T2KK

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Outline

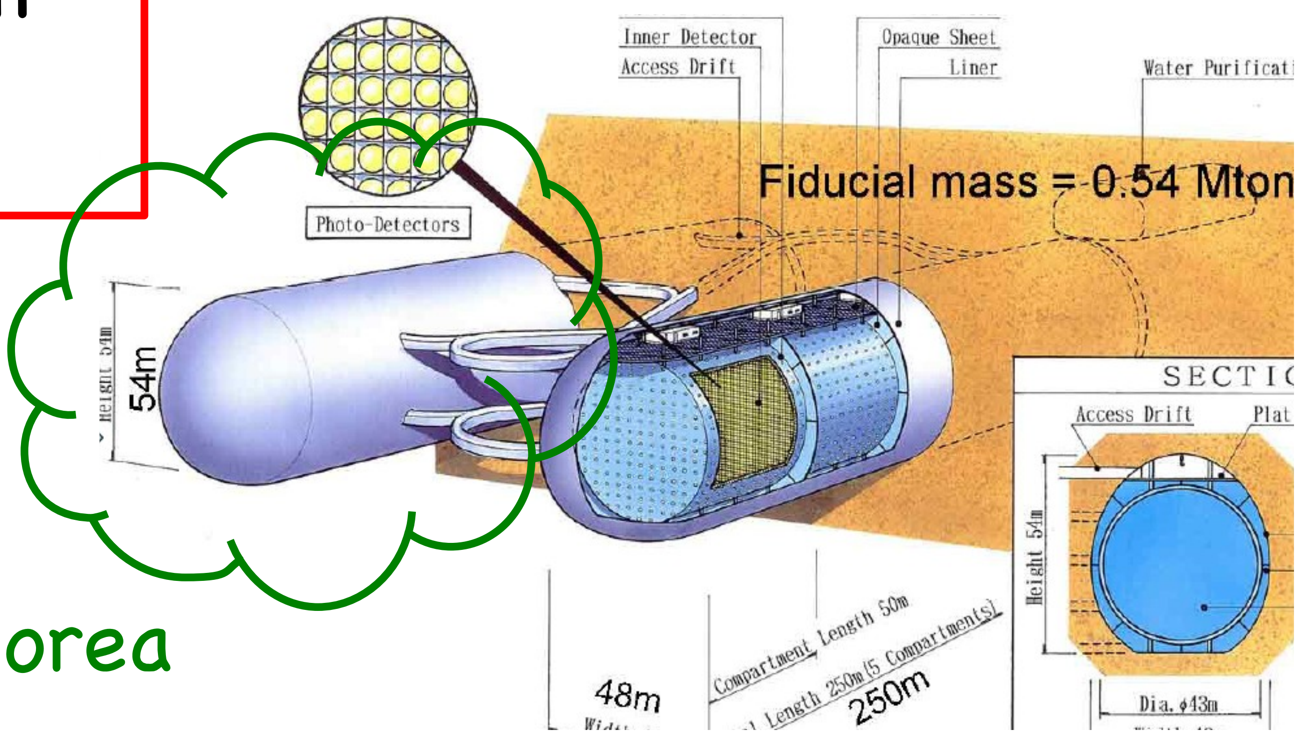
- General motivation for T2KK
  - Why Korea and where in Korea?
- Dealing with the background
  - Simulating the BG (NC especially)
  - Effect of photo-coverage
- T2KK analysis:
  - Event spectrum and χ^2 analysis
  - What is the best off-axis angle?

The Hyper-K project

- Also good for:
  - solar & atmospheric ν
  - proton decay searches
  - supernova

	Total Volume	Fiducial V.
SK	50 kt	23 kt
HK	1000 kt	2x270 kt

- **1 Mton detector split into at least 2 sub-detectors.**

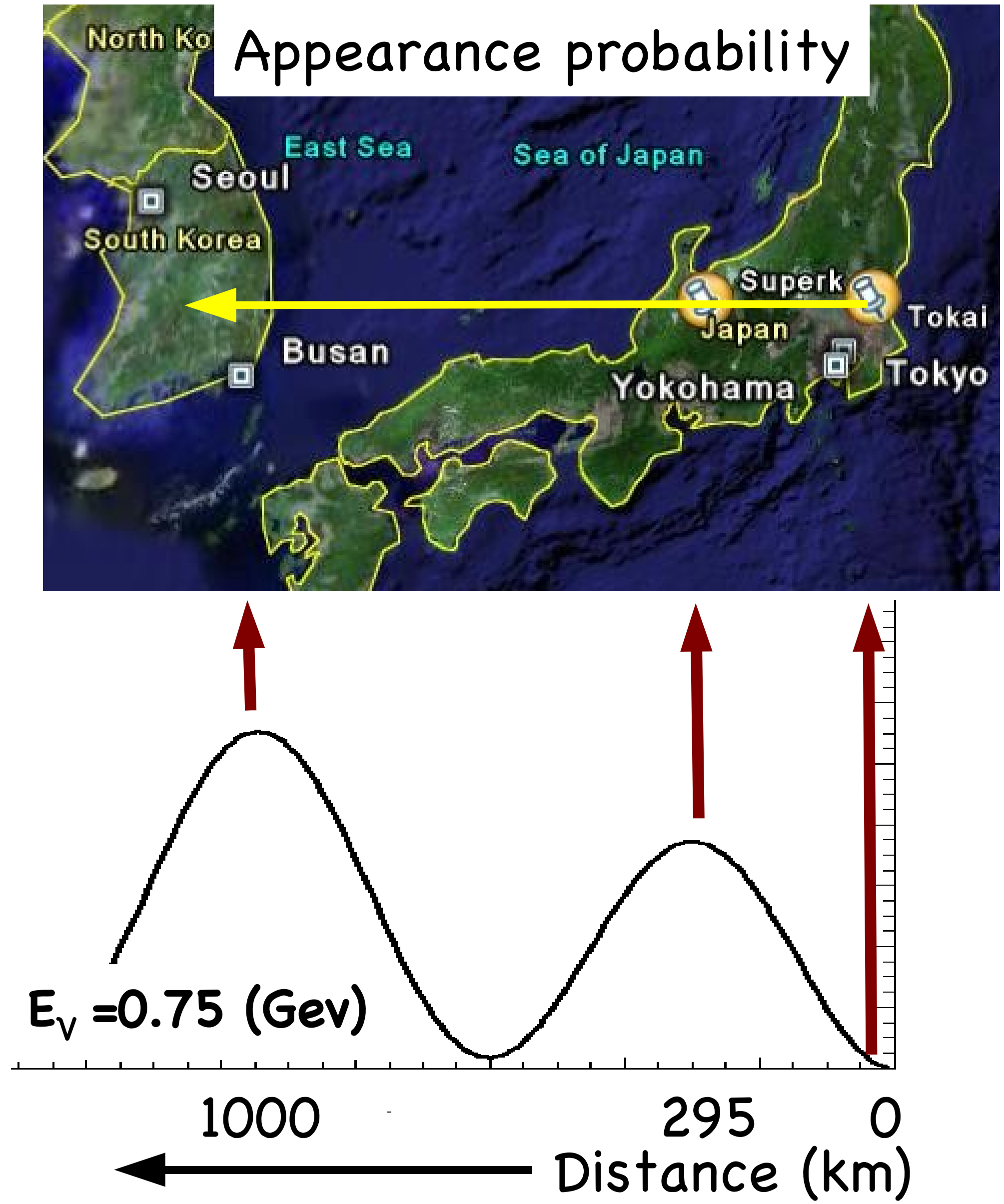


Could be built in Korea

Why a detector in Korea?

Main Physics reasons:

- Observe both **first and second** oscillation maximum in ν_e appearance.

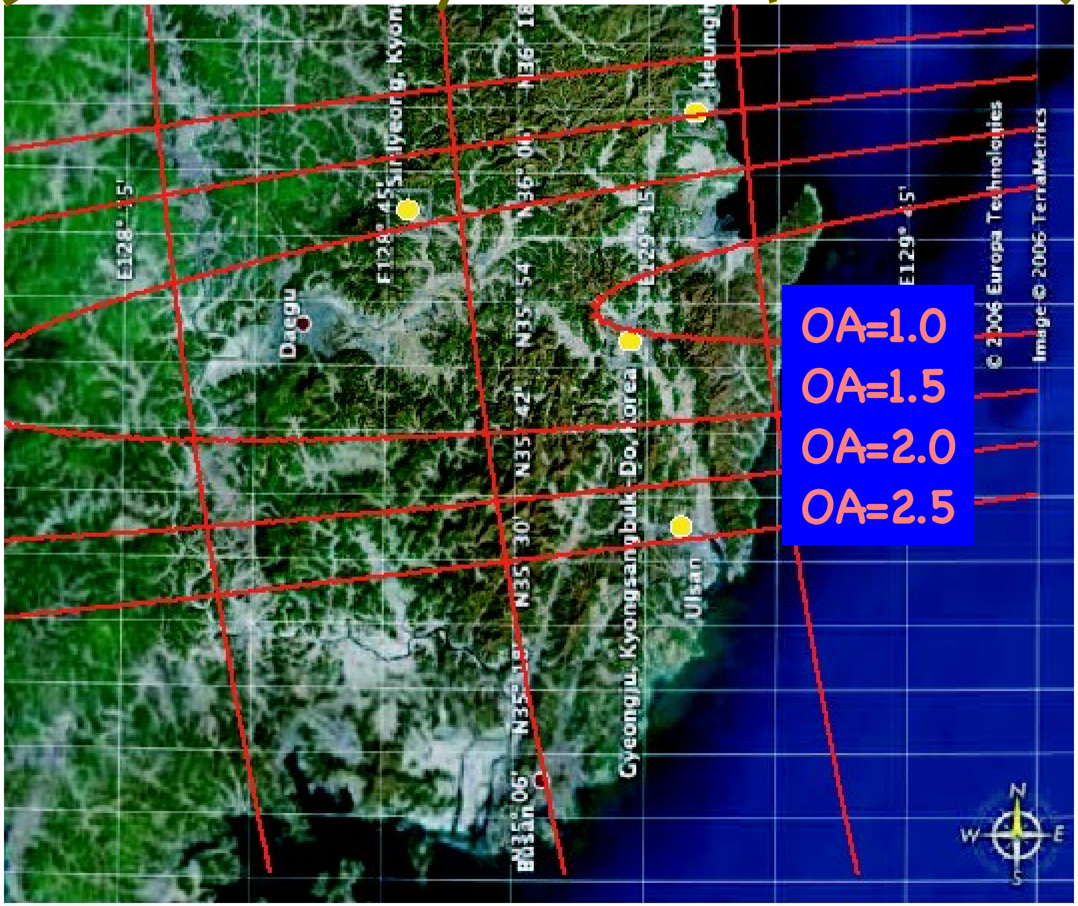


Practical reasons:

- We will already have the beam.
- The Hyper-K project already needs at least 2 sub-detectors.
- Having 2 identical detectors on the same beam minimizes systematic uncertainty.

Where in Korea?

- In Korea, the smallest off-axis angle available is 1.0° .
- Four off-axis angles have been considered.



