Tokai to Kamioka and Korea:Water Cherenkov versus liquid Argon

Fanny Dufour, Université de Genève, June 17th 2009

Outline

- Brief introduction to neutrino oscillation physics
- Why should we do long baseline neutrino experiments ?
- What kind of beam?
- What kind of background?
- Two kinds of detector:
  - Assumptions
  - Expectations
- Conclusions

A bit of theory

Neutrino sources

Atmospheric neutrinos

Energy:

~ 0.1 - 100 GeV

Flight length:

~ 10 - 10'000 km

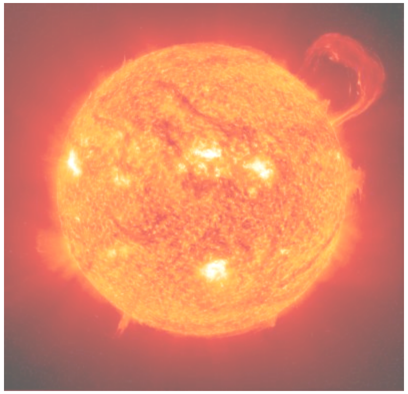
Solar neutrinos

Energy:

~ 0.1- 10 MeV

Flight length:

~ 10^8 km



Reactor neutrinos

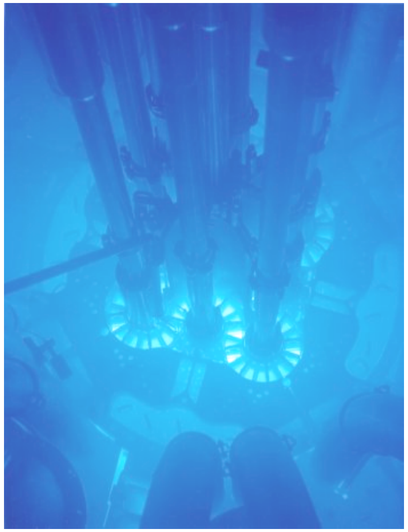
Energy: ~ 3 MeV

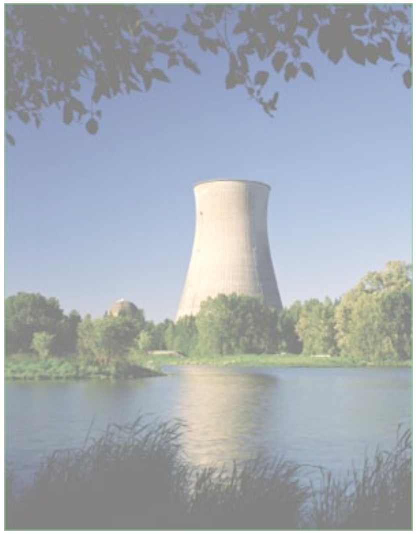
Flight length: ~ 0.1 - 10 km

Accelerator neutrinos

Energy: ~ 1 - 10 GeV

Flight length: ~ 0.1 -1000 km





How did we learn about neutrino oscillation?

- First hint of neutrino oscillation: discrepancy between # of solar neutrinos observed and theoretical models: solar neutrino problem. Observing behavior of ν_e

- Strong evidence of $\nu_\mu \rightarrow \nu_\tau$ by the Super-K collaboration in 1998 using atmospheric neutrinos.

- More evidence of neutrino mixing by the SNO collaboration in 2002.

- Confirmation by K2K & KamLAND

Measurements of oscillation

- Because of the mixing of eigenstates, the neutrinos of a given flavor will oscillate to another flavor as follows:

$$p(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2\Phi_{ij}$$

$$\pm 2\sum_{i>j}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin 2\Phi_{ij}$$

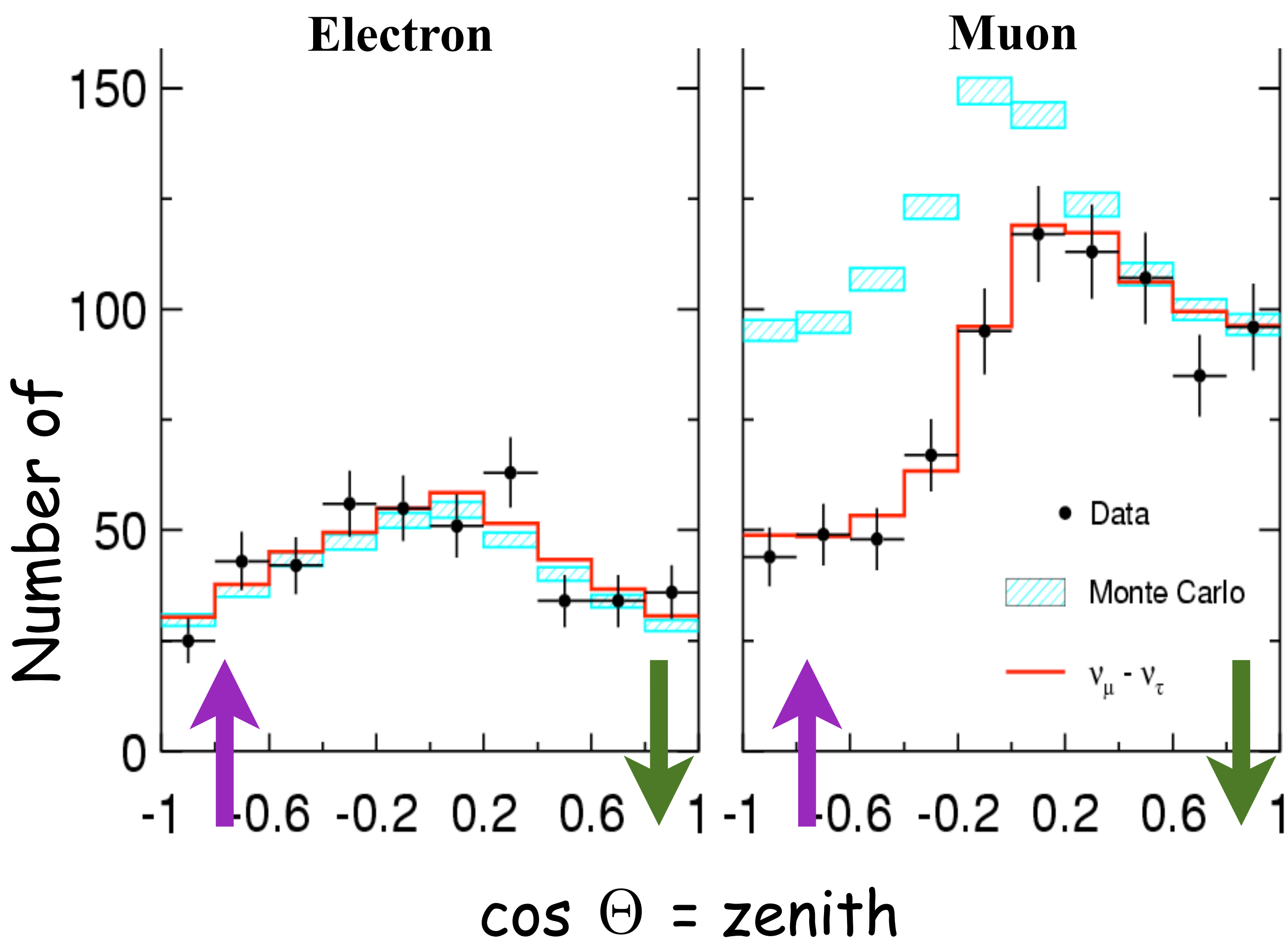
$$\text{With:} \quad \Phi_{ij} = \frac{\Delta m^2_{ij} L}{4E} = \frac{1.27\Delta m^2_{ij}(eV^2)L(km)}{E(GeV)}$$

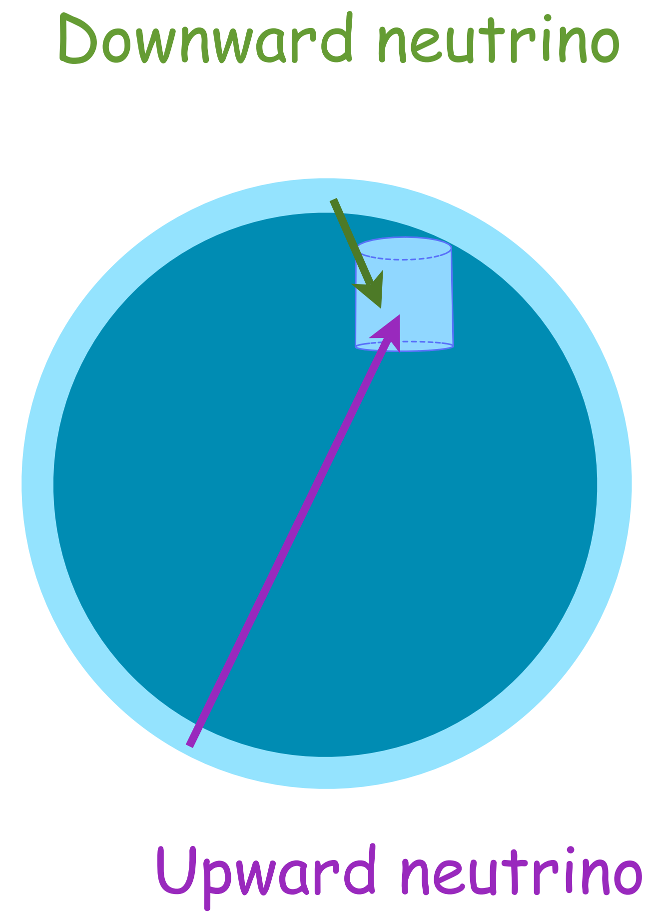
proportional to L/E

$$\Delta m^2 ij = m^2_j - m^2_i$$

- This gives us a chance to measure the parameters of the mixing matrix and the two mass splittings.

Example of Super-Kamiokande Data





We see a deficit of upward going muon events

$\nu_\mu \rightarrow \nu_\tau$ and we do not see tau in the detector.

Neutrino mixing

- Similar to quark mixing through the CKM matrix.
- Neutrino weak interaction eigenstates ≠ neutrino mass eigenstates.
- They are related by a mixing matrix U (PMNS matrix).
- U is a 3x3 Unitary matrix ⟶ 3 angles and 1 CP phase

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{bmatrix} & U_{\alpha i} & \end{bmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$C_{ij}=\cos\theta_{ij}$

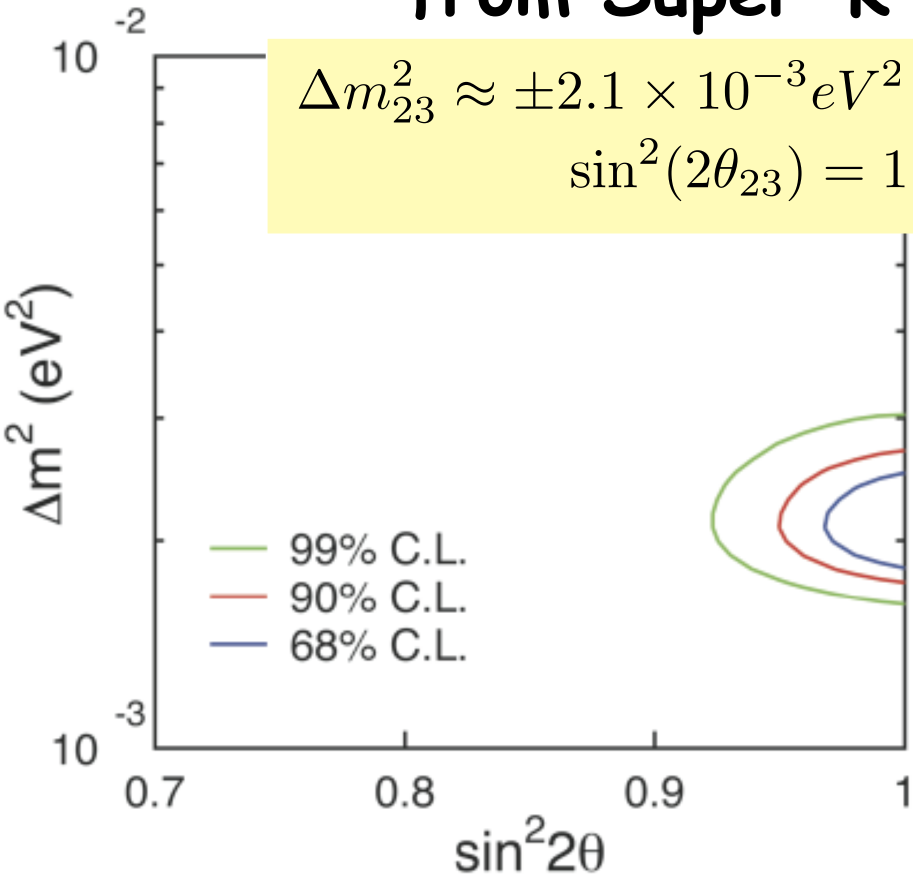
$S_{ij}=\sin\theta_{ij}$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & C_{23} & S_{23} \\ 0 & -S_{23} & C_{23} \end{pmatrix} \begin{pmatrix} C_{13} & 0 & S_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -S_{13}e^{-i\delta} & 0 & C_{13} \end{pmatrix} \begin{pmatrix} C_{12} & S_{12} & 0 \\ -S_{12} & C_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric = θ_{23} **Not well known yet** Solar = θ_{12}

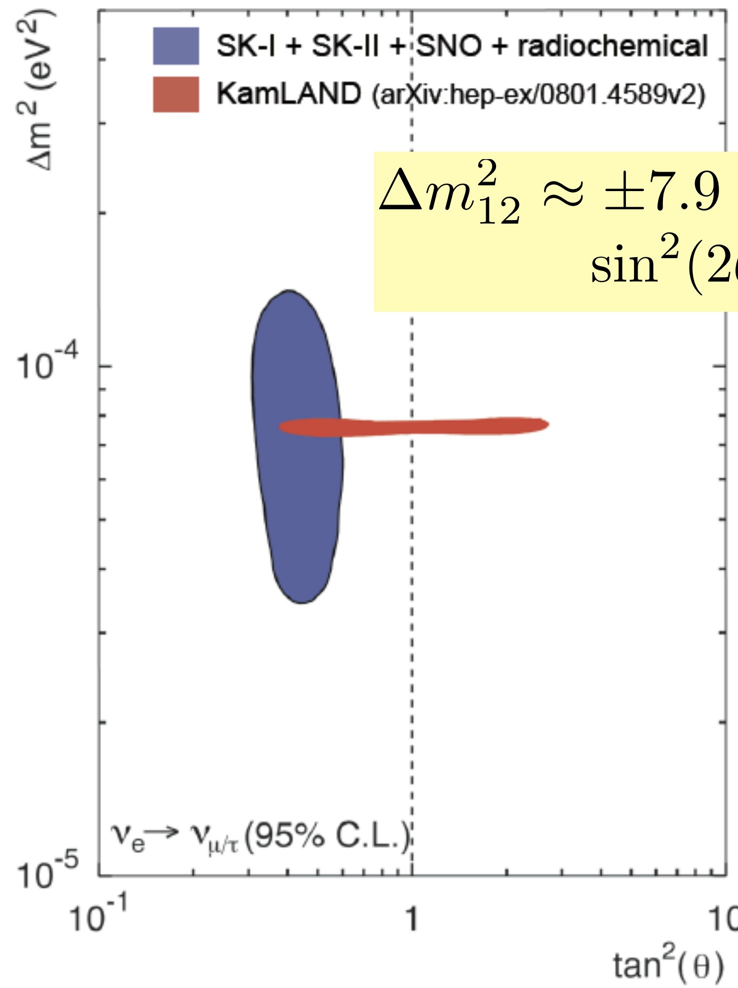
What we already know:

Atmospheric neutrinos: from Super-K



$$\Delta m^2_{23} \approx \pm 2.1 \times 10^{-3} eV^2$$
$$\sin^2(2\theta_{23}) = 1$$

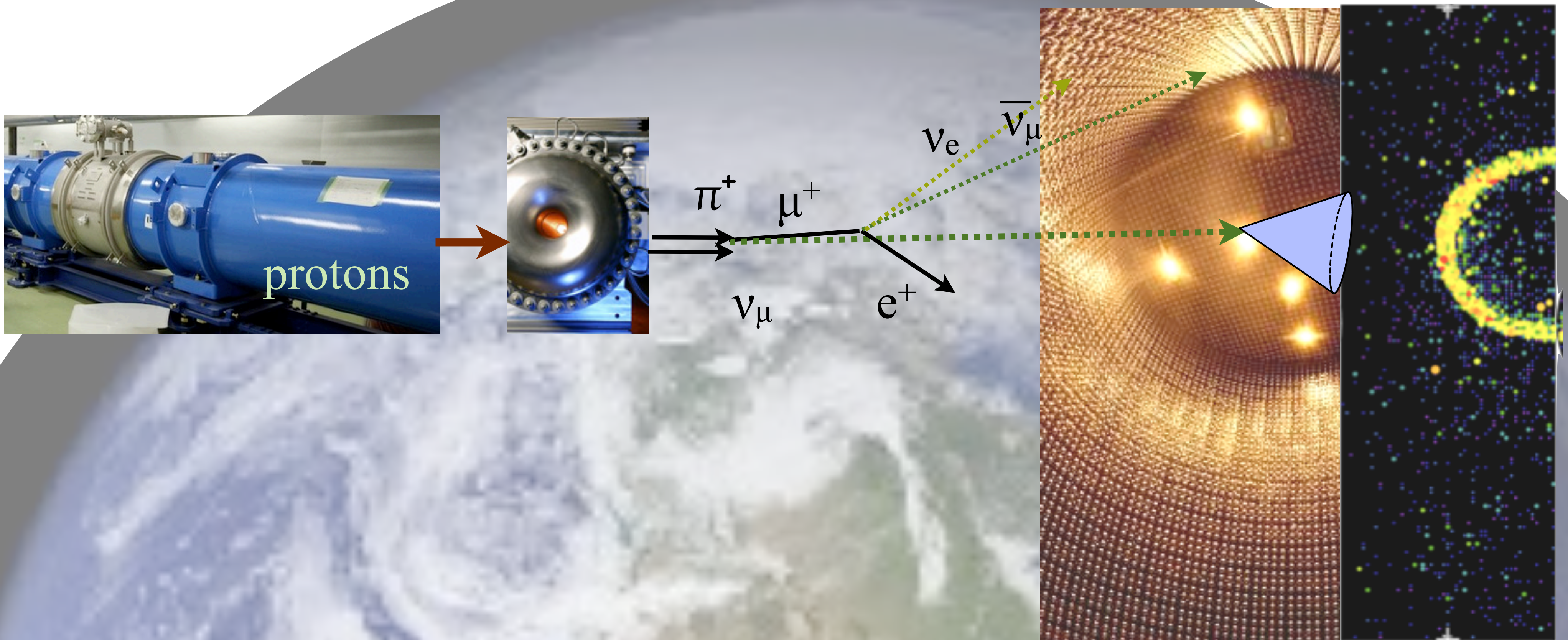
KamLAND + solar neutrinos: from KamLAND



$$\Delta m^2_{12} \approx \pm 7.9 \times 10^{-5} eV^2$$
$$\sin^2(2\theta_{12}) = 0.85$$

CHOOZ experiment:

$$\sin^2(2\theta_{13}) < 0.1 \text{ at } 90\% C.L.$$



Why do long baseline neutrino experiments?

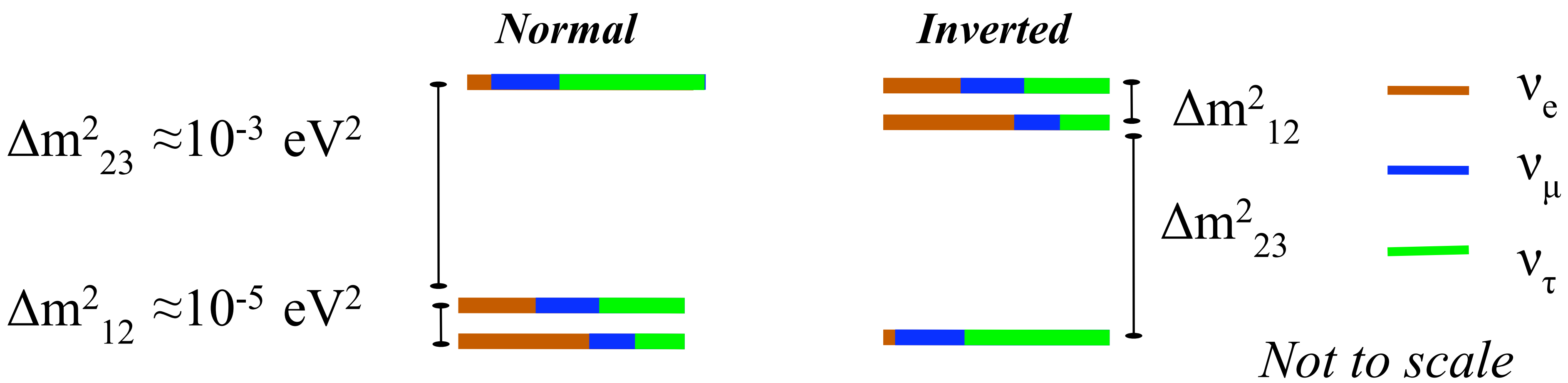
Open question - CP phase δ

- C = Charge conjugation: (particle ↔ antiparticle)
- P = Parity (image ↔ mirror image)

- **Why is CP violation important?**
  - Needed condition to explain matter-antimatter asymmetry in universe

- **What we already know:**
  - CP is violated in the quark sector (= there is a non-zero CP phase in the CKM matrix)
  - CP violation in quark sector is not big enough to account for matter-antimatter asymmetry.

