T2K + Korea = T2KK

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?

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NOW 2008
Sept 6th-13th 2008

Thanks to T.Kajita, K. Okumura and E. Kearns for their help with this study.

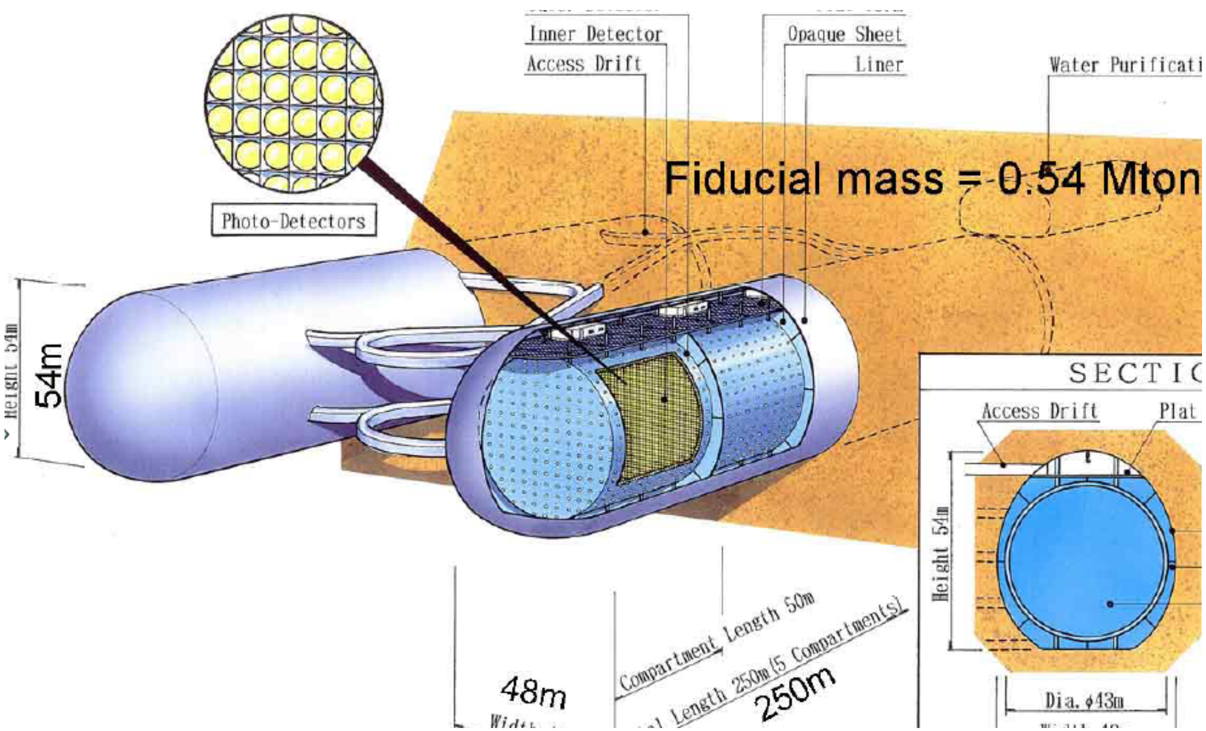
The Hyper-K project

In addition to ν_e appearance:

- 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.



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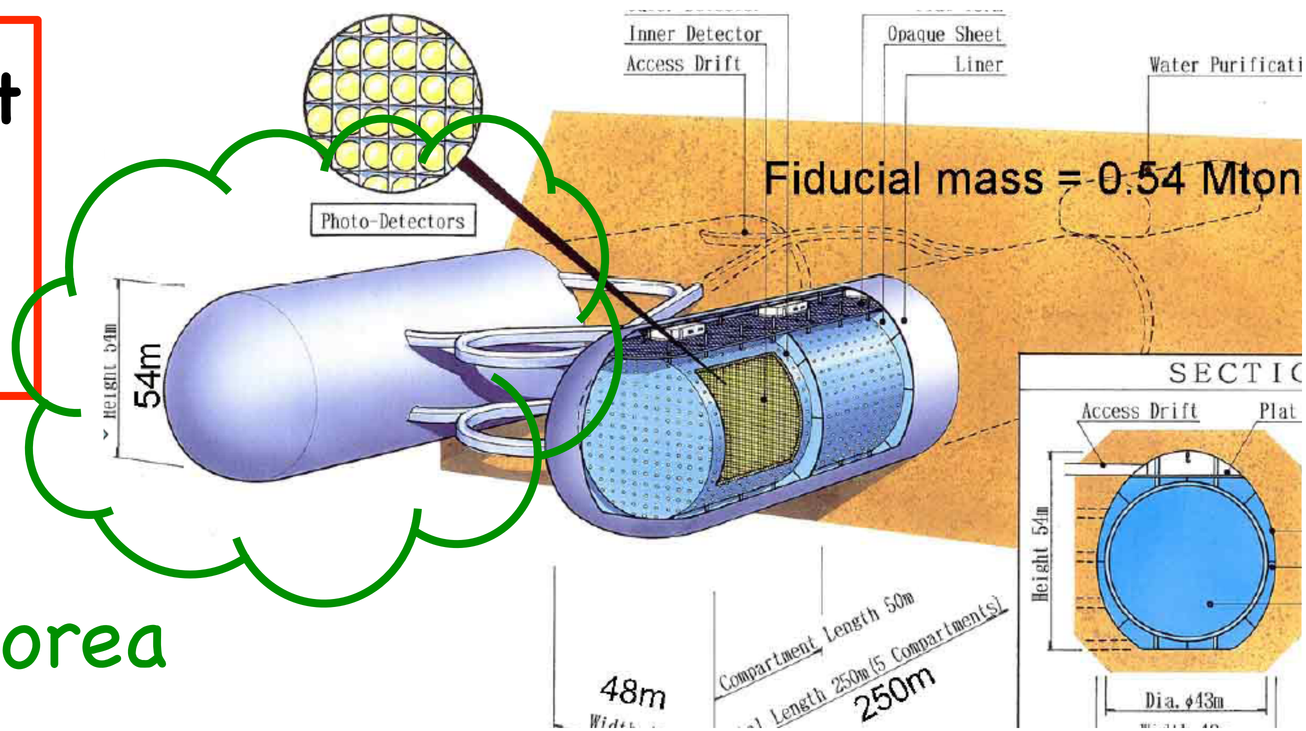
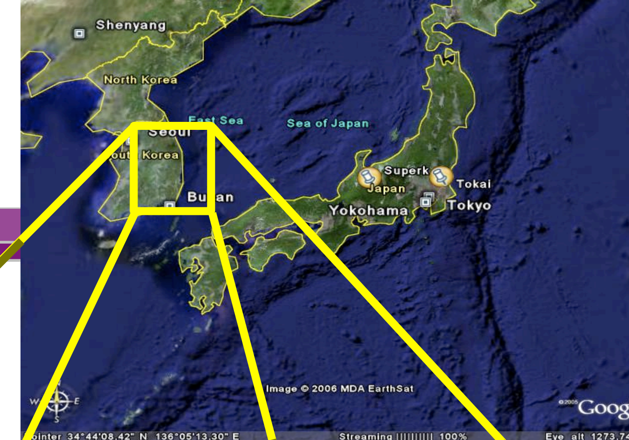


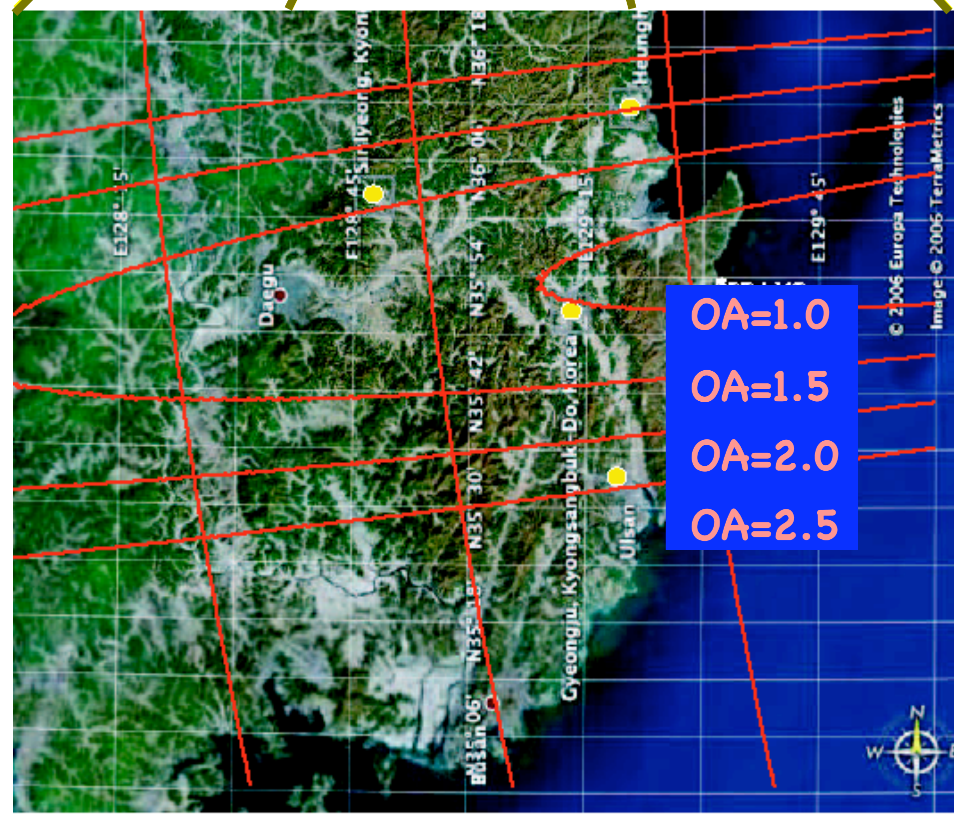
Could be built in Korea

Why & where in Korea?



