CP violation Physics at a J-PARC beam

~ Liquid Argon TPC case ~

A.Bueno, T.Hasegawa, T.Kobayashi, A.Marchionni, A.Meregaglia, T.Maruyama, K.Nishikawa, A.Rubbia

The way to extract CP phase

$$U = \begin{pmatrix} c_{12}c_{13} & c_{13}s_{12} & e^{-i\delta}s_{13} \\ -s_{12}c_{23} - e^{-i\delta}c_{12}s_{13}s_{23} & c_{12}c_{23} - e^{i\delta}s_{12}s_{13}s_{23} & c_{13}s_{23} \\ -e^{i\delta}c_{12}s_{13}c_{23} + s_{12}s_{23} & -e^{i\delta}s_{12}s_{13}c_{23} - c_{12}s_{23} & c_{13}c_{23} \end{pmatrix}$$

- See the energy spectrum of oscillation signal in neutrino beam (i.e. only neutrino run could have strong hints)

$\nu_e \rightarrow \nu_\mu$ oscillation probability

$$P(\nu_e \rightarrow \nu_\mu) \approx \sin^2 2\theta_{13} T_1 + \alpha \sin 2\theta_{13} (T_2 + T_3) + \alpha^2 T_4$$

$$T_1 = \sin^2 \theta_{23} \frac{\sin^2[(1-A)\Delta]}{(1-A)^2}$$

Atmospheric

$$T_2 = \underline{\sin \delta_{CP}} \sin 2\theta_{12} \sin 2\theta_{23} \underline{\sin \Delta} \frac{\sin(A\Delta)}{A} \frac{\sin[(1-A)\Delta]}{(1-A)}$$

Interference

$$T_3 = \underline{\cos \delta_{CP}} \sin 2\theta_{12} \sin 2\theta_{23} \underline{\cos \Delta} \frac{\sin(A\Delta)}{A} \frac{\sin[(1-A)\Delta]}{(1-A)}$$

$$T_4 = \cos^2 \theta_{23} \sin^2 2\theta_{12} \frac{\sin^2[A\Delta]}{A^2}$$

Solor

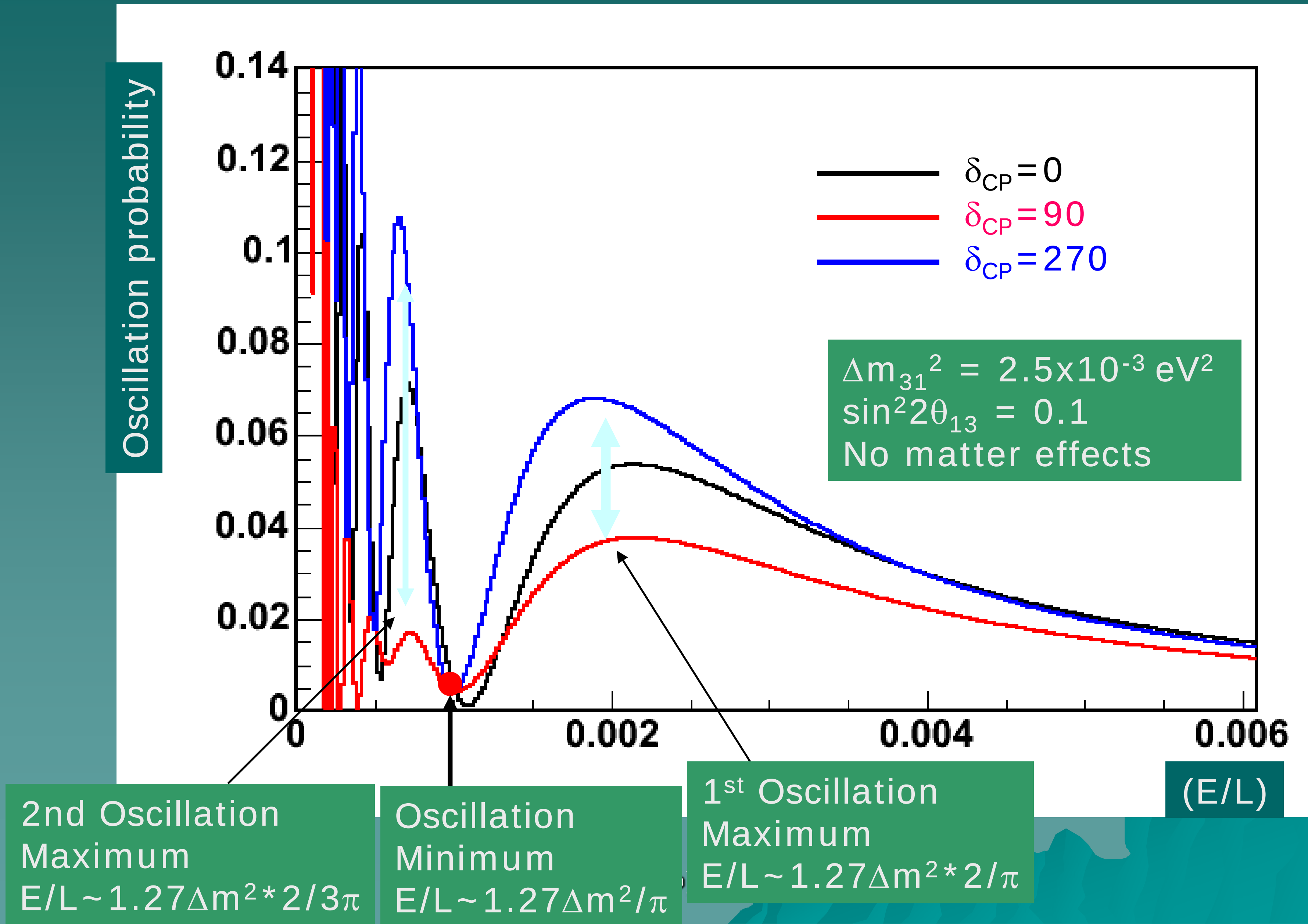
$$\alpha \equiv \frac{\Delta m_{21}^2}{\Delta m_{31}^2} \approx \pm 0.03$$

$$\Delta \equiv \frac{\Delta m_{31}^2 L}{4E}$$

$$A \equiv \frac{2\sqrt{2} G_F n_e E}{\Delta m_{31}^2}$$

Interference term plays important role!!

$\nu_\mu \rightarrow \nu_e$ oscillation probability (on E/L)



Focus on lepton sector CP violation discovery/measurement with LAr TPC

- How to approach CP phase measurement with Liquid Argon TPC detector

  - Liquid Argon TPC has advantage on
    - Good Energy resolution / reconstruction
    - Good background suppression (π^0)
    - Good signal efficiency

  - Thus this detector is suitable for the precision measurement on neutrino energy spectrum to extract CP information. (w/ only neutrino run)

Focus on lepton sector CP violation discovery/measurement with LAr TPC (cont'd)