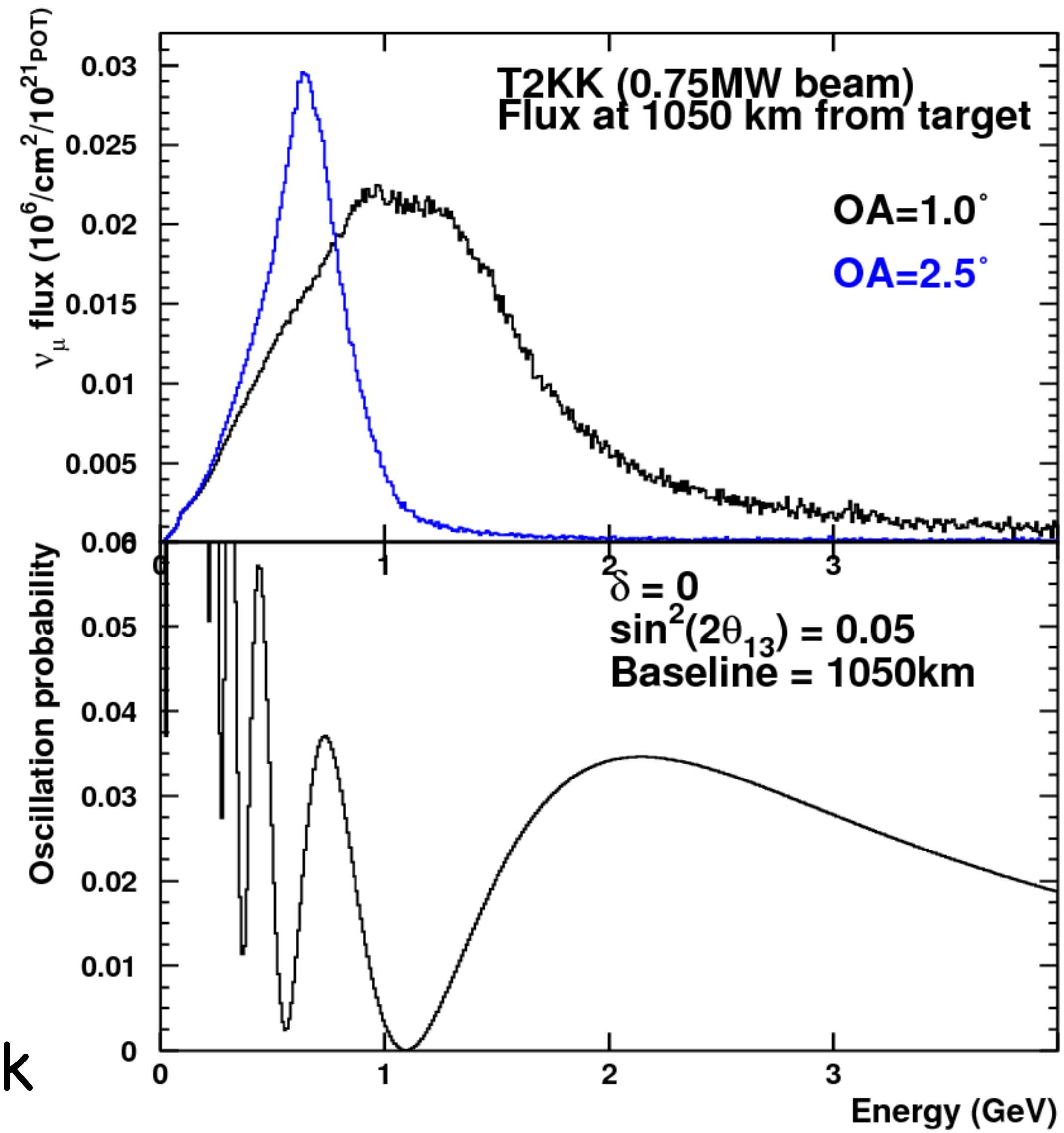
Flux and appearance in Korea

Small off-axis angle:
(high energy tail)

✔ 1st appearance peak
✗ more NC background

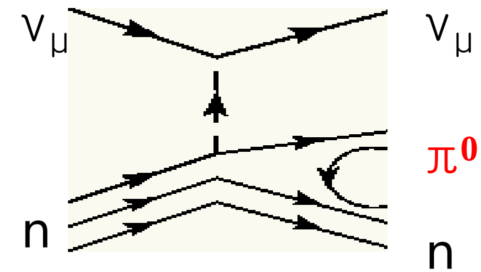
Big off-axis angle:
(narrow peak)

✔ Low background
✗ Low statistics at high E
✗ Only 2nd appearance peak



Likelihood analysis: basics

- Main source of background come from π^0 produced by neutral current when one of the γ is missed.



- The goal of the likelihood is to efficiently separate signal events from NC background events.

- First we select events with a set of precuts (see slide 8) and then we construct the likelihood (see slide 9).

- We tried both T2K and Super-K atmospheric Monte Carlo and since our analysis is binned in energy, the results were comparable.
  → We decided to use the SK atmospheric MC since we can check its accuracy by comparing it to the SK atmospheric data.

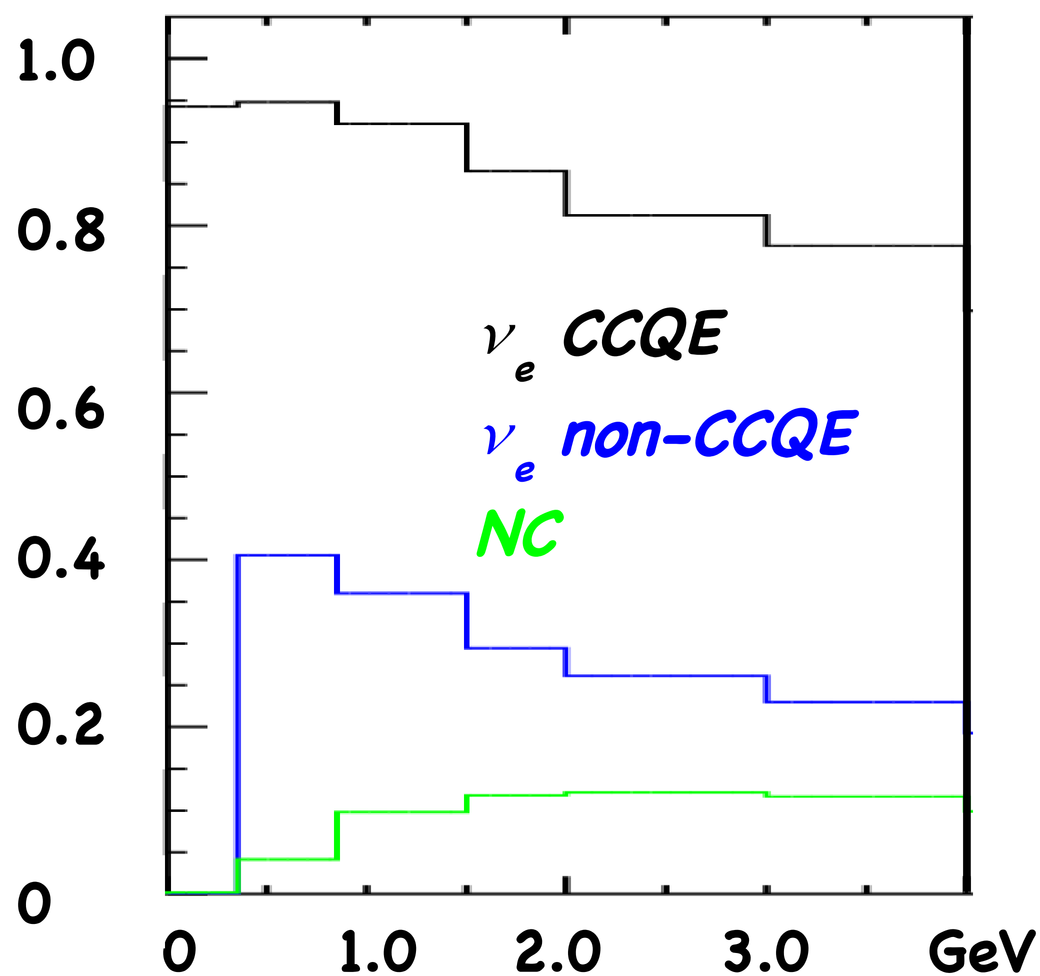
Likelihood analysis: Sample used

We use the Super-K atmospheric Monte Carlo and we keep events if they are:

- single ring
- electron-like
- with no decay electron
- inside the fiducial volume and fully contained.

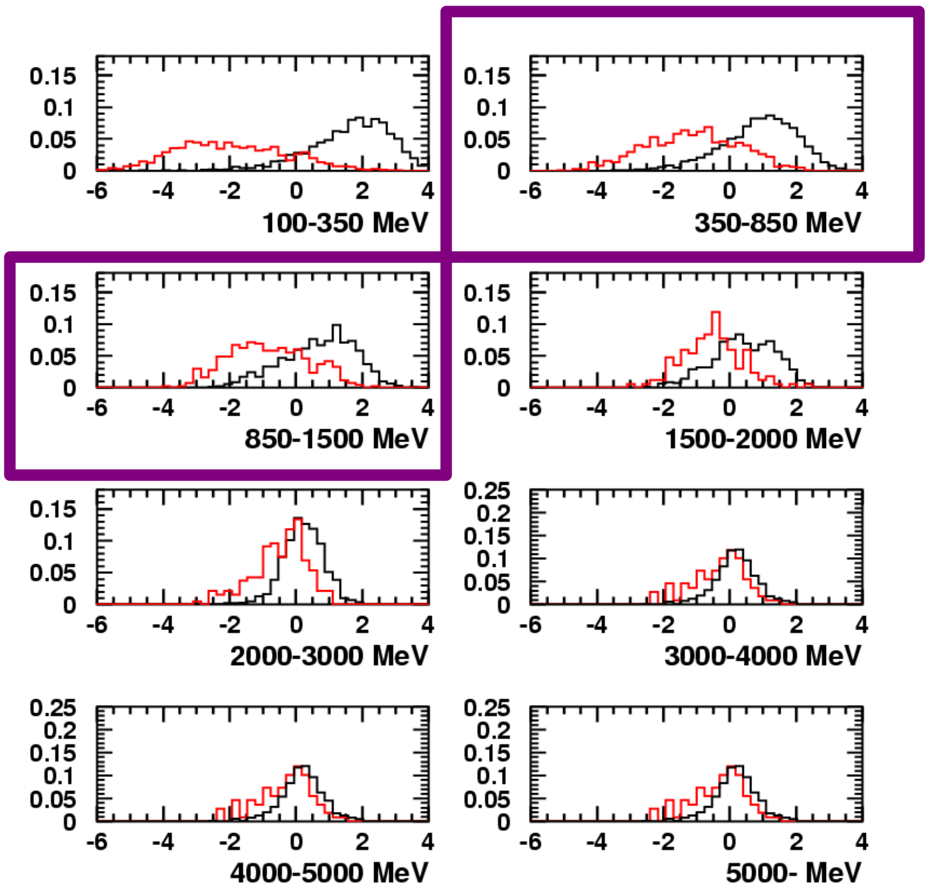
NB: the ν_μ mis-ID BG is not plotted because it is always below 0.01

Precuts effciency



Likelihood analysis: variables

Likelihood per energy bin



Background

Signal (Main signal bin)

Likelihood variables:

Standard SK variables:

ring parameter, PID parameter

POLfit variables:

π^0 mass, π^0 likelihood,

energy fraction of second photon

Variables using beam direction info:

chi_xalong, chi_cosopen,

$\cos\theta_{\nu e}$

Final likelihood efficiency

We did a study of $S/\sqrt{B}$ and we found that keeping 80% of the signal is what gives the best results.