Why:

- Observe both **first and second** oscillation maximum in ν_e appearance.
- 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, the smallest off-axis angle available is 1.0° .
- Four off-axis angles have been considered

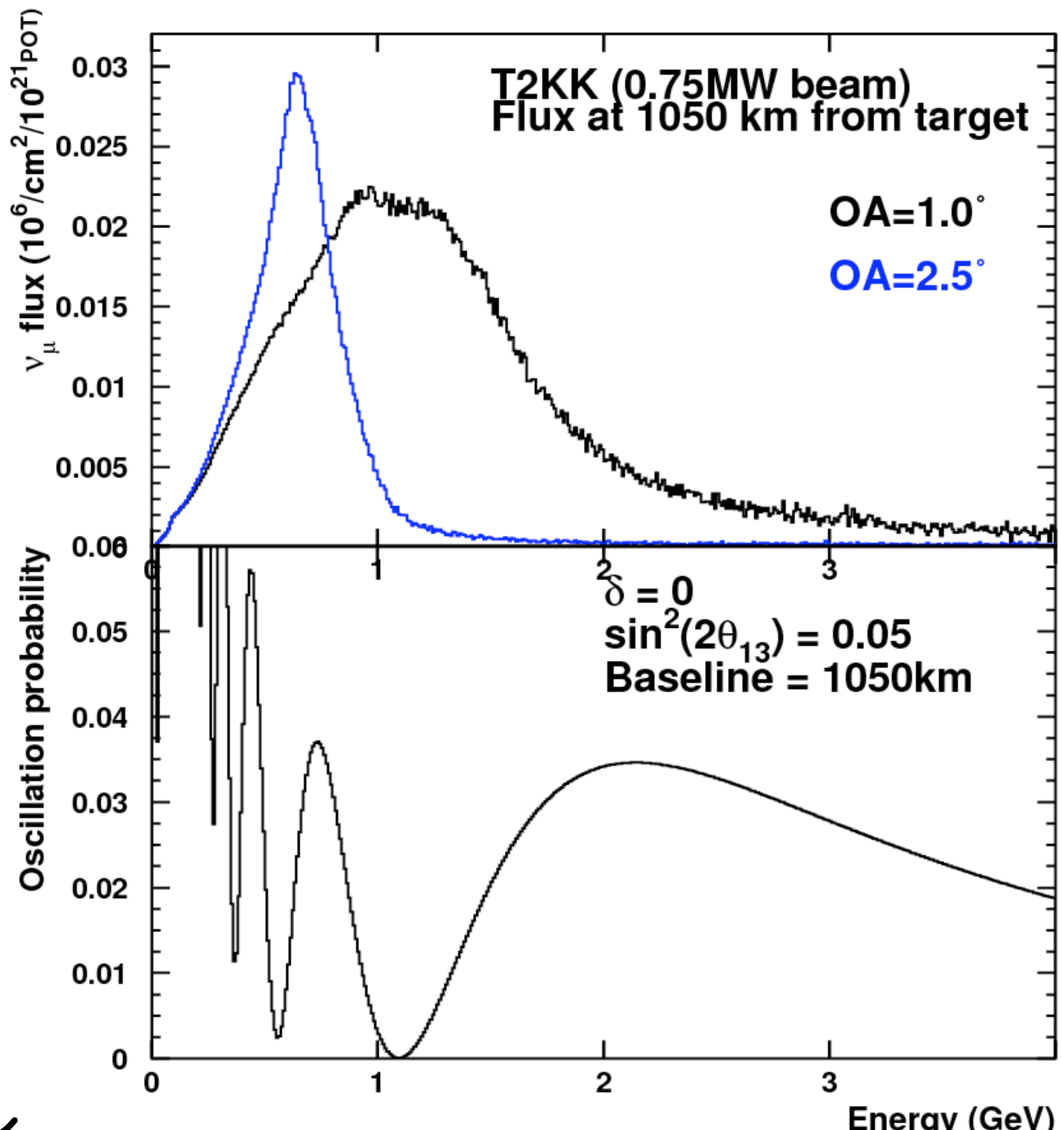
Flux and appearance in Korea

Small off-axis angle:
(high energy tail)

- ✓ 1^{st} appearance peak
- × more NC background

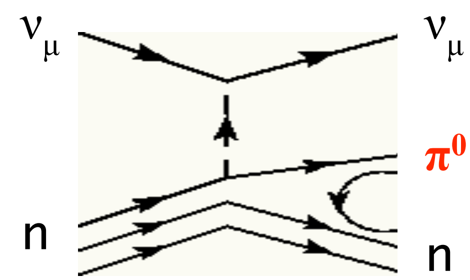
Big off-axis angle:
(narrow peak)

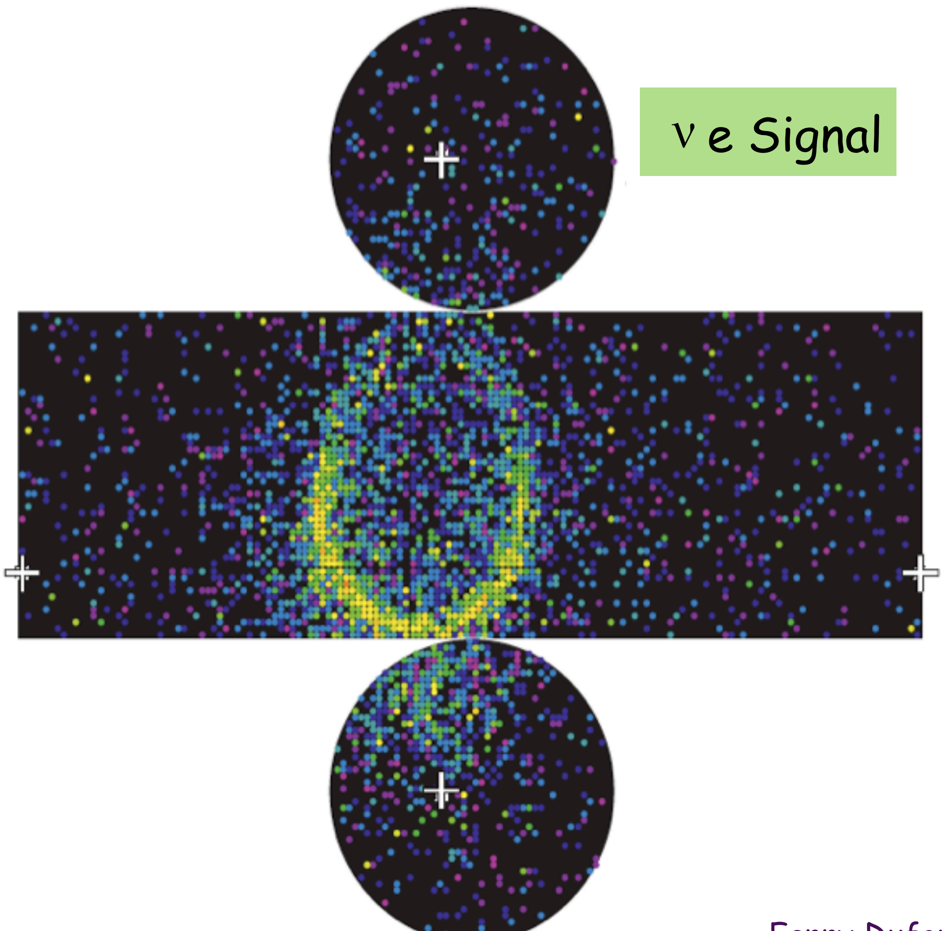
- ✓ Low background
- × Low statistics at high E
- × Only 2^{nd} appearance peak