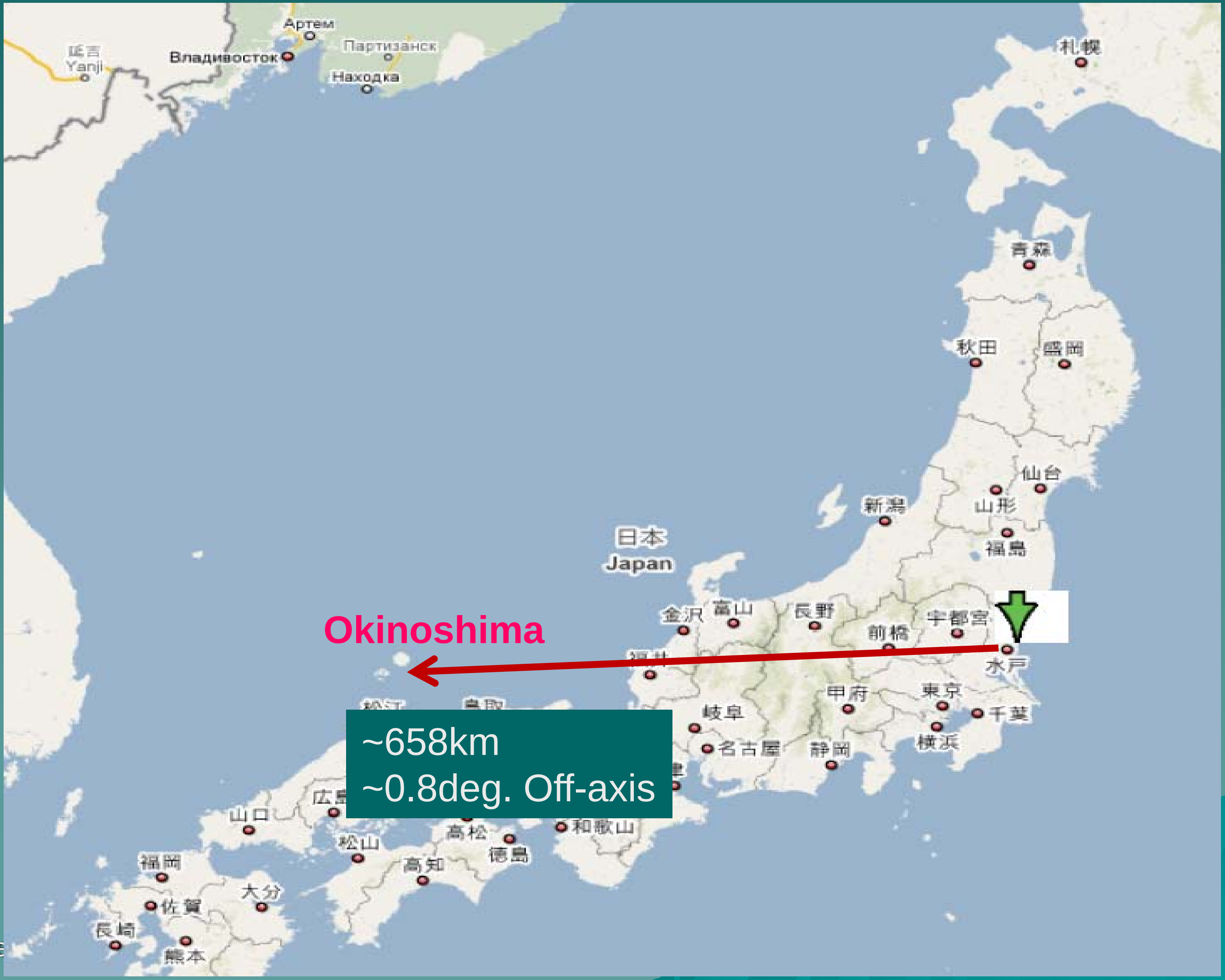
- It is crucial to see;
  - position / height of the first oscillation maximum peak
  - position / height of the second oscillation maximum peak
  - position of the first oscillation minimum.

  of the appearance νe energy spectrum
- In order to do this;
  - The second oscillation maximum peak should stay at sufficient high energy.
  - Beam should cover wider energy range
  - Keep high stat data as much as possible to analyze

Focus on lepton sector CP violation discovery/measurement with LAr TPC (cont'd)

- For example, if the second oscillation maximum has to stay larger than ~400MeV,
  - Baseline is needed to be longer than ~600km
- If the beam should cover wider energy range,
  - Beam should be as on-axis as possible.
- To keep high statistics to analyze;
  - Not too long baseline, but not too short baseline neutrino experiment is needed.

Found suitable place in map



Beam parameters

- Here summarize beam parameters again;
  - 1.66MW
  - 3.45×10^{21} POT / year
  - incident proton kinetic energy is 30GeV
- Okinoshima
  - ~0.8 degree from Tokai
  - ~658 km from Tokai
- This talk is based on 5 years neutrino run.

Caveat; DON'T ask me on geology/sociology of Okinoshima. We will visit it after workshop to investigate it.

Assumptions in this talk

- 100kT LAr is assumed.
- LAr TPC has signal efficiency of 100% for ν_e Charged Current (CC) events.
- NC π^0 BKG is negligible compared to beam ν_e BKG.
- Background is only due to beam ν_e events.
- Effects on neutrino energy resolution will be studied for 0/100/200 MeV (Gaussian smearing) cases.
- No systematics are considered unless otherwise are mentioned.
- Concentrate to extract allowed regions rather than sensitivity plots.

Parameters for oscillation

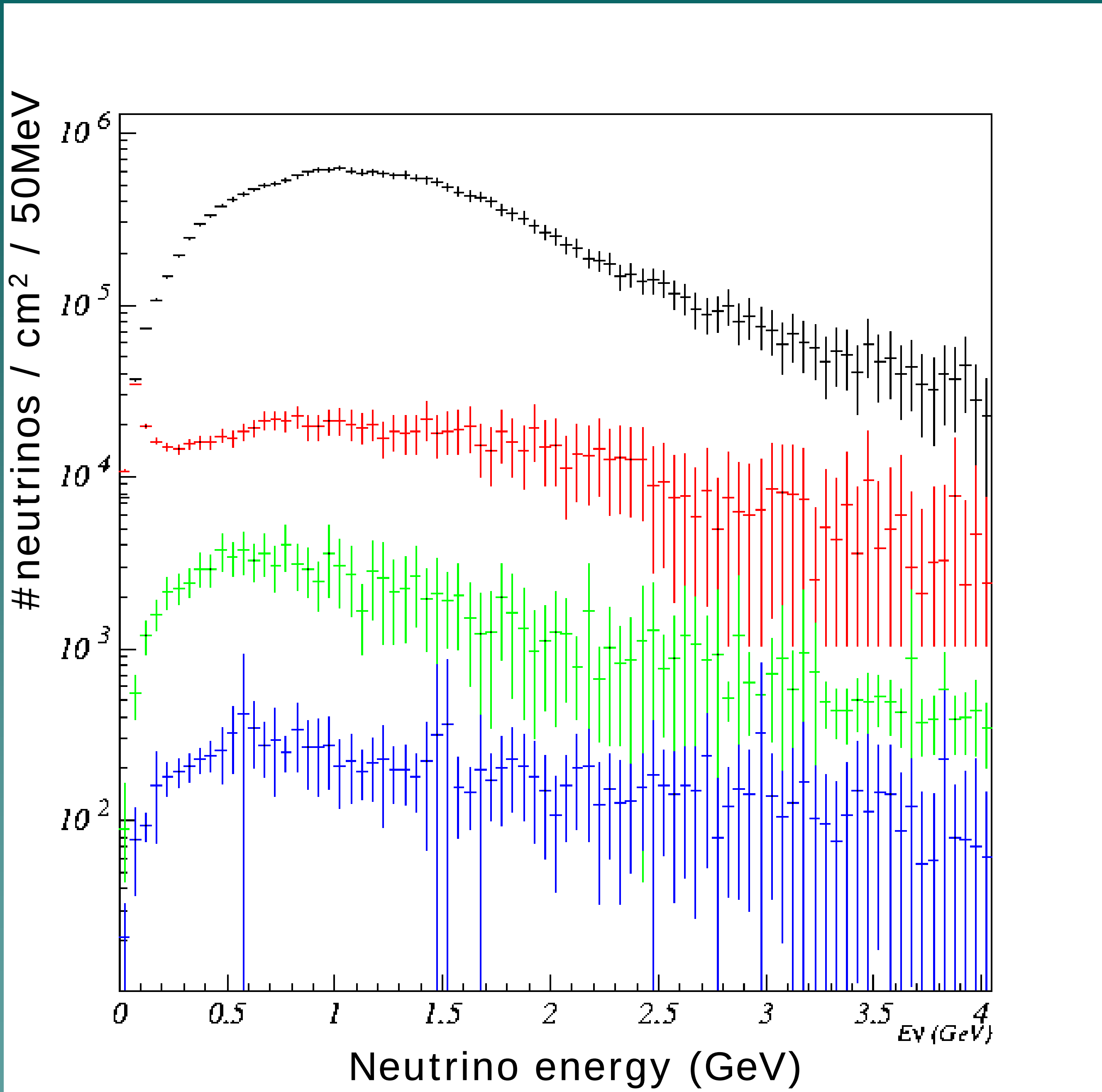
- $\Delta m_{31}^2 = 2.5\text{x}10^{-3}$ eV² <normal hierarchy>
- $\Delta m_{21}^2 = 8.2\text{x}10^{-5}$ eV²
- $\theta_{23} = \pi/4$
- $\theta_{12} = 0.573$
- $\rho = 2.8$ g/cm³ for matter effects

(all parameters are same as PRD 76, 093002 (2007))

- These parameters are assumed to be well determined, thus free parameters are only θ_{13} and δ_{CP}.