	Cut that keeps 80% of signal		
Energy (rec)	ν_e	NC	ν_μ mis-ID
0 - 350 MeV	82.7%	5.2%	6.9%
350 - 850 MeV	84.2%	28.0%	25.3%
850 MeV - 1.5 GeV	83.1%	28.2%	30.2%
1.5 - 2.0 GeV	83.8%	33.3%	39.3%
2.0 - 3.0 GeV	84.5%	27.1%	53.2%
3.0 - 4.0 GeV	79.0%	27.5%	45.9%
4.0 - 5.0 GeV	75.8%	52.3%	41.9%
5.0 - 10.0 GeV	78.8%	19.4%	51.4%

Background Simulation

For the background simulation, we also make use of the SK atmospheric Monte Carlo. This gives a very accurate energy resolution:

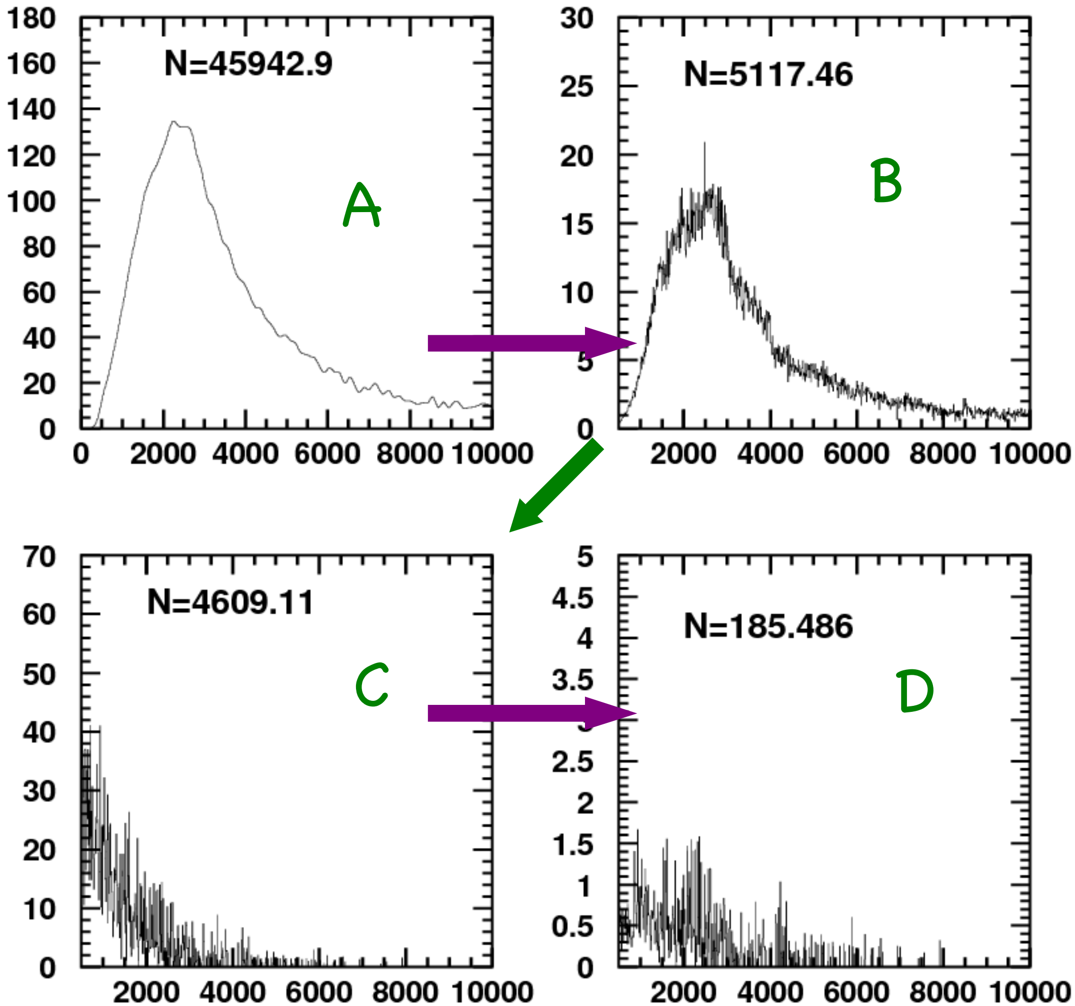
- Run over SK atmospheric MC:
- Keep events if: single ring, electron-like with no decay electron, inside fiducial volume

ie. precuts!

ie. likelihood!

- Apply likelihood efficiency as a function of reconstructed energy. Using reconstructed energy takes care of the energy response.
- Re-weight BG by ratio: (beam ν_μ flux/atmospheric ν_μ flux)
- Normalize for running conditions (#POT, time, volume)

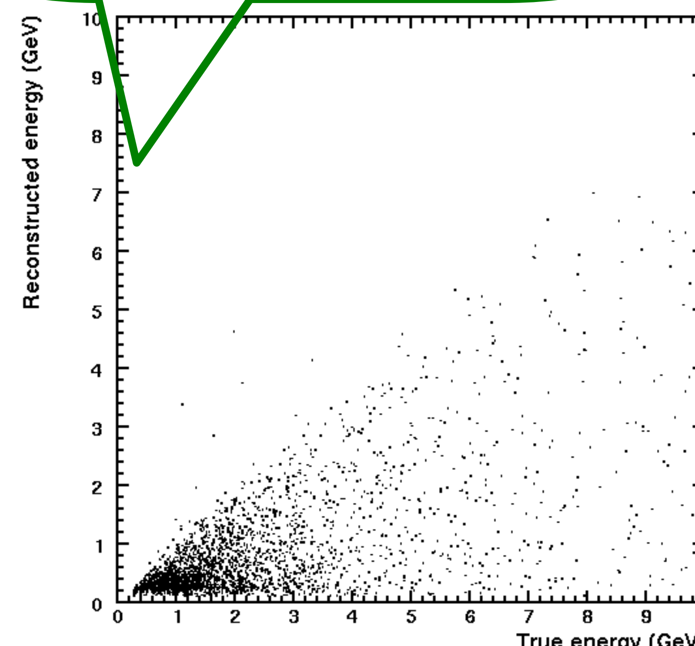
NC Background simulation



A = ν_μ flux x σ_{NC}

B = A x precuts efficiency

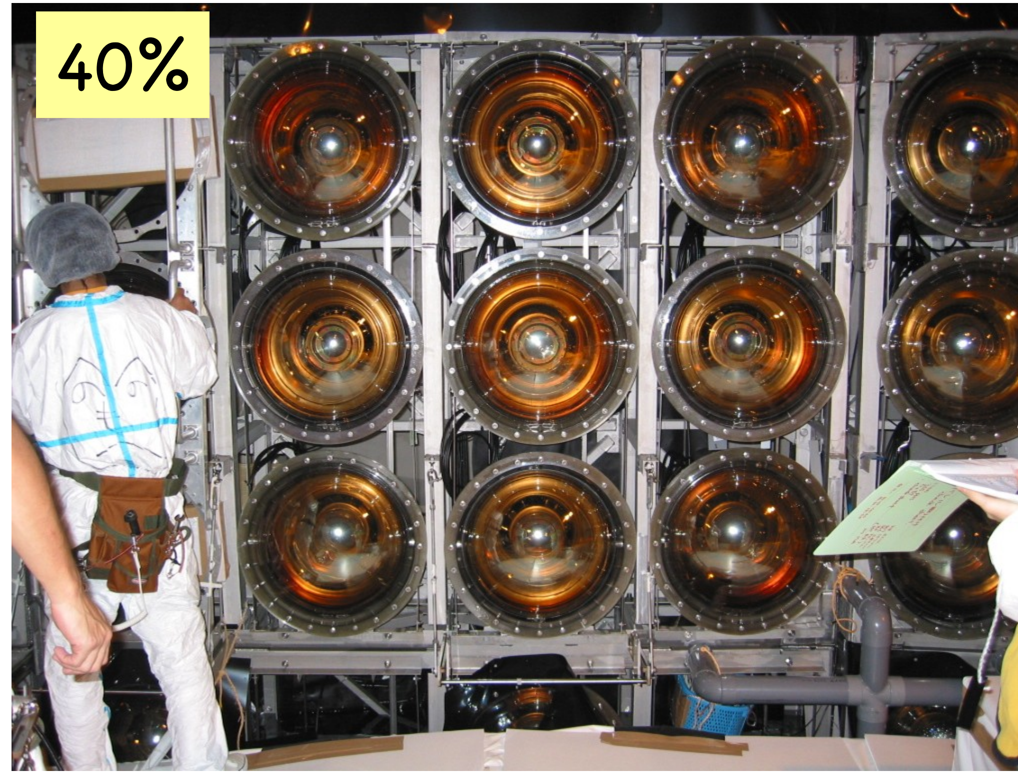
C = B x NC energy smearing

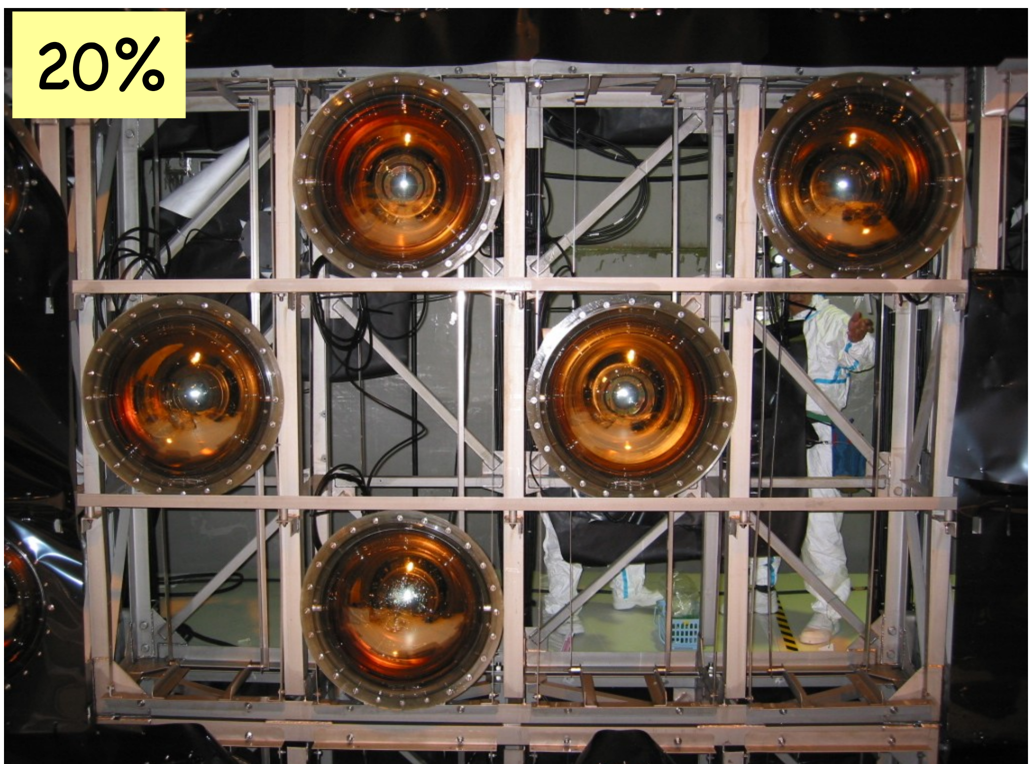


D = C x likelihood efficiency

What about the photo-coverage?

