Neutrinos; Looking forward to the future

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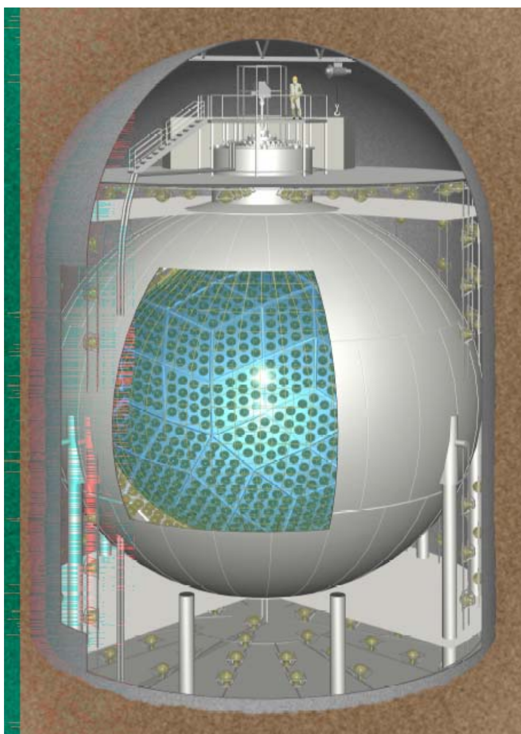
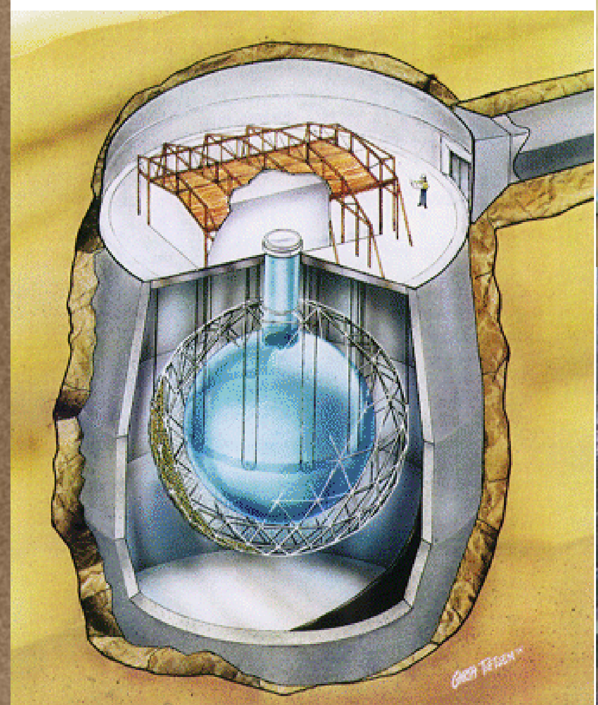
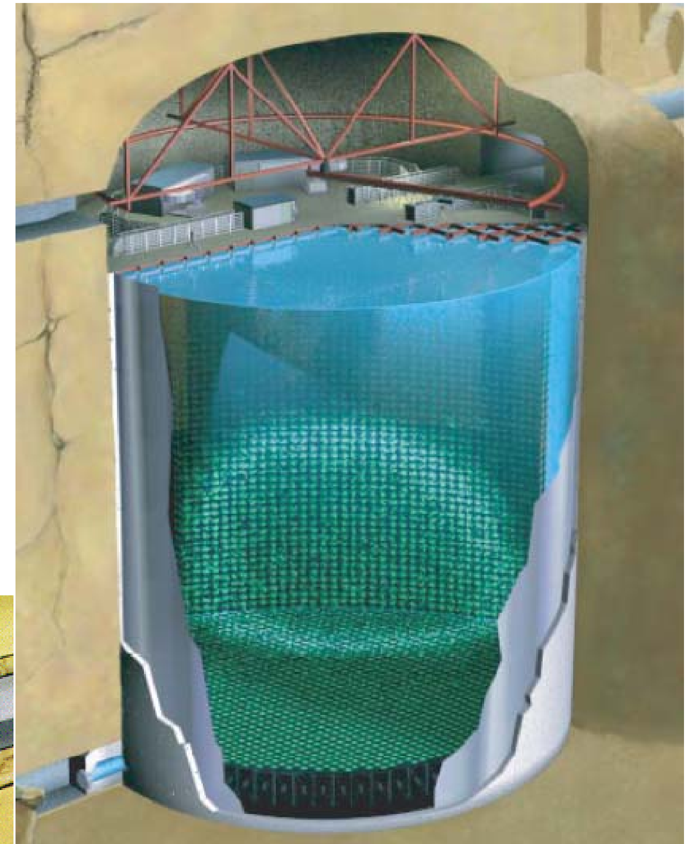
Tokyo Metropolitan University

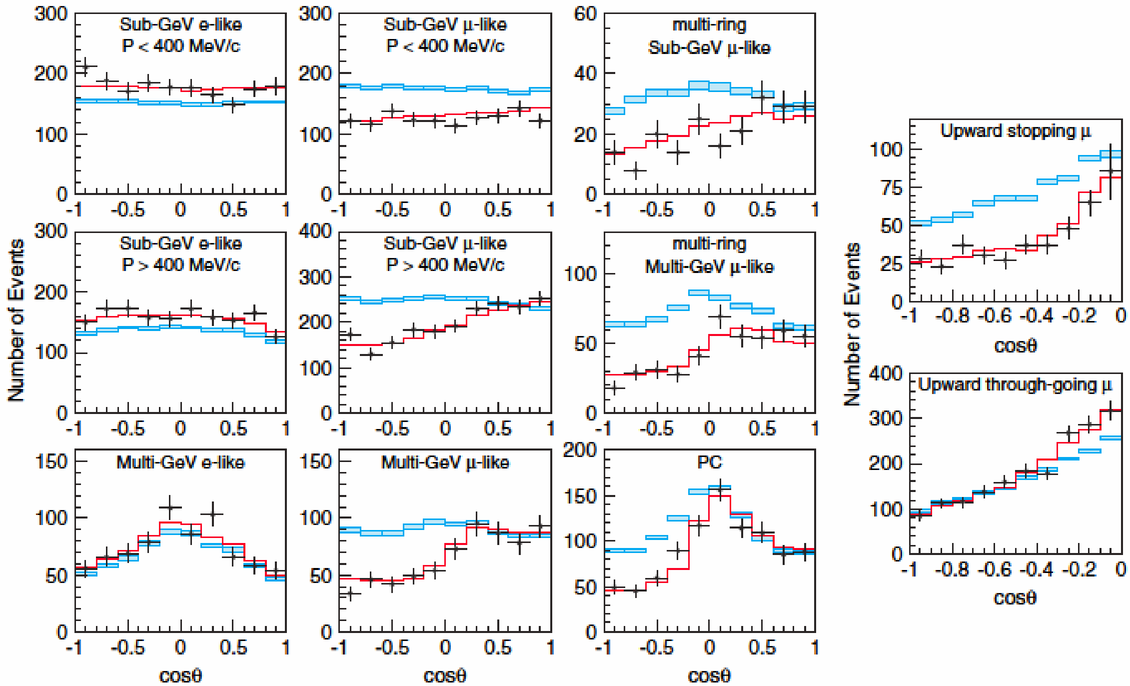
In the last several years we have experienced the most exciting era in ν physics

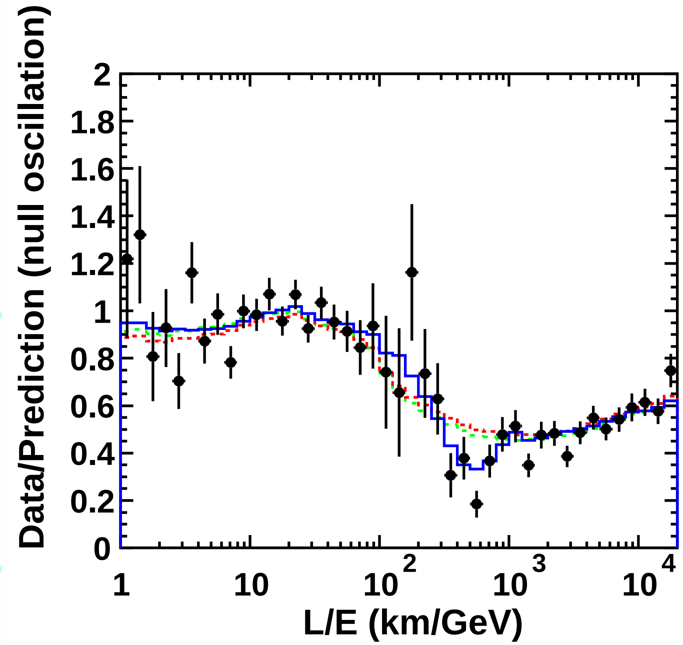


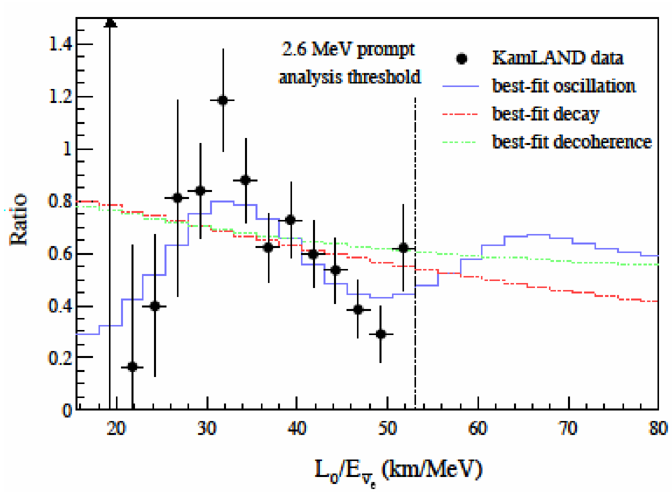


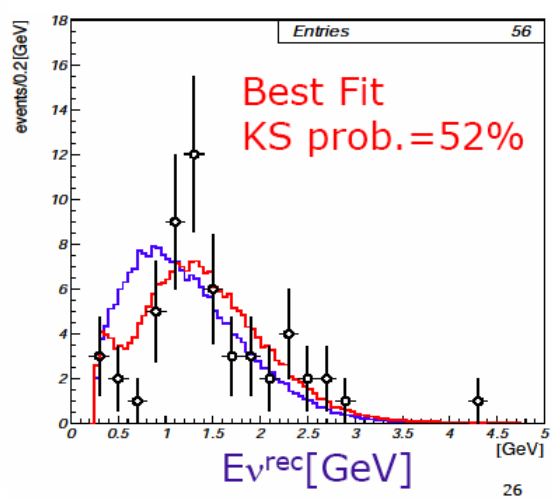


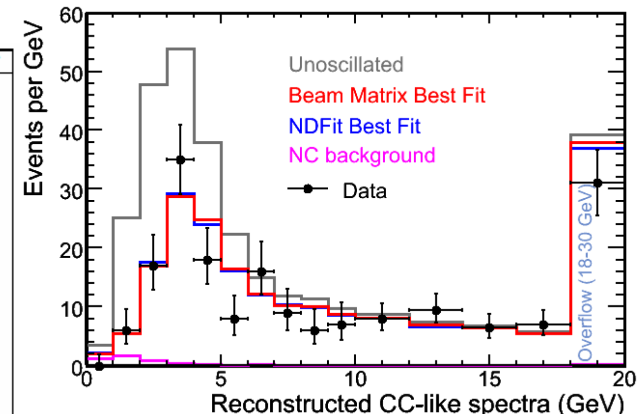
ν oscillation has been seen!





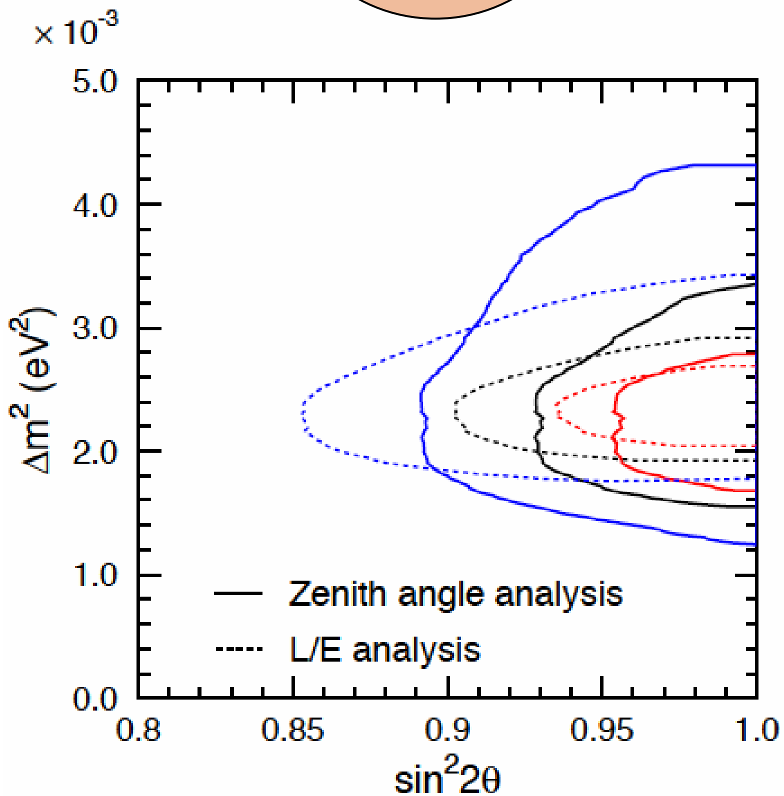


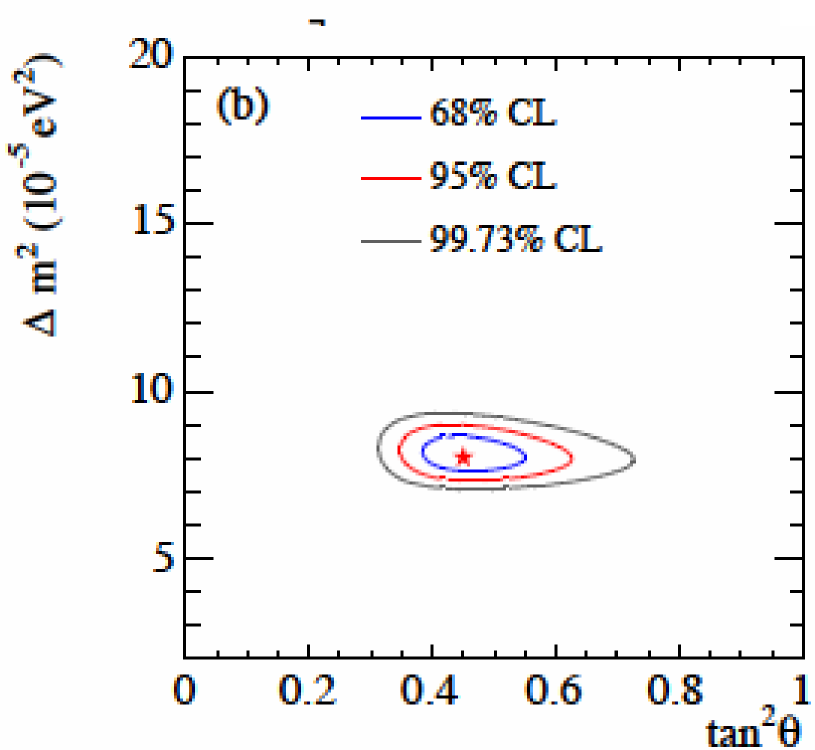




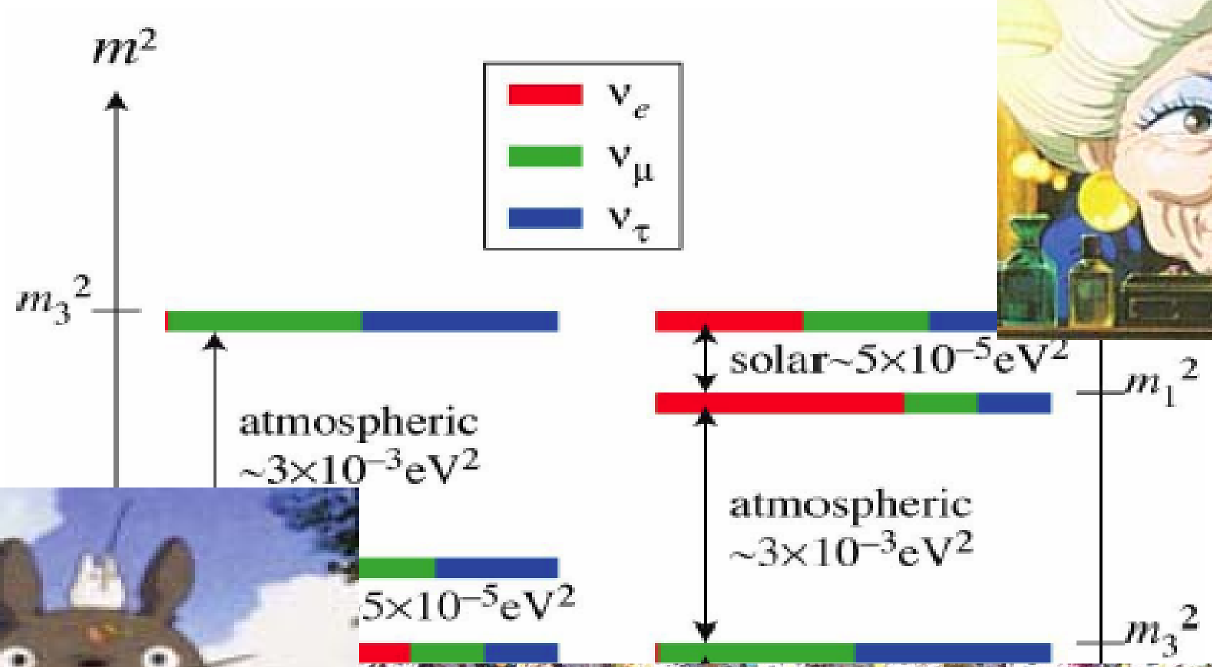
MNS matrix and ν mass pattern

$$U \equiv U_{\rm MNS}\cdot\Gamma = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \times \mathrm{diag}(1, e^{i\beta}, e^{i\gamma})$$





ν mass hierarchy & absolute mass scale



Pressing questions

- Origin of ν masses and mixing
- Large lepton mixing vs. small quark mixing
- Quark lepton symmetry/relationship incl. flavor symmetry
- How to determine remaining parameters?…

Need for some strategic thoughts?

1. How to detect nonzero θ_{13}
2. How to measure CP violation phase δ
3. A coupled problem; CPV-mass hierarchy

θ_{13} first

To measure θ_{13} one needs ν_e

- P(ν_e -> ν_e) is the interference between

e->1 --------> 1->e and e->2 --------> 2->e

e->3 --------> 3->e

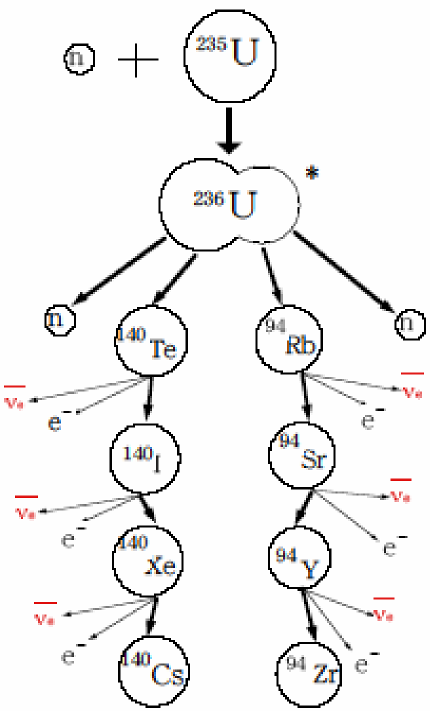
- P(ν_μ -> ν_e) is the interference between

μ->1 --------> 1->e and μ->2 --------> 2->e

μ->3 --------> 3->e

Reactor neutrino experiments

Reactor $\bar{\nu}_e$



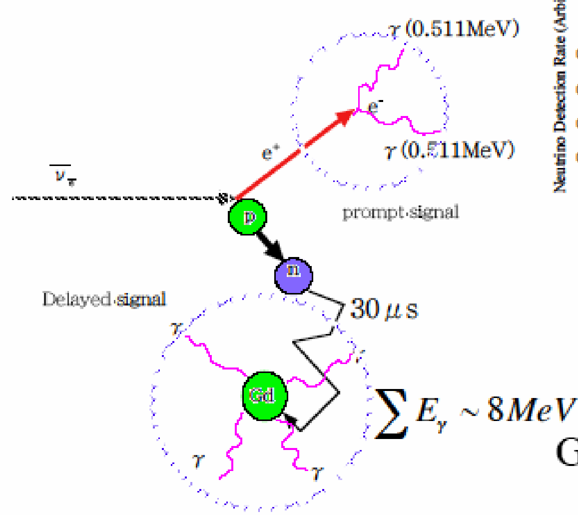
~6ν/fission & ~200MeV/fission

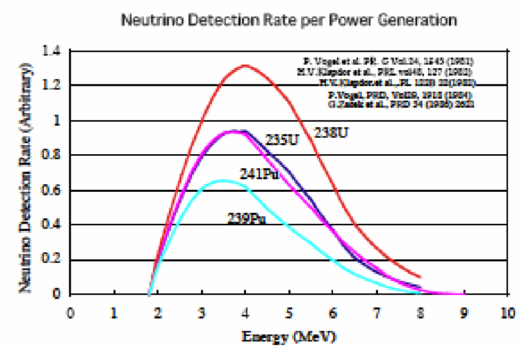
⇓

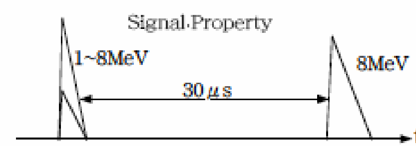
$$\sim 6\times10^{20}\,\bar{\nu}_e\,/\,s\,/\,reactor\quad(1GWe)$$

$\bar{\nu}_e$ Detection

(Most of the proposed project uses Gd-LS)

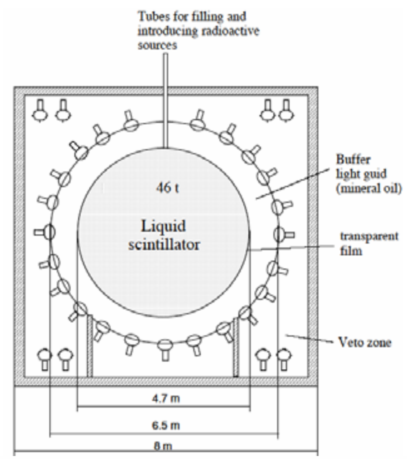






Gd => largest n absorption σ &
emits high energy γs.
Delayed Coincidence
=> Background is severely suppressed