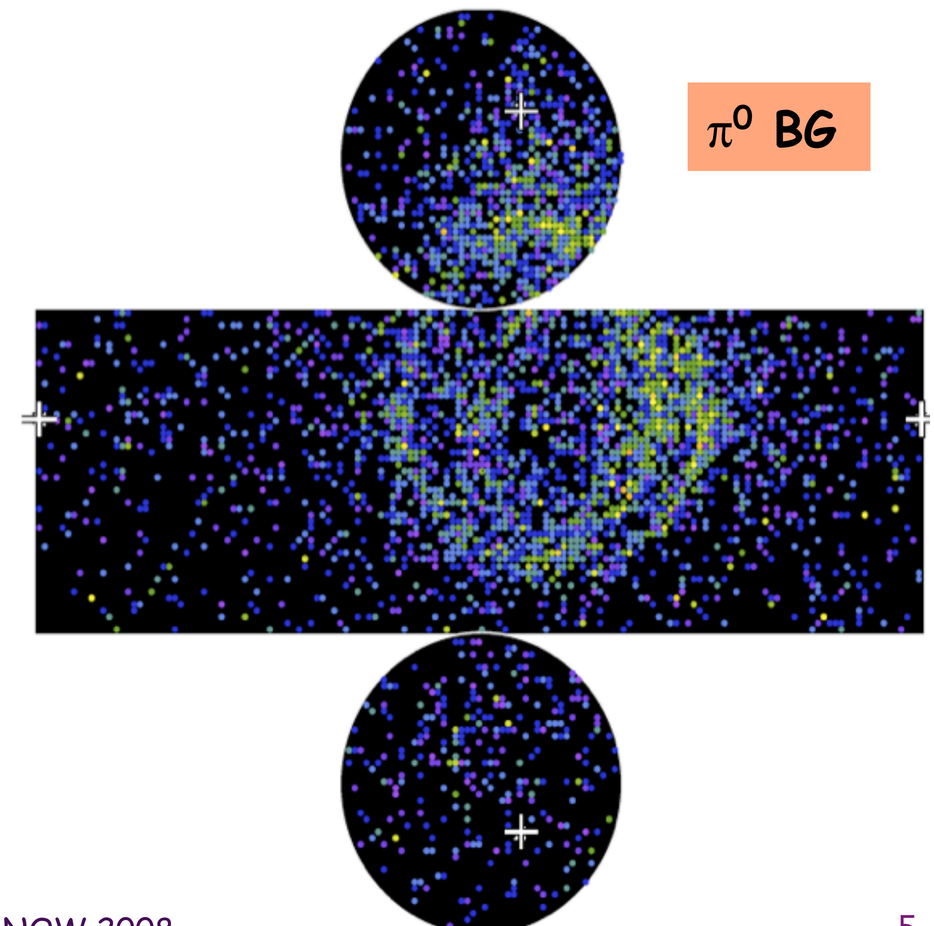


NC background

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







Likelihood analysis: basics

- 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 a likelihood (see slide 9)
- We use SK atmospheric MC and we checked its accuracy by comparing it to the SK atmospheric data.

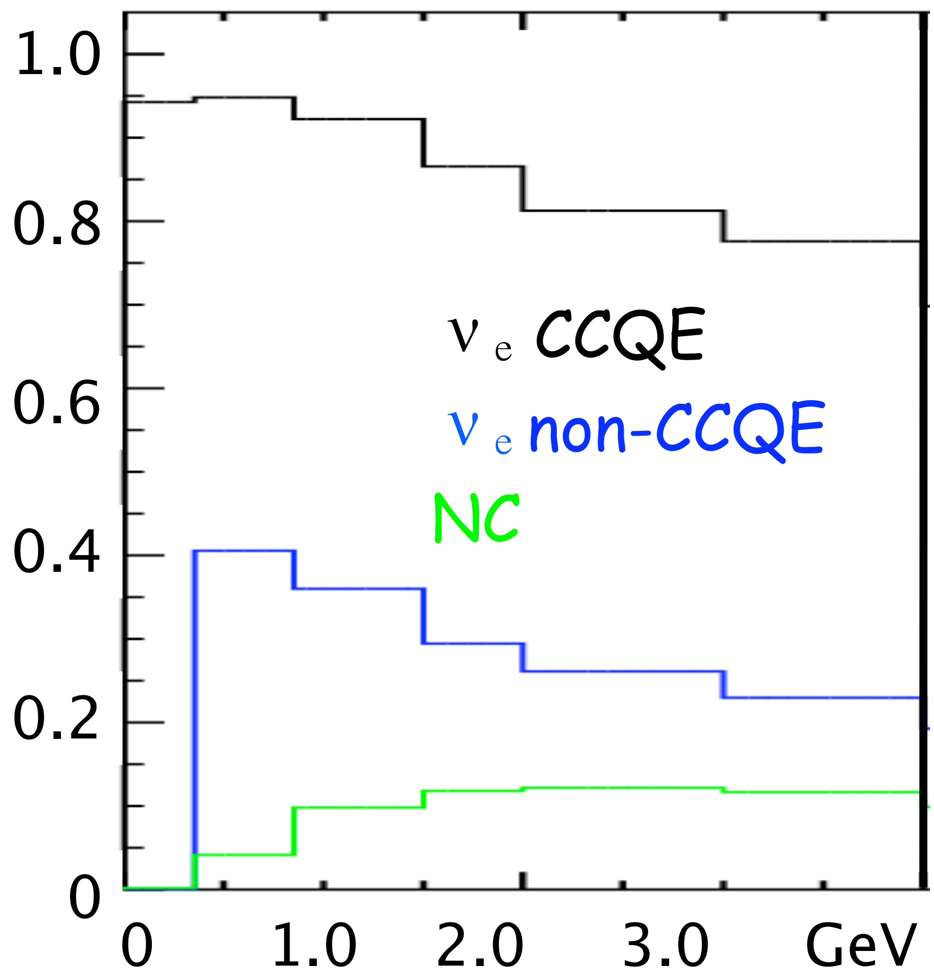
Likelihood analysis sample

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.

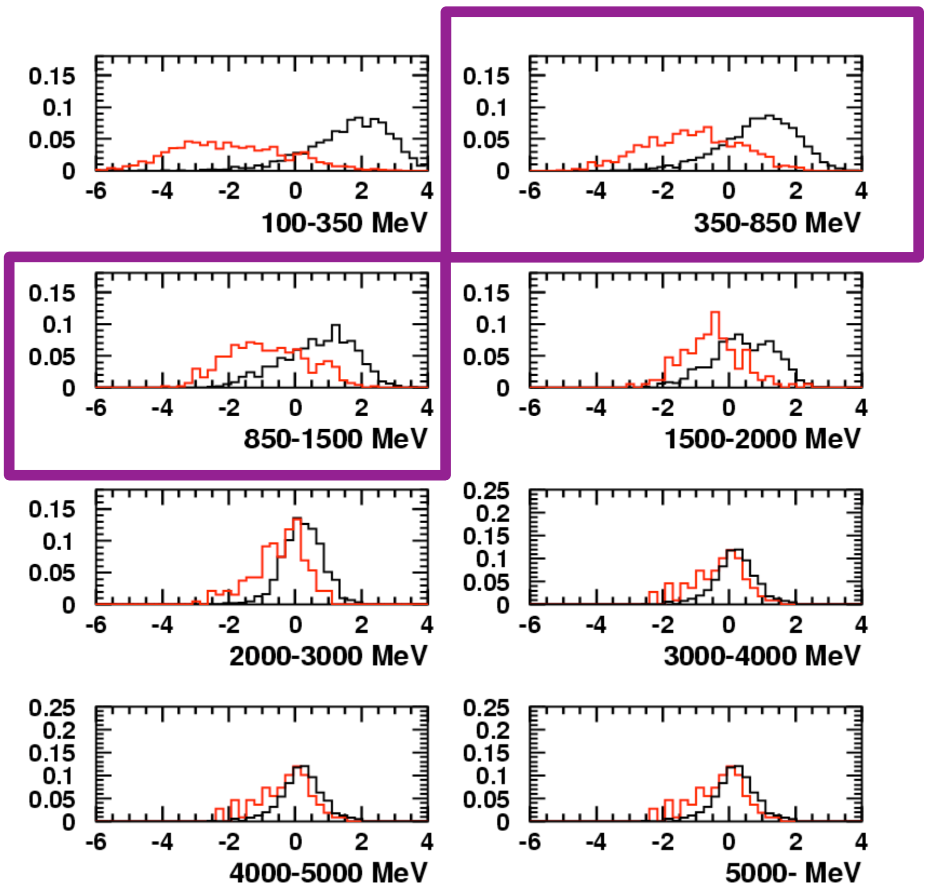
NB: the ν_μ mis-ID BG is not plotted because it is always below 0.01

Precuts effciency



Likelihood analysis: variables

Likelihood per energy bin



Background

Signal (Main signal bin)

Likelihood variables:

Standard SK variables:

ring parameter, PID parameter

Variables related to π^o in SK.