Open question - mass hierarchy



Theoretical:

- Allow us to validate/rule out model
  For example: GUT's model tends to favor normal hierarchy

Experimental:

- The sensitivity of neutrinoless double beta decay depends on the mass hierarchy

How to look for CP violation and mass hierarchy?

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

$$\sin^2 2\theta_{13} s_{23}^2 \sin^2(\phi_{31}) - 1/2\, s_{12}^2 \sin^2 2\theta_{13} s_{23}^2 (2\phi_{21}) \boxed{\sin(2\phi_{31})}$$

$$+\ 2J_r \boxed{\cos\delta}(2\phi_{21})\boxed{\sin(2\phi_{31})} \mp 4J_r \boxed{\sin\delta}(2\phi_{21})\sin^2(\phi_{31})$$

} Vacuum terms

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

$$\mp\ \frac{(a(x)L)}{2} \sin^2 2\theta_{13} \cos 2\theta_{13} s_{23}^2 \boxed{\sin(2\phi_{31})}$$

} Matter Effect terms

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

} Solar term

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

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

□ CP terms.

□ Mass hierarchy terms.

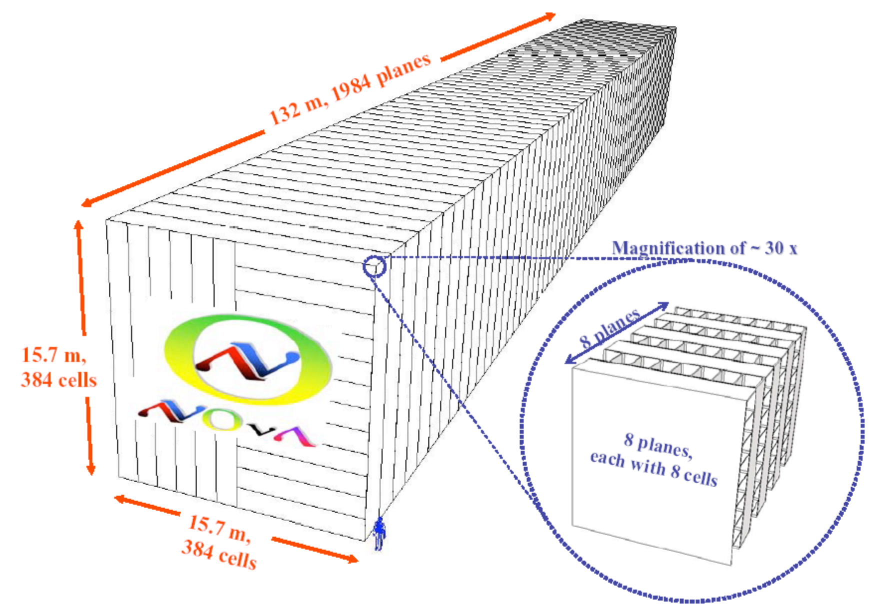
Long baseline → lots of matter effect → Good for mass hierarchy

CP violation does not care about long baseline as much.

First generation of ν_e appearance experiments

We still don't know if θ_{13} is non-zero and this question will be addressed by a new generation of experiments.

The T2K (Tokai to Kamioka) experiment will start to run in 2009
L= 295km E≈0.8GeV



The NOνA proposal (Fermilab), proposed to start running in 2014
L≈ 800km E ≈ 4 GeV

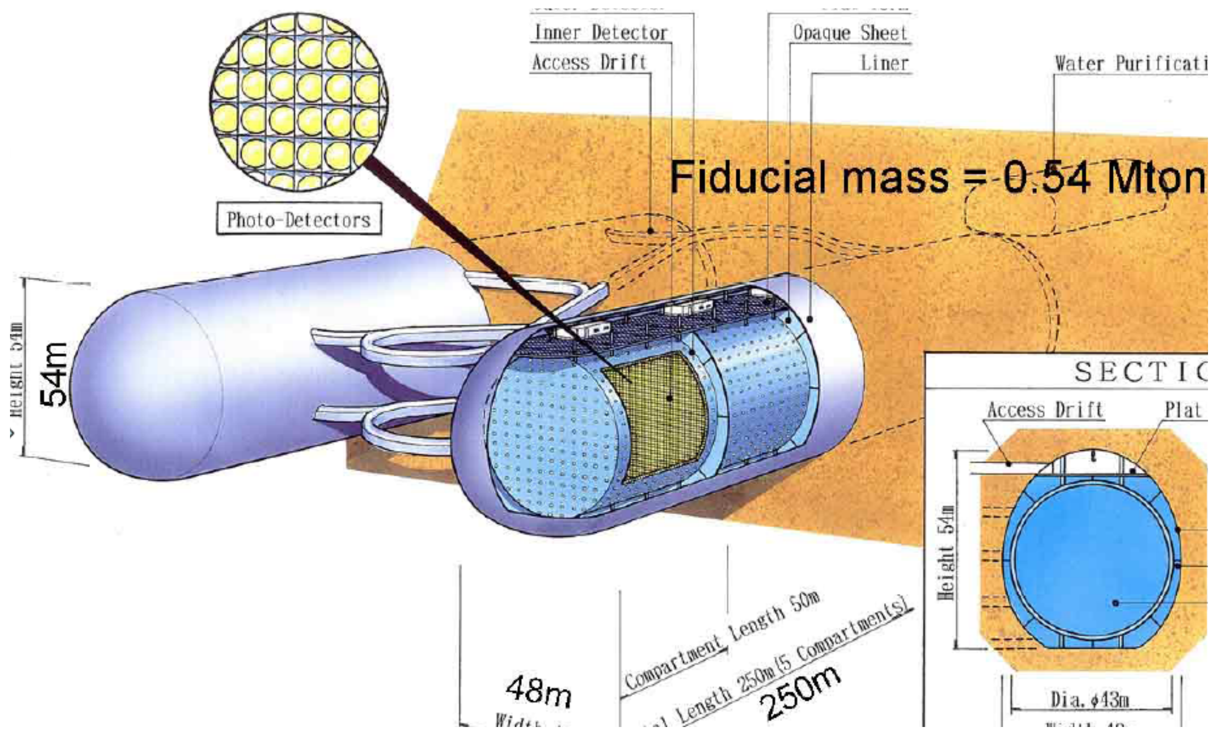
The Hyper-K project

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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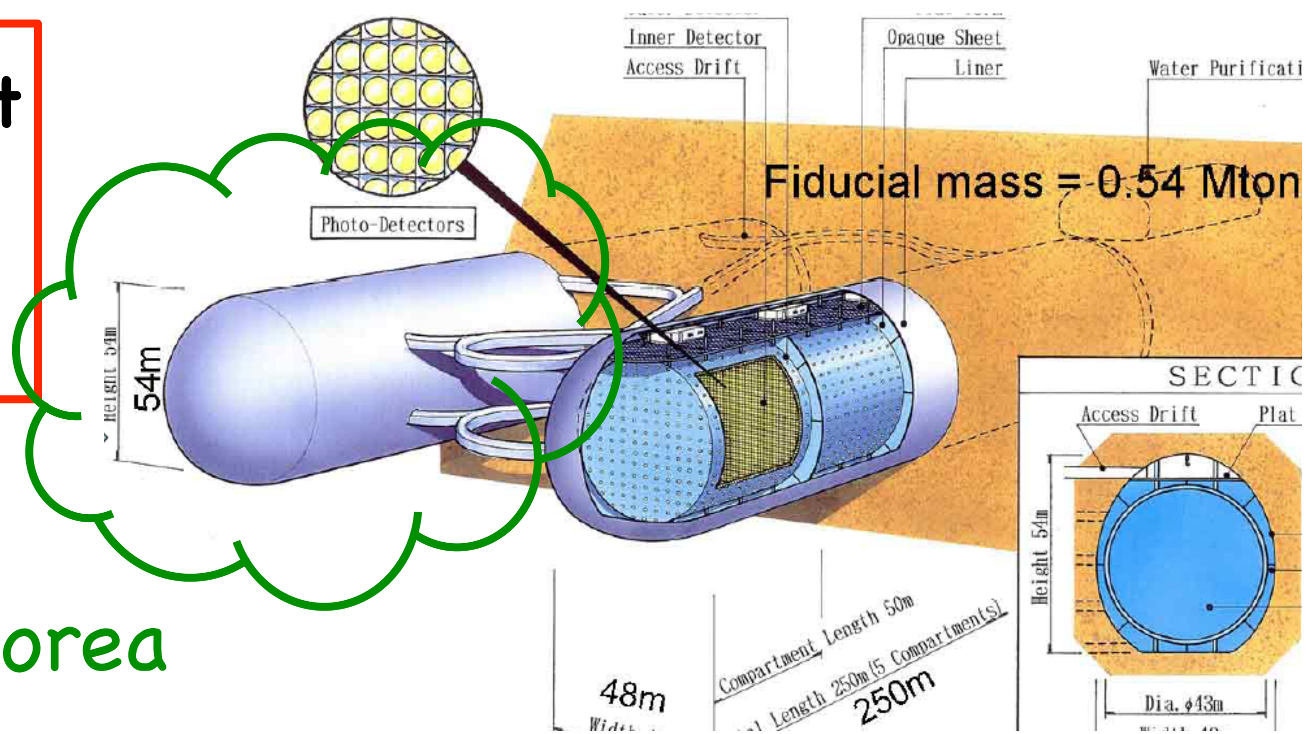


Could be built in Korea

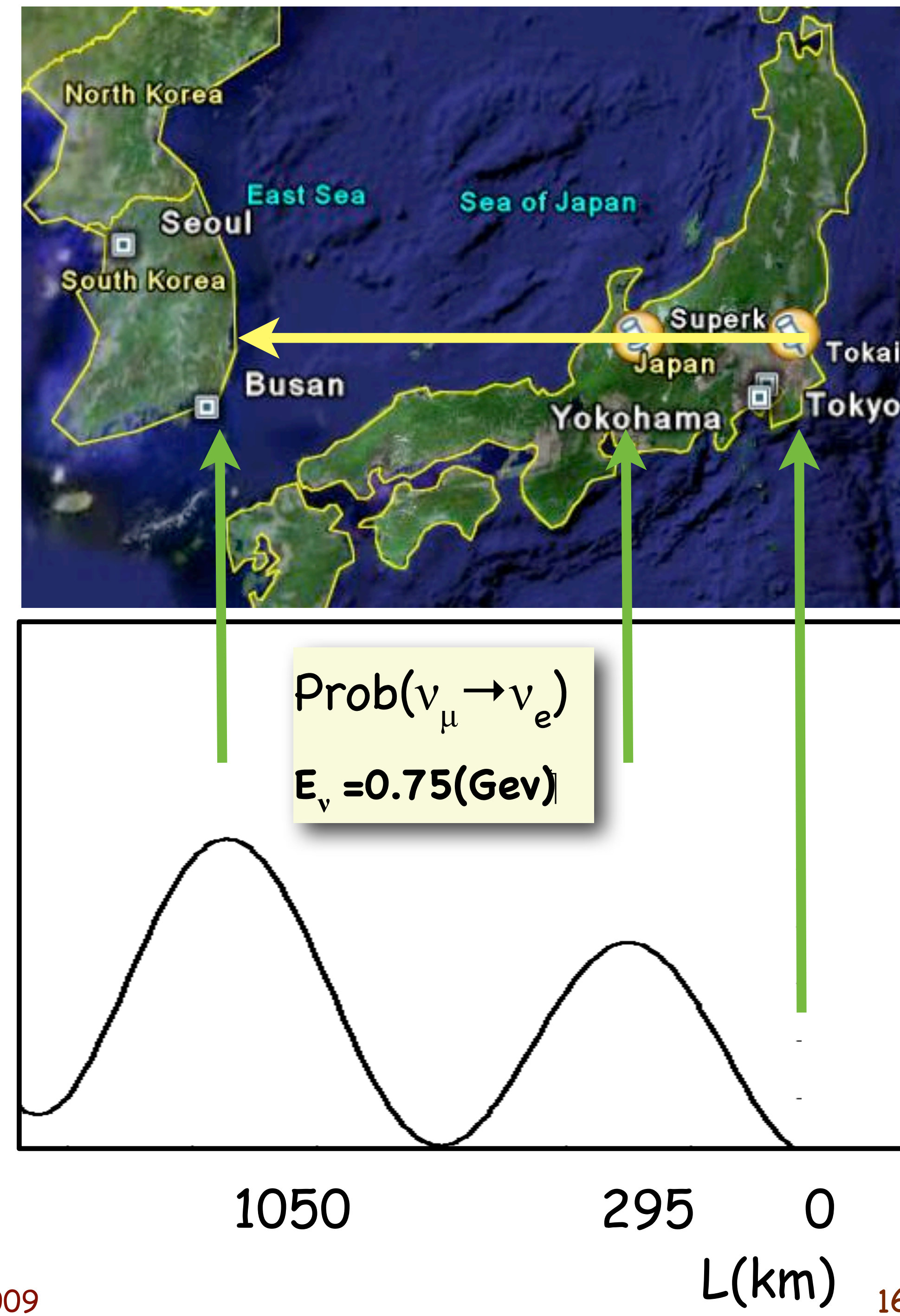
Why put a detector in Korea?

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.

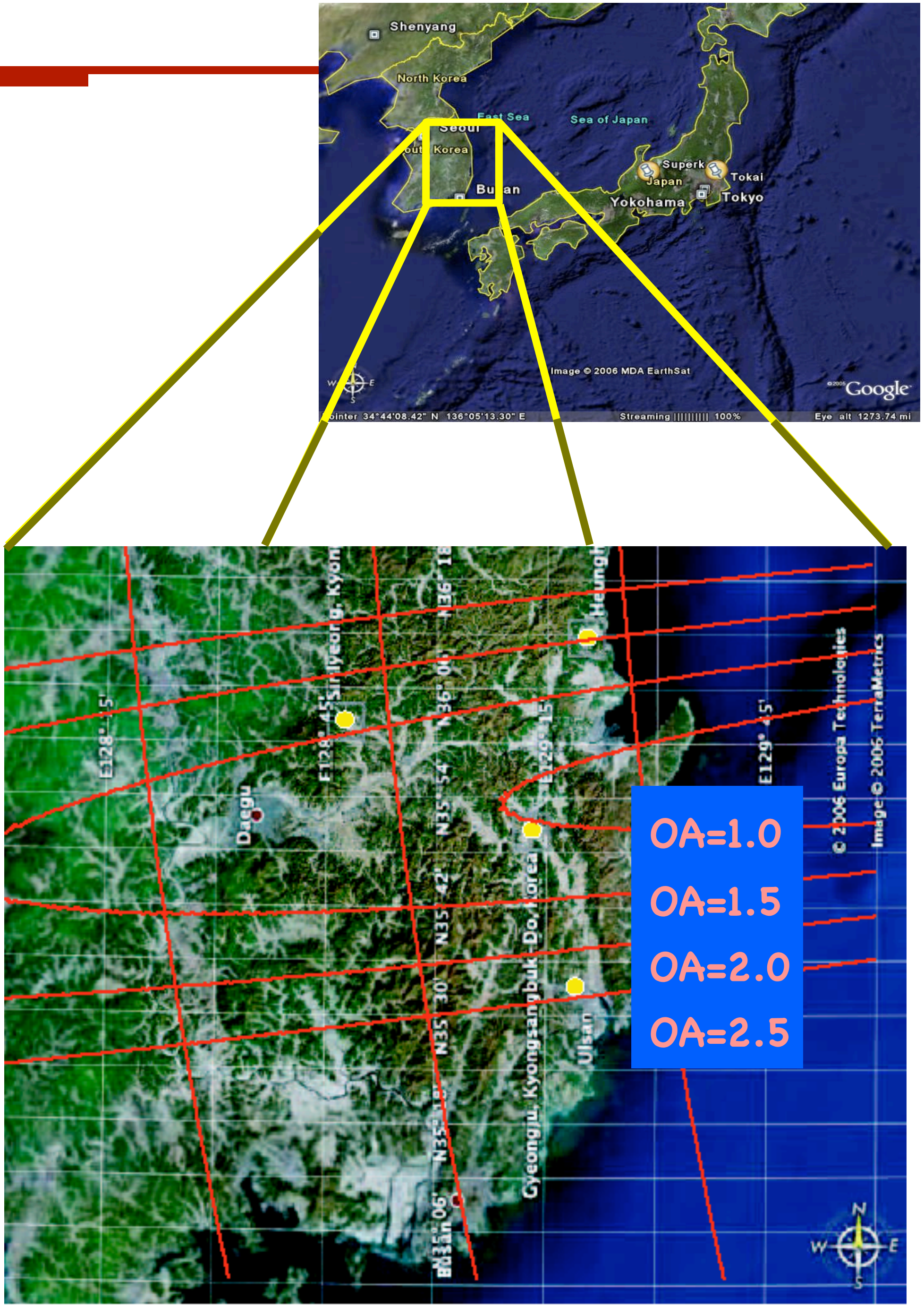


Where in Korea?

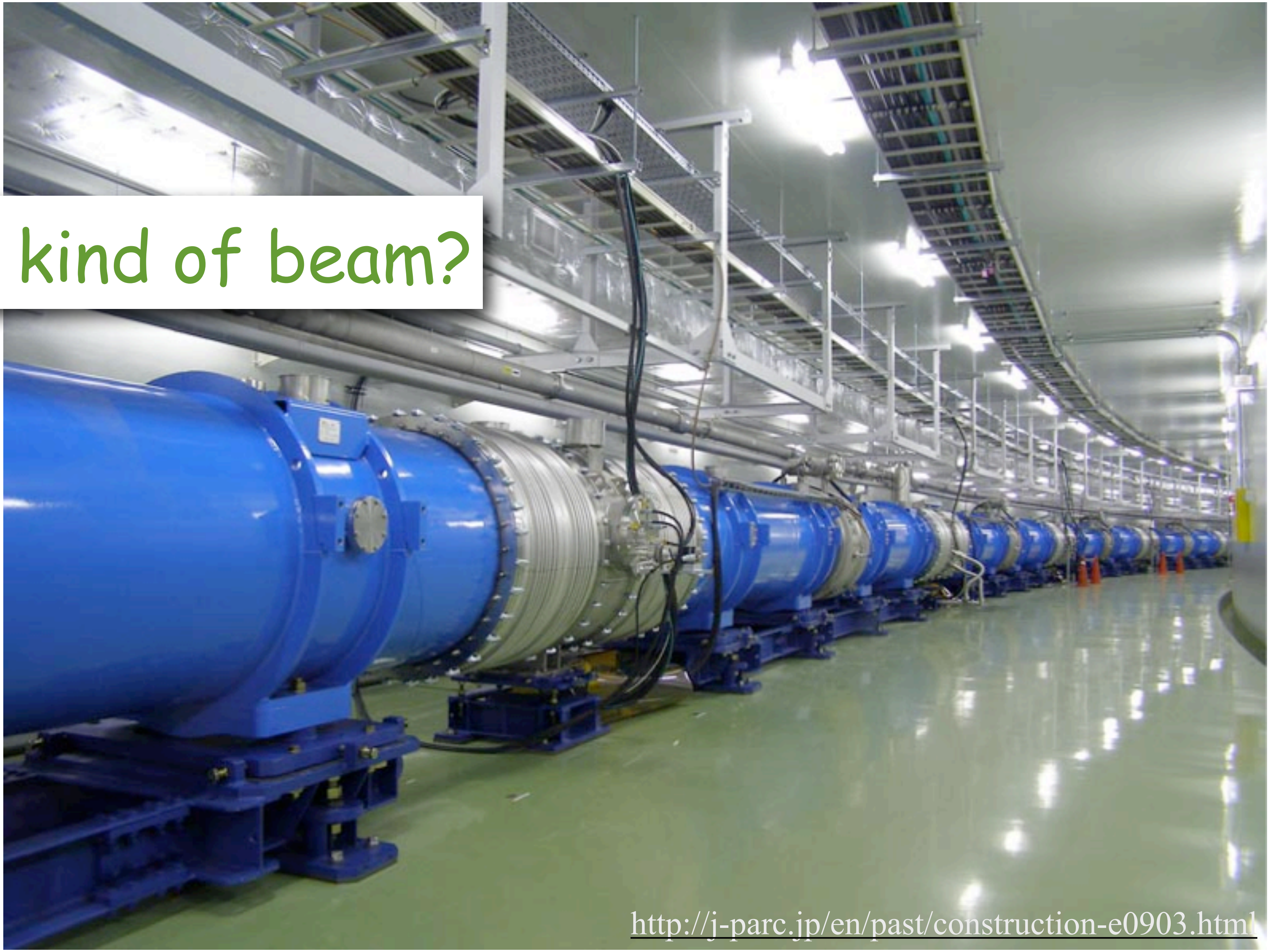
The neutrino beam emerges in the sea, east of Korea.

