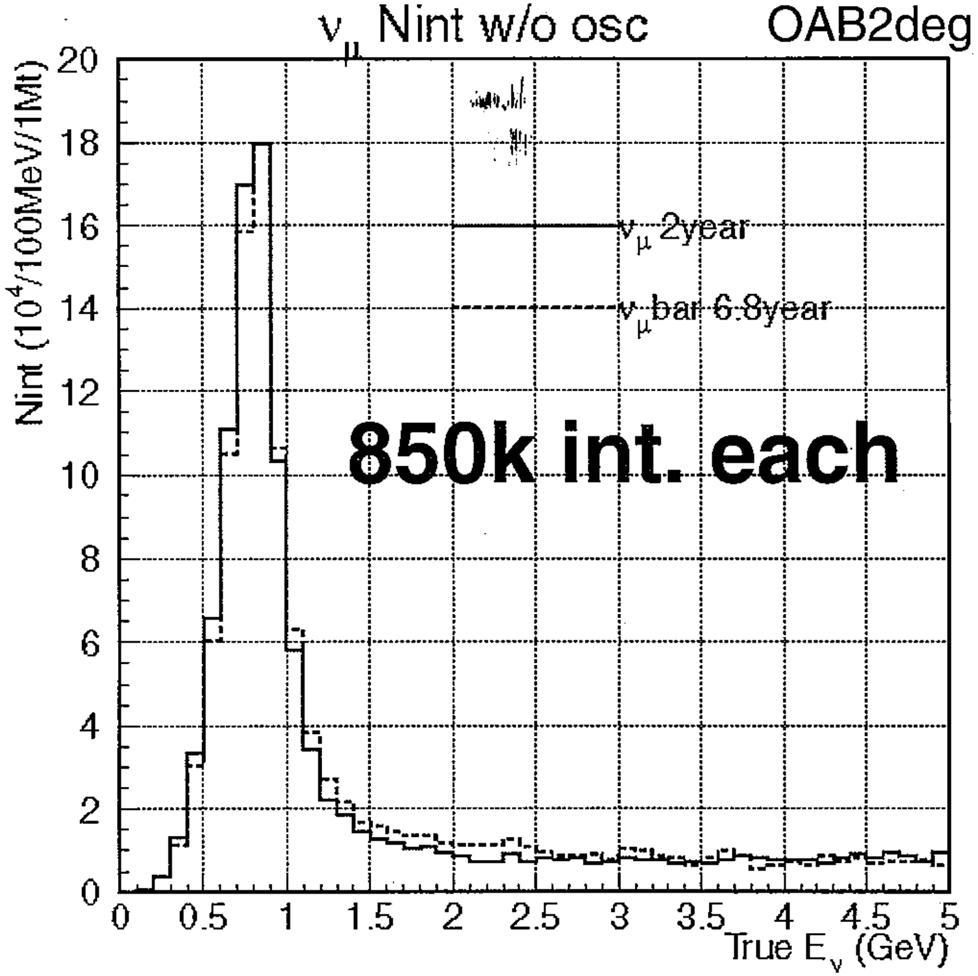
$\nu_\mu/\bar{\nu}_\mu$ # of CC int.



10^{21}pot/yr
(1st phase)

- # of int. for $\bar{\nu}_\mu$ is factor ~3 smaller than ν_μ due to cross section.
- Wrong sign contamination is worse for OAB.

$\nu_\mu/\bar{\nu}_\mu$ normalization by beam



850k int. each

3.4times running time for $\nu_\mu$bar due to small σ.

Slight diff. in spectra causes fake assym→need to correct.

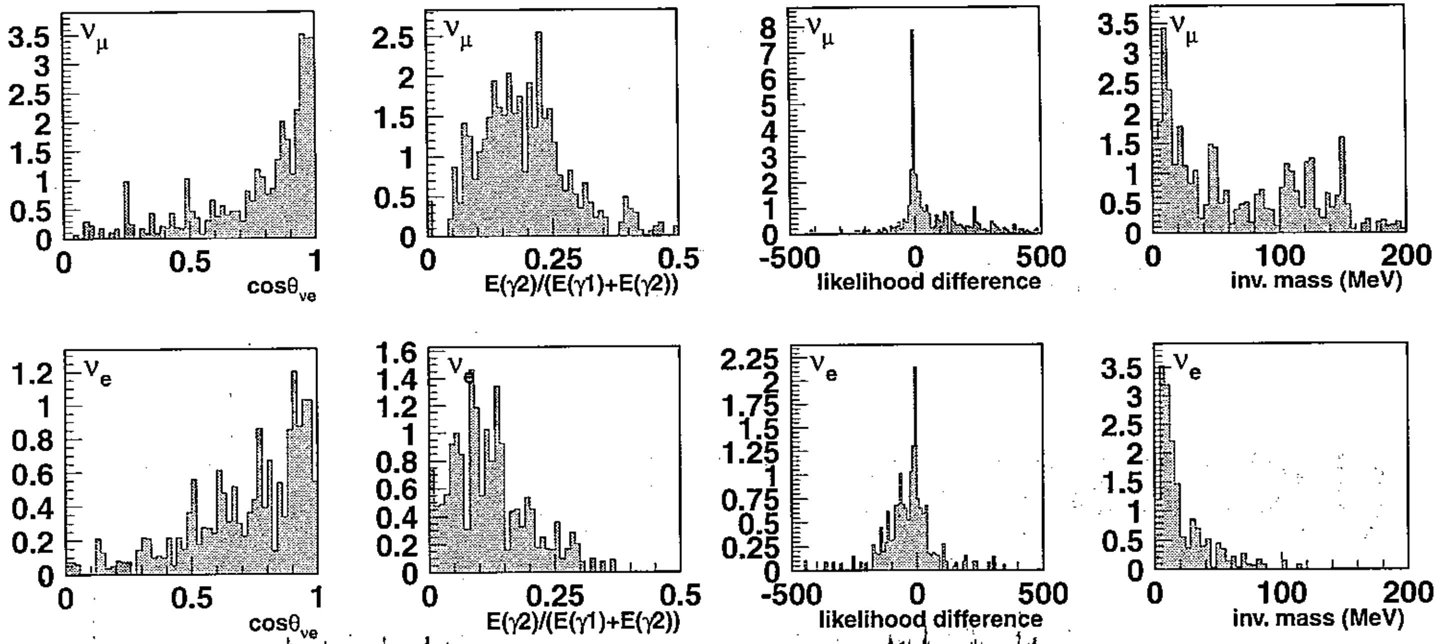
Analysis (Electron Search)

- Fully contained in fiducial volume
- Single ring
- Electromagnetic shower
- no decay electron associated
- Evis > 100MeV (reject NC elastic)
- Tight π^0 rejection
- $0.5<E_{rec}<1.2$GeV