Variables using beam direction info.

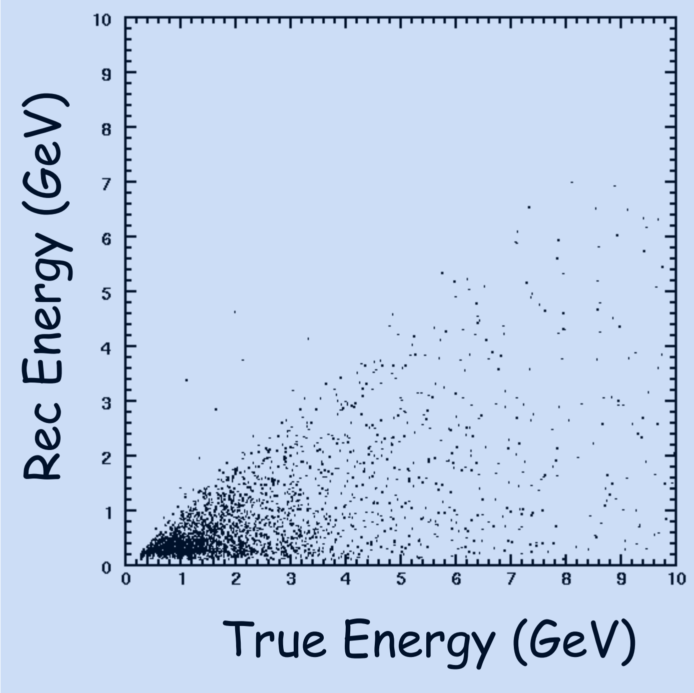
Final likelihood efficiency

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
0-350 MeV	86%	12%
350-850 MeV	81%	28%
850 MeV-1.5GeV	77%	23%
1.5 - 2.0 GeV	77%	29%
2.0 - 3.0 GeV	82%	15%
3.0 - 4.0 GeV	84%	19%
4.0 - 5.0 GeV	83%	25%
5.0 - 10.0 GeV	77%	NA

Background Simulation

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



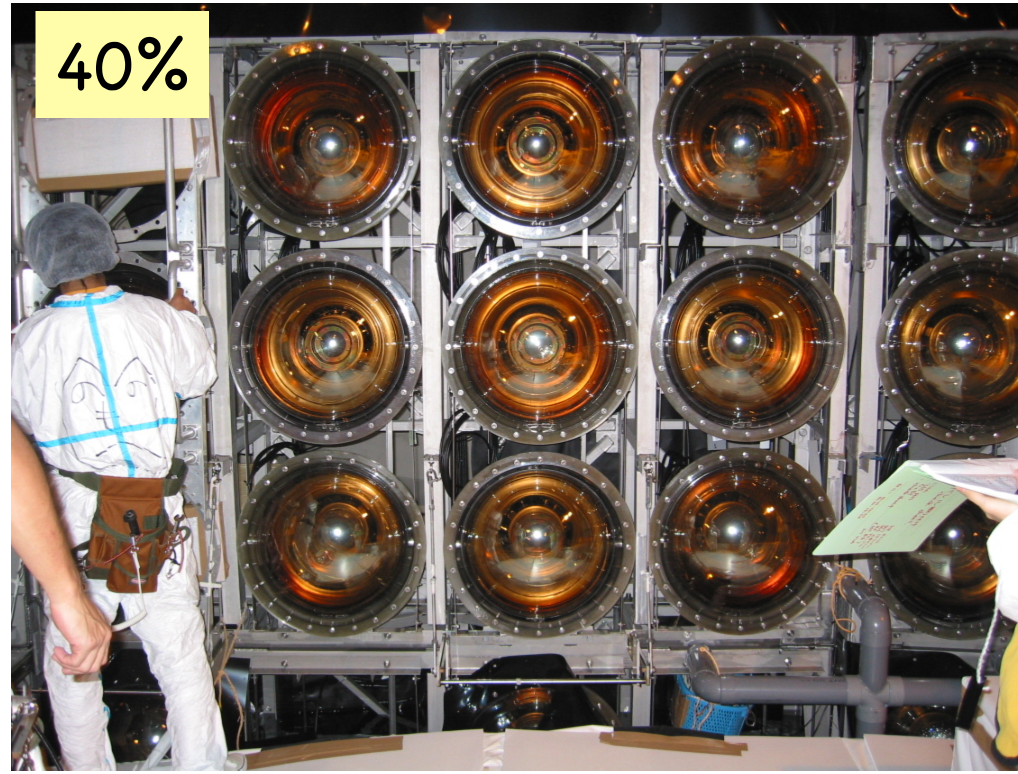
- Run over SK atmospheric MC:
- Keep events if: single ring, electron-like with no decay electron, inside fiducial volume

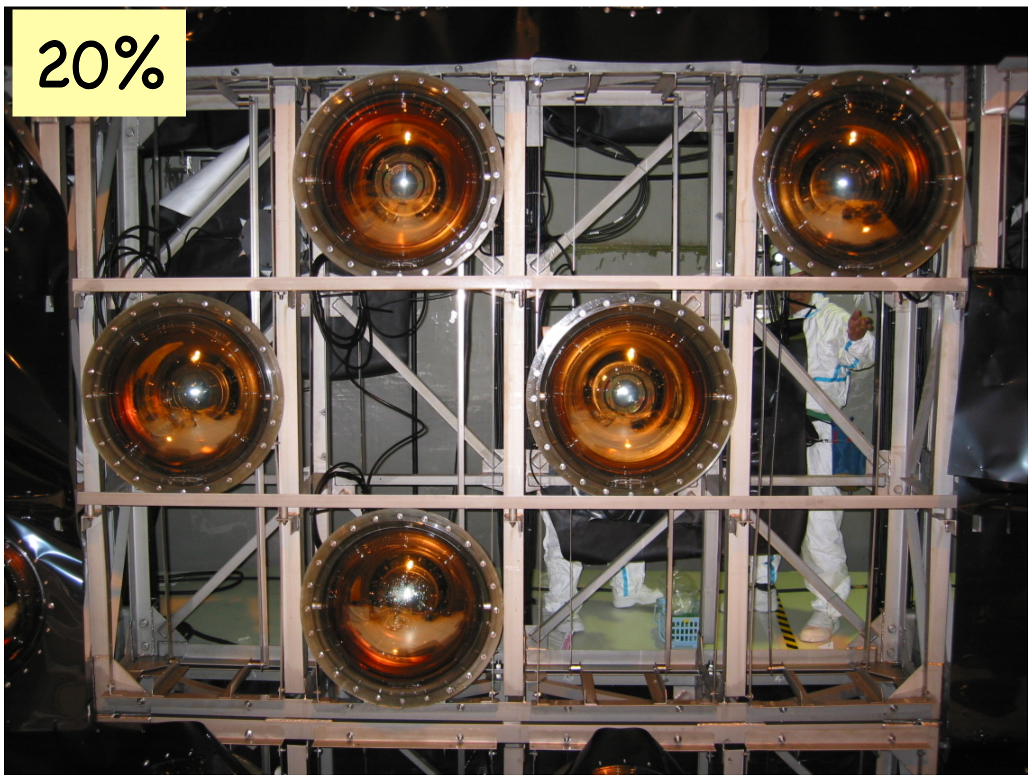
  ie. precuts!
- Apply likelihood efficiency as a function of reconstructed energy. Using reconstructed energy takes care of the energy response.

  ie. likelihood!
- Re-weight BG by ratio: (beam ν_μ flux/atmospheric ν_μ flux)
- Normalize for running conditions (#POT, time, volume)

What about the photo-coverage?