Reactor measurement of θ_{13}



$$1 - P(\bar{\nu}_e \to \bar{\nu}_e) = \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) + O(\epsilon s^2_{13}) + O(\epsilon^2)$$

$$\epsilon \equiv \Delta m^2_{21}/\Delta m^2_{31} \simeq 0.03$$

- Independent of δ, matter effect, θ_{23}, θ_{12}, solar Δm^2

=> Pure measurement of θ_{13}

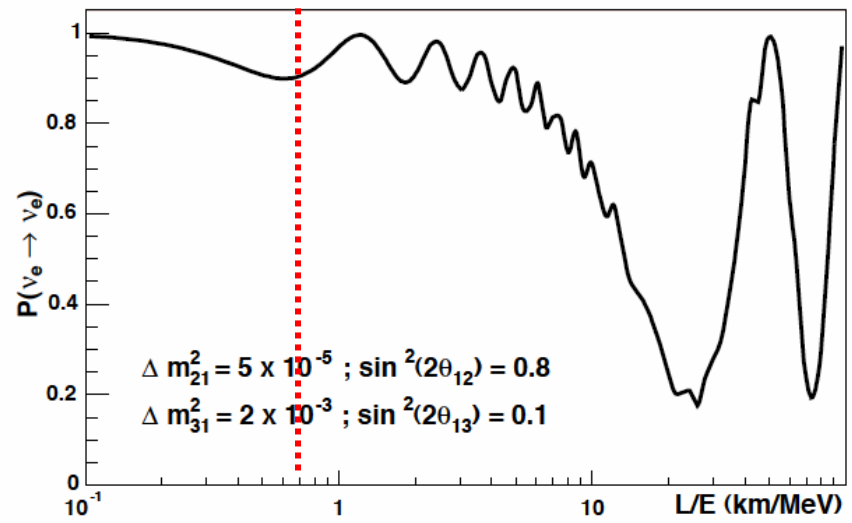
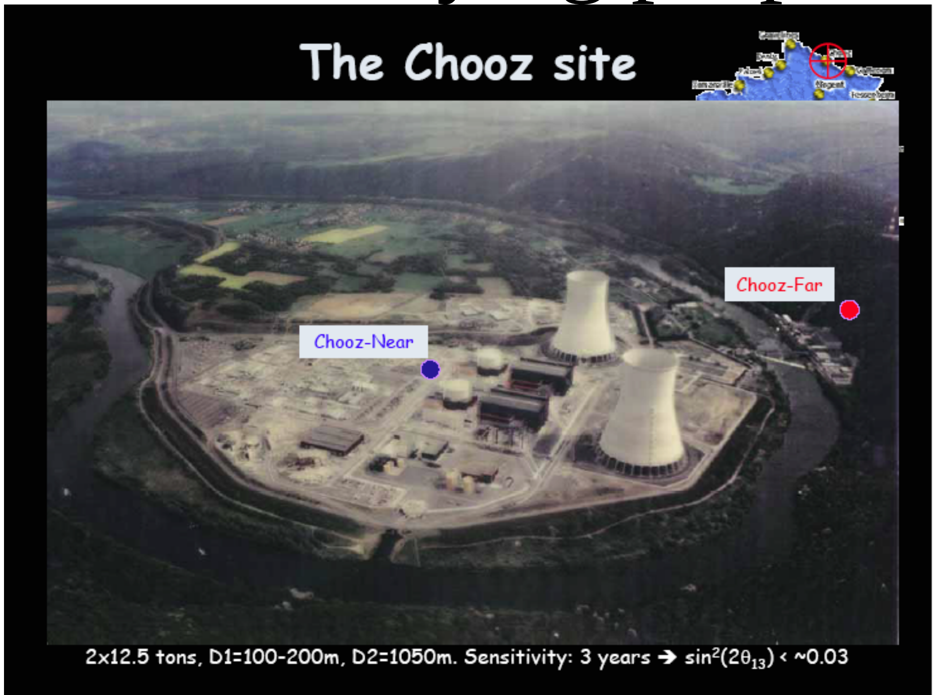
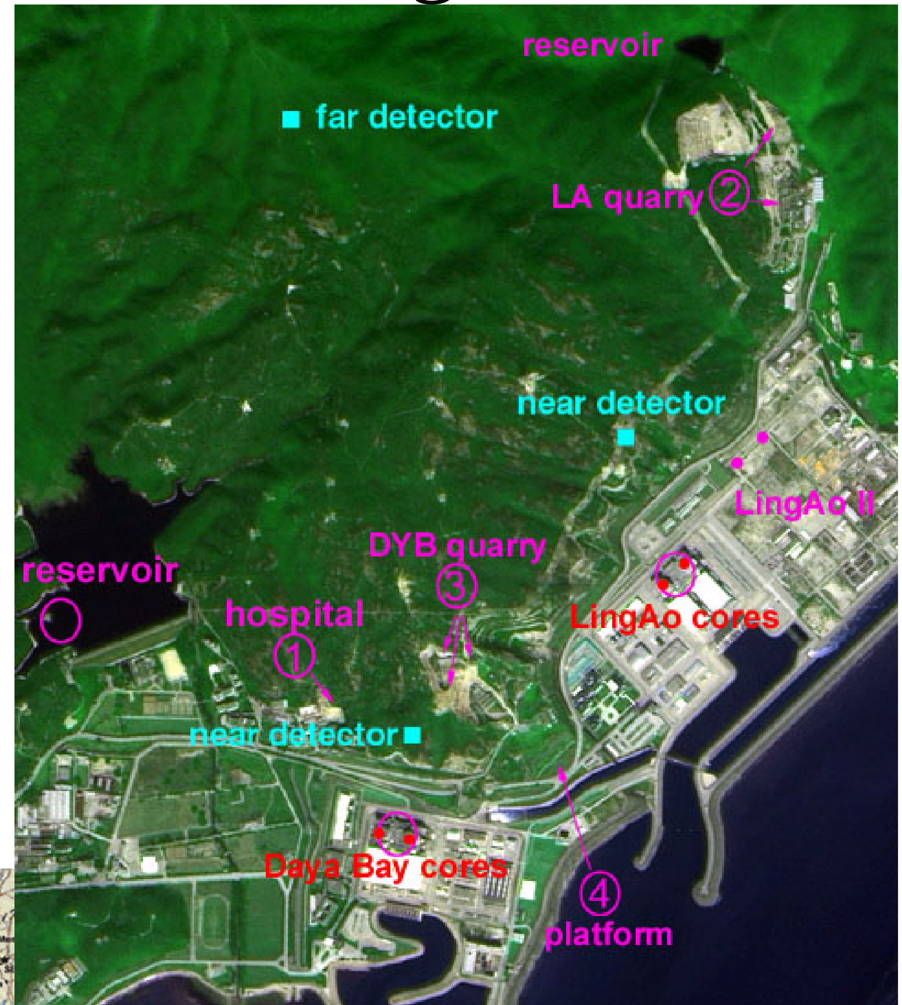
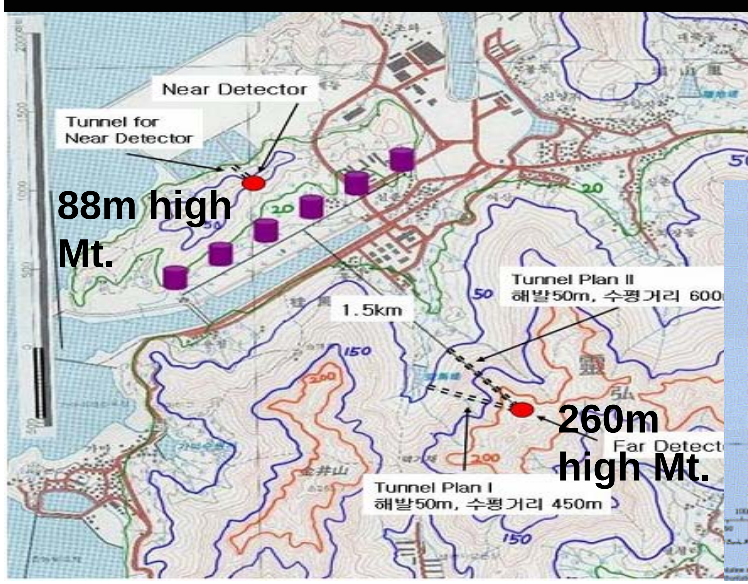


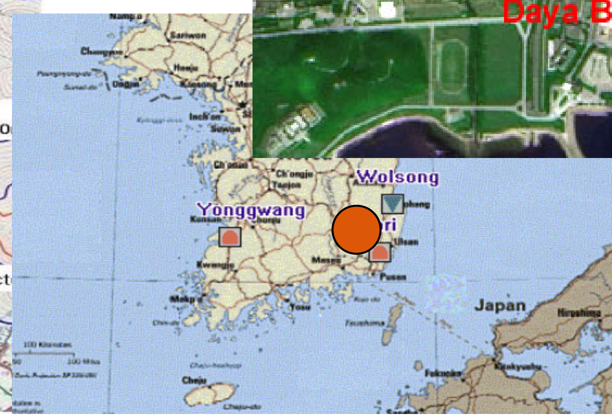
Figure 3: Probability of ν_e disappearance versus L/E for θ_{13} at its current upper limit

Varying proposals over the globe









LBL measurement of θ_{13}

$$P(\nu_\mu \rightarrow \nu_e) \;=\; \left|\sqrt{P_{atm}} + \mathrm{e}^{i\left(\delta \pm \frac{\Delta_{31}}{2}\right)}\sqrt{P_{solar}}\right|^2$$

$$P_{atm} \;=\; \left(s_{13}s_{23}\Delta_{31}\frac{\sin\left(\frac{\Delta_{31}\mp aL}{2}\right)}{\left(\frac{\Delta_{31}\mp aL}{2}\right)}\right)^2$$

$$P_{solar} \;=\; \left(c_{12}s_{12}c_{23}\Delta_{21}\frac{\sin\left(\frac{aL}{2}\right)}{\left(\frac{aL}{2}\right)}\right)^2$$

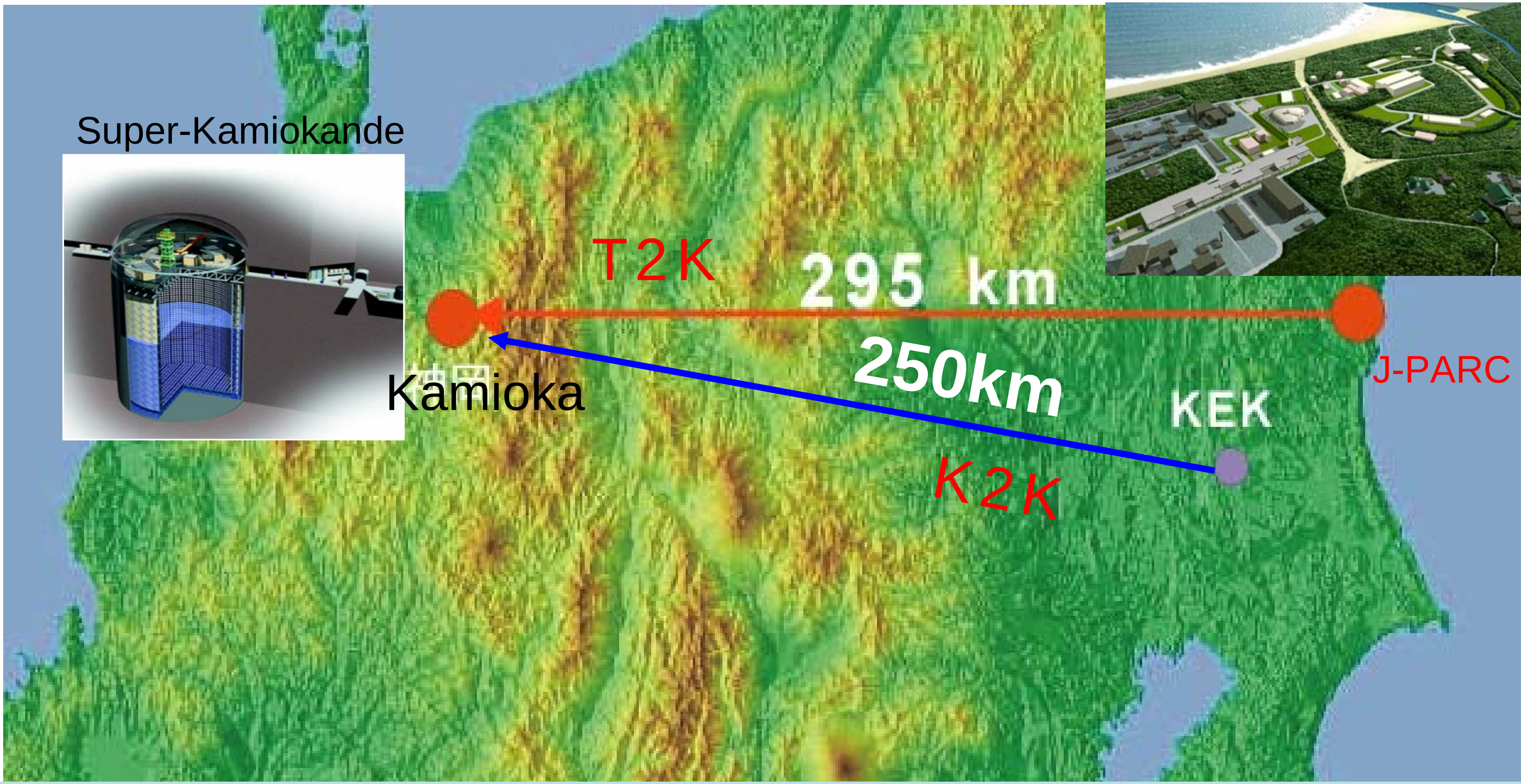
$$\Delta_{31} \;\equiv\; \frac{|\Delta m^2_{31}|L}{2E},\;\; a = \sqrt{2}G_F N_e(x),$$

$$\pm = \text{sign of } \Delta m^2_{31}$$

Some slides come from:

Takaaki Kajita @NOW2006 (Otoranto, Italy) for T2K

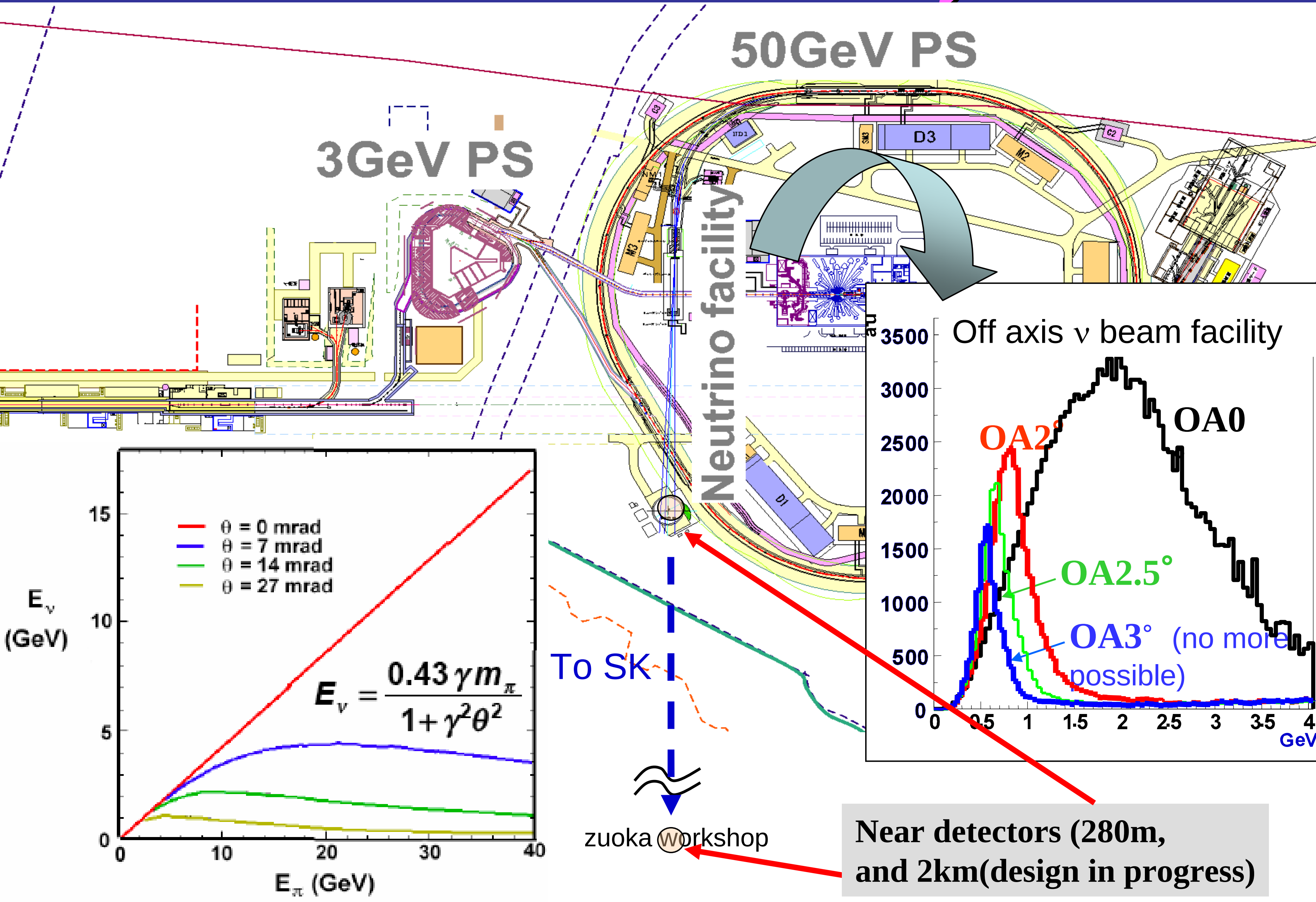
T2K Phase-I



Collaboration (at present): Canada, France, Germany, Italy, Japan, Korea, Poland, Russia, Spain, Switzerland, UK, USA

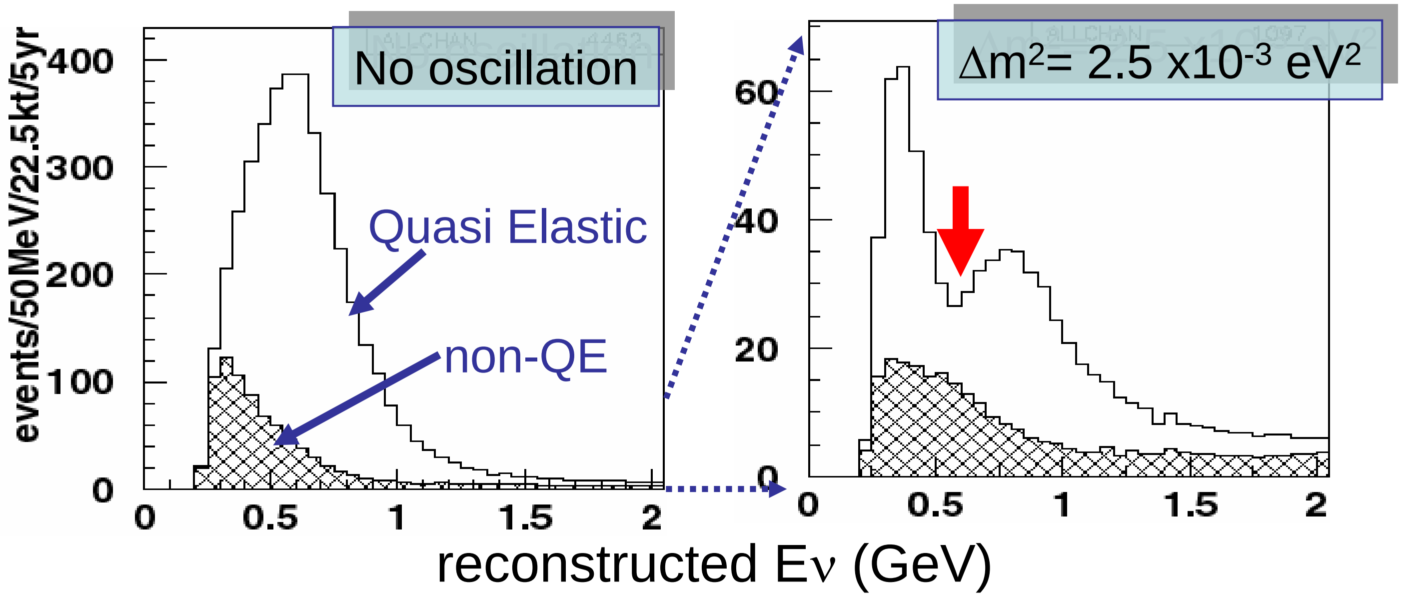
For details: I. Kato' talk

T2K neutrino facility



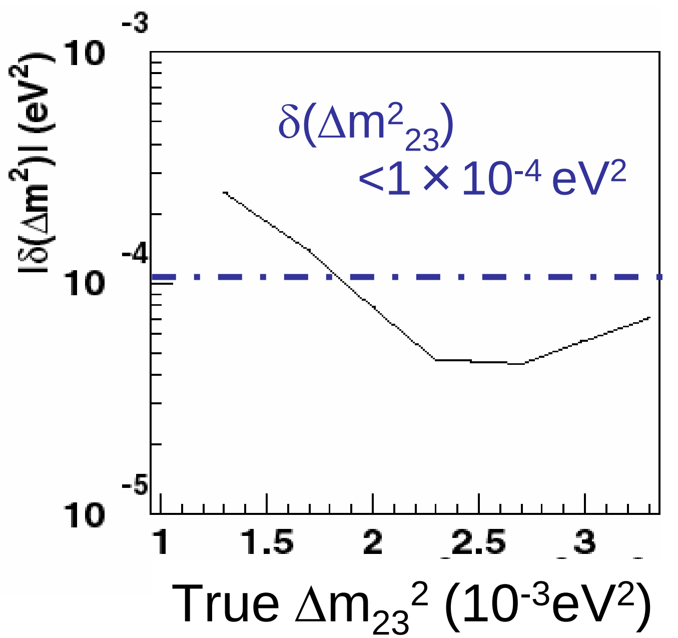
Measurement of Δm^2 and $\sin^2 2\theta_{23}$

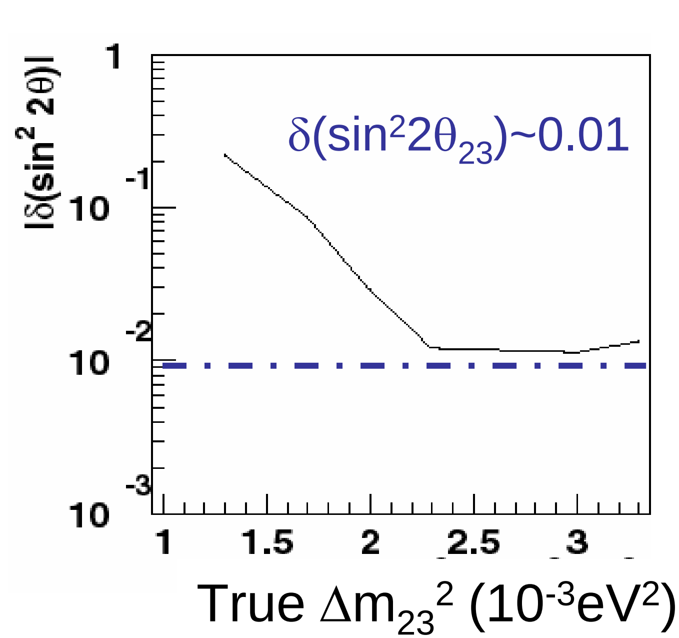
Reconstructed ν energy distribution for single ring μ-events.