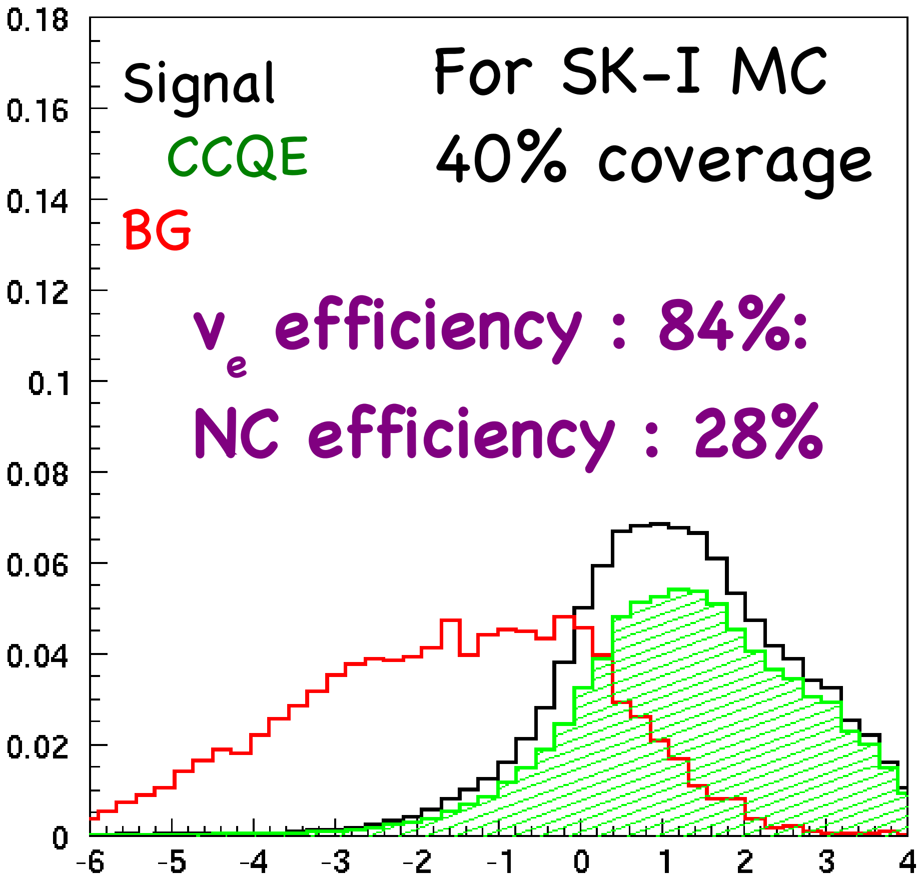
"Thanks" to the accident in SK, we have MC corresponding to 20% and 40% photo-coverage

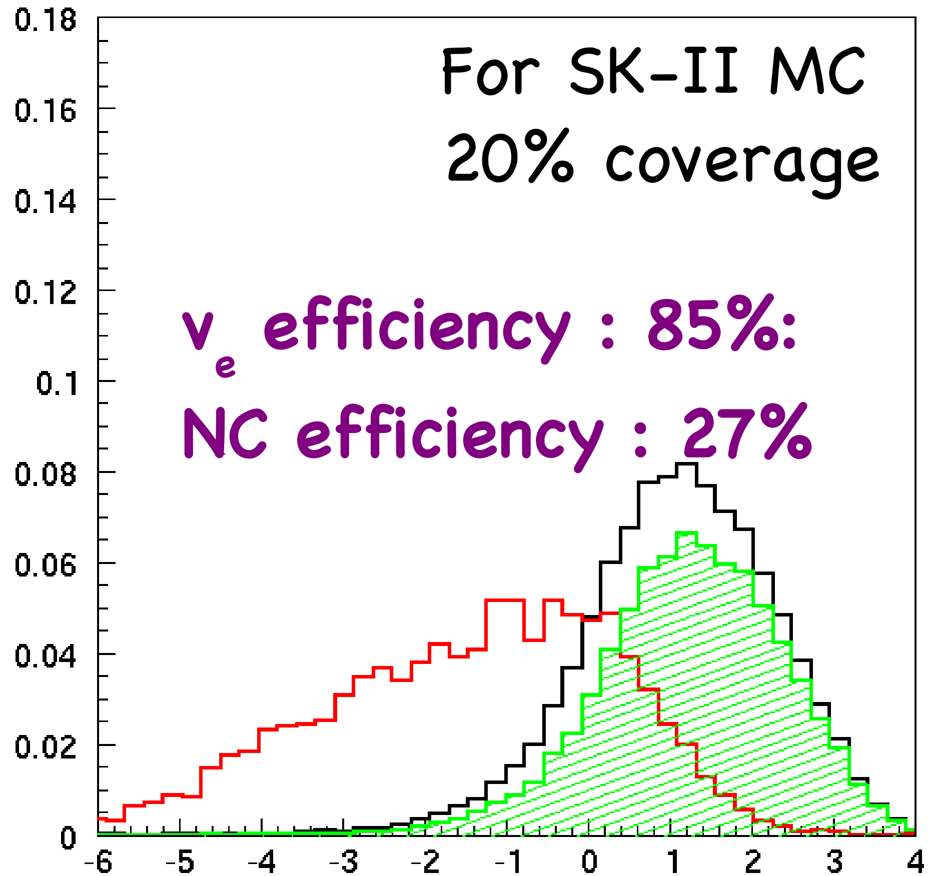




We tested our likelihood on both samples, and it gives very similar results.

Photo-coverage results

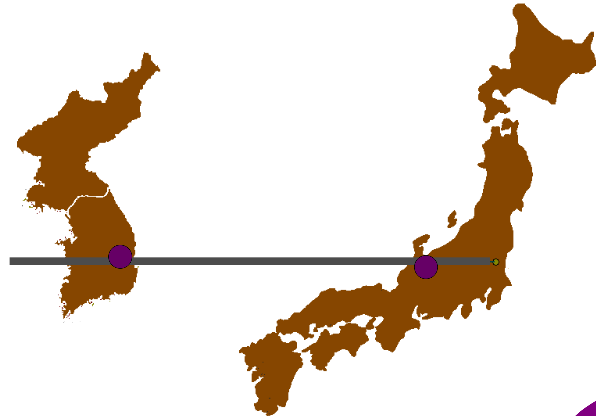




Running on 100 yr of SK-I MC and 60 yr of SK-II MC

350 MeV < E < 850 MeV

The T2KK setup

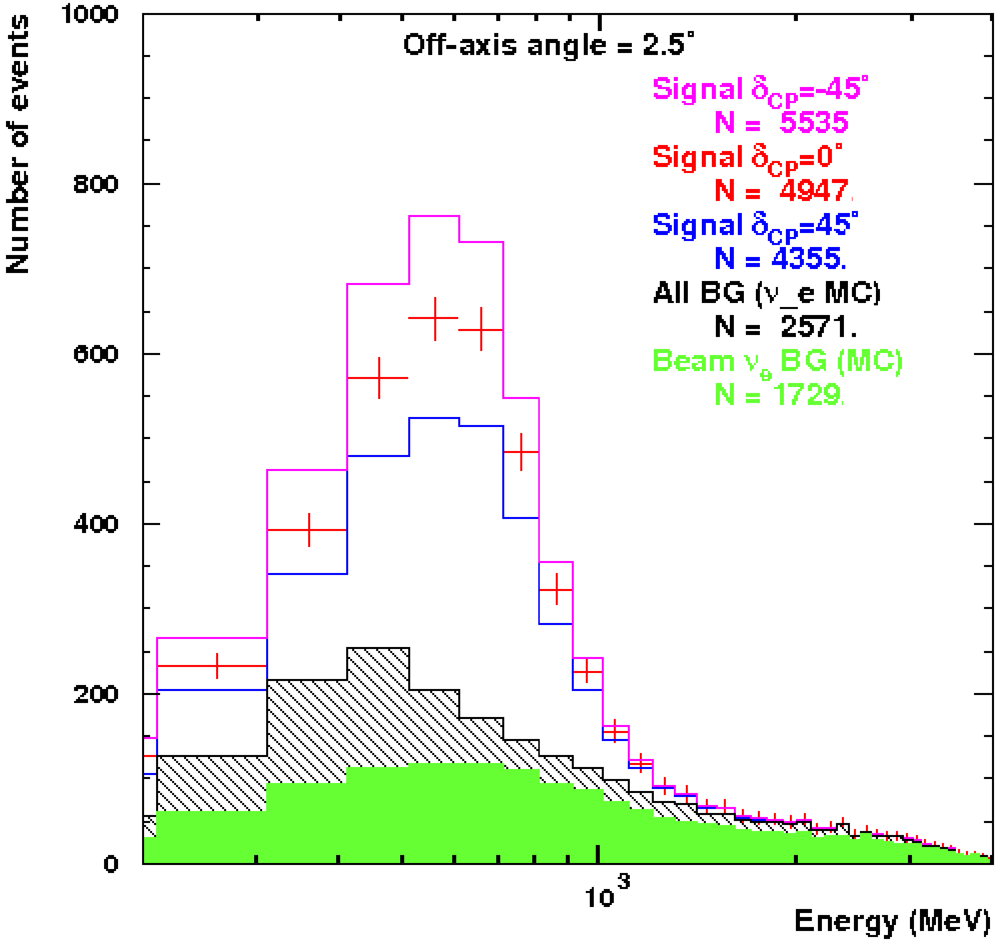


Factor of 0.46
in the number of
neutrinos
(1.66MW*5years)/
(4MW*4years*1.12)