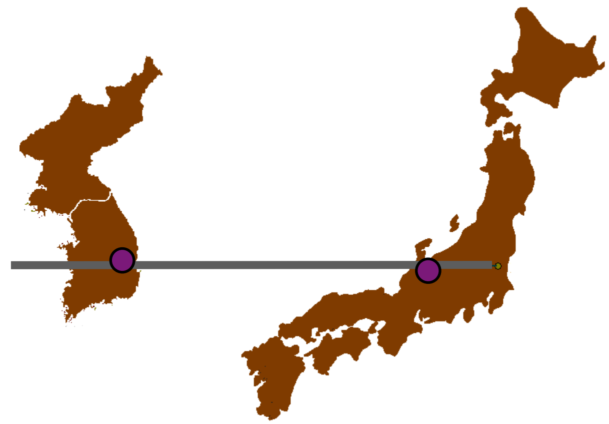
"Thanks" to the accident in SK, we have MC corresponding to 20% and 40% photo-coverage





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

The T2KK setup

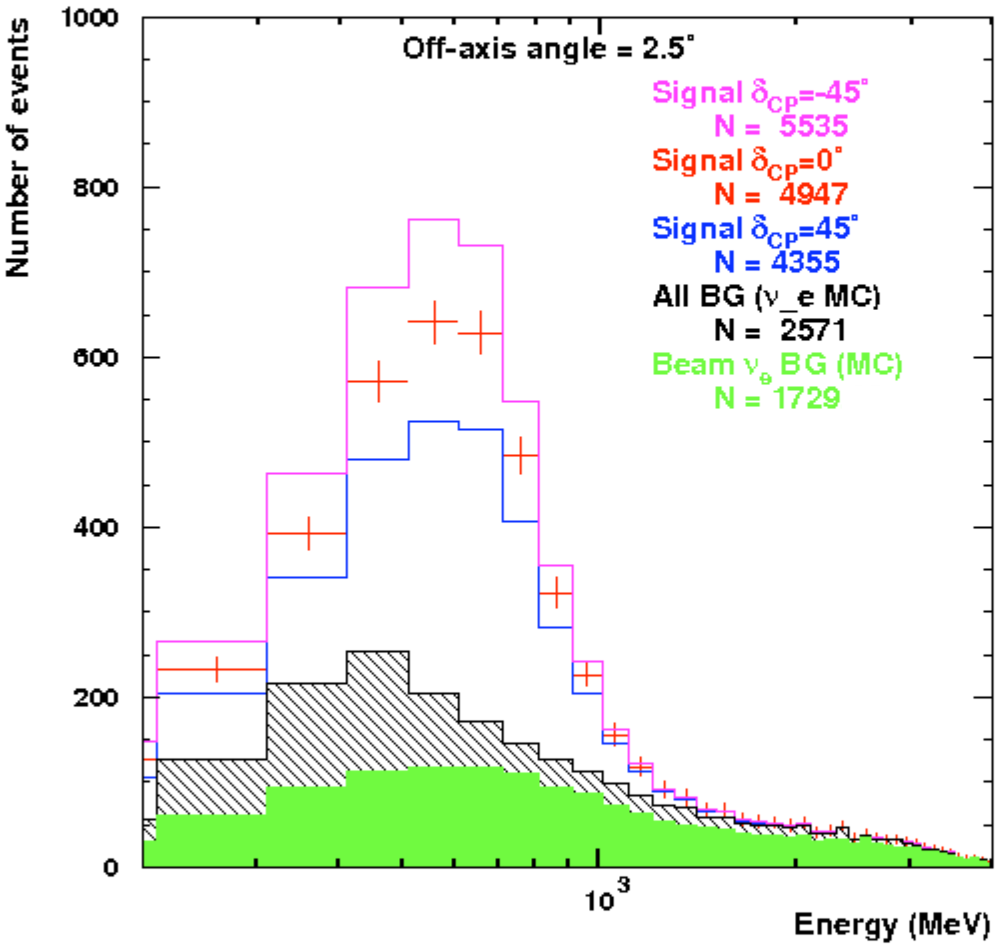


Volume	2 times 0.27 Mton (FV)
Beam Power	1.66 MW
Running time	5 yrs nu + 5 yrs antinu
1 year is	10^7 seconds
Proton energy	30 GeV
Tot # of POT	3.45×10^{21} POT
Distance	295 km and 1050 km
Off-axis angle	2.5 ° and 1.0 ° OA

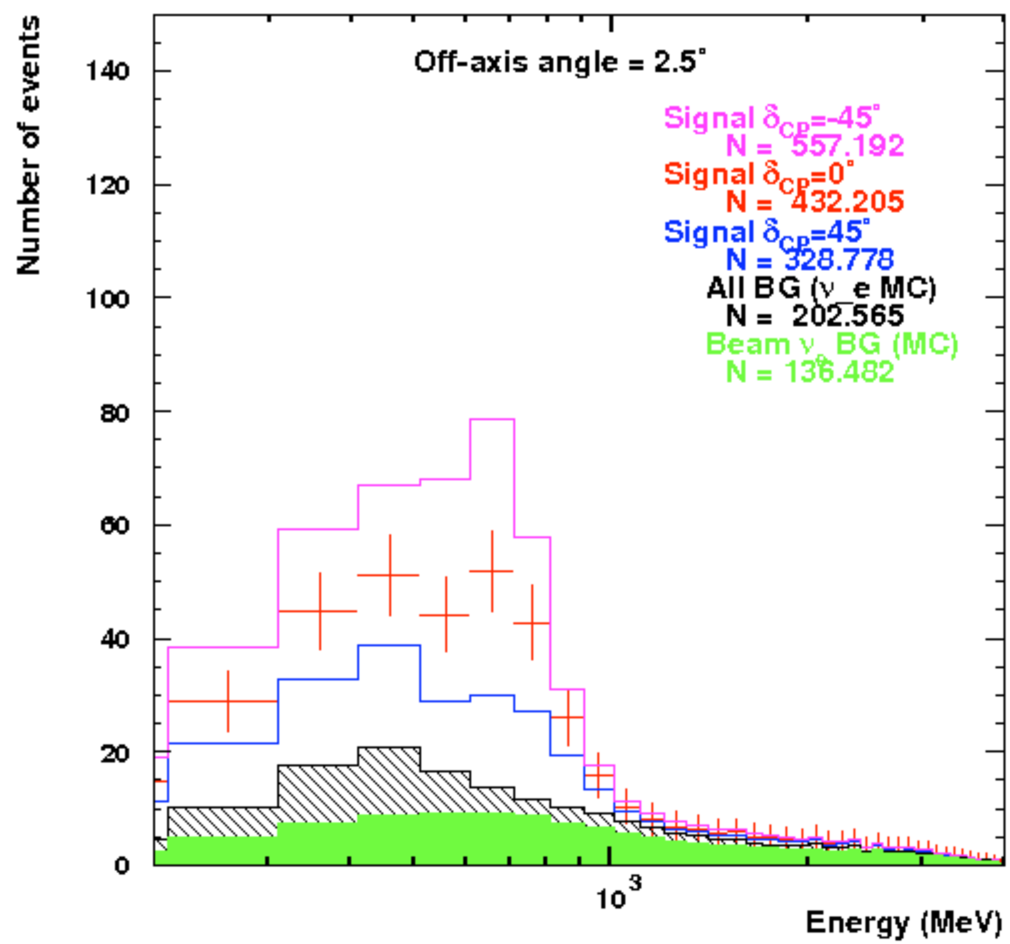
Note: not 4MW as presented in previous T2KK studies