Sensitivity with 0.75MW・5years and

- normalization (5%)
- non-qe/qe ratio (20%)
- E scale (1%)
- Spectrum shape (5%)
- Spectrum width (5%)



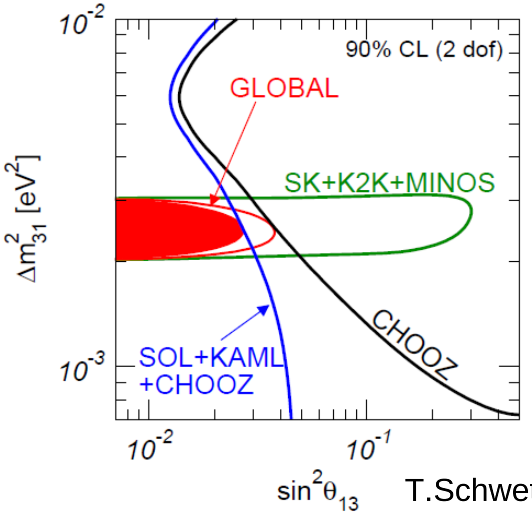


θ_{13}

$$P(\nu_\mu \to \nu_e) = \sin^2\theta_{23} \cdot \sin^2 2\theta_{13} \cdot \sin^2\left(\frac{1.27\Delta m_{23}^2 L}{E}\right)$$

($\Delta m_{12}^2=0$ assumed, matter effect not included)

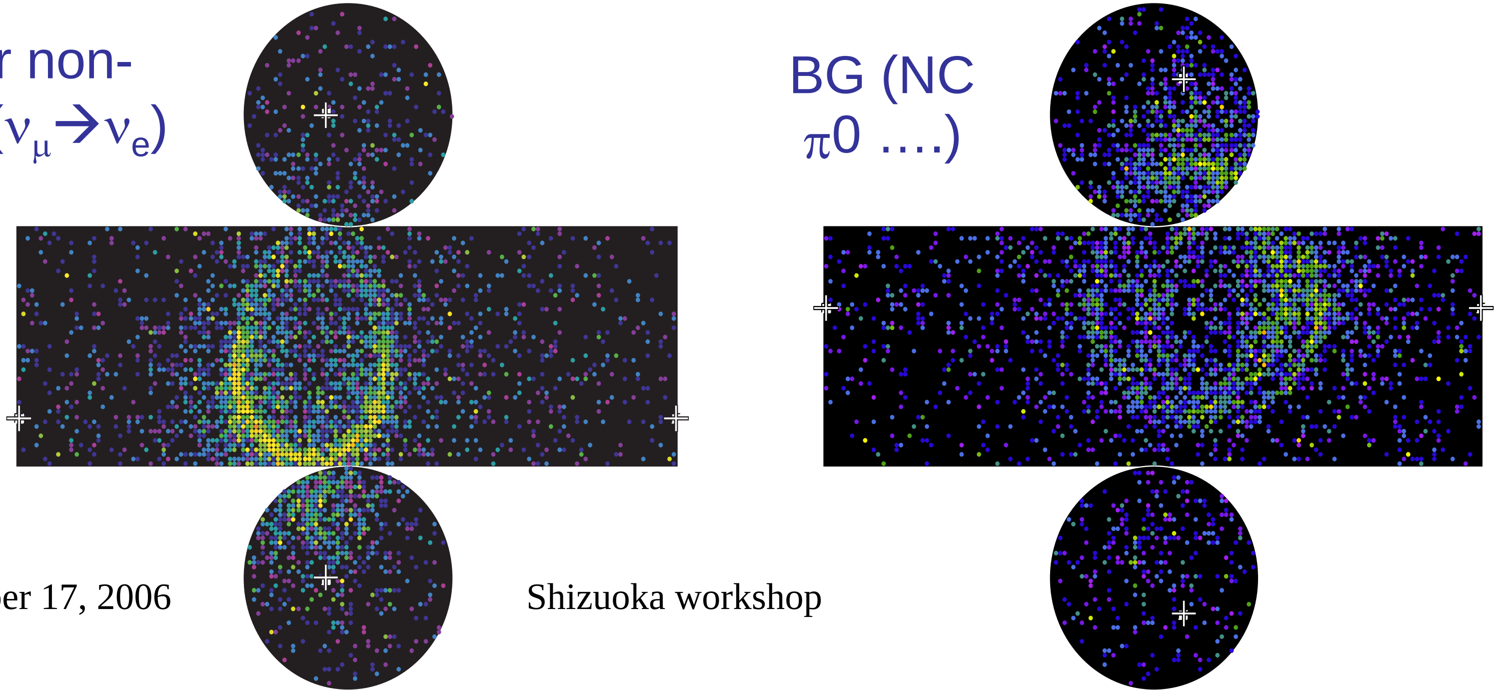
Present status:



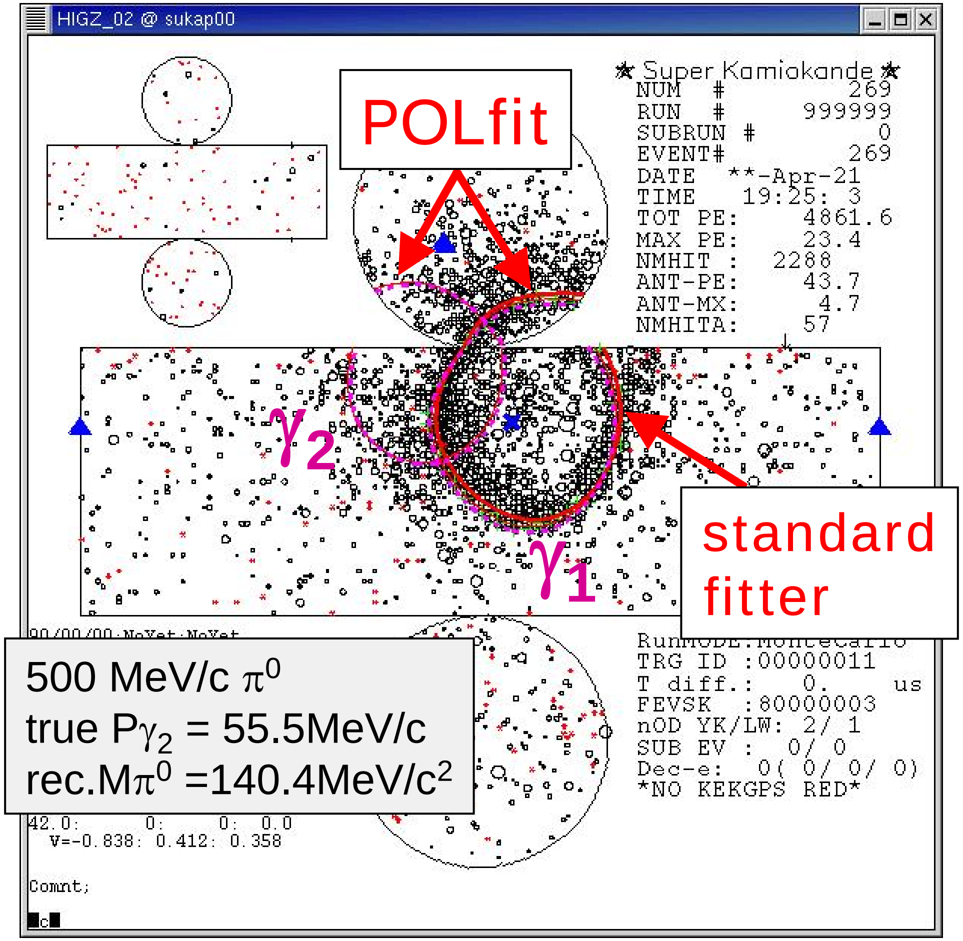
T.Schwetz
hep-ph/0606060

Signal for non-zero θ_{13} ($\nu_\mu \to \nu_e$)

BG (NC π0 ….)



POL(Pattern of Light)fit – π^0 fitter –



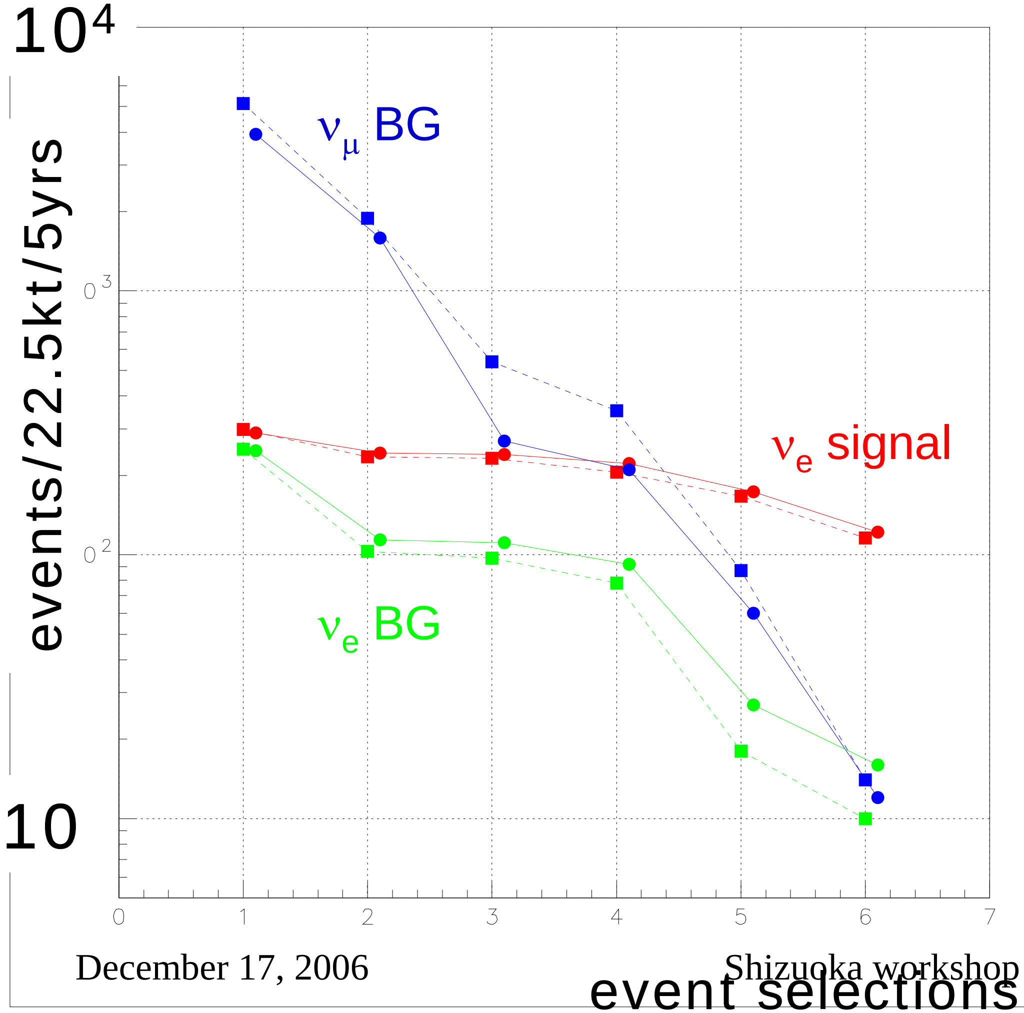
- Target: FCFV 1R-elike events
- $\Delta L \equiv$ Likelihood(2γ assump.) – Likelihood(electron assump.)

- Try to reconstruct two γ rings
- Input: vertex, visible energy, and the 1st γ direction by the standard fitter
- Compare observed & expected (direct+scatter) charge
- Vary the 2nd γ direction and the energy fraction until the best match found

→ $M\pi^0$ etc.

Events vs. Selections

$\Delta m^2 = 2.5 \times 10^{-3}\ eV^2$
$\sin^2 2\theta_{13} = 0.1$



Event selections:

1. FCFV, $E_{vis} > 100$
2. 1 ring
3. e-like
4. no decay-e
5. $0.35 < E_\nu^{rec} < 0.85$
6. π^0 cuts:
   - cos < 0.90
   - $\Delta L < 80$, $M\pi^0 < 100$

Events vs. selections

$\Delta m^2 = 2.5 \times 10^{-3} eV^2, \sin^2 2\theta_{13} = 0.1$

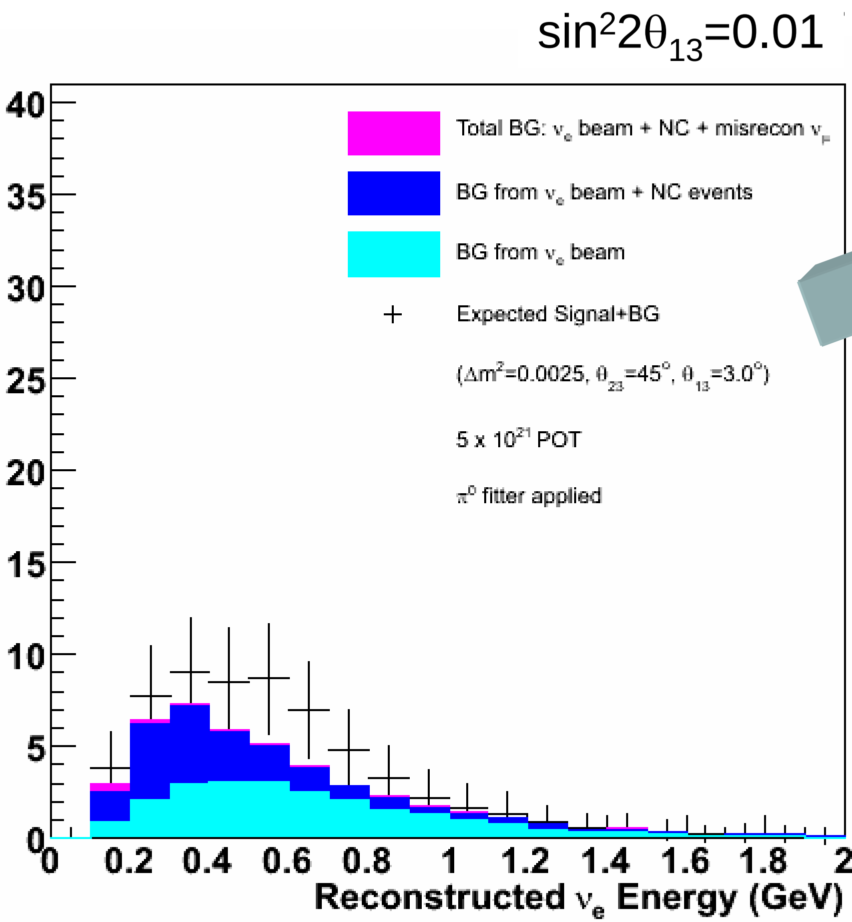
(events / 22.5kt / 5yrs)

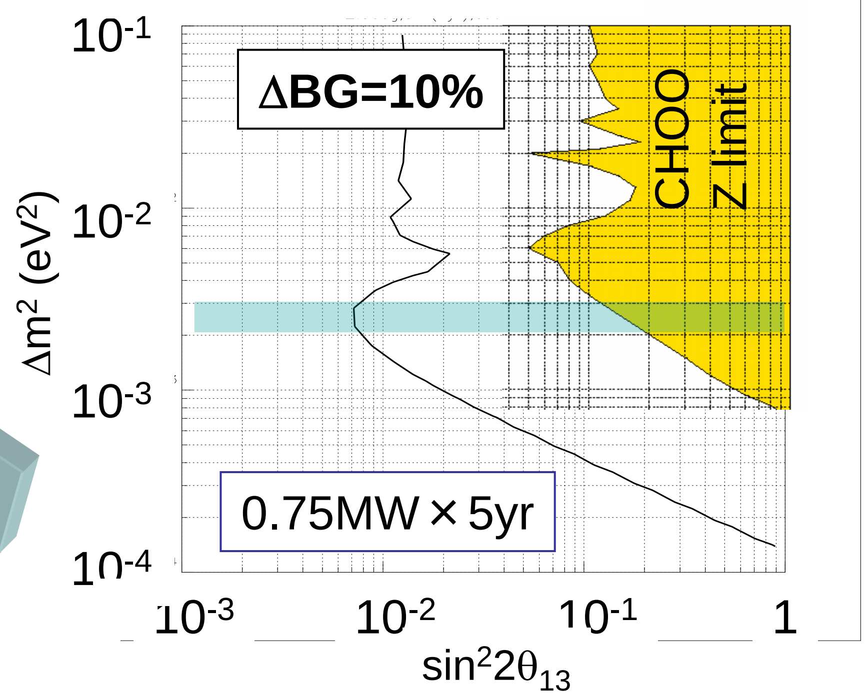
	ν_μCC BG	ν_μNC BG	beam ν_e BG	ν_e(CC) Signal
FCFV, $E_{vis}>100$	**2849**	**1082**	**248**	**290**
1R	**1313(46%)**	**277(26%)**	**114(46%)**	**243(84%)**
e-like	**51(1.8%)**	**219(20%)**	**111(45%)**	**240(83%)**
no decay-e	**15(0.5%)**	**195(18%)**	**92(37%)**	**222(77%)**
$0.35<E_\nu^{rec}<0.85$	**2.2(0.1%)**	**58(5%)**	**27(11%)**	**173(60%)**
ΔL<80,M<100,cos<0.9	**12±0.8(0.3%)** (stat.)		**16±0.4(6%)** (stat.)	**122±3(42%)** (stat.)

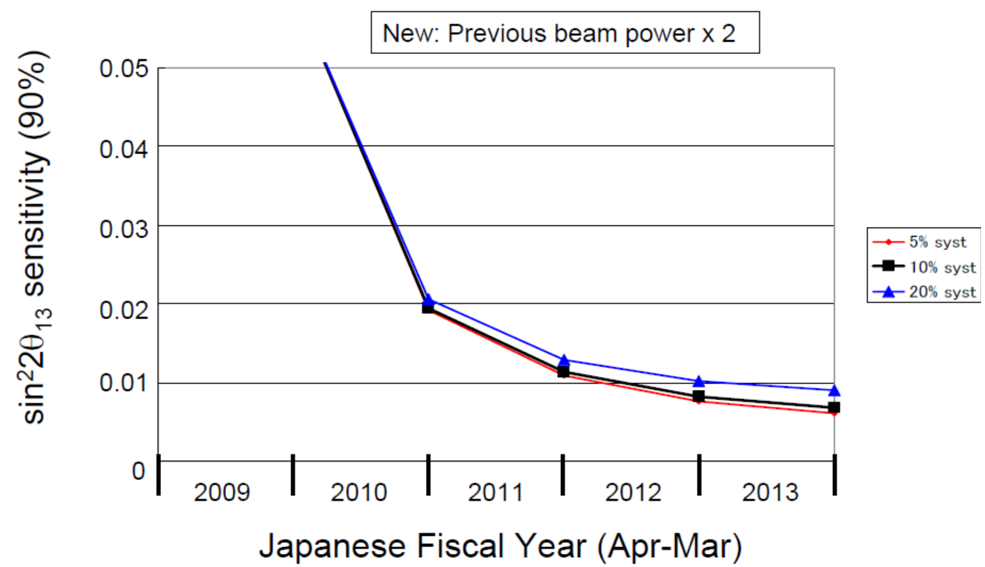
(old π^0 fitter: 12 15 109)

ν_e appearance and θ_{13} sensitivity

ν_e appearance signal and BG at SK.

