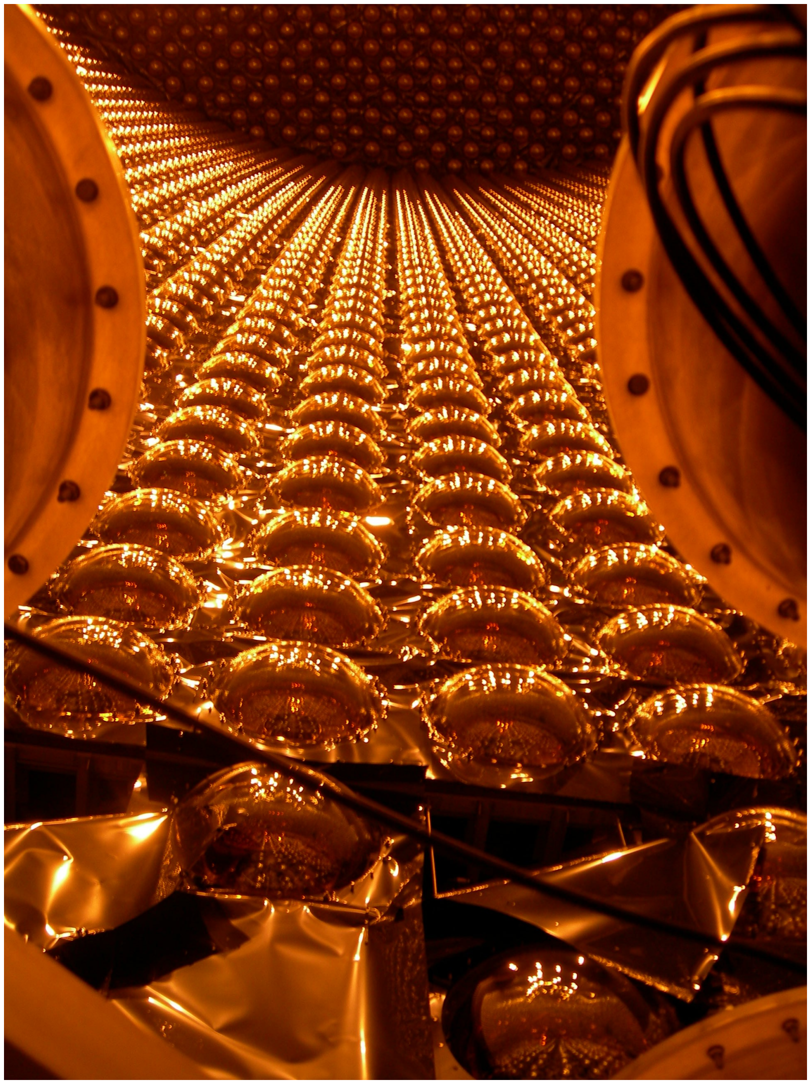


The T2KK project
-
Off-axis sensitivity

Fanny Dufour, Boston University

Outline

- What is T2KK?
- What kind of physics can we do?
- Off-axis beam
- Experimental challenge
  $\rightarrow e/\pi^0$ separation
- Likelihood approach
- χ^2study
- Results

The T2KK project

In neutrino oscillations experiments the baseline L and the neutrino energy E are 2 key parameters.

$P(\nu_\mu \rightarrow \nu_e) \sim \text{Big Mess} * \text{Sin}^2(\Delta m^2 L/4E)$

T2K:

Shoot neutrinos from Tokai to Super-K (295km)

Physics goal: measure θ_{13}

T2KK:

Not all neutrinos from Tokai will stop at Super-K

Let's try to detect them in Korea

(~1000km)

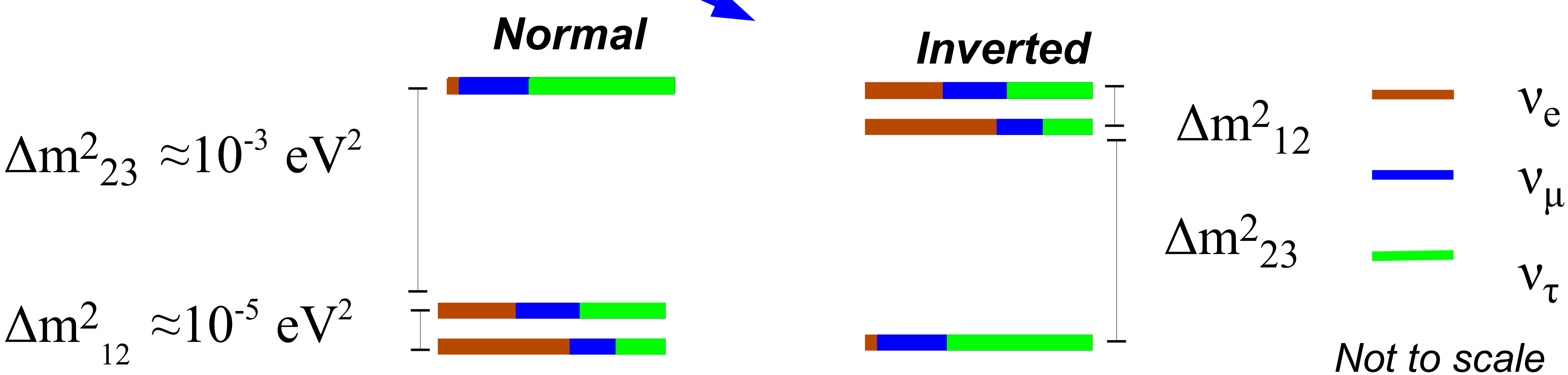
What physics?

CP violation

C: charge conjugation

P: parity

Mass hierarchy



Off-axis beam: why?

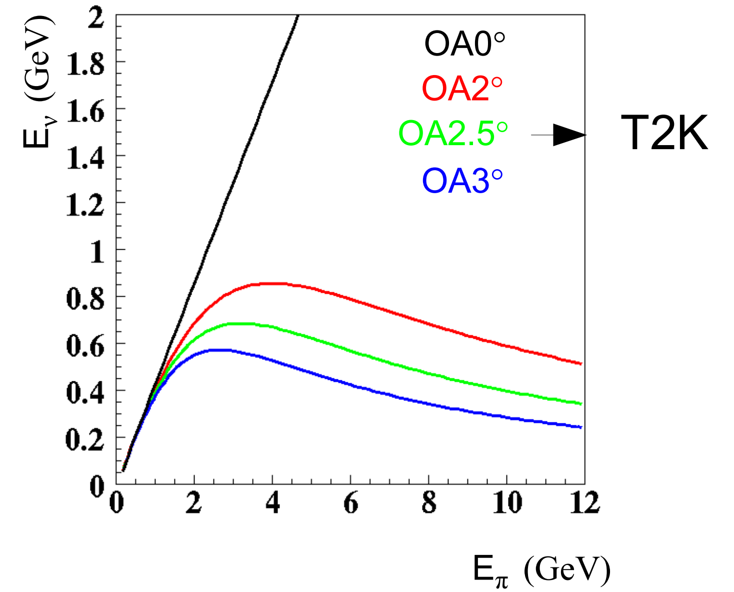
- The energy of the outgoing neutrino is:

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

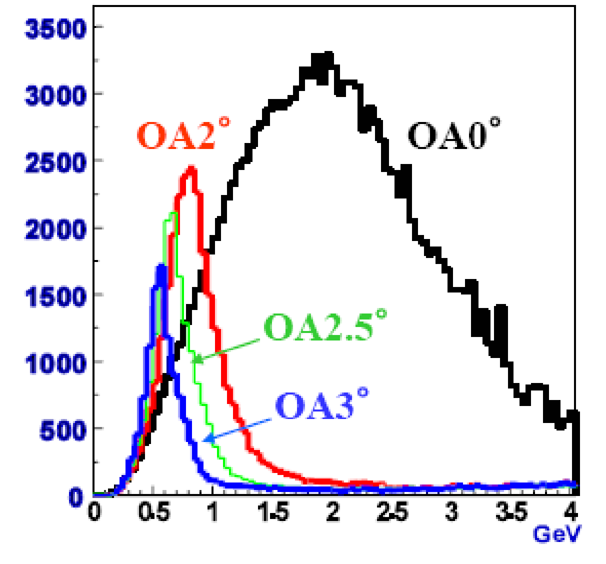
- At off-axis angle of θ, E_ν presents a maximum

- Big off-axis angle
  → narrow energy spectrum

- Small off-axis angle
  → wide energy spectrum



E_ν as a function of E_π



Neutrino energy spectrum

Off-axis physics

Depending on which off-axis angle we choose, we have access to different area of the oscillation probability curve.

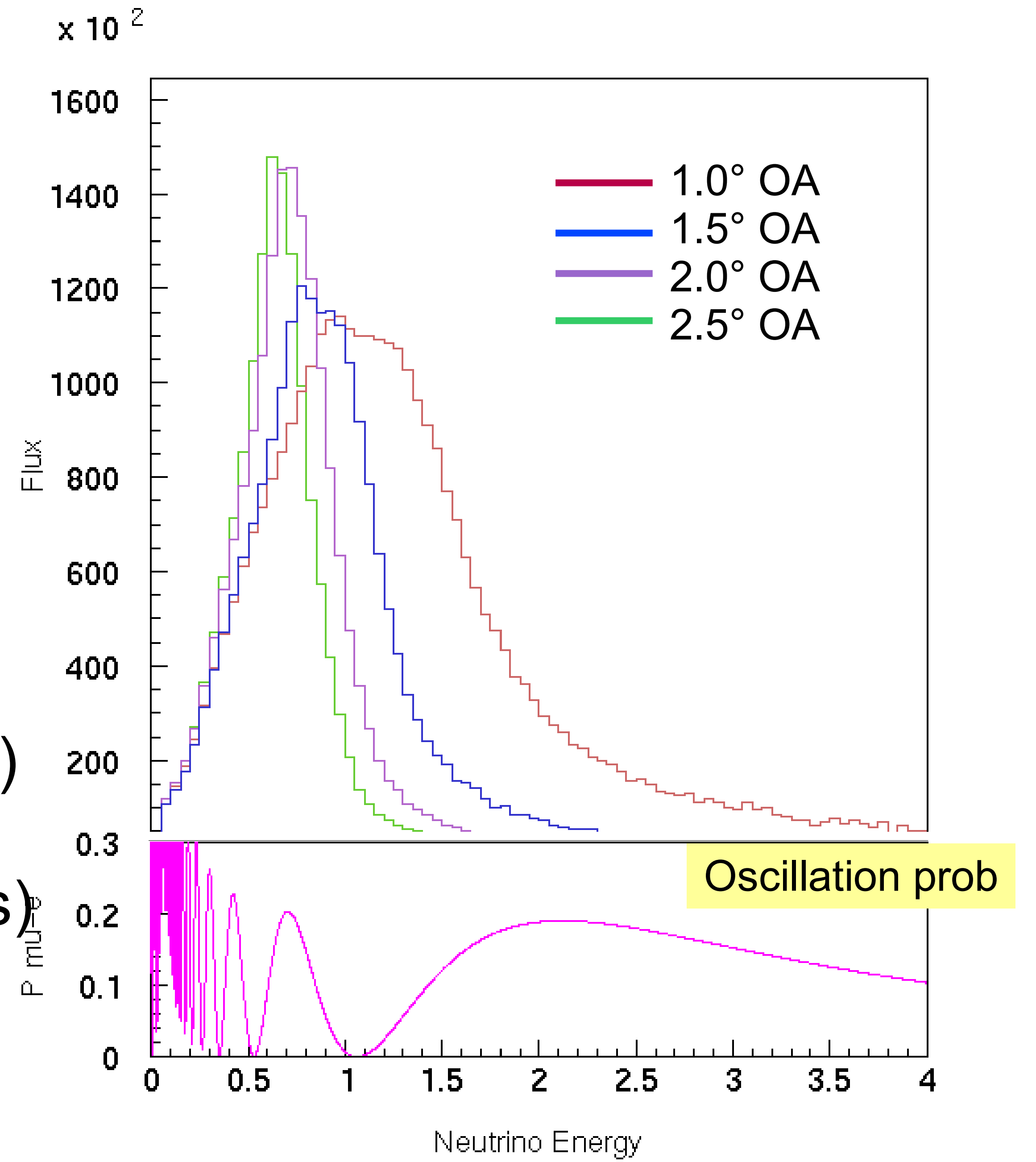
Wide spectrum:

pros: more statistics
scan wider range of osc. prob. (1^{st} & 2^{nd} max)

cons: more NC (i.e. → π^0's) background

Narrow spectrum:

the opposite!