Tight e/π^0 separation

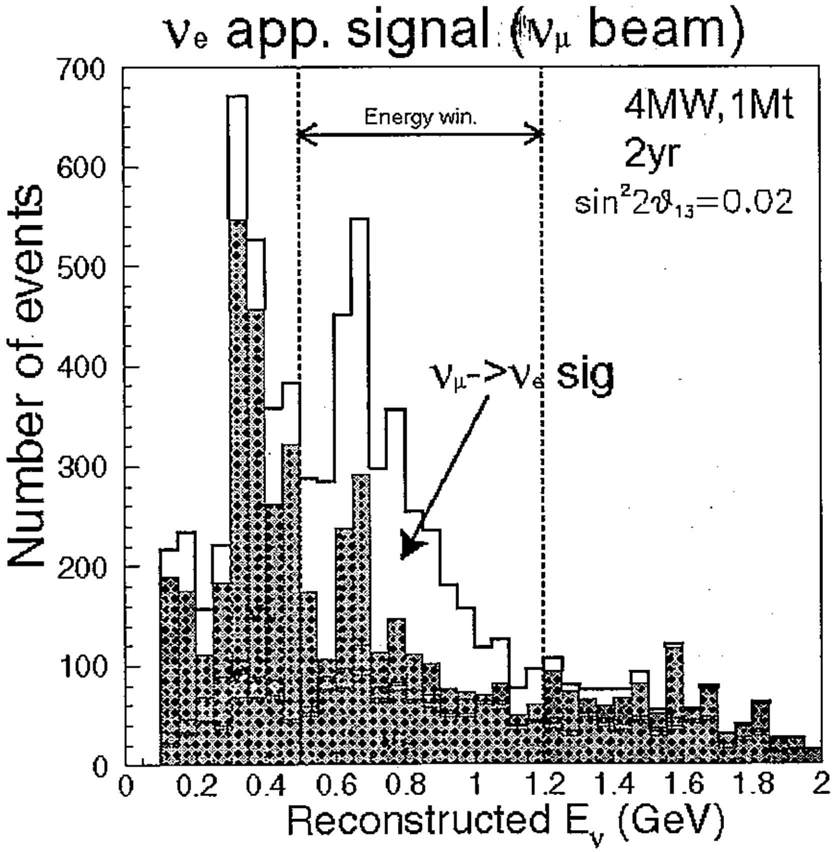
- Shower direction w.r.t. beam
  - $\cos\theta_{\nu e}$: γ from π^0 tend to have a forward peak
- Force to find 2nd ring and…
  - $E(\gamma_2)/E(\gamma_1+\gamma_2)$: Large for BG
  - Likelihood diff. between 1-ring and 2-rings
  - Invariant mass: Small for ν_e

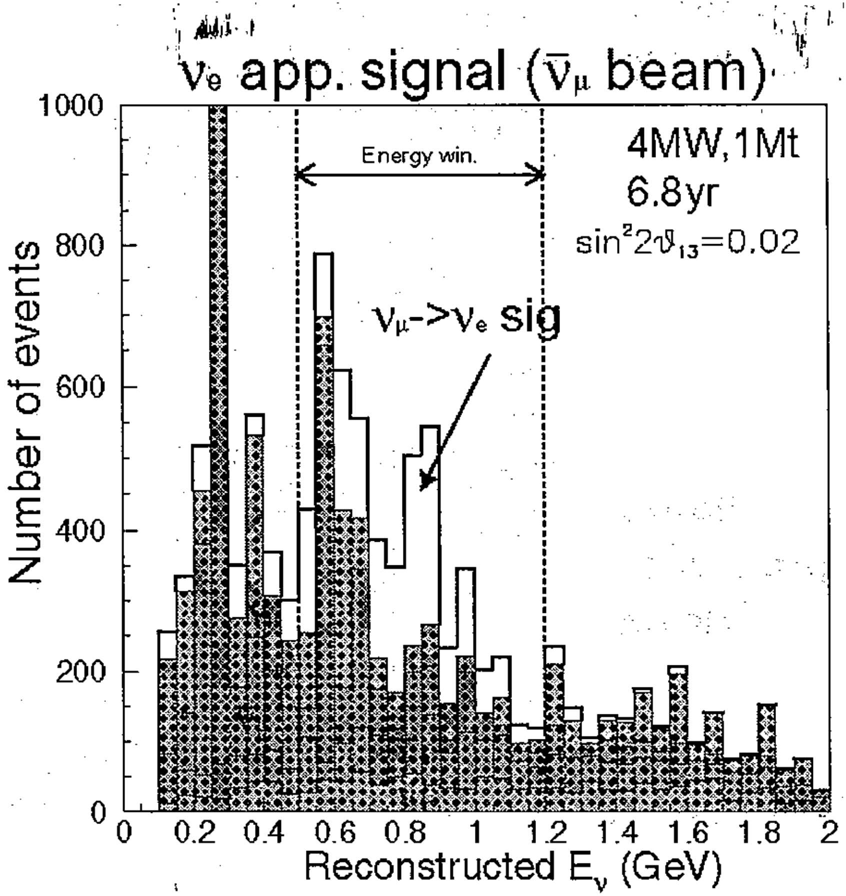
Obayashi



Electron Candidates

(e/π^0 sep. algorism developed for JHF-SK)


ν_e app. signal (ν_μ beam)


ν_e app. signal ($\bar{\nu}_\mu$ beam)

Expected Signal & BG

4MW, 1Mt, ν_μ2yr, ν_μ6.8yr, $\sin^2 2\theta_{13}$=0.1(Chooz)

ν_μ **beam**	Signal	BG				
		Total	νμ	νμbar	νe	νebar
Gen'ed in FV w/ osc	40k		878k	99k	28k	4.7k
Selected	8893	1691	686	122	834	49
Efficiency	22%		0.08%	0.12%	3.00%	1.04%
QE	8404	w/π0	613	96	33	3.4
from En>1.2GeV			355	115	196	20

νμ BG: 88%π^0, 58%HE

wrong sign cont. small

$\bar{\nu}_\mu$ **beam**	Signal	BG				
		Total	νμ	νμbar	νe	νebar
Gen'ed in FV w/ osc	40k		1079k	830k	44k	30k
Selected	9272	3572	799	1316	594	862
Efficiency	23%		0.07%	0.16%	1.35%	2.89%
QE	8228	w/π0	714	1112	50	28
from En>1.2GeV			734	682	210	203

νμ BG: 86%π^0, 67%HE

All src. compara.

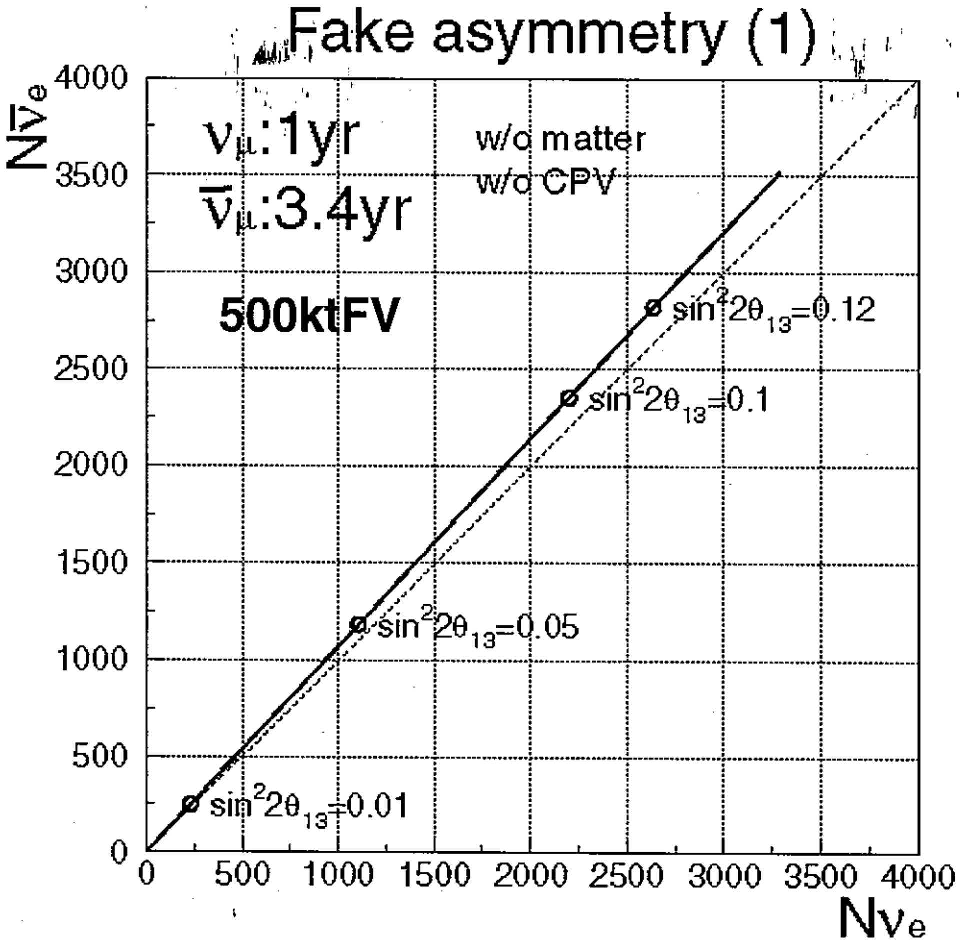
Signal: ~90% CCQE

Fake asymmetry (FA) (1)