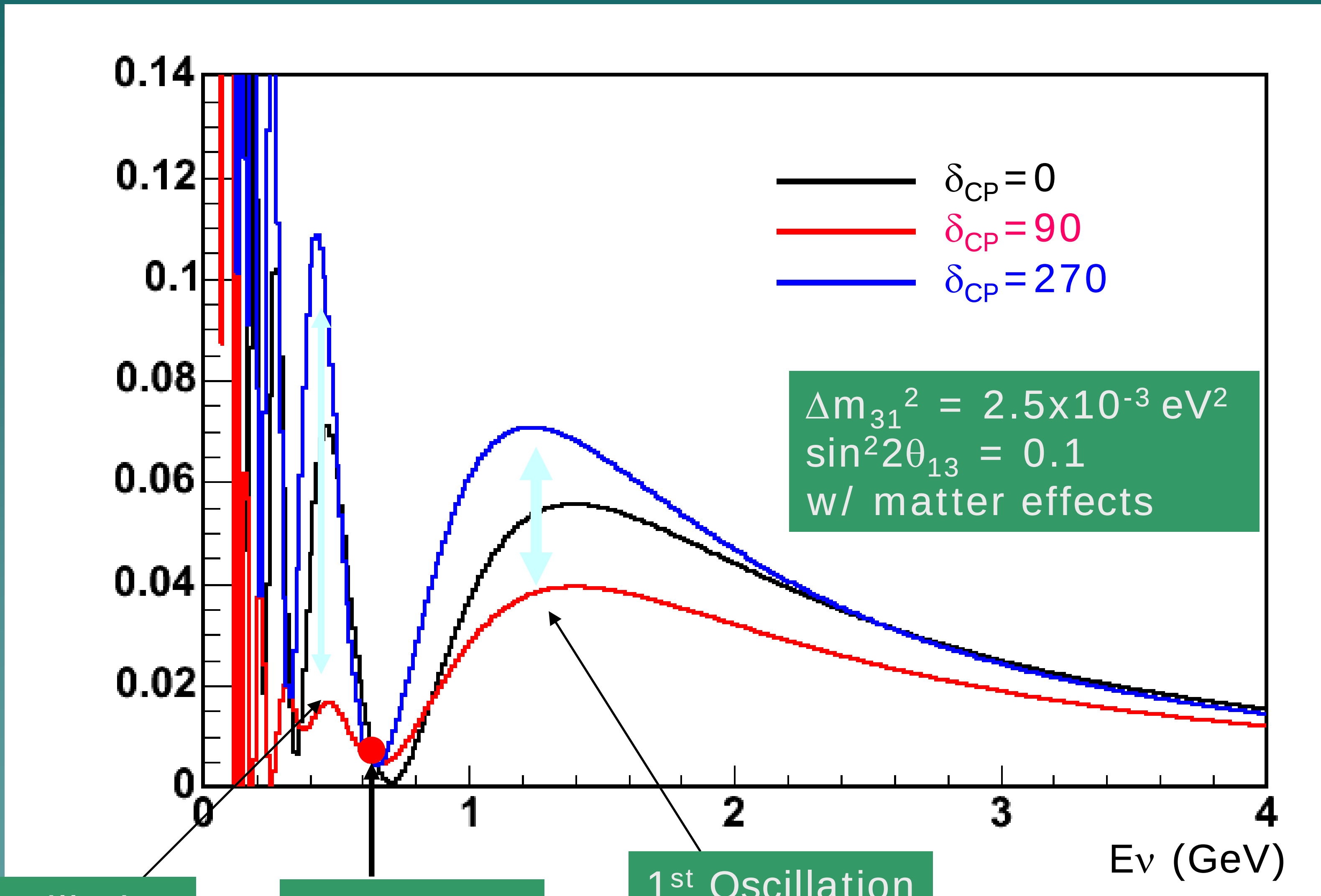
Flux

- Colors in plot
  - Black; ν_μ
  - Red; $\bar{\nu}_\mu$
  - Green; ν_e (~1% compared to ν_μ)
  - Blue; $\bar{\nu}_e$
- This flux corresponds to one year neutrino run (3.5×10^{21} POT)



A.Bueno et al

$\nu_\mu \rightarrow \nu_e$ oscillation probability (L~660km)

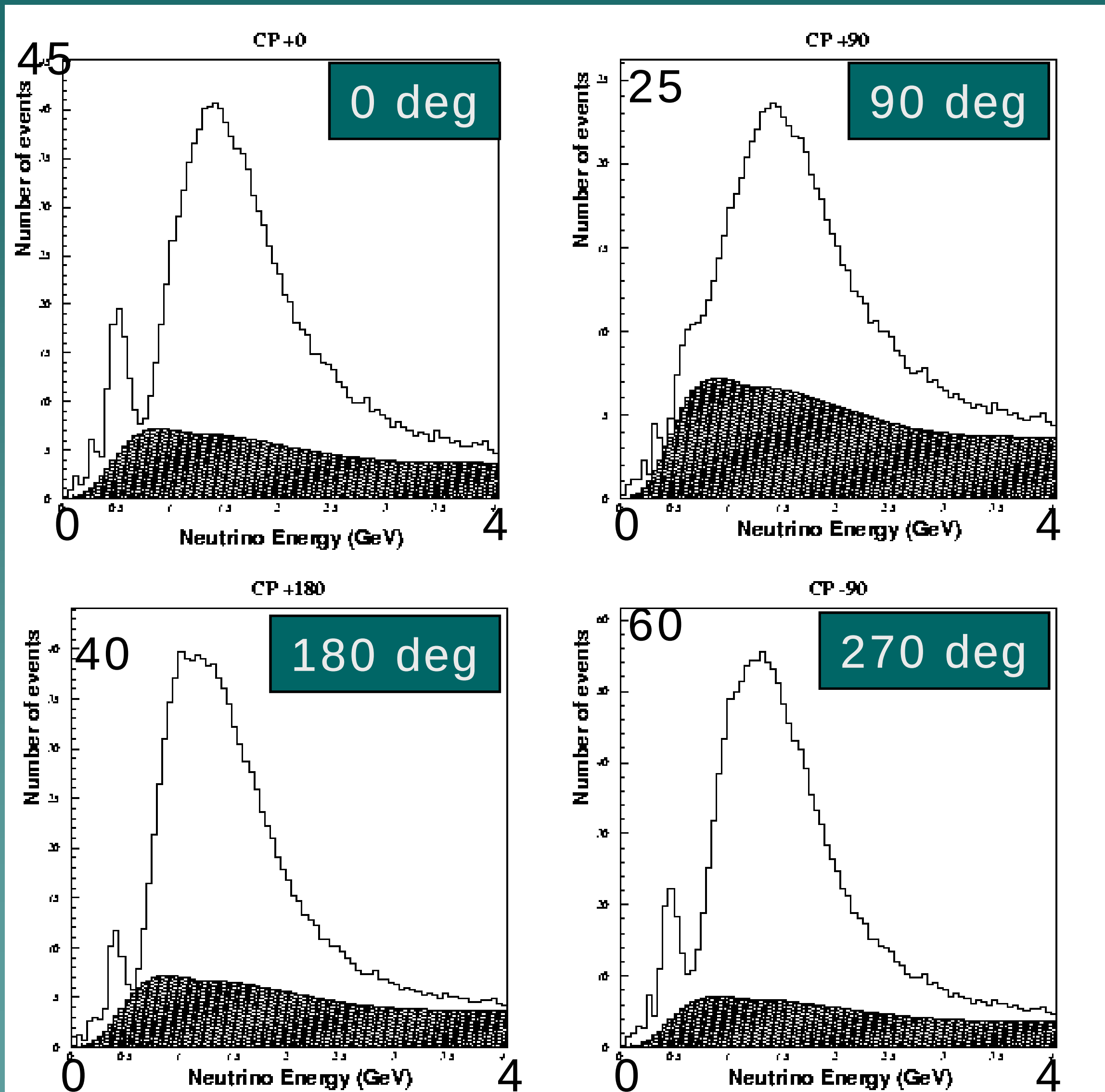


2nd Oscillation Maximum E~0.44GeV

Oscillation Minimum E~0.67GeV

1st Oscillation Maximum E~1.3GeV

Spectra for ν_e CC events



- Shaded is beam ν_e background, while histogram shows the osc'd signal.
- δ_{cp} effects are seen in 1st and 2nd osc. Maxima.