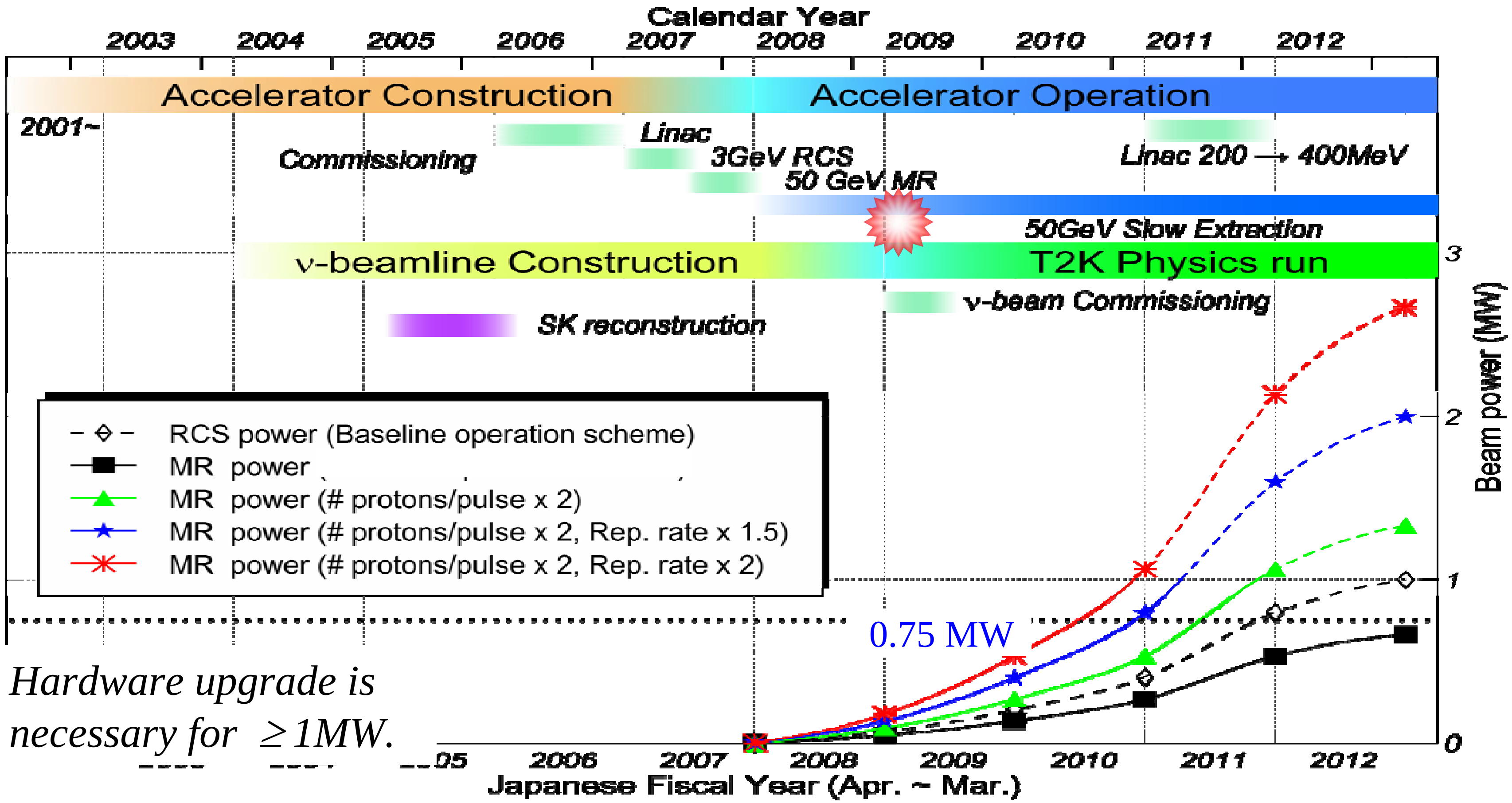






J-PARC schedule & Beam Power estimation

Nakadaira neutrino2006

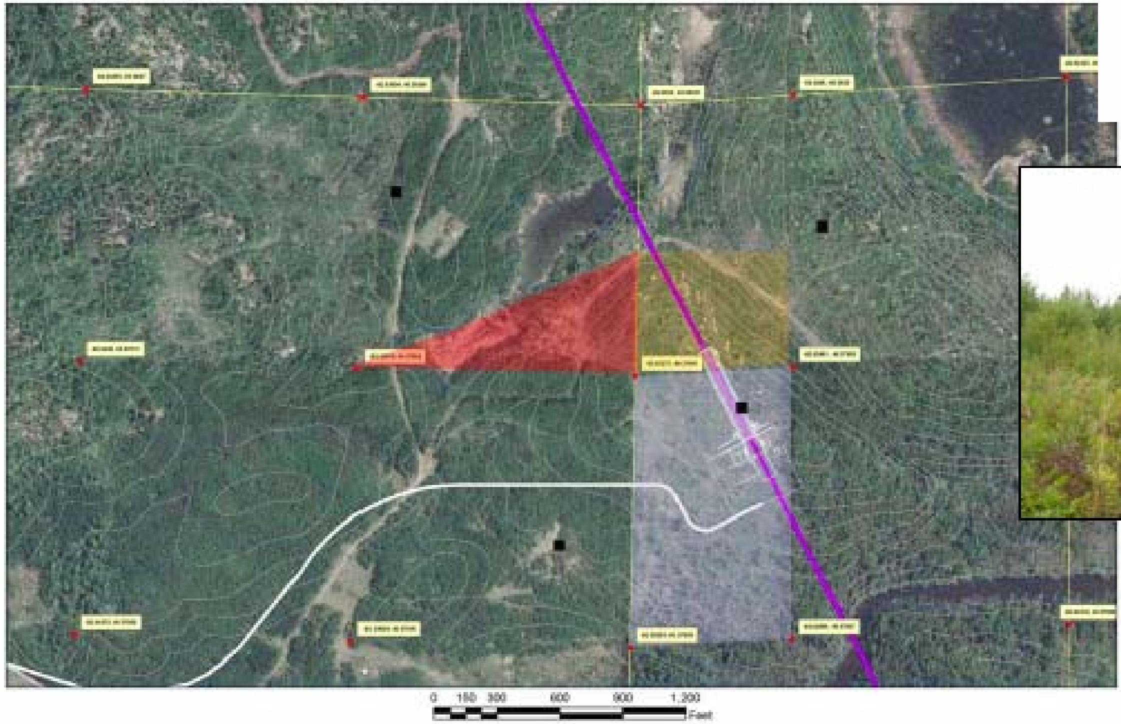


Hardware upgrade is necessary for ≥1MW.

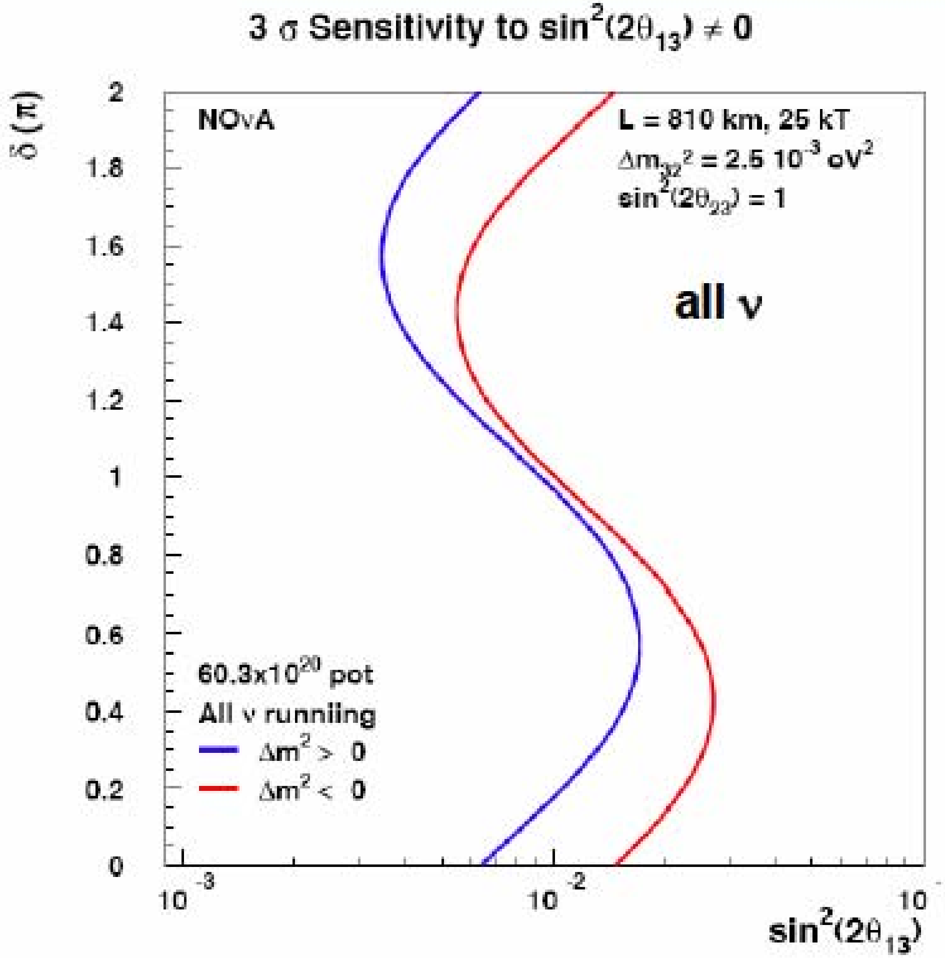
Target date for new RF system installation.

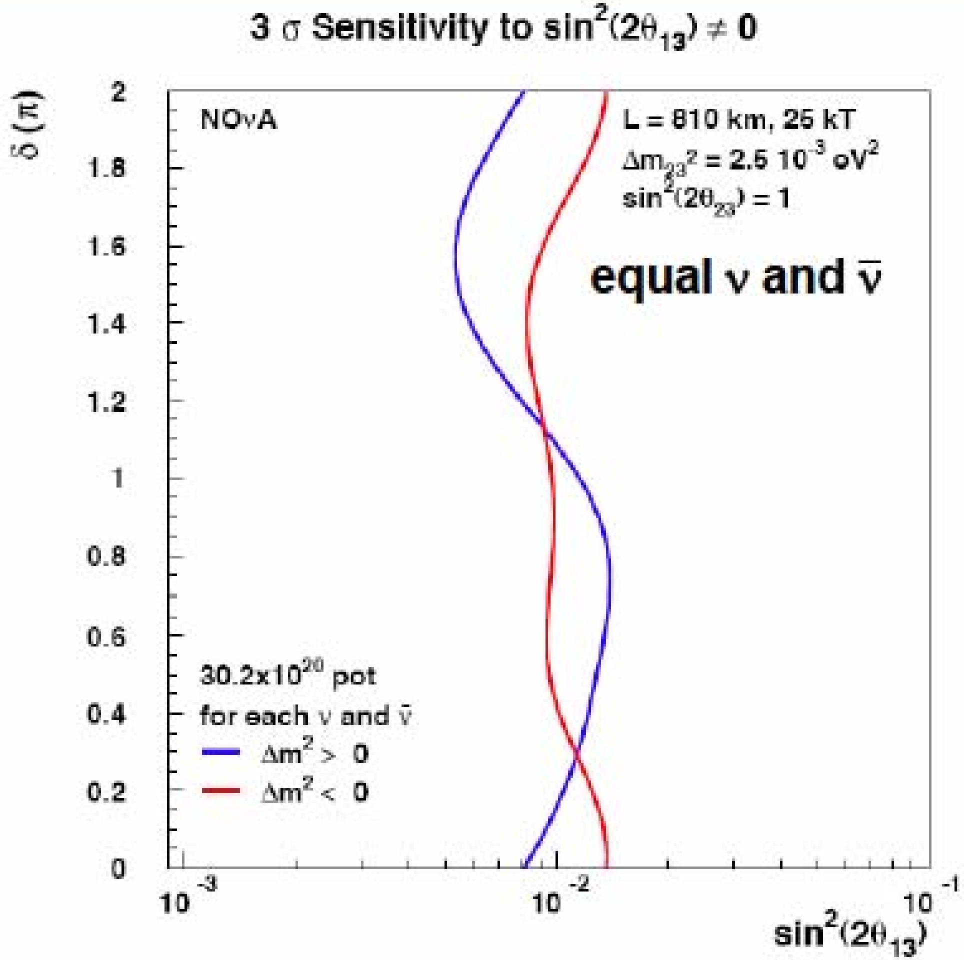
Site – Ash River Trail

- 503 miles (810 km) from Fermilab
- 3.6 Mile Access Road
- Electrical Upgrade

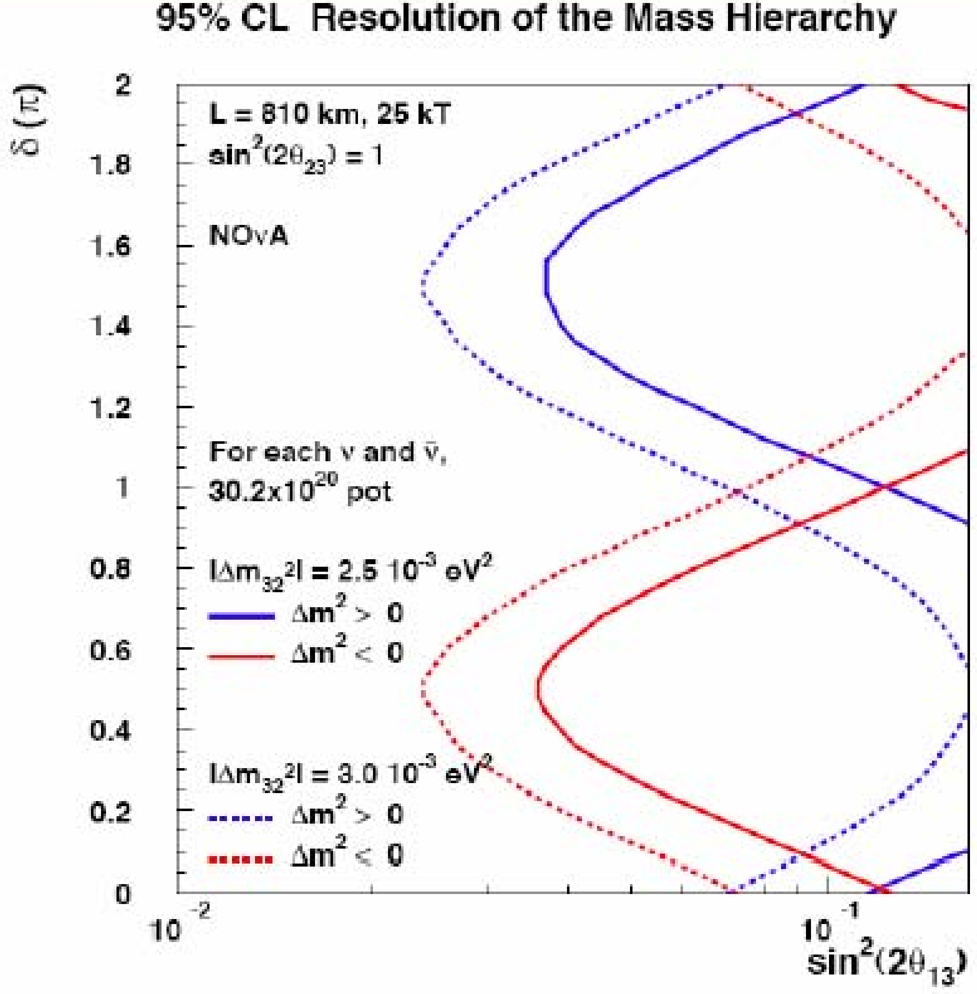


3 σ Sensitivity to $\theta_{13} \neq 0$





95% CL Resolution of the Mass Ordering

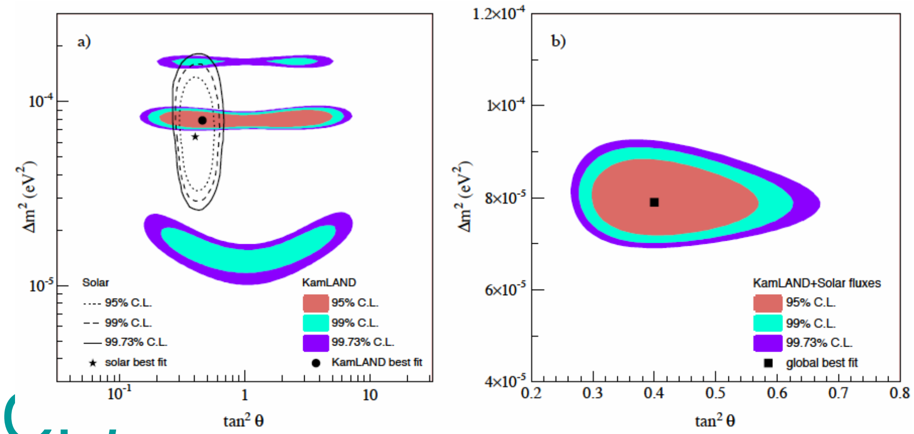


Need for beyond the next generation (NG) experiments

- NG exp. will not determine (unless very lucky) the mass hierarchy
- NG exp. does not have sensitivity to CP violation
- NG exp. may not be able to see nonzero θ_{13} (what happens then?)
- Question: how accurately should we need to know Δm^2 and θ's?

Quark-lepton complementarity ?

$\theta_C + \theta_{solar} = 45.1^o \pm 2.4^o\ (1\sigma)$



$36.8^o < \theta_{atm} < 53.2^o$ (90% CL)

$2.3^o < \theta_{23}^q < 2.5^o$ (90% CL)

$\theta_{23}^q + \theta_{atm} = 47.4^o \pm 8.3^o$ (90% CL)

Foreseeing the future

Things changes at $\sin^2 2\theta_{13}$~0.01

- Conventional super ν_μ beam + Mton water detector work
- Known beam technology
- Background highly nontrivial
- ν_e beam contamination not negligible but tolerable

- beta beam / neutrino factory required
- Requires long-term R&D efforts
- Low background
- pure ν_e beam (β) / well understood combination of ν_e and ν_μ beam (

Various beam options

ν-factory ⇒

$$\text{proton} \xrightarrow{\text{target}} \pi^+ + \ldots$$

$$\hookrightarrow \mu^+ + \nu_\mu \quad \text{(super-beam)}$$

$$\hookrightarrow e^+ + \nu_\mu + \bar{\nu}_e$$

and charge conjugated

beta-beam ⇒

$$\text{proton} \xrightarrow{\text{target}} \text{isotope}$$

$$\hookrightarrow \text{isotope}^* + e^+ + \nu_e$$

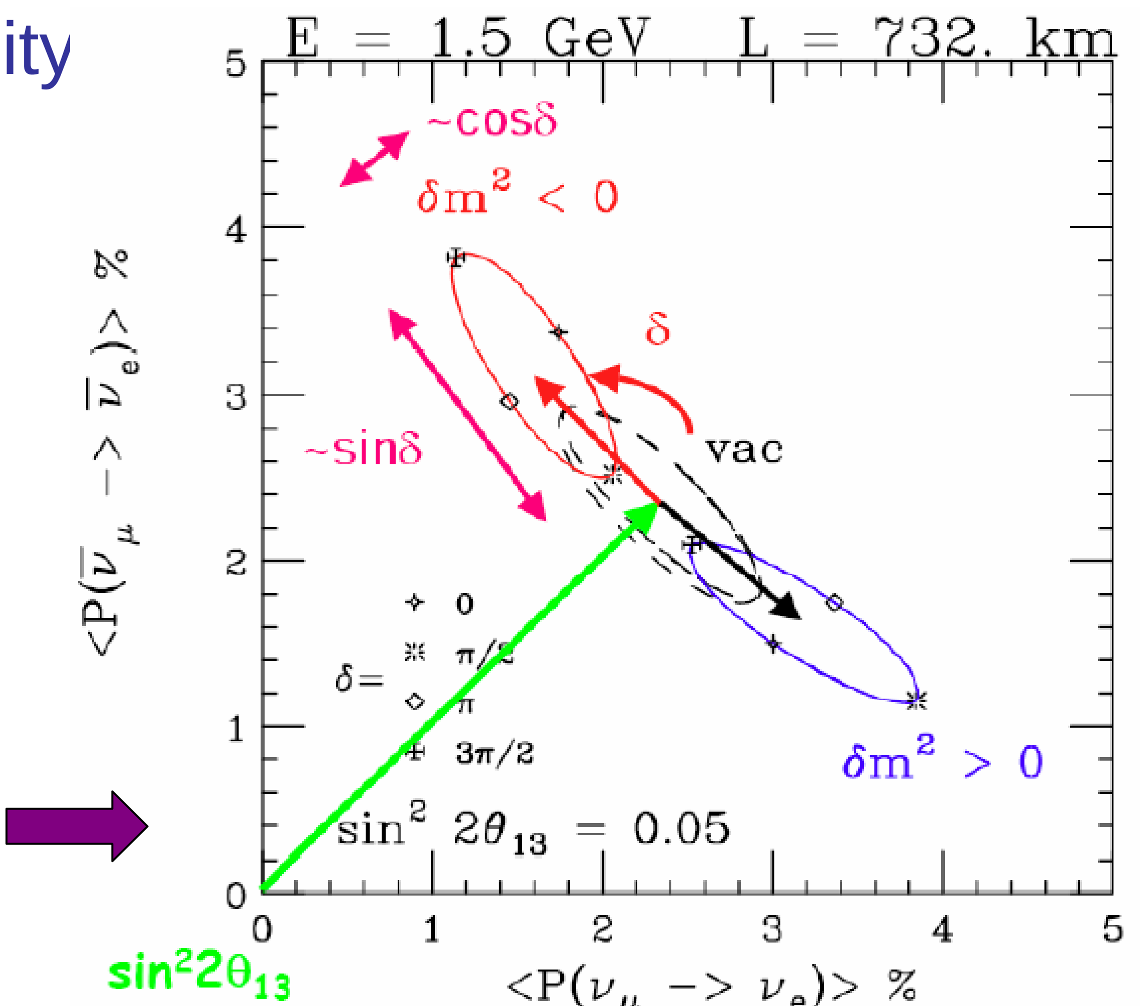
- ν-factory uses beam of 4th generation.
- Beta-beam uses 3rd generation beam.
- Beta-beam is technically closer to existing/used accelerator technology.