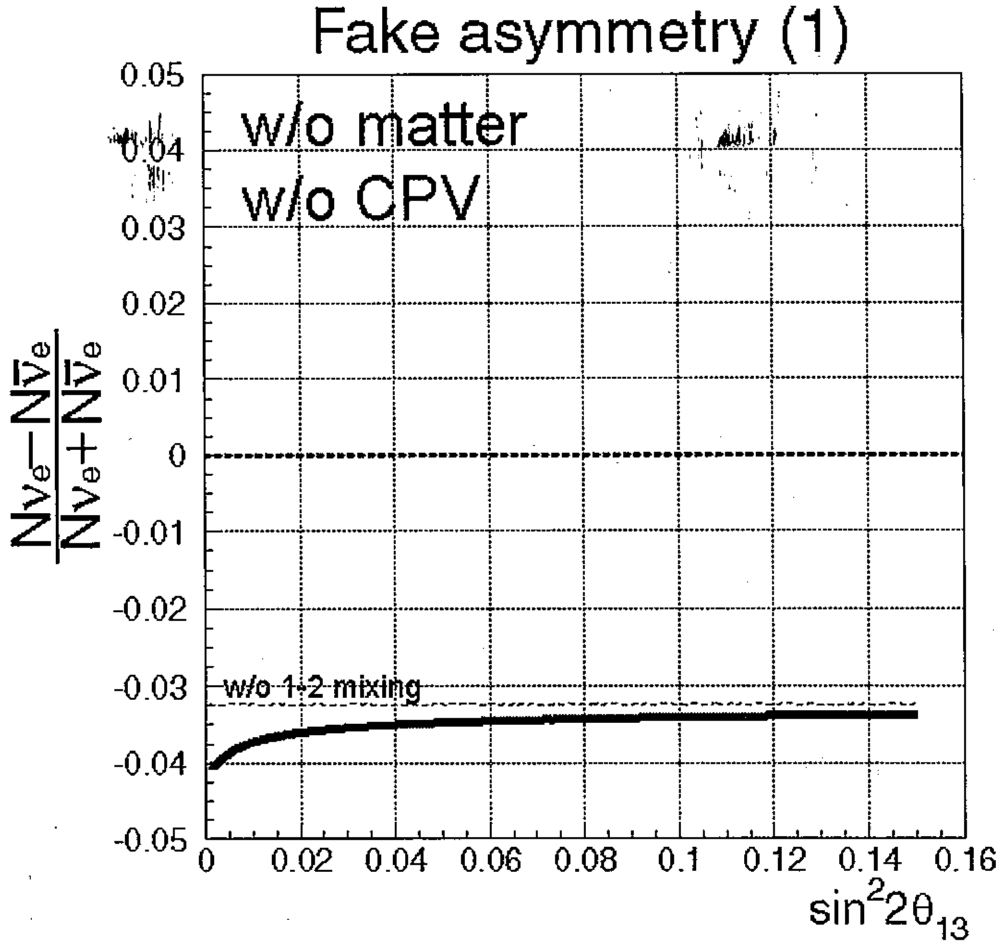
- spectrum $\Phi(E)$
- cross section

  $\sigma_e/\sigma_\mu - \sigma_{\bar{e}}/\sigma_{\bar{\mu}}$
- detection efficiency

  $\varepsilon_e/\varepsilon_\mu - \varepsilon_{\bar{e}}/\varepsilon_{\bar{\mu}}$

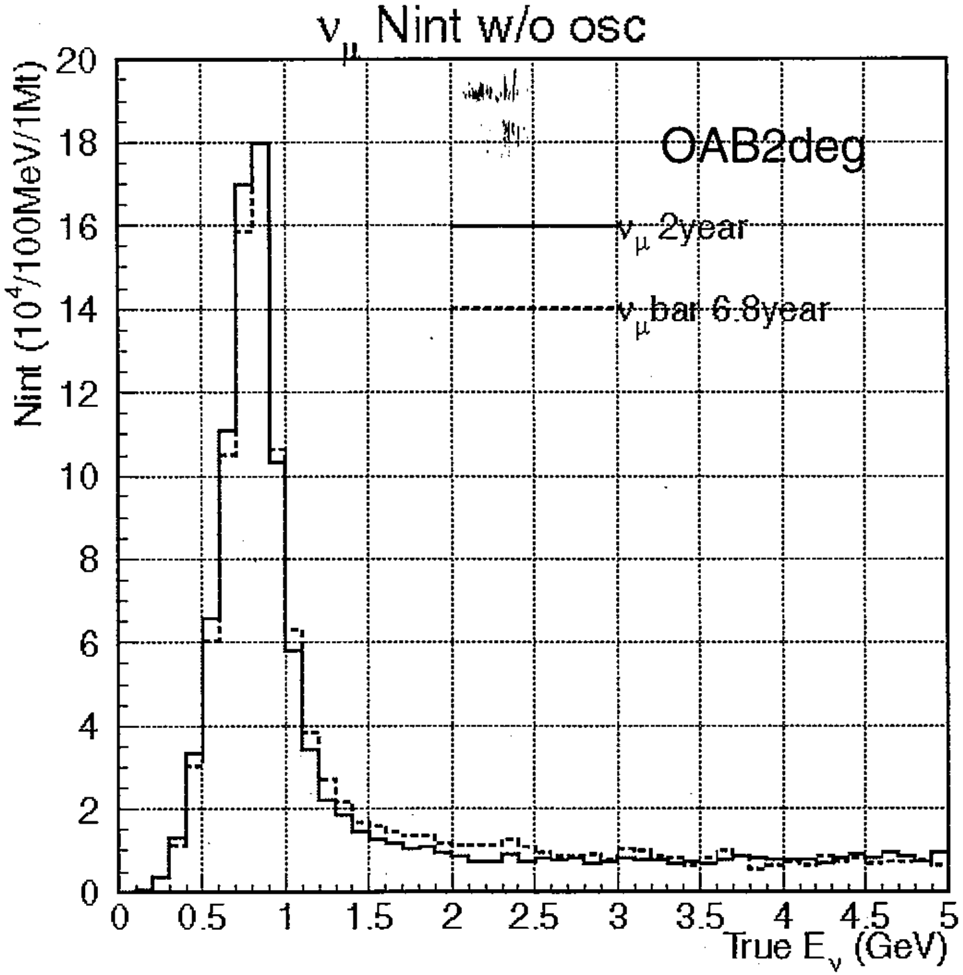


Fake asymmetry (1)