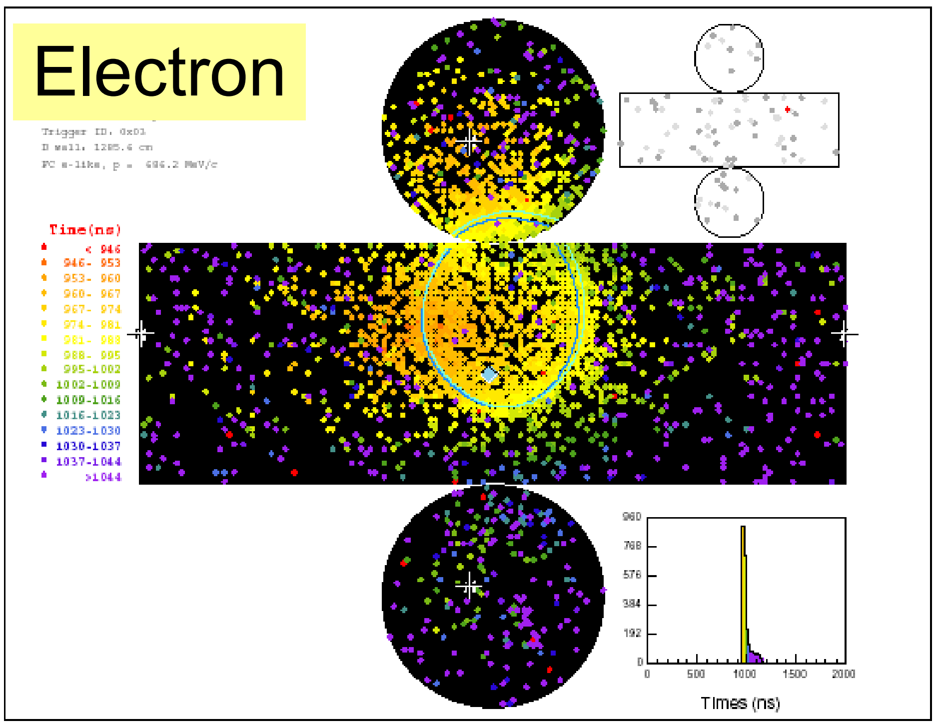
e/π^0 separation

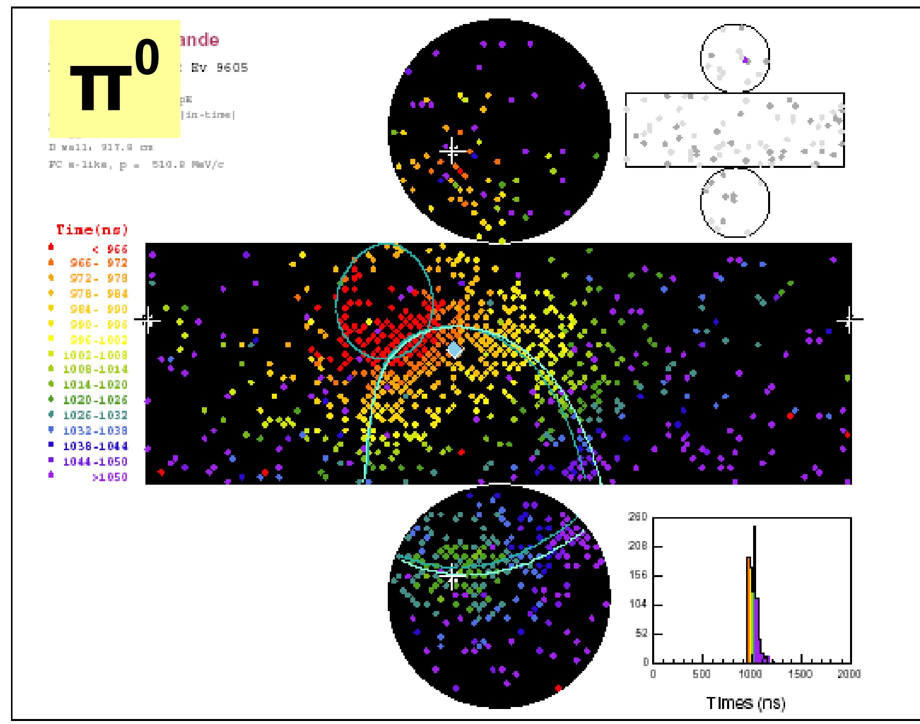
Electrons and π^0 can be very similar in a water Cherenkov detector.

e$\rightarrow \gamma \rightarrow$ more e and γ (EM shower): one fuzzy ring

pi0 $\rightarrow \gamma\gamma$: each γ gives an EM shower: two fuzzy rings

BUT if one initial photon is missed, π^0 looks like electron.





Likelihood

Define a set of 8 variables which are different for electrons and π^0.

Use part of the MC to create template distributions of each variable for background and signal events

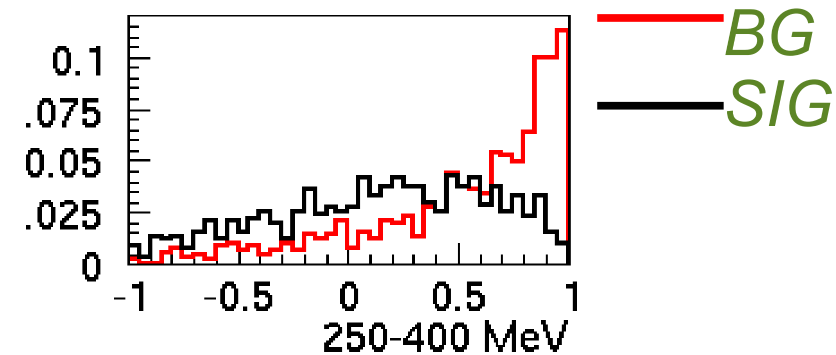
Using the rest of the MC, assign likelihood value (sig & bckg) for each variable.

Multiply each likelihood value (sig & bckg) and take the log

Take the difference of L_{sig} and L_{bckg}

If L > 0 keep the event.