In Korea, the smallest off-axis angle available is 1.0°.

And it was found that it gives the best results to probe mass hierarchy and CP violation.

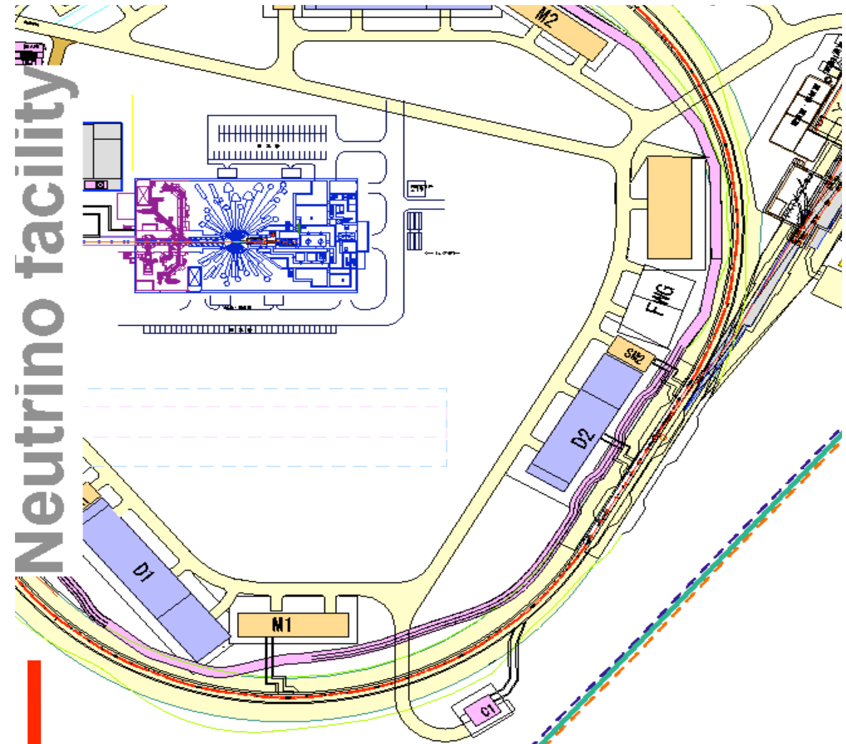


What kind of beam?



Making the ν_μ beam

- For T2KK: 30 GeV proton synchrotron
  1.66 MW
- Protons hit target,
  pions (and kaons) created
- Pions focused and decay
  in decay pipe:
  $\pi \rightarrow \mu \, \nu_\mu$
  $K \rightarrow \mu \, \nu_\mu$
  but also $K \rightarrow e \, \nu_e$, $\pi \, e \, \nu_e$
- To have a narrow energy band
  we use an off-axis beam



Super-K and Korea

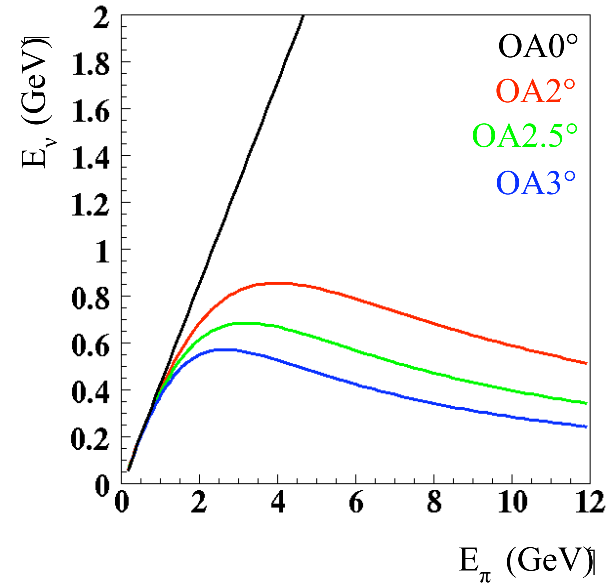
Narrow energy band: Off-axis Beam

- The energy of the outgoing neutrino is:

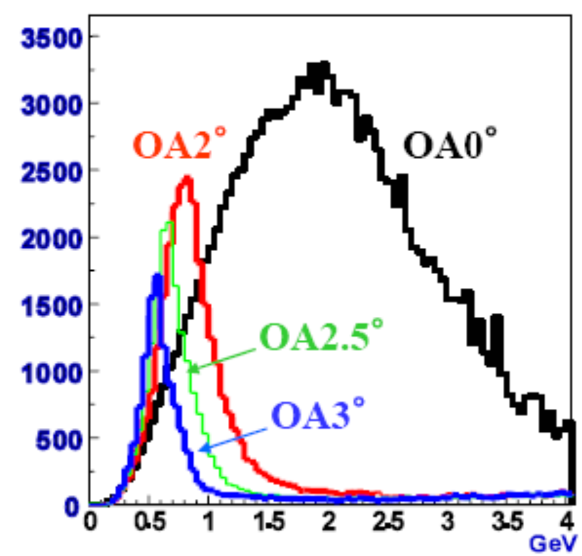
$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{2(E_\pi - p_\pi \cos\theta)}$$

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

- Gives a neutrino beam with a narrow energy spectrum:
  - Lower integrated flux
  - Higher peak flux



E_ν as a function of E_π



Neutrino energy spectrum

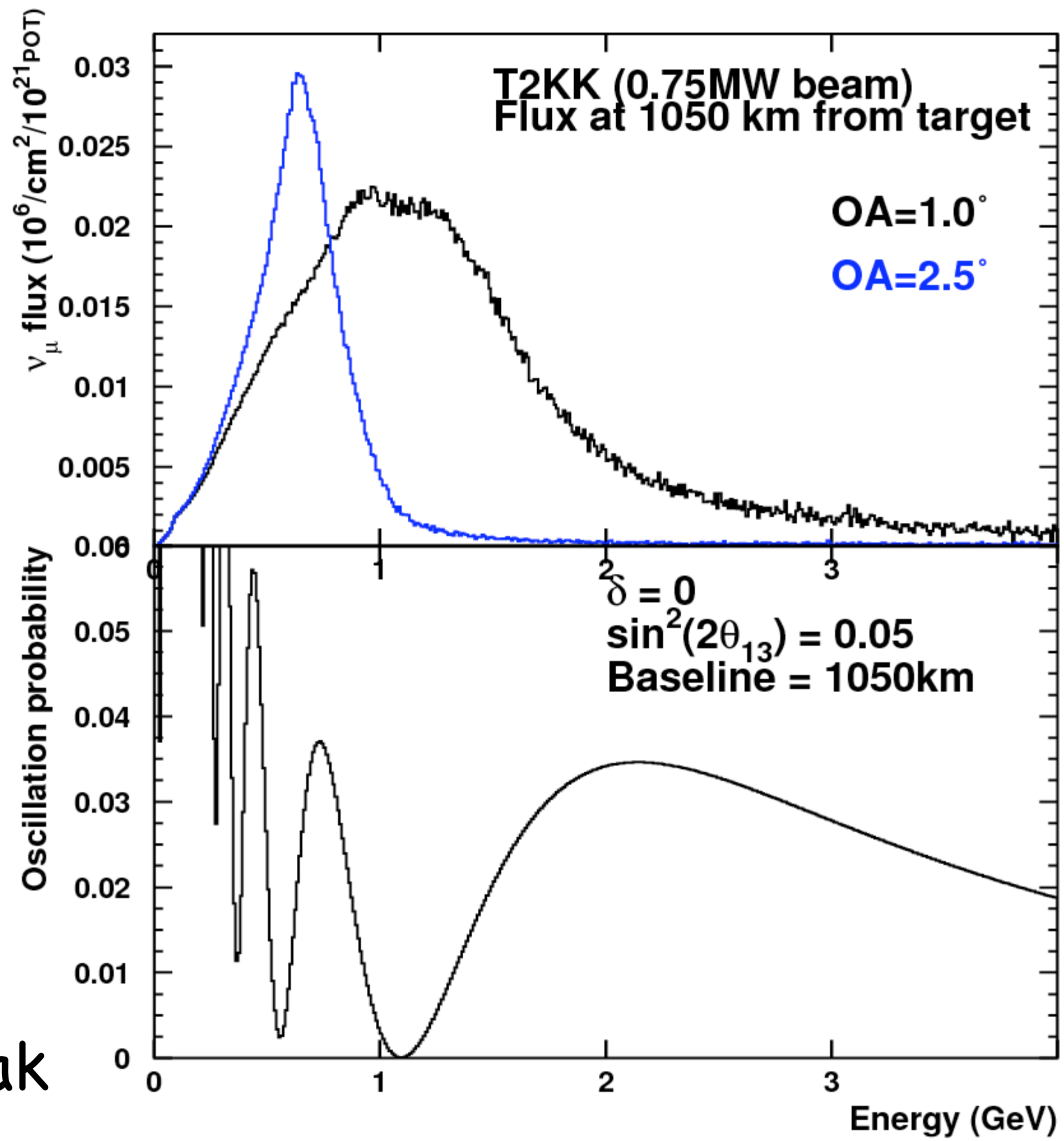
Flux and appearance in Korea

Small off-axis angle:
(high energy tail)

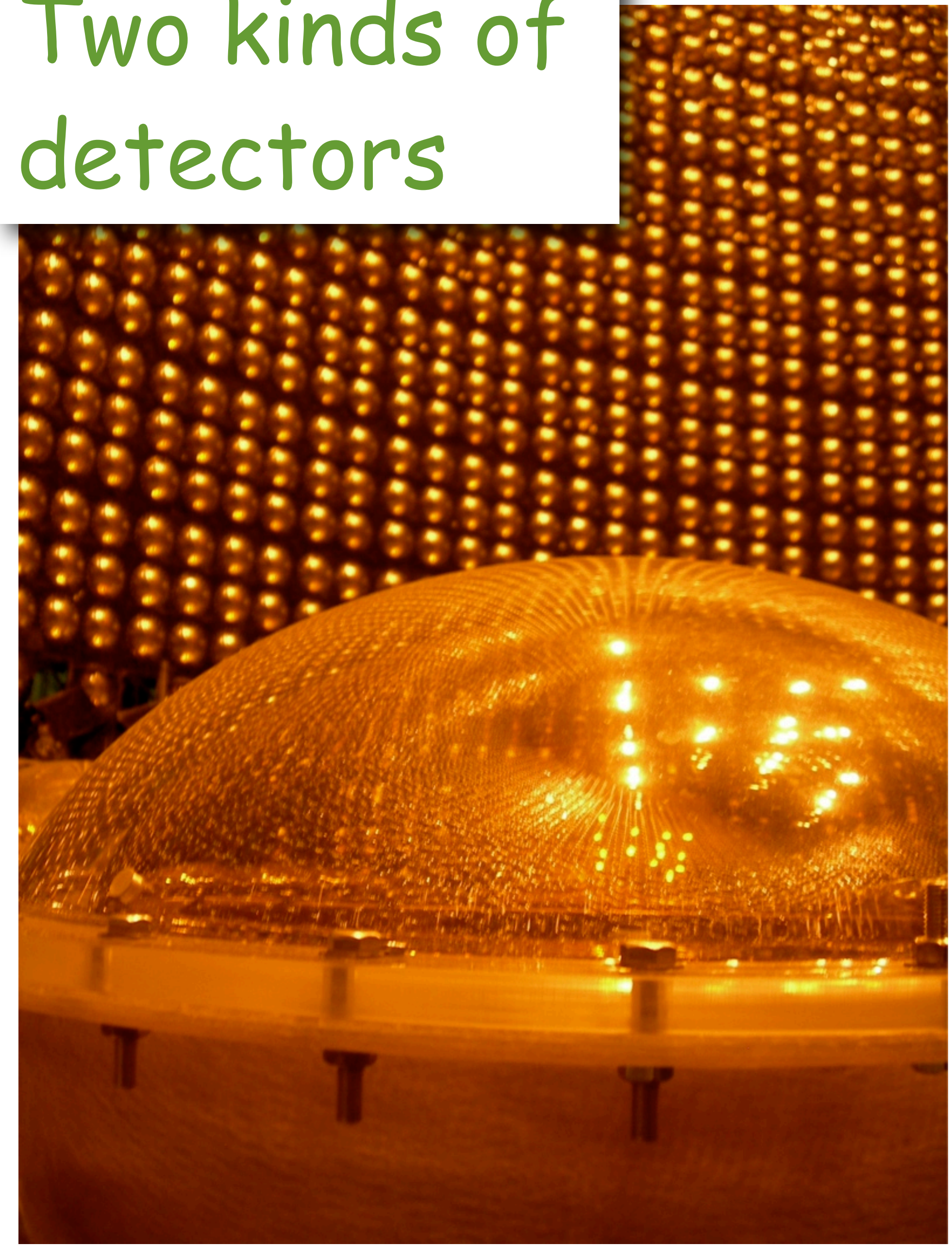
✓1st appearance peak
✗ more NC background

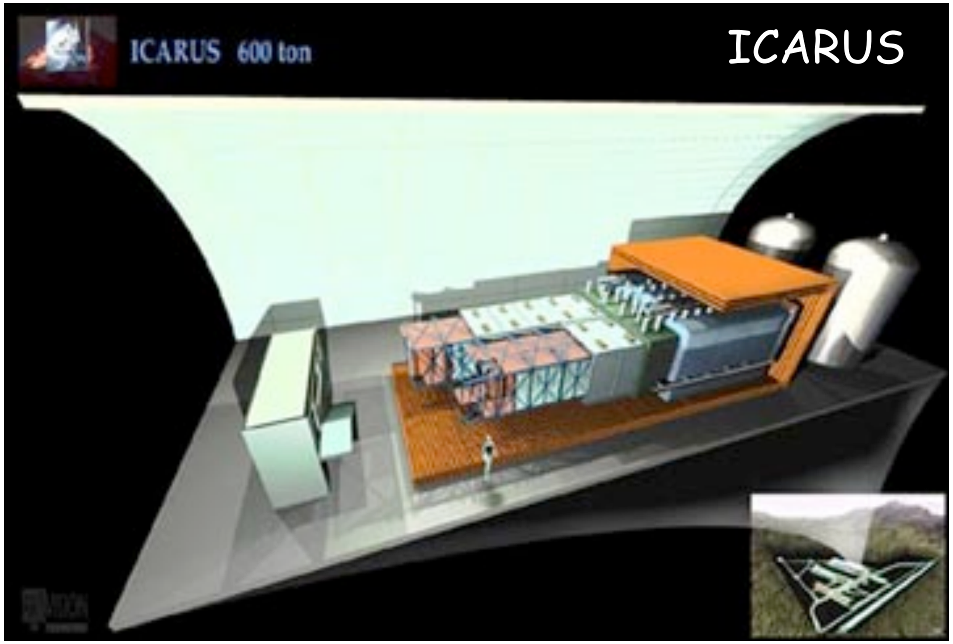
Big off-axis angle:
(narrow peak)

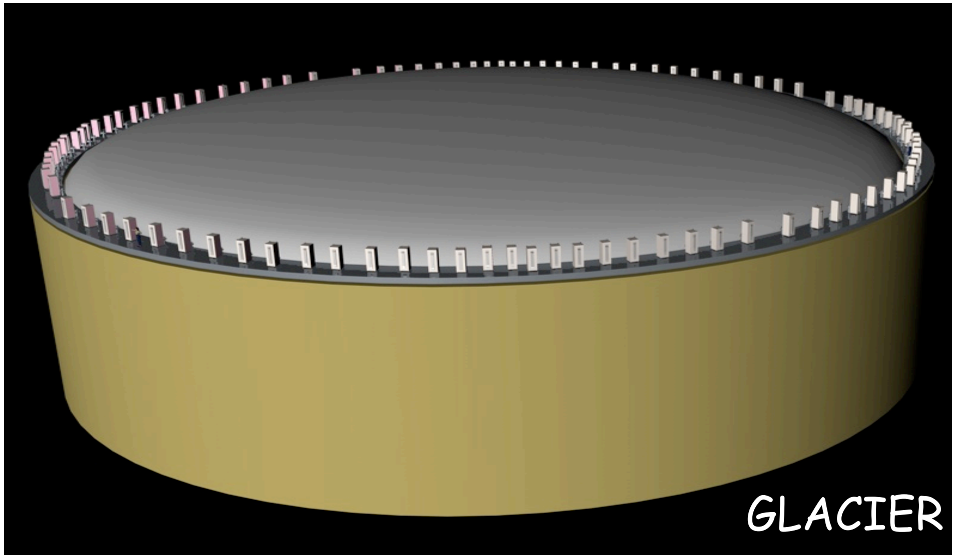
✓Low background
✗Low statistics at high E
✗Only 2nd appearance peak



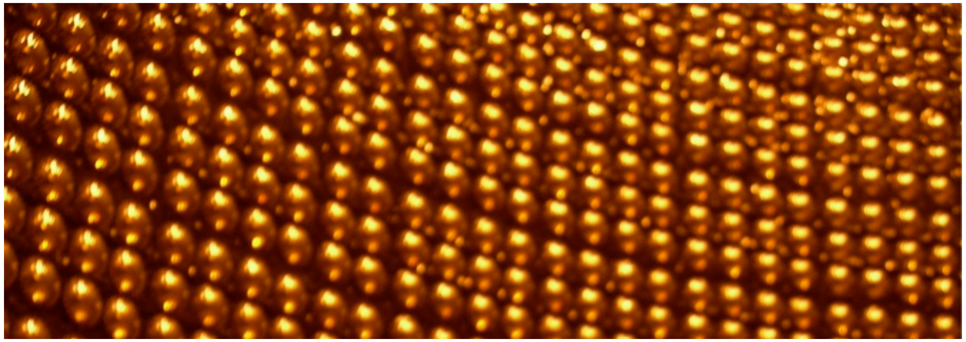
Two kinds of detectors

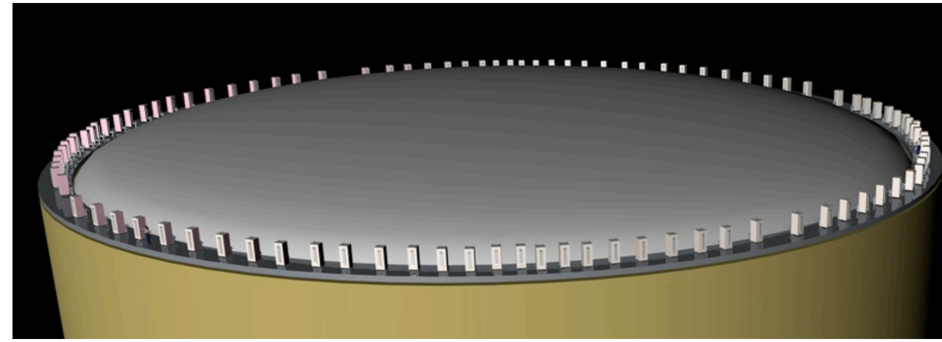






How do they work?





Water Cherenkov:

Look for Cherenkov rings:

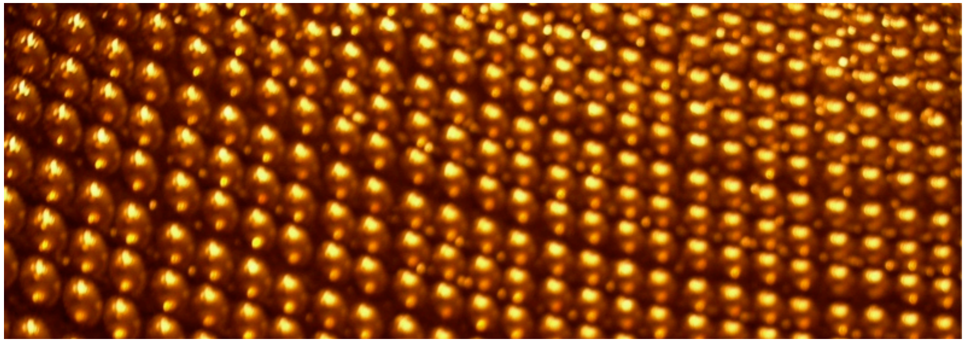
- Particle ID: (EM shower versus **mu-like** particle)
- No charge ID
- Need to be above Cherenkov threshold

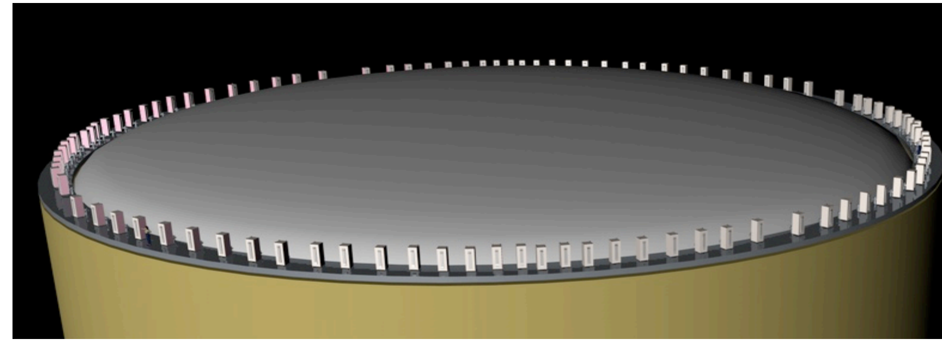
  ie: Usuallly we don't see the proton in a CCQE interaction

Liquid Argon Time Projection Chamber:

- Particle ID based on dE/dx
- Maybe possible to imbed the detector in magnetic field --> Charge ID
- The proton is reconstructed in CCQE interaction.

