Future neutrino oscillation experiments

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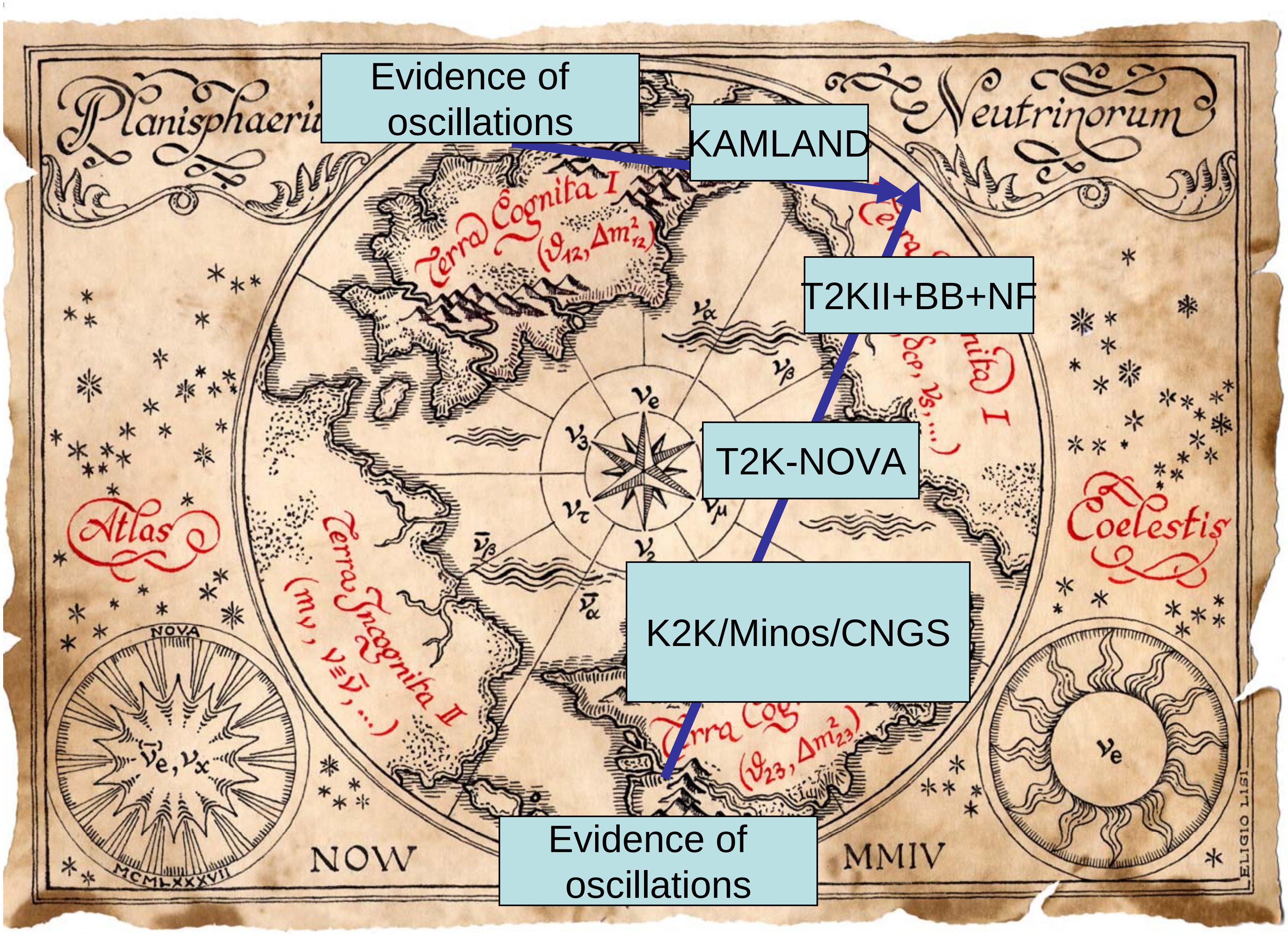
Original results presented in this talk based on work done in collaboration with P. Hernández, J. Burguet-Castell, E. Couce, and D. Casper

A trip to terra incognita



Evidence of oscillations

KAMLAND

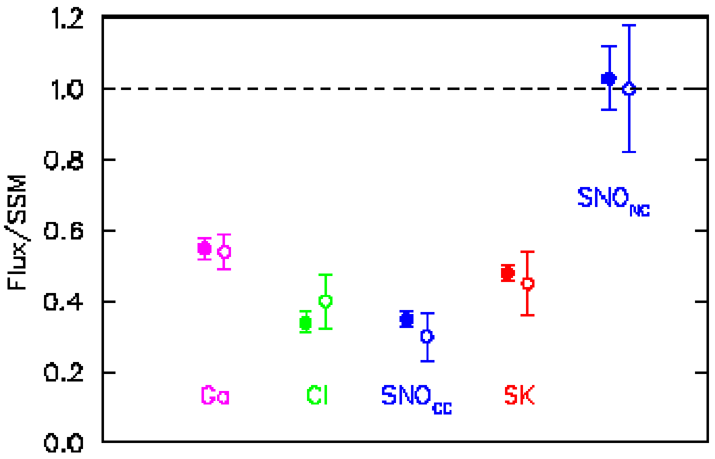
T2KII+BB+NF

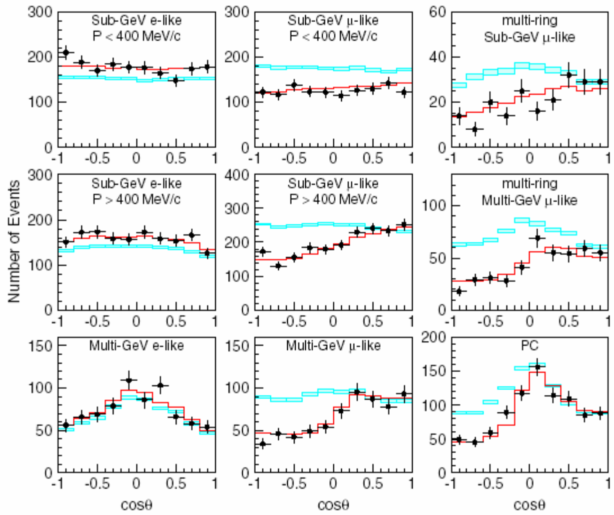
T2K-NOVA

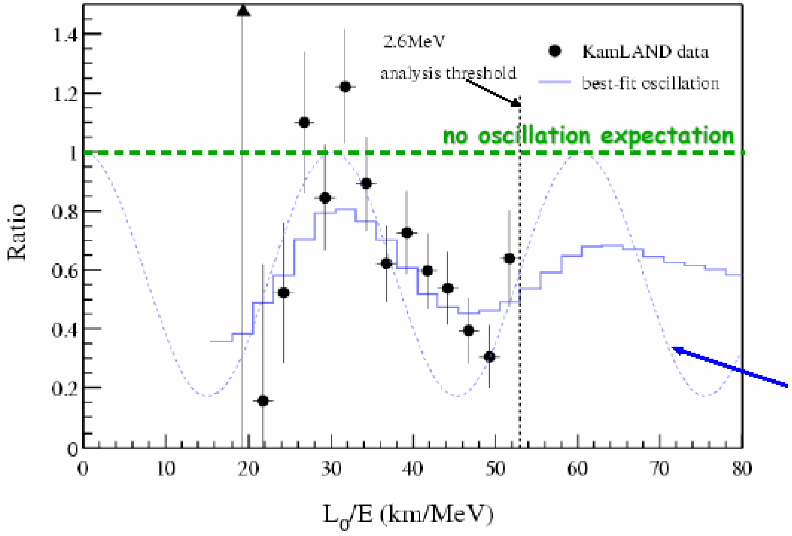
K2K/Minos/CNGS

Evidence of oscillations

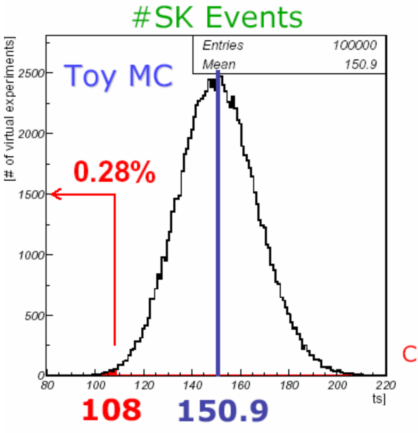
Evidence of neutrino oscillations



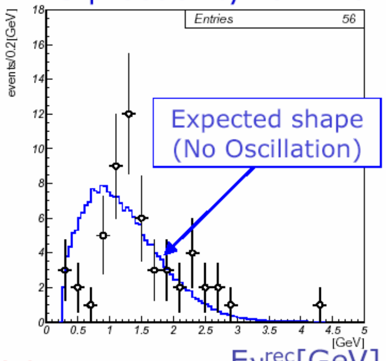




$$L_{norm}(f^x) \qquad L_{shape}(f^x)$$



KS probability=0.11%



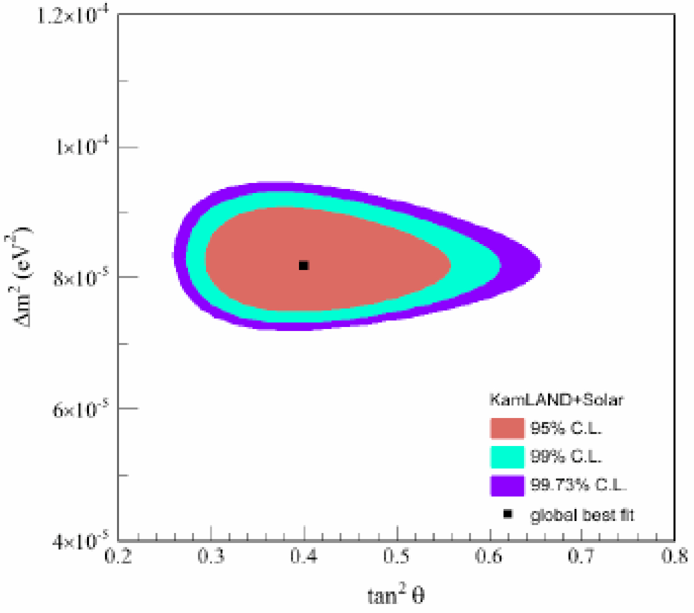
Eν^{rec}[GeV]

CC-QE assumption

$$E_\nu^{rec} = \frac{(m_N - V)E_\mu - m_\mu^2/2 + m_N V - V^2/2}{(m_N - V) - E_\mu + p_\mu \cos\theta_\mu}$$

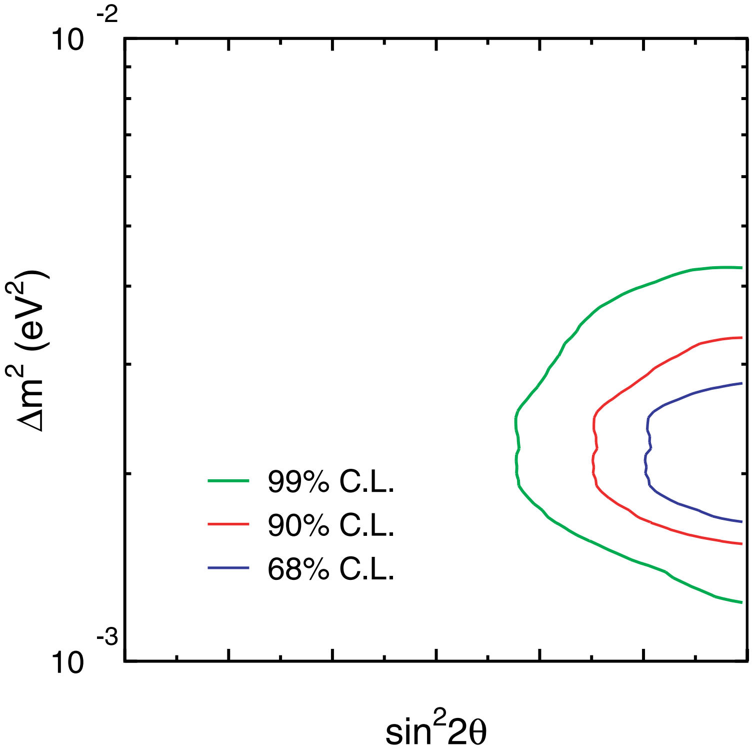
$$\Delta m_{12}^2 = 8.2^{+0.6}_{-0.5} \times 10^{-5}\, eV^2$$

$$\tan^2 \theta_{12} = 0.40^{+0.09}_{-0.07}$$

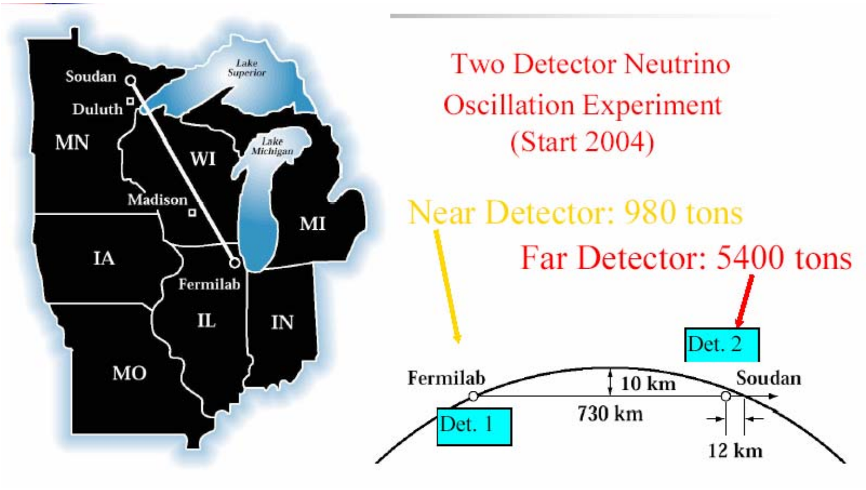


$$\Delta m^2 = 2.1 \cdot 10^{-3}\, eV^2$$

$$\sin^2 2\theta \approx 1$$



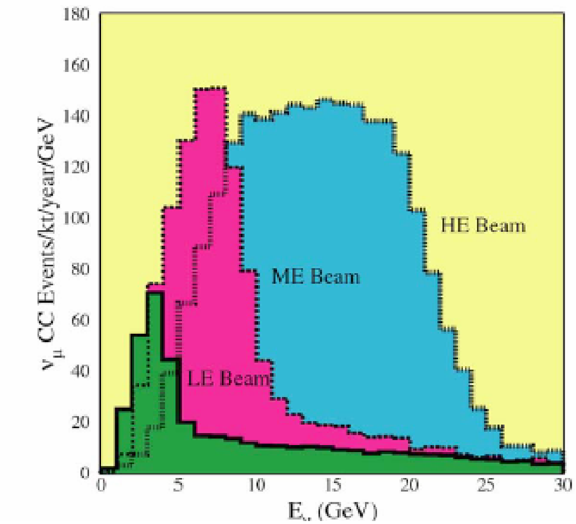
Long Base Line Experiments

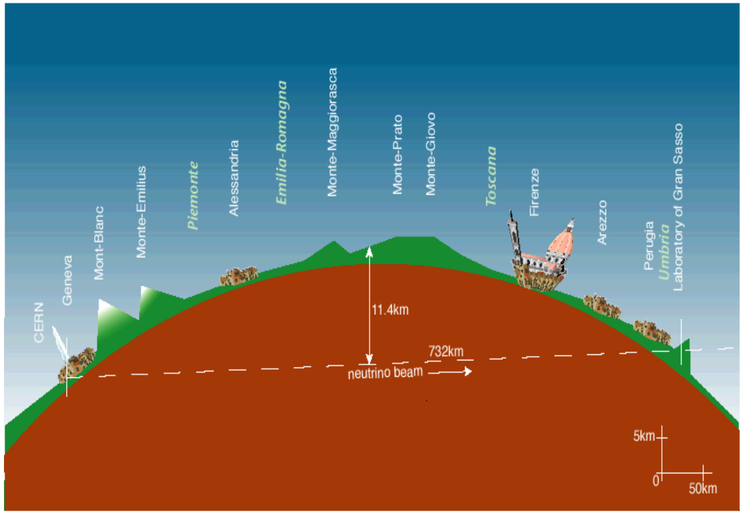


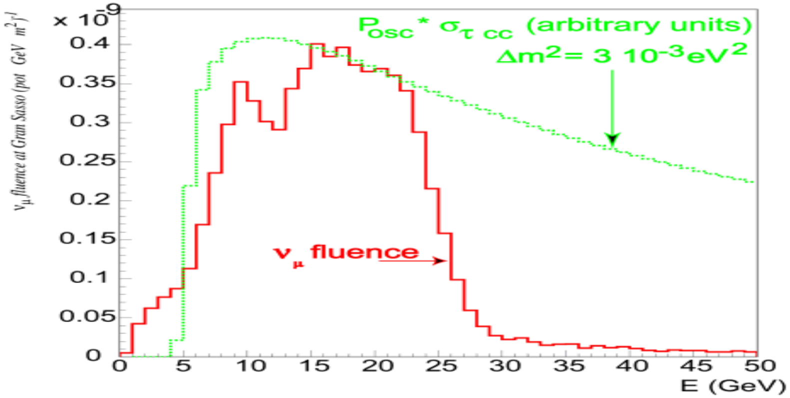
Two Detector Neutrino Oscillation Experiment (Start 2004)

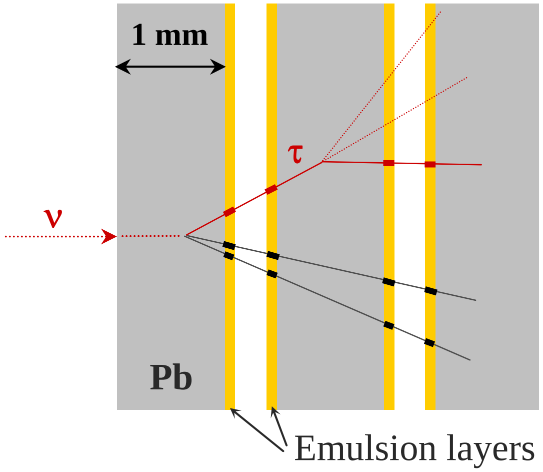
Near Detector: 980 tons

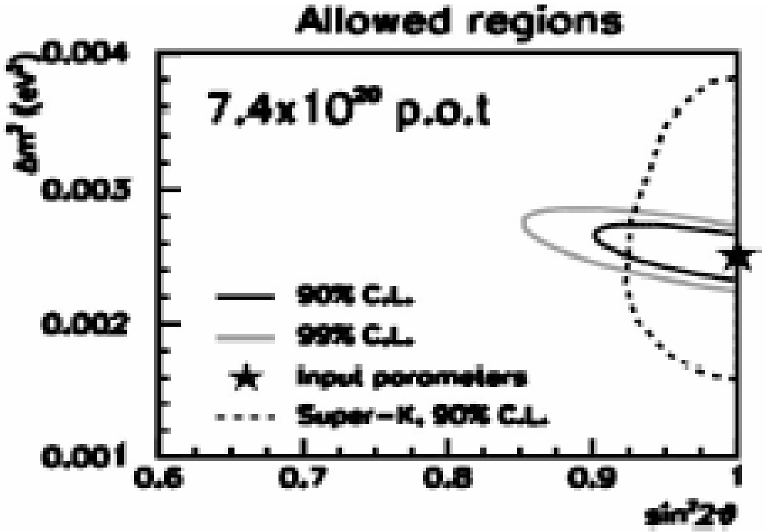
Far Detector: 5400 tons

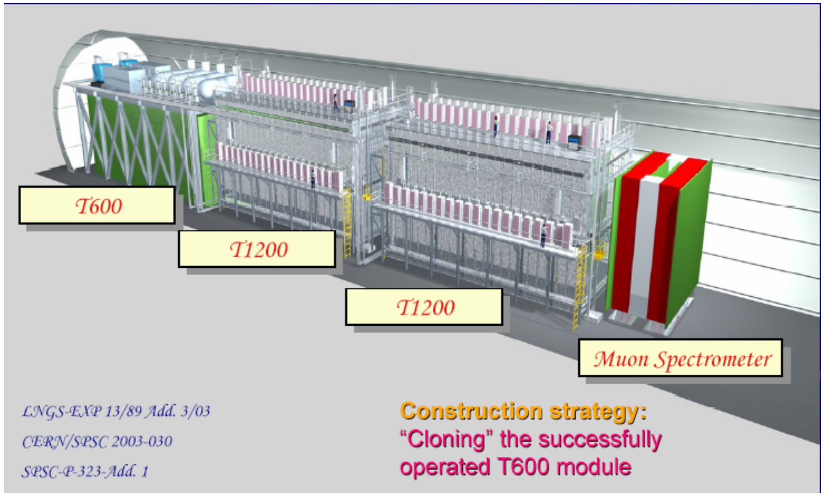






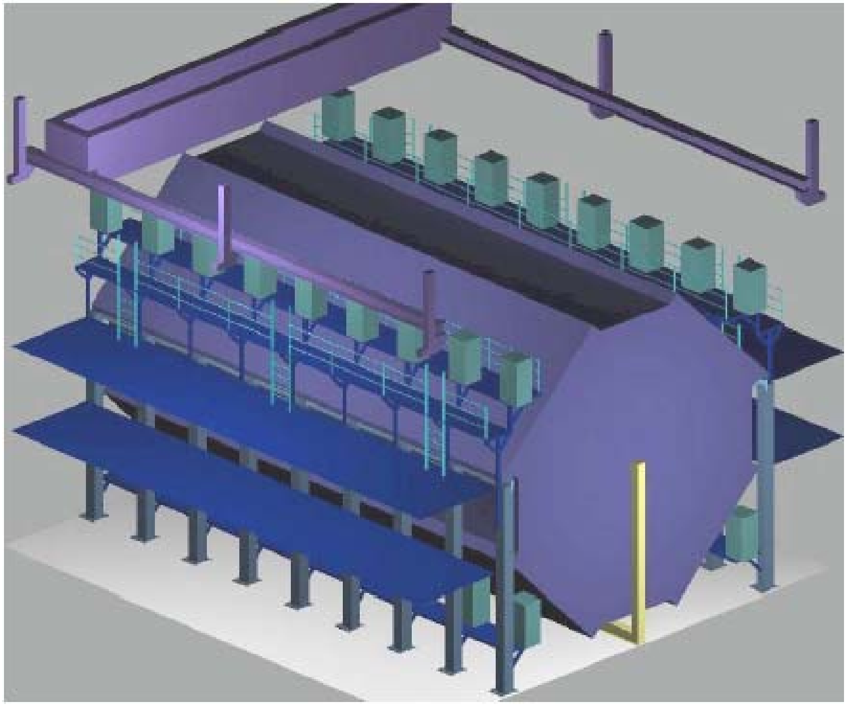






LNGS-EXP 13/89 Add. 3/03
CERN/SPSC 2003-030
SPSC-P-323-Add. 1

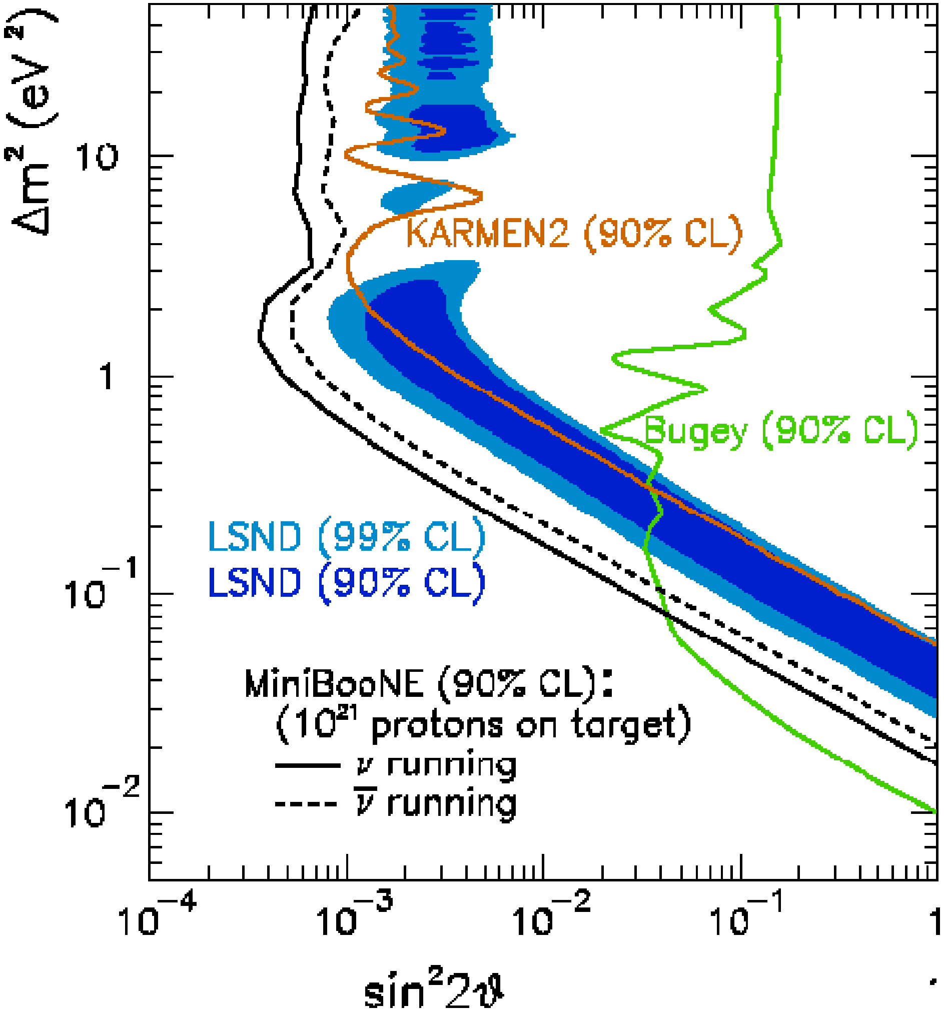
Construction strategy:
"Cloning" the successfully operated T600 module