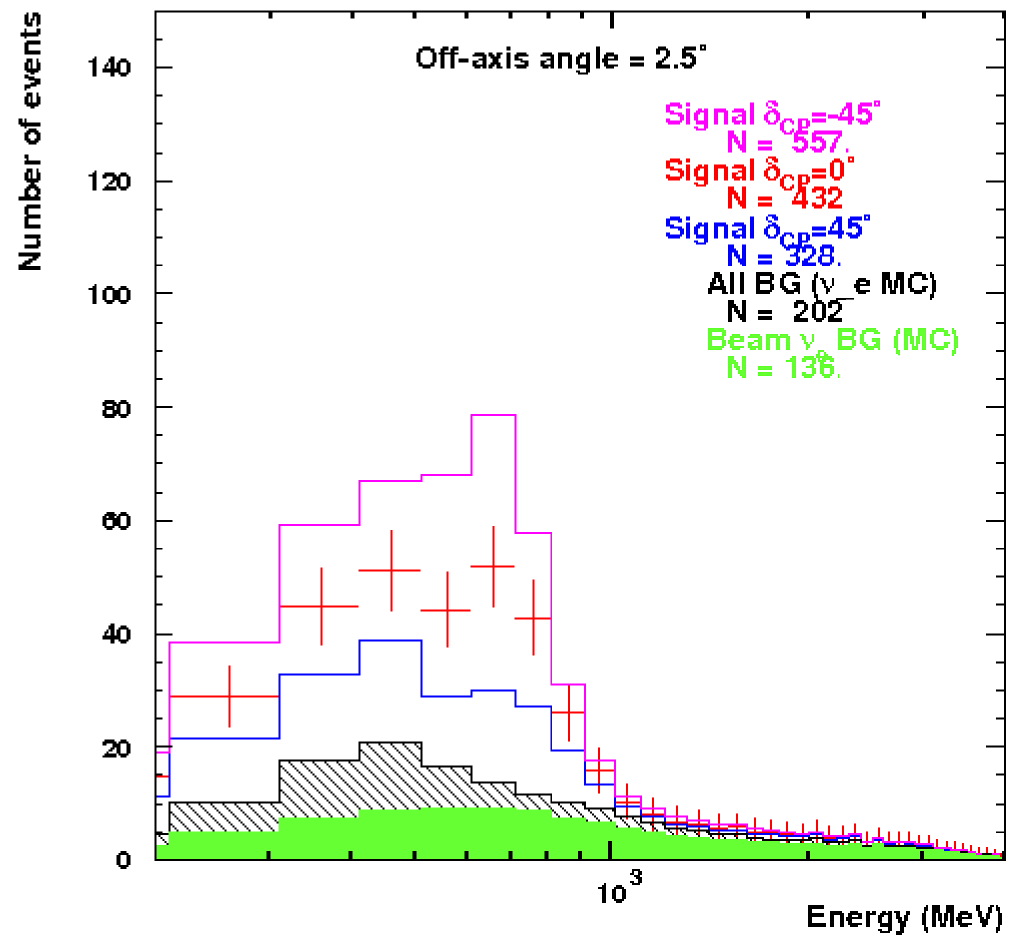
	T2KK	Scenario B
Volume	2 times 0.27Mton (FV)	2 times 0.27Mton (FV)
Beam power	4MW	1.66MW
Running time	4yrs nu + 4yrs antinu	5yrs nu + 5yrs antinu
1 year is	1.12×10^7 seconds	10^7 seconds
Proton energy	40GeV	30 GeV
Tot #POT	**28×10^{21} POT**	**3.45×10^{21} POT**
Distance	295 km and 1050 km	295 km and 1050 km
OA angle	2.5° OA and 1.0° OA	2.5° OA and 1.0° OA

Spectra in Kamioka and Korea

Spectrum at Kamioka



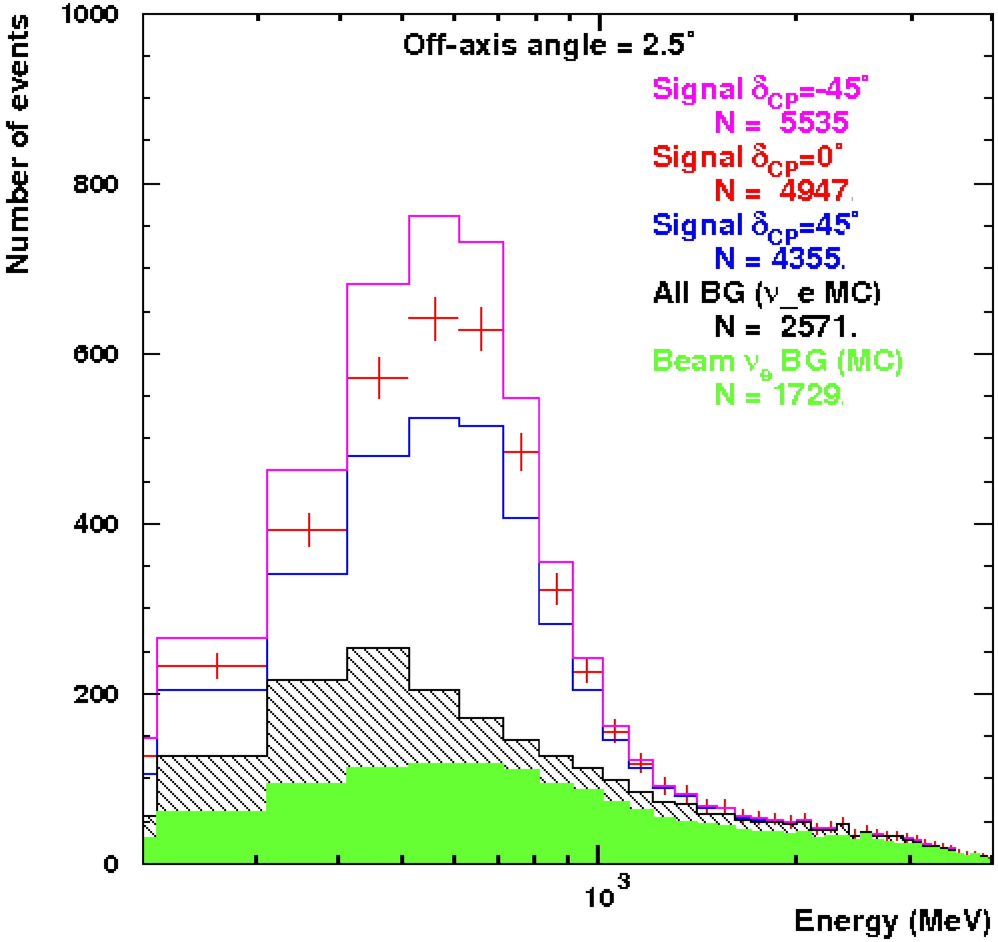
Spectrum at Korea 2.5° OA



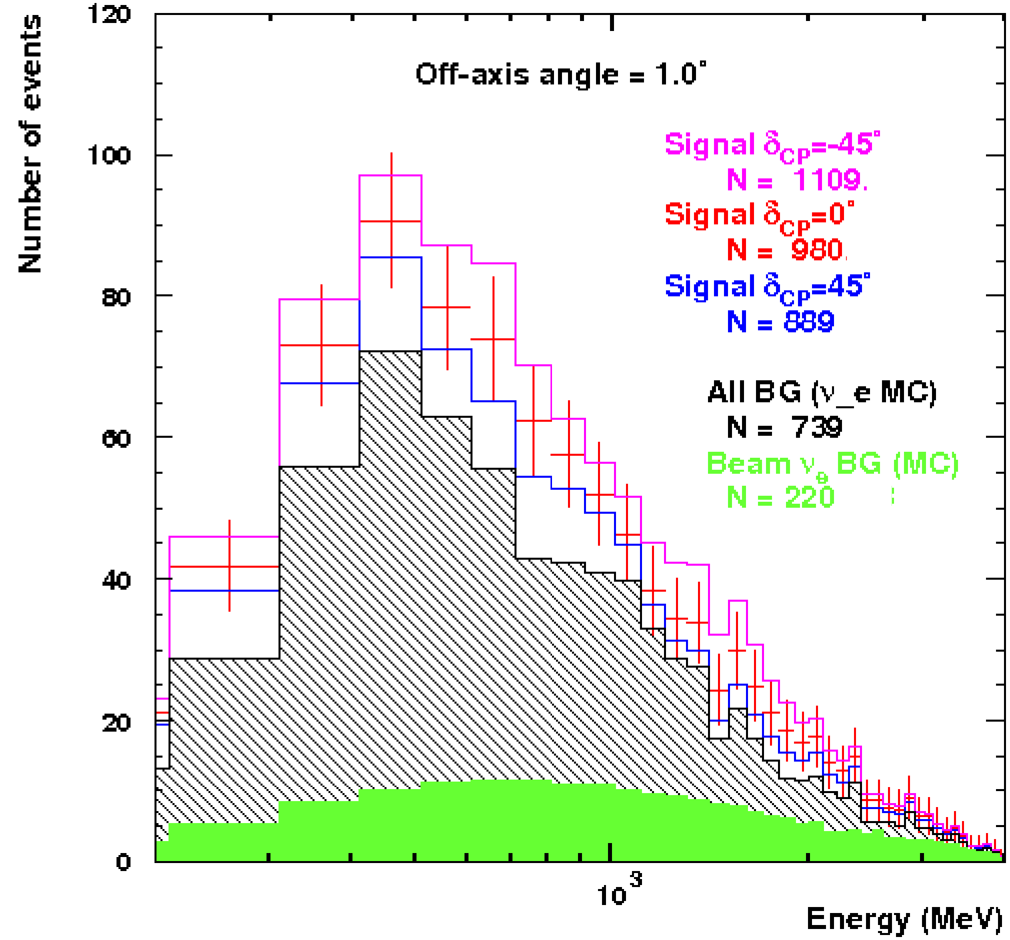
$Sin^2(2\theta_{13})$=0.04, neutrino, normal hierarchy, Scenario B

Spectra in Kamioka and Korea

Spectrum at Kamioka



Spectrum at Korea 1.0° OA



$\sin^2(2\theta_{13})$=0.04, neutrino, normal hierarchy, Scenario B

Definition of the χ^2 analysis.

The oscillation analysis was done for: 1.66MW beam

k=1,4
- 0.27Mton at Kamioka
- 0.27Mton in Korea
- 5 years running of neutrino
- 5 years running of anti-neutrino

j=1,3

We assumed a 5% systematic uncertainty on:
- the BG shape
- the BG normalization
- the detection efficiency of electrons and positrons

cf:Phys Rev D, 72 033003 (2005)

With the following energy bins (MeV):

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

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

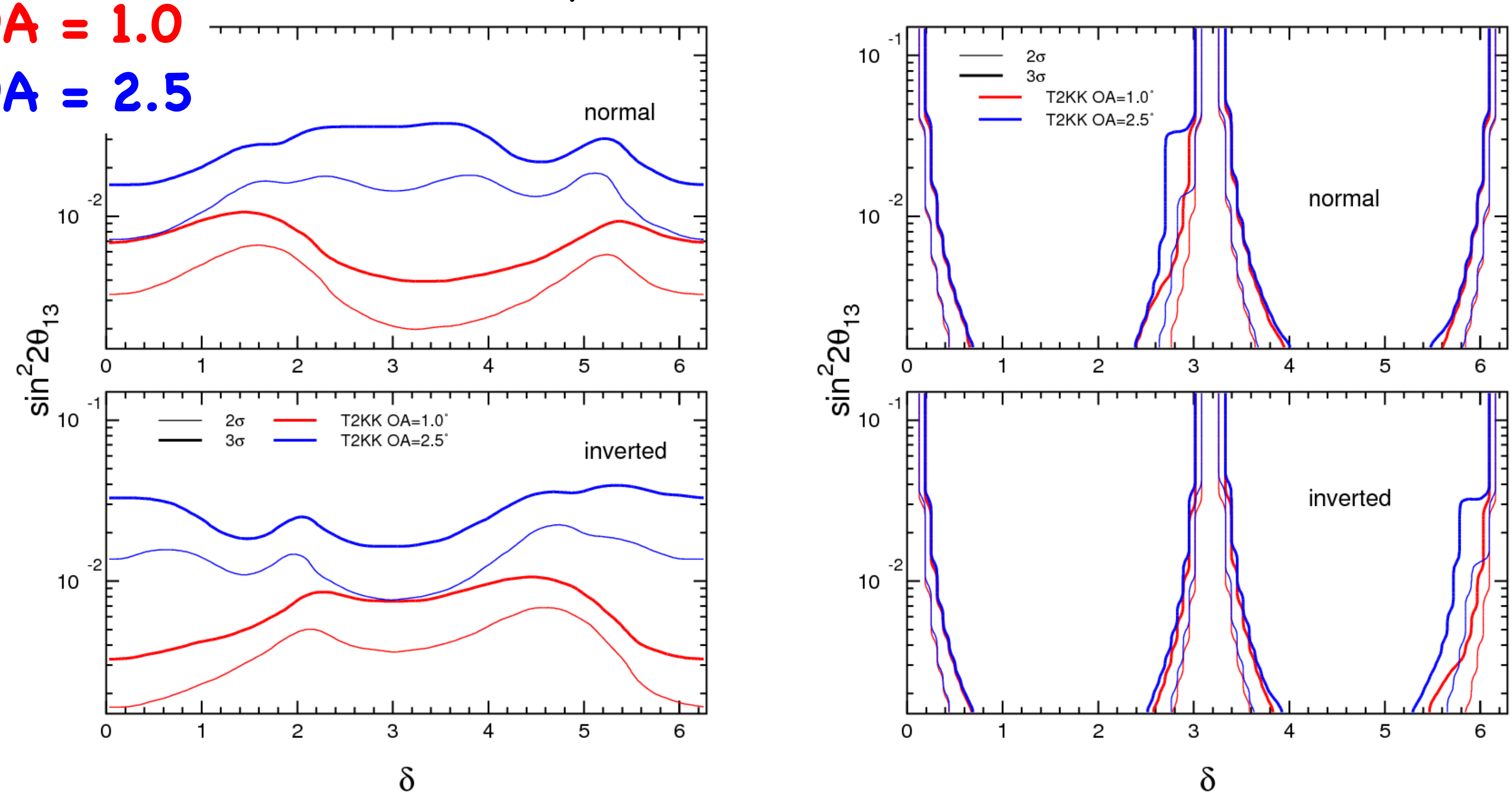
$$N(e)_i^{\mathrm{exp}} = N_i^{\mathrm{BG}} \cdot \left(1 + \sum_{j=1}^{2} f_j^i \cdot \epsilon_j\right) + N_i^{\mathrm{signal}} \cdot \left(1 + f_3^i \cdot \epsilon_3\right) \quad .$$