(perfect resolution case)

Number of CC events

- No oscillation case

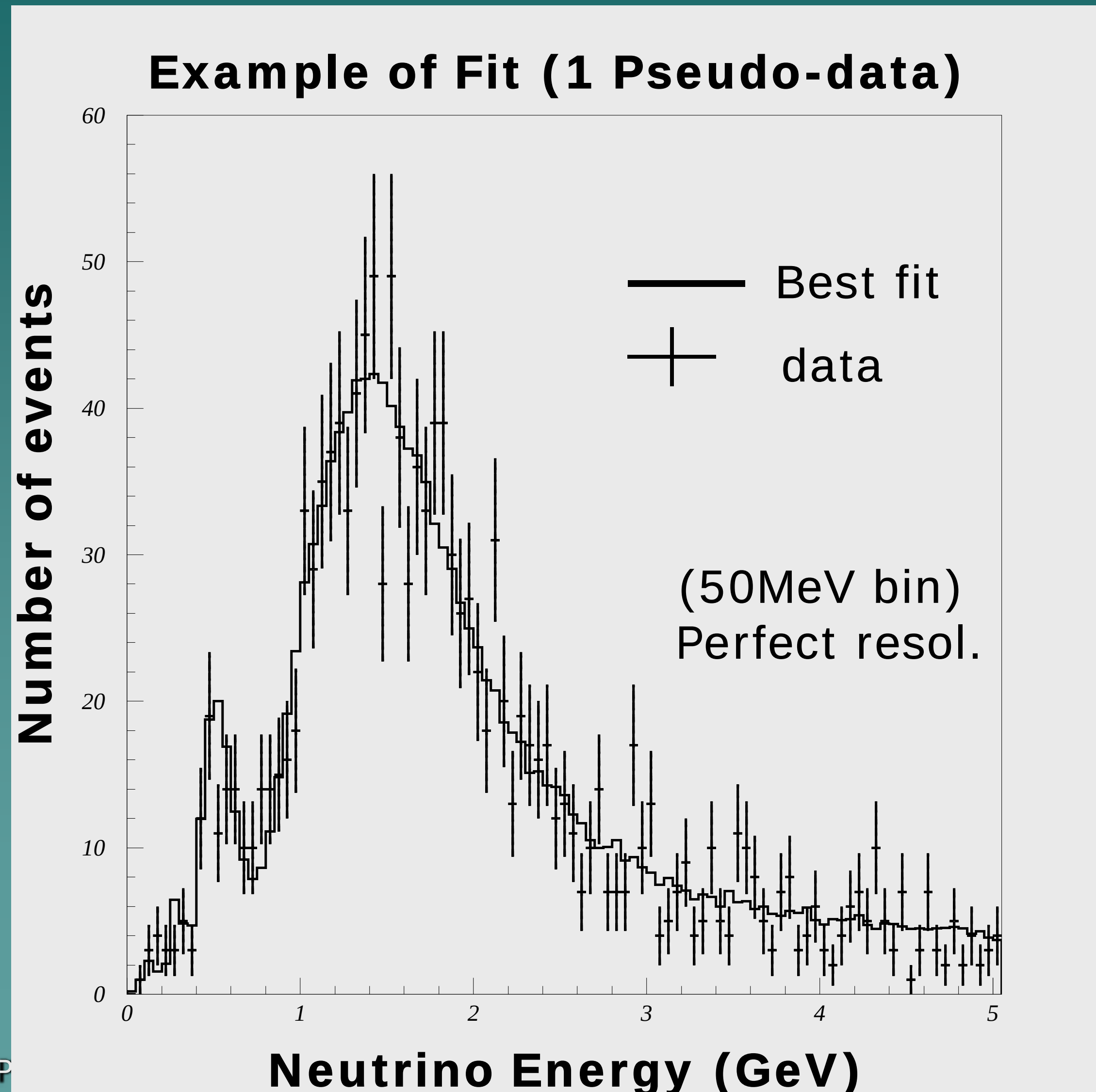
	ν_μ	ν_e	$\bar{\nu}_\mu$	$\bar{\nu}_e$
5 years	**82000**	**750**	**1460**	**35**

- ν_e appearance signal at various δ_{cp}

δ_{cp} (deg)	**0**	**90**	**180**	**270**
$\sin^2 2\theta_{13}=0.1$	2867	2062	2659	3464
$\sin^2 2\theta_{13}=0.05$	1489	1119	1342	1908
$\sin^2 2\theta_{13}=0.03$	942	506	829	1266

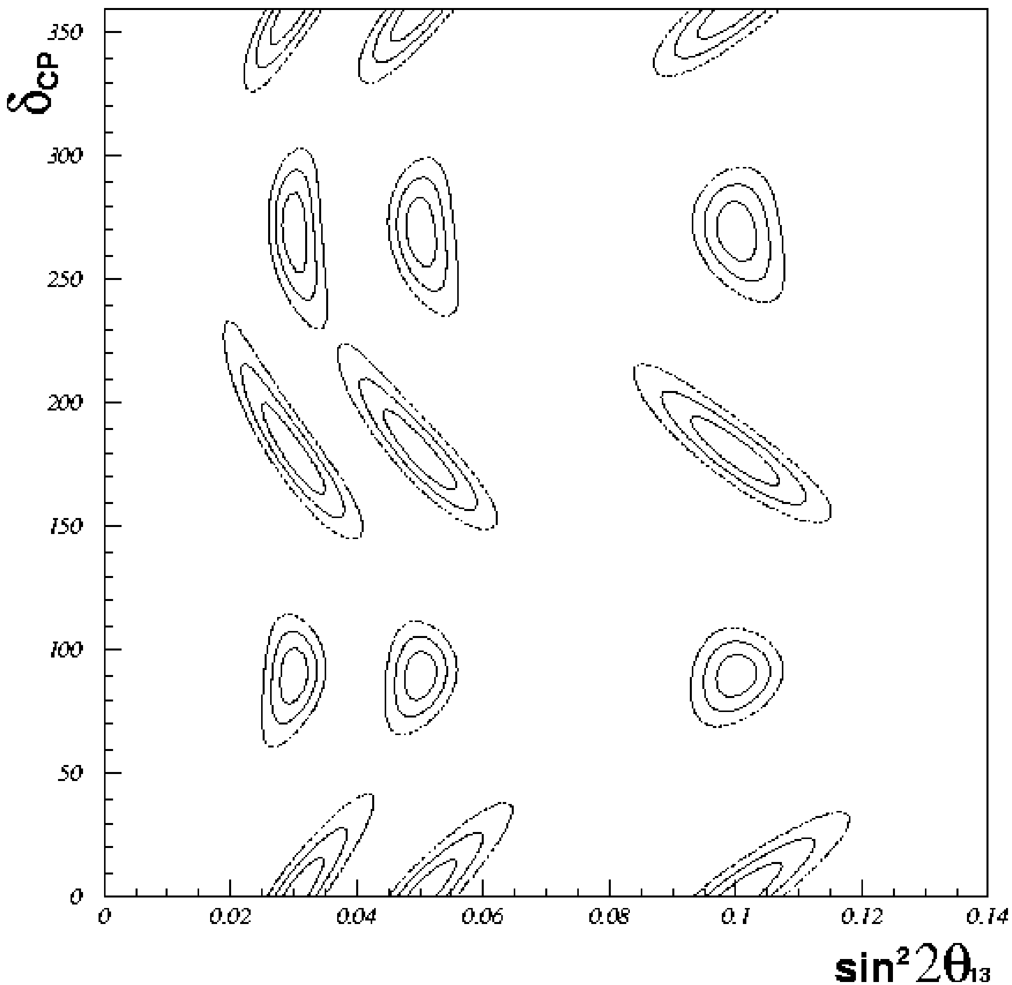
Fitter to extract the parameters

- The spectrum is fit by varying free parameters. (δ_{CP} and θ_{13})
- Fit is based on Poisson probability of bin by bin. (binned likelihood)
- right plot
  - True $\delta_{CP}=0$, $\sin^2\theta_{13}=0.03$
  - Best fit $\delta_{CP}=-0.5$, $\sin^2\theta_{13}=0.031$