Challenge to build massive detectors





Water Cherenkov

- Cost of PMT 's

But mainly we know how to build very large Water Cherenkov detector.
CF Super-Kamiokande.

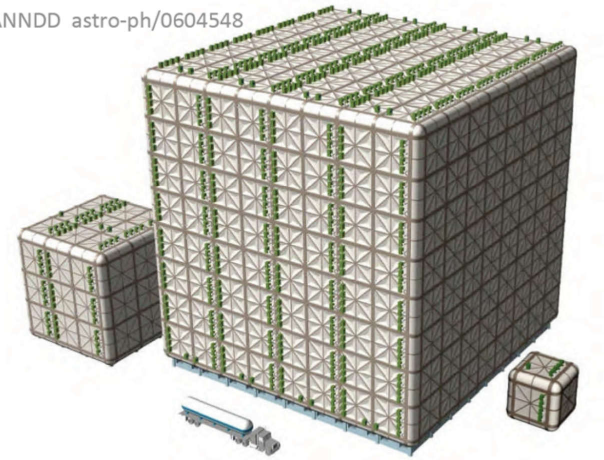
Liquid Argon

- Several meters drifts: need very pure Argon
- Long wires: mechanical robustness, tensioning, assembly
- Signal processing: noise due to long wires

http://www-lartpc.fnal.gov/summary.htm

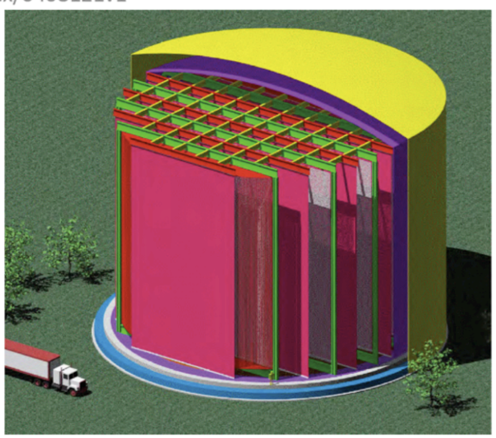
Three possible liquid Argon detectors

LANNDD astro-ph/0604548



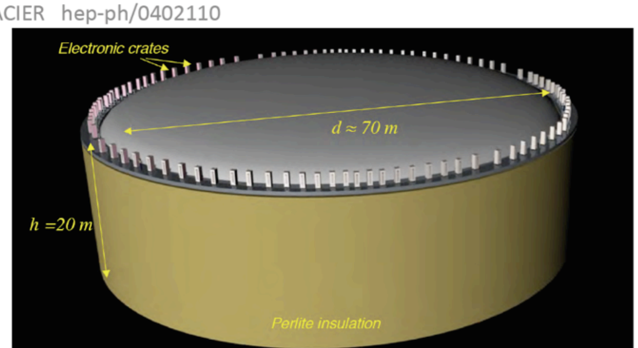
LANND, MODULAR: Modules with wires

FLARE hep-ex/0408121v1



FLARE: Large volume with wires

GLACIER hep-ph/0402110



GLACIER: Large volume without wires

10/28/08

Experimental challenges - Background

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

good e/μ ring identification: 0.7%

- ν_e contamination in the beam

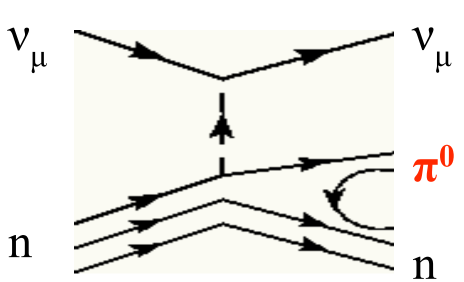
$K \rightarrow \pi \nu_e e$

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

0.2-0.3% Known from near detector

- π^0 when one of the γ is missed:

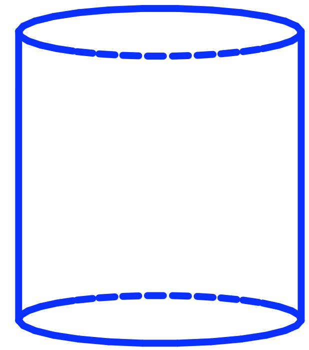
- produced by neutral current

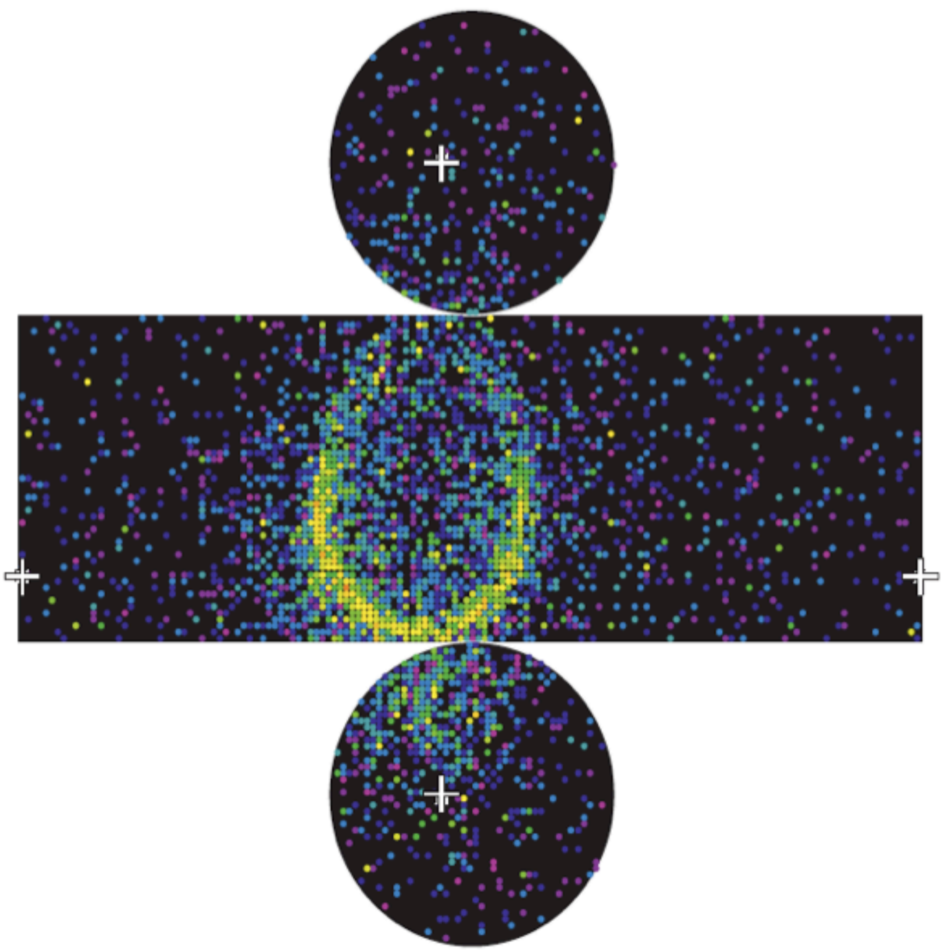


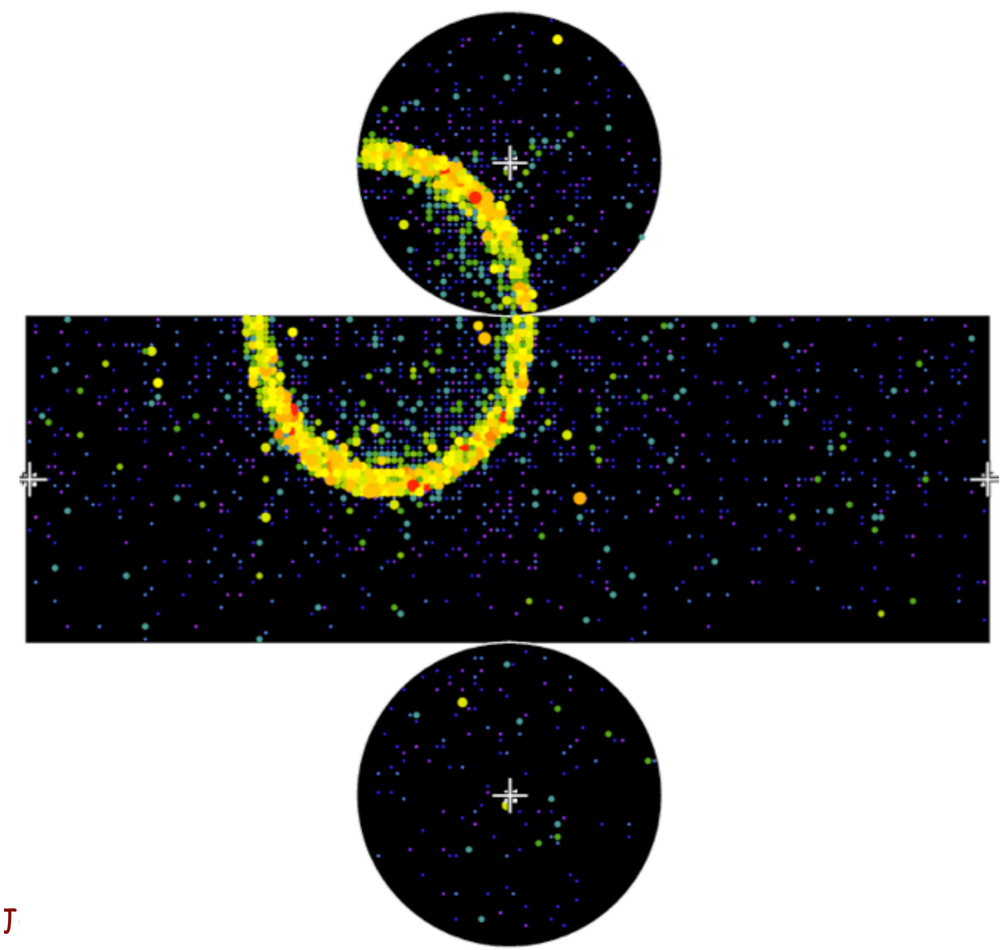
Mainly for Water Cherenkov

Difference between electron and muon (Cherenkov)

Electrons create EM showers:
fuzzy ring
Muons do not make showers:
clear ring







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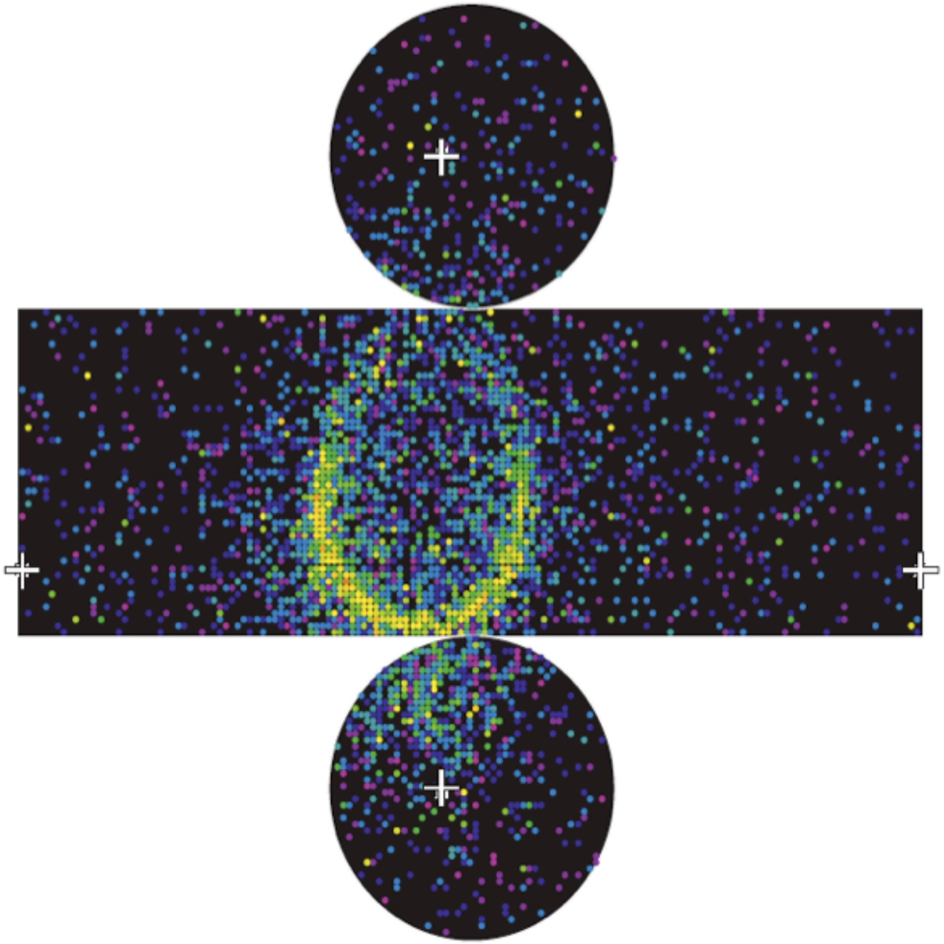

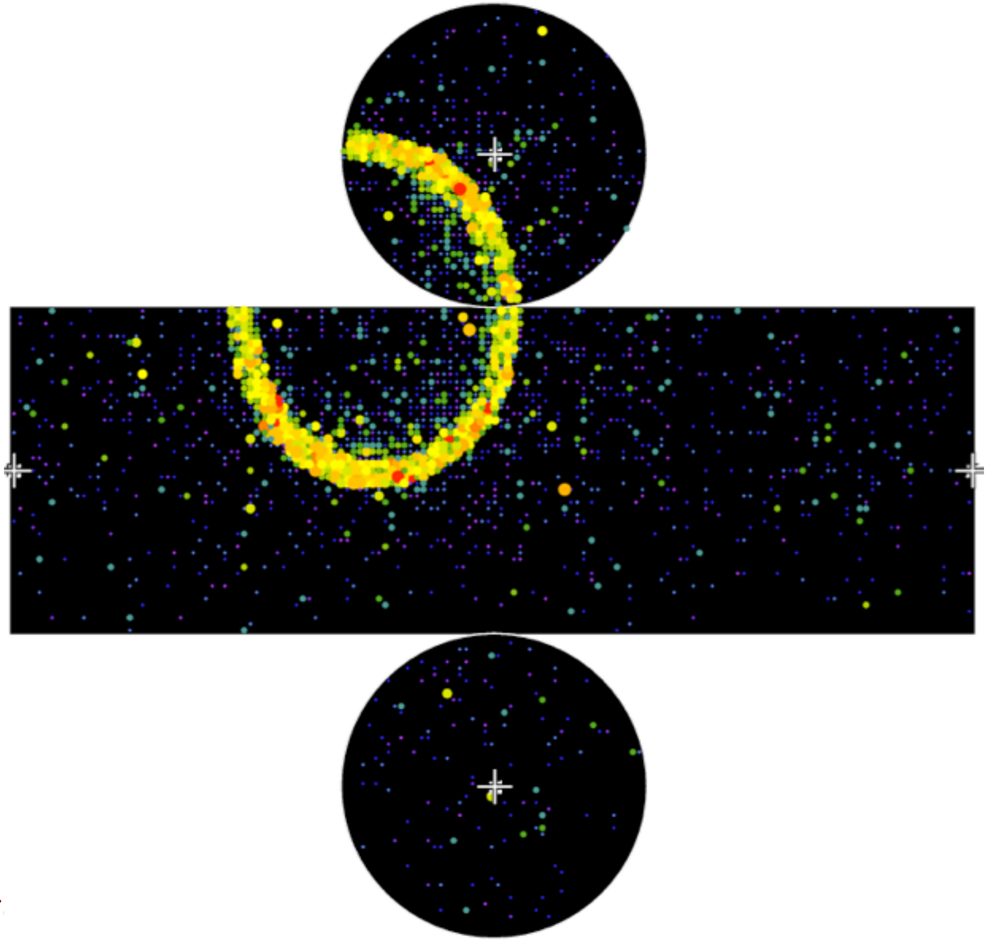

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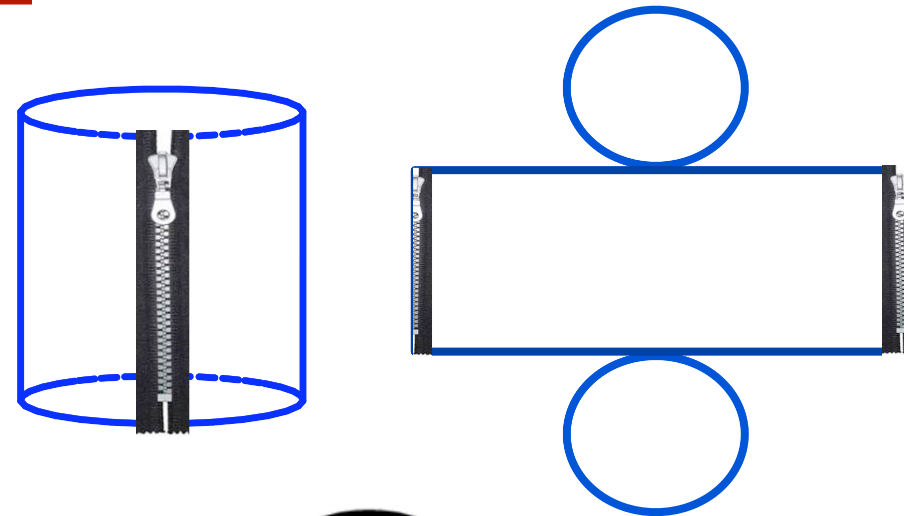