cf:Phys Rev D, 72 033003 (2005) eq 3) and 4)

Sensitivity for 2 off-axis angles

Mass hierarchy *Scenario B* CP violation

OA = 1.0
OA = 2.5



- The best results for mass hierarchy is given with the far detector located at 1° off-axis angle.
- The results for CP violation are comparable.

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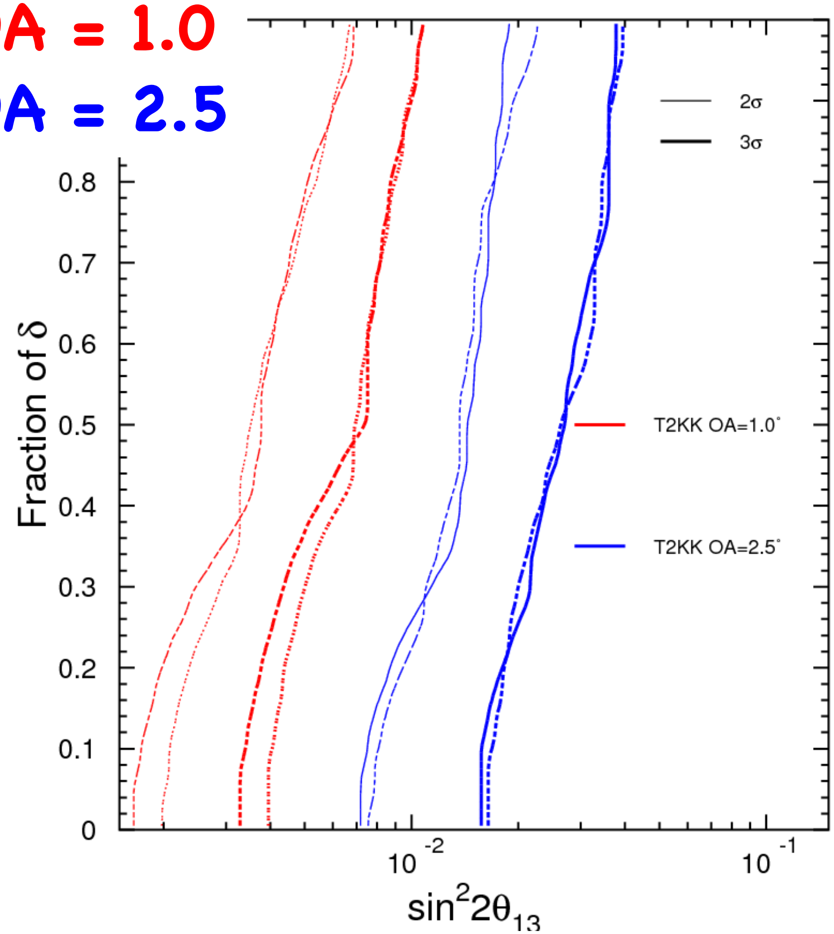
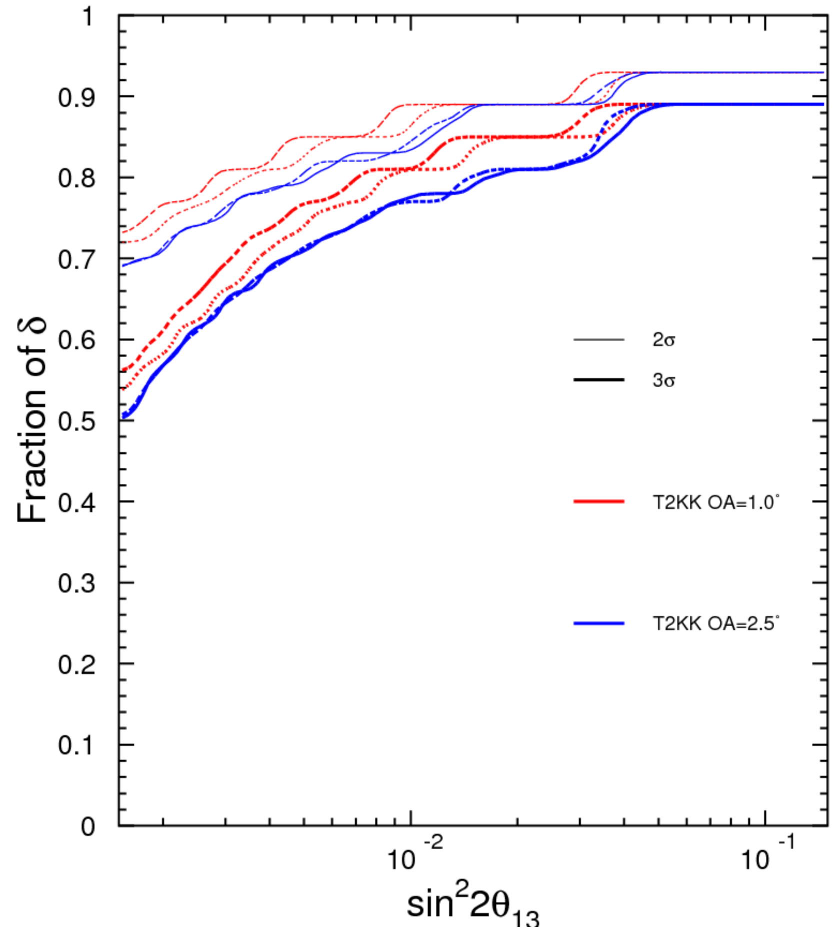




- The best results for mass hierarchy is given with the far detector located at 1° off-axis angle.
- The results for CP violation are comparable.

Conclusions

- A detector in Korea allows to extract information from the first and second ν_e appearance maximum.

- Dealing with NC background is a major challenge:
  - We constructed a likelihood which can remove around 70% of NC BG
  - 20% and 40% photo-coverage give similar results for BG rejection

- About location of the far detector:
  - For mass hierarchy: The T2KK setup with the Korean detector at 1° off-axis angle is the best.
  - For CP violation: There is no strong preference on the location of the far detector.

Backups...

Converting running conditions

	Workshop	Fanny	Comments
Proton energy	30 GeV	40 GeV	Given, cannot change
Beam power	1.66 MW	1.66 MW	Want to keep constant
POT/yr	3.45×10^{21}	2.6×10^{21}	
Running sec/year	10^{7} sec	10^{7} sec	
Proton/bunch	8.3×10^{13}		
Bunch/cycle	8		
Rep. Cycle	1.92		
#proton/rep cycle	34.5×10^{13}	26×10^{13}	Accelerator conditions

To keep beam power constant with higher energy protons,

Eq 1) >>> I have to decrease the number of POT accordingly.
Eq 2) >>> I have to loosen the Accelerator conditions.

Converting POT....

I only had flux files that were generated with 40 GeV protons but the running conditions for the workshop specify 30 GeV protons.

How to convert properly?

Quick reminder:

$$\text{POT} = \frac{(\text{proton/bunch}) * (\text{bunch/cycle}) * (\text{sec/year})}{\text{reptition cycle}} \quad \text{eq (1)}$$

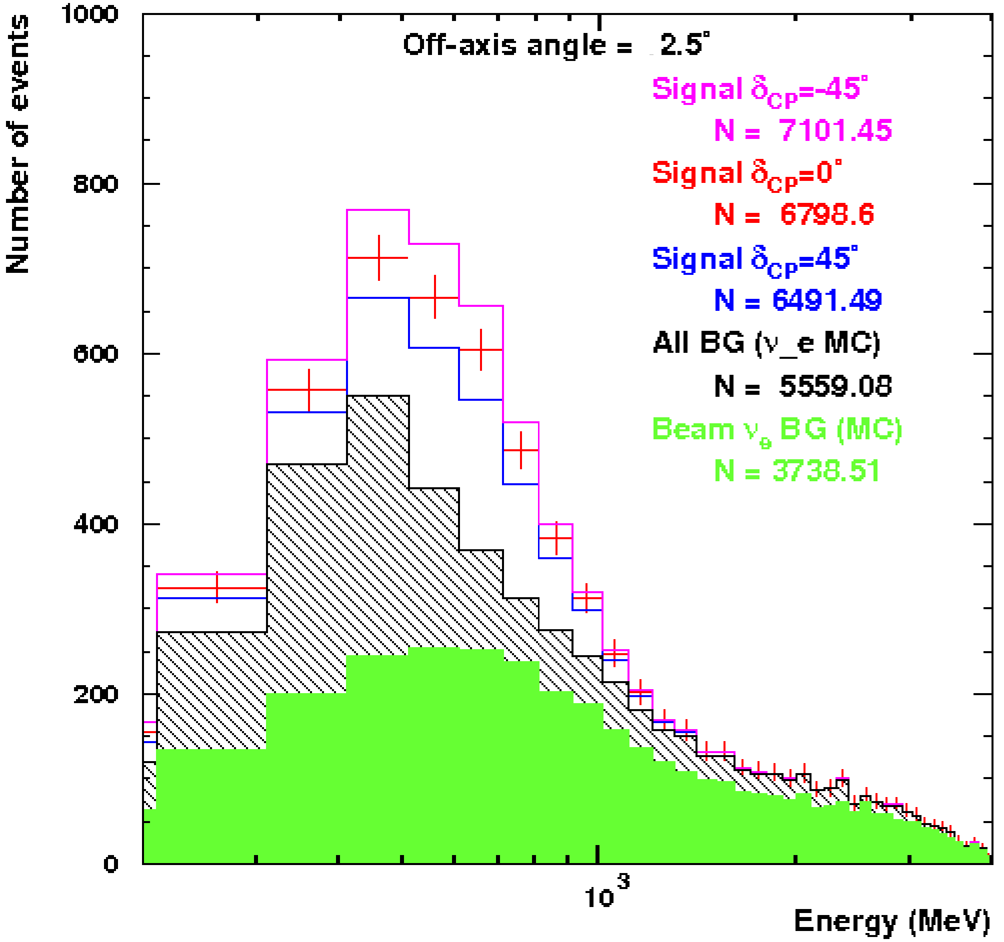
(proton/bunch) * (bunch/cycle) → proton/cycle

$$\text{Neutrino flux} \propto \text{Beam power} = \frac{\text{Energy (protons)} * (\text{protons/cycle})}{\text{repetition cycle}} \quad \text{eq(2)}$$