Allowed regions

Perfect resolution case



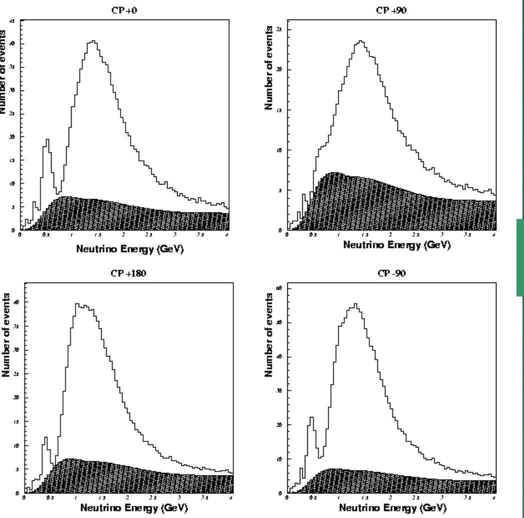
- This is perfect energy spectrum case
- Cases at δ_{cp}=0,90,180,270 and $\sin^2 2\theta_{13}$=0.1,0.05,0.03 are overlaid.
- Each point has 67,95,99.7% C.L contours

Importance of Resolution (1)

- "Resolution" includes;
  - neutrino interaction
    - **Fermi motion**
    - **Nuclear interaction for final state particles.**
    - **Vertex nuclear activities (e.g. nuclear break up signal)**
    - **NC π^0 event shape including vertex activity**
  - detector medium
    - **Ionization**
    - **Scintillation**
    - **Charge/light correlation**
    - **Signal quenching (amount of ionization charge/scinti. light is non-linear to dE/dx. E.g.including recombination)**
    - **hadron transport**
    - **Signal diffusion and attenuation**
  - readout system including electronics
    - **Signal and Noise Ratio**
    - **Signal amplification**
    - **Signal shaping**
  - reconstruction
    - **Pattern recognition**
    - **π^0 event shape**
    - **Particle ID**

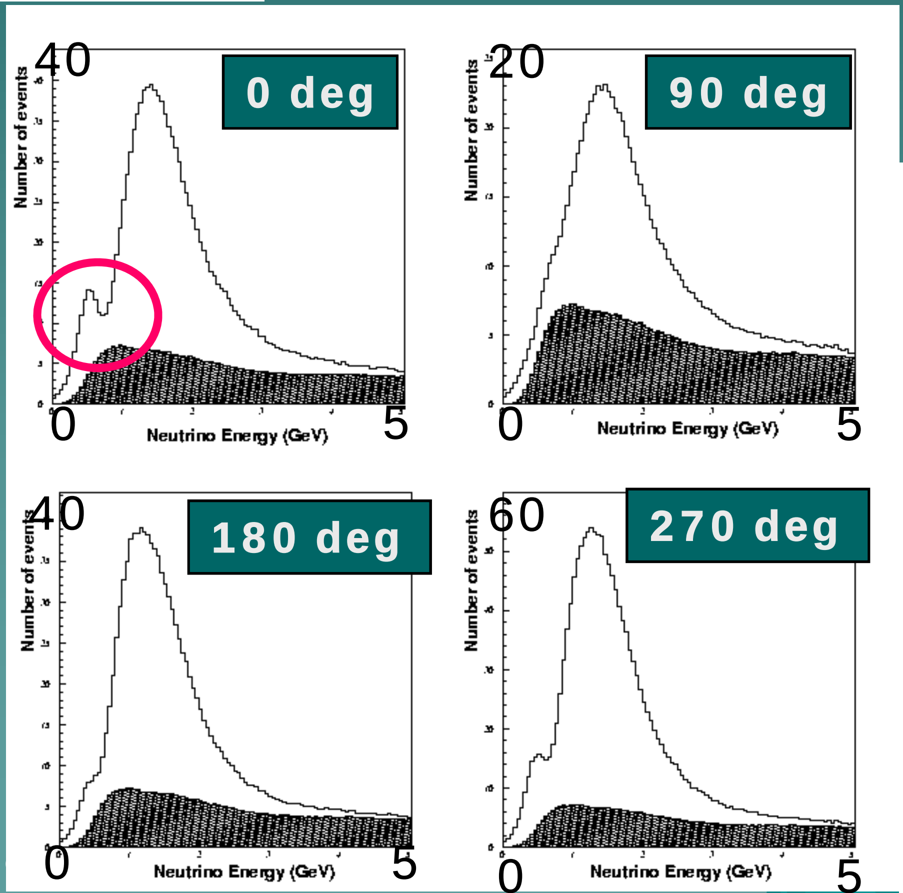
We assume these effects causes Gaussian resolution, then see the results

Importance of Resolution(2)



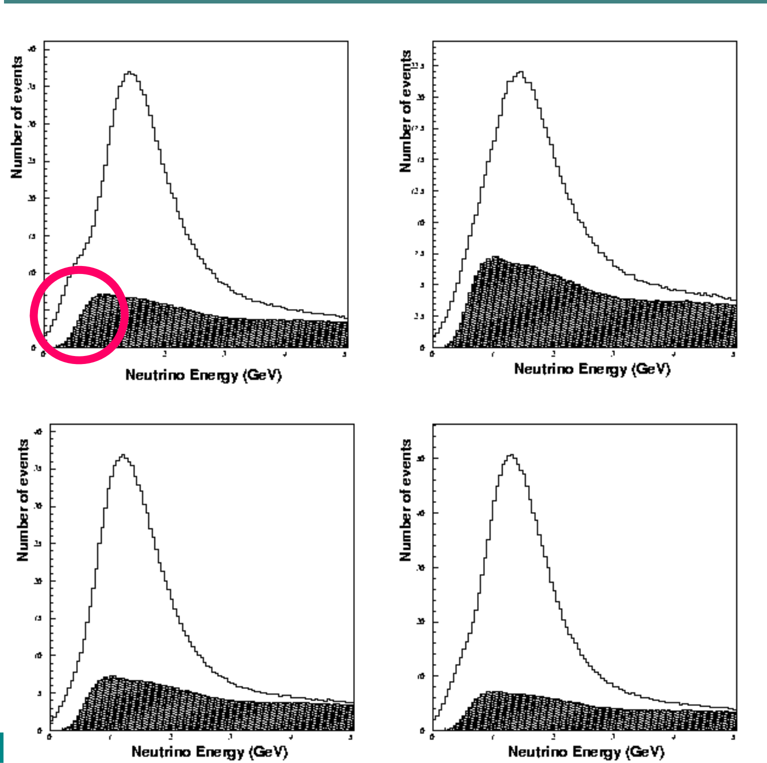
perfect

- Assuming constant Gaussian resolution independent on energy
- Looks resolution is crucial (100MeV at most)