The last anomaly

- LSND
  - Does not fit in a 3 family scenario
    - 2 Δm^2
- MiniBooNE (Fnal)
  - Testing it …
- If it is confirmed (2005)!?
  - Change our vision of ν
  - (has happened before…)

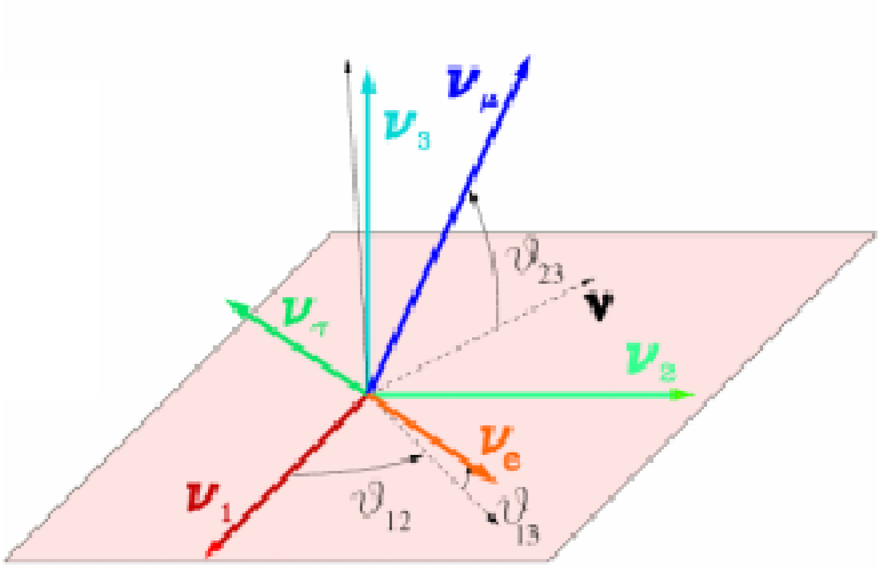
$$\overline{\nu}_\mu \to \overline{\nu}_e ?$$

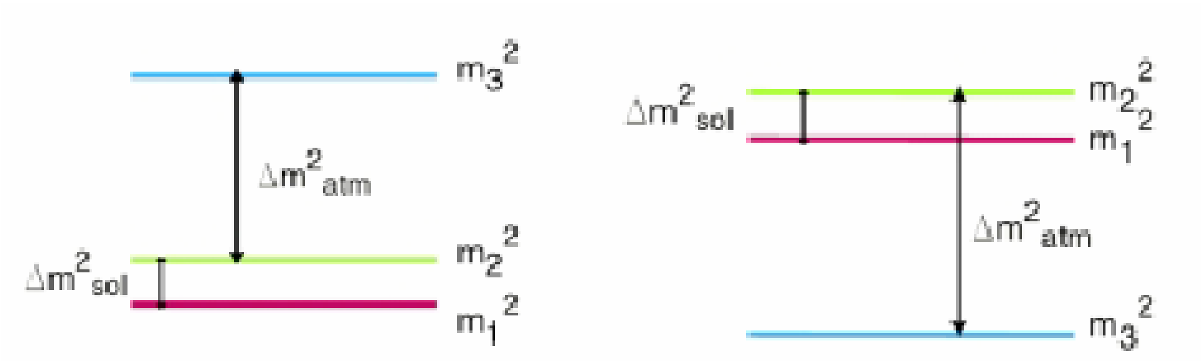


Oscillations in 3D

Solar data. The ν_e is oscillating (via enhanced matter resonance, MSW) to the other two flavours with $\Delta m_{12} \approx 10^{-4}$ eV^2, $\theta_{12} \approx 30^0$

Atmospheric data. Largely $\nu_\mu \to \nu_\tau$ (vacuum) oscillations with $\Delta m_{23} \approx 10^{-3}$ eV^2 $\theta_{23} \approx 45^0$





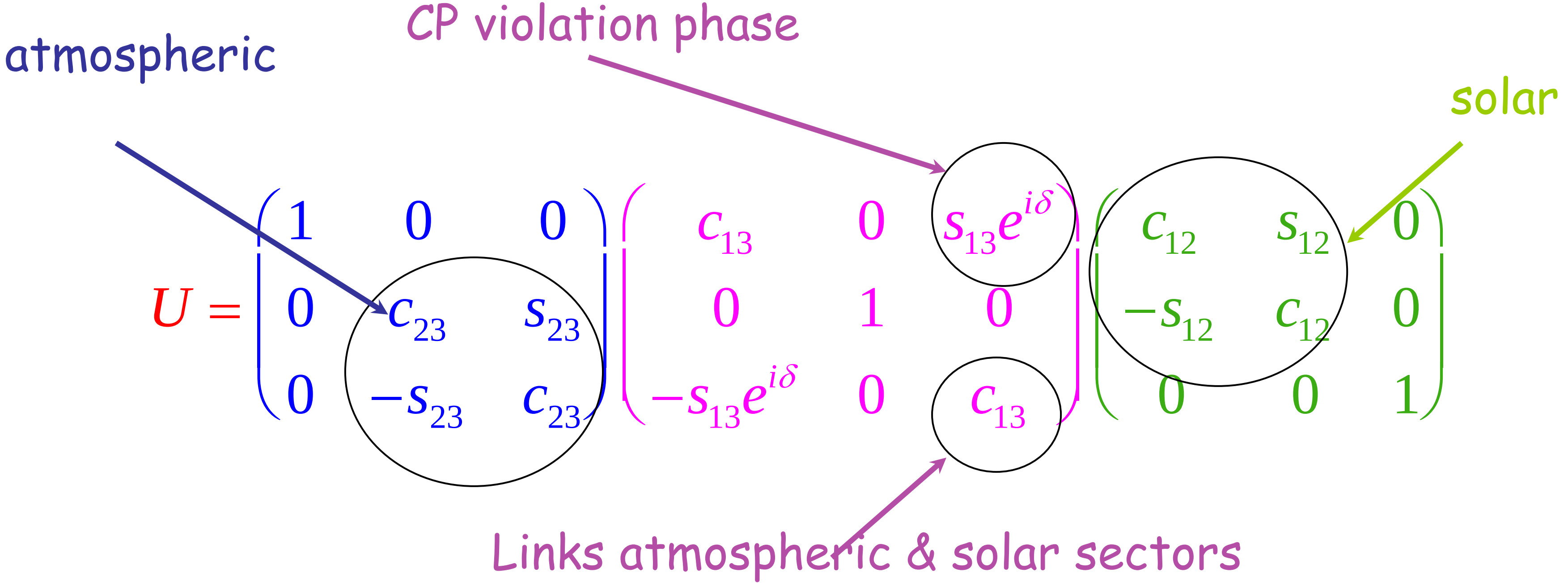
Two mass differences → need 3 neutrinos

The PMNS matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Unless the other two angles θ_{13} is small (experimental upper limit $\theta_{13} < 10^0$)

If $\delta \neq 0, \pi, 2\pi$…then weak interactions violate CP symmetry in the lepton sector (as in the quark sector)



CP violation phase

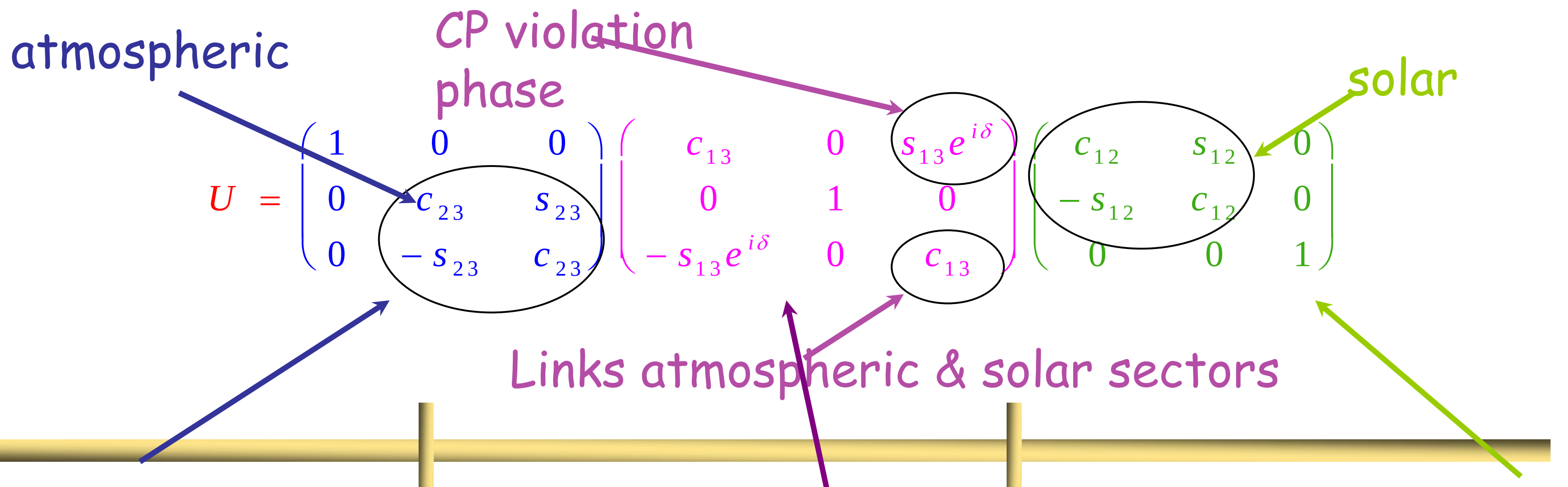
atmospheric

solar

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

Links atmospheric & solar sectors

Neutrino oscillation physics: you are here



atmospheric

CP violation phase

solar

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

Links atmospheric & solar sectors

Observed by Super-Kamiokande, confirmed by K2K. CNGS+NUMI will measure parameters to about 20-30 %

θ_{13} limited by CHOOZ to be smaller than about 10^0. Nothing known about δ.

Observed by 30 years of solar neutrinos experiments, nailed down by SNO and Kamland. Parameters known at 10%

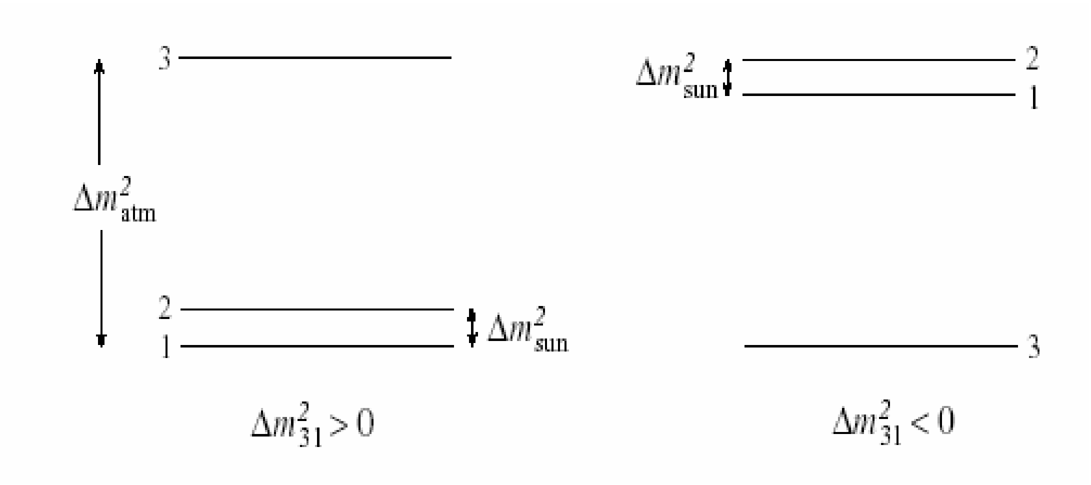
The quest

$$\begin{pmatrix} c_{13} & 0 & \boxed{s_{13}e^{i\delta}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}$$

What is the value of θ_{13}?

What is the value of δ?

Is there CP violation?



Which mass spectrum?

θ$_{13}$: link between atmospheric and solar oscillations

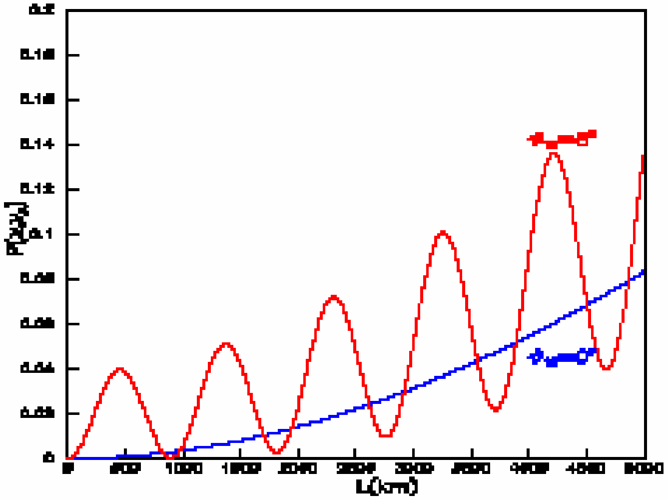
$\theta_{13} = 0$	$P(\nu_e \to \nu_\mu) = c_{23}^2 \sin^2 2\theta_{12} \sin^2(\frac{\Delta m_{12}^2 L}{4E})$	solar
$\theta_{13} \neq 0$	$P(\nu_e \to \nu_\mu) = c_{23}^2 \sin^2 2\theta_{12} \sin^2(\frac{\Delta m_{12}^2 L}{4E})$	solar
	$+ s_{23}^2 \sin^2 2\theta_{13} \sin^2(\frac{\Delta m_{23}^2 L}{4E})$	atmospheric
	$+ J \cos(\pm\delta - \frac{\Delta m_{23}^2 L}{4E}) \frac{\Delta m_{12}^2 L}{4E} \sin(\frac{\Delta m_{23}^2 L}{4E})$	interference

$$J = c_{13} \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23}$$

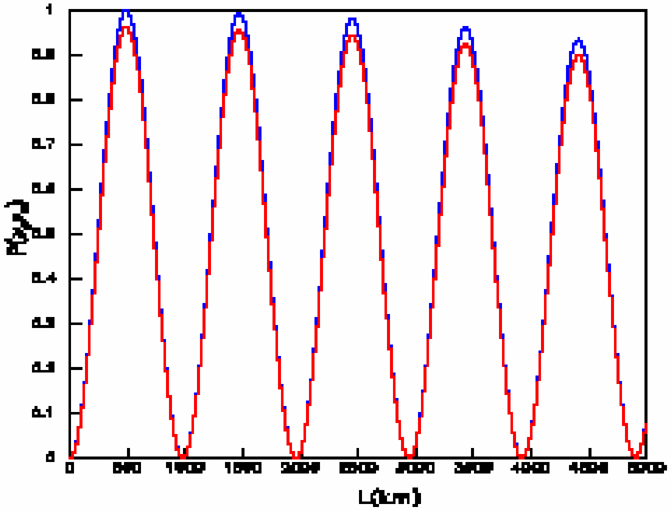
Sensitivity to θ_{13}: subleading transitions

Subleading: $\nu_e \to \nu_\mu$, $\nu_e \to \nu_\tau$: sensitive to θ_{13} and δ

Leading: $\nu_\mu \to \nu_\tau$: rather insensitive to θ_{13} and δ



$$P(\nu_e \to \nu_\mu)$$



$$P(\nu_\mu \to \nu_\tau)$$

CP violation in ν oscillations

CP violation in ν oscillations →Oscillation probability is different for neutrinos and antineutrinos.

Thus, one can measure non-vanishing asymmetries A_{CP}

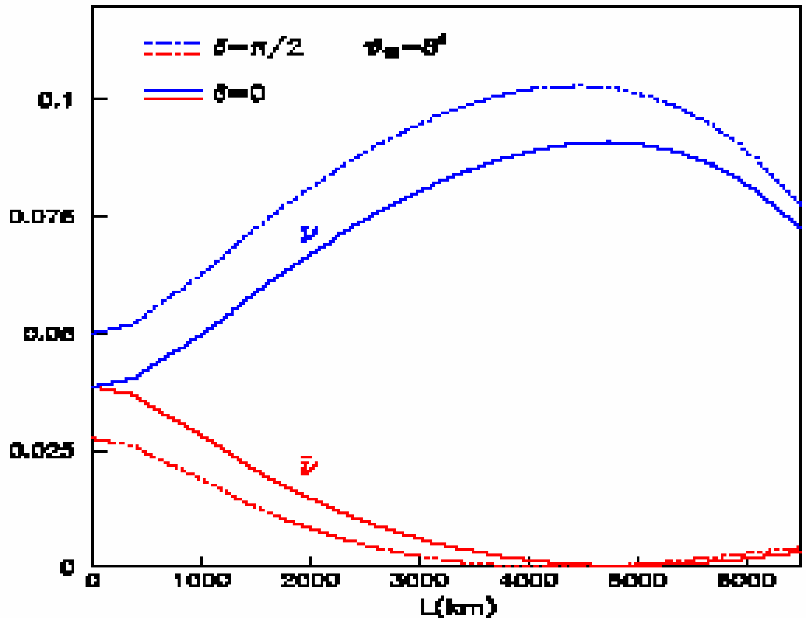
$$A^{CP}_{\nu_e\nu_\mu} = \frac{P(\nu_e \to \nu_\mu) - P(\bar{\nu}_e \to \bar{\nu}_\mu)}{P(\nu_e \to \nu_\mu) + P(\bar{\nu}_e \to \bar{\nu}_\mu)}$$

$$= \frac{2 \overbrace{\sin\delta}^{\text{CP violating phase}} \overbrace{c_{13}\sin 2\theta_{13}}^{\text{Interference}} \overbrace{\sin 2\theta_{12} \frac{\Delta m^2_{12} L}{4E}}^{\text{solar}} \overbrace{\sin 2\theta_{23} \sin^2 \frac{\Delta m^2_{13} L}{4E}}^{\text{atmospheric}}}{P^{CP-even}_{\nu_e\nu_\mu}}$$

Determine mass spectrum

The same experiments that will measure δ and θ_{13} can establish the ν mass hierarchy by studying the matter effects on Earth

- One gets a large amplification/supression of $P(\nu_e \rightarrow \nu_\mu)$ depending on whether the hierarchy is “natural” or “inverted”



Measurement of θ_{13}. Correlations

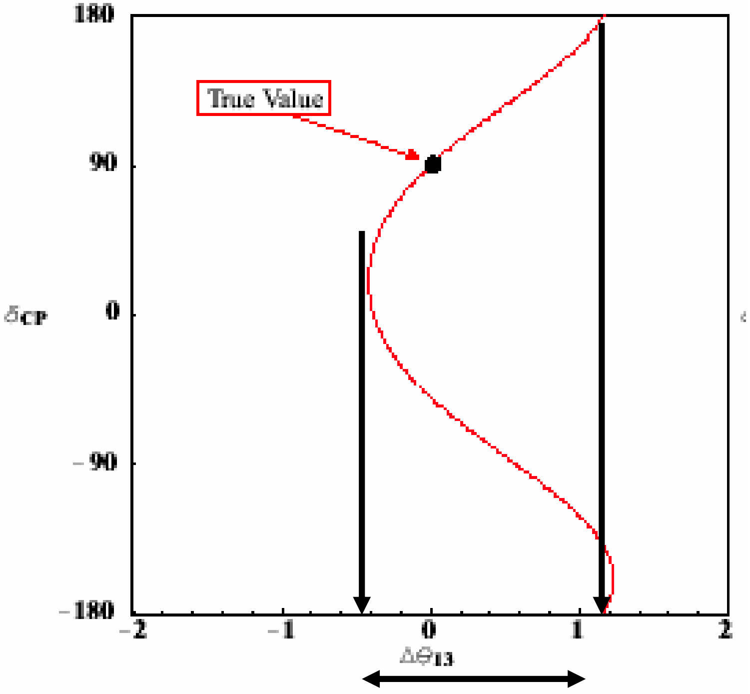
$$P^{\pm}_{\nu_e\nu_\mu}(\theta_{13},\delta) \approx X_{\pm}\sin^2 2\theta_{13} + \left(Y^c_{\pm}\cos\delta \mp Y^s_{\pm}\sin\delta\right)\sin 2\theta_{13} + Z$$

(DeRujula99, Cervera00)

The appearance probability P(∐θ_{13},∐δ) obtained for neutrinos at fixed (E,L) with input parameters (∐θ_{13},∐δ) has no unique solution. Indeed the equation:

$$P_{\alpha\beta}(\bar{\theta}_{13},\bar{\delta}) = P_{\alpha\beta}(\theta_{13},\delta)$$

has a continuous number of solutions



Correlation error

Measurement of θ_{13}: Intrinsic degeneracy

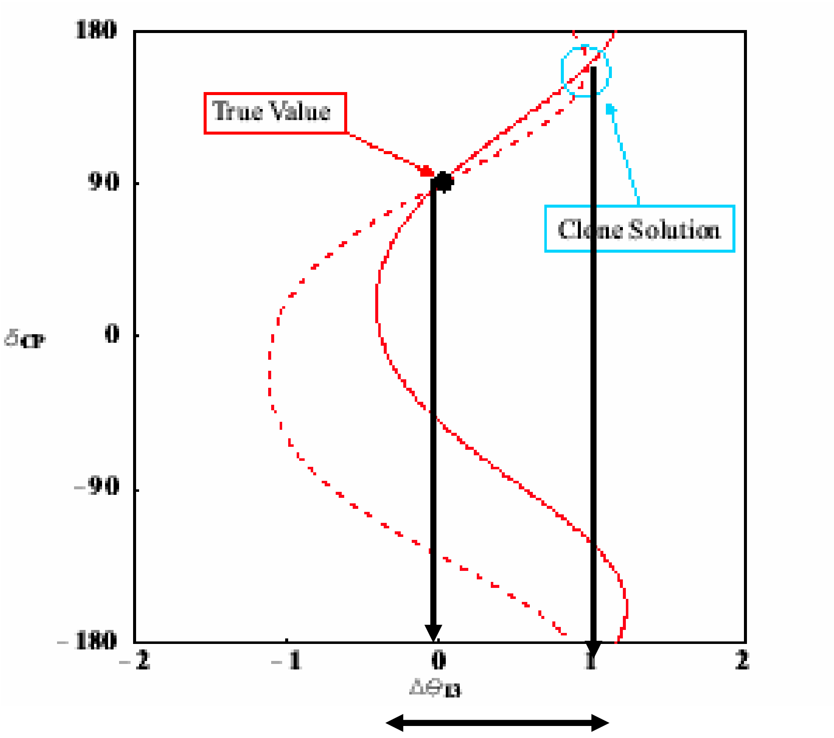
$$P^{\pm}_{\nu_e\nu_\mu}(\theta_{13},\delta) \approx X_{\pm}\sin^2 2\theta_{13} + \left(Y^c_{\pm}\cos\delta \mp Y^s_{\pm}\sin\delta\right)\sin 2\theta_{13} + Z$$

J. Burguet-Castell *et al.* Nucl. Phys. B 608 (2001) 301;

For neutrinos and antineutrinos of the same energy and baseline the system of equations

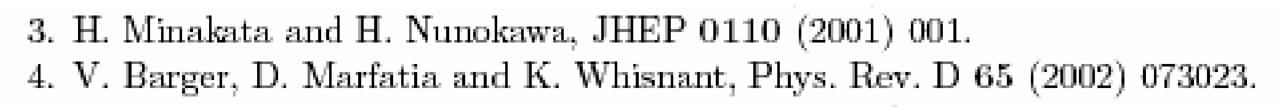
$$P_{\alpha\beta}{}^{\pm}(\bar{\theta}_{13},\bar{\delta}) = P_{\alpha\beta}{}^{\pm}(\theta_{13},\delta)$$

has two intersections. The true one $(\amalg\theta_{13},\amalg\delta)$ and a second, energy dependent point (clone) that introduces and ambiguity in the determination of the parameters



Degeneracy error

Discrete degeneracies



3. H. Minakata and H. Nunokawa, JHEP 0110 (2001) 001.
4. V. Barger, D. Marfatia and K. Whisnant, Phys. Rev. D 65 (2002) 073023.