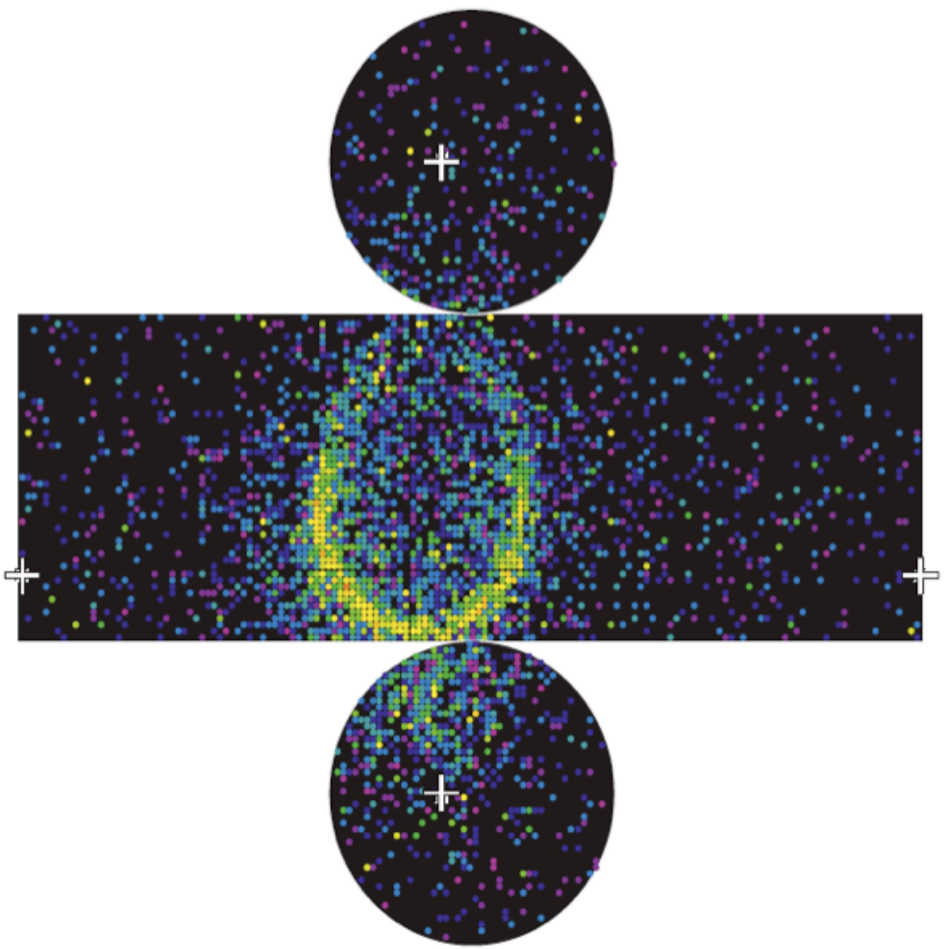

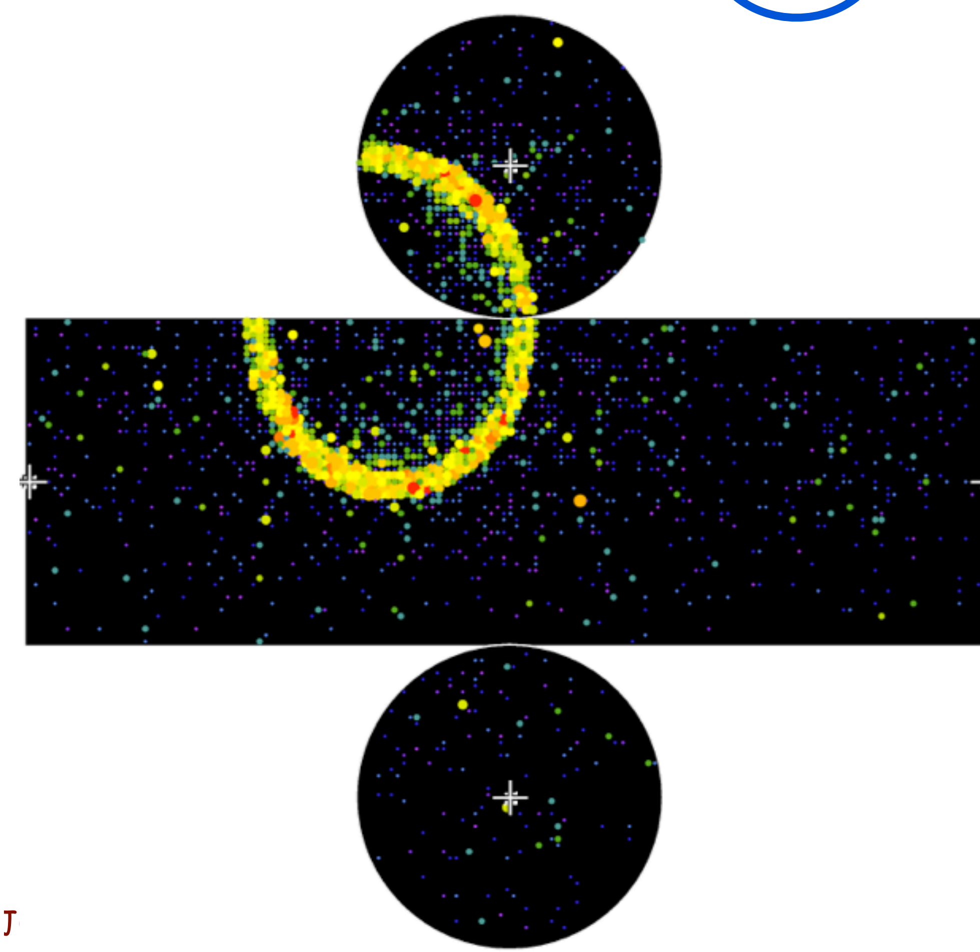

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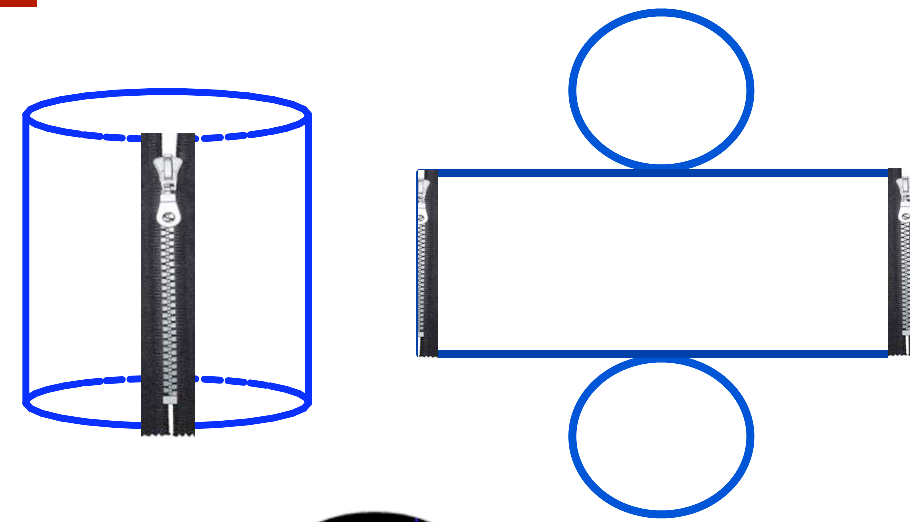
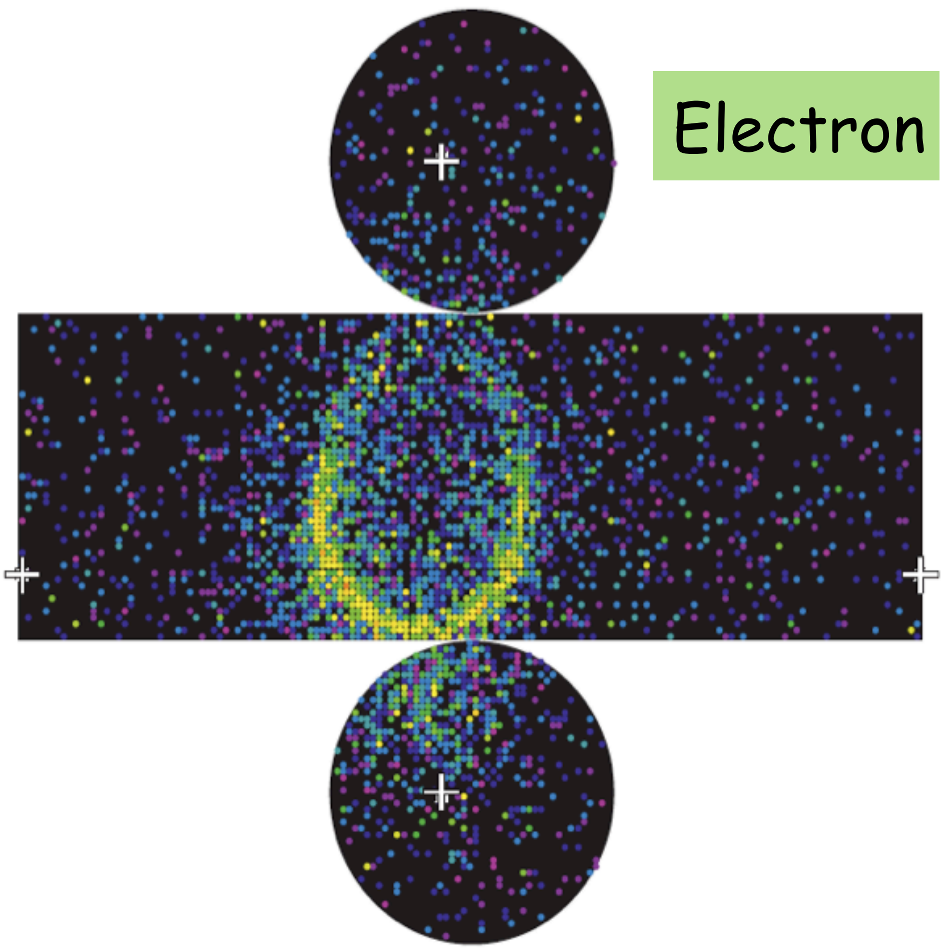
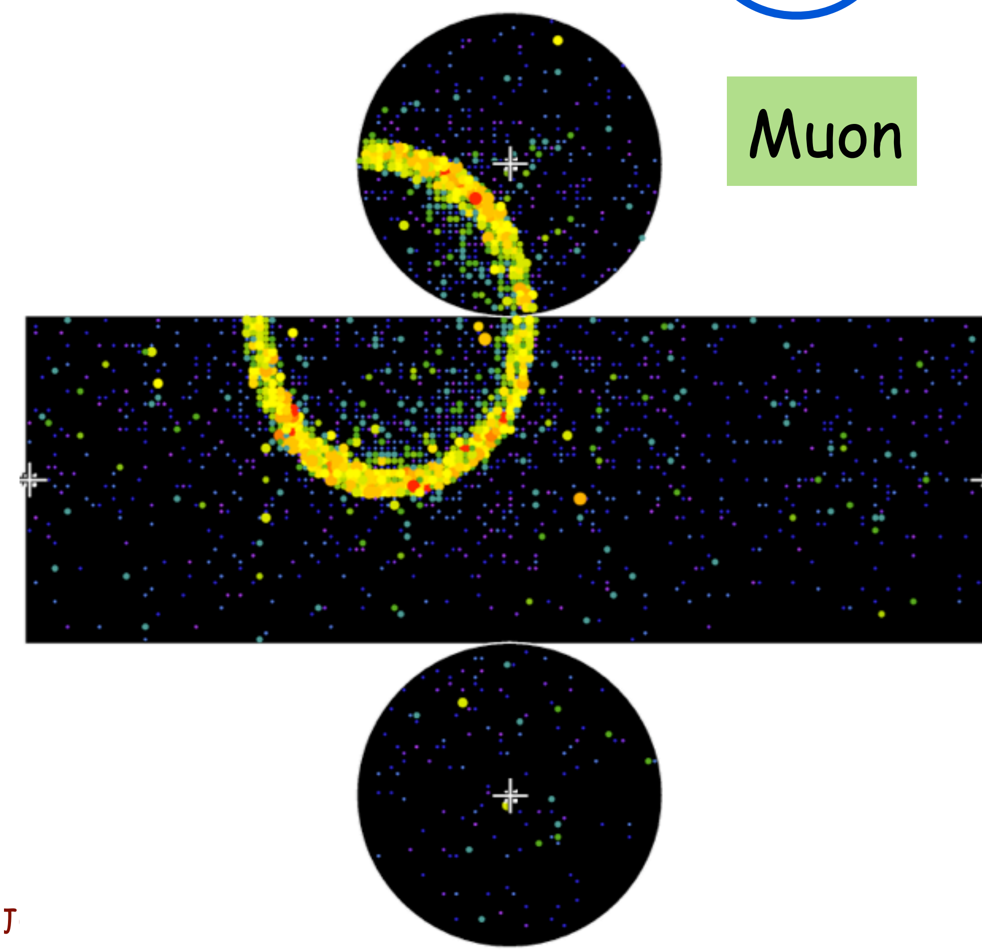




Electron

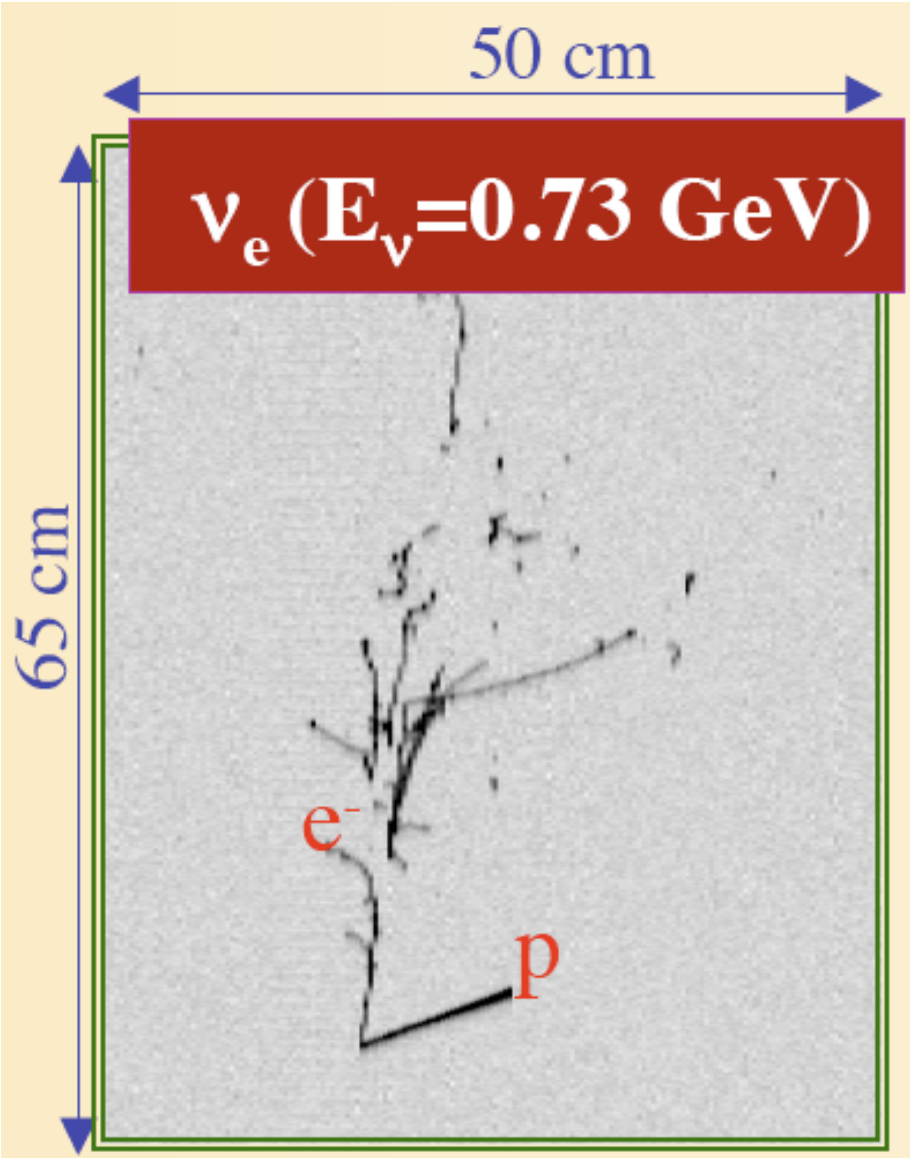


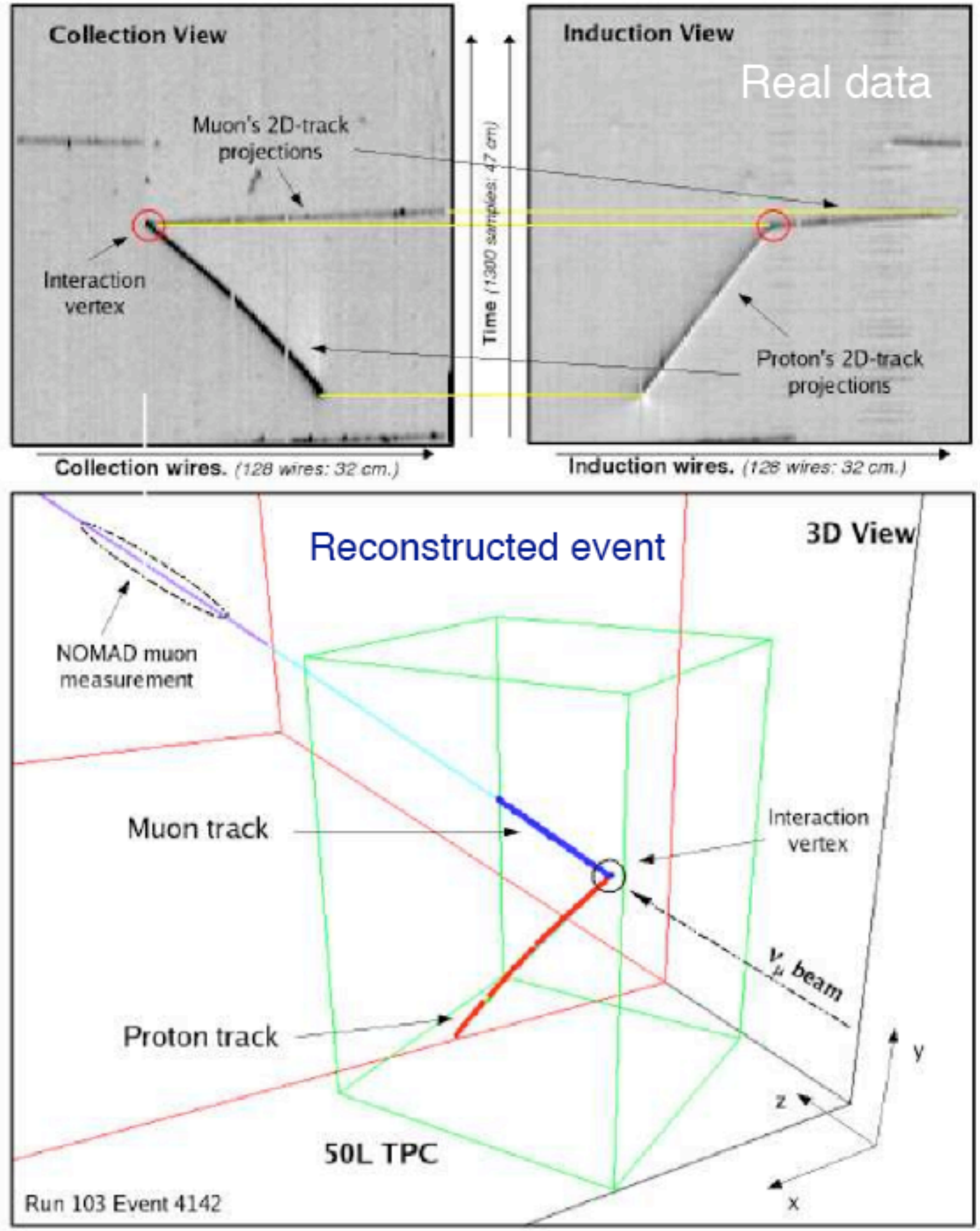
Muon

J

Muon and electron in liquid argon

Antonio Bueno, NP08, ICARUS images

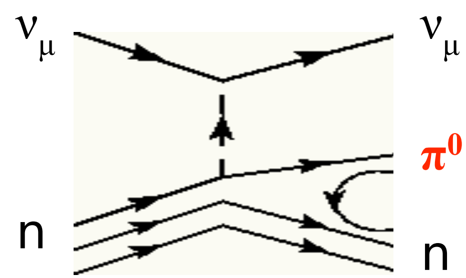


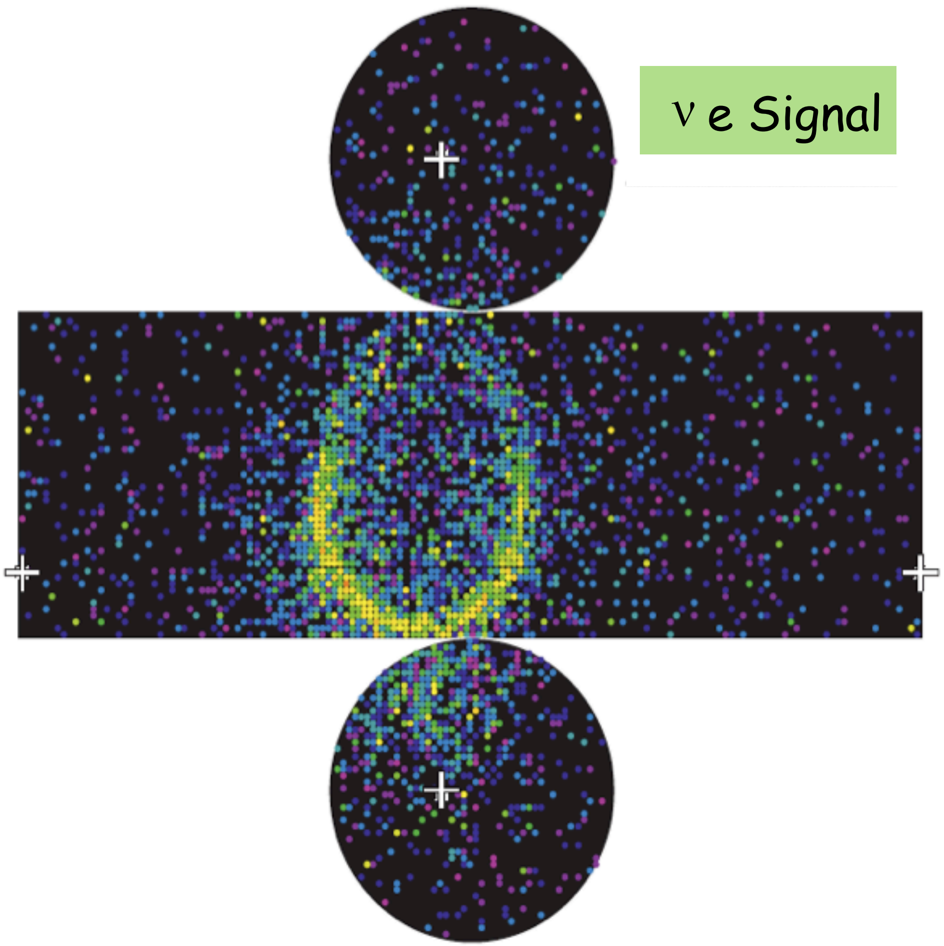


(Phys. Rev. D 74 (2006) 112001)

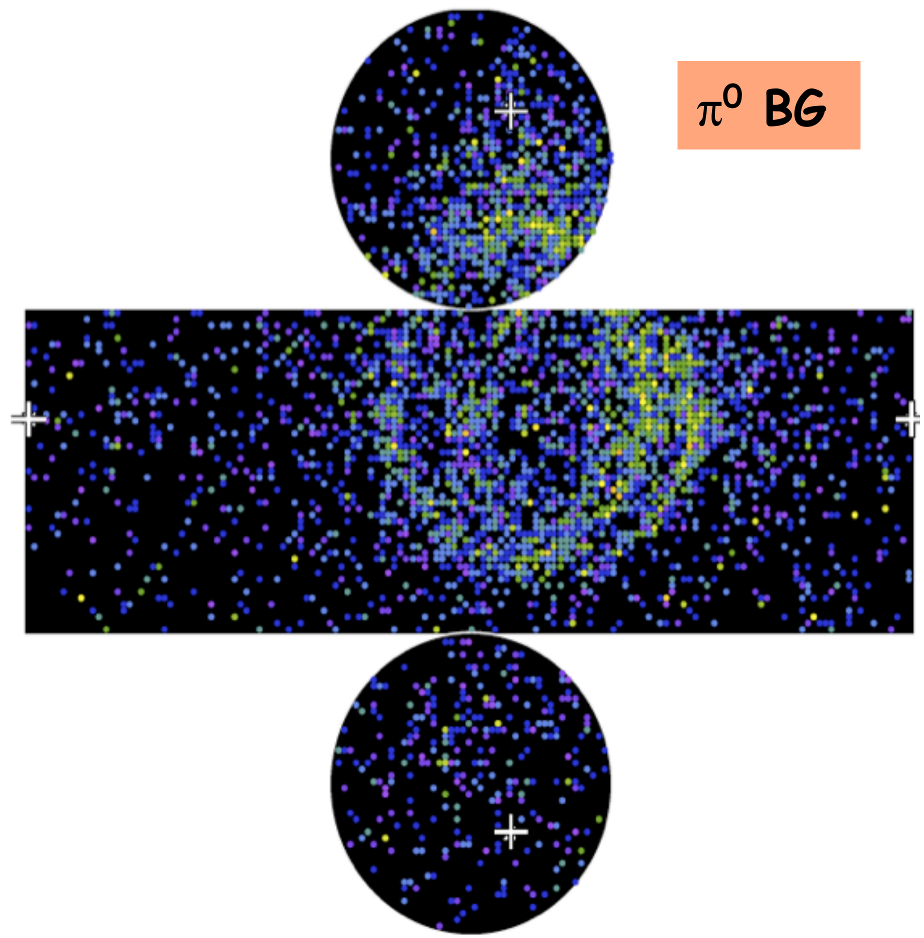
Main BG in Water Cherenkov?