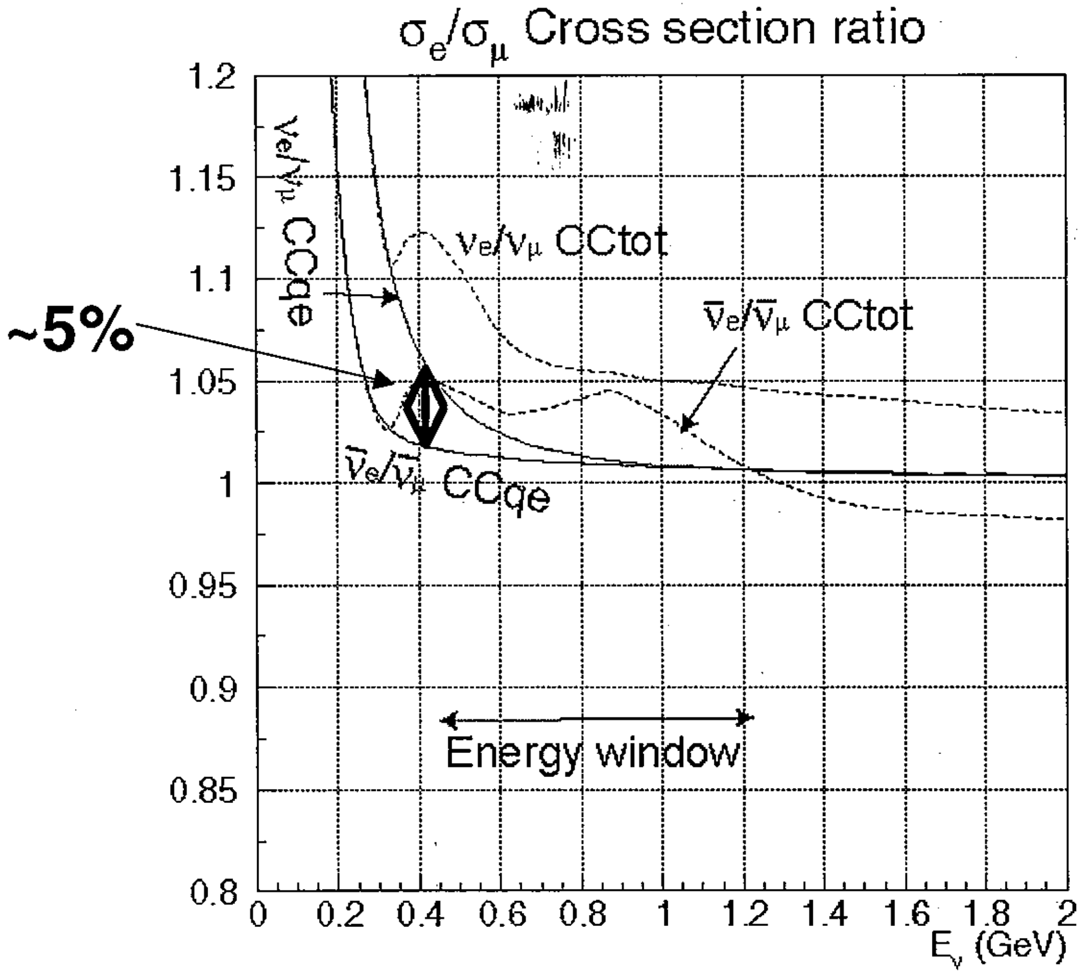
$$A_{fake1} \sim -0.04$$

Spectrum Difference



**In real experiment,
FD measures spectrum
and make correction.**

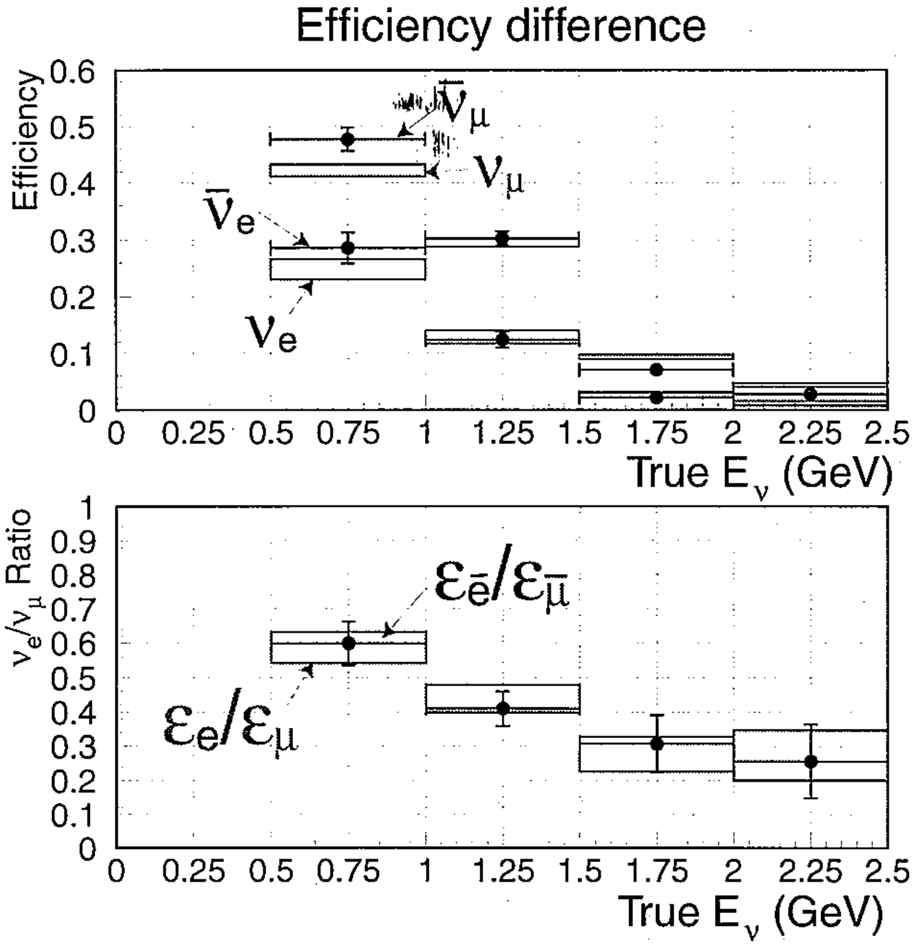
Cross section difference



CCqe ratio diff
1~5% @ energy window

Quick rise in low energy side → need detailed info.
➔ cross section measurement? (νfact?)