Two other sources of degeneracy.

1. Ignorance of the sign of Δm_{23}^2

$$s_{atm} = \mathrm{sgn}(\Delta m_{23}^2)$$

2. Ignorance of the octant of θ_{23}

$$s_{oct} = \mathrm{sgn}(\tan(2\theta_{23}))$$

These two discrete values assume the value ±1

Eightfold degeneracy

4. V. Barger, D. Marfatia and K. Whisnant, Phys. Rev. D 65 (2002) 073023.

Experimental measurement. Number of observed chaged leptons Nβ

Integrate P over Φ_ν, σ, and detector efficiencies.

$$N_\beta^\pm(\bar{\theta}_{13},\bar{\delta};\bar{s}_{atm},\bar{s}_{oct}) = N_\beta^\pm(\theta_{13},\delta;s_{atm}=\bar{s}_{atm},s_{oct}=\bar{s}_{oct}) \quad \beta = e,\mu,\tau$$

Since s_{atm} & s_{oct} not known, one should consider also 2 other equations which result in an 8-fold degeneracy

$$N_\beta^\pm(\bar{\theta}_{13},\bar{\delta};\bar{s}_{atm},\bar{s}_{oct}) = N_\beta^\pm(\theta_{13},\delta;s_{atm}=-\bar{s}_{atm},s_{oct}=\bar{s}_{oct})$$

$$N_\beta^\pm(\bar{\theta}_{13},\bar{\delta};\bar{s}_{atm},\bar{s}_{oct}) = N_\beta^\pm(\theta_{13},\delta;s_{atm}=\bar{s}_{atm},s_{oct}=-\bar{s}_{oct})$$

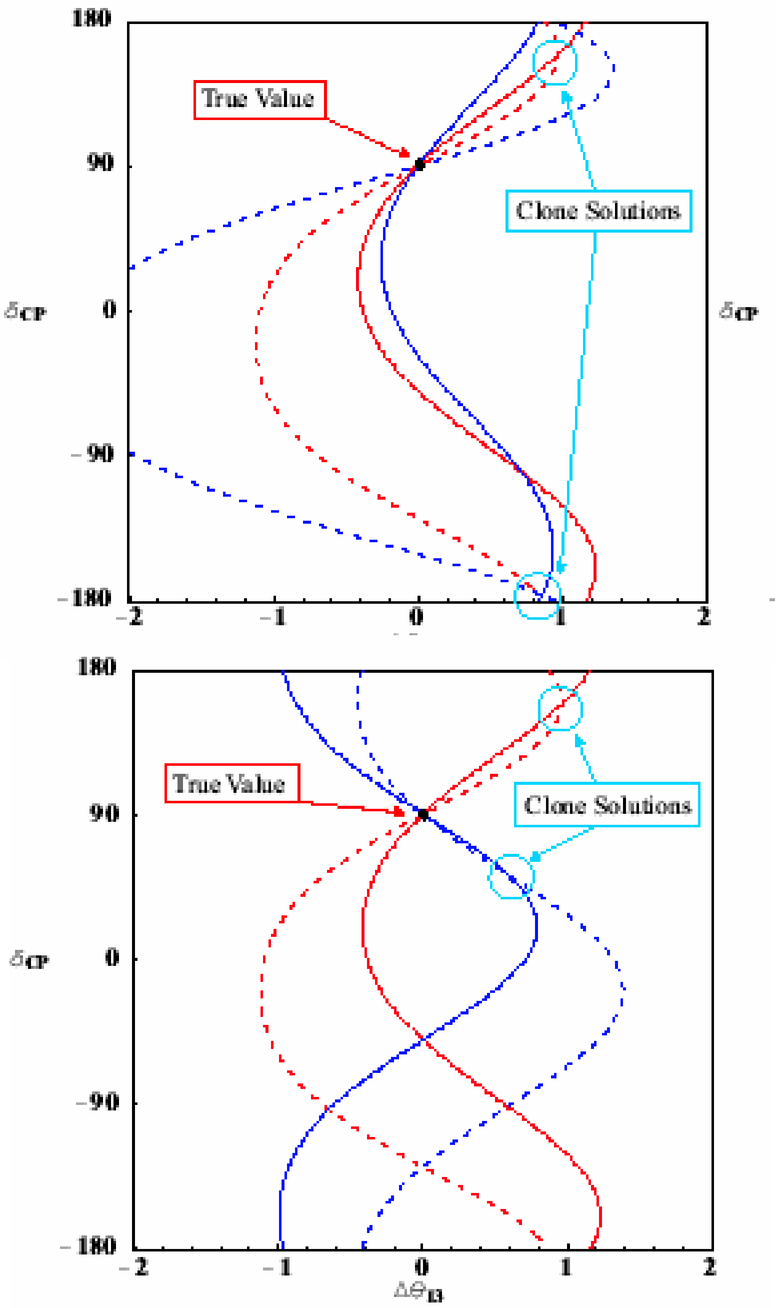
$$N_\beta^\pm(\bar{\theta}_{13},\bar{\delta};\bar{s}_{atm},\bar{s}_{oct}) = N_\beta^\pm(\theta_{13},\delta;s_{atm}=-\bar{s}_{atm},s_{oct}=-\bar{s}_{oct})$$

How to solve degeneracies

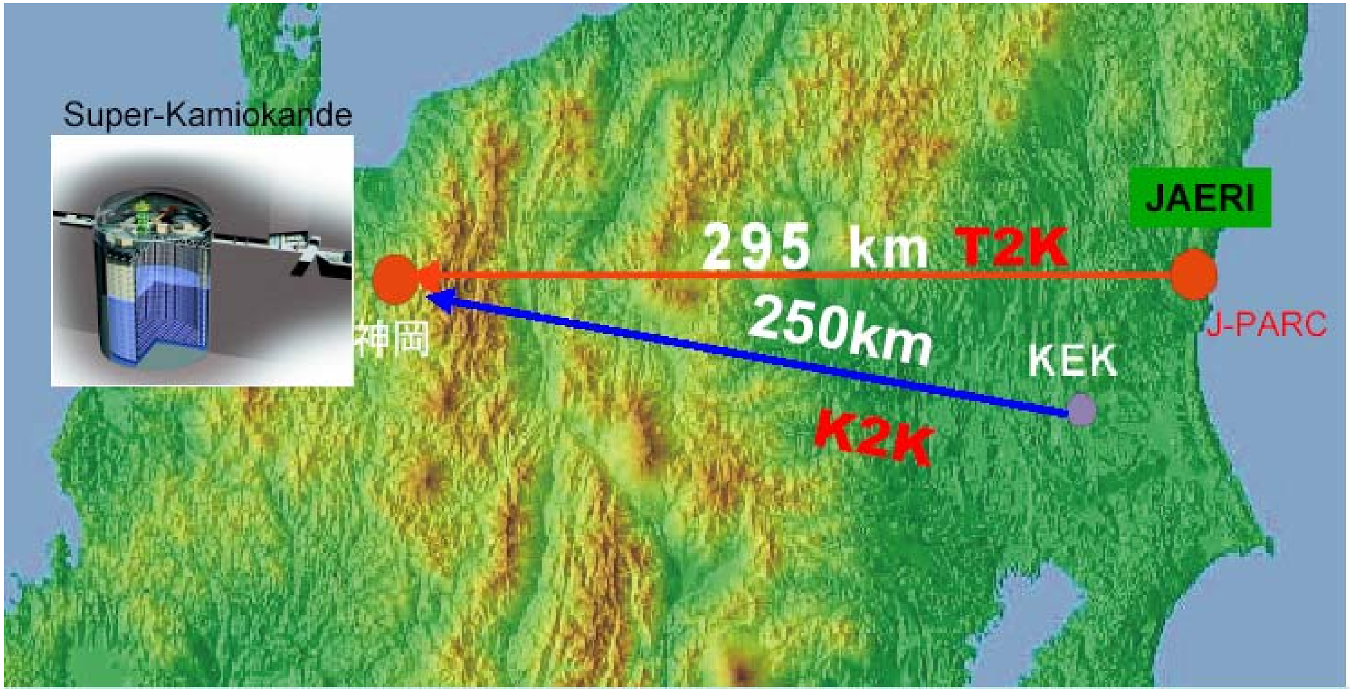
1. Use spectral information on oscillation signals→ experiment with energy resolution
2. Combine experiments differing in E/L (and/or matter effects) → need two experiments
3. Include other flavor channels: silver channel $\nu_e \to \nu_\tau$. Need a tau-capable detector

Burguet et al, **Nucl.Phys.B608:301-318,2001**

Donini, Meloni, Migliozzi, hep-ph/0206034
Donini, Meloni, Rigolin, hep-ph/hep-ph/0312072

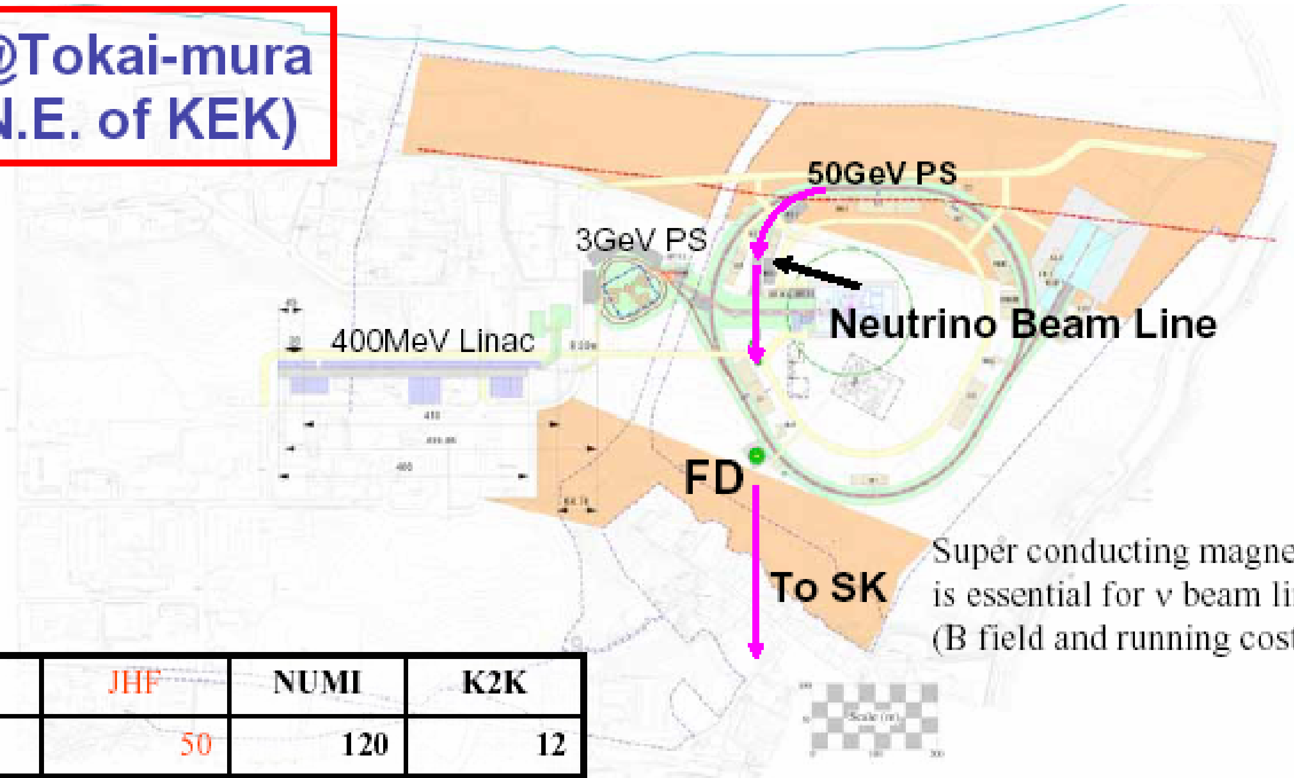


The first Super-Beam: T2K



Neutrino beam line

JAERI@Tokai-mura
(60km N.E. of KEK)

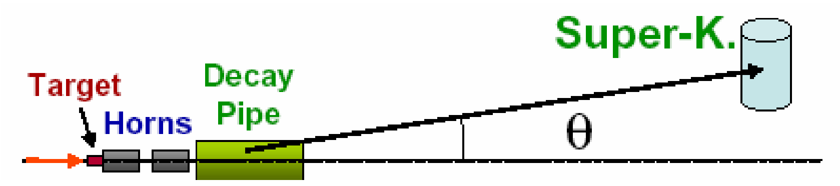


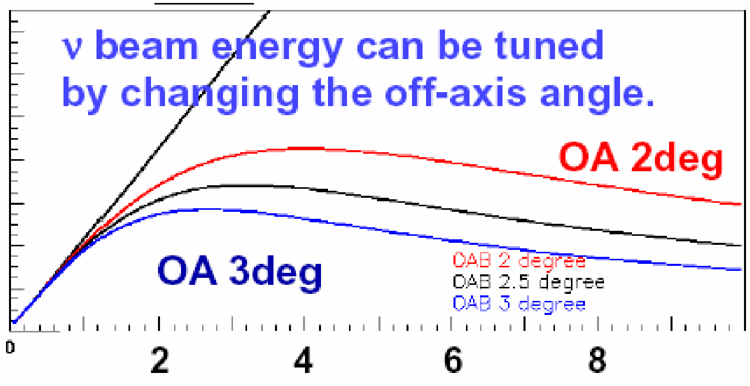
Super conducting magnet
is essential for ν beam line
(B field and running cost)

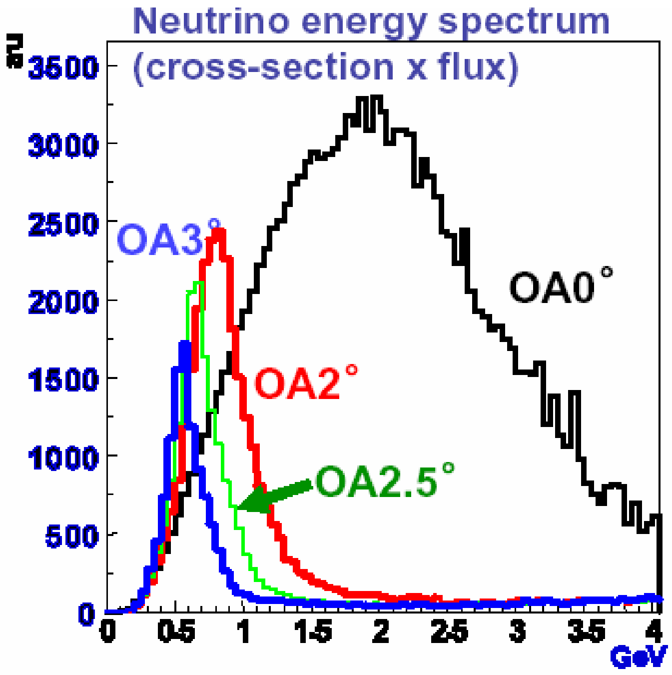
	JHF	NUMI	K2K
E(GeV)	50	120	12
Int.(10^{12}ppp)	330	40	6
Rate(Hz)	0.292	0.53	0.45
Power(MW)	0.77	0.41	0.0052

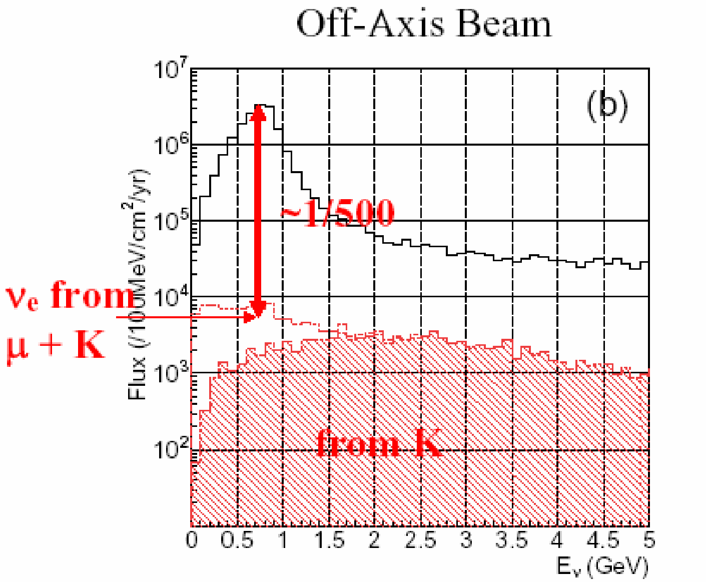
10^{21}POT(130day)≡ "1 year"

Off-Axis beam



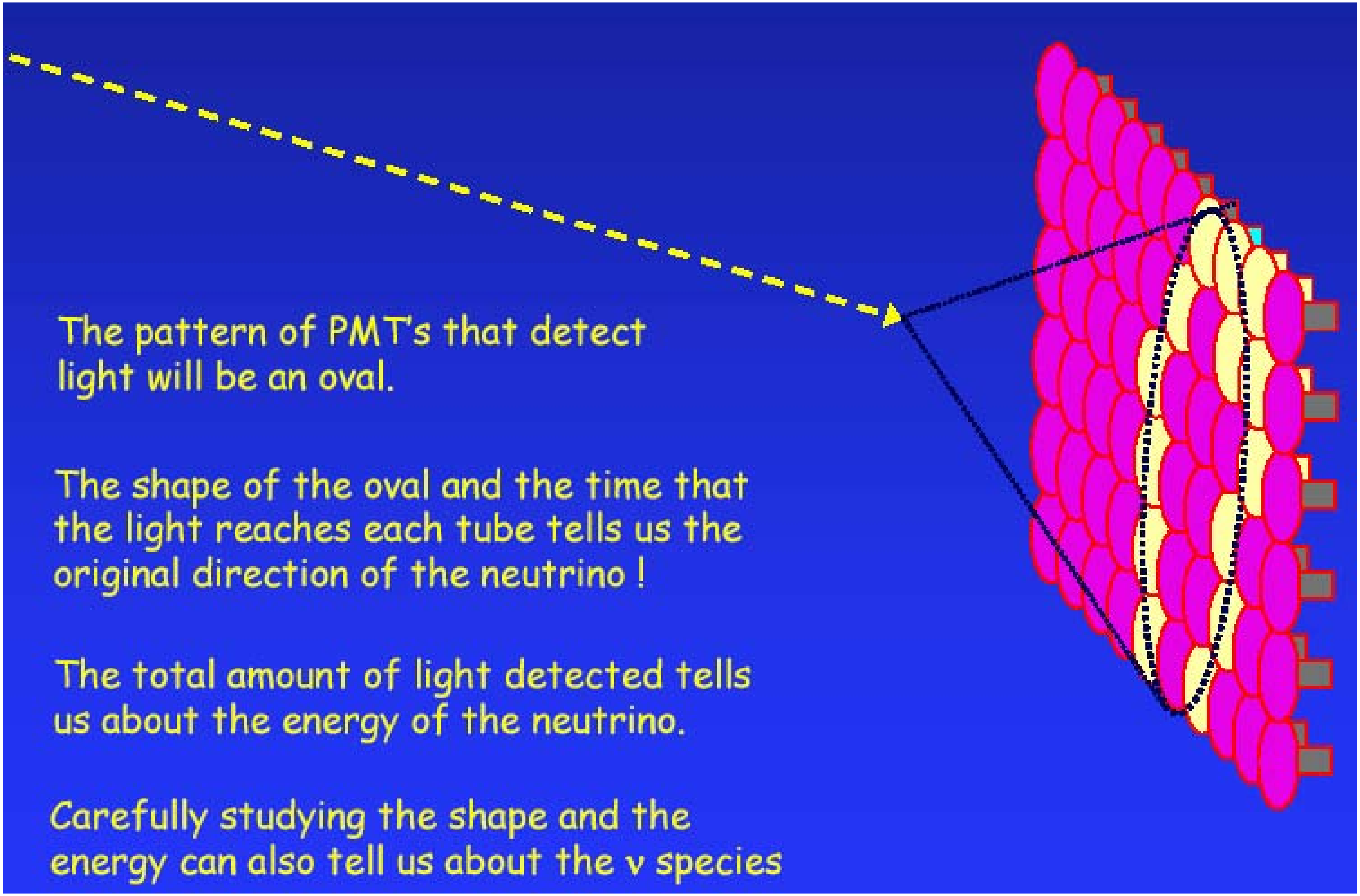

ν beam energy can be tuned by changing the off-axis angle.