2.5 degree off-axis angle

Spectrum at Kamioka



Spectrum at Korea 2.5° OA

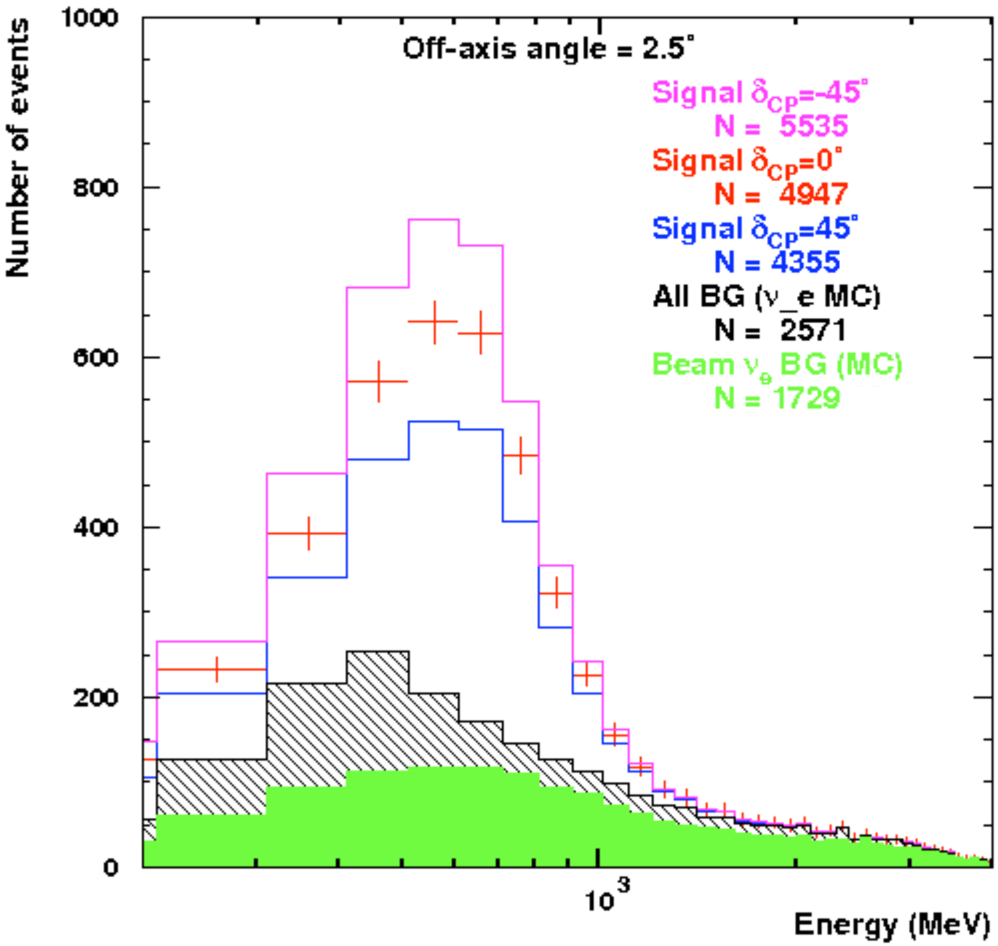


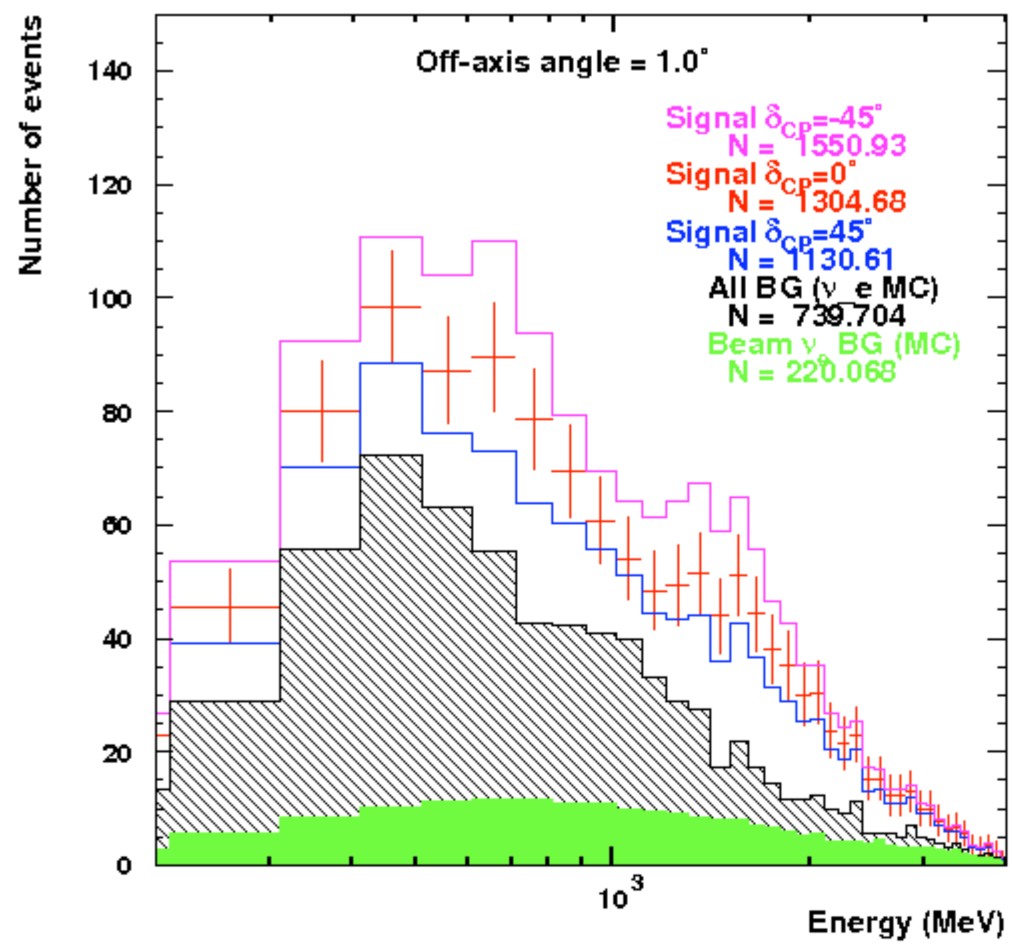
$\sin^2(2\theta_{13})$=0.04, neutrino, normal hierarchy

1.0 degree off-axis angle

Spectrum at Kamioka

Spectrum at Korea 1.0° OA





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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 antineutrino

j=1,15

We have 15 systematic errors.

New since NP08 and Neutrino 2008

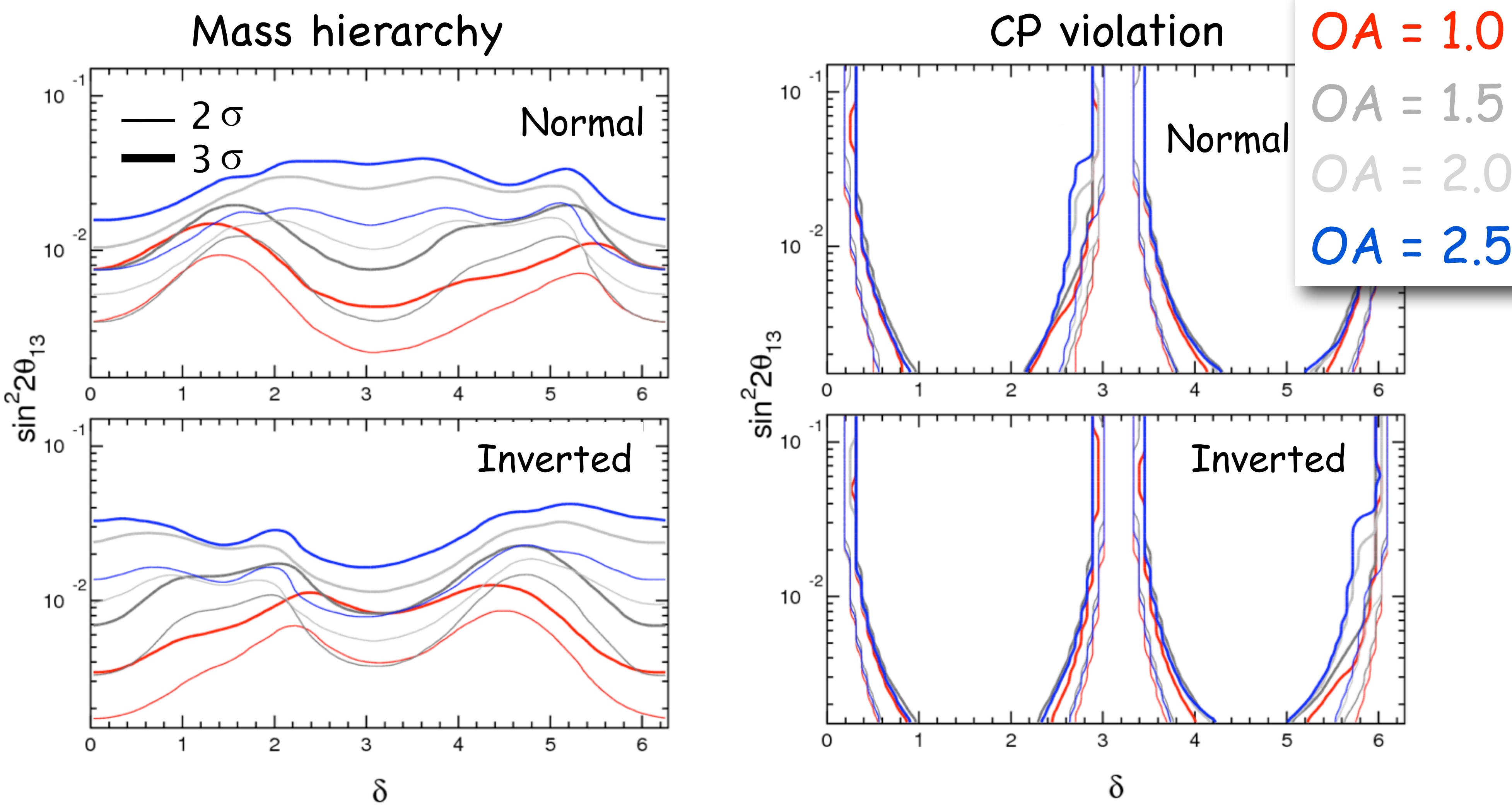
(before we had 9 terms)

With the following energy bins (MeV):

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

$$\chi^2 = \sum_{k=1}^{4} \left(\sum_{i=1}^{7} \frac{(N(e)_i^{obs} - N(e)_i^{exp})^2}{\sigma_i^2} \right) + \sum_{j=1}^{15} \left(\frac{\epsilon_j}{\tilde{\sigma}_j} \right)^2$$