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





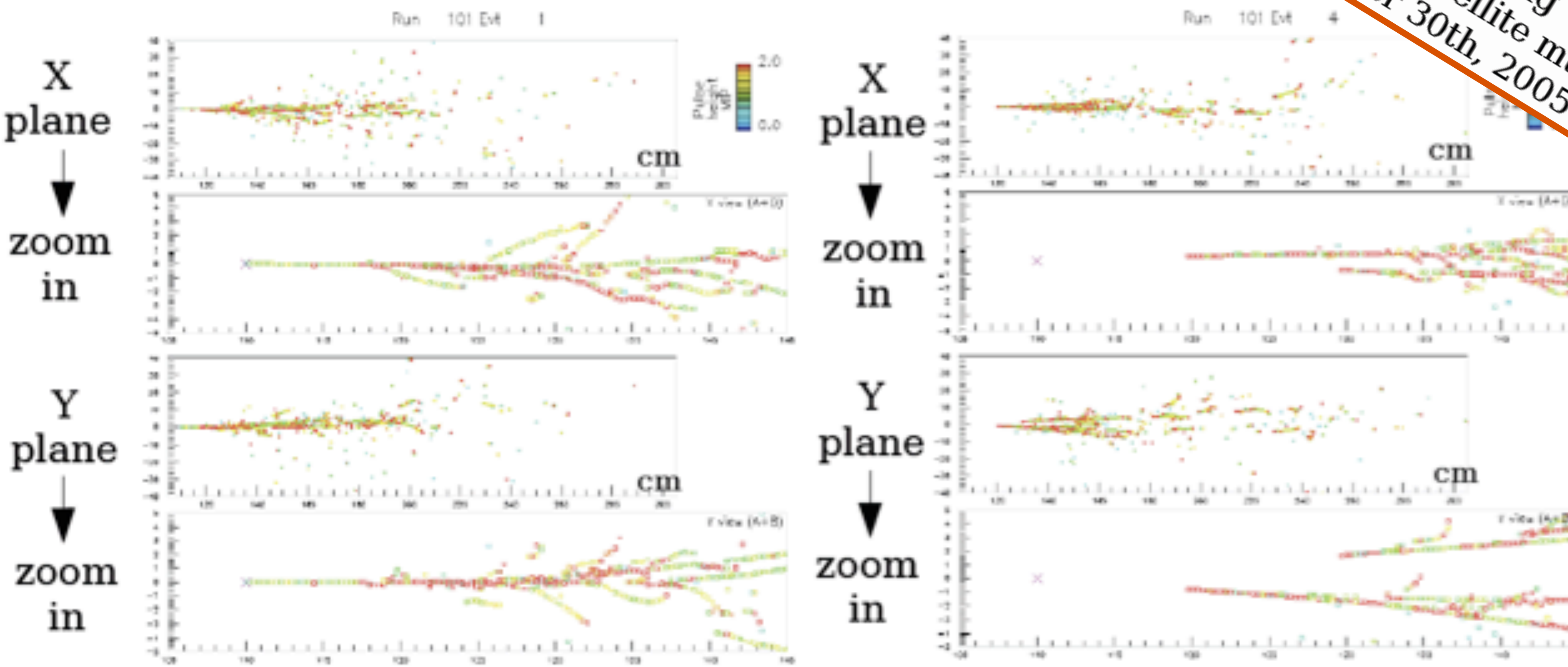
ν e Signal



π^0 BG

e/π^0 in liquid Argon

Bonnie Fleming
PANIC satellite mtg
October 30th, 2005



Electrons

Single track (mip scale) starting from a single vertex

π^0

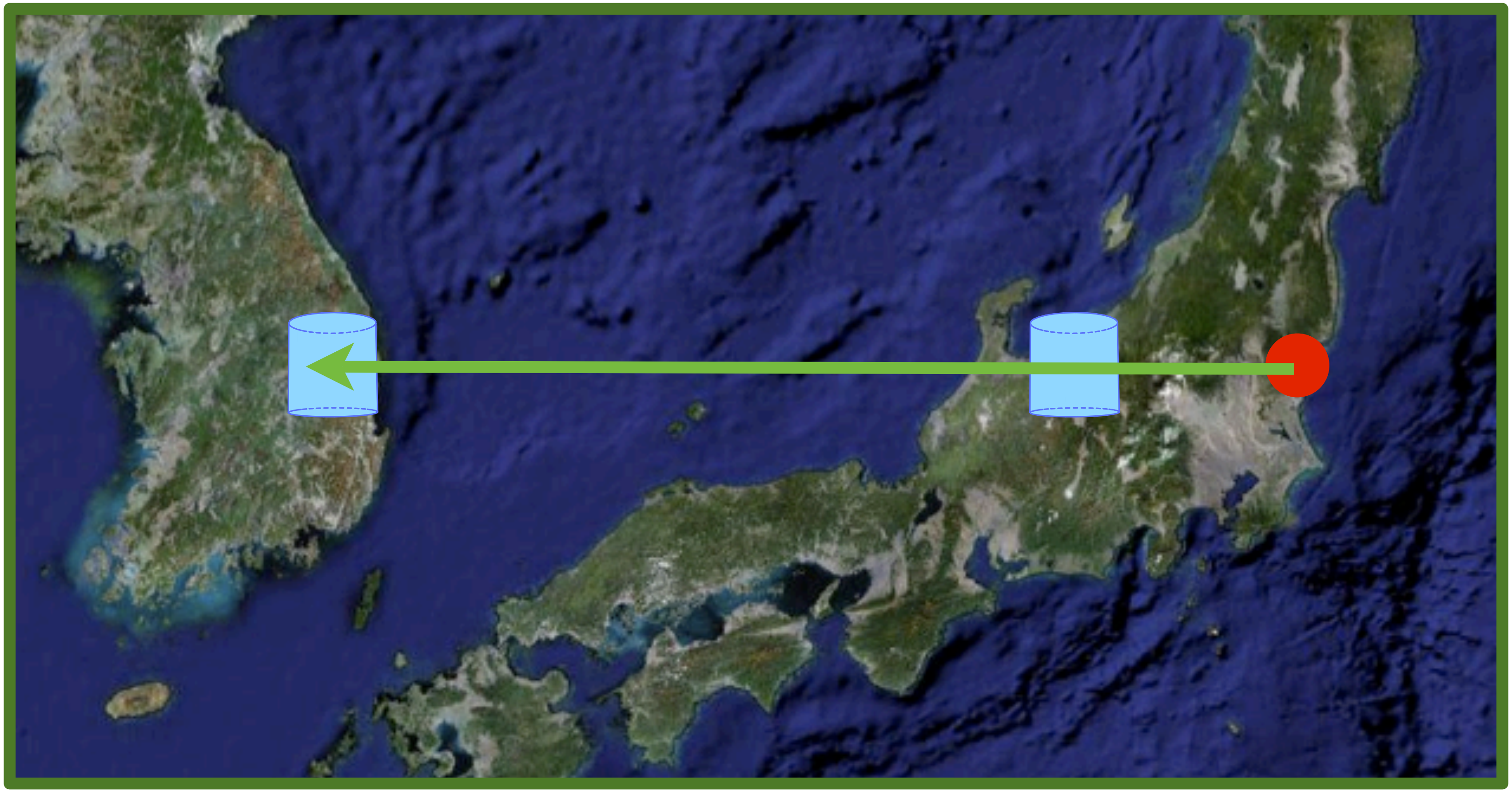
Multiple secondary tracks can be traced back to the same primary vertex

PID on dE/dX and topology

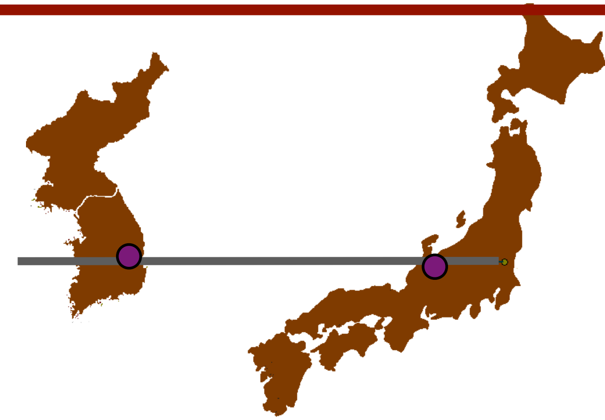
Efficiency for both technologies (Assumptions)

	Water Cherenkov			Liquid Argon		
Energy (GeV)	QE	non-QE	BG (NC)	QE	non-QE	BG (NC)
0.35-0.85	~80% cut needed to remove NC	~ 40% cut needed to remove NC	~ 1%	90% cf. MODULar 2008 paper		~ 0.1% cf. MODULar and Icarus
0.85-1.5			~ 3%			
1.5-2.0			~ 3%			
2.0-3.0			~ 4%			
3.0-4.0			~ 4%			

T2KK sensitivities



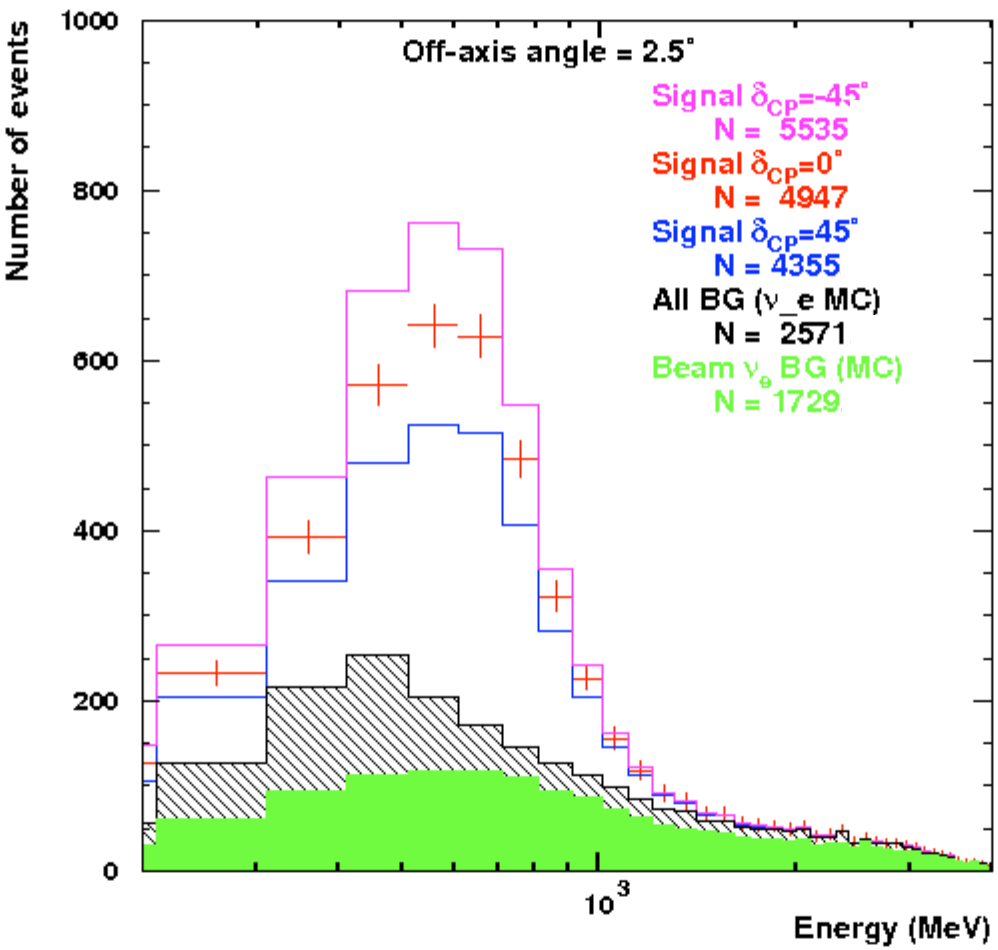
The T2KK setup



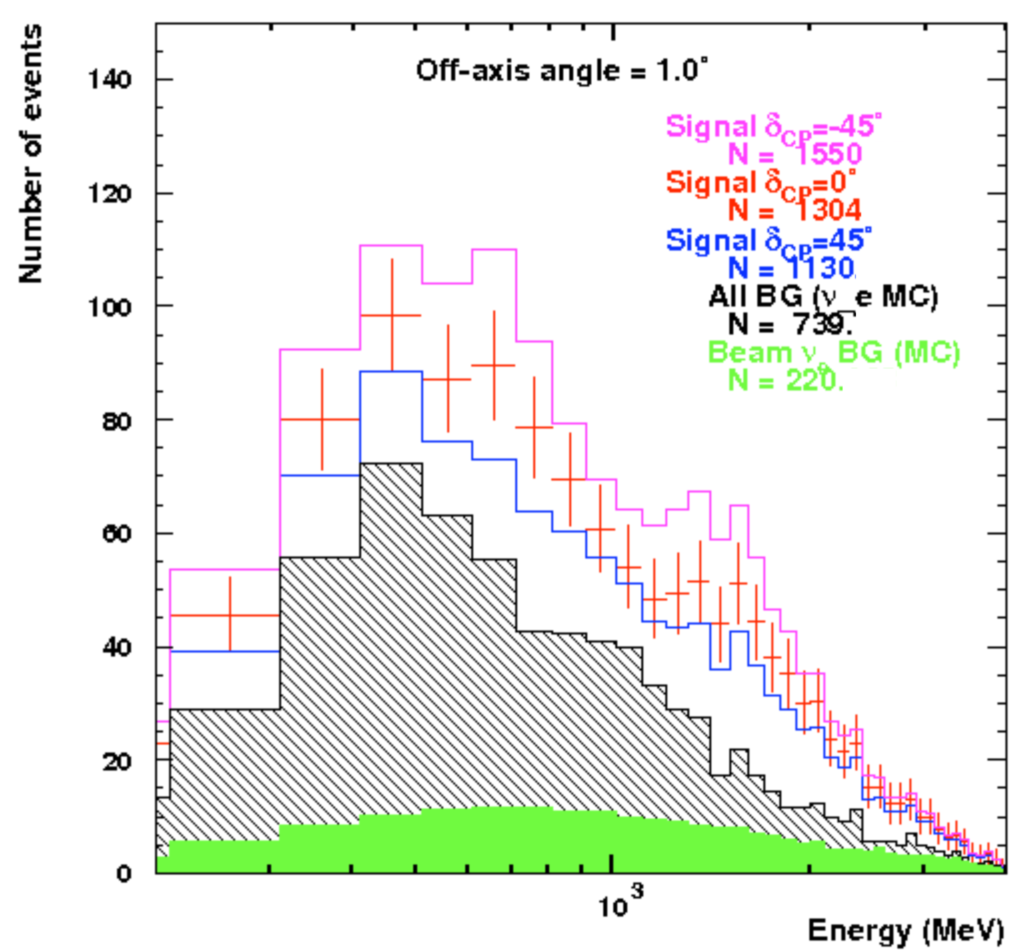
Volume	2 x 270 kton WC / 270 kton WC + 100 kton LAR
Beam Power	1.66 MW
Running time	5 yrs nu + 5 yrs antinu
1 year is	10^7 seconds
Proton energy	30 GeV
Tot # of POT	3.45×10^{21} POT
Distance	295 km and 1050 km
Off-axis angle	2.5 ° (Kamioka) and 1.0 ° (Korea) Off-axis

1 degree off-axis in Korea with Water Cherenkov

Spectrum at Kamioka



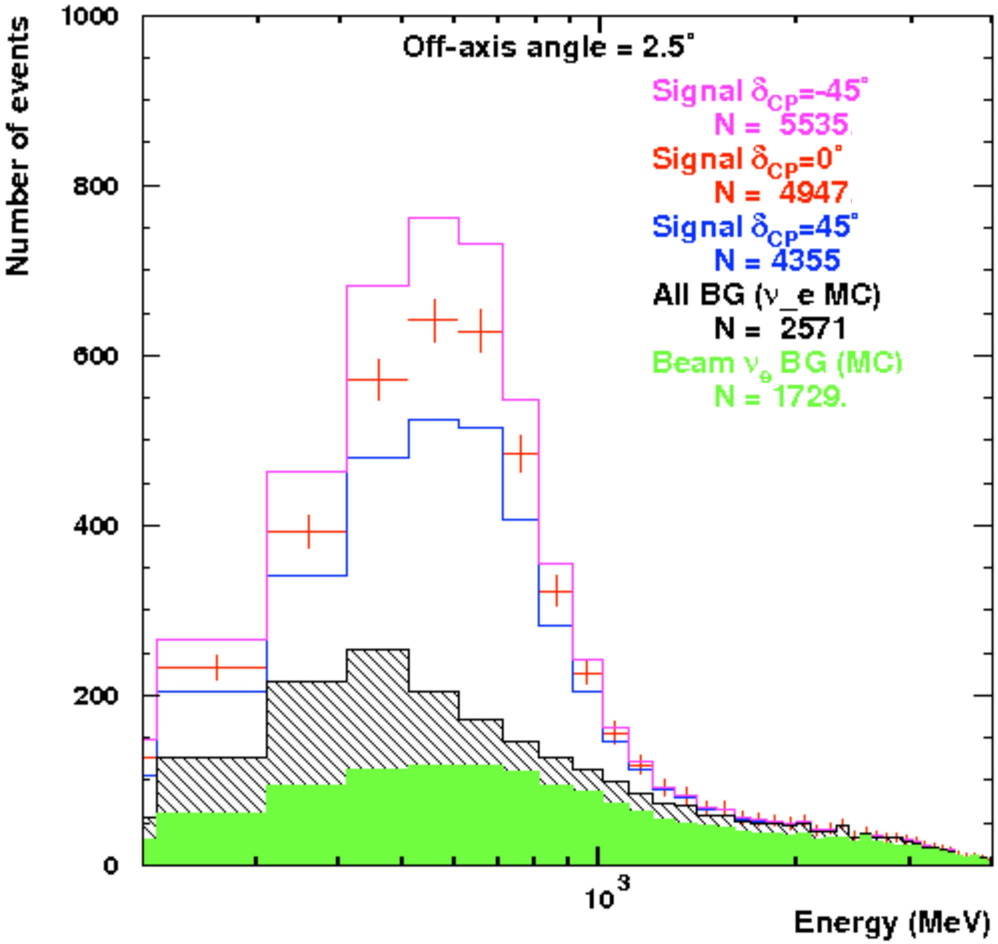
Spectrum at Korea 1.0° OA



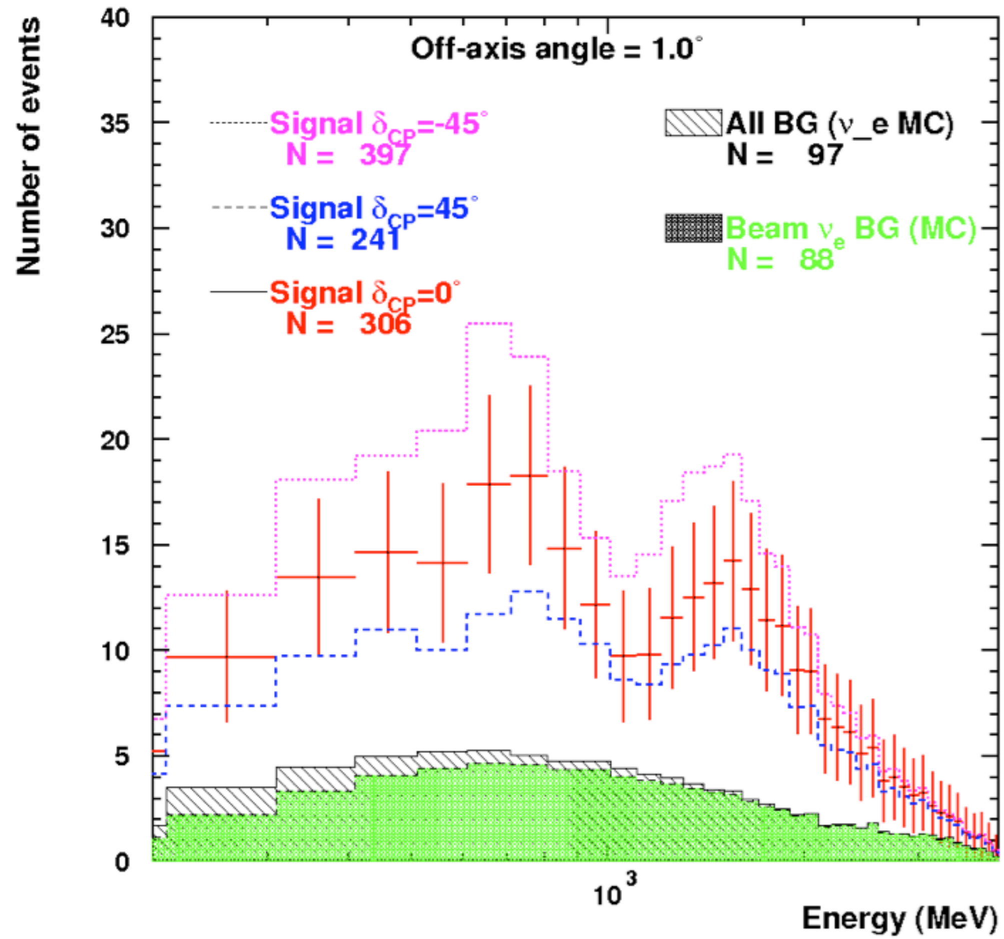
$\sin^2(2\theta_{13})$=0.04, neutrino, normal hierarchy