Ion source ⇒ Acceleration ⇒ Storage ⇒ Neutrino beam

Degeneracy; a notorious obstacle

A machinery in my talk

- Oscillation probability draw ellipse if plotted in bi-P plane
- Role played by CP phase δ and the matter clearly distinguished



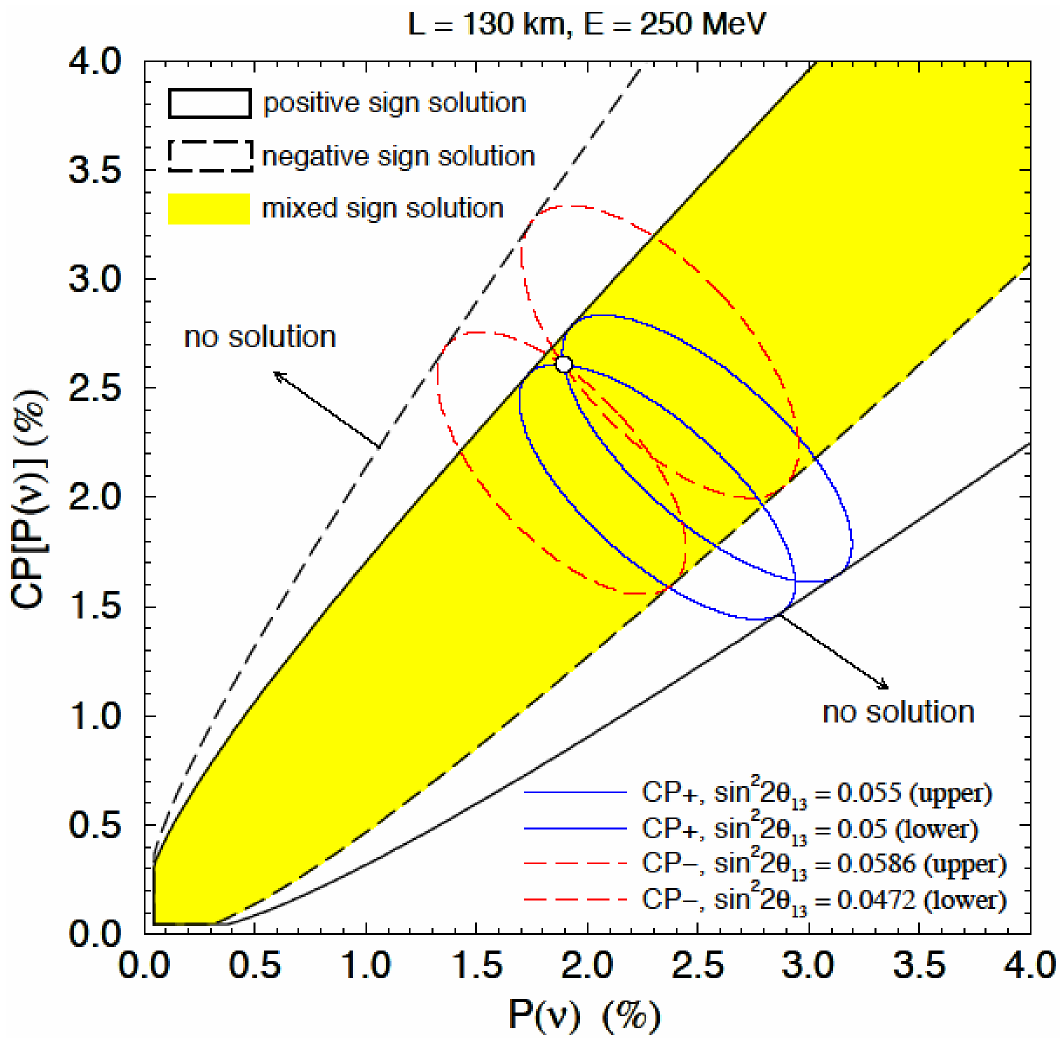
Cause of the degeneracy; easy to understand

- You can draw two ellipses from a point in P-Pbar space

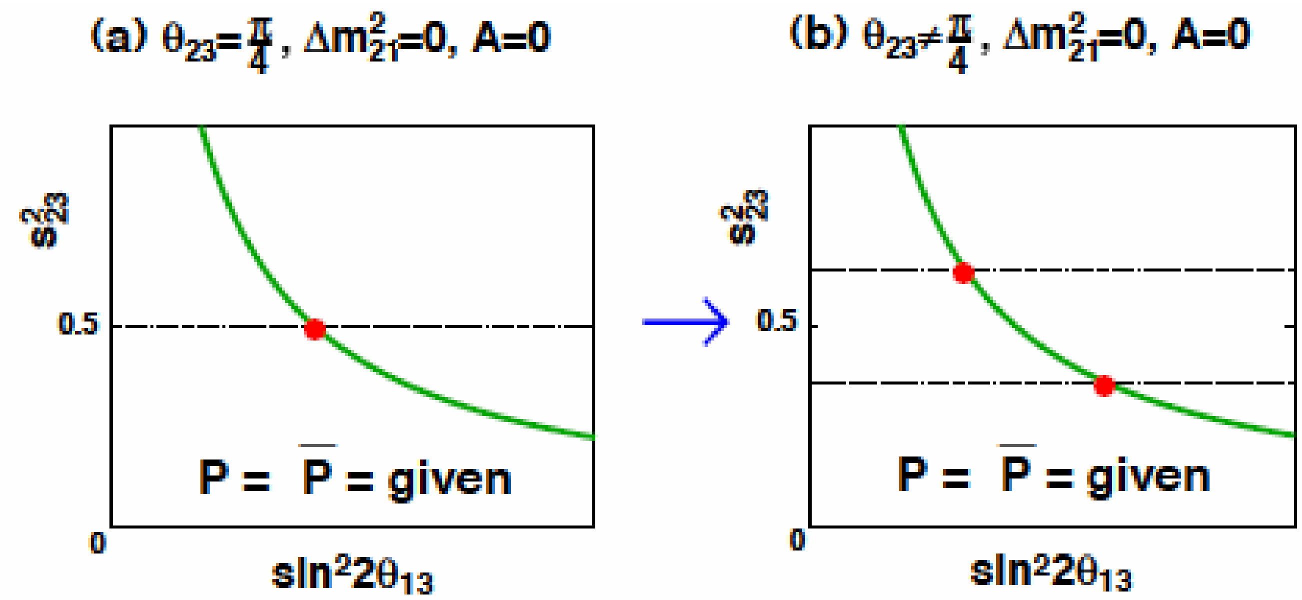
→ Intrinsic degeneracy

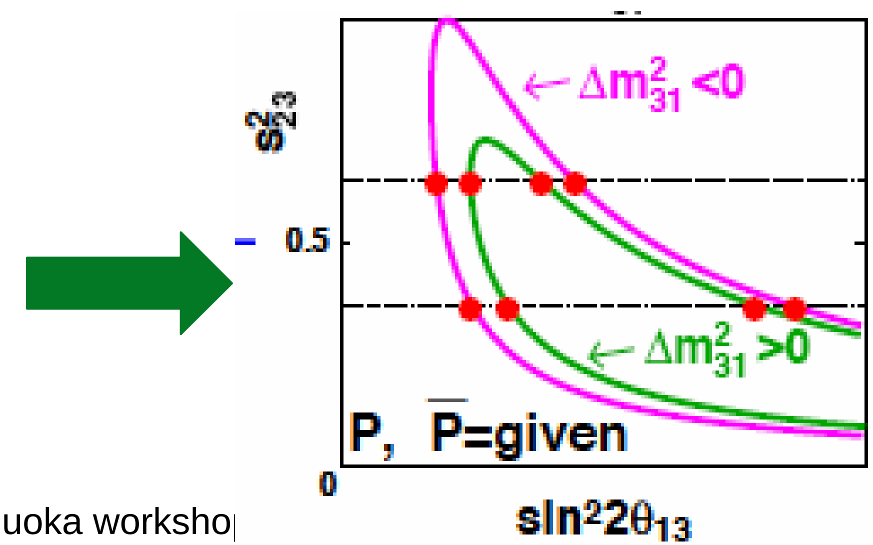
- Doubled by the unknown sign of Δm^2

→ 4-fold degeneracy

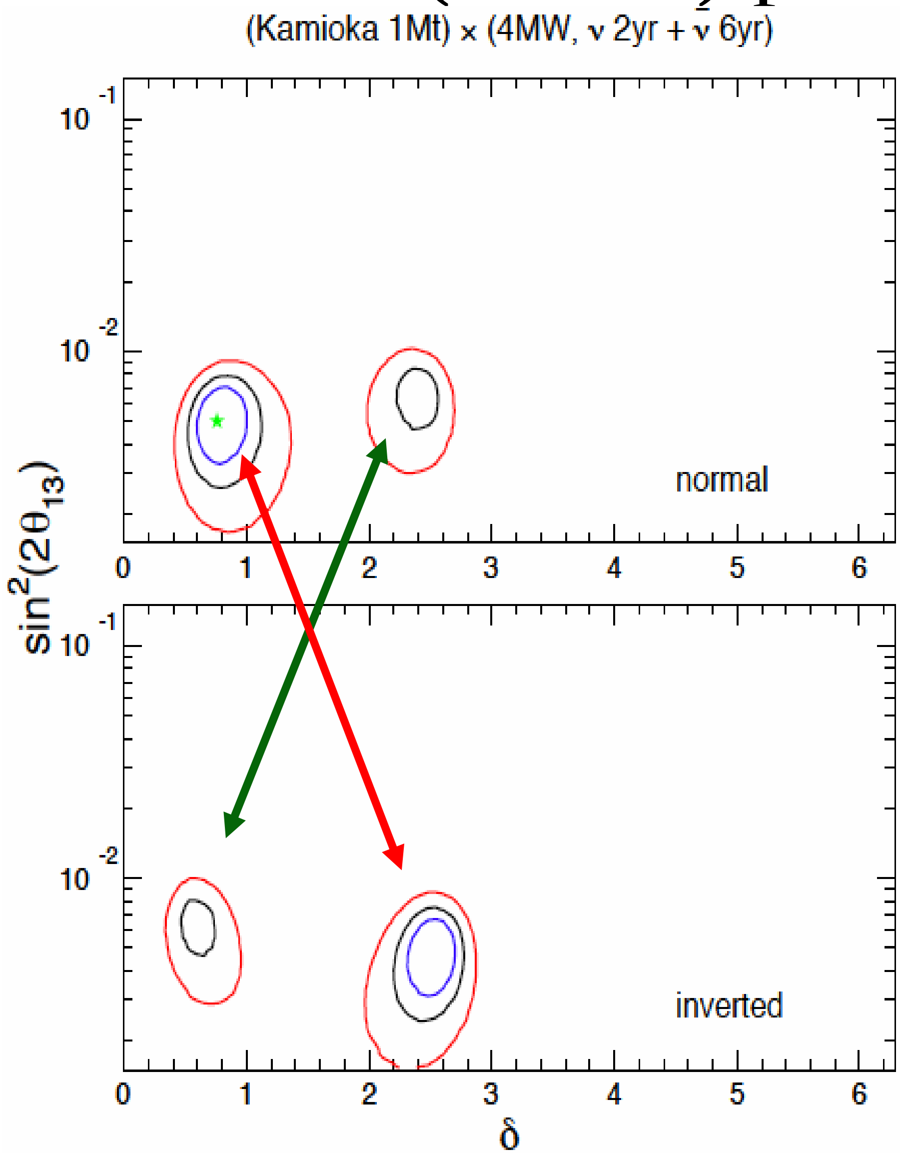


θ_{23} octant degeneracy





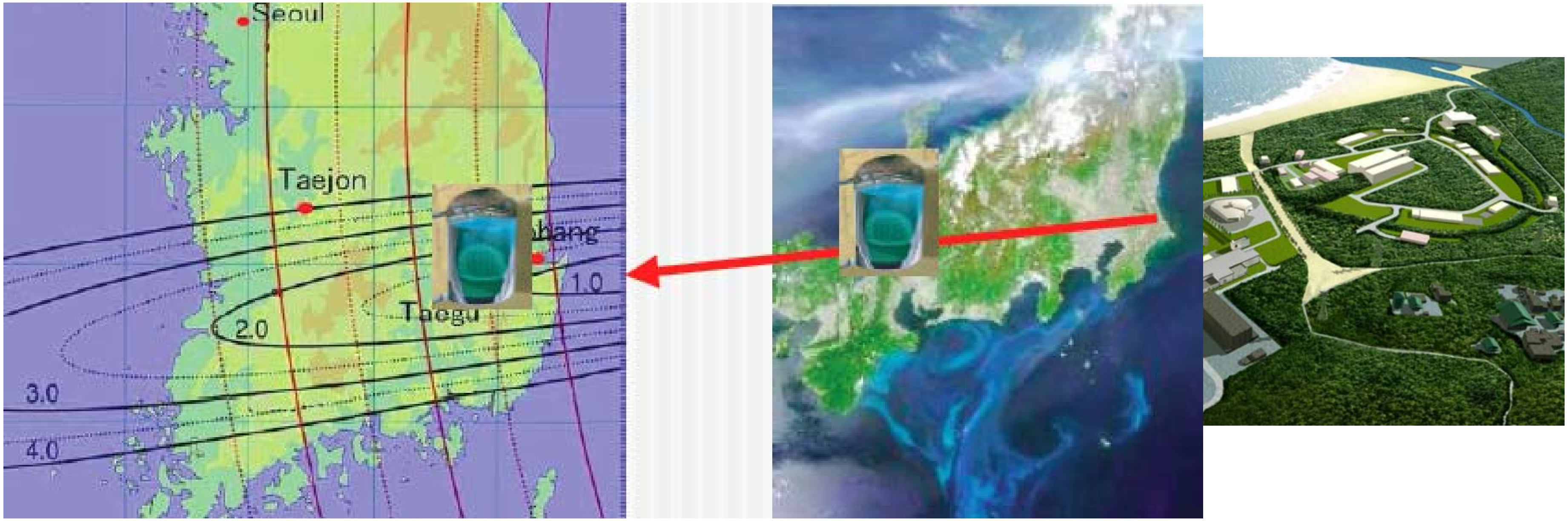
Structure of intrinsic & sign-Δm^2 degeneracy in (matter) perturbative regime



- Intrinsic degeneracy; $\delta_2 = \pi - \delta_1$
- sign(Δm^2)-δ degeneracy arises because P is approx. invariant under:
- $\Delta m^2 \longrightarrow -\Delta m^2$
- $\delta \longrightarrow \pi - \delta$

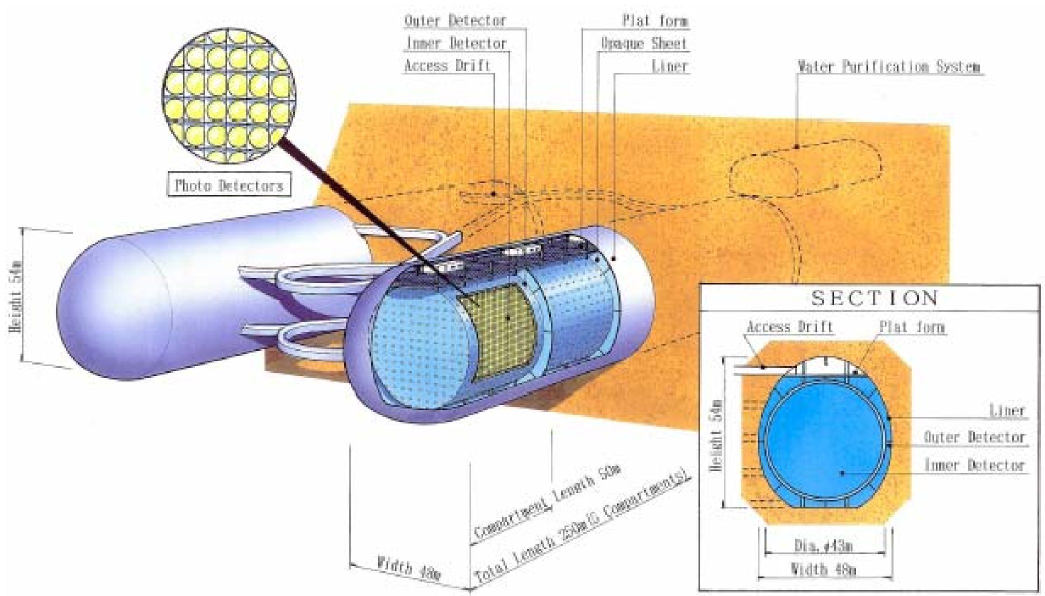
T2KK; Tokai-to-Kamioka-Korea identical two-detector complex

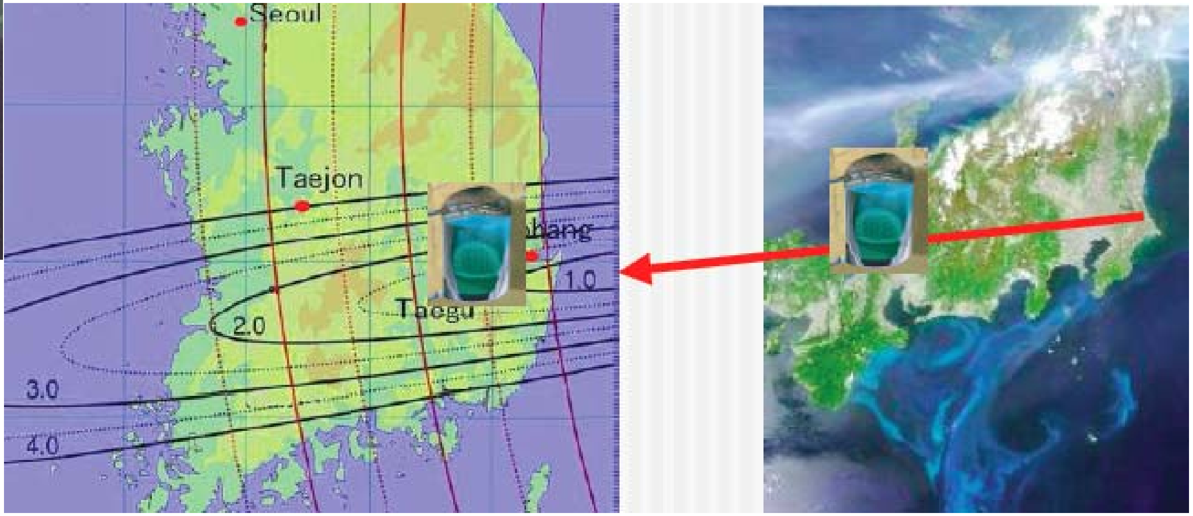
- An improvement over T2K II design with Hyper-K @ Kamioka with 1 megaton water



What's good in T2KK? (what about NOVA?)

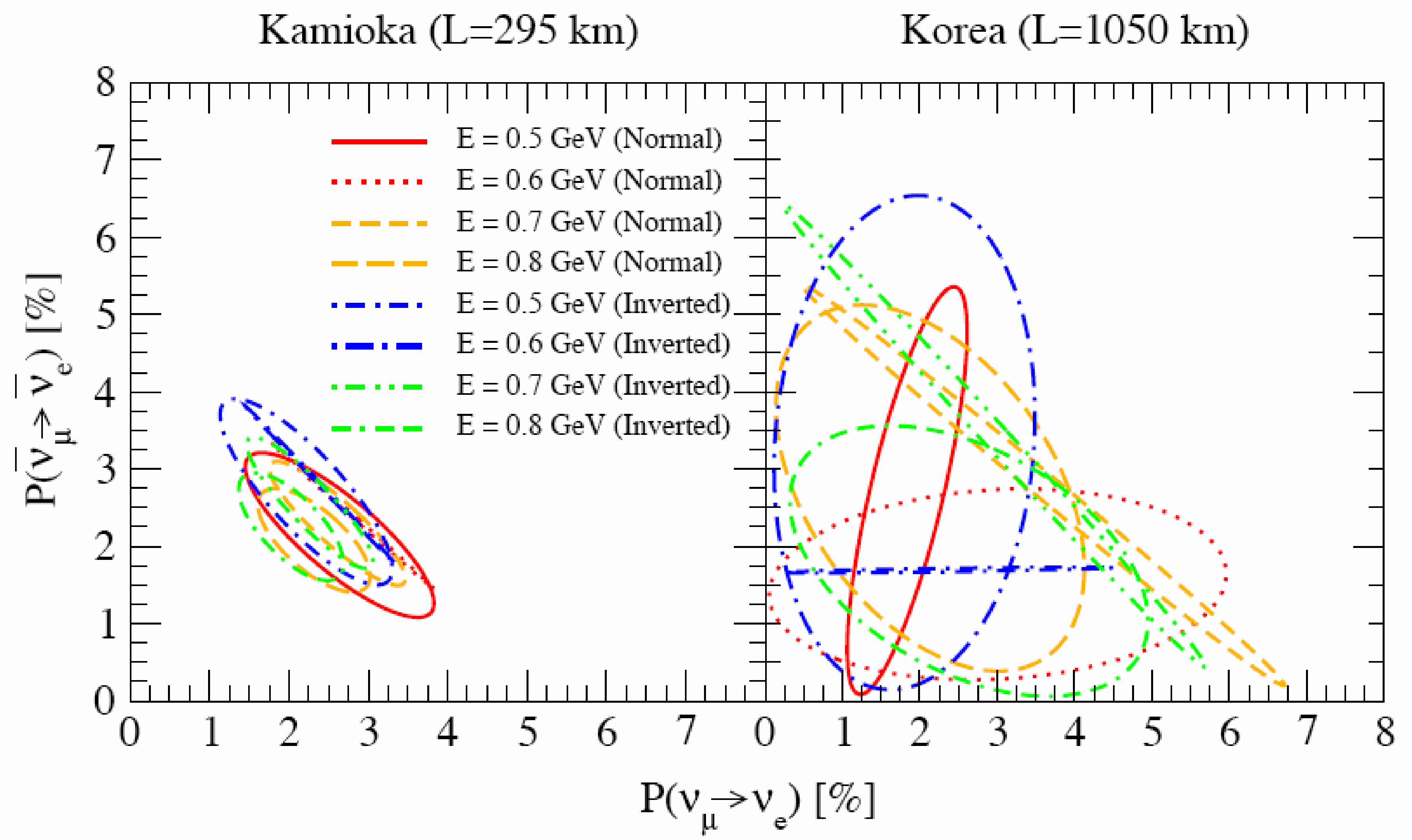
#1. Current design of Hyper-Kamiokande contains 2 tanks !