For example: $Cos\theta_{\nu e}$



For new event, if $cos\theta_{\nu e}=0.9$

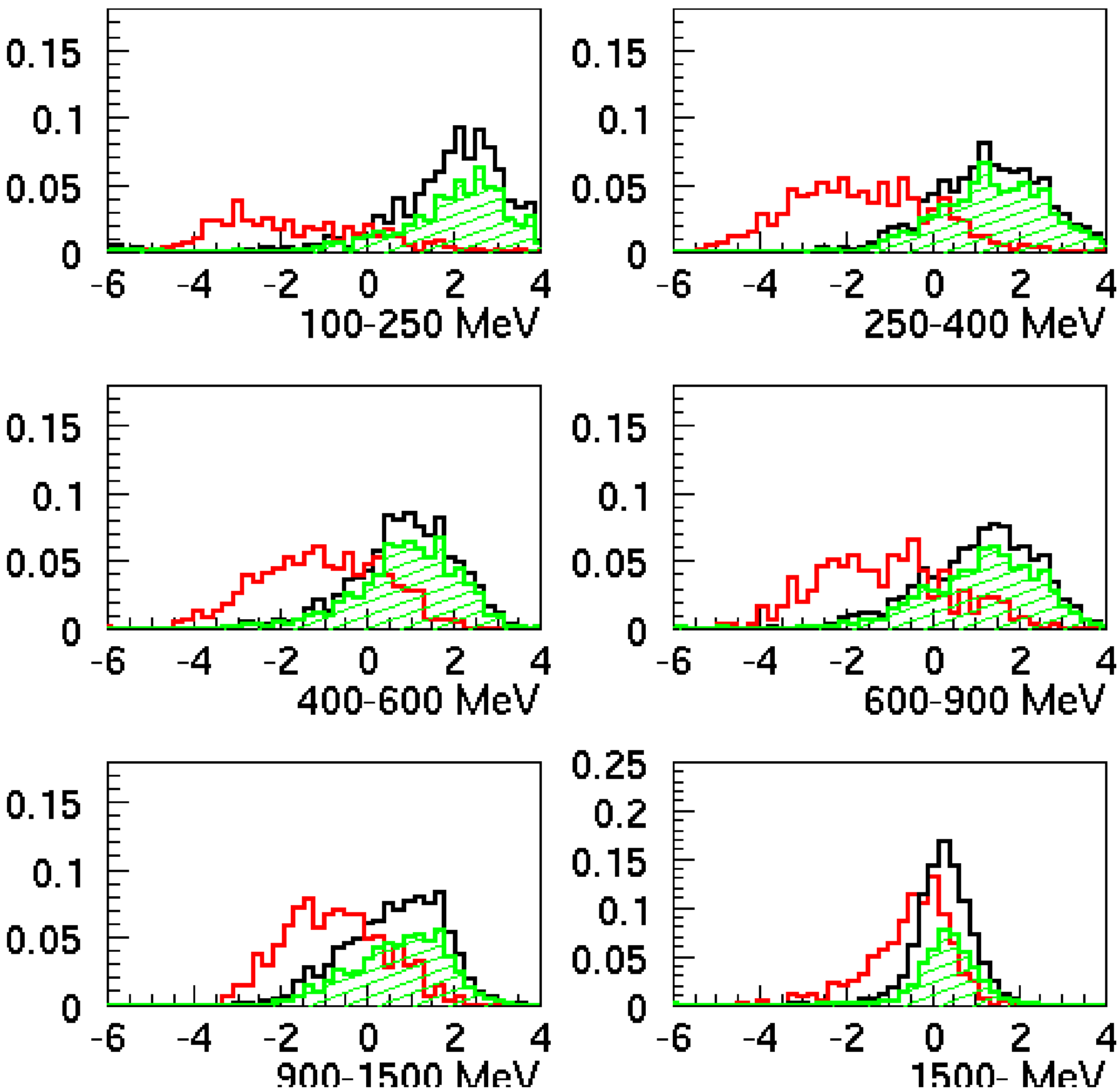
then event has $prob_{bg}=0.1$

and $prob_{sig}=0.02$

$L_{sig} = \Sigma \log(L^{sig}_i)$ *,same for bckg*

$L = L_{sig} - L_{bckg}$

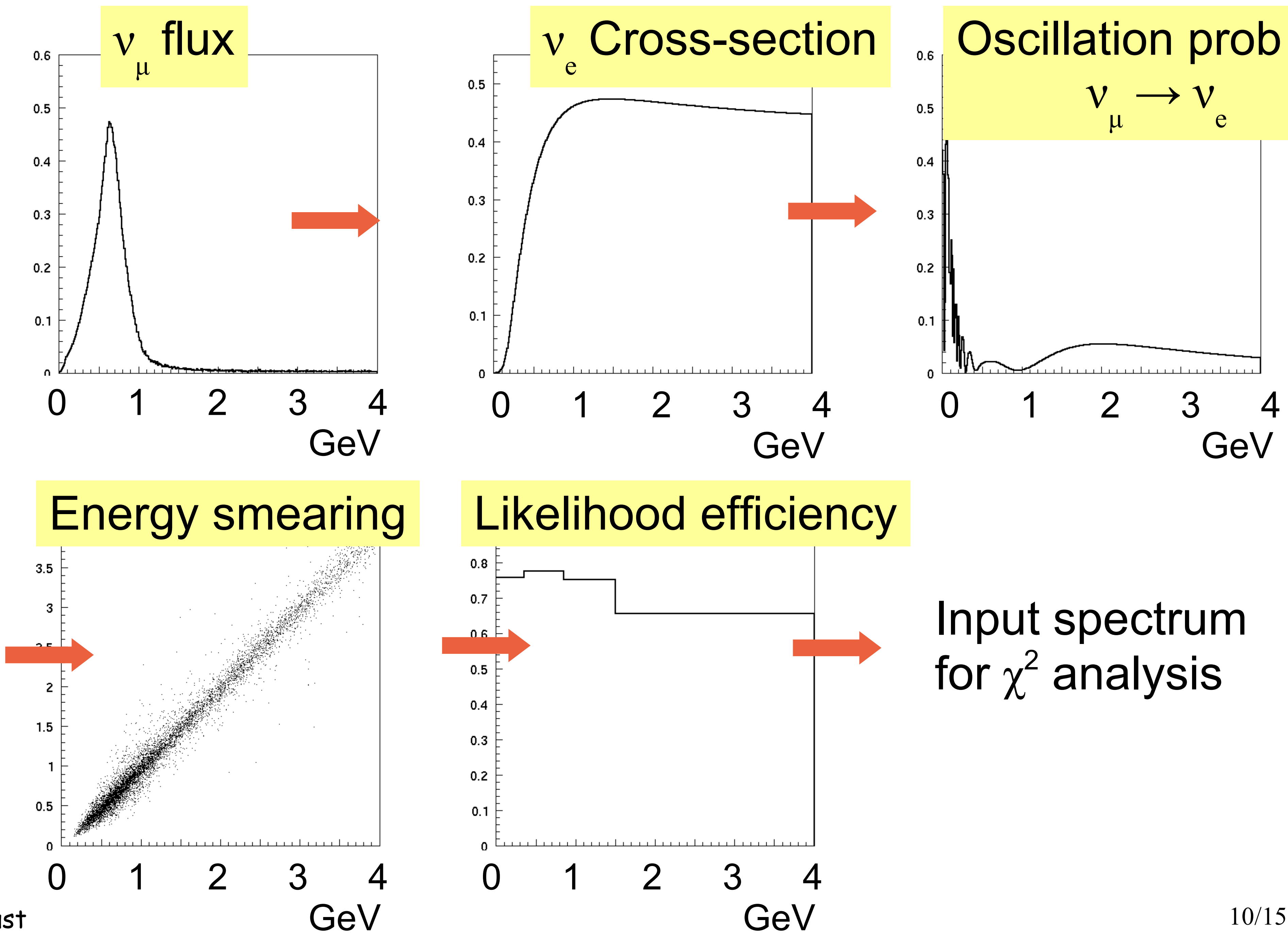
Results of the likelihood



Background
Signal
ν_e CCQE

At high energy the separation becomes worse.