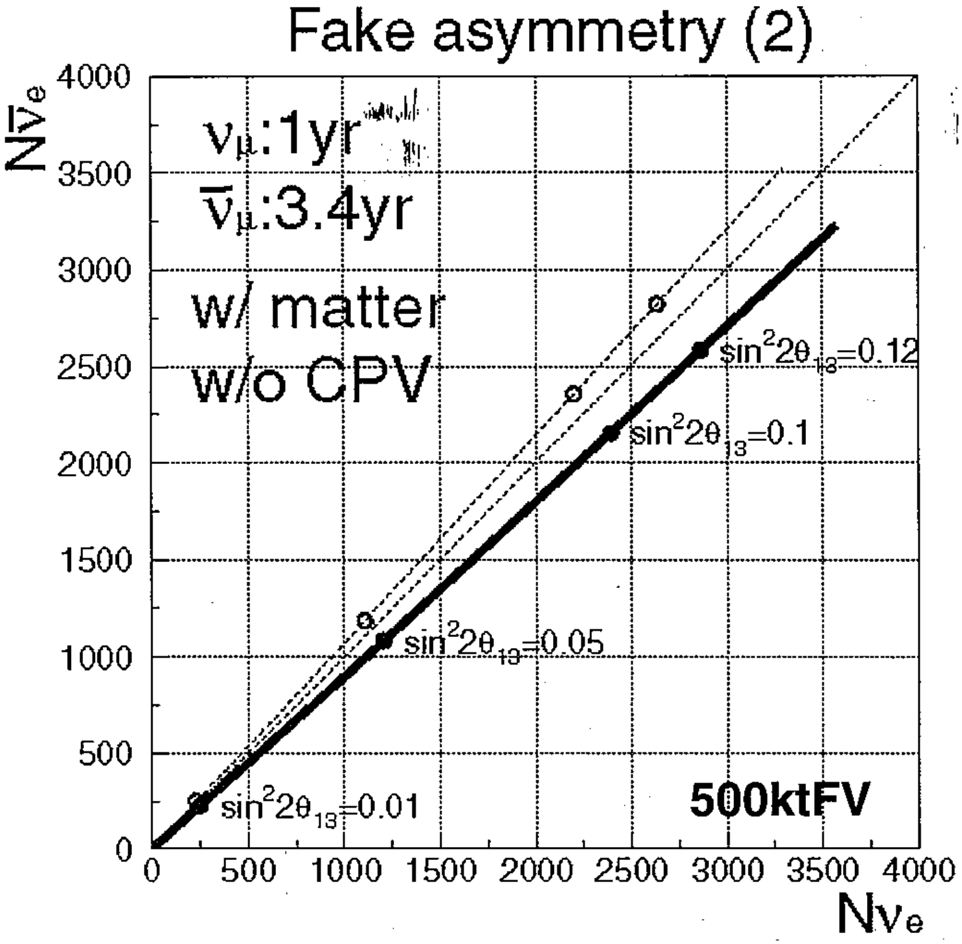
Efficiency difference



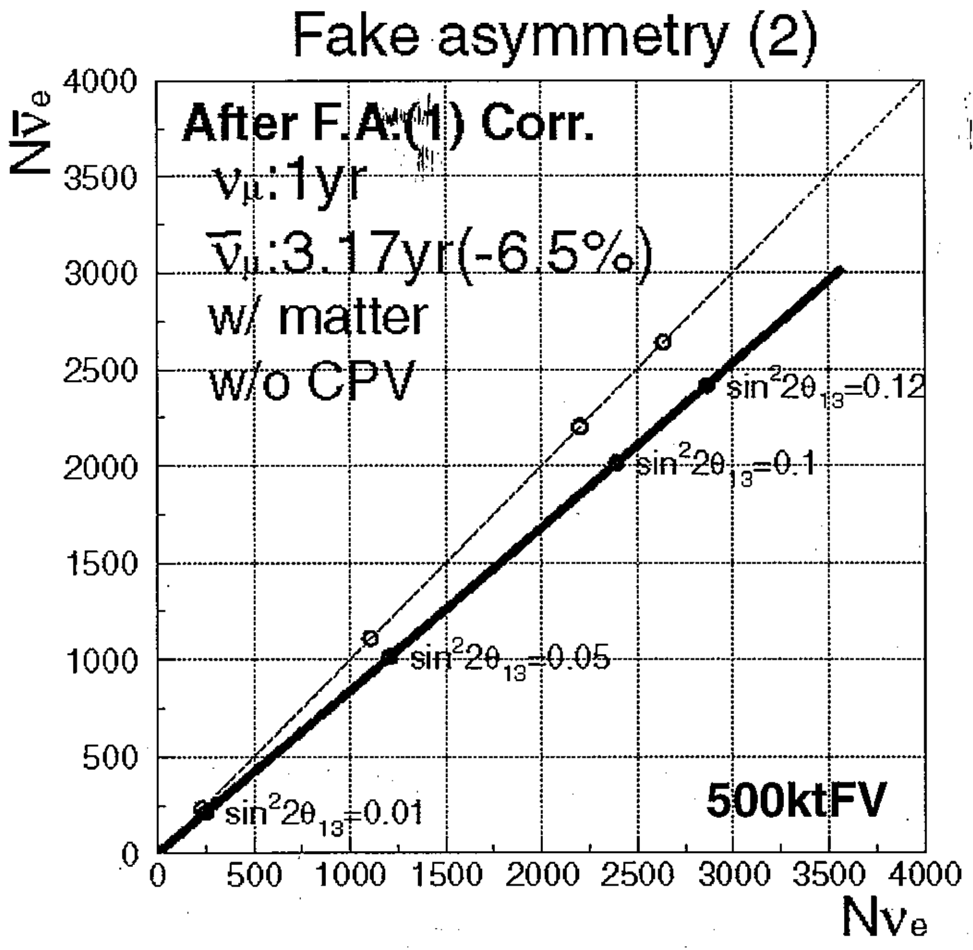
"MC" says
No significant diff.
in efficiency ratio
within MC stat.

But,,,,

Fake asymmetry (2): matter

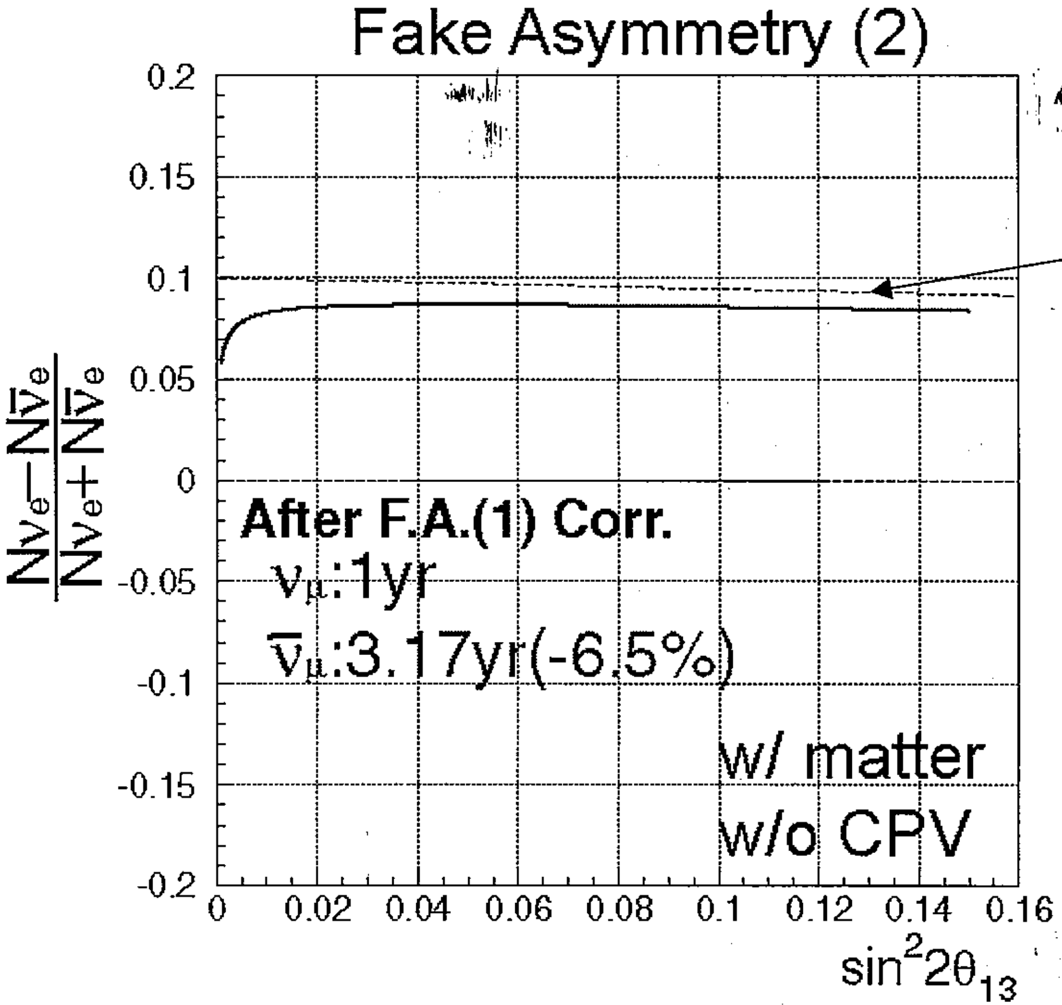


Fake asymmetry (2): FA(1)corr.