Neutrino energy spectrum (cross-section x flux)



Intrinsic background: ν_e / ν_μ (peak) ~ 0.002

Water detectors: Concept



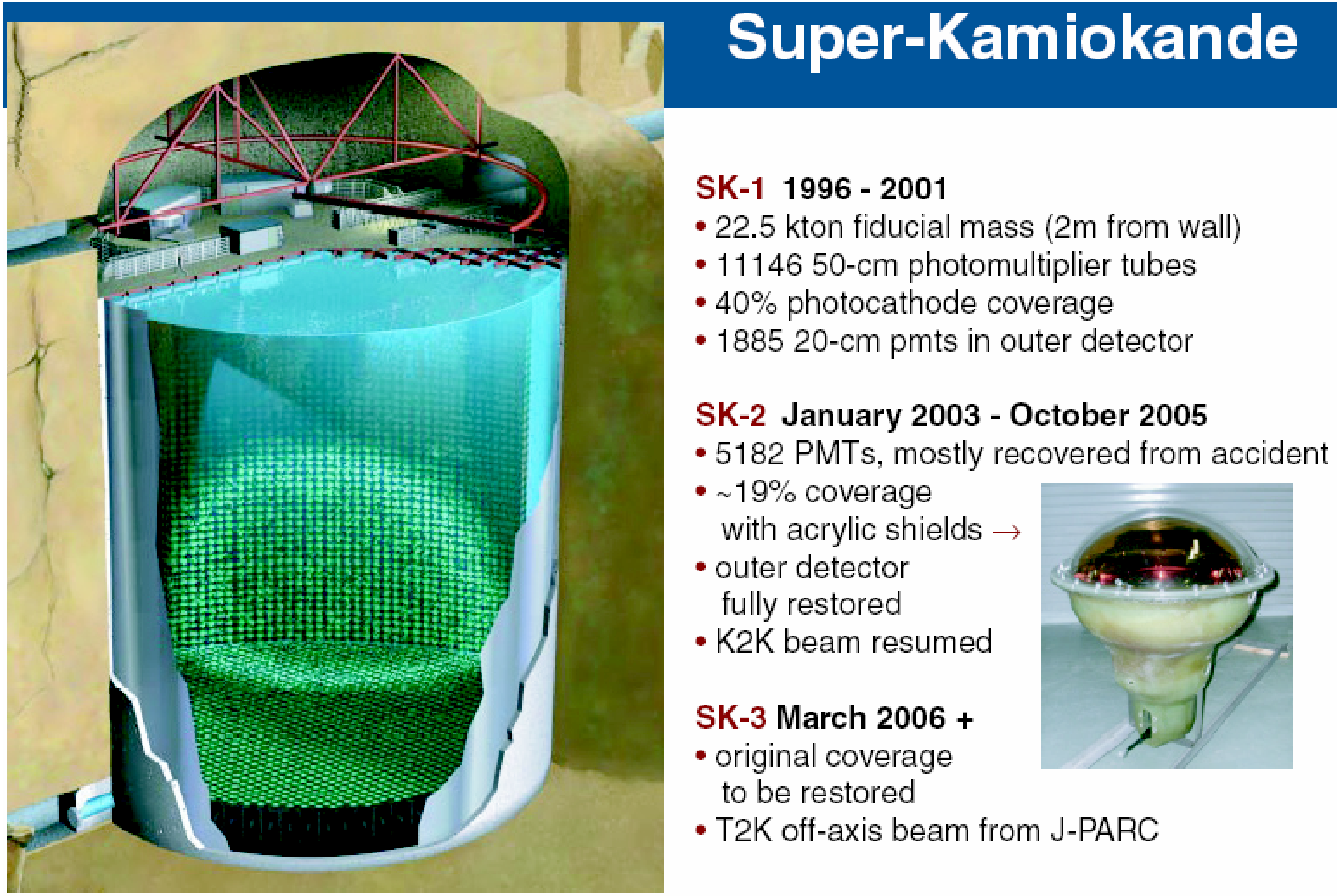
The pattern of PMT's that detect light will be an oval.

The shape of the oval and the time that the light reaches each tube tells us the original direction of the neutrino !

The total amount of light detected tells us about the energy of the neutrino.

Carefully studying the shape and the energy can also tell us about the ν species

Super-K



Super-Kamiokande

SK-1 1996 - 2001

- 22.5 kton fiducial mass (2m from wall)
- 11146 50-cm photomultiplier tubes
- 40% photocathode coverage
- 1885 20-cm pmts in outer detector

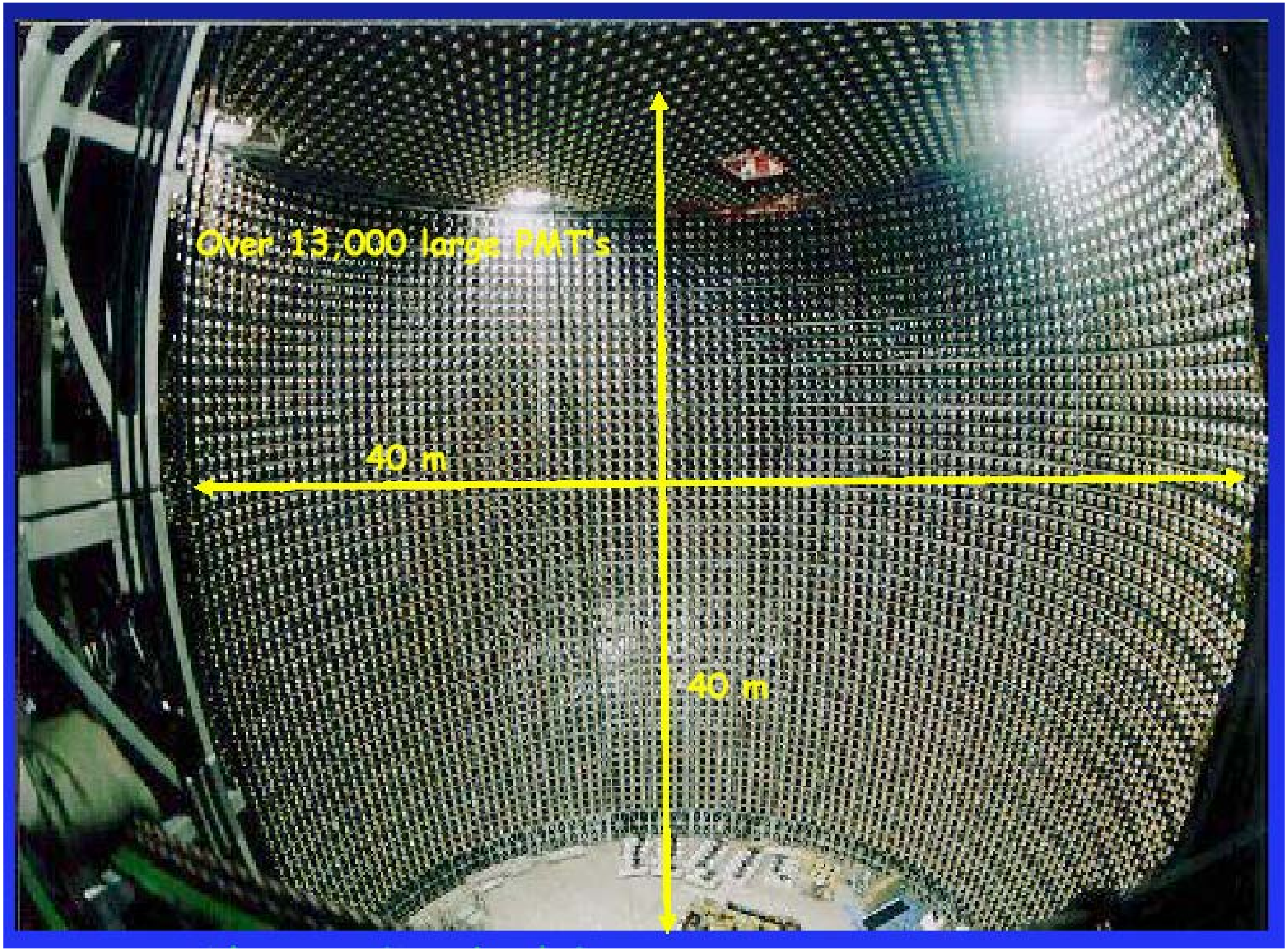
SK-2 January 2003 - October 2005

- 5182 PMTs, mostly recovered from accident
- ~19% coverage with acrylic shields →
- outer detector fully restored
- K2K beam resumed

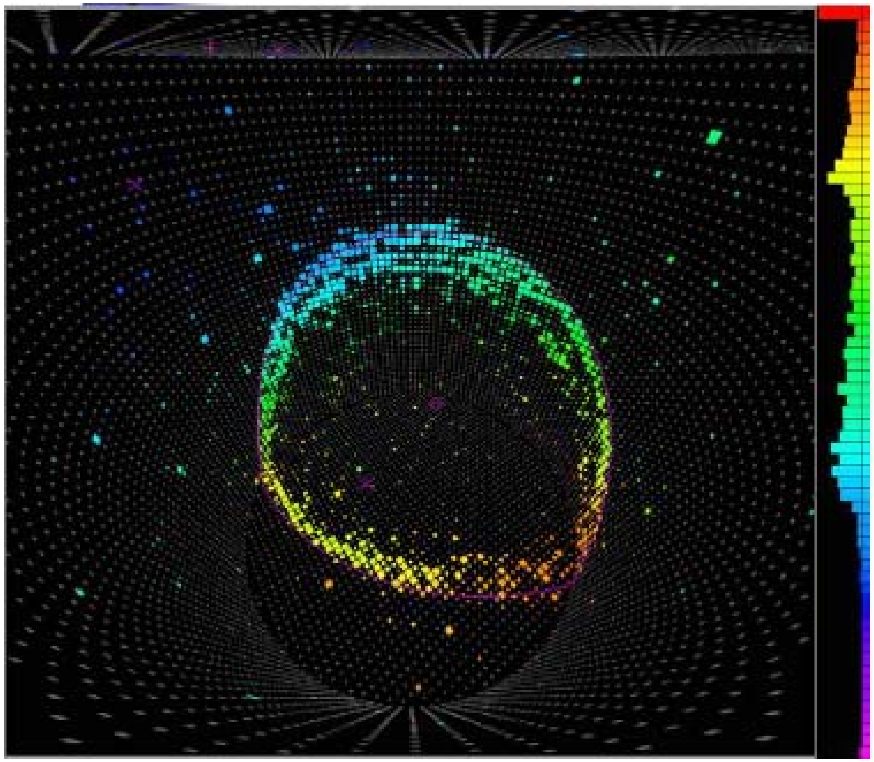
SK-3 March 2006 +

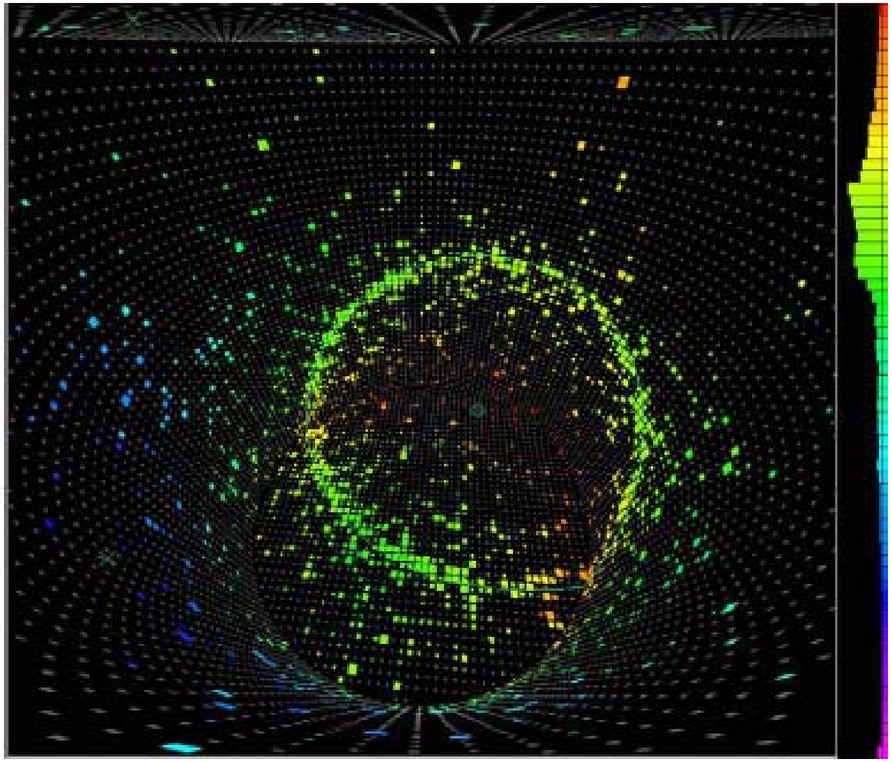
- original coverage to be restored
- T2K off-axis beam from J-PARC

The cathedral of light



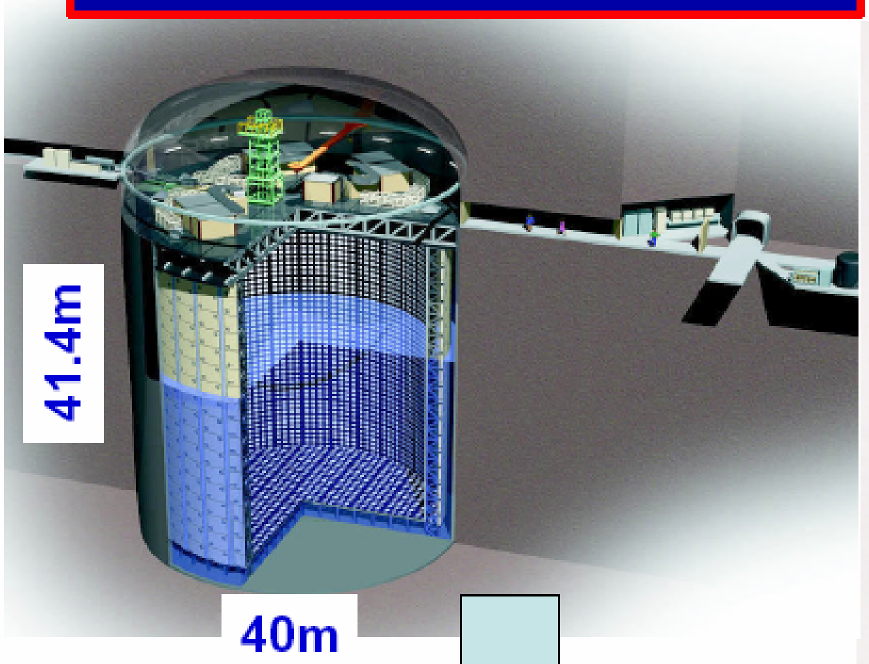
The eyes of Super-Kamiokande



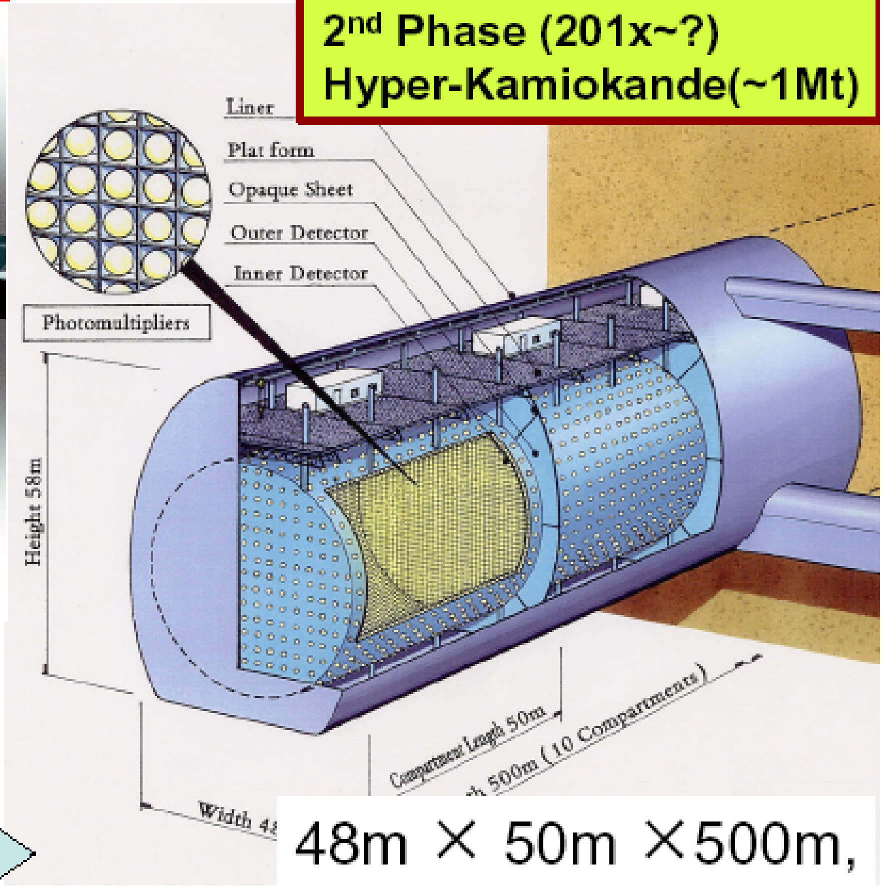


Water detectors

1st Phase (2009~, ?5yrs)
Super-Kamiokande(22.5kt)

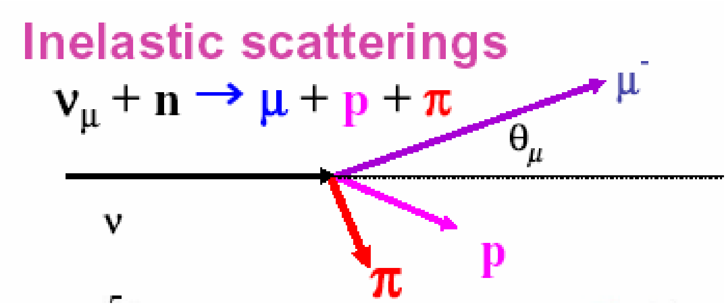


2nd Phase (201x~?)
Hyper-Kamiokande(~1Mt)



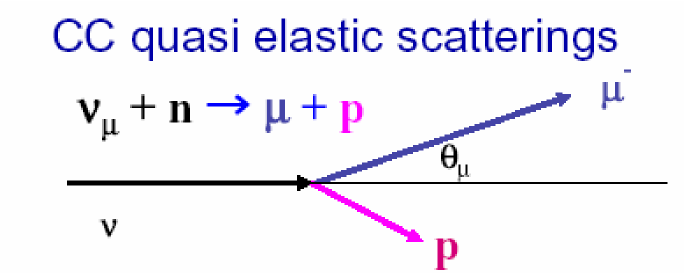
48m × 50m ×500m,
Total mass = 1 Mton

Cross sections and energy reconstruction



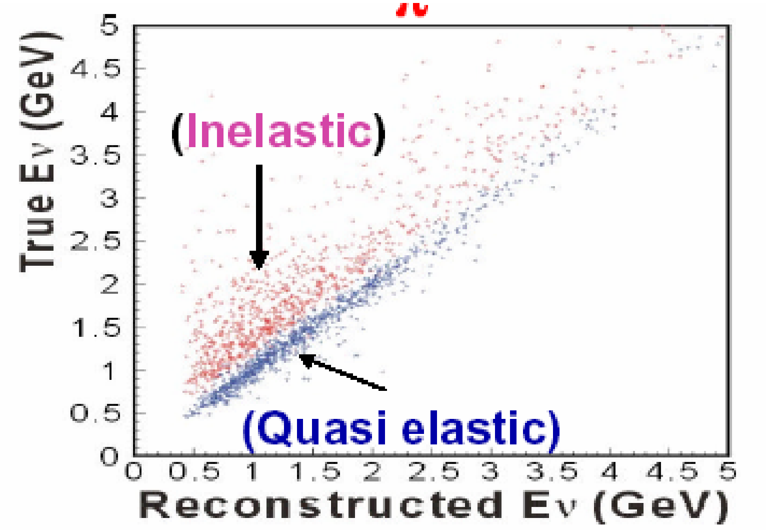
Inelastic scatterings

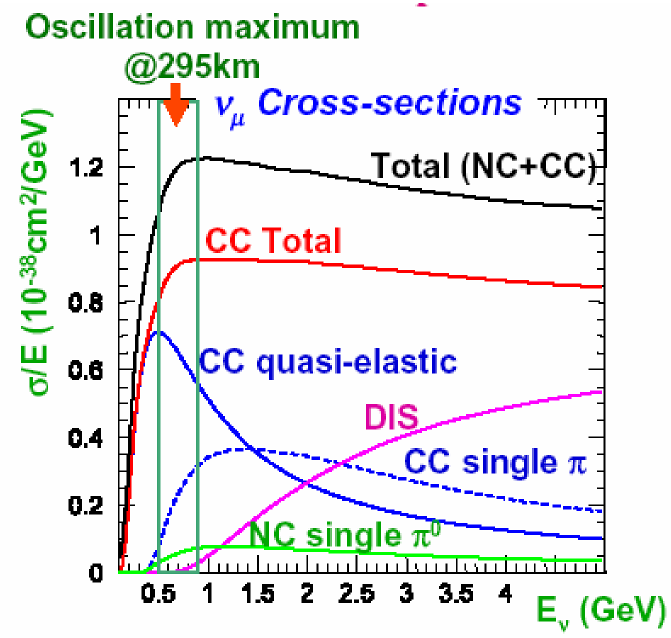
$\nu_\mu + n \rightarrow \mu + p + \pi$



CC quasi elastic scatterings

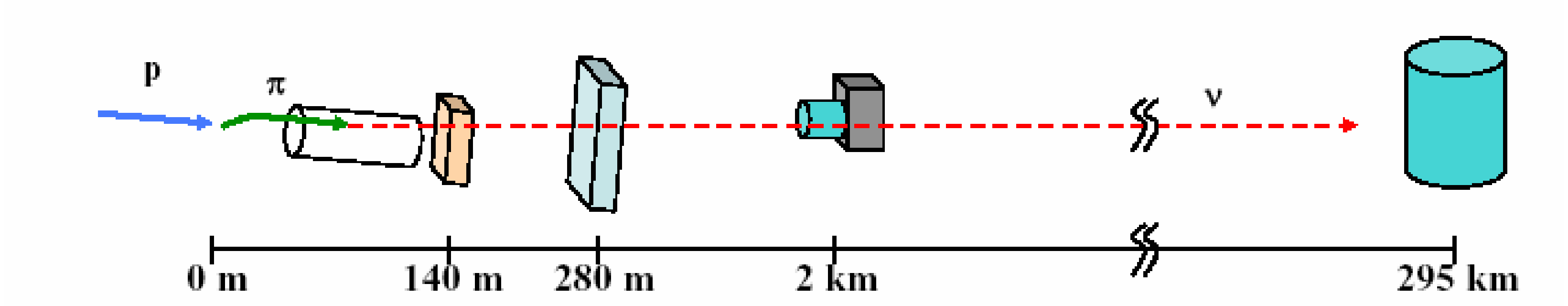
$\nu_\mu + n \rightarrow \mu + p$





Oscillation maximum
@295km

Measurement of neutrino flux



Muon monitors @ ~140m

Fast (spill-by-spill) monitoring of beam direction & intensity

Front detector @280m

Neutrino energy spectrum, intensity and direction

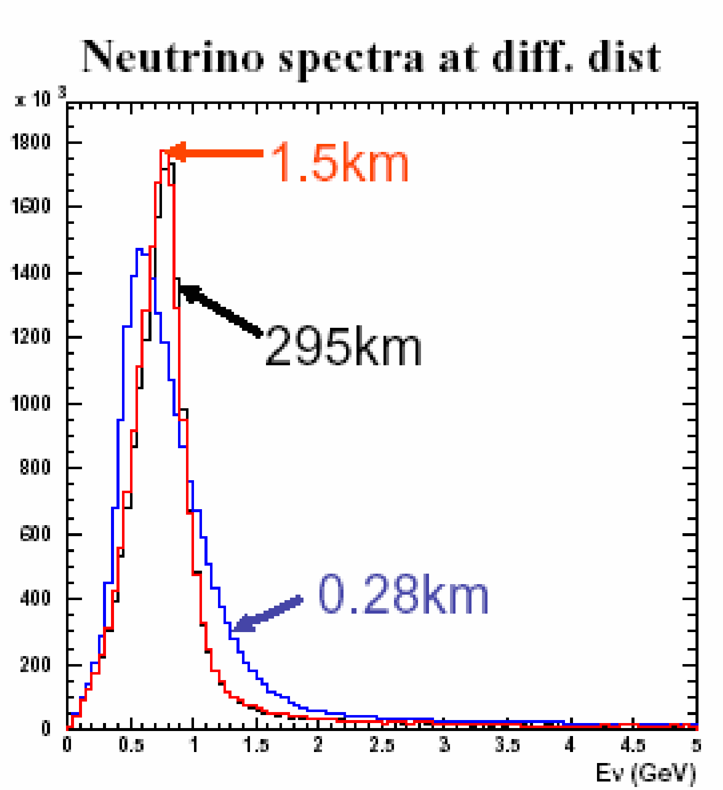
Far detector @ 295km

Super-Kamiokande(50kt)