1 degree off-axis in Korea with LAr

Spectrum at Kamioka

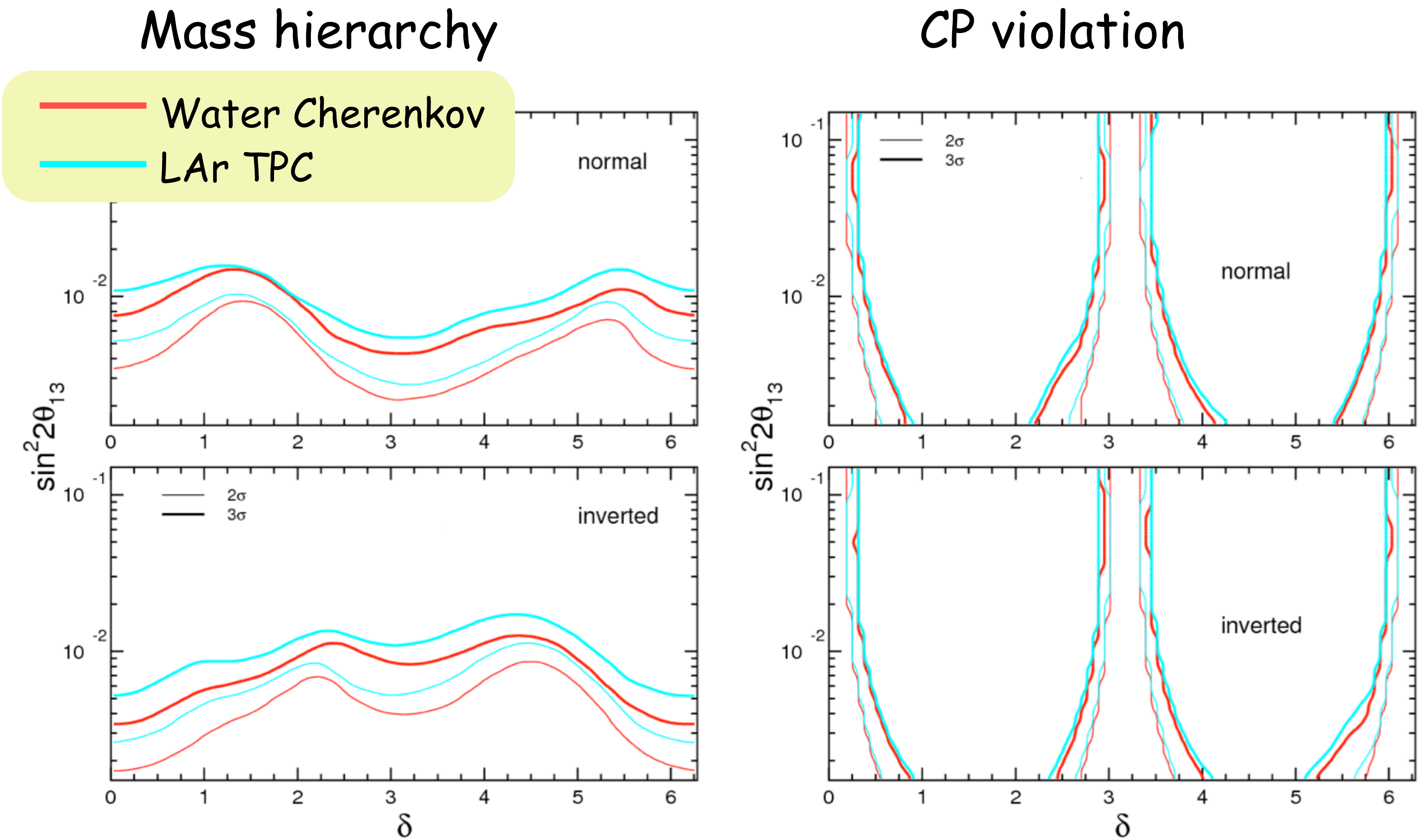


Spectrum at Korea 1.0° OA



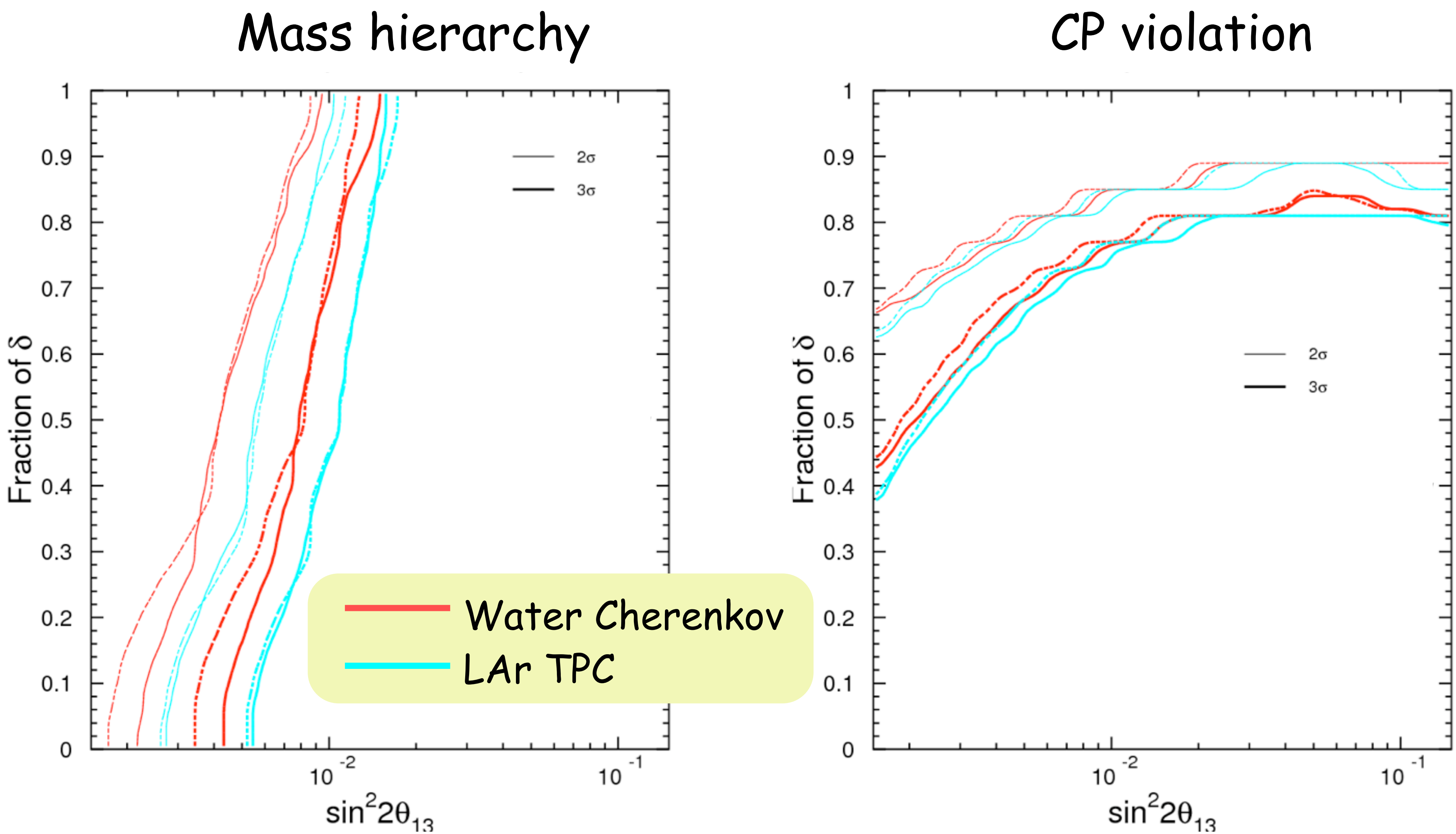
$\sin^2(2\theta_{13})$=0.04, neutrino, normal hierarchy

Sensitivities T2KK (far detector at 1° off-axis)



For the given setup, Water Cherenkov and Liquid Argon are very much comparable.

Sensitivity as a fraction of CP



For the given setup, Water Cherenkov and Liquid Argon are very much comparable.

Summary

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

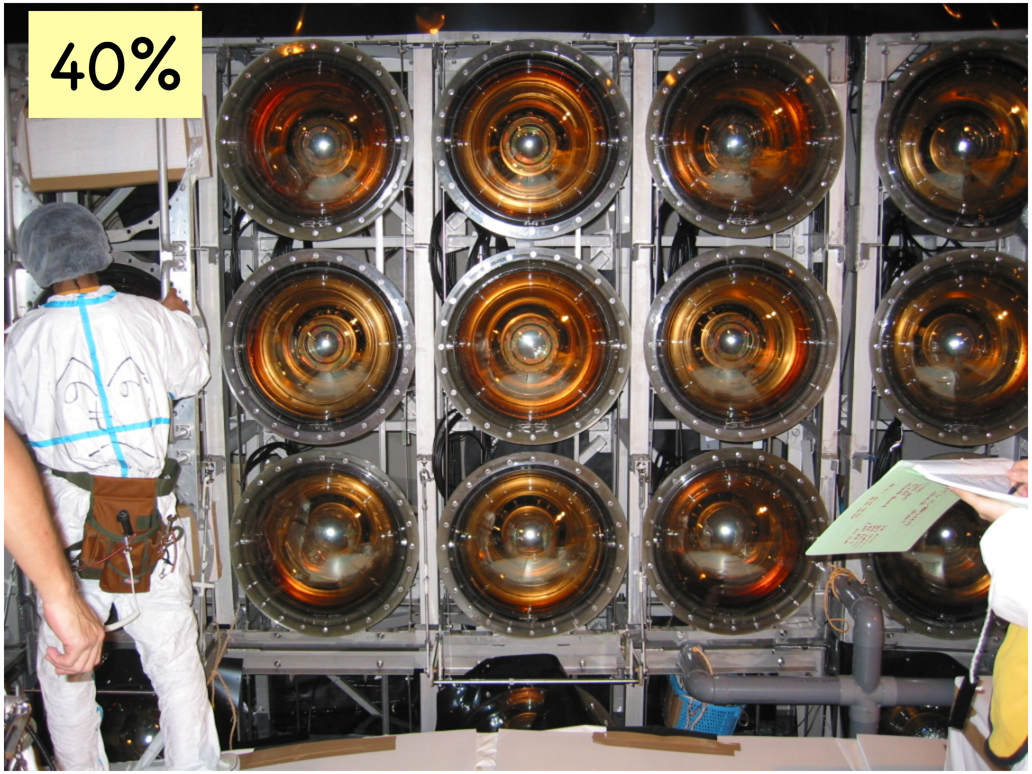
- I tested two options for the Korean detector:
  - Water Cherenkov and Liquid Argon

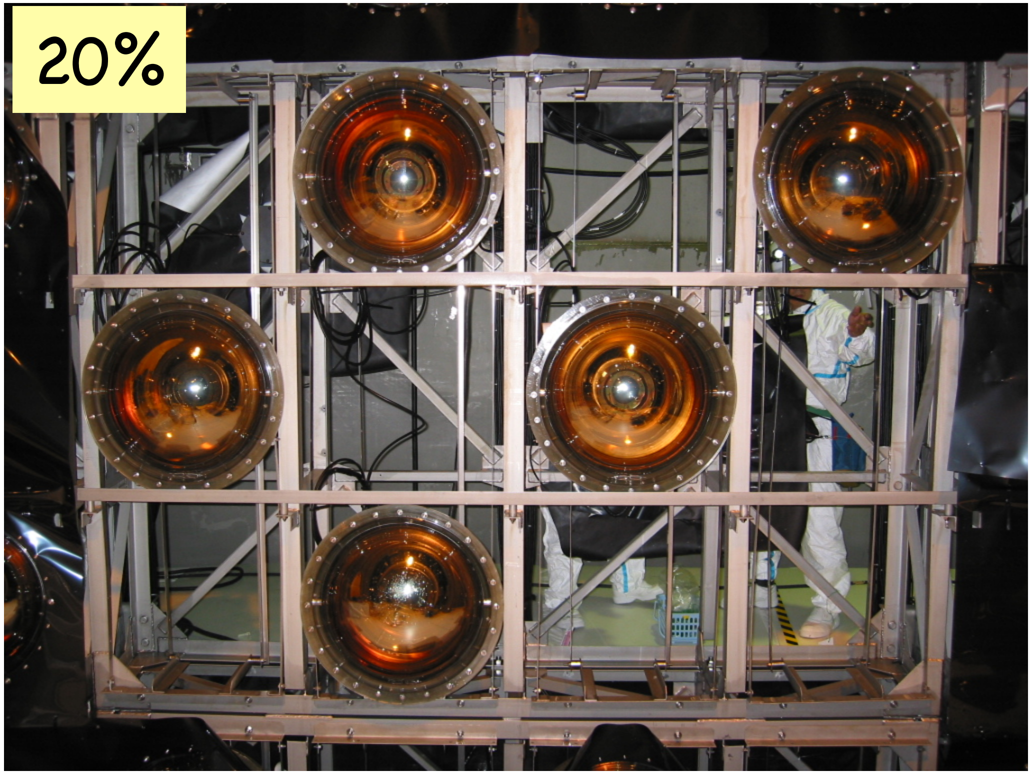
- Both solutions are comparable if:
  - Water Cherenkov is three times bigger than the liquid Argon.
  - The liquid Argon is basically background free (except from a known beam ν_e contamination).

backups

Photo-coverage

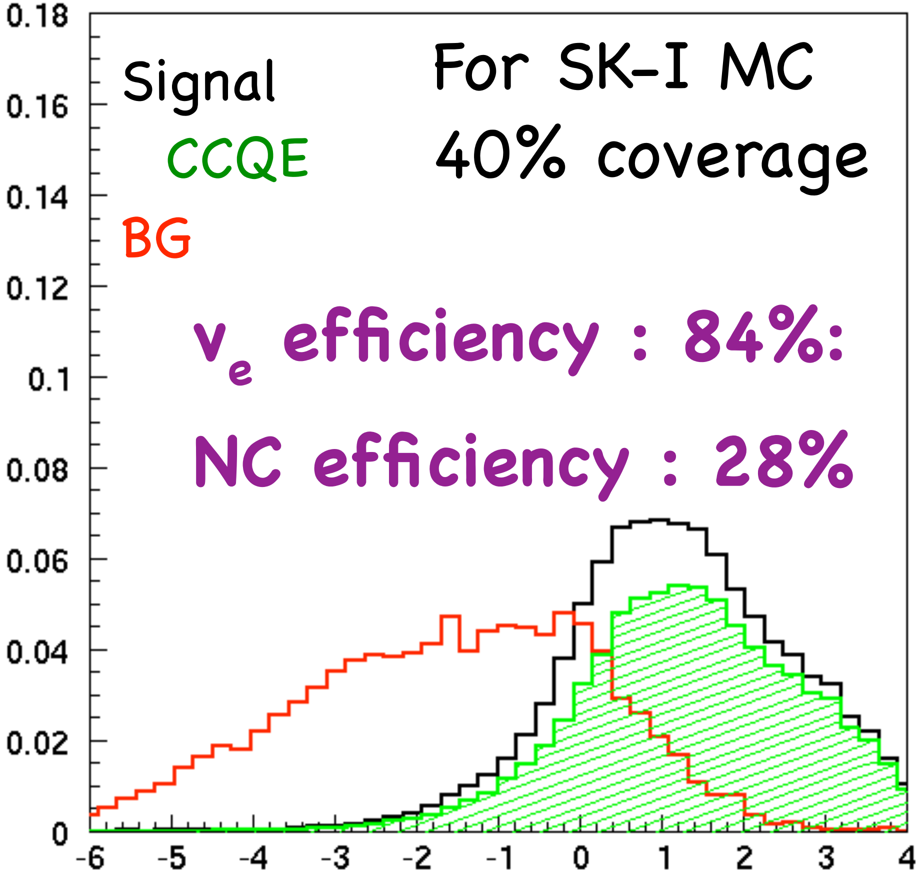
"Thanks" to the accident in SK, we have MC corresponding to 20% and 40% photo-coverage

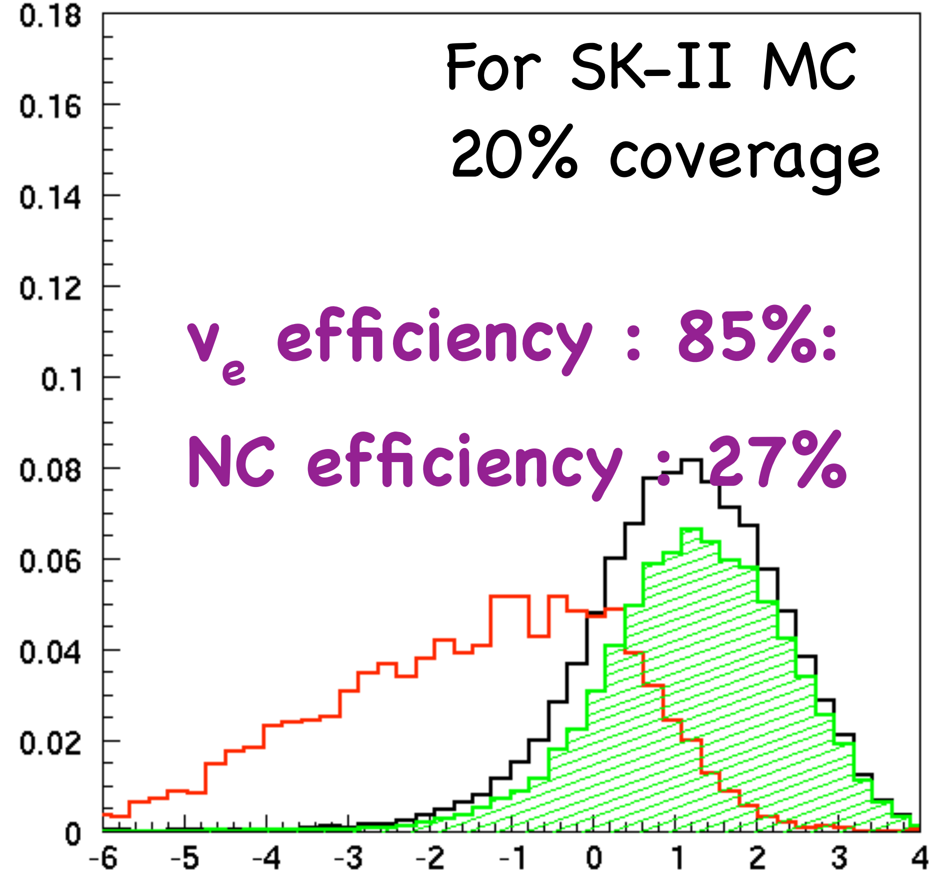




We tested our likelihood on both samples, and it gives very similar results.