Oscillation analysis



χ^2 Definition

The oscillation analysis is done with 28 bins:

k=1,4
- 0.27Mton at Kamioka or 0.54Mton in Kamioka
- 0.27Mton in Korea *When Kamioka only*
- 4 years running of neutrino
- 4 years running of antineutrino

With the following energy bins (MeV):

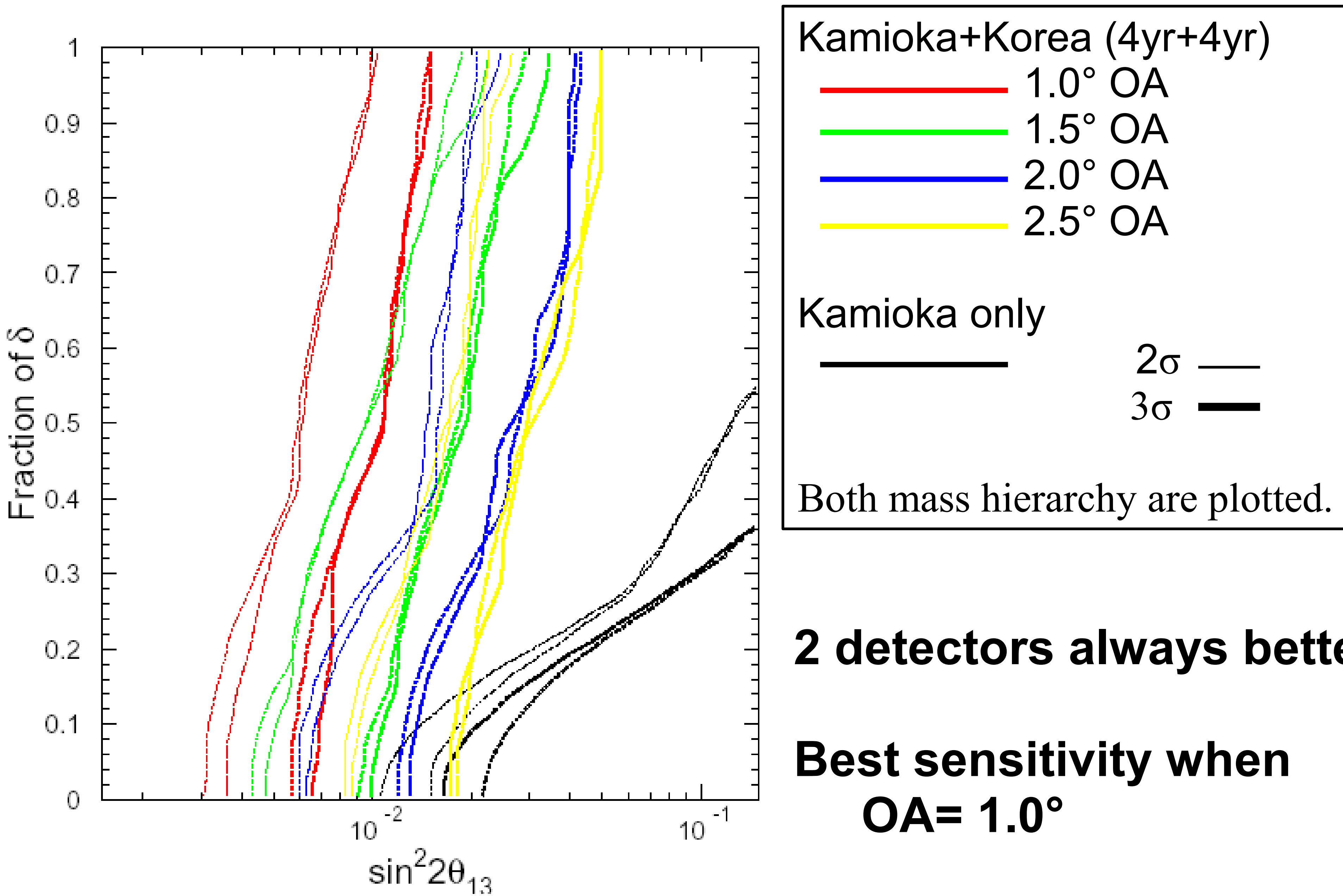
i=1,7
- 400-500, 500-600, 600-700, 700-800,
- 800-1200,1200-2000, 2000-3000

$$\chi^2 = \sum_{k=1}^{4} \left(\sum_{i=1}^{7} \frac{\left(N(e)_i^{\mathrm{obs}} - N(e)_i^{\mathrm{exp}}\right)^2}{\sigma_i^2} \right) + \sum_{j=1}^{3} \left(\frac{\epsilon_j}{\tilde{\sigma}_j} \right)^2$$

$$N(e)_i^{\mathrm{exp}} = N_i^{\mathrm{BG}} \cdot (1 + \sum_{j=1}^{2} f_j^i \cdot \epsilon_j) + N_i^{\mathrm{signal}} \cdot (1 + f_3^i \cdot \epsilon_3) \quad .$$

hep-ph 0604026 eq 3) and 4)