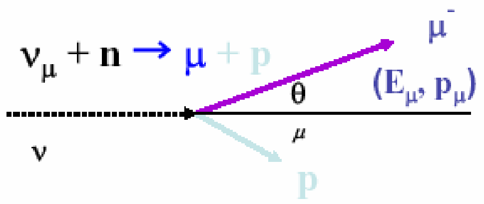
Future upgrade

Second Front Detector @ ~2km

Almost same E_ν spectrum as SK



Measurement of atmospheric parameters



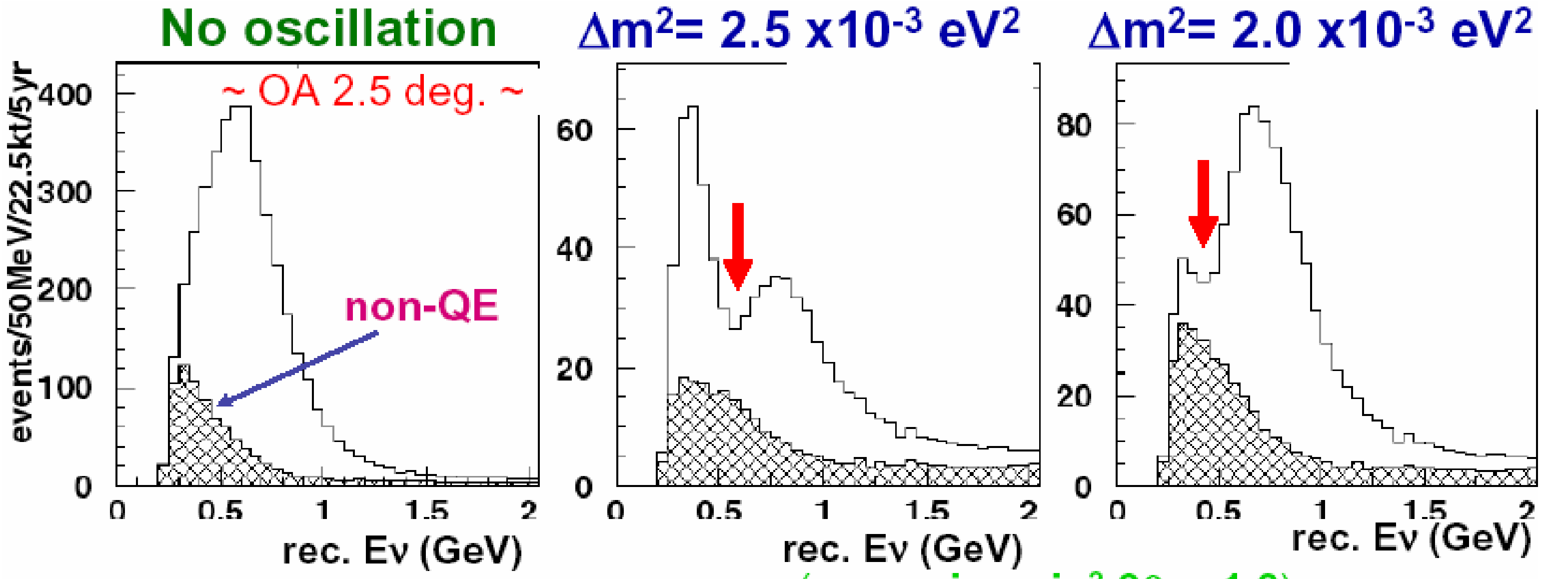
✧ CC QE

✧ can reconstruct $E\nu \leftarrow (\theta_\mu, p_\mu)$

$$E_\nu^{rec} = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + p_\mu \cos\theta_\mu}$$

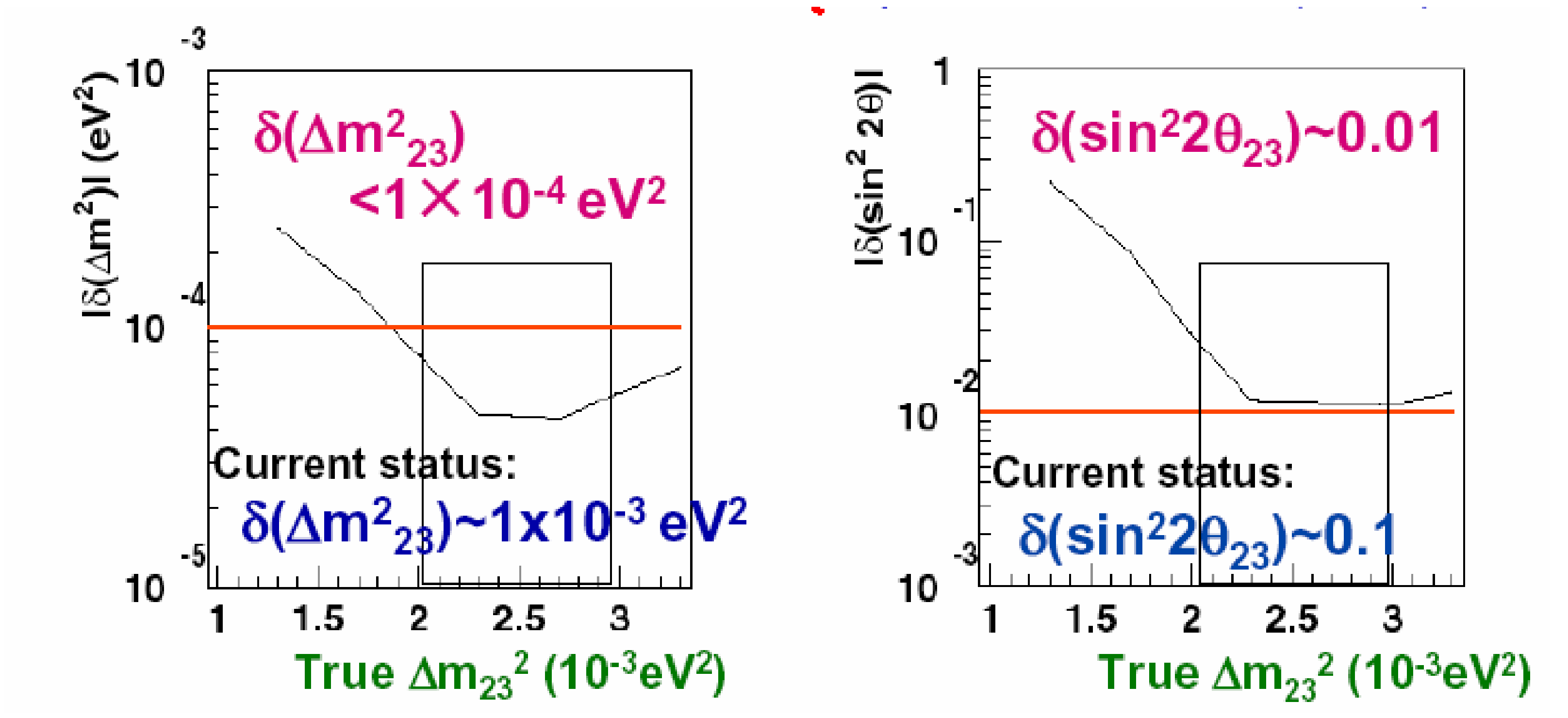
systematic errors

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



(assuming $\sin^2 2\theta_{23}=1.0$)

Precision on θ_{23} ,Δm_{23}



Improve one order of magnitude LBL measurements

Search for subleading oscillations

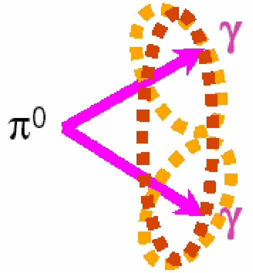
Possible background sources

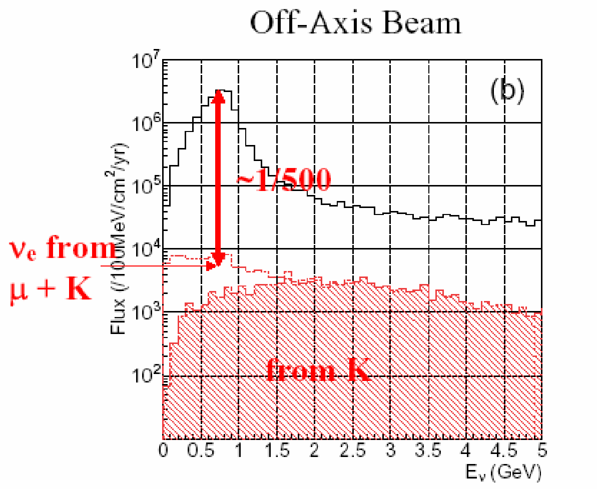
1) Beam ν_e

ν_e/ν_μ flux ~ 0.2% (@peak)

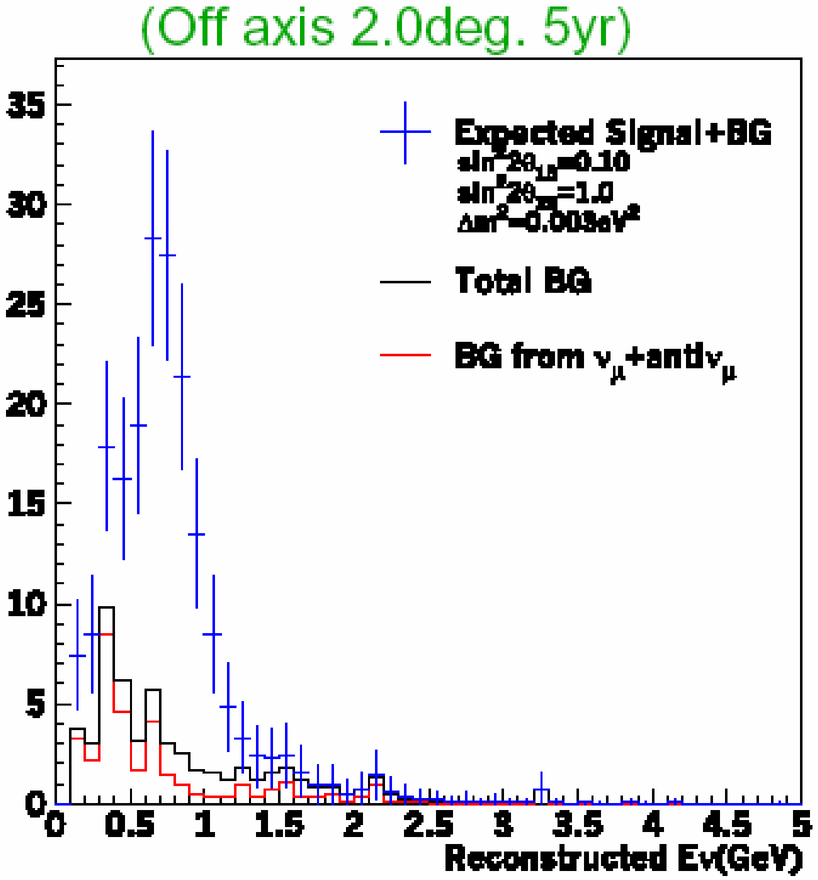
2) π^0 production

2-ring merged to 1-ring

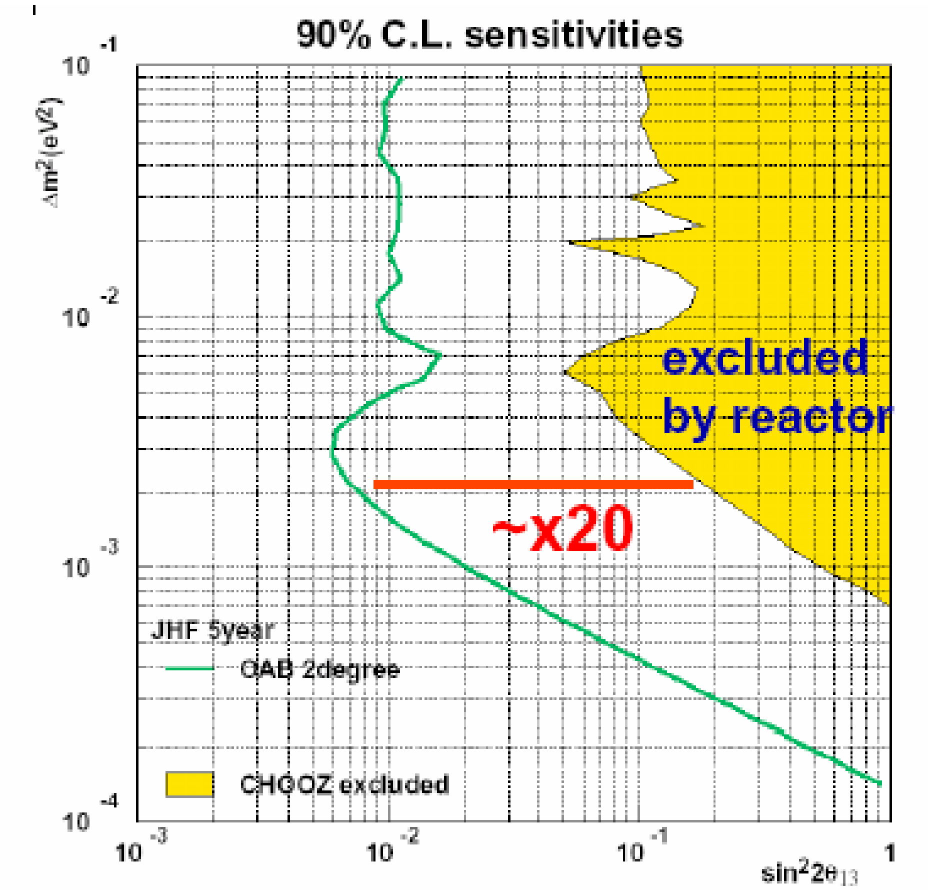




Intrinsic background: ν_e/ν_μ (peak) ~ 0.002



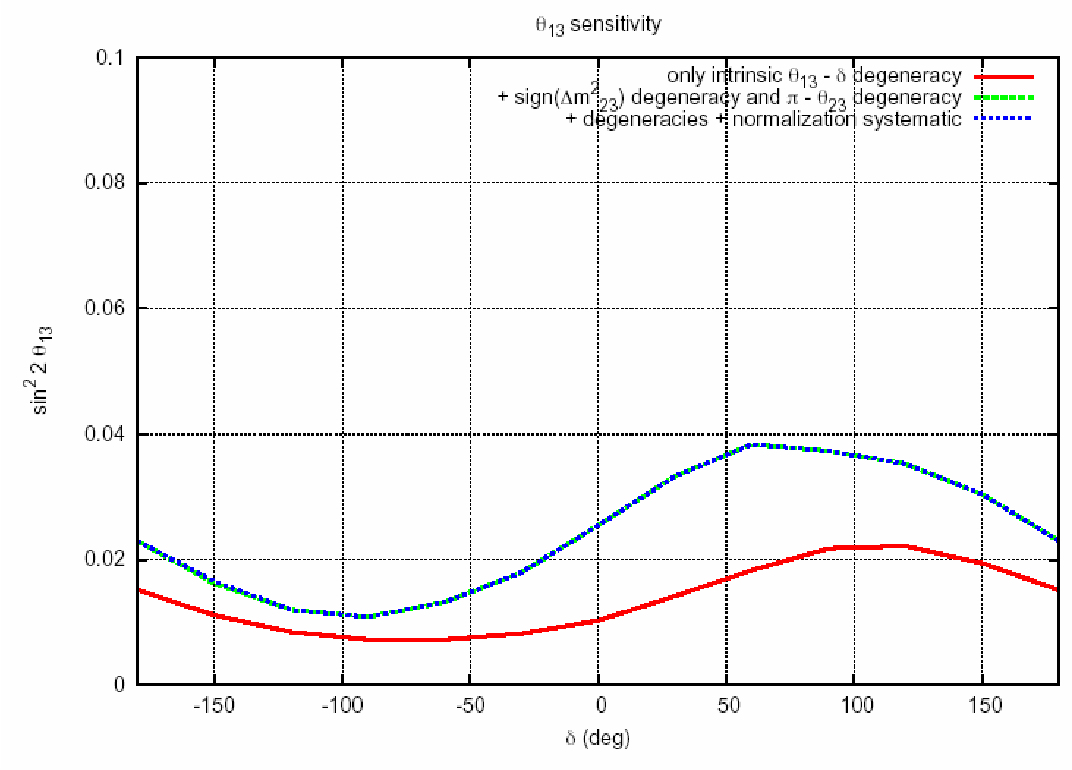
Sensitivity at fixed delta



$\sin^2 2\theta_{13} > 0.006$ (90%)

$\sin^2 2\theta_{13} > 0.018$ (3σ)

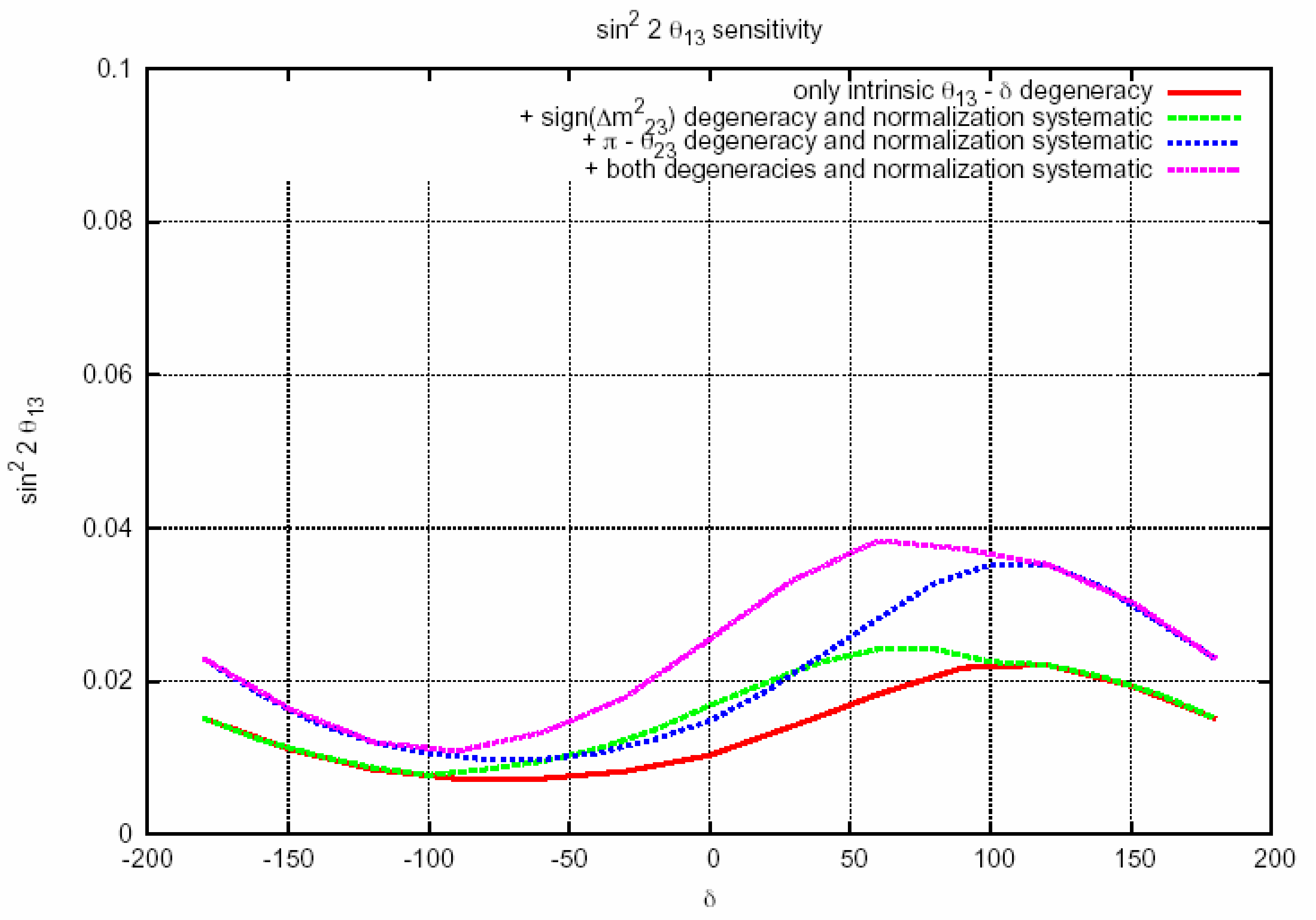
The effect of correlation and degeneracies



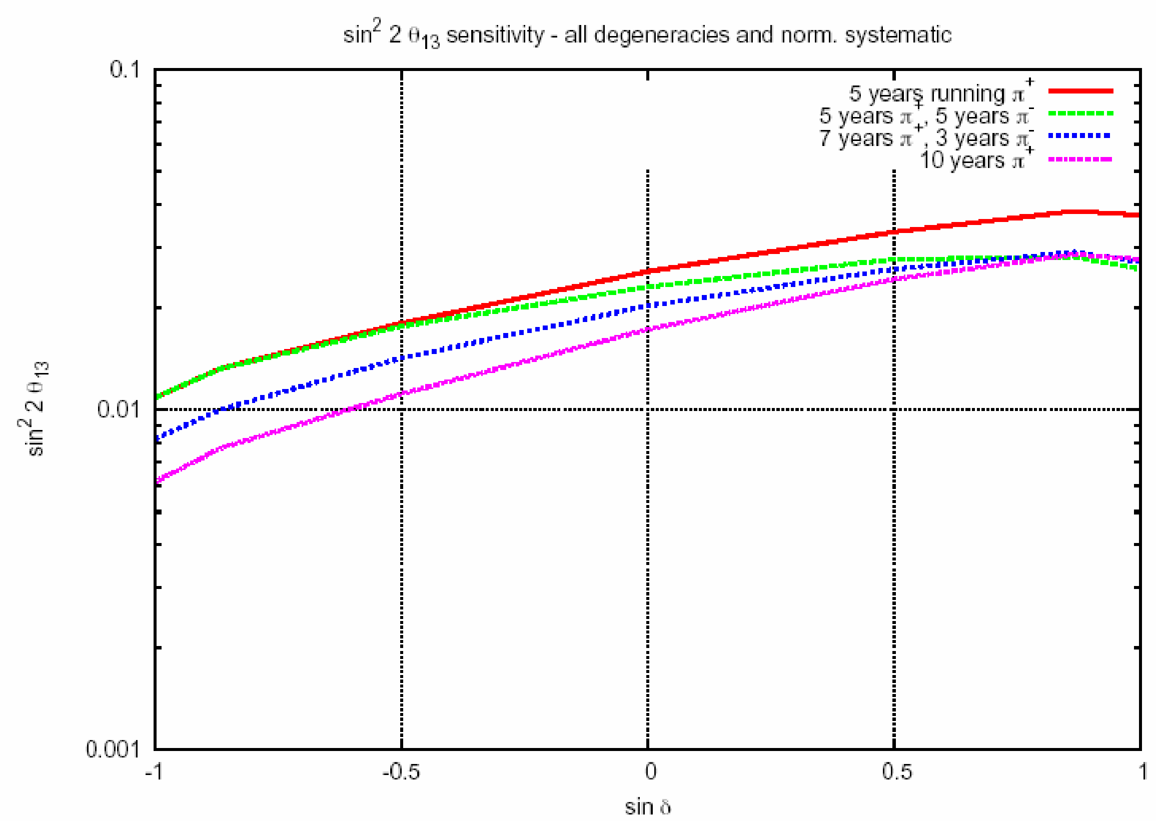
It spoils seriously the sensitivity to θ_{13}

Depends on δ

The effect of correlation and degeneracies II



Running strategy for K2K-I



Running antineutrinos does not help to break the correlation with theta13 (for “low” statistics)

Summary on T2K-I

T2K is a discovery experiments.

If we see a signal,we will open the way to a next generation of neutrino experiments.

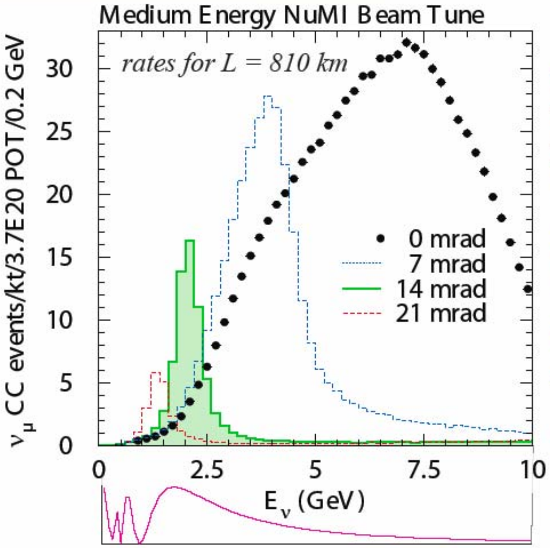
If no signal is seen uncertainties will be large.