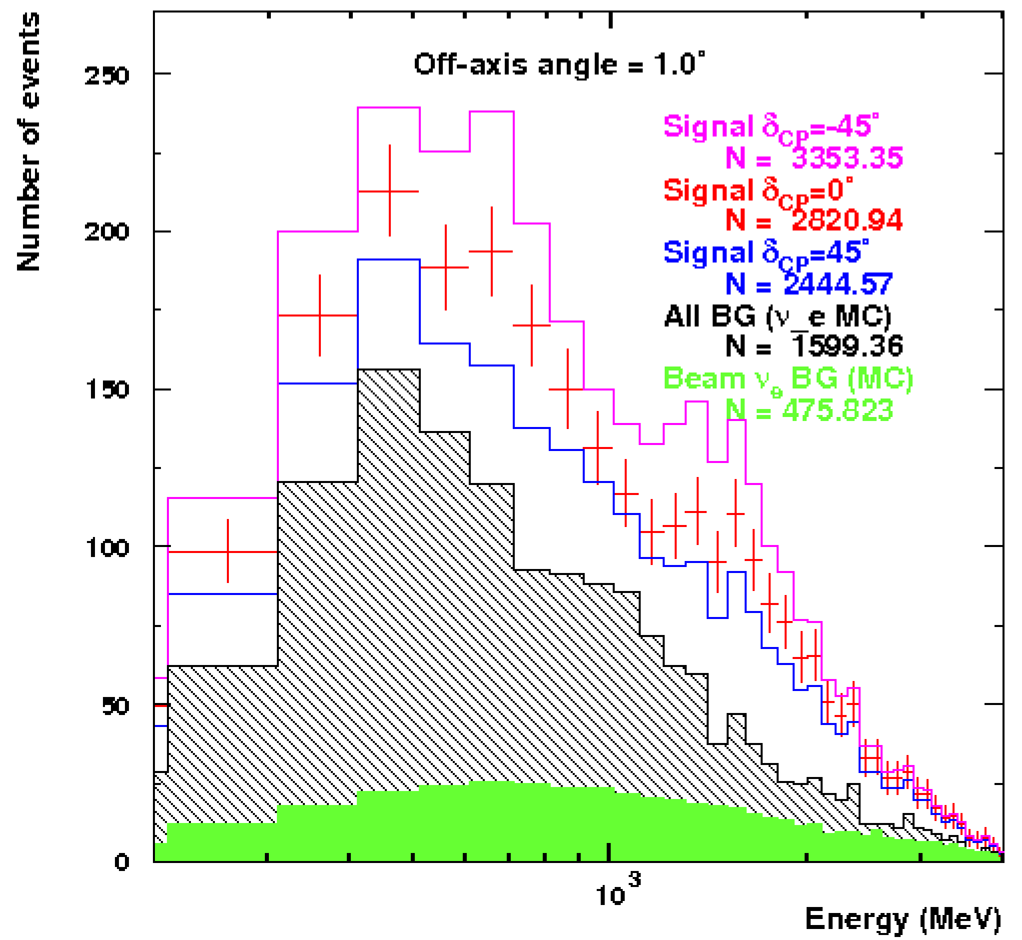
So what I want to keep constant is the beam power, since the neutrino flux is proportional to the beam power

T2KK results using best likelihood

Spectrum at Kamioka



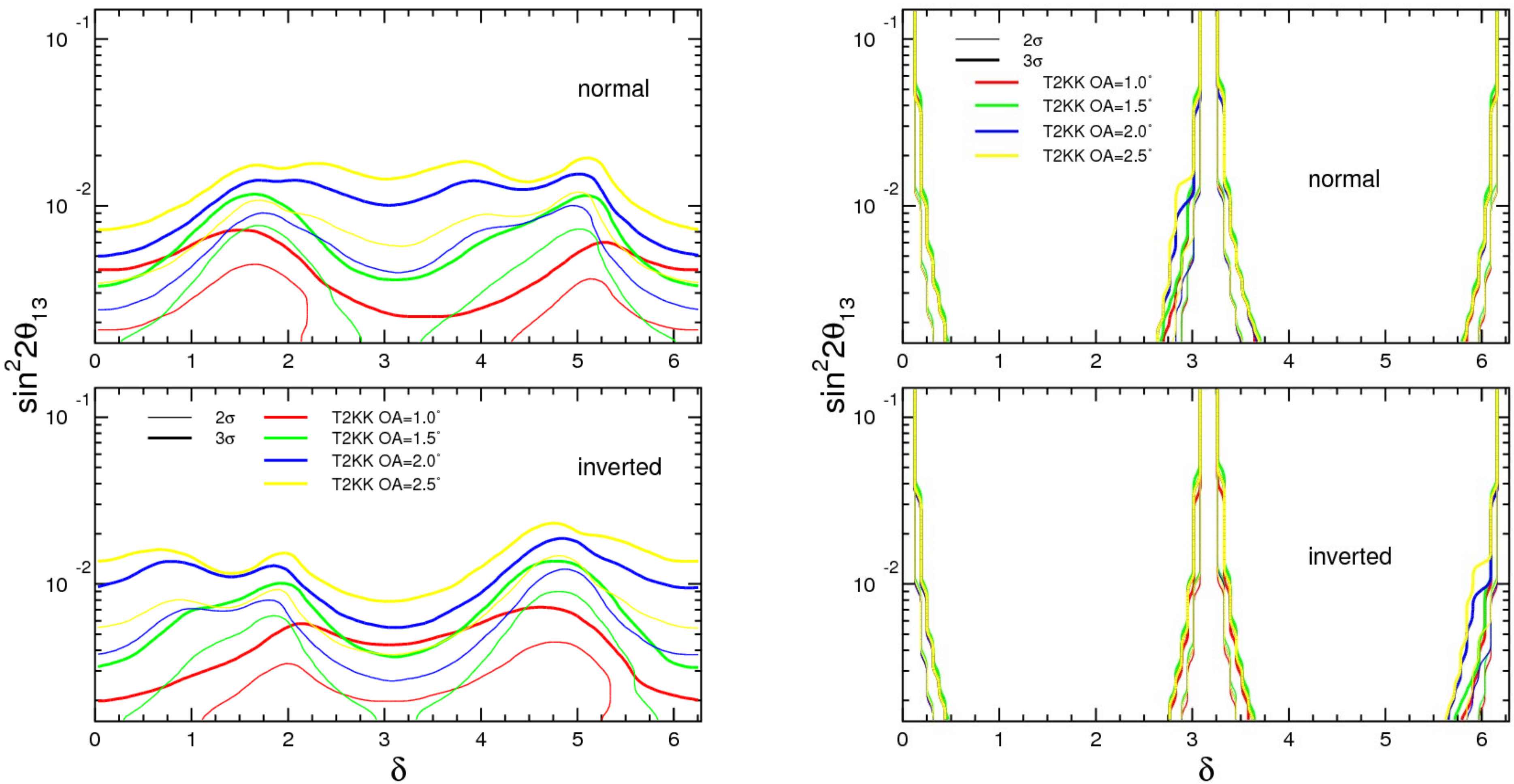
Spectrum in Korea 1°OA



$Sin^2(2\theta_{13})$=0.04, neutrino, normal hierarchy (4MW etc...)

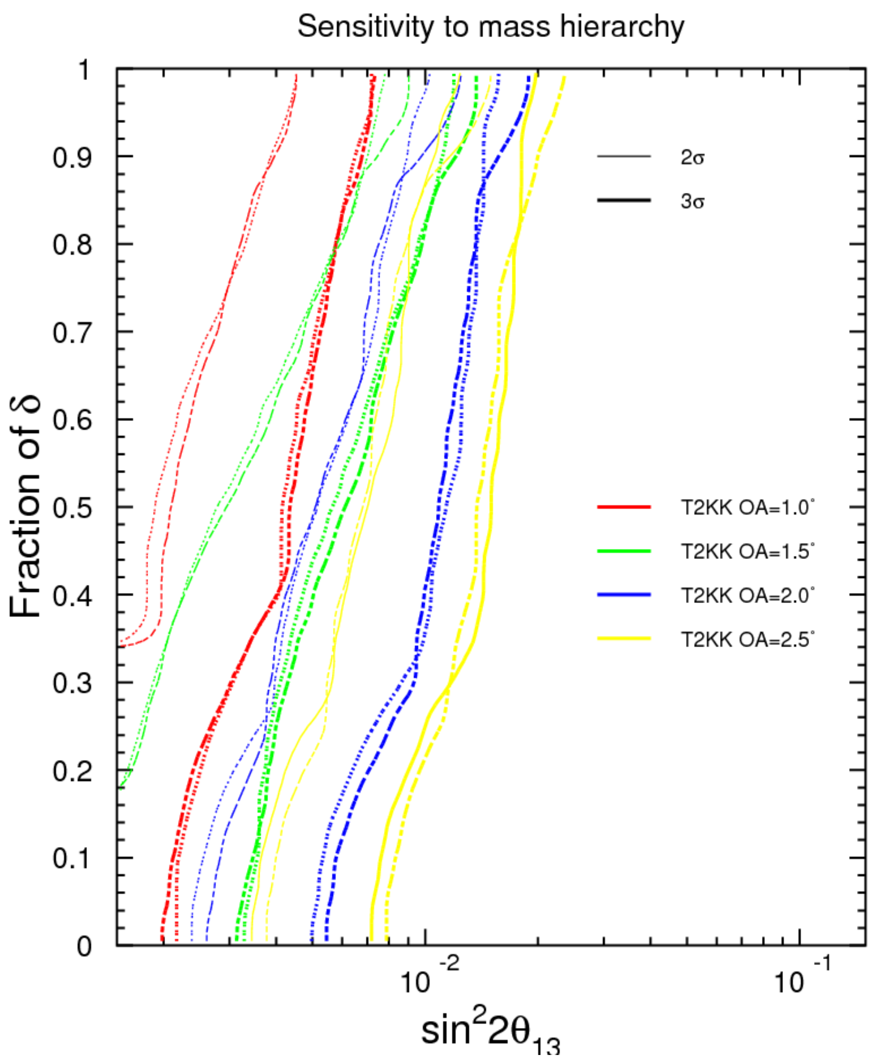
Region plots (4MW etc...)