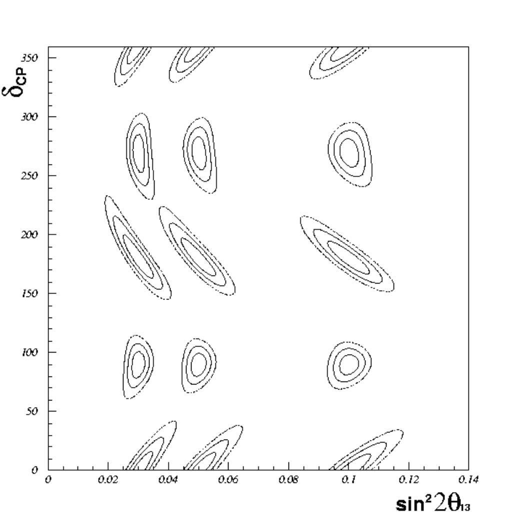
100MeV

200MeV



A.Bueno

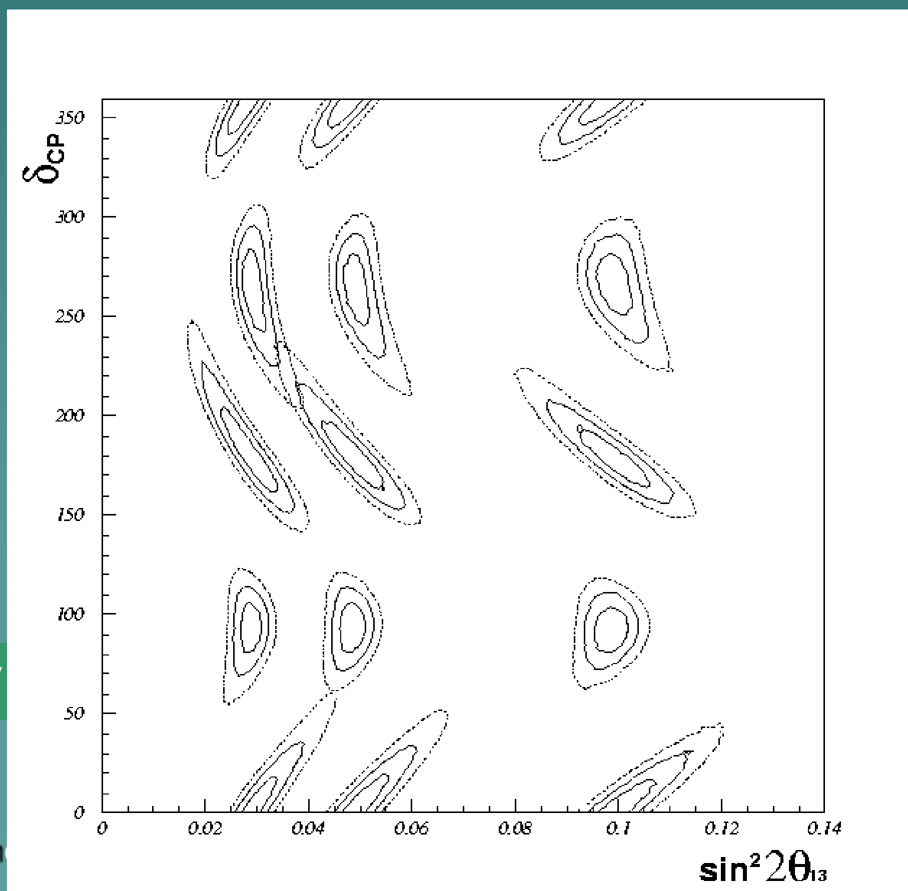
Importance of Resolution



perfect

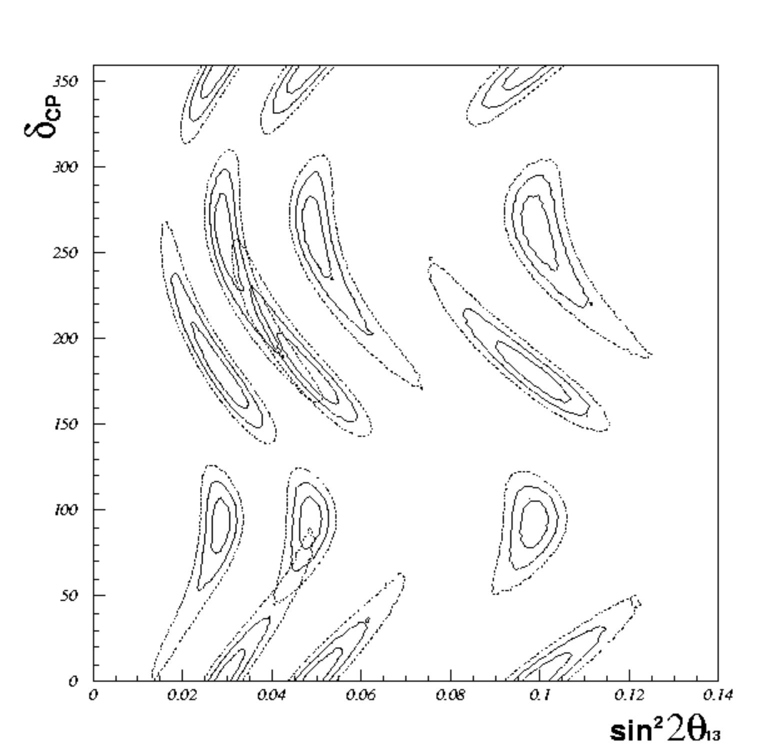
- 200MeV resolution can still make some results, however, 100MeV is really preferable to see the 2nd oscillation maximum visually.

“”robustness of the result”



100MeV

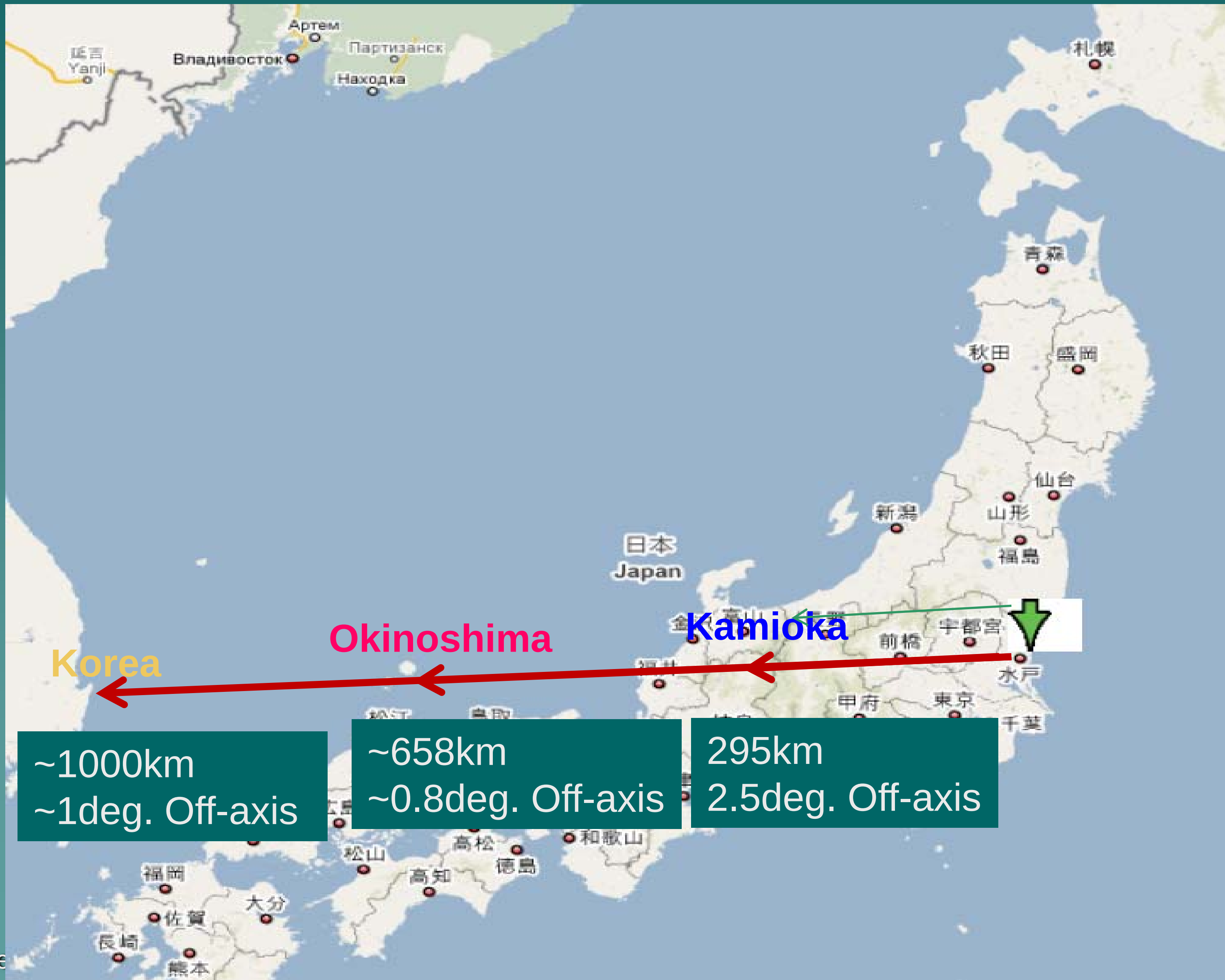
200MeV



Resolution importance (cont'd)