Only neutrino run

We need a 2km detector/hadroproduction experiment to reduce to understand the neutrino flux at depth.

NOVA

Neutrino spectra off the NuMI axis



Using NuMI ME tune beam at 14 mrad peaks at ~2 GeV and has ~20% width

High energy flux suppressed

Sits just above oscillation maximum

$\Delta m^2 = 2.5\times10^{-3}$ eV^2

Event rates off NuMI beam axis

Event rates for:

L = 810 km, T = 12 km

$\Delta m^2_{23} = 2.5\times10^{-3}$ eV^2

$\sin^2 2\theta_{23} = 1$, $\sin^2 2\theta_{13} = 0.01$

Sets goals for detector

Most ν_μ oscillate away.

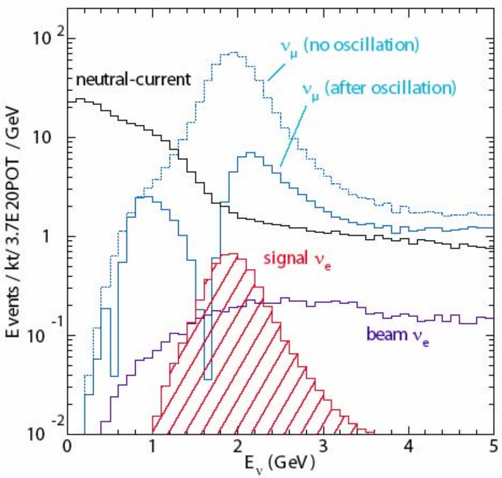
☞ need only 50:1 rejection of ν_μ CC *(Easy!)*

Need ~> 100:1 NC rejection

☞ fine grained, low density detector

Good energy resolution

☞ reject beam ν_e

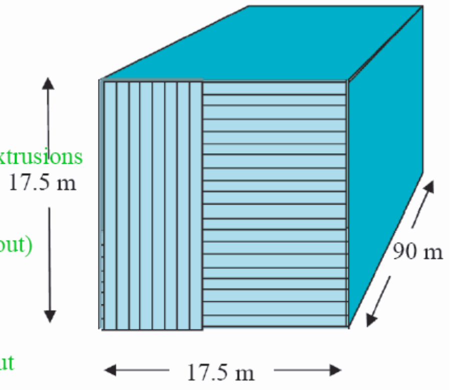


25 kilo-ton total mass
4 kilo-ton passive
21 kilo-ton active (85%)

Liquid scintillator contained in
1.28 m x 4.9 cm x 17.5 m PVC extrusions
32 cells per extrusion
24 extrusions per plane
1845 planes (alternating x/y readout)
= 25,830 extrusions
= 826,560 channels

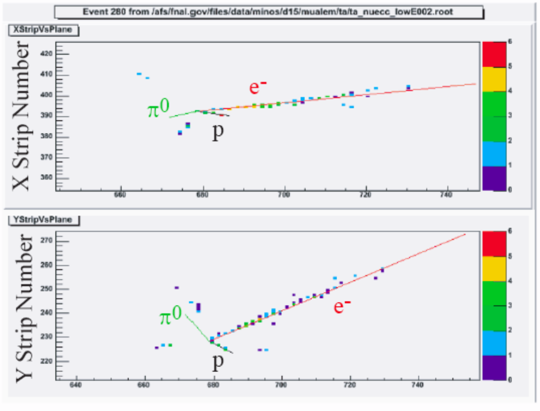
Looped WLS fiber to APD readout

No absorber



$$\nu_e + n \rightarrow p + e^- + \pi^0$$

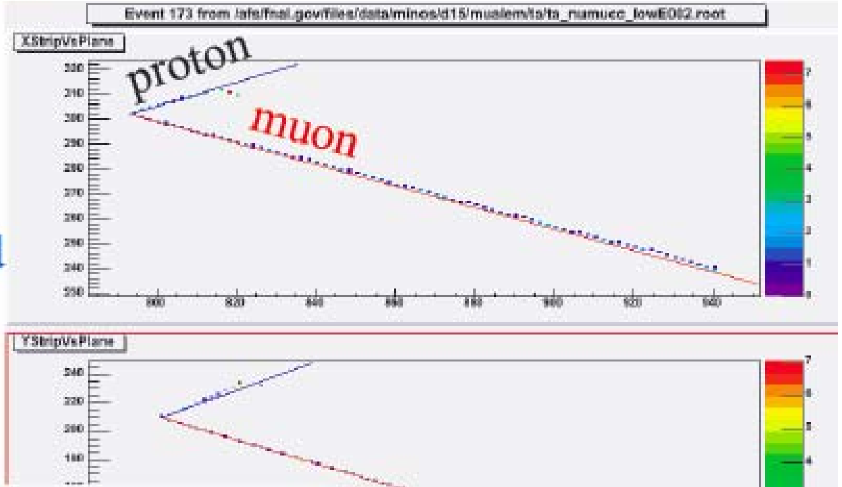
$E_\nu = 1.65$ GeV

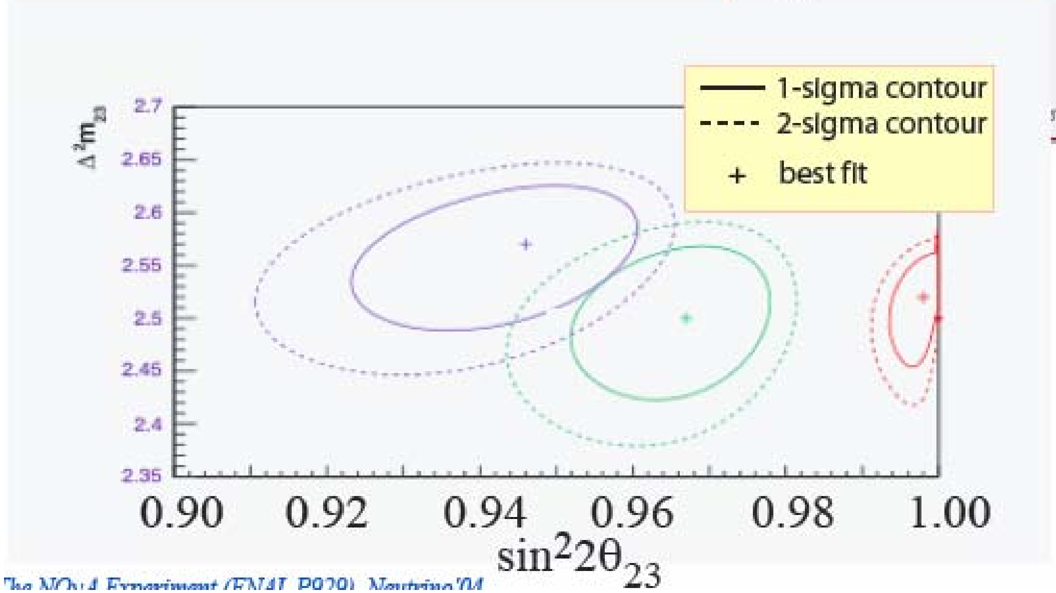


color prop. to pulse height

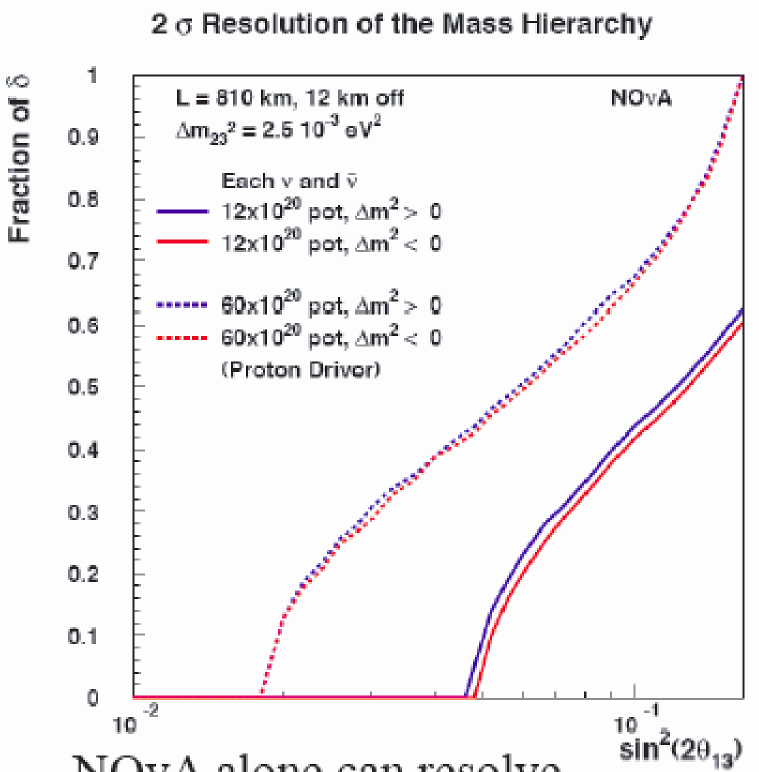
TAS Detector $\sin^2 2\theta_{23}$ measurement

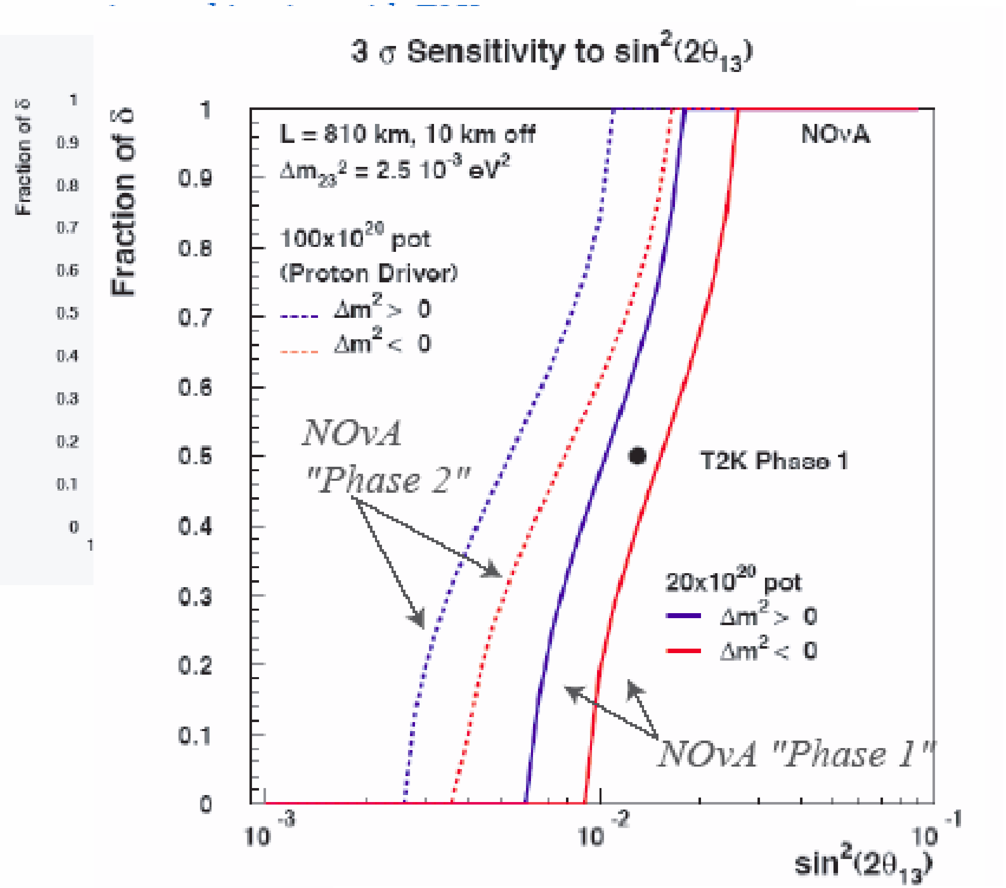
- Quasi-elastic events are very clean in TASD
- Excellent energy resolution
- Essentially zero NC background
- Allow for clean measurement of $\sin^2 2\theta_{23}$ to roughly 1-2% level





NOvA Alone





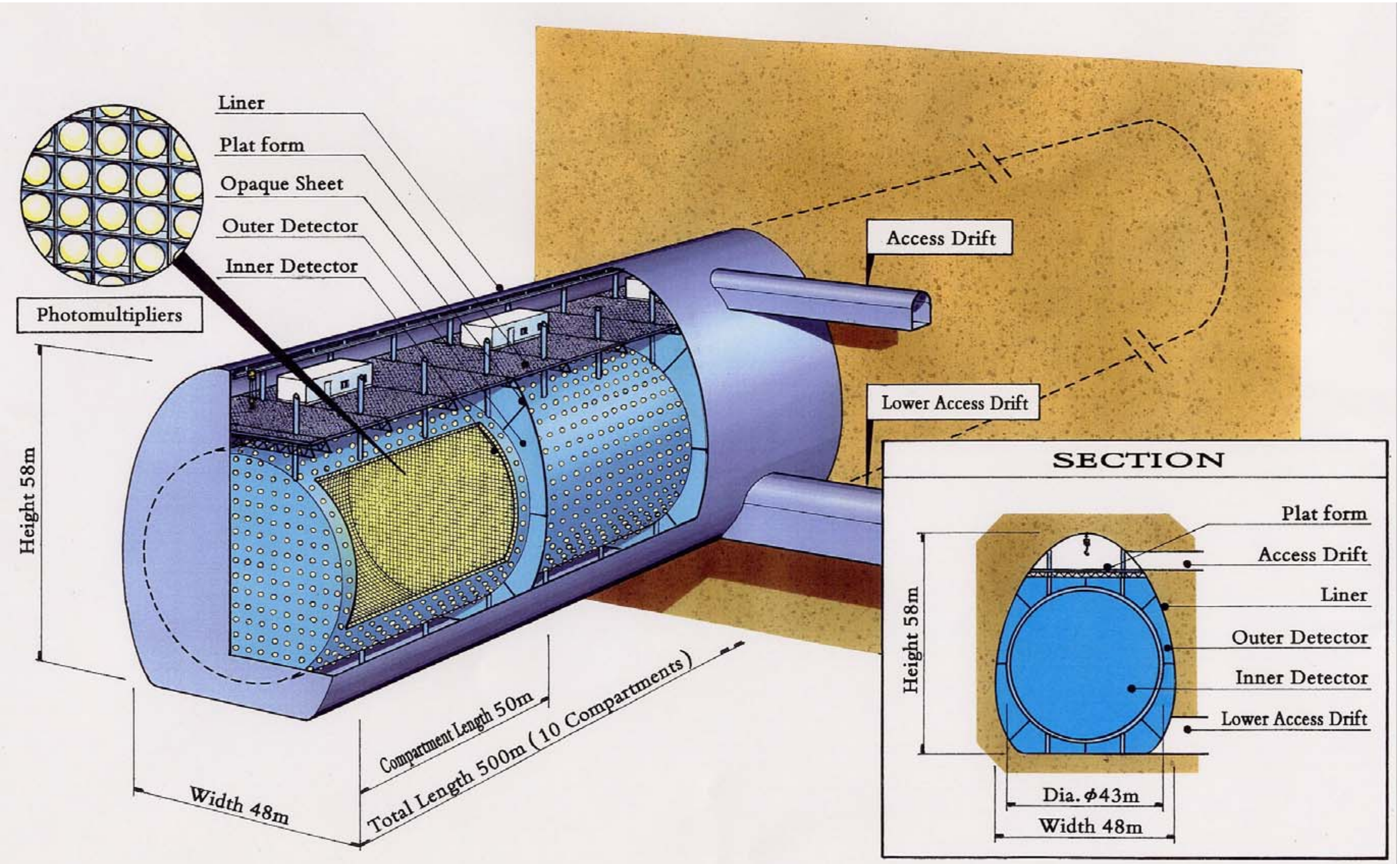
NOvA alone can resolve heirarchy for large $\sin^2(2\theta_{13})$ over 30-40% of δ phase space. Proton Driver extends this reach by a factor of 2

T2K Phase II

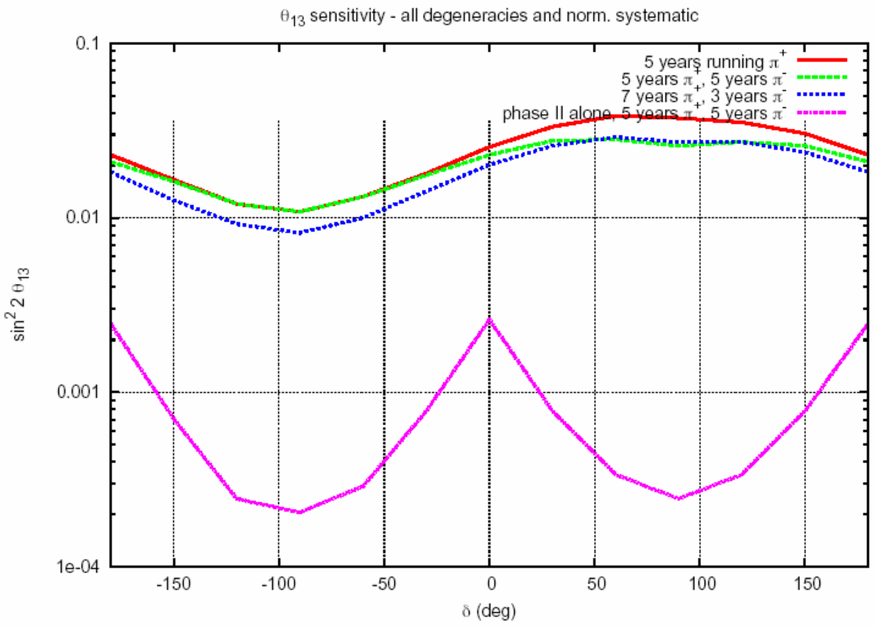
Phase-I (0.75MW + Fully reconstructed Super-K)~K2K x 100

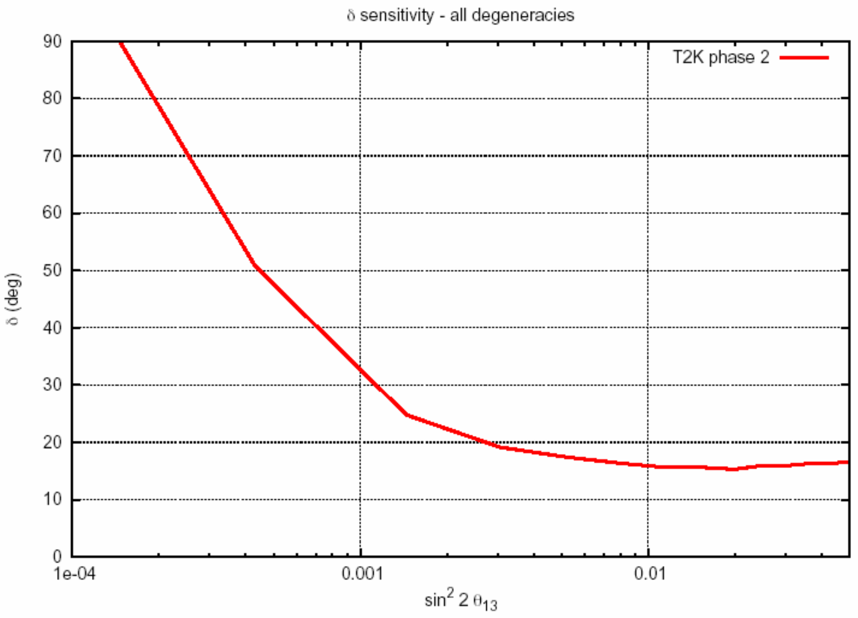
Phase-II (4MW+Hyper-K) ~ Phase-I×100

MTON water detector



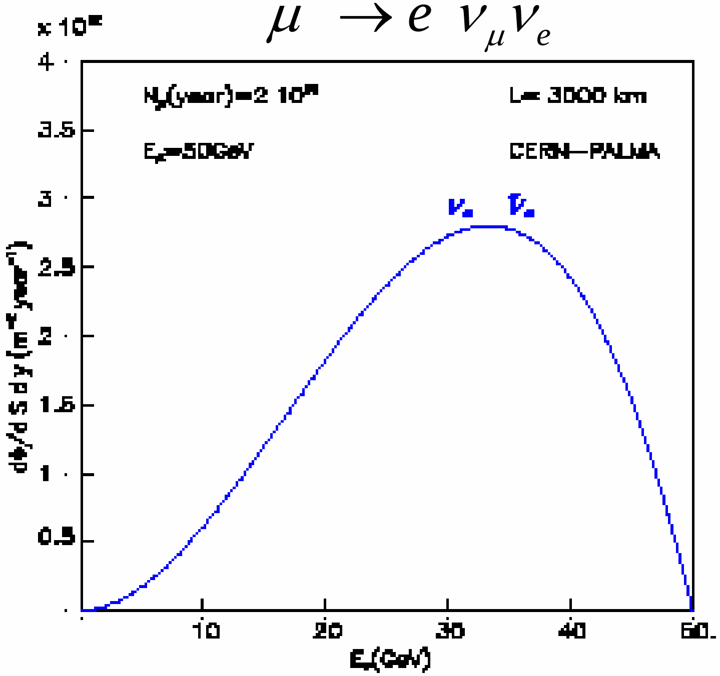
Sensitivity of T2K-II





Fluxes from muon and radioactive β ions decay

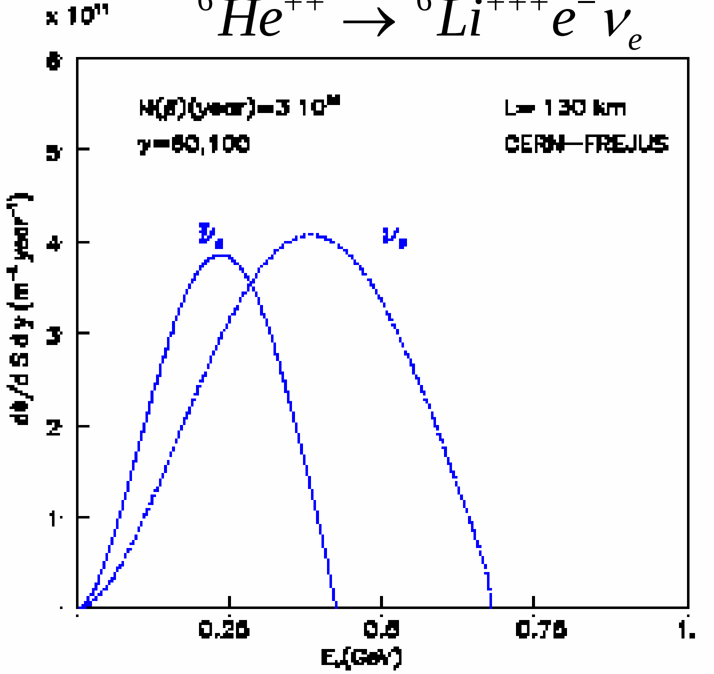
$$\mu^- \rightarrow e^- \nu_\mu \overline{\nu}_e$$



$$\left.\frac{d\Phi}{dSdy}\right|_{\theta\approx 0} \approx \frac{N_\mu}{\pi L^2} 12\gamma^2 y^2 (1-y),$$

$$y = \frac{E_\nu}{E_\mu}$$

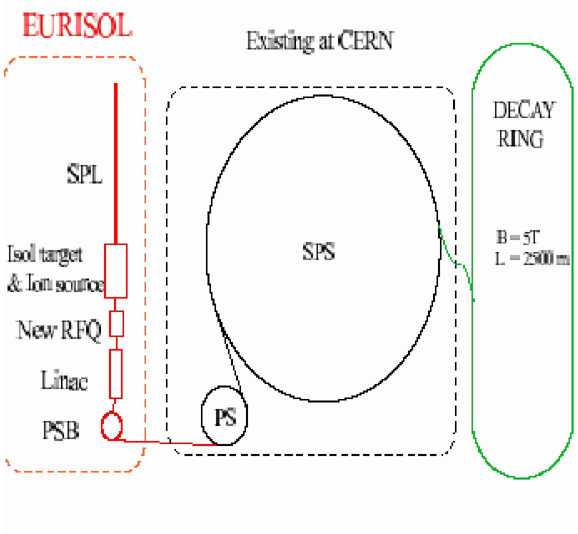
$$^6He^{++} \rightarrow {}^6Li^{+++} e^- \overline{\nu}_e$$