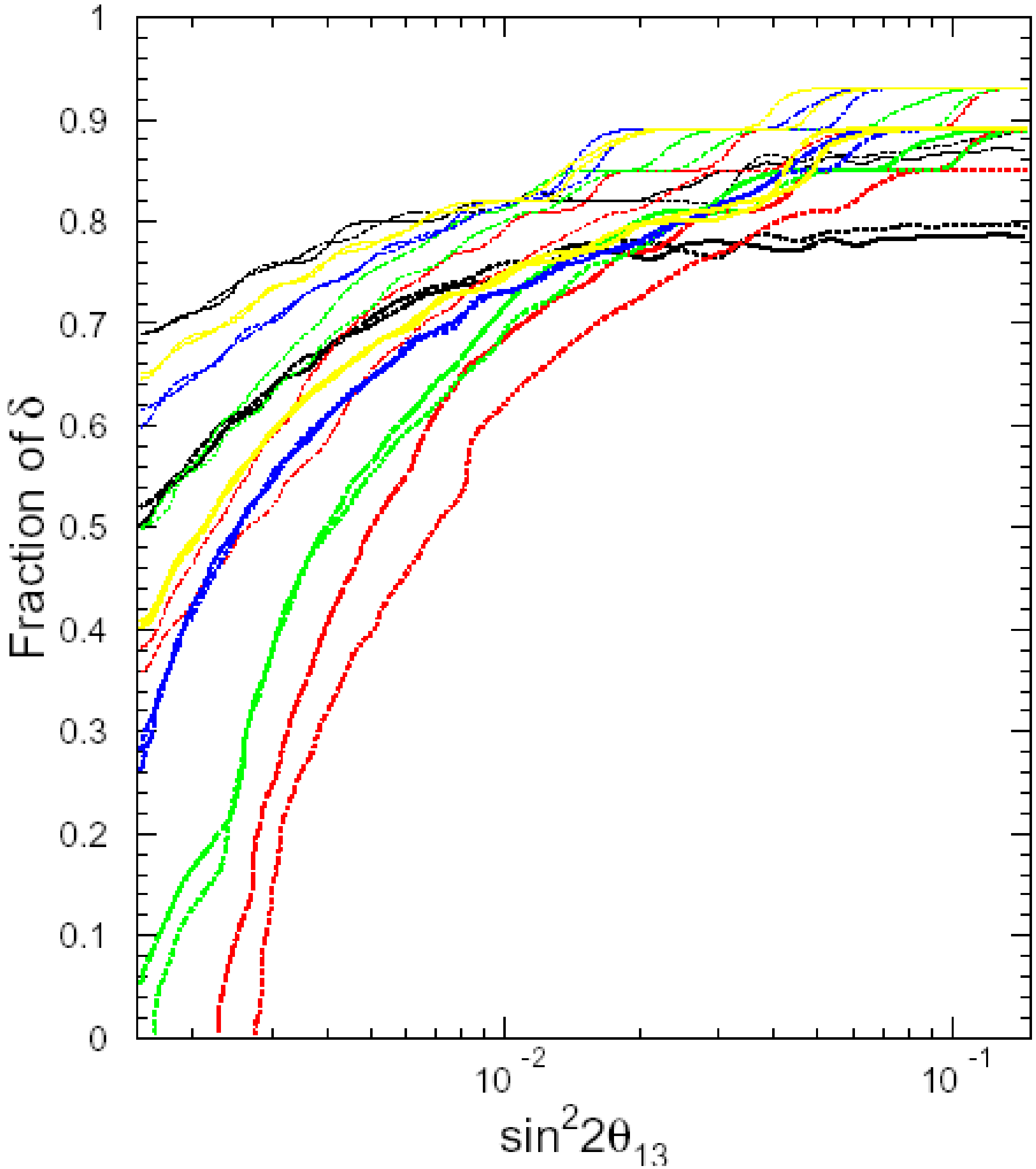
Sensitivity to mass hierarchy



2 detectors always better

Best sensitivity when OA= 1.0°

Sensitivity to CP violation



If $\sin^2 2\theta_{13}$ is big:

Best sensitivity with 2 detectors (& big OA)

If $\sin^2 2\theta_{13}$ is small:

Best sensitivity with Kamioka only

Conclusions

For mass hierarchy:

Best set up is when OA is small (= 1.0°)

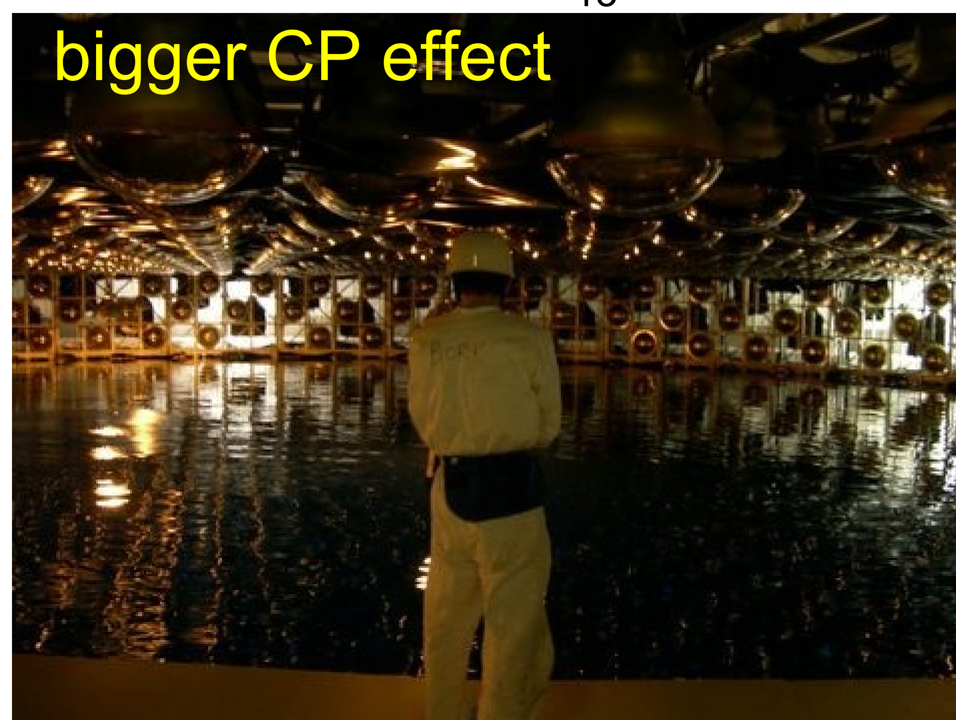
1^{st} osc maximum → matter effect

For CP violation study:

Best set up is Kamioka only (for small $\sin^2 2\theta_{13}$)

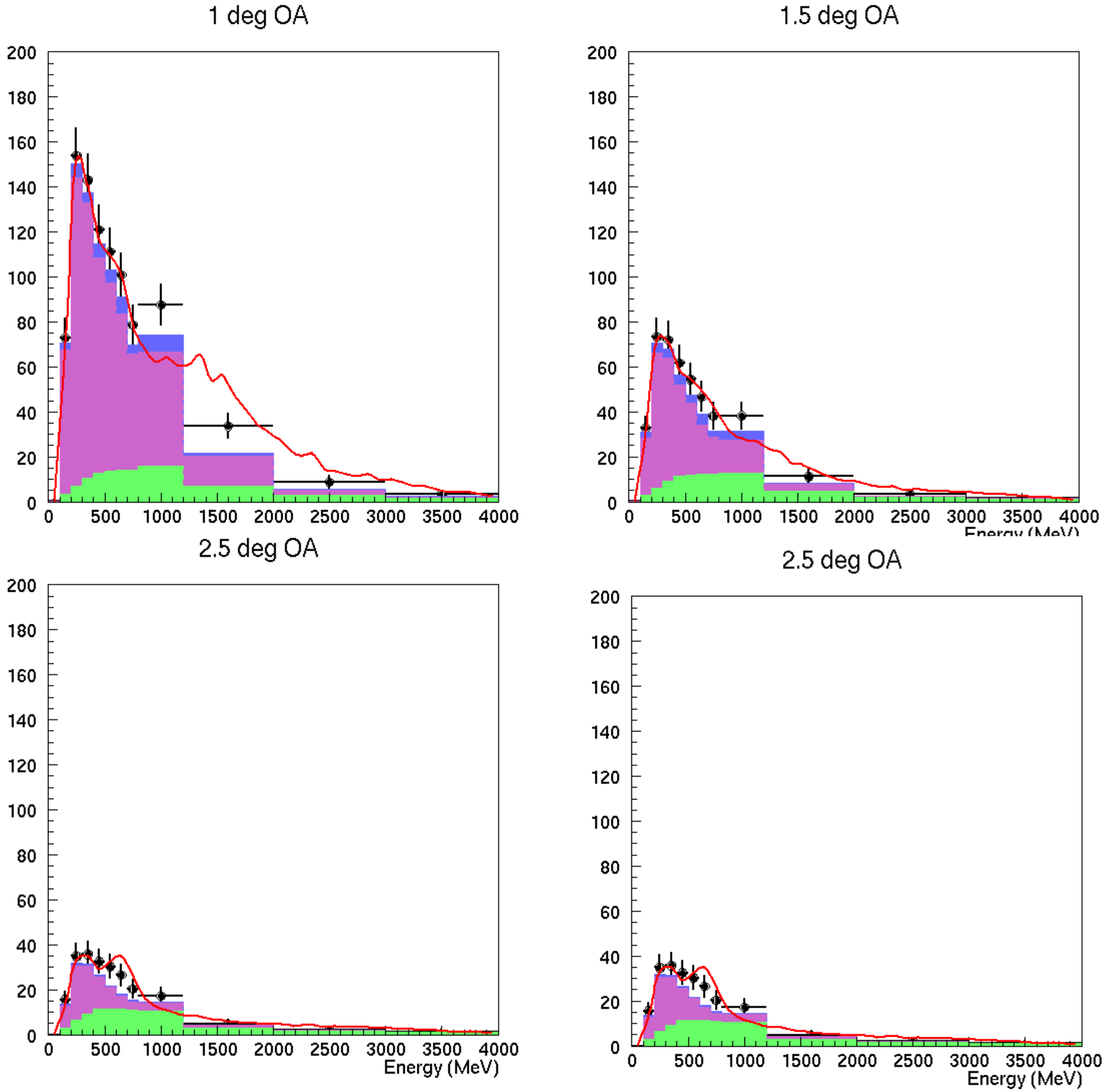
or OA big (= 2.5°) if 2 detectors (for big $\sin^2 2\theta_{13}$)