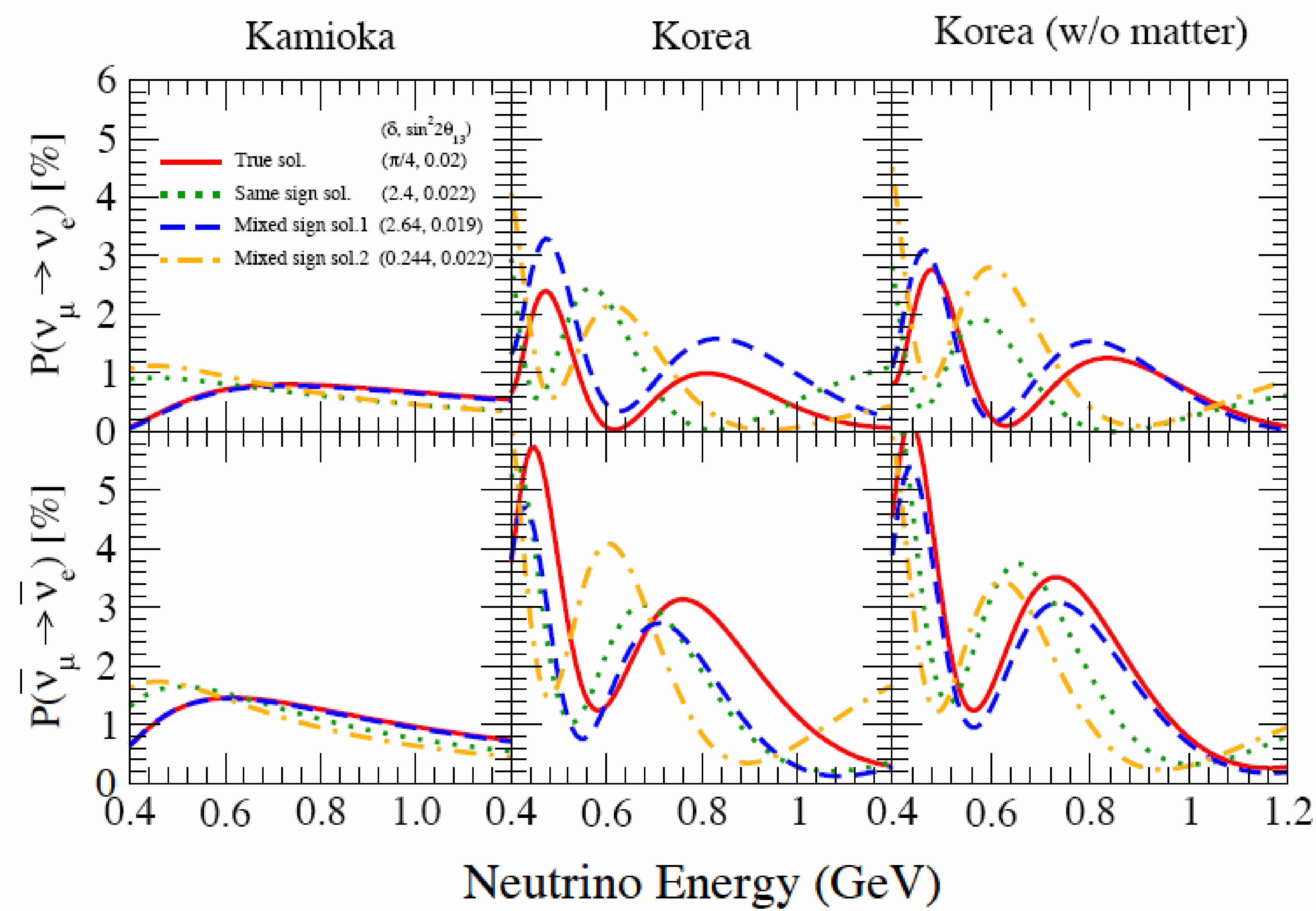


December 17, 2006

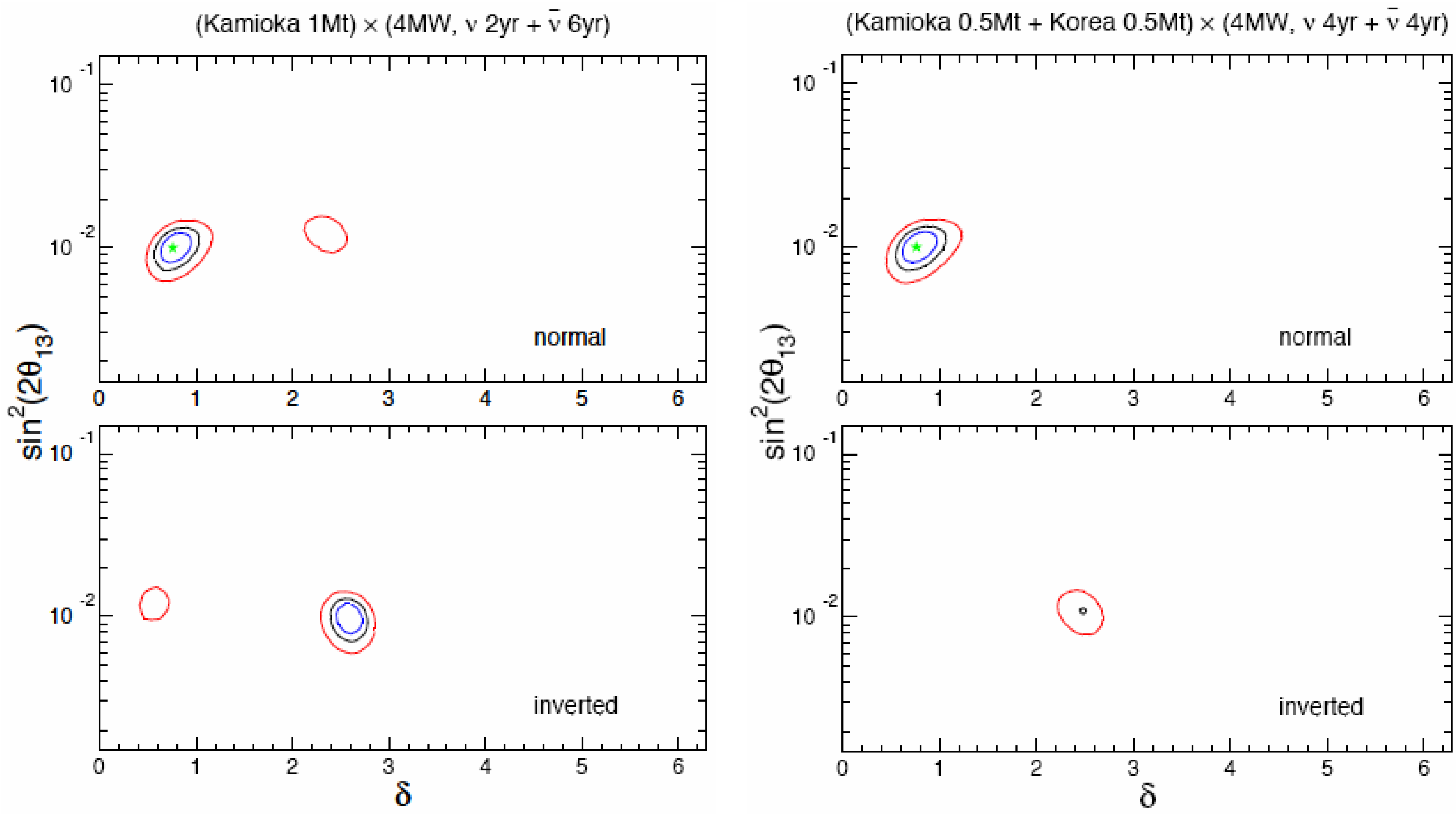
Sensitive to δ because energy dependence is far more dynamic in 2nd oscillation maximum



Spectral information solves degeneracy



Spectral information solves intrinsic degeneracy



χ^2 definition

detector x beam combination

e-like bins

μ-like bins

systematic error term

$$\chi^2 = \sum_{k=1}^{4}\left(\sum_{i=1}^{5}\frac{\left(N(e)_i^{\rm obs}-N(e)_i^{\rm exp}\right)^2}{\sigma(e)_i^2} + \sum_{i=1}^{20}\frac{\left(N(\mu)_i^{\rm obs}-N(\mu)_i^{\rm exp}\right)^2}{\sigma(\mu)_i^2}\right) + \sum_{j=1}^{7}\left(\frac{\epsilon_j}{\tilde{\sigma}_j}\right)^2$$

$$N(e)_i^{\rm exp} = N(e)_i^{\rm BG}\cdot(1+\sum_{j=1,2,7} f(e)_j^i\cdot\epsilon_j) + N(e)_i^{\rm signal}\cdot(1+\sum_{j=3,7} f(e)_j^i\cdot\epsilon_j)$$

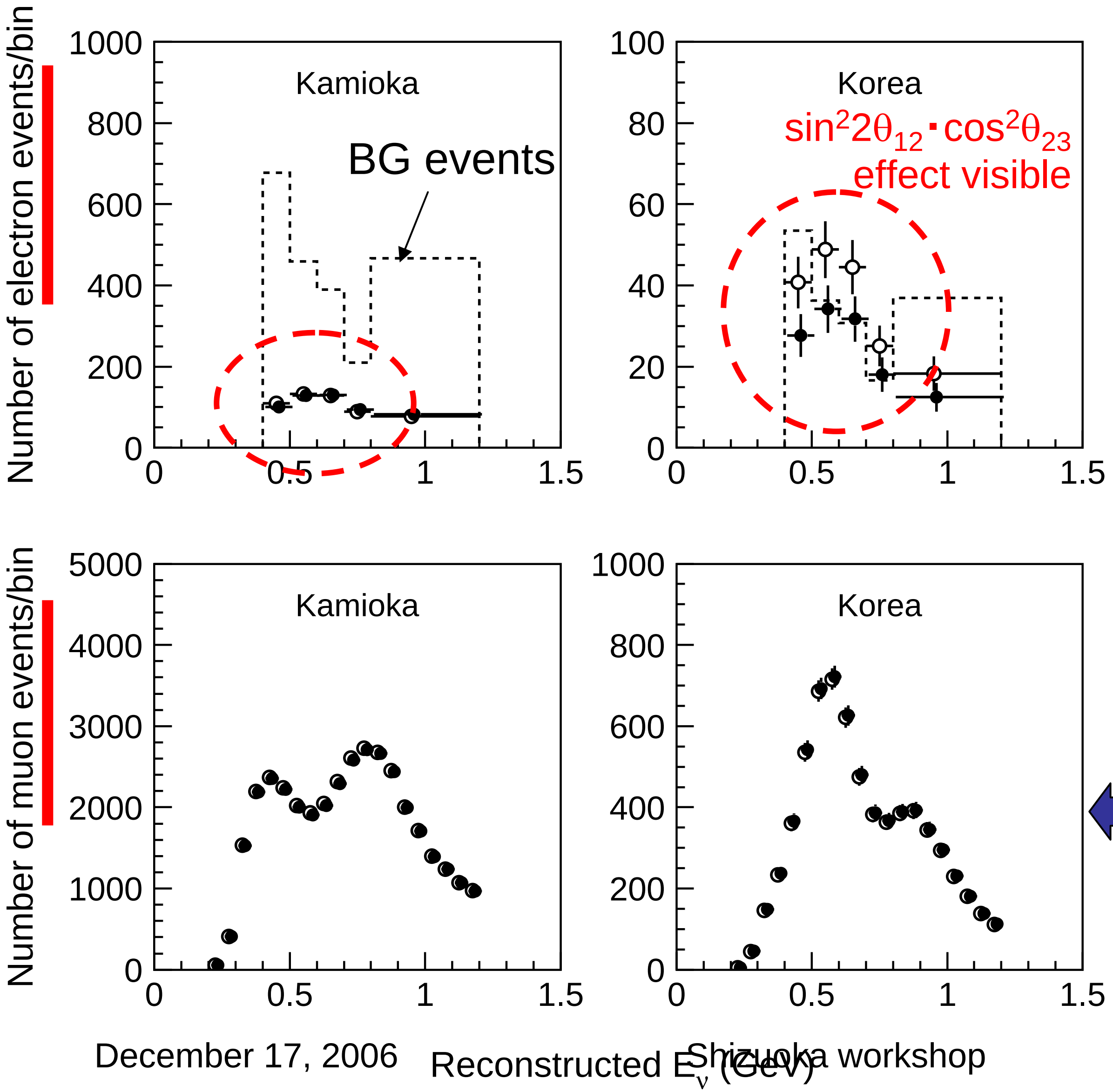
$$N(\mu)_i^{\rm exp} = N(\mu)_i^{\rm BG}\cdot(1+\sum_{j=4,5,7} f(\mu)_j^i\cdot\epsilon_j) + N(\mu)_i^{\rm signal}\cdot(1+\sum_{j=5,6,7} f(\mu)_j^i\cdot\epsilon_j)$$

f^i_j : fractional change in the predicted event rate in the i^{th} bin due to a variation of the parameter ε_j

ε_j : systematic error parameters, which are varied to minimize χ^2 for each chioce of the oscillation parameters

"Pull Approach" G.L.Fogli et al. PRD66 (2002) 053010

Effect of the solar term



○ $\sin^2\theta_{23} = 0.4$, $\sin^2 2\theta_{13} = 0.01$

● $\sin^2\theta_{23} = 0.6$, $\sin^2 2\theta_{13} = 0.0067$

(These parameters are chosen to so that $\sin^2\theta_{23}\cdot\sin^2 2\theta_{13}$ is equal.)

Δm^2: positive

$\delta=\pi 3/4$

Included in this analysis, since θ_{23} is relevant.

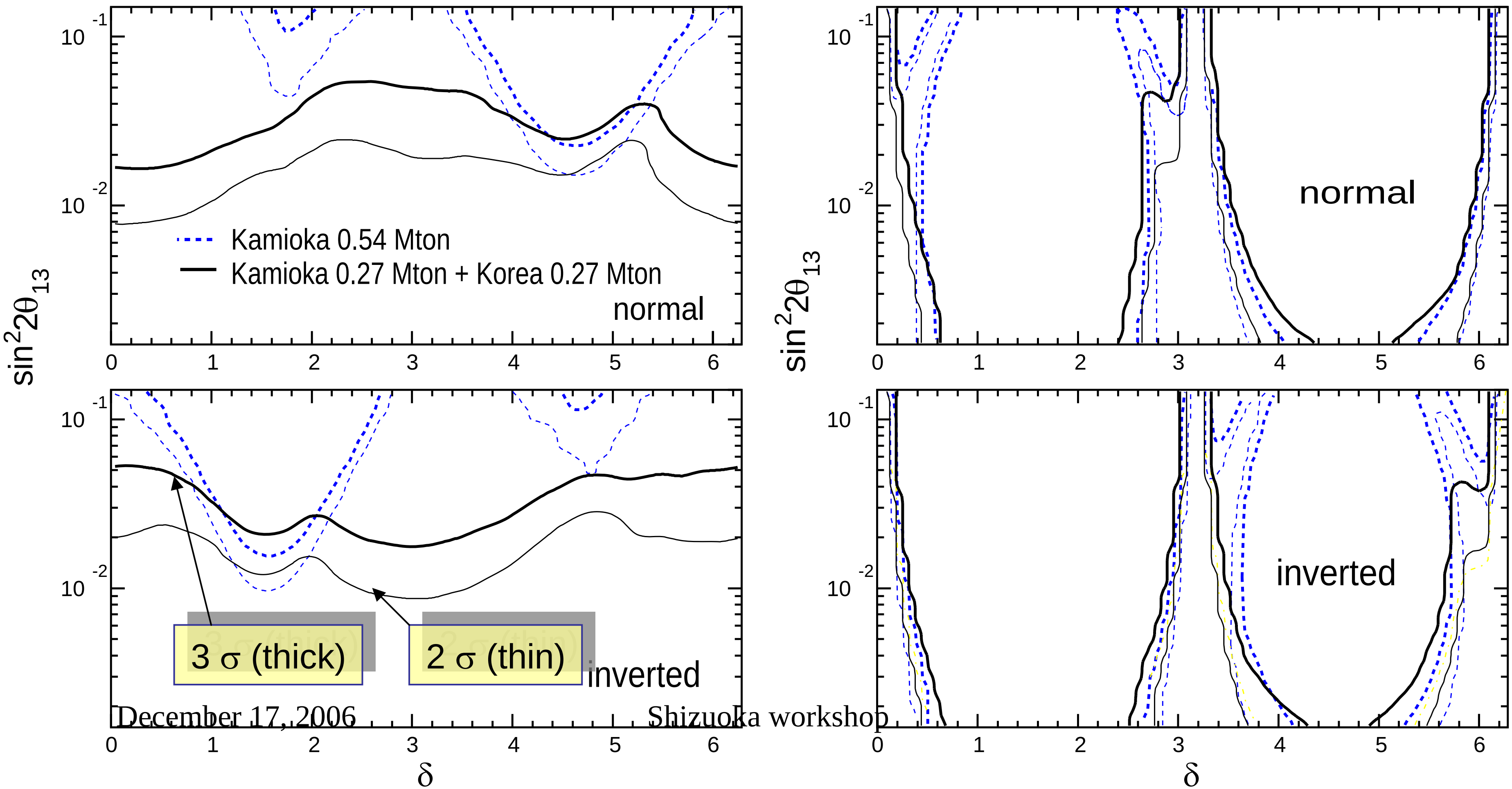
T2KK vs. T2K II Comparison

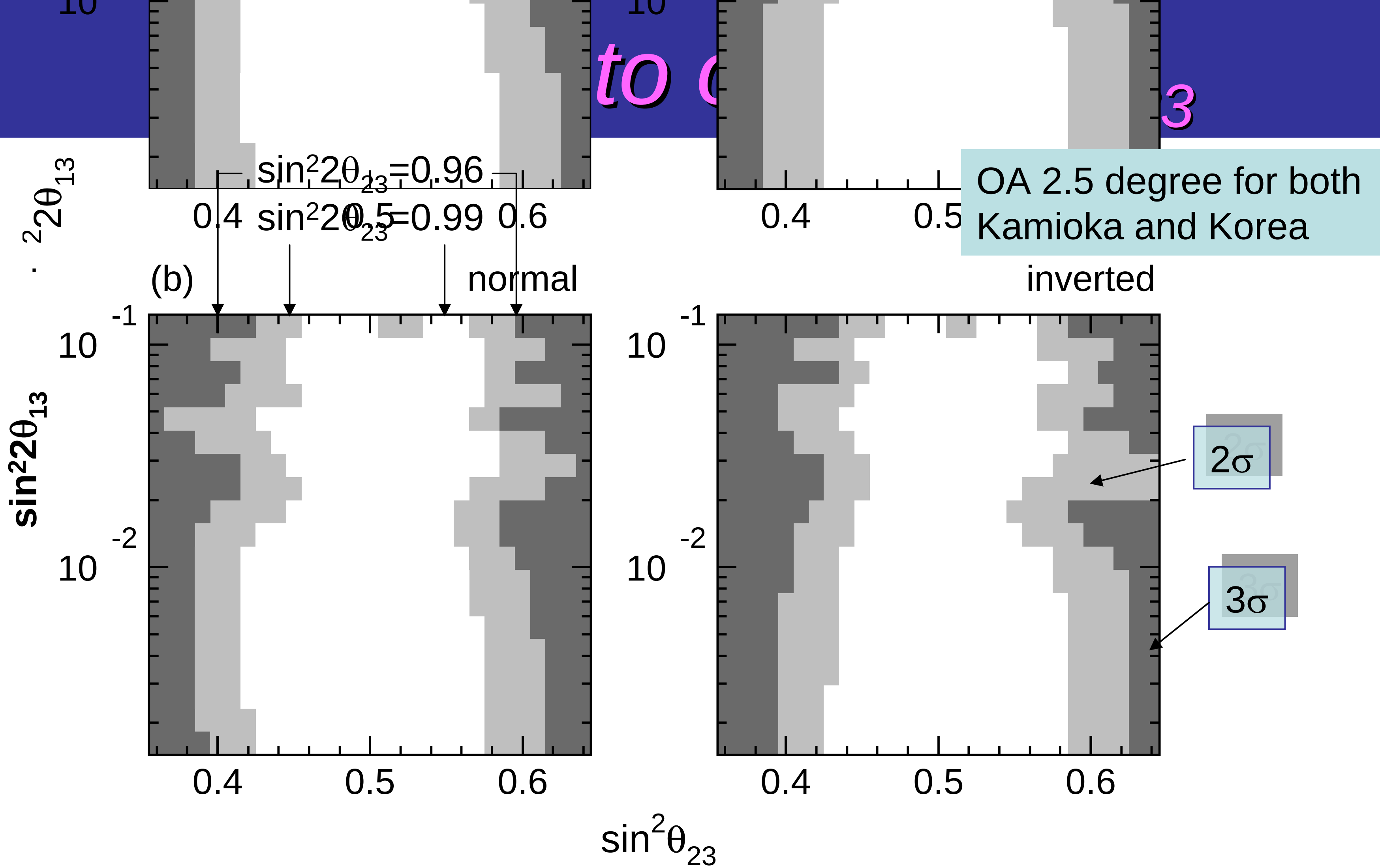
hep-ph/0504026

Total mass of the detectors = 0.54 Mton fid. mass
4 years neutrino beam + 4 years anti-neutrino beam

Mass hierarchy

CP violation ($\sin\delta \neq 0$)





Octant ambiguity of θ_{23} can be resolved if $\sin^2 2\theta_{23}$ < ~0.97 at 2σ (almost independent of the value of $\sin^2 2\theta_{13}$ and mass hierarchy).

Can resolve the 8 fold degeneracy of the oscillation parameters.

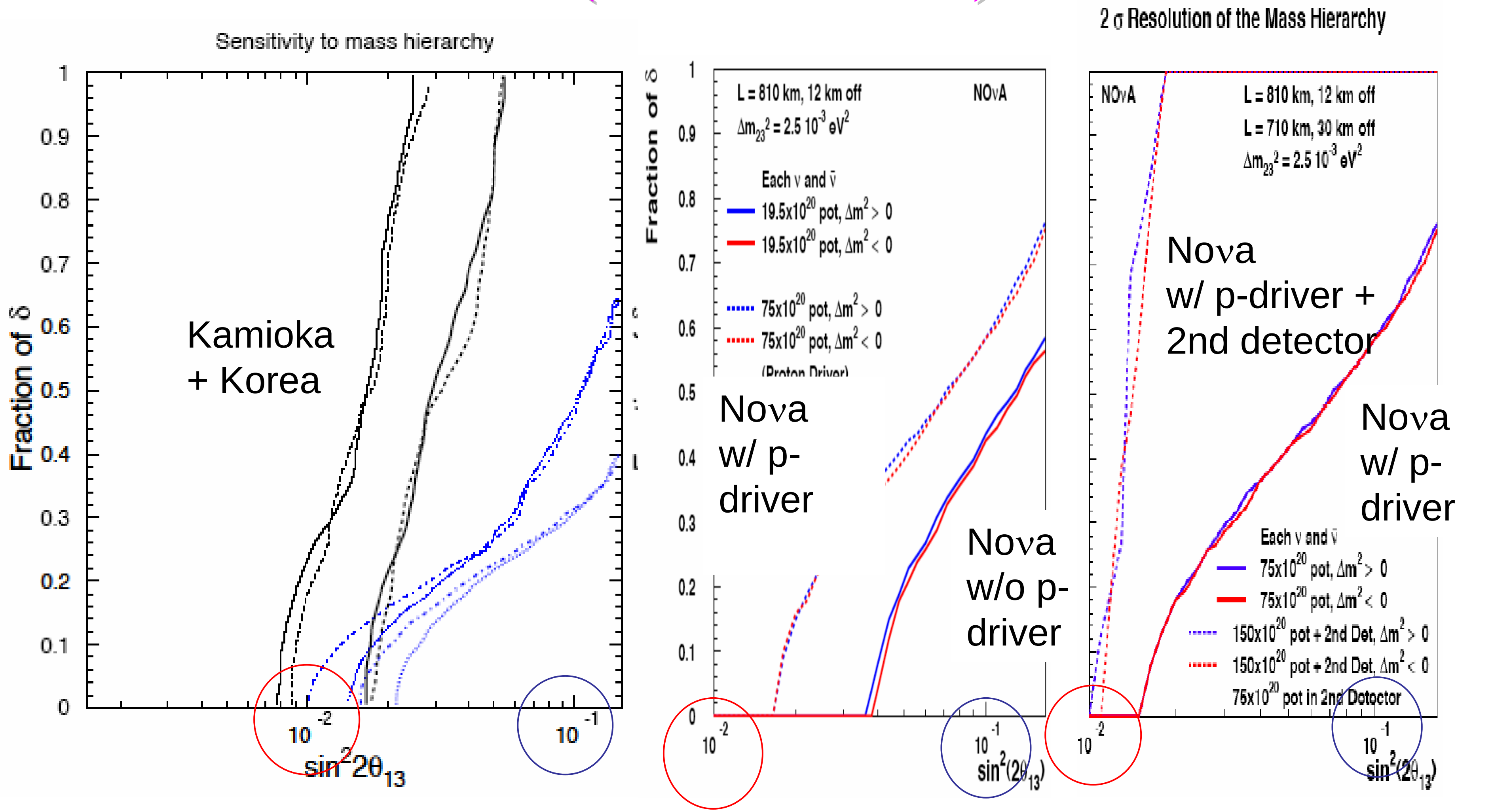
θ_{23} and sign-Δm^2 degeneracy decouple

- For example, one can show, to first order in matter effect, the followings:
- ΔP(octant) = P(1st octant) - P(2nd) is invariant under the interchange of two sign-Δm^2 degenerate pair
- ΔP(hierarchy) = P(Δm^2 +) - P(Δm^2 -) is invariant under the interchange of two θ_{23} octant degenerate pair
- in T2K or T2KK setting, the intrinsic degeneracy is resolved by spectrum analysis decouple from the game

In a nutshell, 8 fold degeneracy can be resolved by T2KK because ..