Photo-coverage results





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

350 MeV < E < 850 MeV

Definition of 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.

With the following energy bins (MeV):

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

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

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

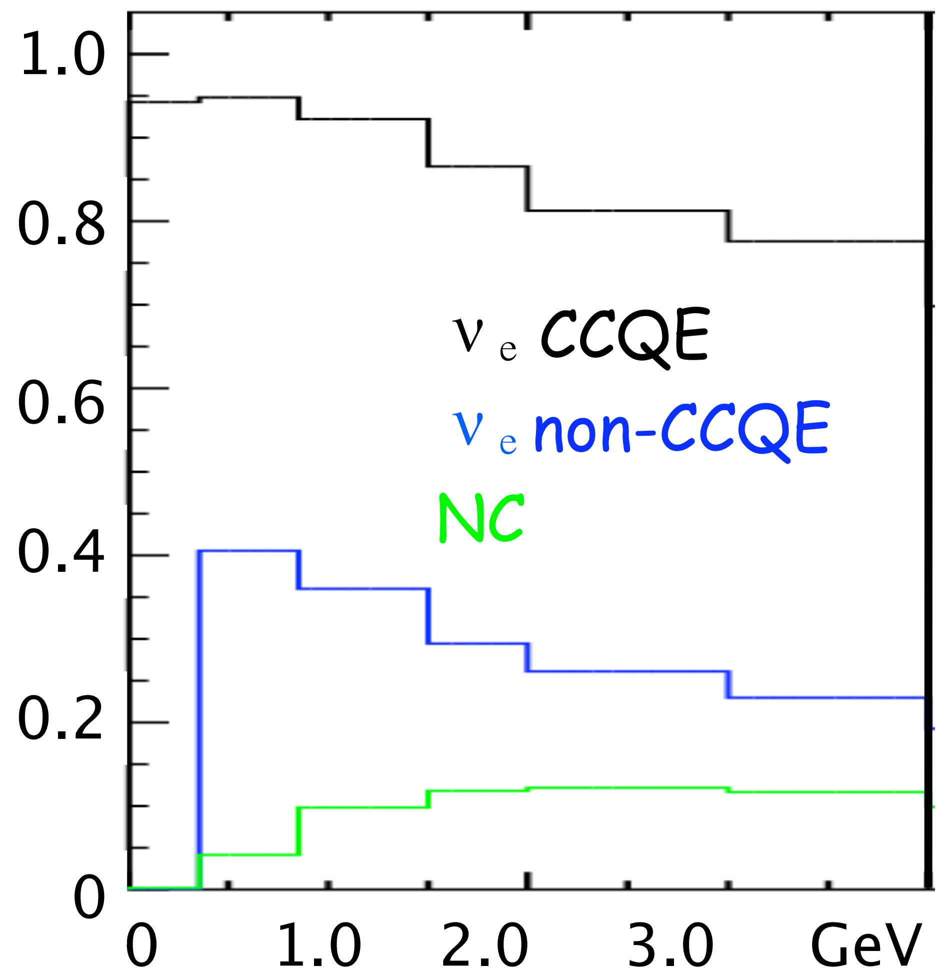
Likelihood analysis sample

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 efficiency



Final likelihood efficiency

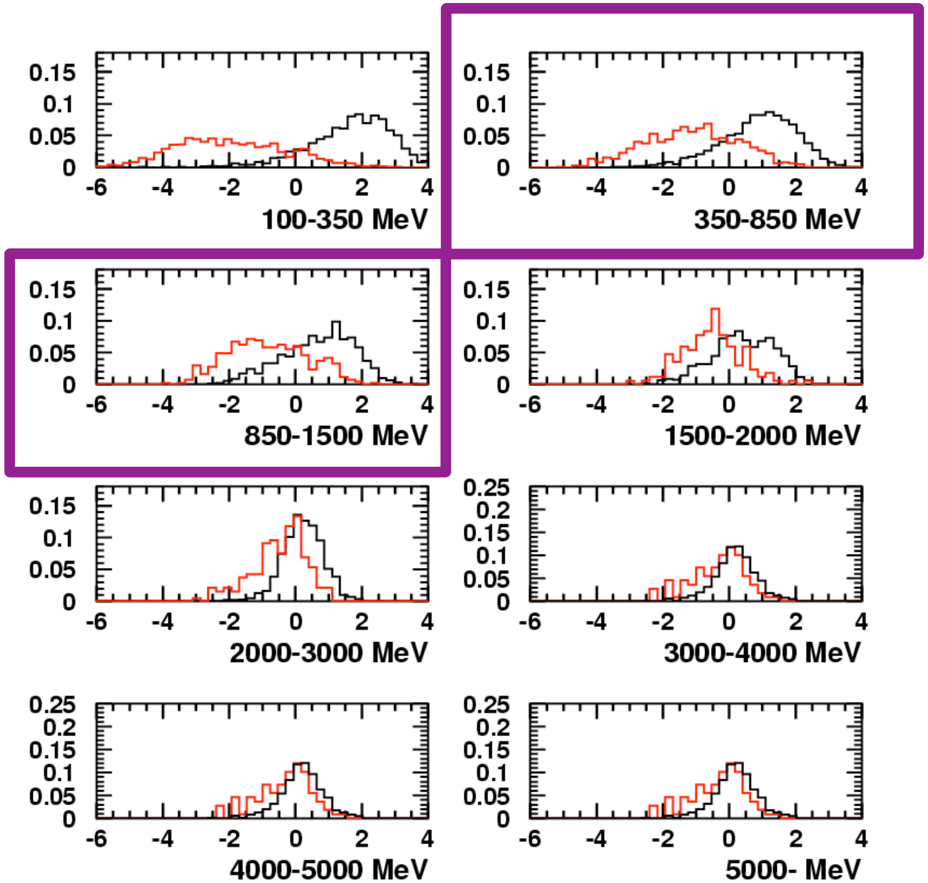
We did a study of $S/\sqrt{B}$ and we found that keeping 80% of the signal is what gives the best results.

	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

Precuts NC reduction ~ 90%
Total reduction ~ 97%

Likelihood variables

Likelihood per energy bin



Likelihood variables:

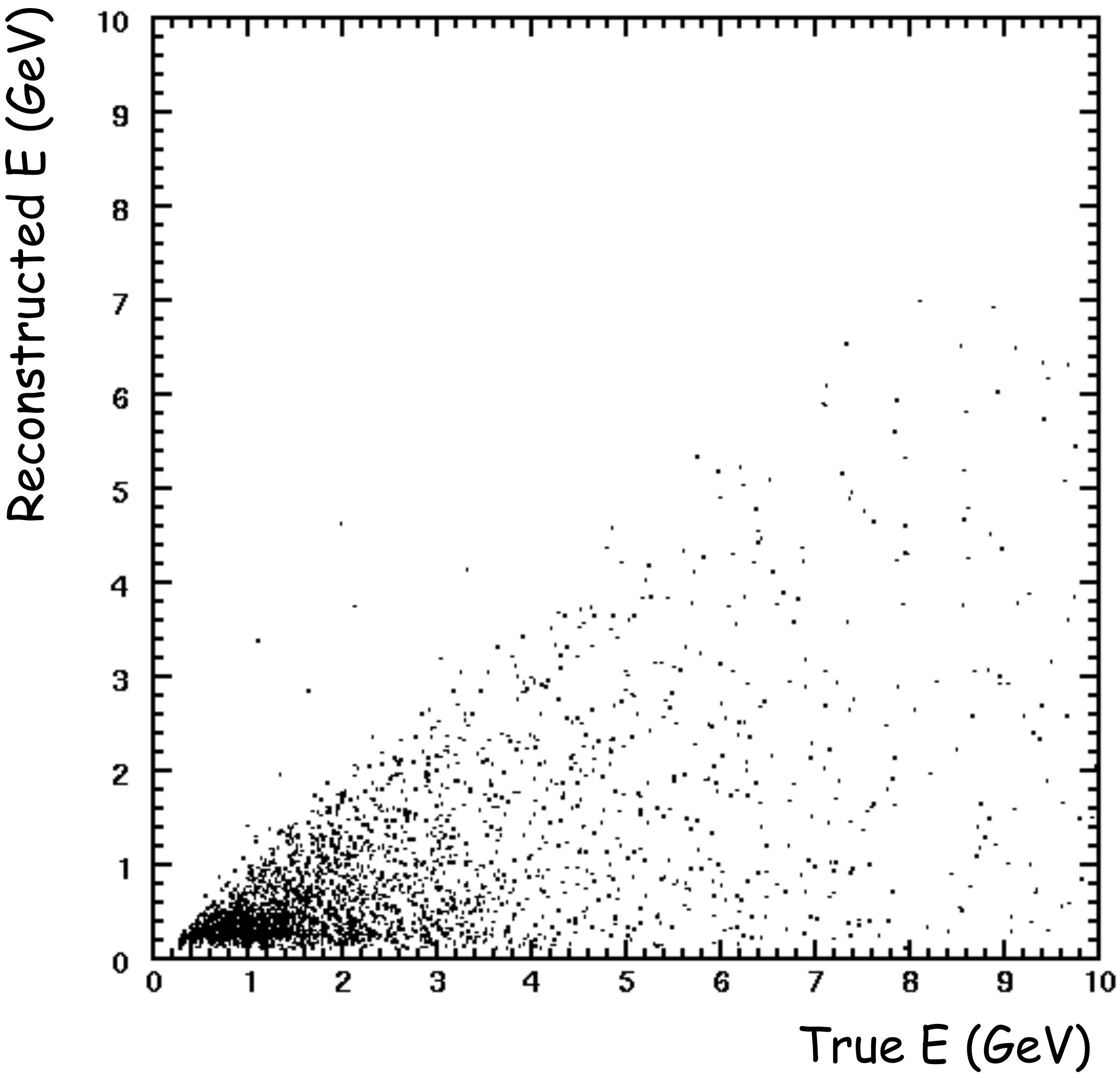
Standard SK variables:
ring parameter, PID parameter

Variables related to π^0 in SK.

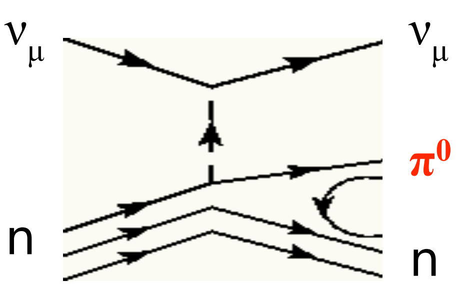
Variables using beam direction info.

Background
Signal (Main signal bin)

NC energy response

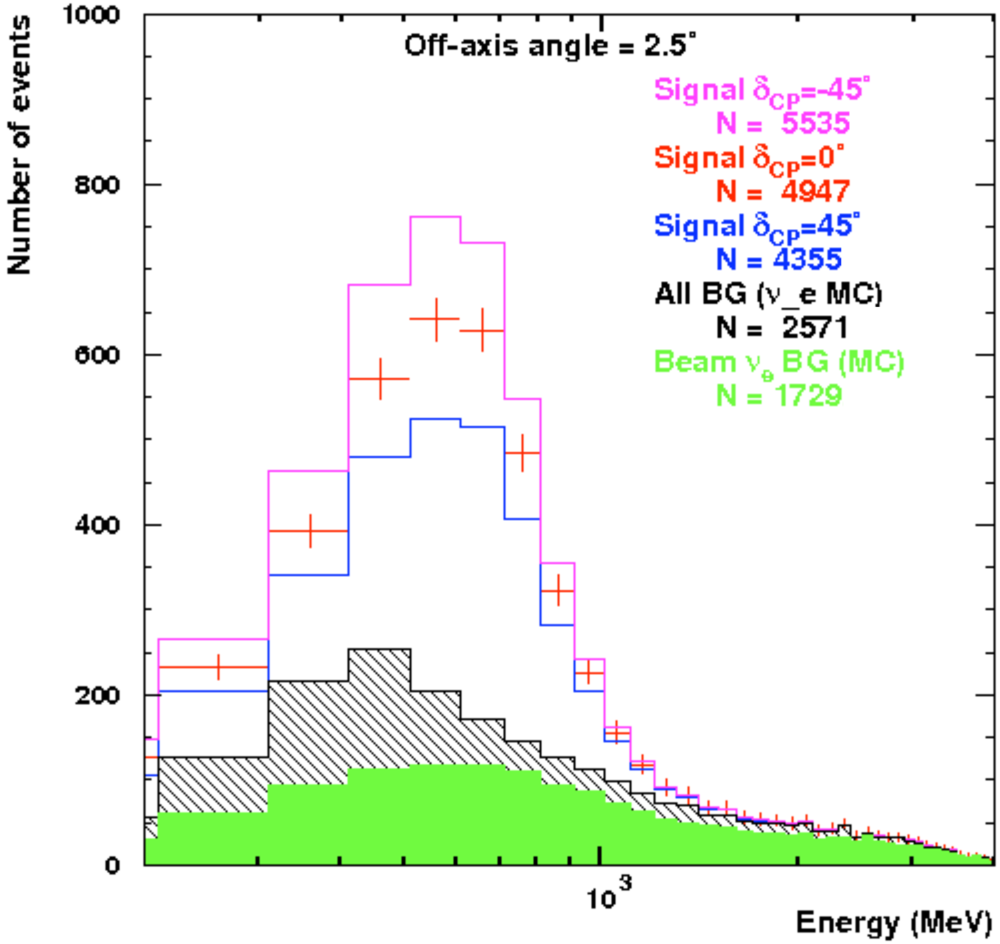


The energy response of neutral current events is completely non linear since what we observe is the pion and this pion can have any energy.

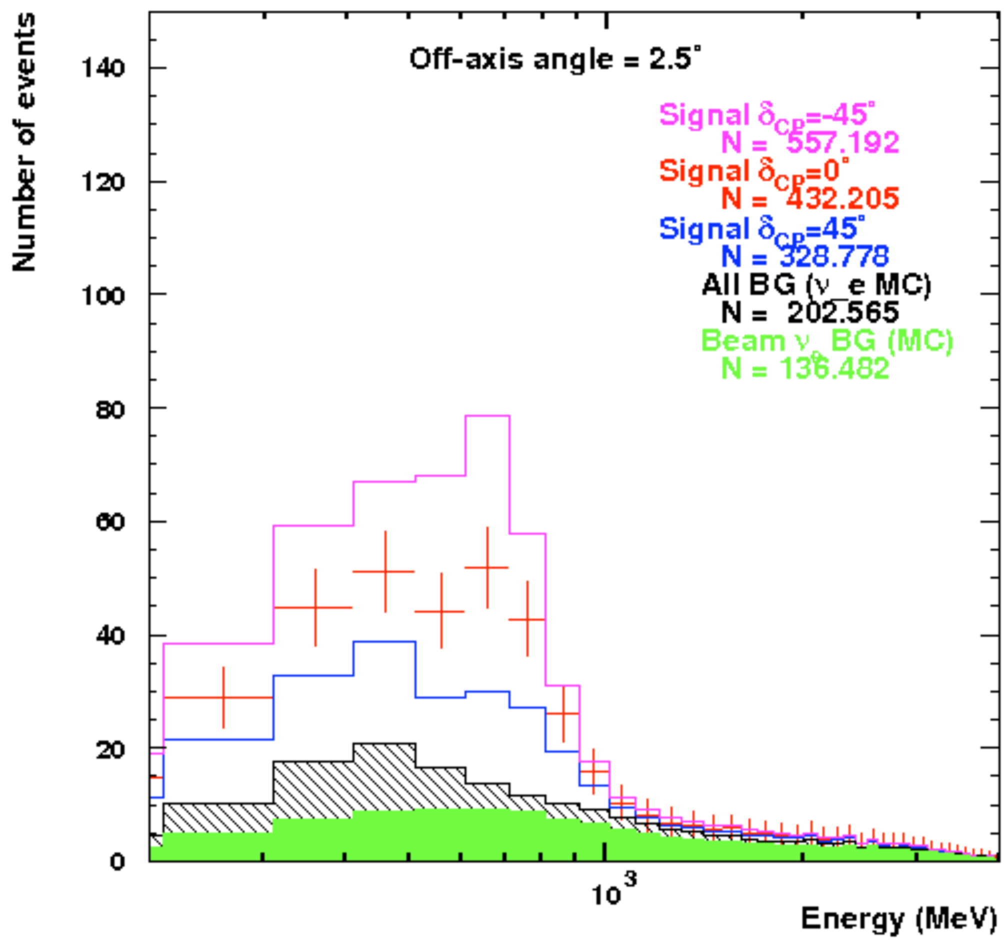


2.5 degree off-axis in Korea

Spectrum at Kamioka

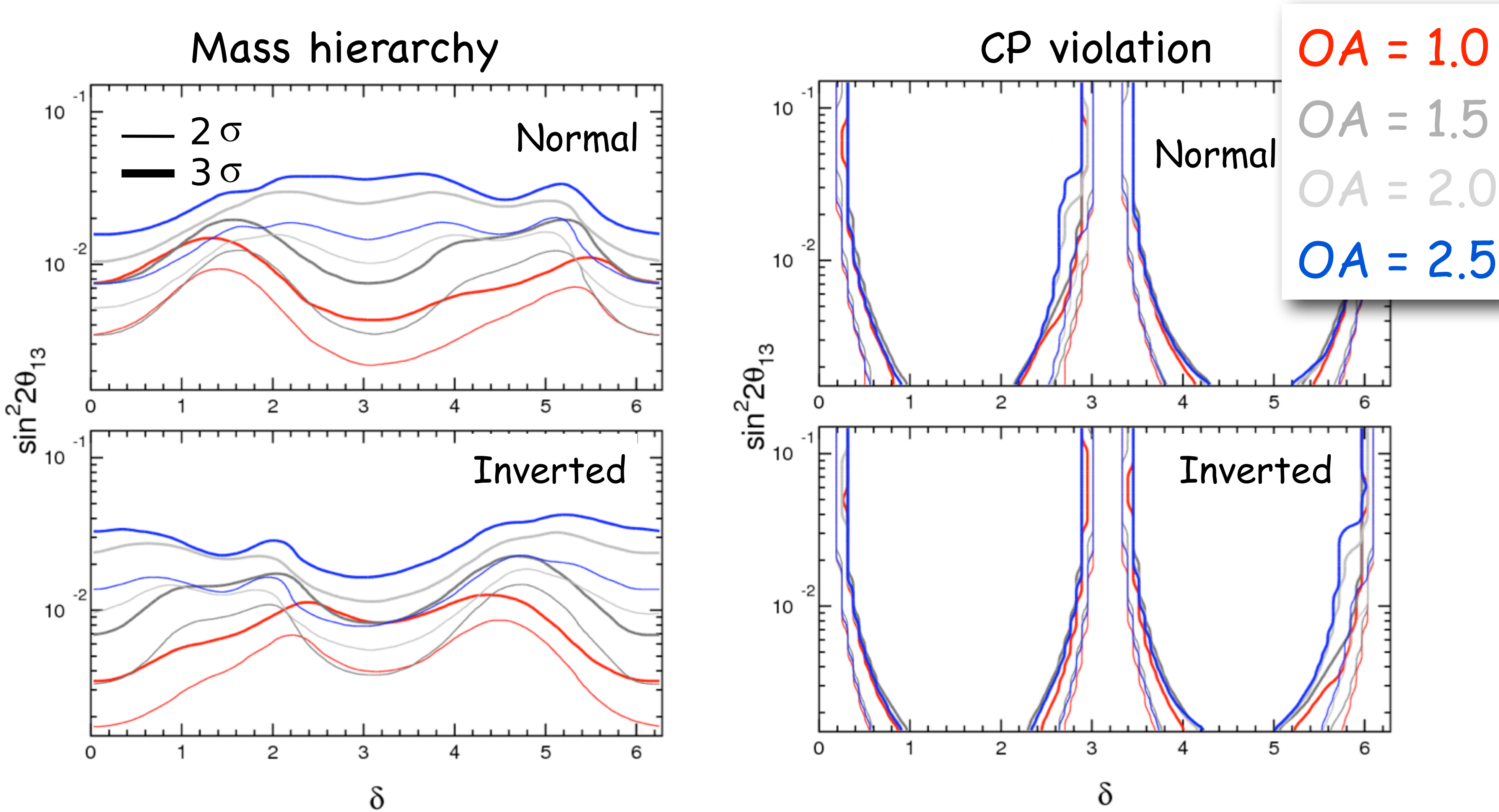


Spectrum at Korea 2.5° OA



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

T2KK Sensitivities



- 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.