Correct FA(1) by adjusting only normalization (running time) by -6.5%

Fake Asymmetry (2): matter



$$\theta_{12} = 0, \quad \Delta m_{32} = \Delta m_{31}$$

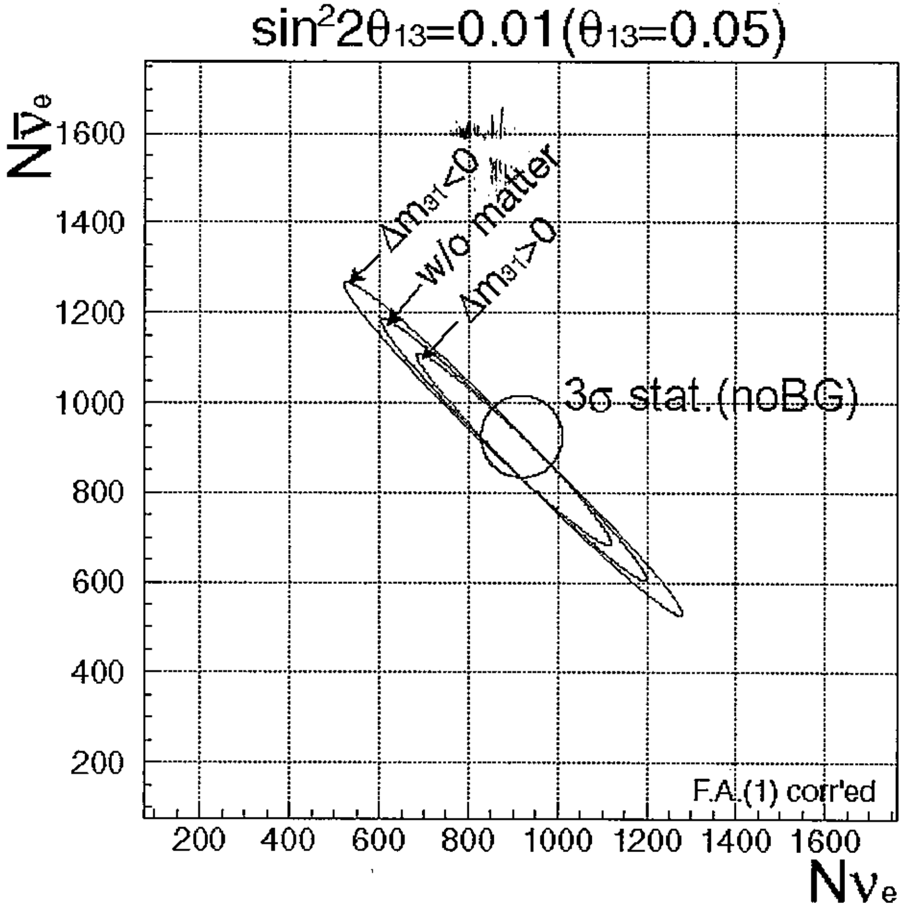
$$\Rightarrow A = 2(a/\Delta m_{31}) \cos 2\theta_{13}$$

$$\approx 0.1(1 - 2\theta_{13}^2)$$

mild function on osc.param.

- 10% level correction
- Effect from θ_{12}: 2nd order

CP measurement

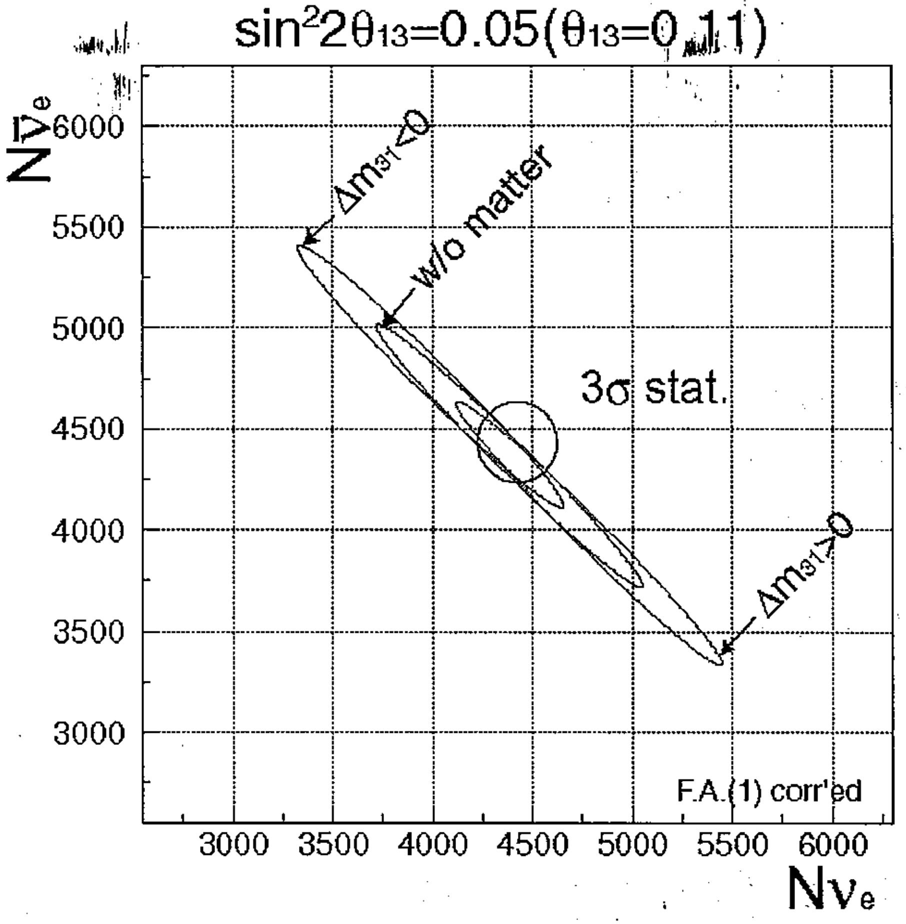


Matter effect is small.

CPV could be established w/o precise knowledge on matter effect.

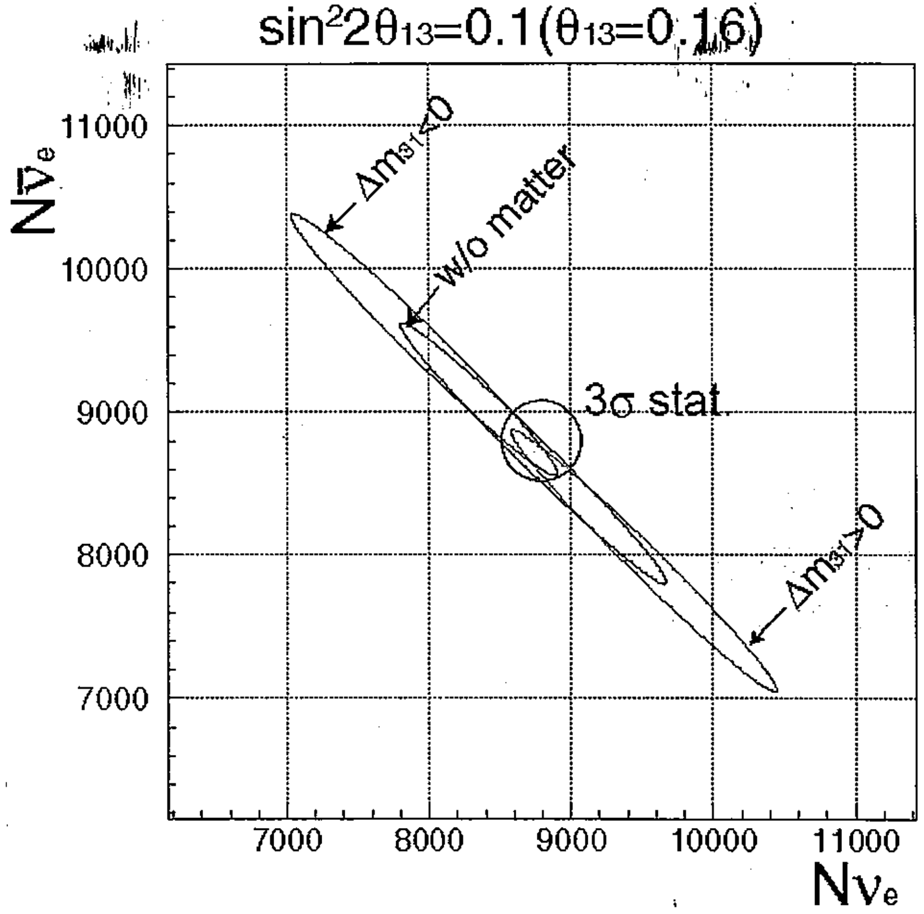
4MW
1Mt
ν2yr
$\bar{\nu}$6.8yr

CP measurement (2)