- intrinsic degeneracy is resolved by spectrum information
- sign-Δm^2 degeneracy is solved with matter effect + 2 identical detector comparison
- θ_{23} octant degeneracy is solved by identifying the solar oscillation effect in T2KK

Sensitivity to mass hierarchy:
T2K-II vs. (Kam+Korea) vs. Nova

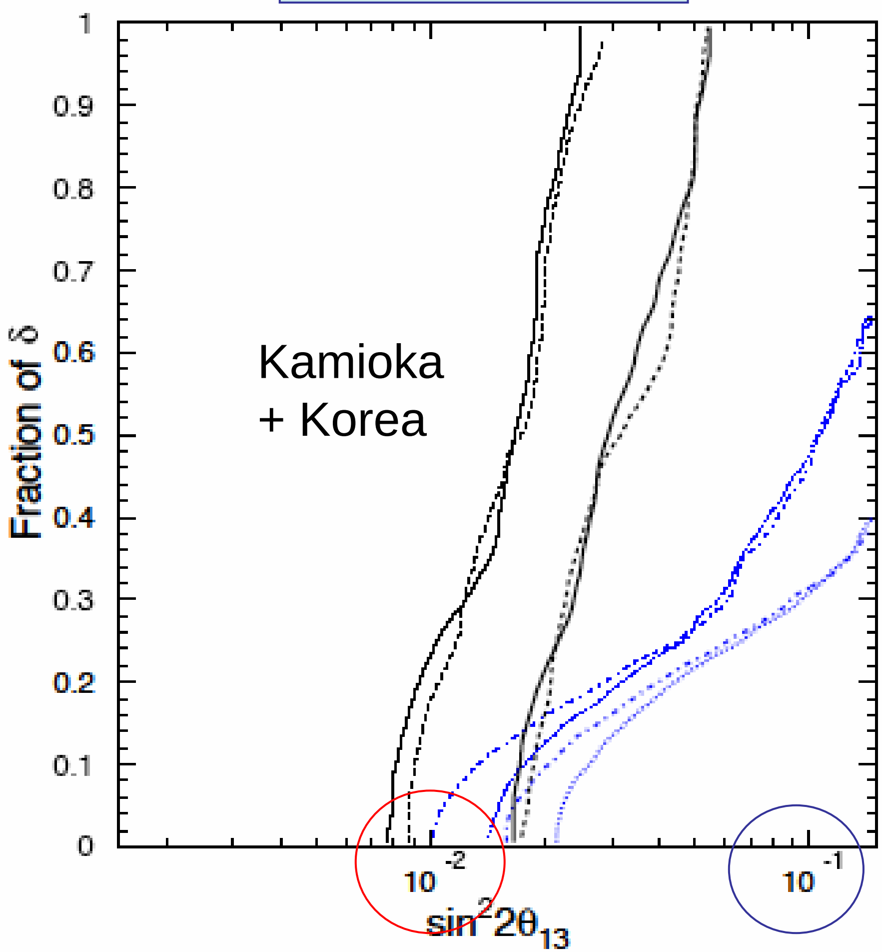


Expected sensitivity (2)

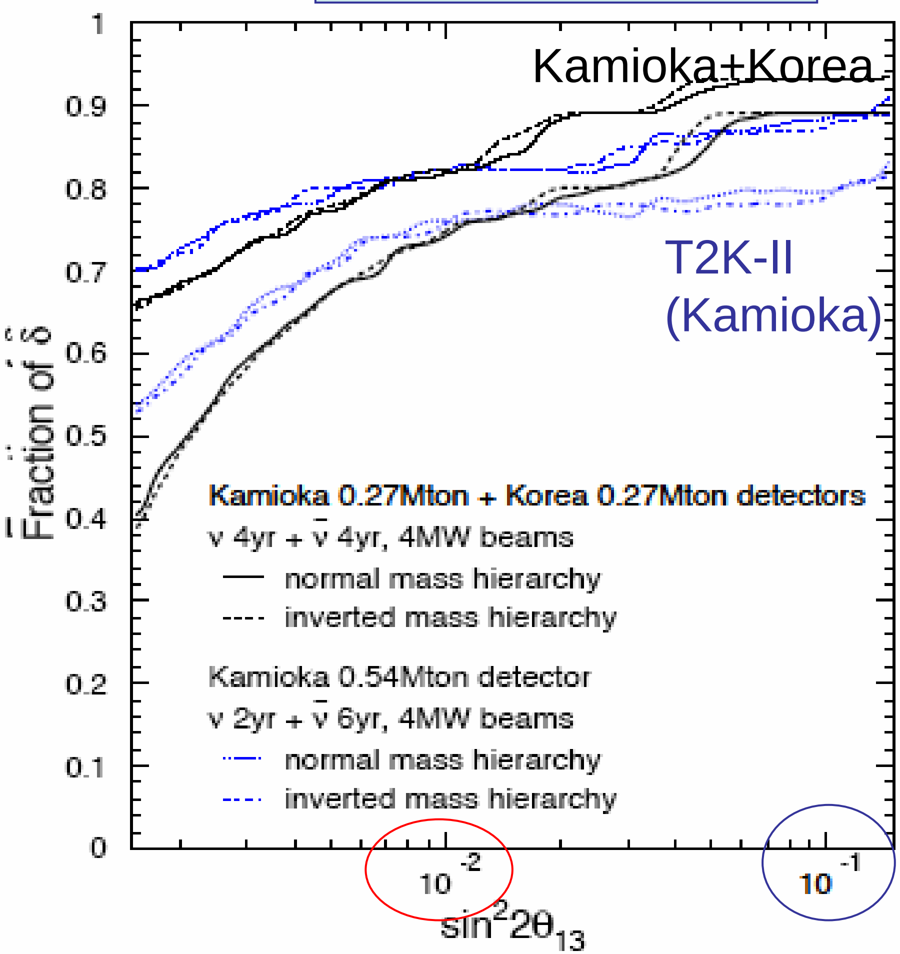
hep-ph/0504026

Total mass of the detectors = 0.54 Mton fid. mass
4 years neutrino beam + 4 years anti-neutrino beam

Mass hierarchy



CP violation (sinδ≠0)



T2KK; points of emphasis

- Observing Leptonic CP violation is a challenging goal → projects have to be expensive
- Sensitivity estimate has to be a reliable one, otherwise …
- Restrict to: known background rejection technology by SK + conservative estimate of the systematic errors (5%) + identical 2 detector setting

Beta beam

Beta beam in a word

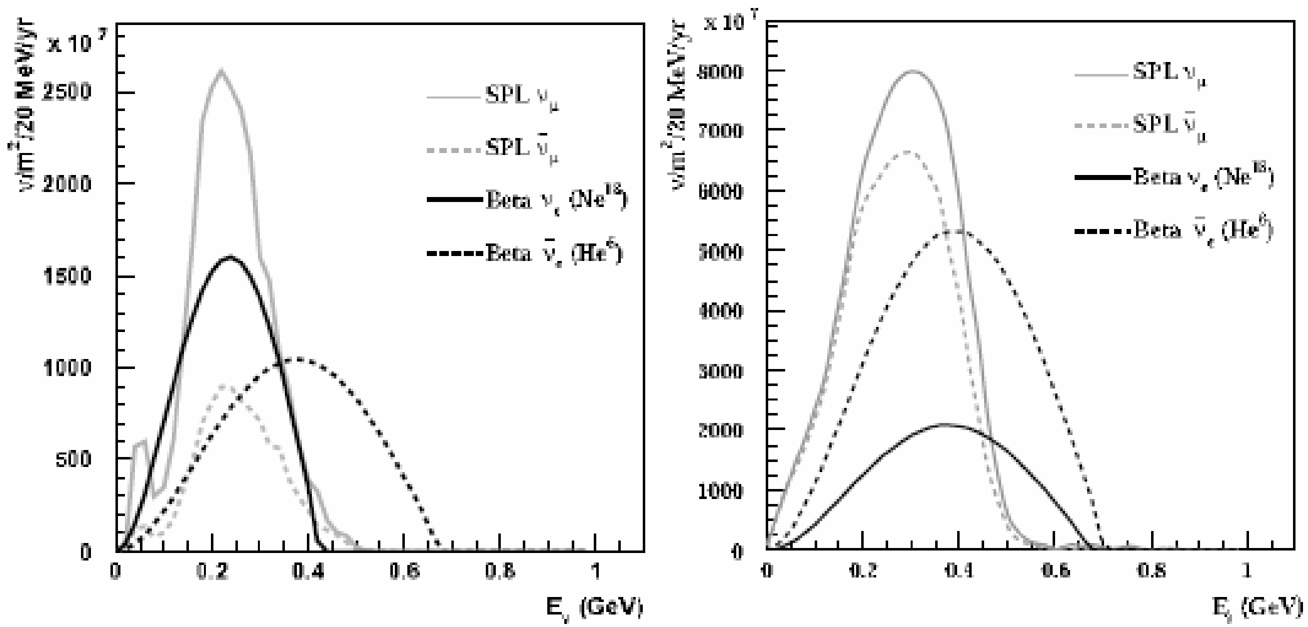


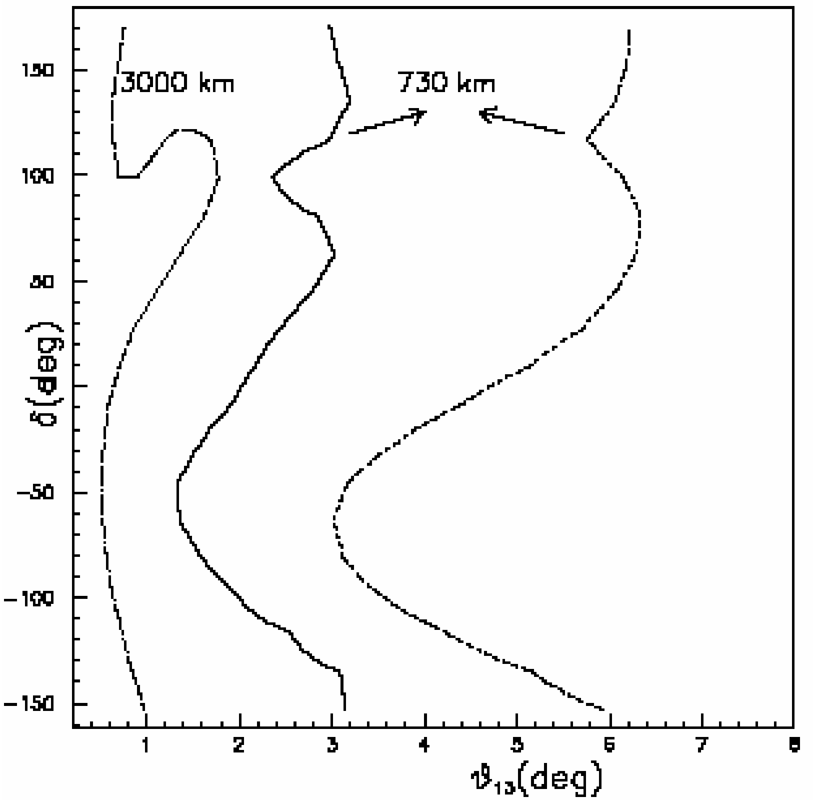
Figure 6. Comparison of neutrino fluxes from a super-beam (SPL) and a beta-beam. The neutrino beams are produced at CERN and sent to the Fréjus Underground Laboratory, 130 km from CERN. Two options for the beta-beam are shown here. Left: The ions circulate together in the storage ring, with $\gamma = 60$ (100) for ^{6}He (^{18}Ne) (Mezzetto 2005). Right: The ions circulate at the same $\gamma = 100$, independently, in the storage ring. Note that the average neutrino energies are related to the ion boost through $E_\nu \approx 2\gamma Q_\beta$ (Guglielmi *et al* 2005).

What is good in Beta beam?

- pure ν_e (^{18}Ne) or ν_e-bar (^{6}He) beam
- charged pion background seems tolerable
- e-μ separation required but no charge ID required
- multi-MW proton beam NOT required

Low vs. high γ beta beam

- Setup I, low energy: $\gamma = 60$ for ^{6}He and $\gamma = 100$ for ^{18}Ne, with $L = 130$ km (CERN–Fréjus) as in [12, 22]. [7]
- Setup II, medium energy: $\gamma = 350$ for ^{6}He and $\gamma = 580$ for ^{18}Ne, with $L = 732$ km (e.g. CERN–Gran Sasso with a refurbished SPS or with the LHC, FNAL–Soudan).
- Setup III, high energy: $\gamma = 1500$ for ^{6}He and $\gamma = 2500$ for ^{18}Ne, with $L = 3000$ km (e.g. CERN–Canary islands with the LHC).



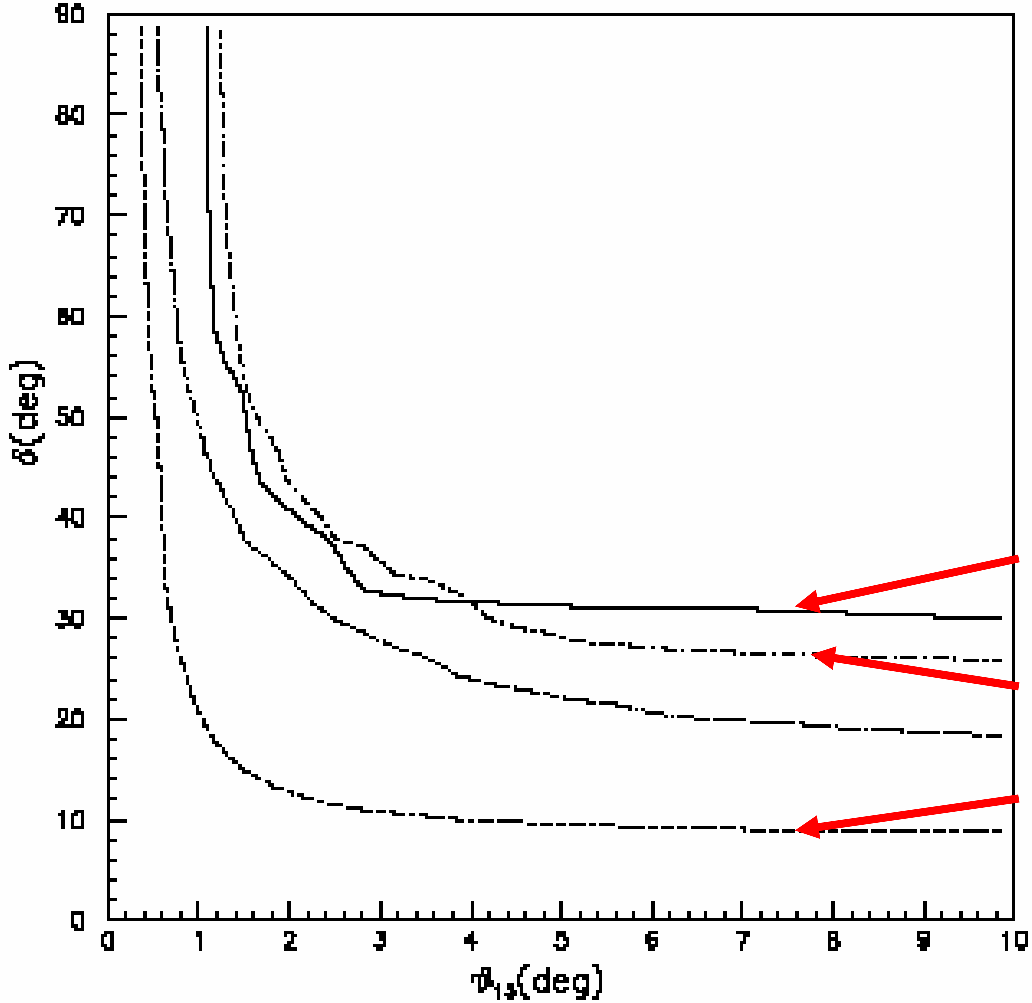
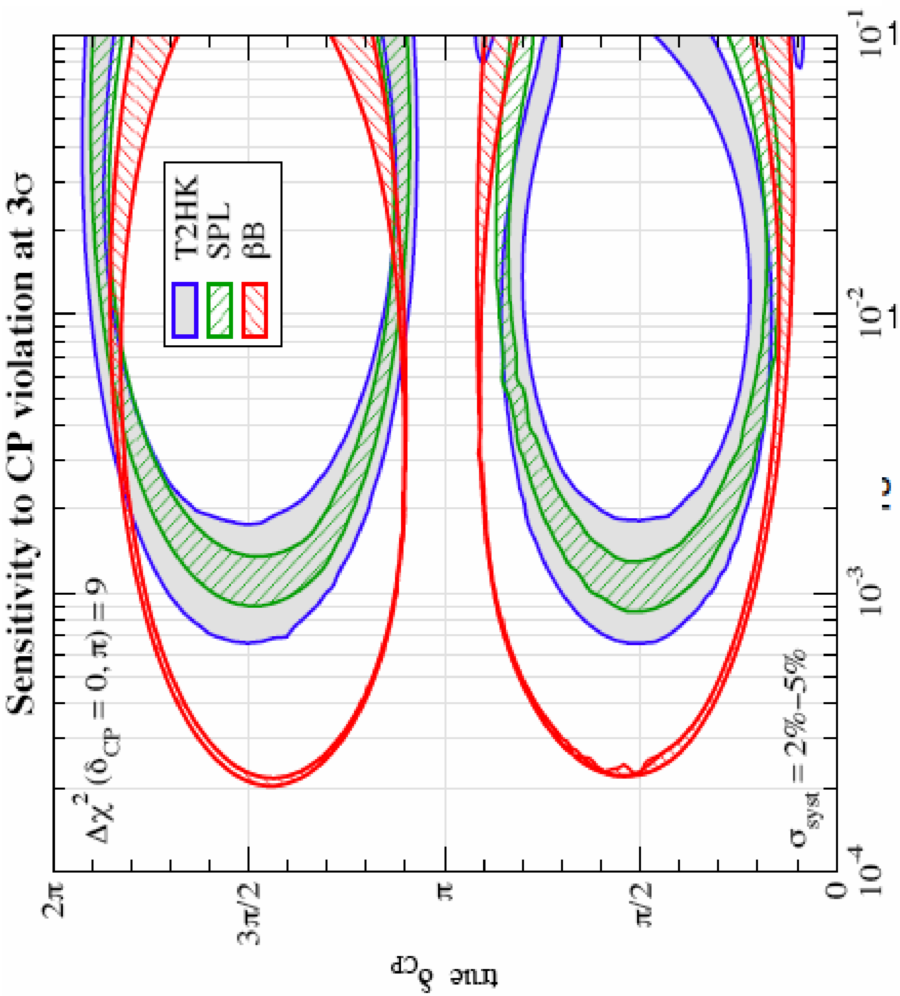
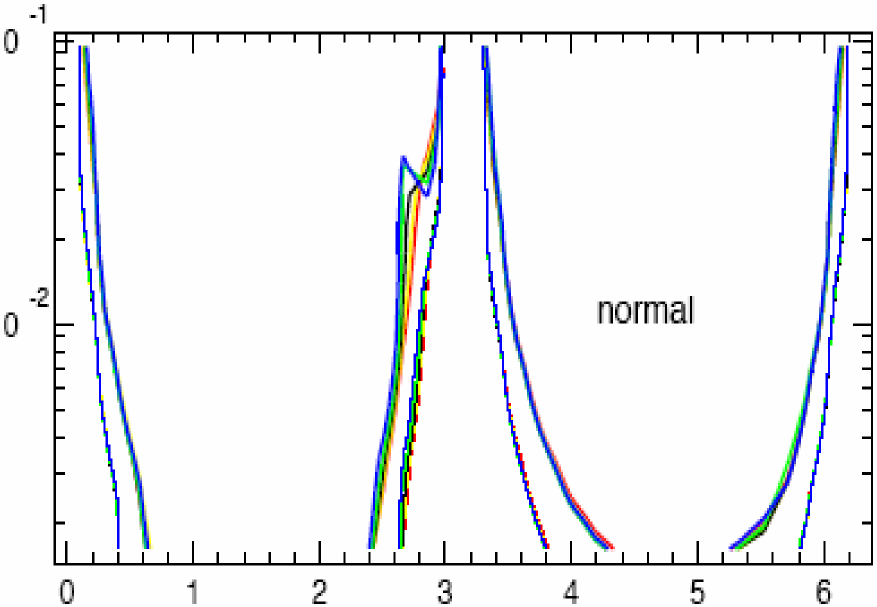


Figure 13: Region where δ can be distinguished from $\delta = 0$ or $\delta = 180°$ with a 99% CL for setup I (solid), setup II with the UNO-type detector of 400 kton described in section 3.1 (dashed) and with the same detector with a factor 10 smaller mass (dashed-dotted) and setup III (dotted) with a 40 kton tracking calorimeter described in section 3.4.