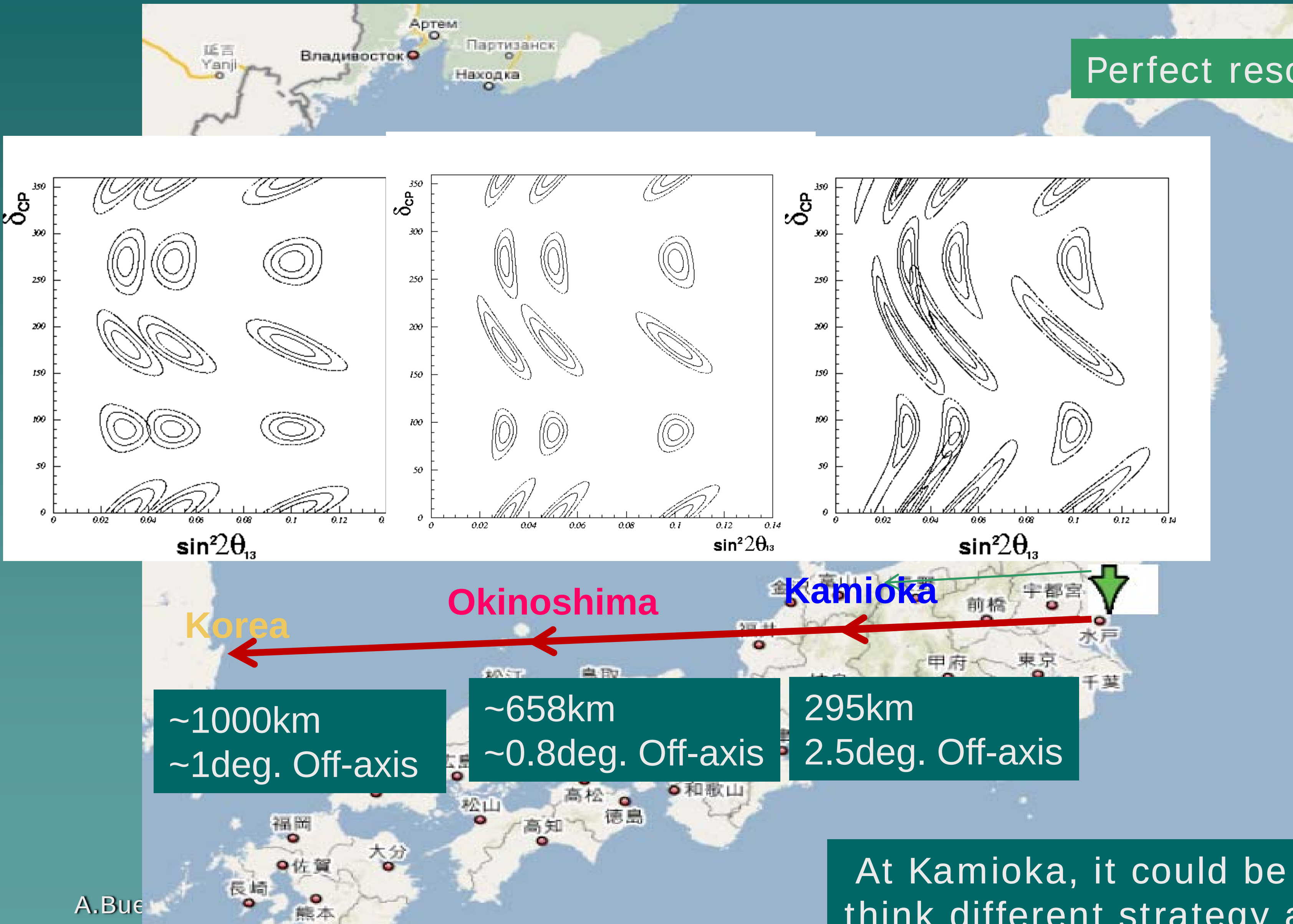
- To confirm the resolution, it could be nice to perform the test-beam using off-axis neutrino beam (narrow spectrum)
  - 1ton level
    - vertex activity (nuclear effect)
    - π^0 vertex and the first track
    - etc
  - kton level
    - All measurements mentioned so far
- Prototype physics performance would be same as 100 kt level detector, essentially. (i.e. scalable)

Baseline options



Sites for 100kT LAr

Perfect resolution



~1000km
~1deg. Off-axis

~658km
~0.8deg. Off-axis

295km
2.5deg. Off-axis

At Kamioka, it could be nice to think different strategy as well!

A.Bue

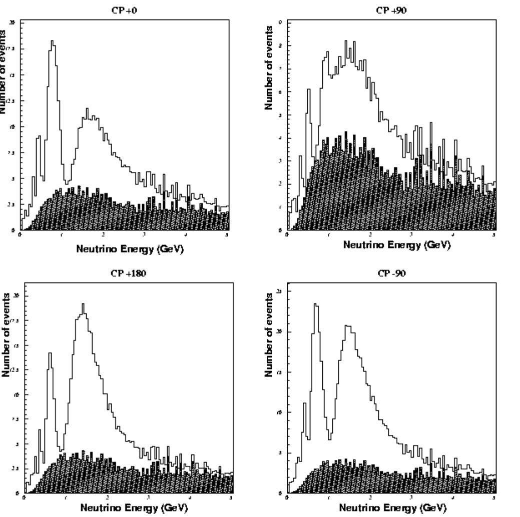
Summary and Plans

- CP phase measurement with neutrino energy spectrum with Liquid Argon TPC using neutrino run only.
  - Okinoshima is a good candidate.
  - To prove energy resolution experimentally, need neutrino test-beam.
    - 1ton
    - 1kt

    somewhere neutrino beam is available.
  - Power of π^0 rejection will be examined with test-beam as well.

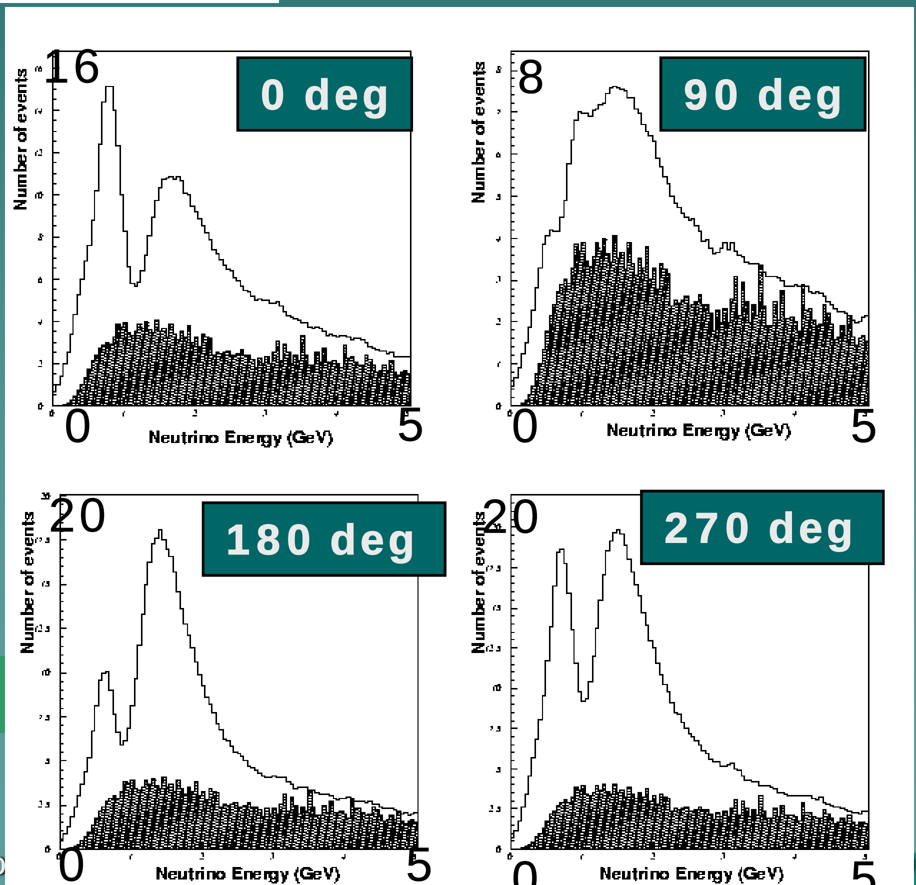
Backup slides

Resolution (Korea)