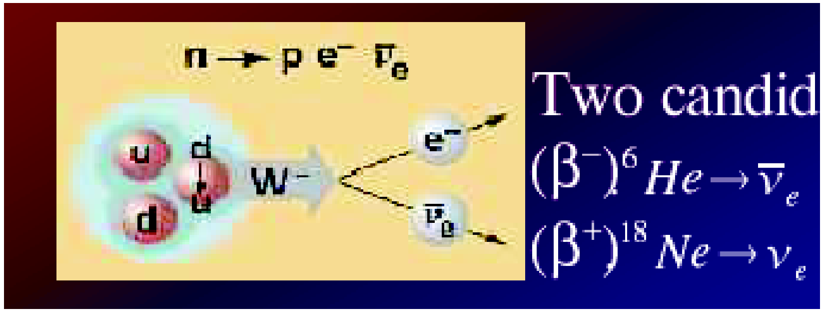


$$\left.\frac{d\Phi}{dSdy}\right|_{\theta\approx 0} \approx \frac{N_\beta}{\pi L^2} \frac{\gamma^2}{g(y_e)} y^2 (1-y) \sqrt{(1-y)^2 - y_e^2}$$

$$y = \frac{E_\nu}{2\gamma E_0}, y_e = \frac{m_e}{E_0}$$

Beta Beam

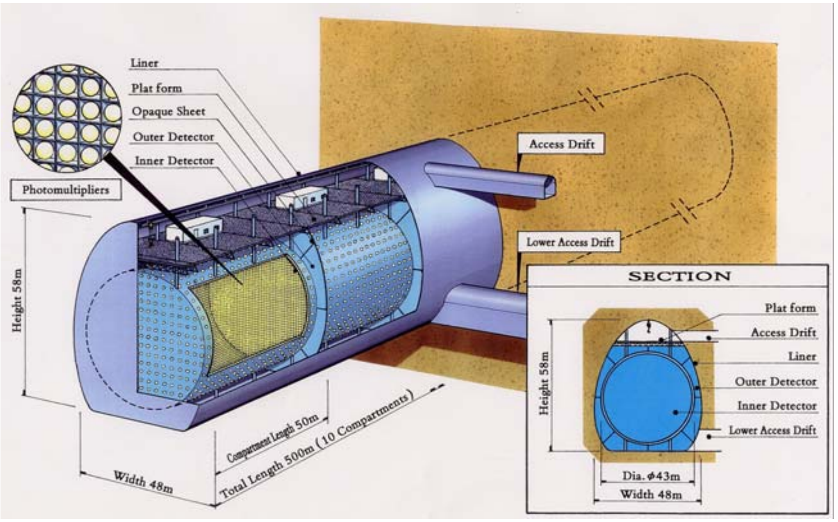


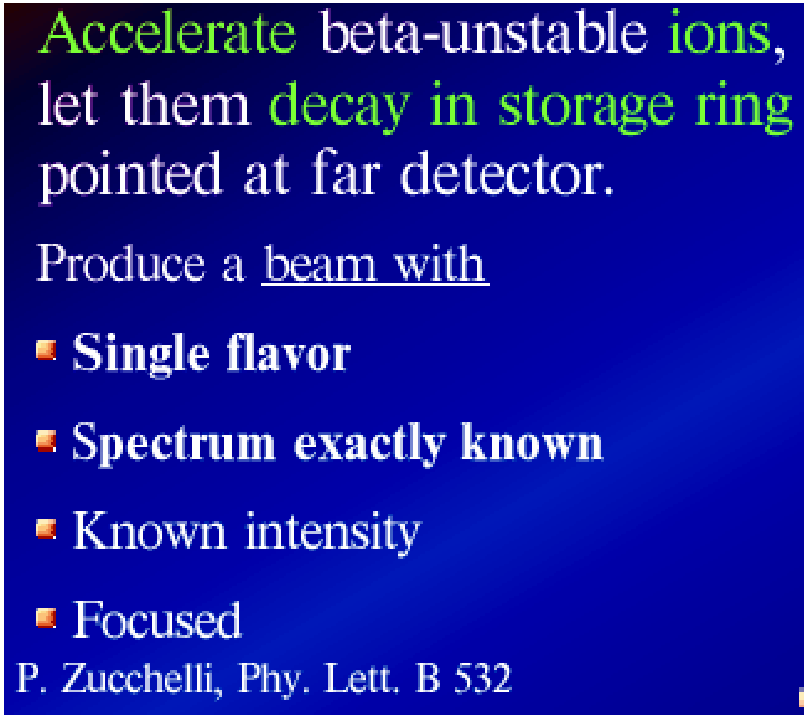


Two candid

$(\beta^-)^6 He \to \bar{\nu}_e$

$(\beta^+)^{18} Ne \to \nu_e$



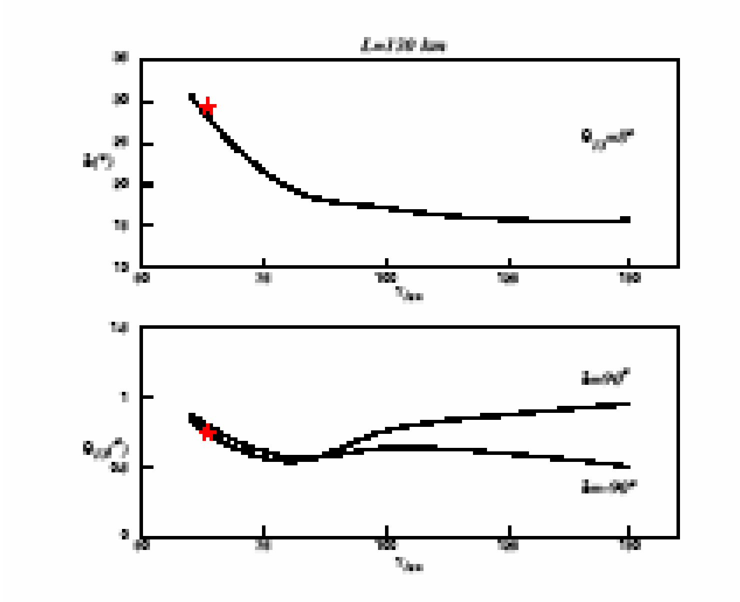

Accelerate beta-unstable ions, let them decay in storage ring pointed at far detector.

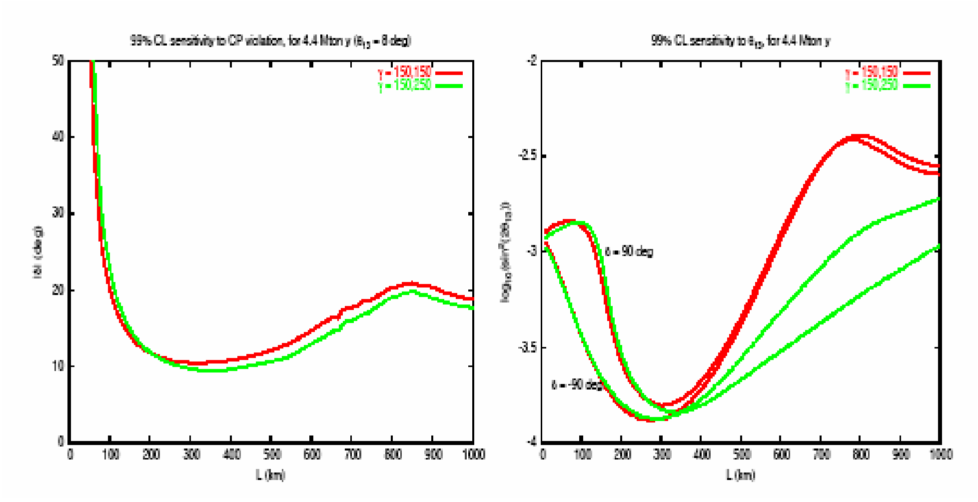
Produce a beam with

- **Single flavor**
- **Spectrum exactly known**
- Known intensity
- Focused

P. Zucchelli, Phy. Lett. B 532

SPS Beta-Beam





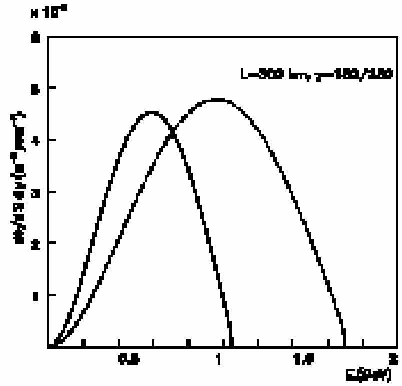


Figure 1: $\bar{\nu}_e$ (solid) and ν_e (dashed) fluxes as a function of the neutrino energy at $L = 300$ km for the maximum acceleration of the ^{6}He ($\gamma = 150$) and ^{18}Ne ($\gamma = 250$) at the CERN-SPS.

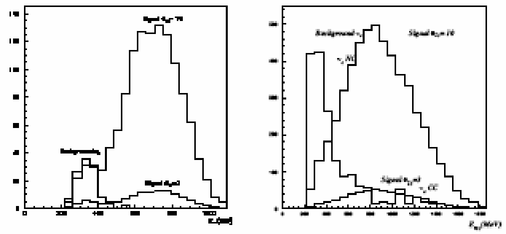
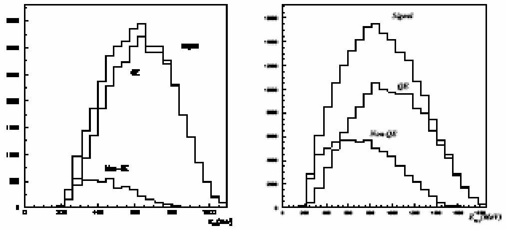
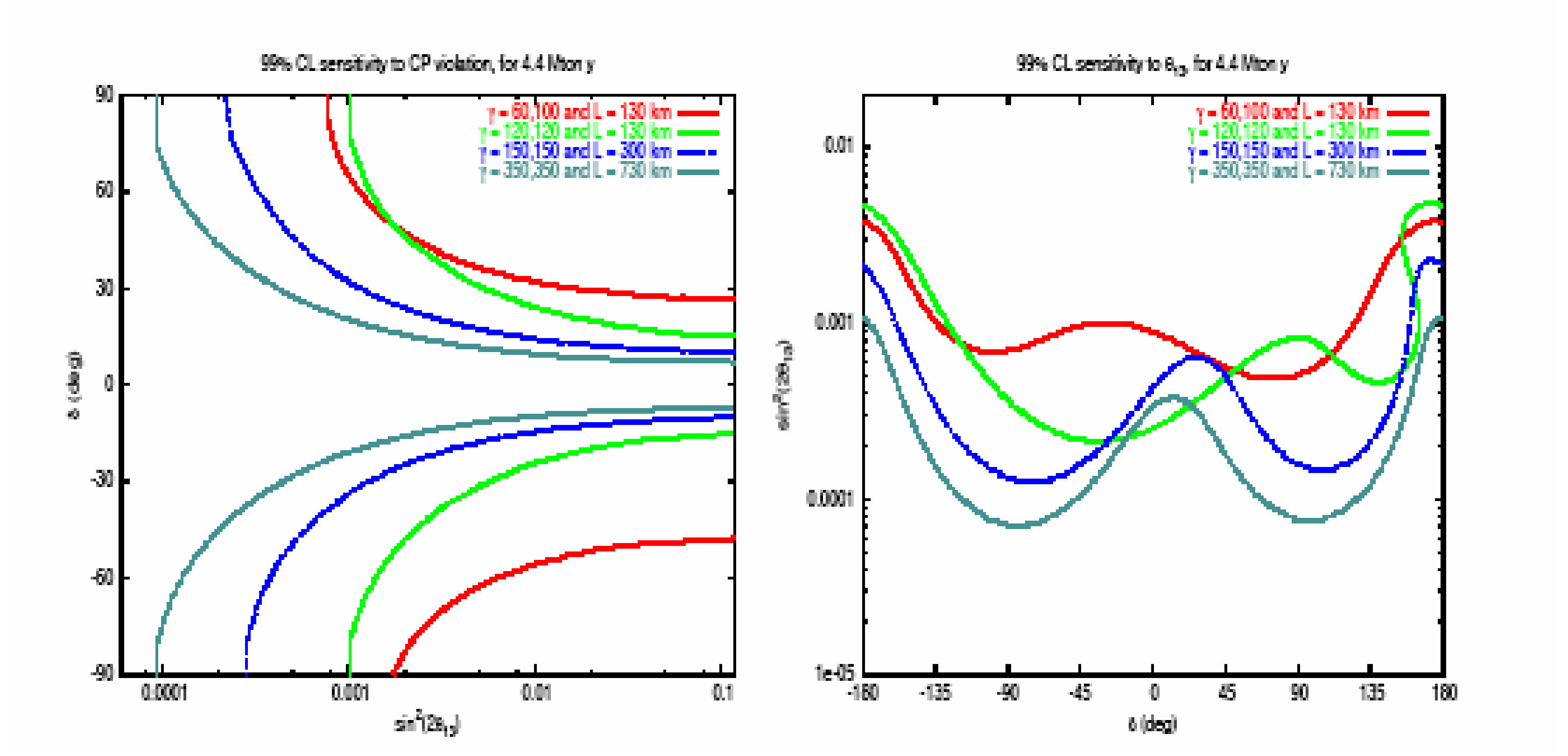
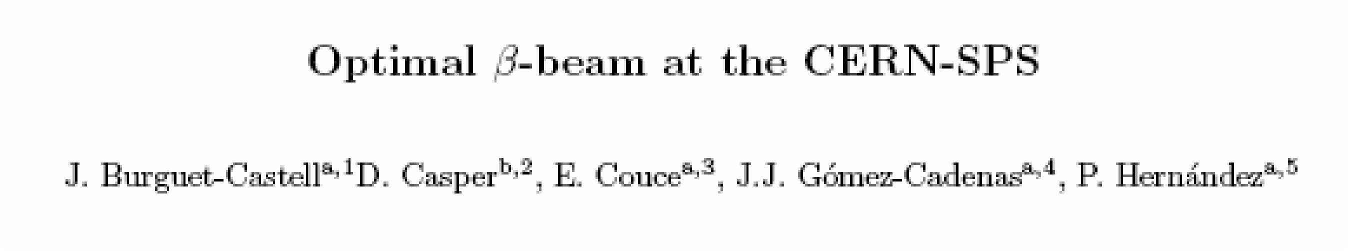


Figure 2: Reconstructed energy for signal with $\theta_{13} = 8°$ (solid) and $\theta_{13} = 3°$ (dashed)) and background (dotted) at the maximum acceleration of ^{6}He (left) and ^{18}Ne (right) ions at the CERN-SPS. The absolute normalization corresponds to one year.