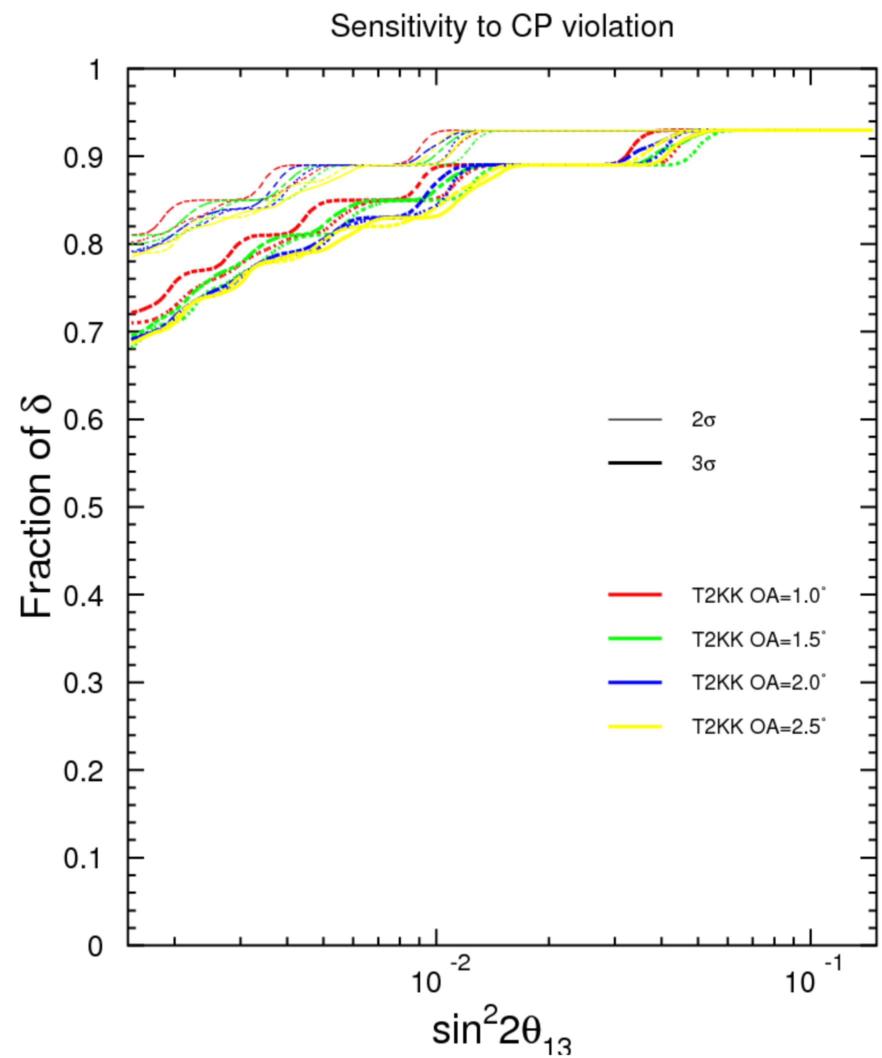
Best mass hierarchy sensitivity for OA = 1°
Doesn't matter much for CP violation



Fraction plots (4MW etc...)

Best mass hierarchy sensitivity for OA = 1°
Doesn't matter much for CP violation





Background simulation (NC)

Compare the background simulation obtained with

Full SK Monte Carlo (MC method):

Use the atmospheric Monte Carlo sample.

Get very realistic energy resolution

Smearing method:

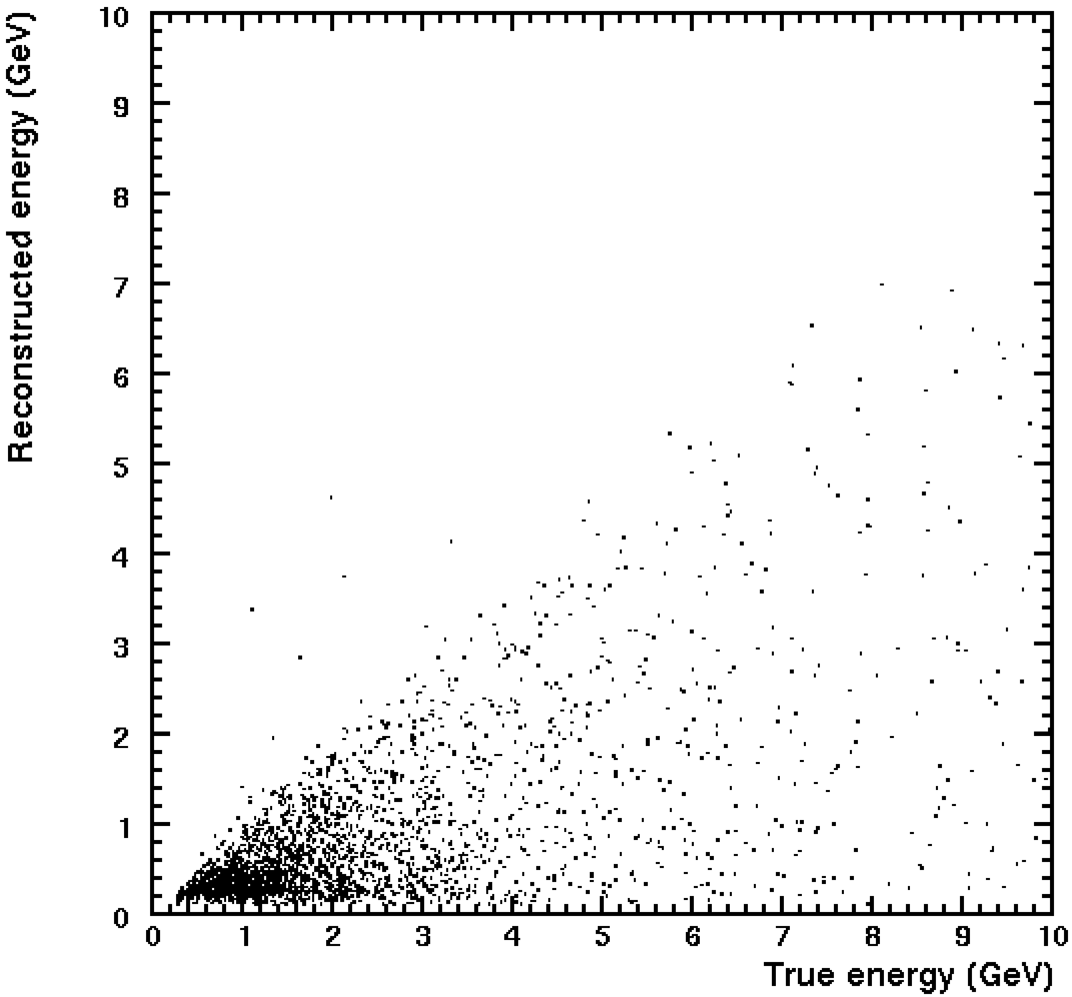
Start with a neutrino flux spectrum and multiply by energy smearing matrix and efficiencies.

Similar to GloBES, but I am not using GloBES itself

Question: Is the smearing approach as good as using a Monte Carlo sample?

Example of energy smearing for NC

Dealing with energy response is crucial!



True energy:

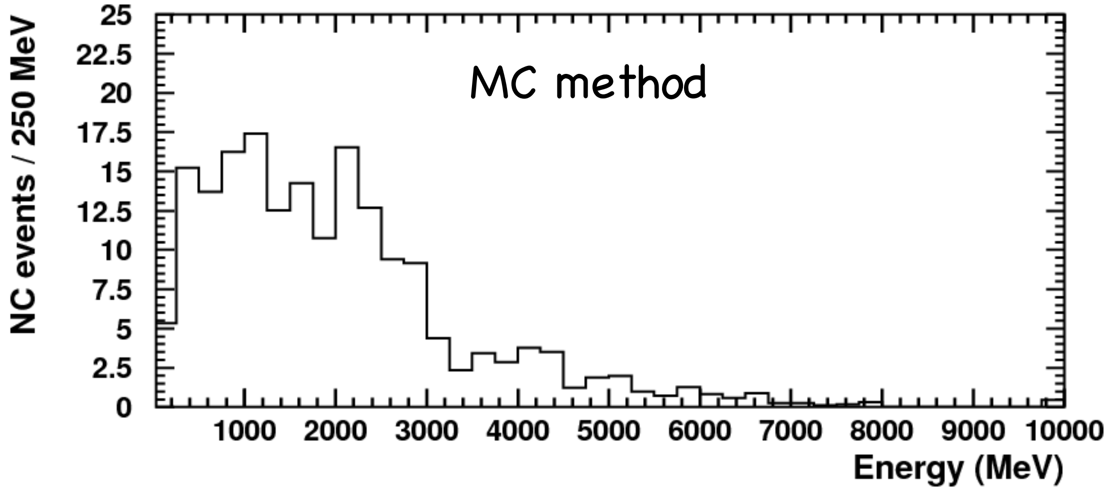
This is the true neutrino energy

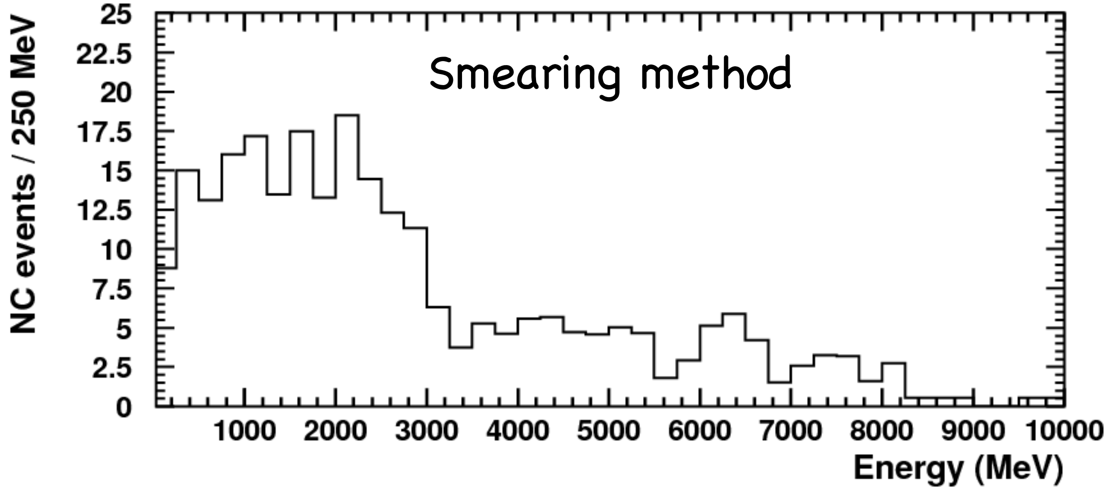
Reconstructed energy:

$$E_{rec}=\frac{m_n E_e - m_e^2/2}{m_n - E_e + (P_e \cos\theta_{\nu e})}$$

We used SK atmospheric MC, NC events, for events that passed the precuts.

Comparison of background





Both methods give very similar spectra, even if the amount of high energy background, varies slightly.

The smearing approach is suitable as long as the response from E_{true} to E_{rec} for neutral current is properly used.

What kind of background?

- $\nu_\mu \rightarrow \mu$ with e/μ misidentification

good e/μ ring identification
0.7%

- ν_e contamination in the beam

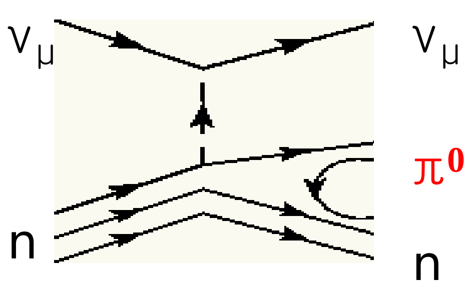
$$K \rightarrow \pi \nu_e e$$

$$\mu \rightarrow e \nu_\mu \bar{\nu}_e$$

0.2-0.3%
Known from 2km detector

- π^0 when one of the γ is missed:

Main source of background



- produced by neutral current