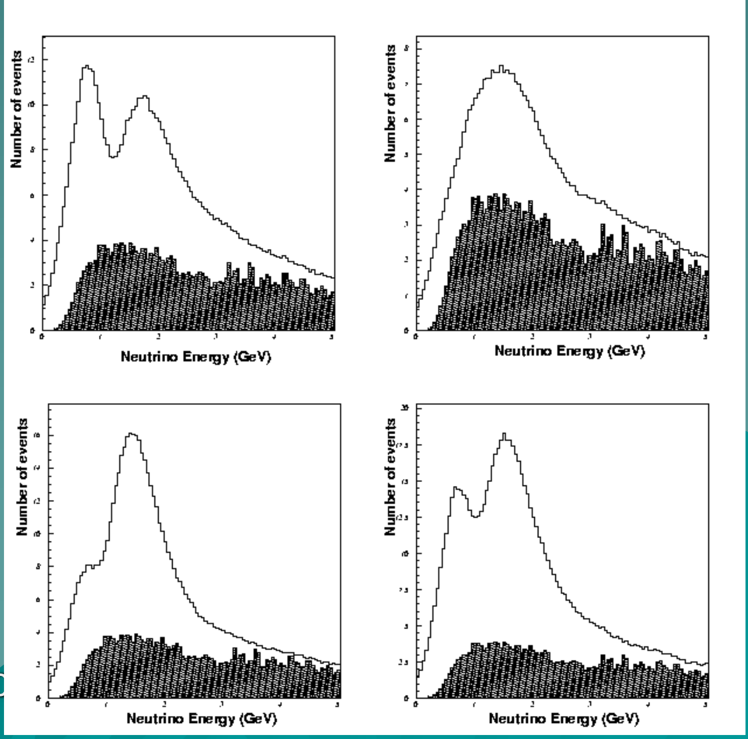
perfect

- Assuming constant Gaussian resolution independent on energy
- Looks resolution is crucial (100MeV at most)



100MeV

200MeV



Number of CC events (Korea)

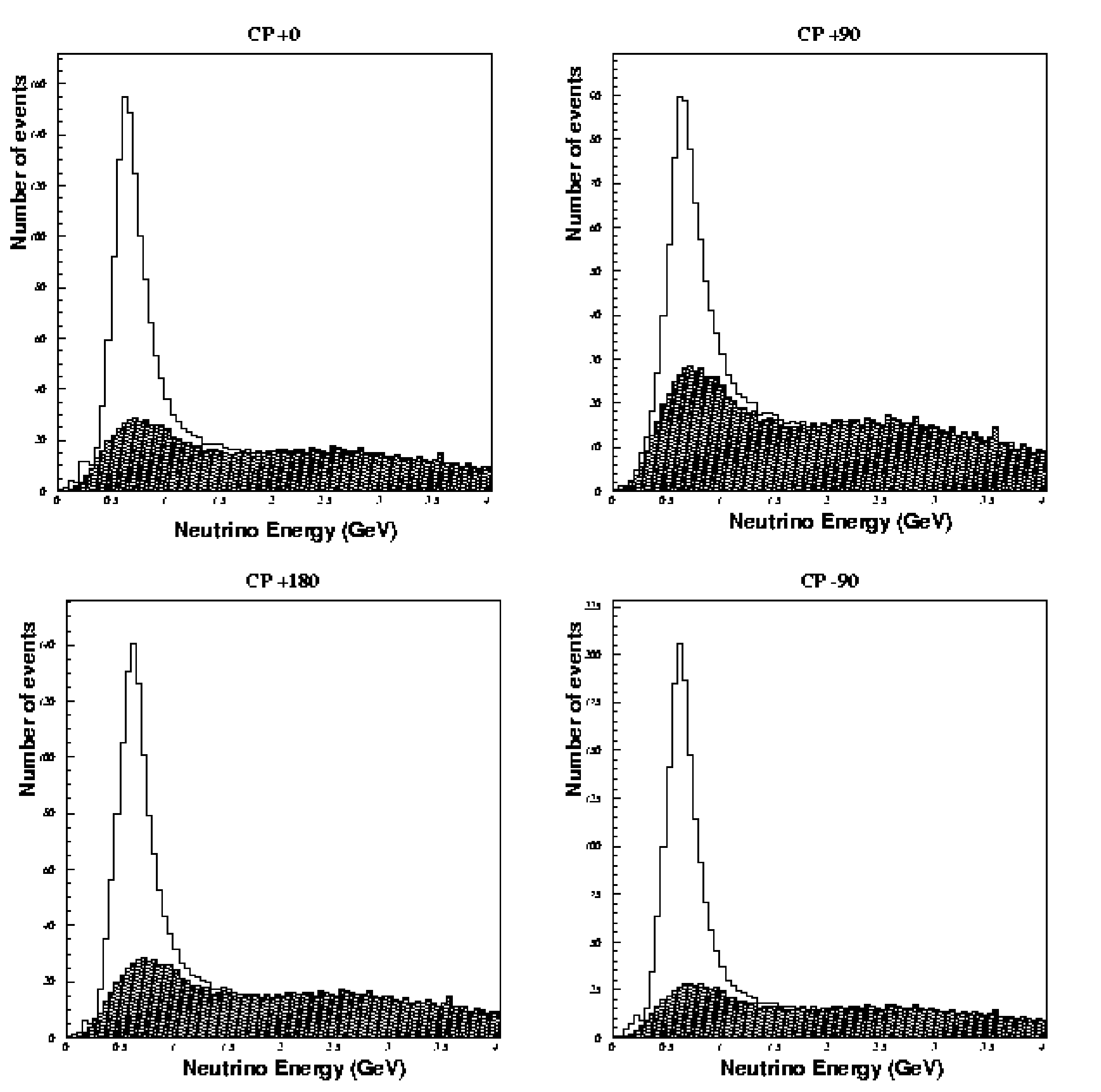
- No oscillation case

	ν_μ	ν_e	$\bar{\nu}_\mu$	$\bar{\nu}_e$
5 years	**33200**	**350**	**----**	**----**

- ν_e appearance signal at various δ_{cp}

δ_{cp} (deg)	**0**	**90**	**180**	**270**
$\sin^2 2\theta_{13}=0.1$	1050	707	1073	1415
$\sin^2 2\theta_{13}=0.05$	568	327	583	824
$\sin^2 2\theta_{13}=0.03$	379	192	391	577

Spectra for ν_e CC events (Kamioka)



- Shaded is beam ν_e background, while histogram shows the osc'd signal. (essentially same as T2K)
- δ_{cp} affects 1st maximum mainly.

Number of CC events (Kamioka)

- No oscillation case

	ν_μ	ν_e	$\bar{\nu}_\mu$	$\bar{\nu}_e$
5 years	**83410**	**1511**	**----**	**----**

- ν_e appearance signal at various δ_{cp}

δ_{cp} **(deg)**	**0**	**90**	**180**	**270**
$\sin^2 2\theta_{13}$=0.1	2830	2033	2651	3450
$\sin^2 2\theta_{13}$=0.05	1452	891	1325	1886
$\sin^2 2\theta_{13}$=0.03	906	473	808	1241