4MW
1Mt
ν2yr
$\bar{\nu}$6.8yr

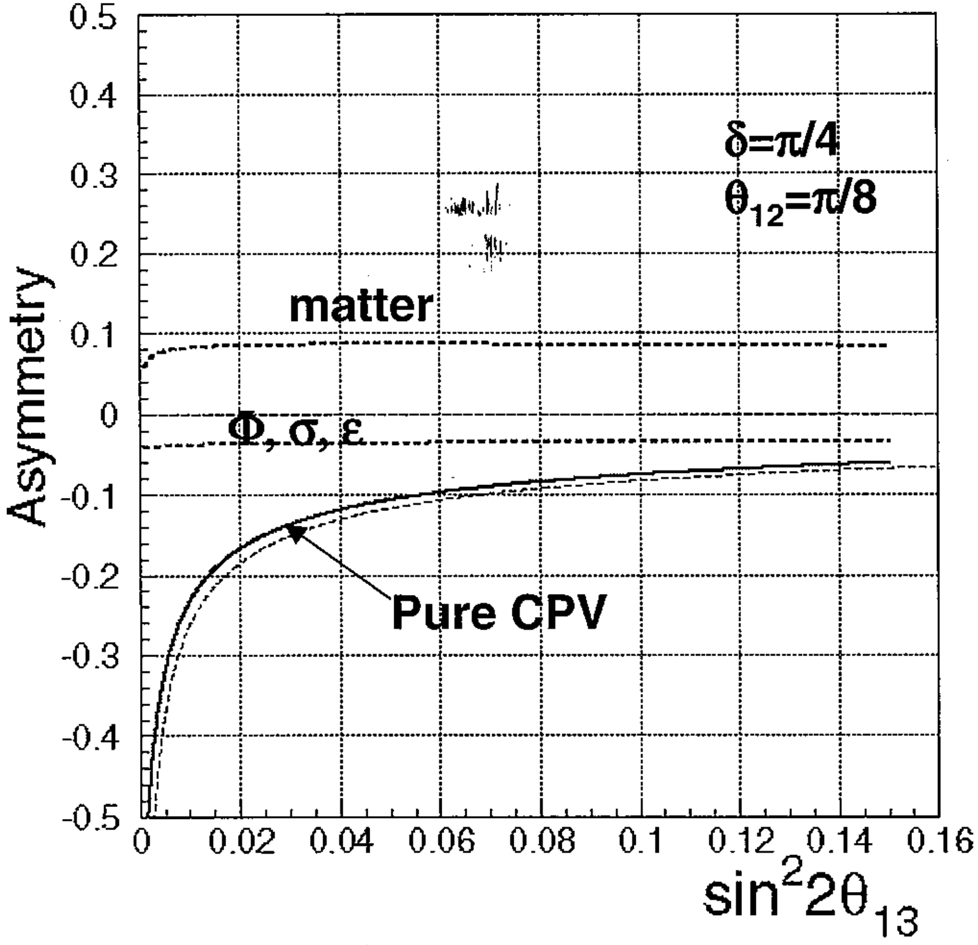
CP measurement (3)



4MW
1Mt
ν2yr
$\bar{\nu}$6.8yr

At large θ_{13}, matter effect cannot be neglected.

CP asymmetry



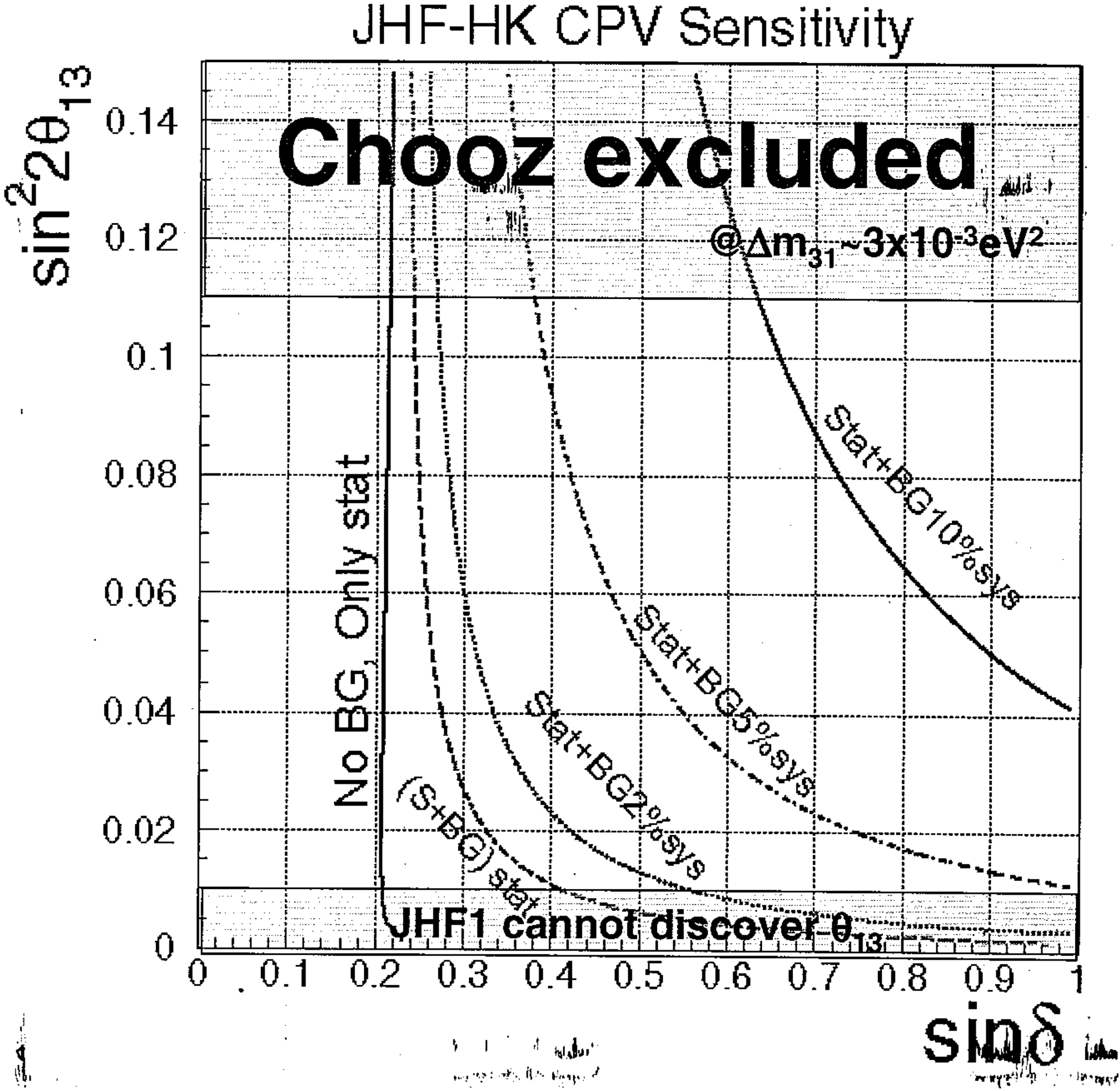
Both correction need to be estimated at ~10% level
→ΔA<0.01

Φ,σ,ε cor.

$$\mathbf{A_{CP} \sim A_{obs} - 0.04 + 0.1}$$

matter corr.