Sensitivity for 2 off-axis angles



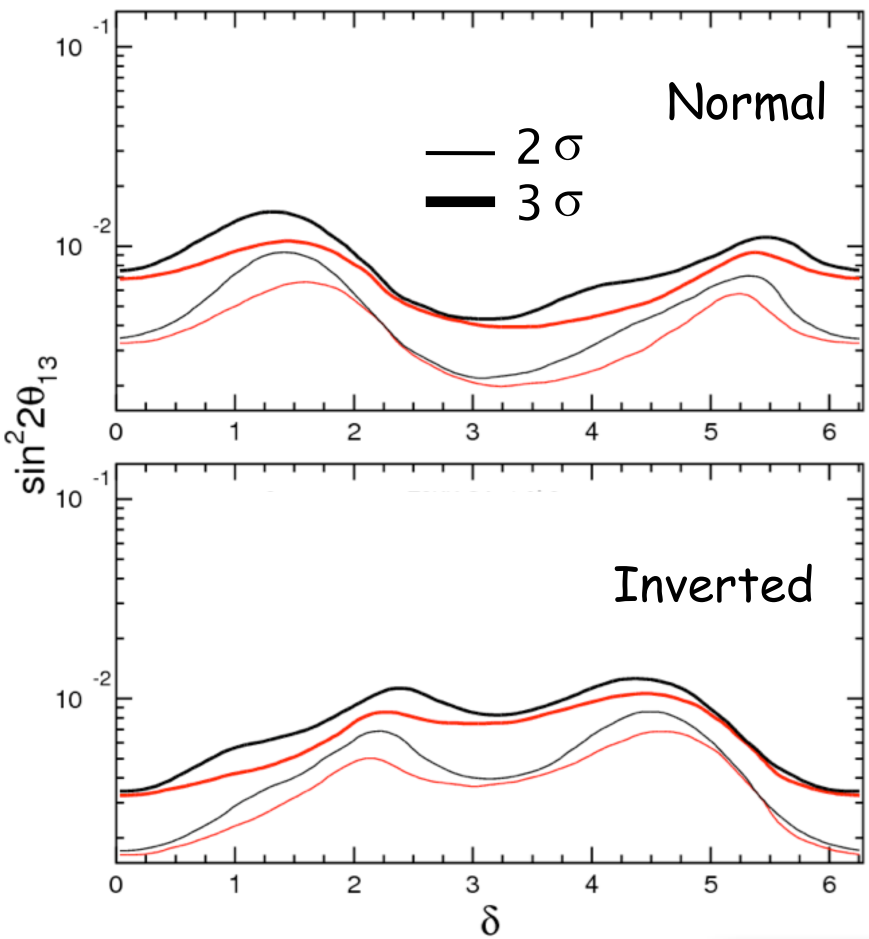
- The best results for mass hierarchy is given with the far detector located at 1° off-axis angle.
- The results for CP violation are comparable.

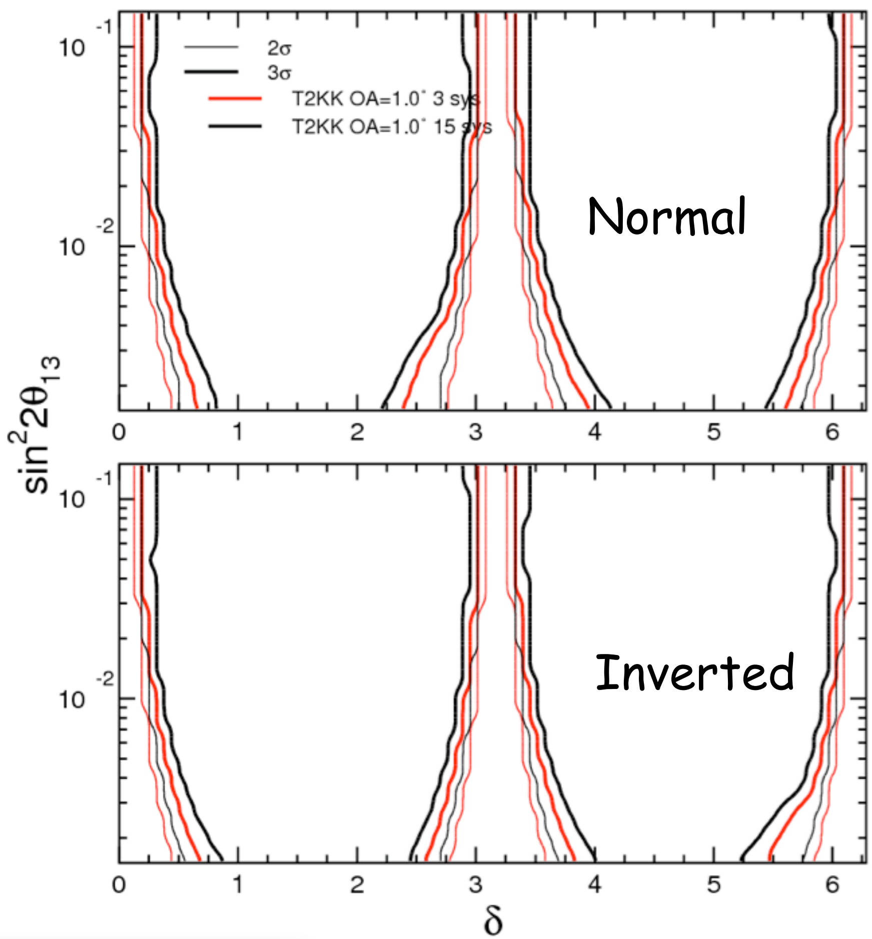
Conclusions

- 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 after the precuts are applied.
  - 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...

Effect of systematics





T2KK 1° OA 15 systematics
T2KK 1° OA 3 systematics

Systematic errors

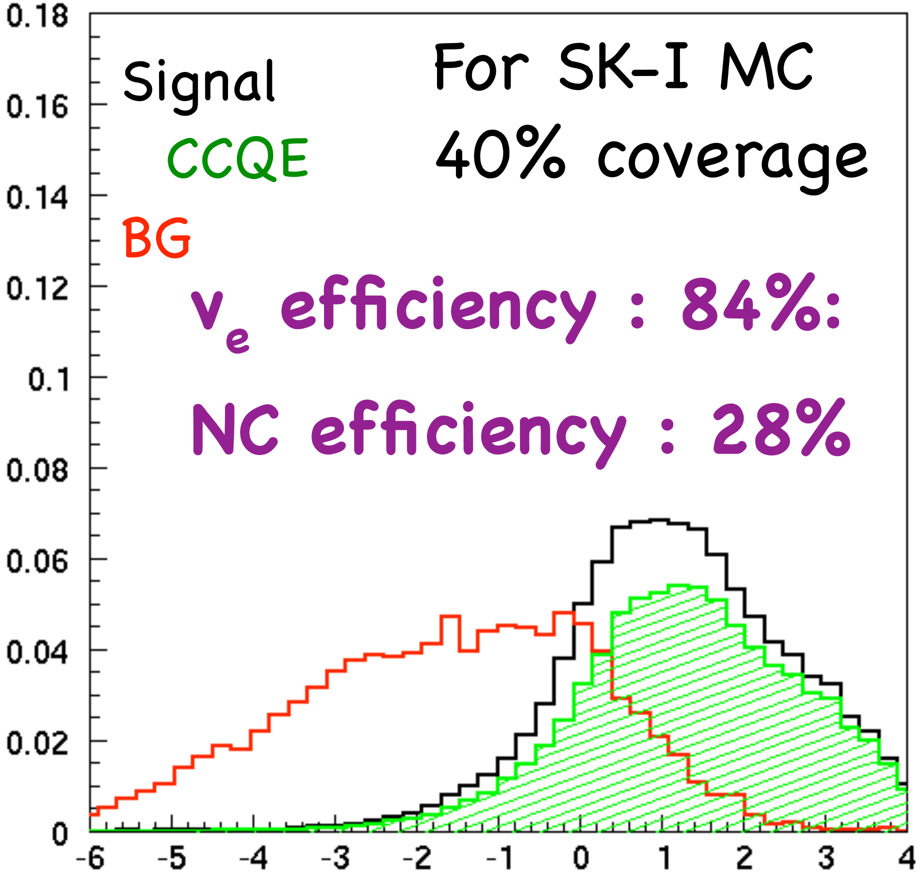
Systematic errors	Value
BG normalization below 1.2 GeV (Kamioka)	5%
BG normalization above 1.2 GeV (Kamioka)	5%
BG normalization below 1.2 GeV (Korea)	5%
BG normalization above 1.2 GeV (Korea)	5%
BG norm. between ν_e and anti-ν_e below 1.2 GeV	5%
BG norm. between ν_e and anti-ν_e above 1.2 GeV	5%
BG spectrum (common for Kamioka and Korea)	5%
Signal normalization below 1.2 GeV	5%
Signal normalization above 1.2 GeV	20%
$[\sigma(\nu_\mu)/\sigma(\nu_e)]/[\sigma(\nu_\mu)/\sigma(\nu_e)]$ below 1.2 GeV	5%
$[\sigma(\nu_\mu)/\sigma(\nu_e)]/[\sigma(\nu_\mu)/\sigma(\nu_e)]$ above 1.2 GeV	5%
Efficiency difference between Kamioka and Korea < 1.2GeV	1%
Efficiency difference between Kamioka and Korea > 1.2GeV	1%
Energy scale difference between Kamioka and Korea	1%
Energy scale difference between near and Kamioka/Korea	1%