2^{nd} osc maximum → bigger CP effect



Backups...

Spectrum for each off-axis angle



0.27 Mton (FV)
4 yr ν run
4MW
$\sin^2 2\theta_{13}=0.1$
$\delta = \pi/2$

Background:
- beam ν_e
- NC
- ν_μ mis-ID

Signal+Background:
- Without detector effect
- With detector effect

You asked for it!

$$P[\nu_\mu(\bar{\nu}_\mu) \rightarrow \nu_e(\bar{\nu}_e)] =$$

$$\sin^2 2\theta_{13} s_{23}^2 \sin^2(\phi_{31}) - 1/2\, s_{12}^2 \sin^2 2\theta_{13} s_{23}^2 (2\phi_{21}) \boxed{\sin(2\phi_{31})}$$
$$+\ 2J_r \boxed{\cos\delta}(2\phi_{21})\boxed{\sin(2\phi_{31})} \mp 4J_r \boxed{\sin\delta}(2\phi_{21})\sin^2(\phi_{31})$$

} Vacuum terms

$$\pm\ \cos 2\theta_{13} \sin^2 2\theta_{13} s_{23}^2 \frac{(4\mathrm{Ea}(x))}{(\Delta m_{31}^2)} \sin^2\phi_{31}$$
$$\mp\ \frac{(a(x)L)}{2} \sin^2 2\theta_{13} \cos 2\theta_{13} s_{23}^2 \boxed{\sin(2\phi_{31})}$$

} Matter Effect terms

$$+\ c_{23}^2 \sin^2 2\theta_{12} (\phi_{21})^2$$

} Solar term

$$\phi_{ij} = \frac{(\Delta m_{ij}^2 L)}{(4E)}$$

$$a(x) = \sqrt{(2)}\, G_F N_e(x)$$

Green box: CP terms.

Purple box: Mass hierarchy terms.

This equation is a 1st order approximati
in matter effect.

Likelihood variables

Standard SK variables:

Ring parameter
PID parameter

Special π^o fitter variables: (POLfit, Pattern Of Light)

π^o mass
π^o likelihood
Energy fraction of 2nd ring

New variables, defined for this analysis:

Chi_Xalong
Chi_cos(open)

Beam related variable:

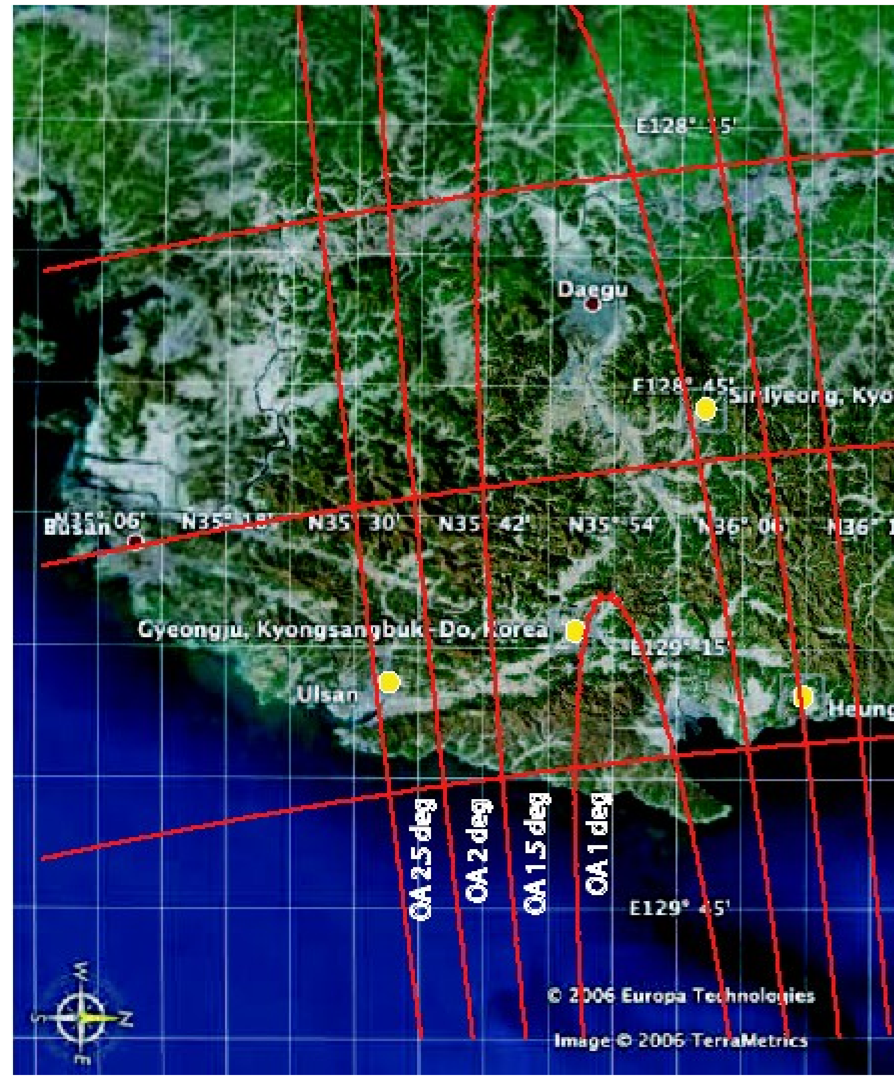
$\text{Cos}\theta_{\nu e}$

Likelihood effciency

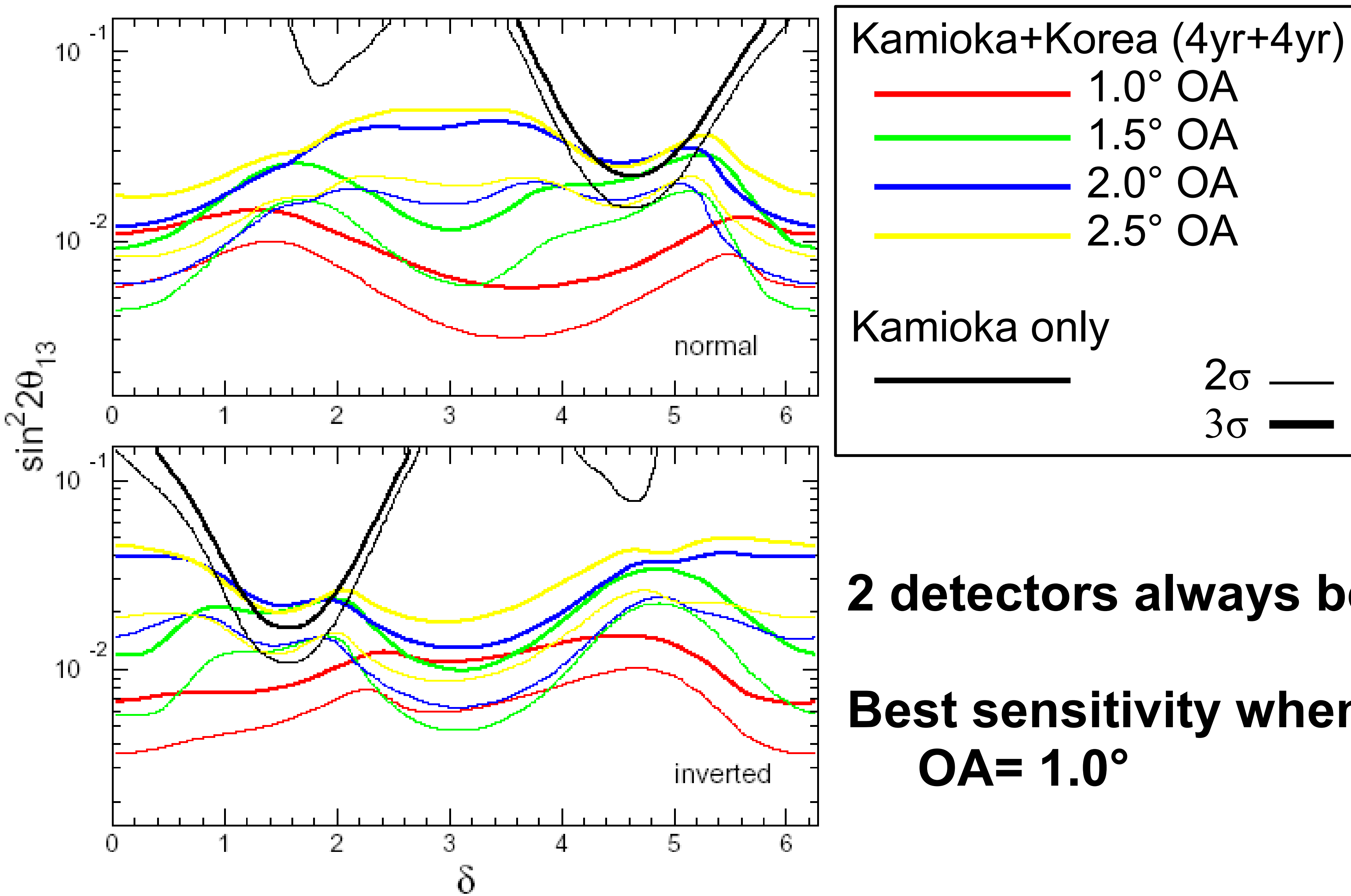
E_{rec} (GeV)		0-0.35	0.35-0.85	0.85-1.5	1.5-
ν_μ CC	fcfv	286.9	415.7	370.4	995.0
	1ring	170.2	220.8	146.3	433.6
	e-like	3.6	4.5	5.3	25.4
	nodecay-e	1.4	1.5	1.9	11.9
	likelihood	0.2	0.5	0.6	2.2
	efficiency	14.6%	31.4%	32.0%	18.7%
NC	fcfv	422.0	229.6	86.0	83.6
	1ring	89.0	66.2	26.0	41.1
	e-like	53.4	57.2	24.9	39.6
	nodecay-e	50.4	53.1	20.8	32.6
	likelihood	5.1	10.9	4.0	11.1
	efficiency	10.1%	20.5%	19.5%	34.0%
ν_e	fcfv	12.2	36.7	33.7	73.3
	1ring	5.7	21.6	16.9	37.4
	e-like	5.6	21.3	16.8	37.2
	nodecay-e	4.7	18.9	14.5	30.8
	likelihood	4.0	15.4	11.3	22.1
	efficiency	85.4%	81.8%	78.3%	71.7%

NB: arbitrary numbers

Off-axis question



Other Sensitivity curve (mass)



2 detectors always better

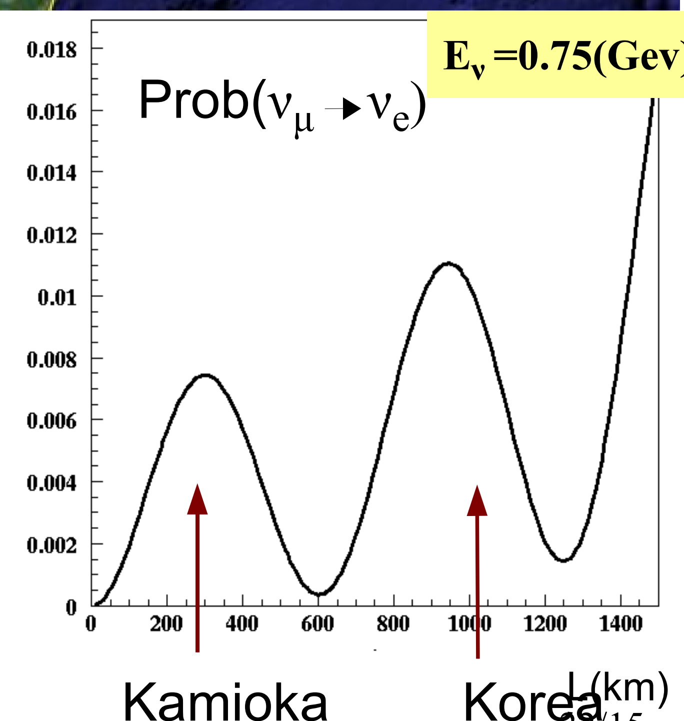
Best sensitivity when OA= 1.0°

The T2KK project

T2K:
Shoot neutrinos from Tokai to Super-K (295km)

T2KK:
the neutrinos from Tokai won't stop at Super-K
Let's try to detect them in Korea (~1000km)

Advantages:
- More points on oscillation probability curve give better results
- 2 detectors on same beam minimizes systematics



χ^2 Definition

The oscillation analysis is done for: 4MW beam

k=1,4
- 0.27Mton at Kamioka or 0.54Mton in Kamioka
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