Sensitivity



BG sys 2%のとき

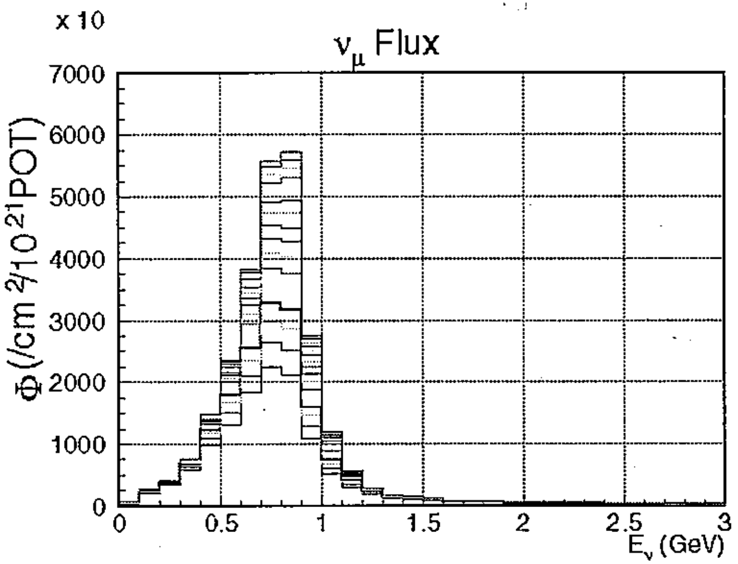
$\sin^2 2\theta_{13}=0.01$
→$\sin\delta>0.55$
(33deg)

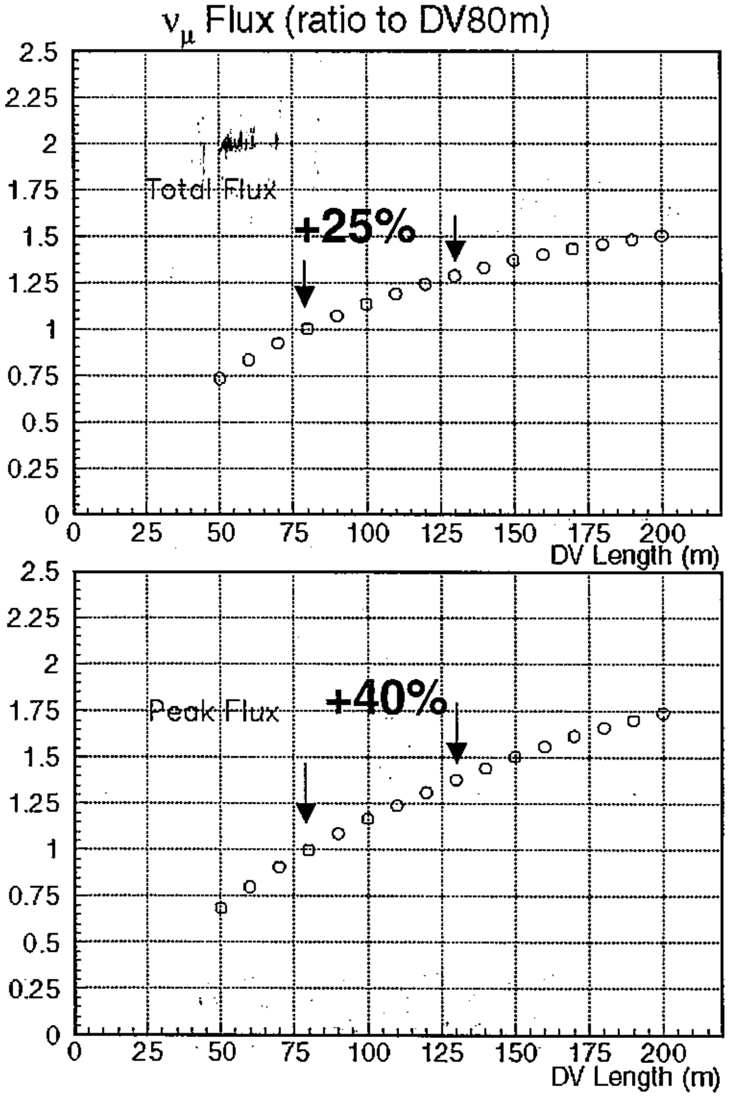
large $\sin^2 2\theta_{13}$
→$\sin\delta>0.25$
(14deg)

Possible Improvement

- BG reduction
  - Optimize beam line➔ reduce HE tail factor ~2?
  - Refine analysis ➔ factor < 2?
  - Improve HK hardware…
- BG estimation
- Flux estimation

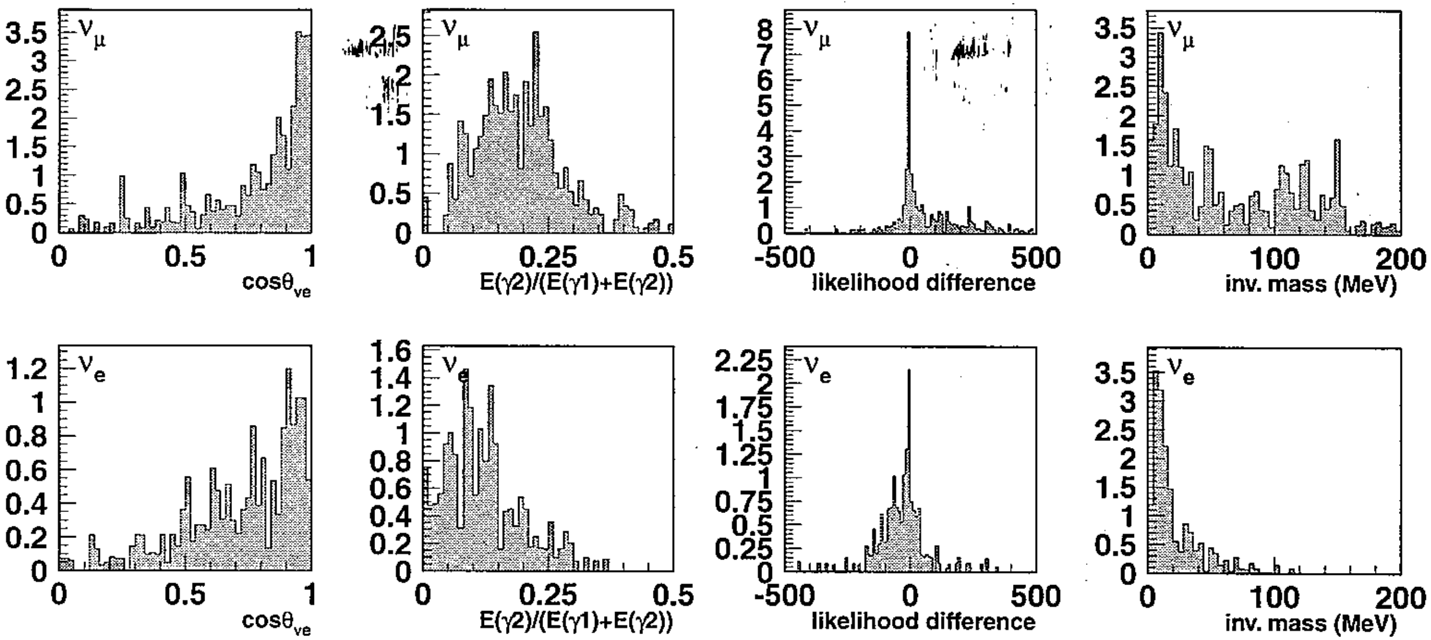
Beam improvement: decay pipe len





Improve statistics
HE tail -10% relative

Possible improvement



Define likelihood➔ improve factor 2?

まとめ

- JHF-HKでのCPV測定の可能性を調べた。
- 4MW, 1Mt FV ν_{μ}2yr, ν_{μ}bar 6.8yr
  - →それぞれ~850k int.(w/o osc)
- **現在の技術**で到達可能範囲
  - **sin22q13=0.01→sind>0.55 (33deg)**
  - **large $\sin^2 2\theta_{13}$→$\sin\delta$>0.25 (14deg)**
- 感度向上のための更なる努力が必要。
  - ハード、ソフト