Beta vs. T2KK



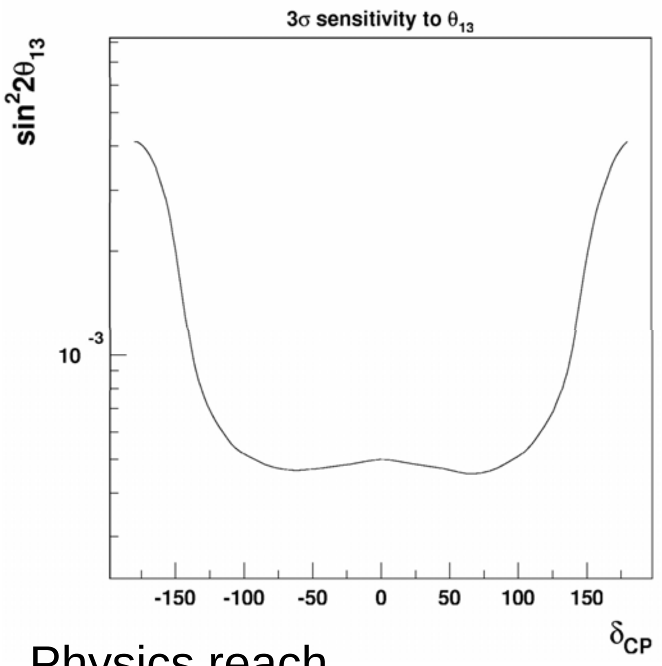
Sensitivity to CP violation at 3σ
T2HK
SPL
βB
$\Delta\chi^2(\delta_{CP} = 0, \pi) = 9$
$\sigma_{syst} = 2\%-5\%$
true δ_{CP}

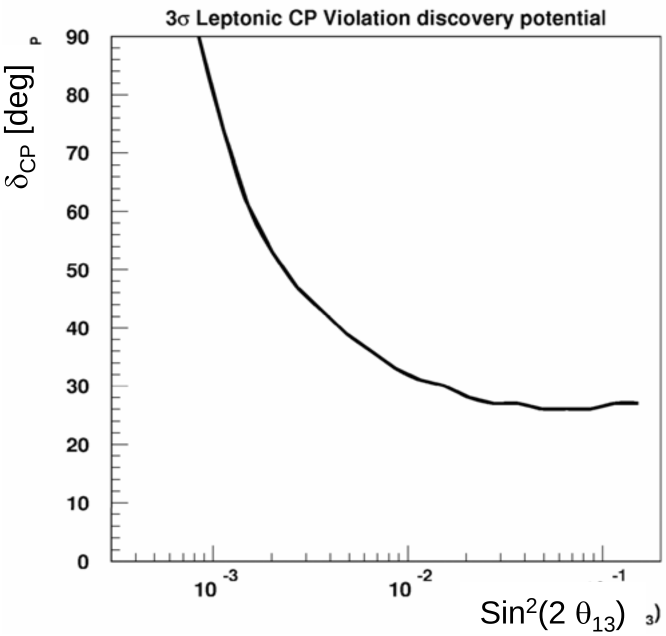


normal

Physics reach; low γ

- EURISOL scenario
  - γ=100
  - each ^{6}He and ^{18}Ne with a 5-year run
  - 2.9*10^{18} ^{6}He decays/year or 1.1*10^{18} ^{6}Ne decays/year



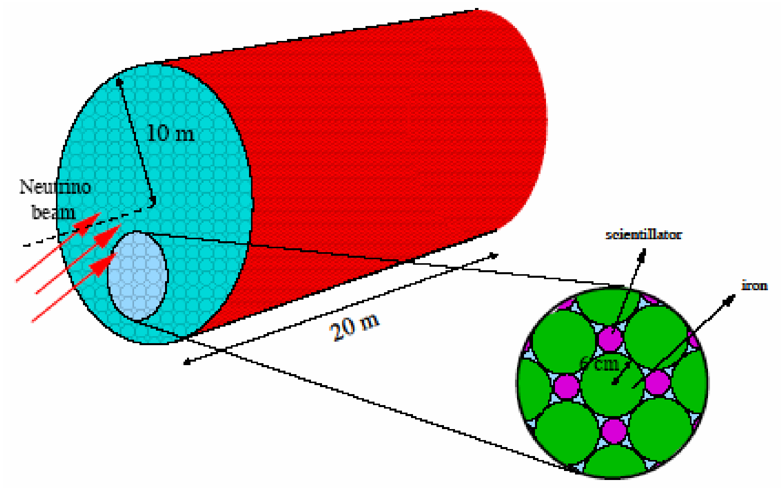


- Physics reach
  - Sensitivity on Θ_{13} down to ~1°

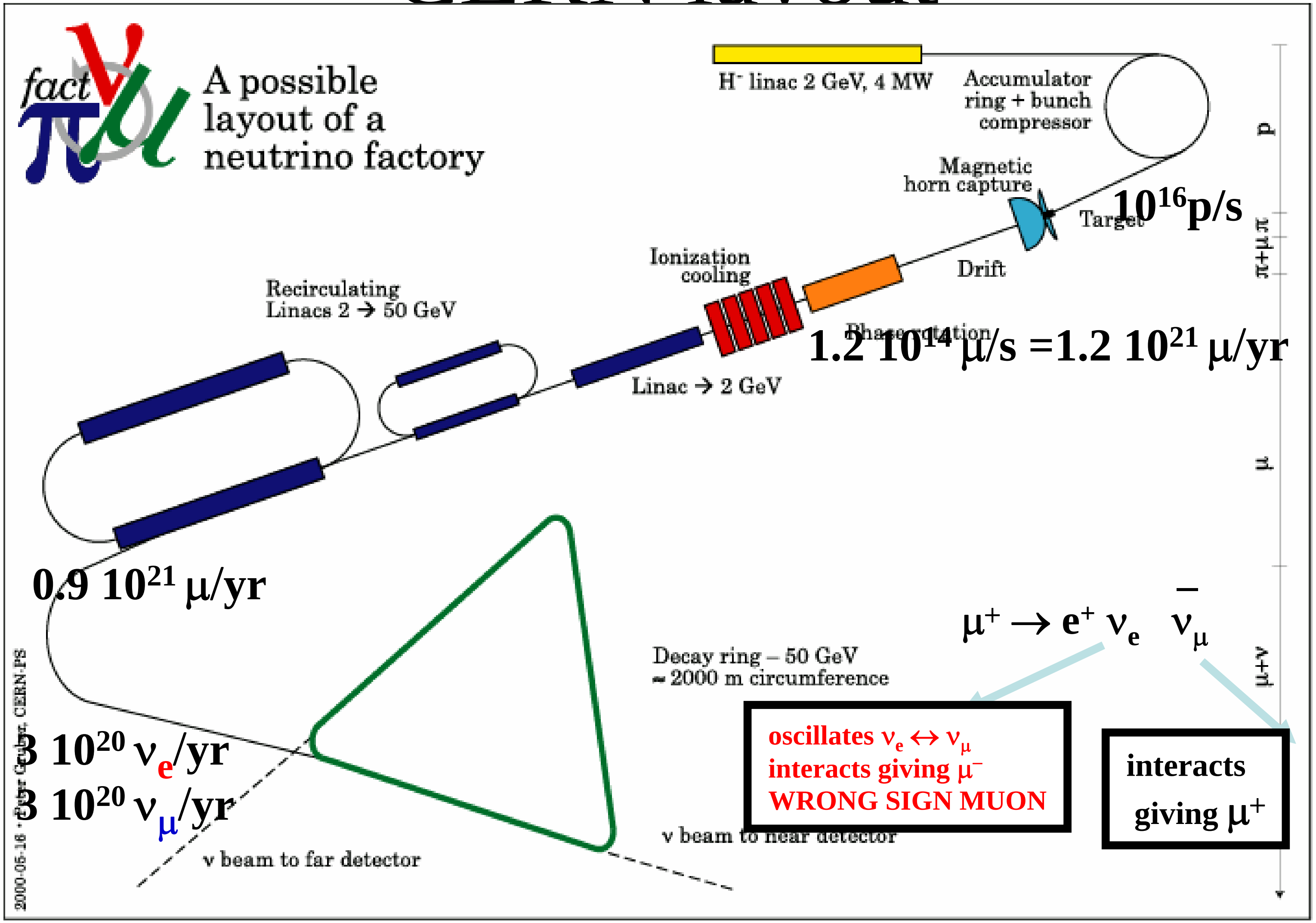
Neutrino factory

What is good in Neutrino factory ?

- well understood combination of ν_e and ν_μ beam with precisely ($\sim 10^{-5}$) known muon energy
- small background (how small, $10^{-4} - 10^{-5}$?)
- muon charge ID required
- multi-MW proton beam required



-- Neutrino Factory -- CERN layout



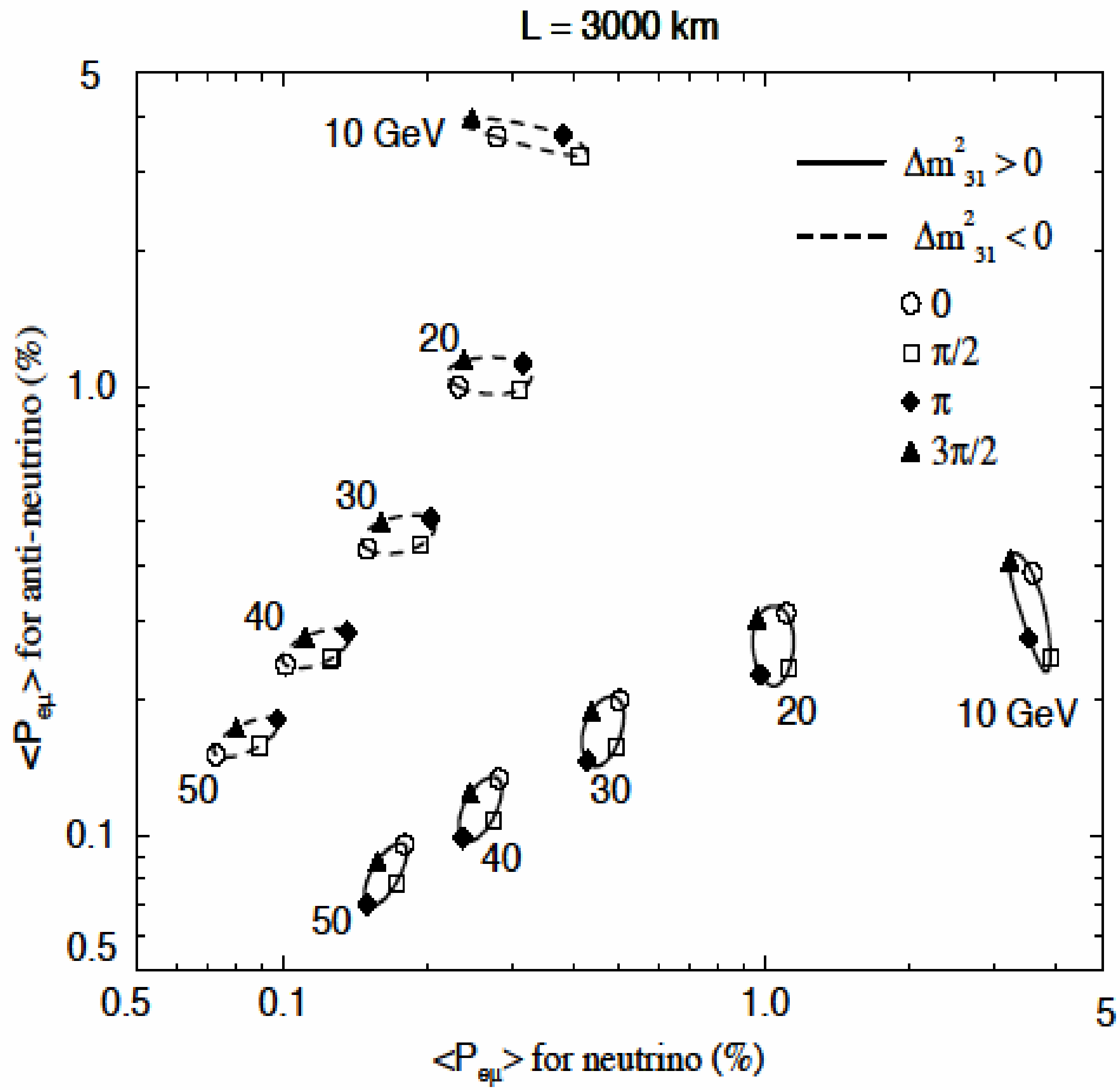
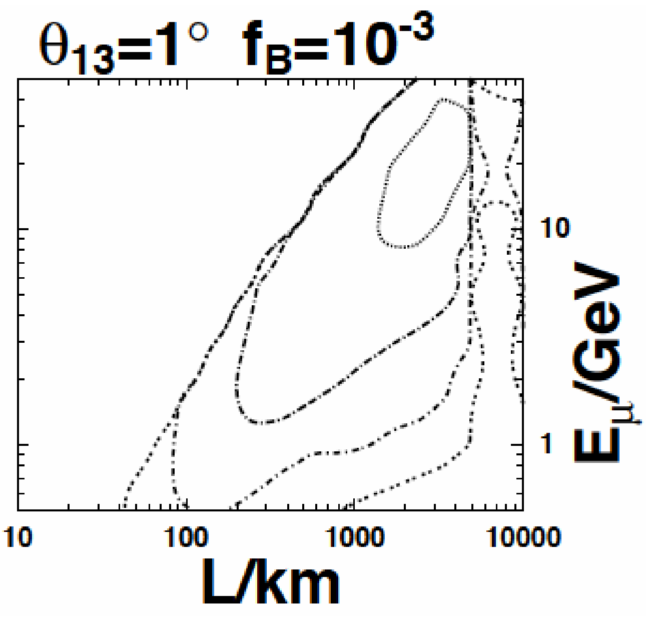


Figure 8: The CP trajectory diagram in bi-probability plane for $L = 3000\,\text{km}$ and much higher neutrino energies $E = 10-50\,\text{GeV}$ which correspond to so called "Neutrino Factory" situation. The mixing parameters are fixed to be the same as in figure 1 except that we take $\rho Y_e = 2.0\ \text{g/cm}^3$.

Optimal energy E & baseline L

- $E = 30 \sim 50$ GeV
- $L \sim 3000$ km
- # of events = $(E^2 / L^2) \times E \times (L/E)$

$= (E^2 / L^2) \times L = (E / L) \times E$



Magic baseline or refraction length

$$P(\nu_\mu \to \nu_e) = \left|\sqrt{P_{atm}} + e^{i\left(\delta \pm \frac{\Delta_{31}}{2}\right)}\sqrt{P_{solar}}\right|^2$$

$$P_{atm} = \left(s_{13} s_{23} \Delta_{31} \frac{\sin\left(\frac{\Delta_{31} \mp aL}{2}\right)}{\left(\frac{\Delta_{31} \mp aL}{2}\right)} \right)^2$$

$$P_{solar} = \left(c_{12} s_{12} c_{23} \Delta_{21} \frac{\sin\left(\frac{aL}{2}\right)}{\left(\frac{aL}{2}\right)} \right)^2$$

$$\Delta_{31} \equiv \frac{|\Delta m^2_{31}| L}{2E}, \quad a = \sqrt{2} G_F N_e(x),$$

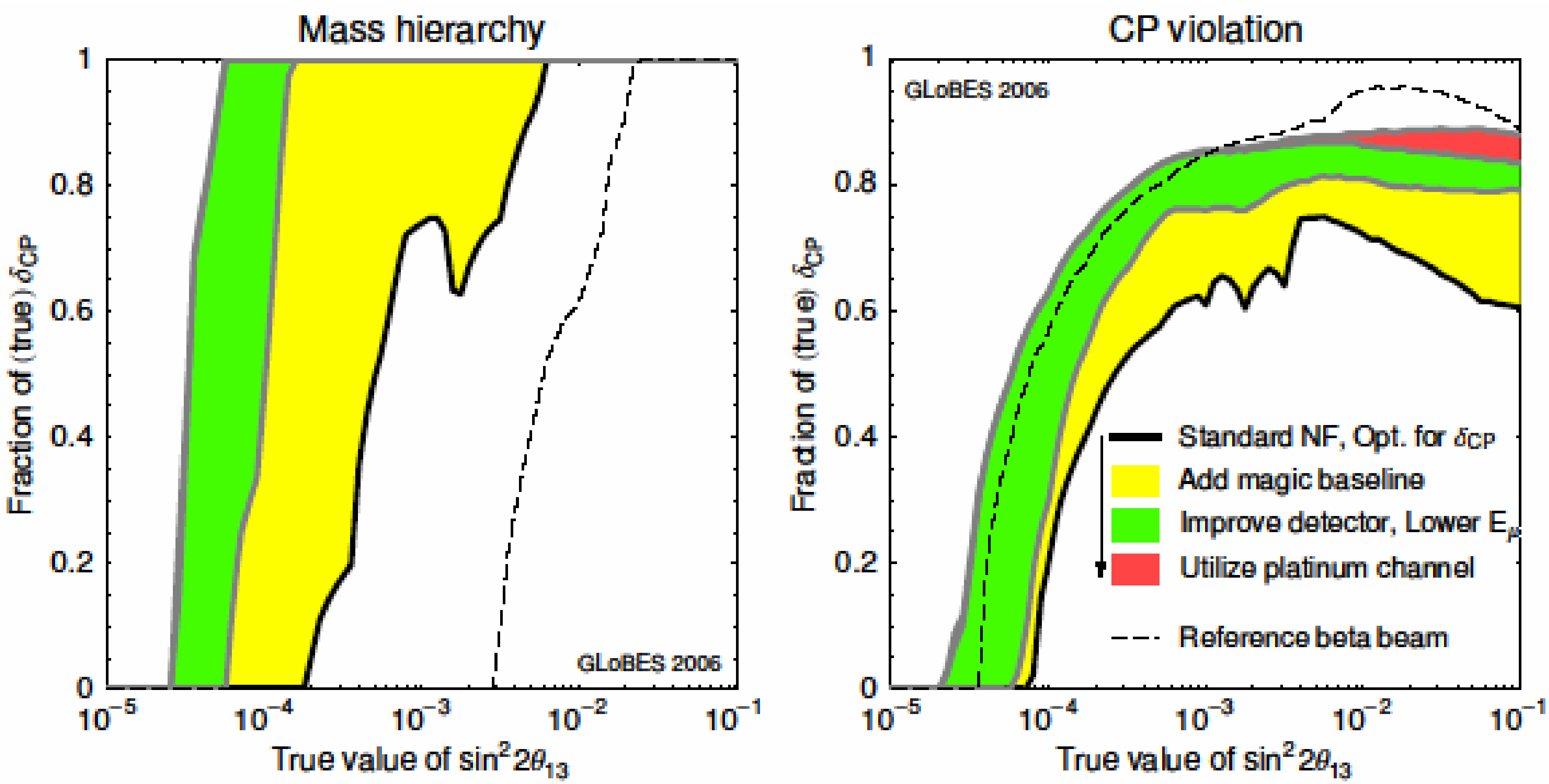
$$\pm = \text{sign of } \Delta m^2_{31}$$

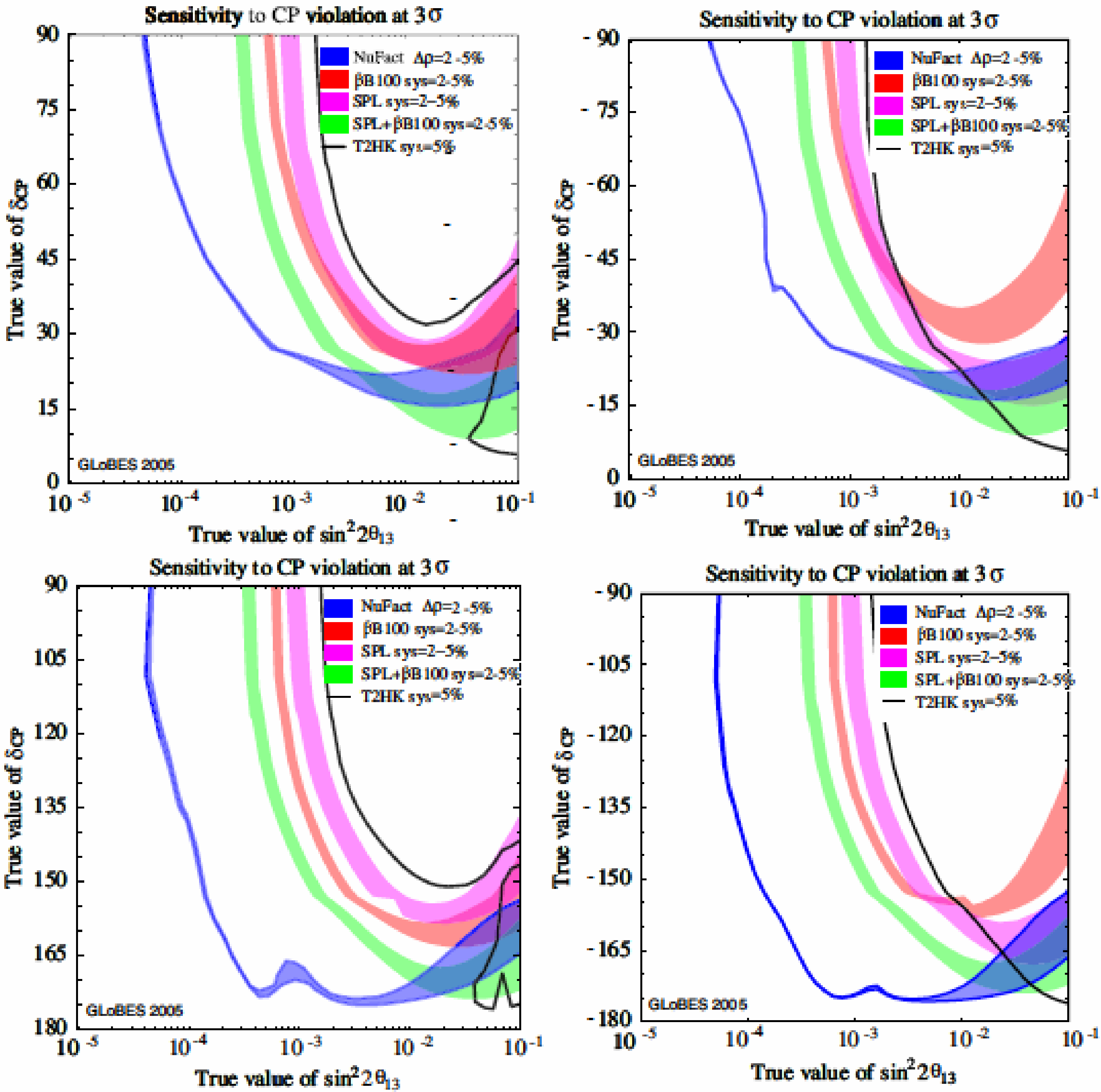
At $aL=2\pi$, P_{solar} vanishes --> No CP phase dependence

"magic baseline"

Help resolve degeneracy

Nufact sensitivity





Sensitivity to CP violation at 3 σ
NuFact Δρ=2 -5%
βB100 sys=2-5%
SPL sys=2–5%
SPL+βB100 sys=2-5%
T2HK sys=5%
GLoBES 2005
True value of δ_{CP}
True value of $\sin^2 2\theta_{13}$
90
75
60
45
30
15
0
-90
-75
-60
-45
-30
-15
105
120
135
150
165
180
-105
-120
-135
-150
-165
-180
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}

Conclusion

- The next-generation and some future options for LBL experiments are reviewed
- still long way to complete the MNS matrix; θ_{13} first, and then δ and mass hierarchy
- T2KK is powerful enough to solve 8-fold parameter degeneracy in situ
- if $\theta_{13} < 3^o$, we need β beam and/or neutrino factory; the choice is highly debatable -> exciting possibilities because the small θ_{13} may imply "symmetry"

Koide-san and teQuila