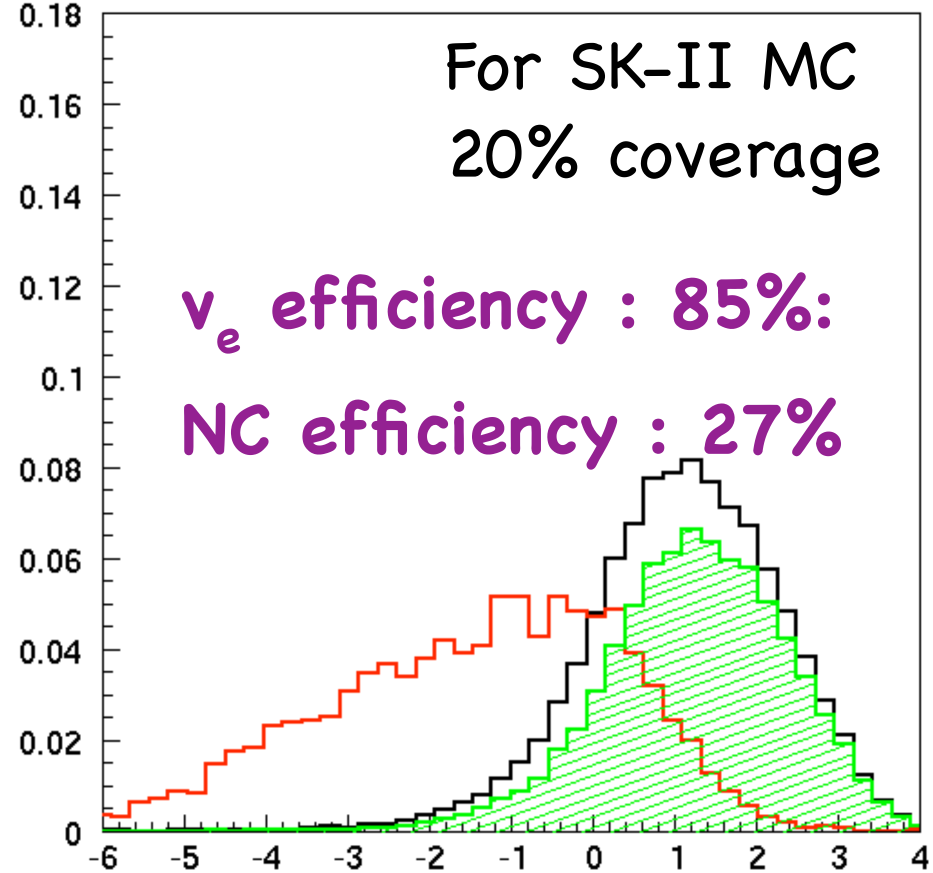
Error on BG variables

Error on Signal variables

Error on Kamioka/Korea

Photo-coverage results

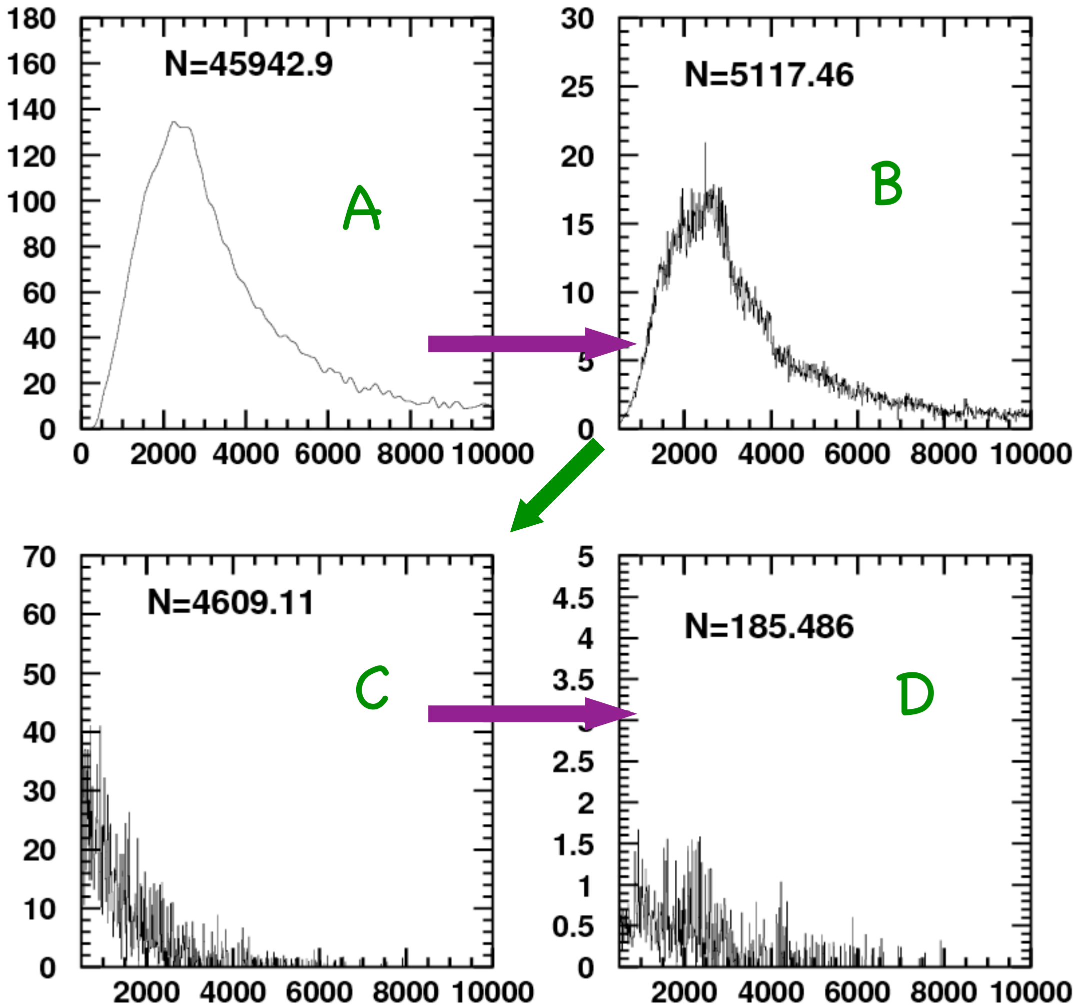




Running on 100 yr of SK-I MC and 60 yr of SK-II MC

350 MeV < E < 850 MeV

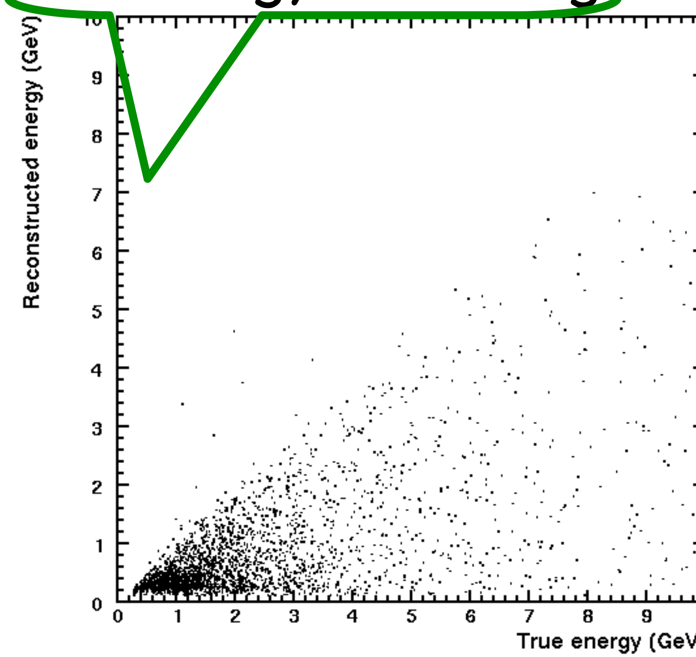
NC Background simulation



A = ν_μ flux x σ_{NC}

B = A x precuts efficiency

C = B x NC energy smearing



D = C x likelihood efficiency