Sensitivity of the beta-beam

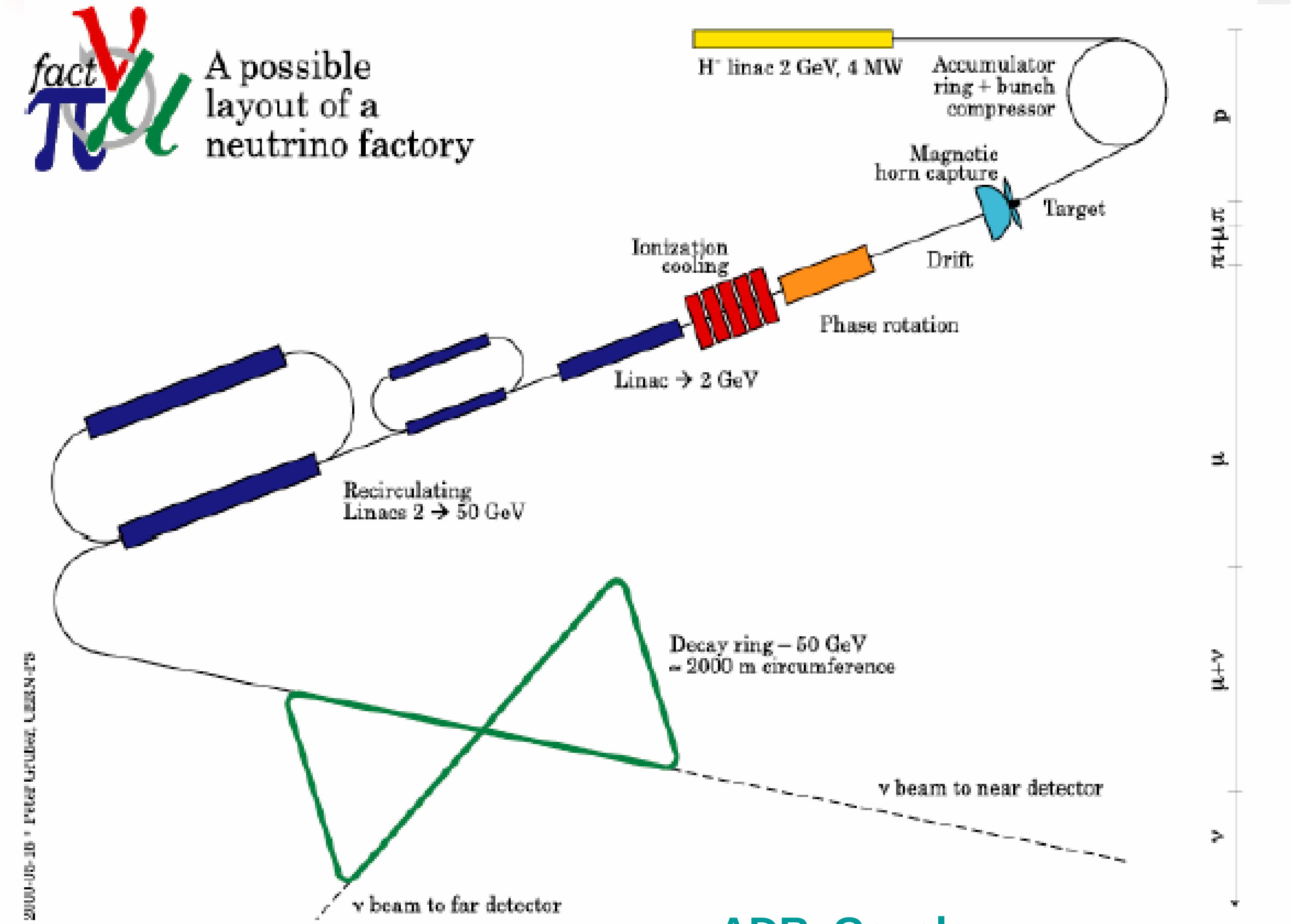




Optimal β-beam at the CERN-SPS

J. Burguet-Castell[a,1] D. Casper[b,2], E. Couce[a,3], J.J. Gómez-Cadenas[a,4], P. Hernández[a,5]

Neutrino Factory



S. Geer

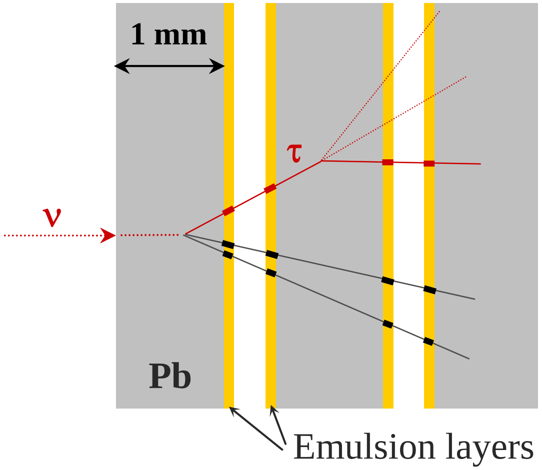
ADR, Gavela, Hernández

Detectors for NUFACT

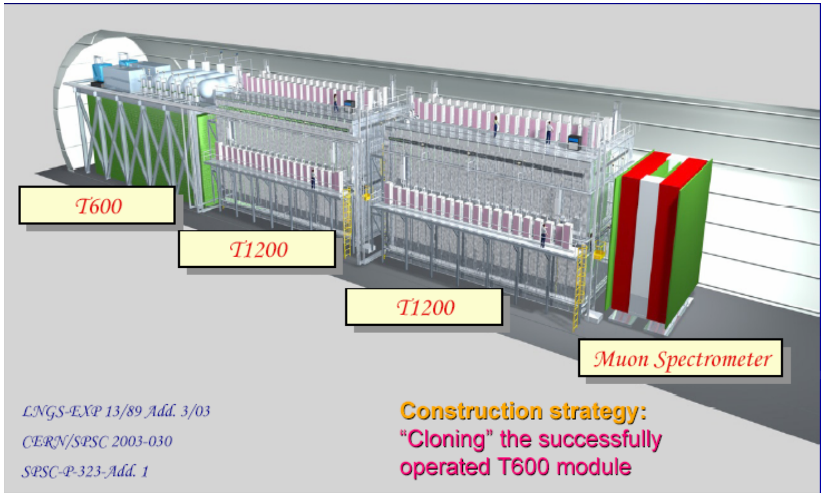
10 x Minos

5 x Opera

10 x Icarus



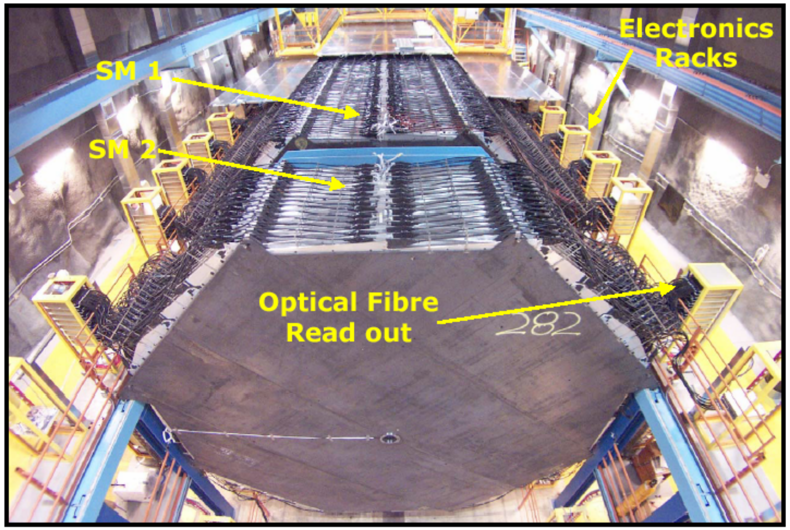
Migliozzi



LNGS-EXP 13/89 Add. 3/03
CERN/SPSC 2003-030
SPSC-P-323-Add. 1

Construction strategy:
"Cloning" the successfully operated T600 module

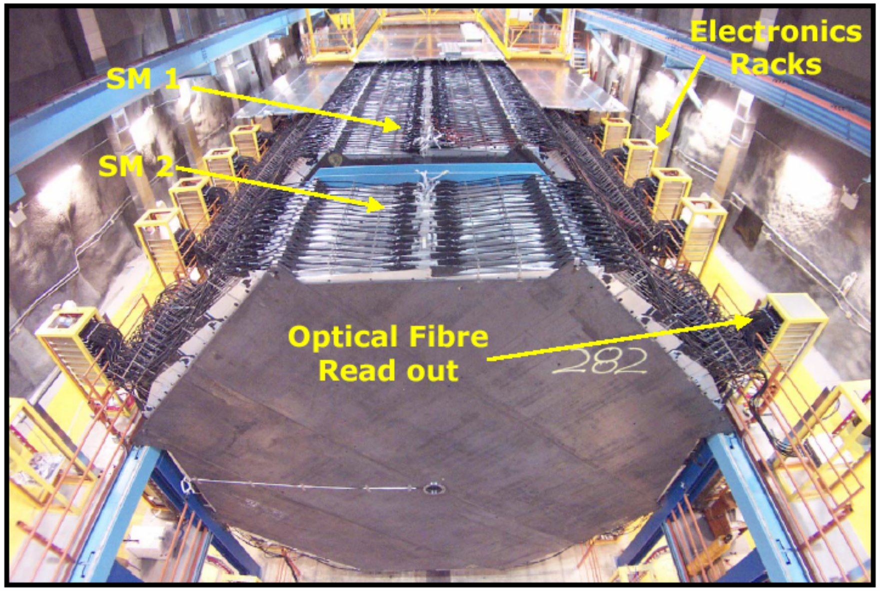
Rubbia, Bueno, Campanelli



Cervera, Didak, JJGC

Golden muons

$$\mu^+ \longrightarrow e^+ + \bar{\nu}_\mu + \nu_e$$



$$\bar{\nu}_\mu + N \longrightarrow \mu^+ + X$$ CC

right sign muon

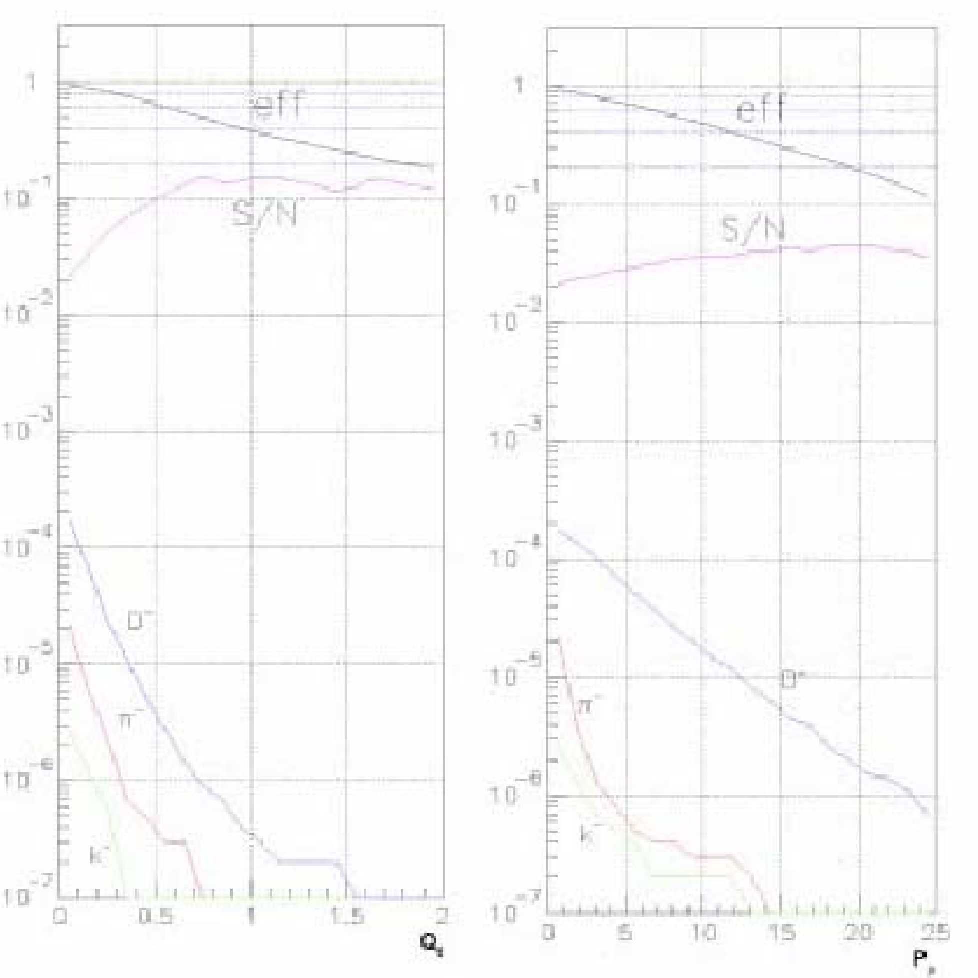
$$\bar{\nu}_\mu + N \longrightarrow \bar{\nu}_\mu + X$$ NC

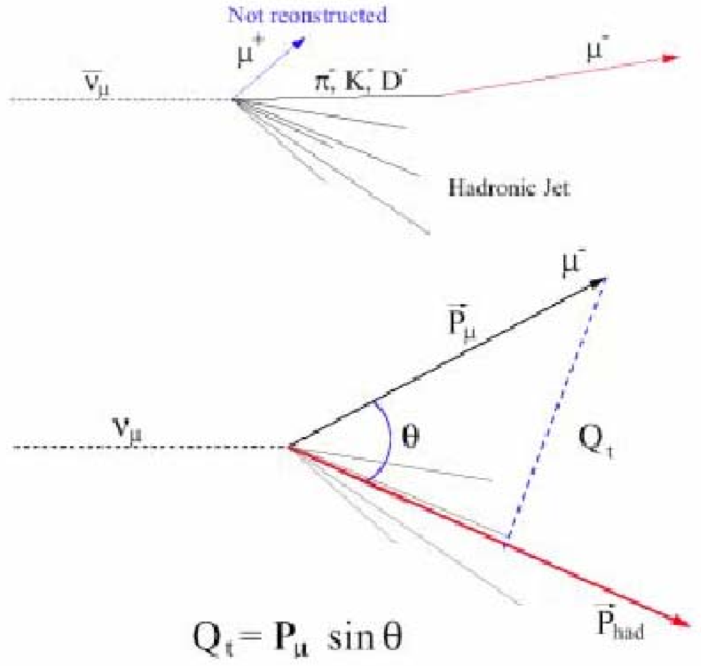
$$\nu_e \overset{osc}{\sim} \nu_\mu$$

$$\nu_\mu + N \longrightarrow \mu^- + X$$ SIGNAL

wrong sign muon

Control of backgrounds

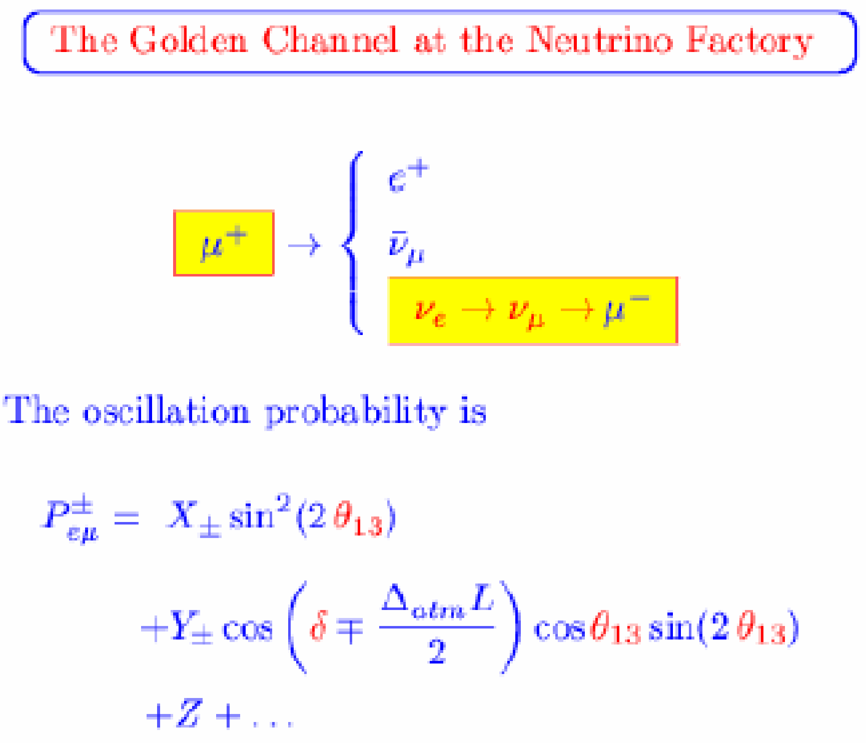




$$Q_t = P_\mu \sin\theta$$

Golden & Silver channels at NUFACT

$$\mu^+ \longrightarrow e^+ + \bar{\nu}_\mu + \nu_e$$



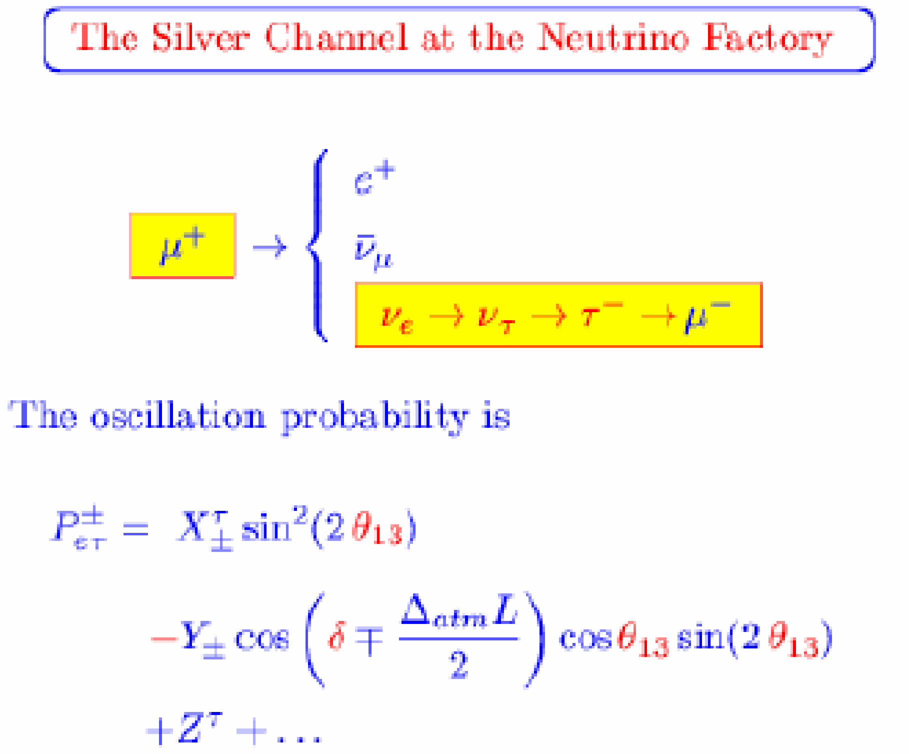
The Golden Channel at the Neutrino Factory

$$\boxed{\mu^+} \to \begin{cases} e^+ \\ \bar{\nu}_\mu \\ \boxed{\nu_e \to \nu_\mu \to \mu^-} \end{cases}$$

The oscillation probability is

$$\begin{aligned} P^{\pm}_{e\mu} = {} & X_\pm \sin^2(2\,\theta_{13}) \\ & + Y_\pm \cos\left(\delta \mp \frac{\Delta_{atm} L}{2}\right) \cos\theta_{13} \sin(2\,\theta_{13}) \\ & + Z + \dots \end{aligned}$$

ADR, Gavela, Hernández



The Silver Channel at the Neutrino Factory

$$\boxed{\mu^+} \to \begin{cases} e^+ \\ \bar{\nu}_\mu \\ \boxed{\nu_e \to \nu_\tau \to \tau^- \to \mu^-} \end{cases}$$

The oscillation probability is

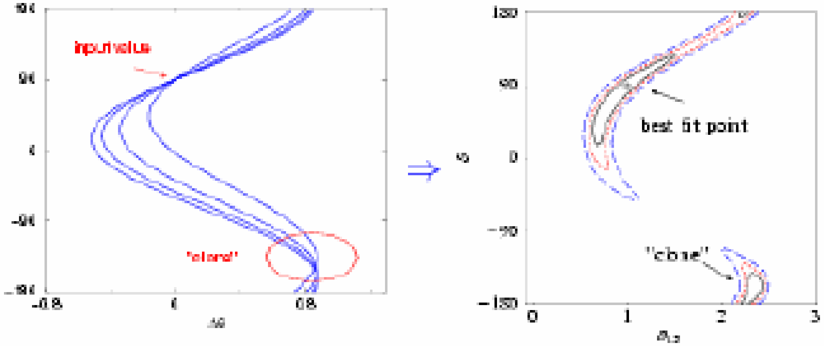
$$\begin{aligned} P^{\pm}_{e\tau} = {} & X^\tau_\pm \sin^2(2\,\theta_{13}) \\ & - Y^\tau_\pm \cos\left(\delta \mp \frac{\Delta_{atm} L}{2}\right) \cos\theta_{13} \sin(2\,\theta_{13}) \\ & + Z^\tau + \dots \end{aligned}$$

Donini, Migliozzi, Meloni

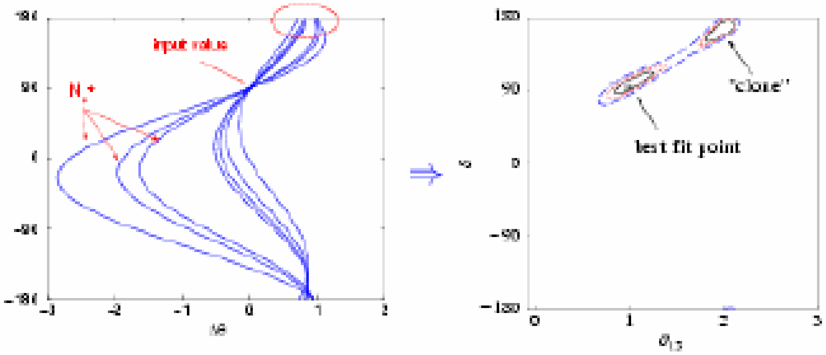
Solving degeneracies at NUFACT

Results for golden muons at $L = 3000$ Km

Five years of data taking: one polarity only (μ^+ in the storage ring)



Ten years of data taking: two polarities (μ^+ and μ^- in the storage ring)

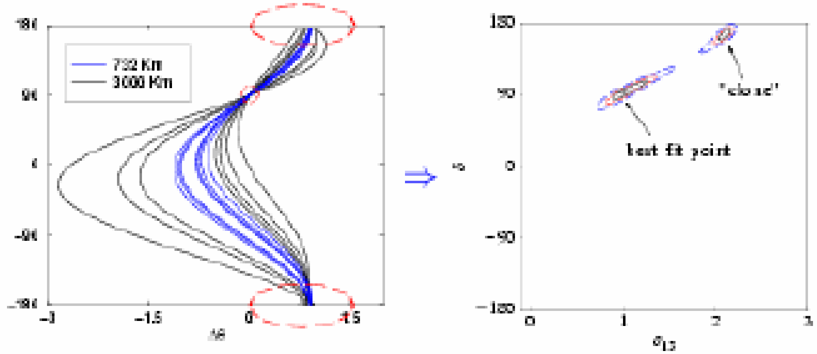


donini

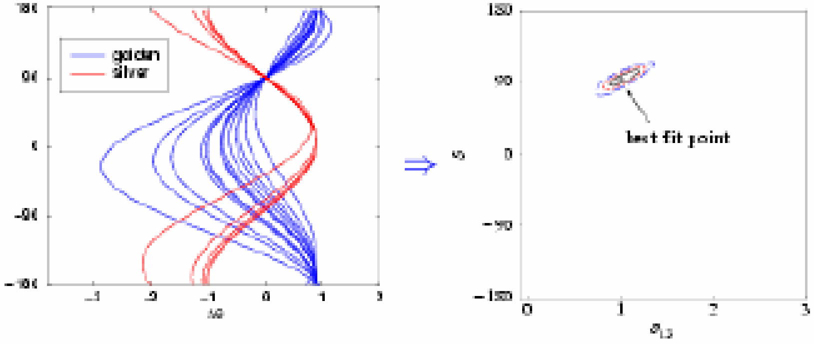
Input parameters: $\bar{\theta}_{13} = 1^\circ, \bar{\delta} = 90^\circ$

Using golden and silver muons

Setup A: two iron detectors and two baselines (golden muons only)

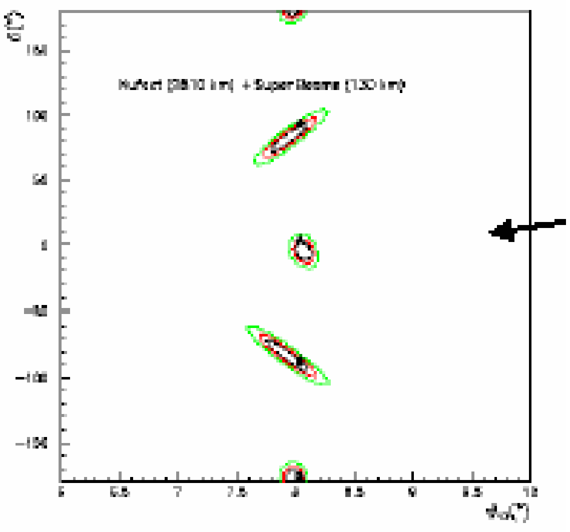


Setup B: one iron and one emulsion detectors (golden and silver muons; IDEAL emulsion detector)

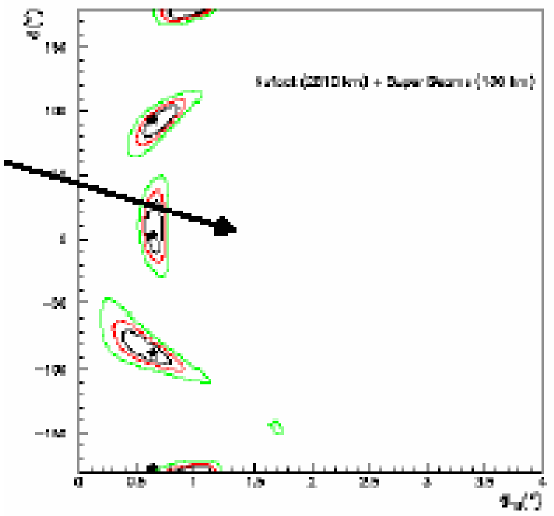


Input parameters: $\bar{\theta}_{13} = 1^\circ, \bar{\delta} = 90^\circ$

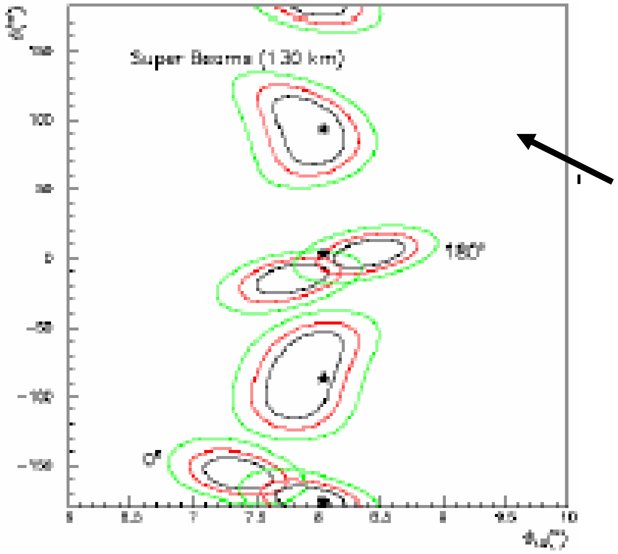
NUFACT sensitivity



NF

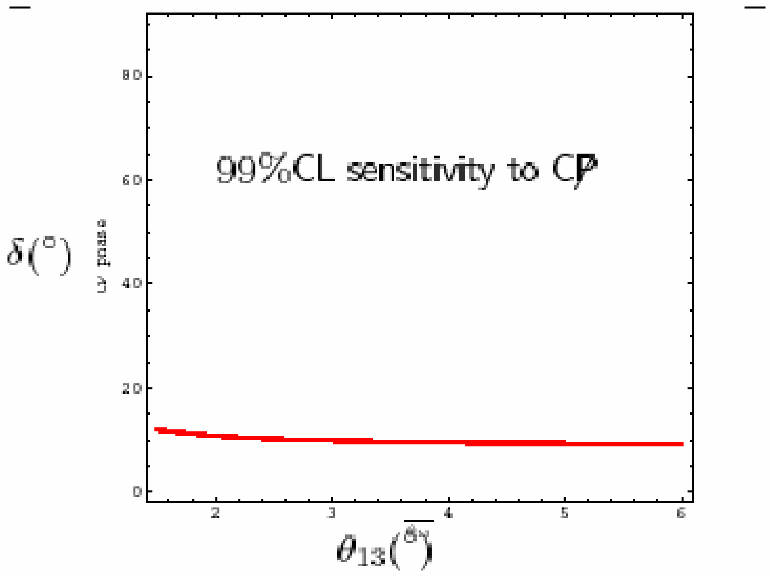


SPLSB
+NF



SPL

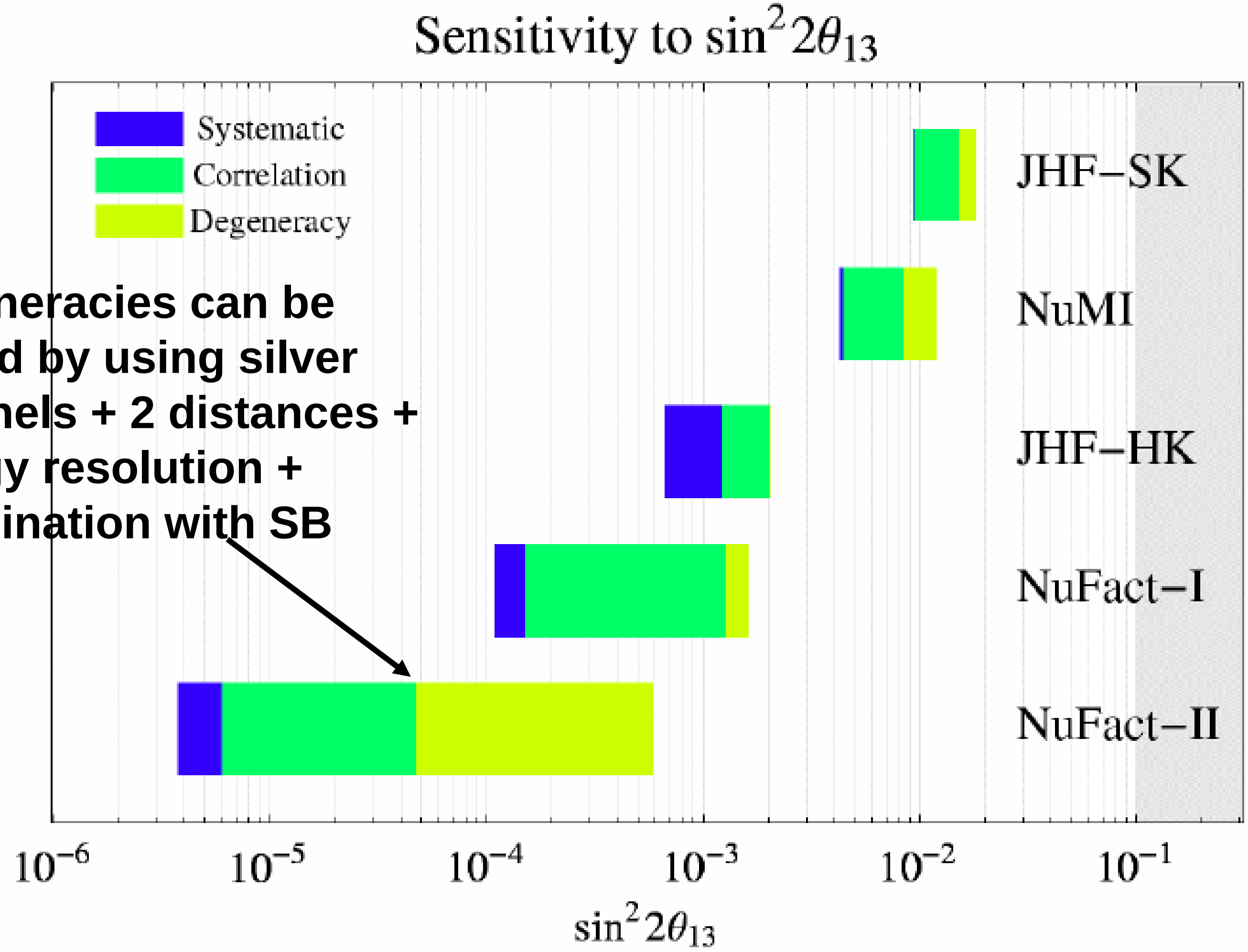
SB



Mena

Sensitivity of NUFACT

Huber, ML, Winter, hep-ph/0204352


Sensitivity to $\sin^2 2\theta_{13}$

Degeneracies can be solved by using silver channels + 2 distances + energy resolution + combination with SB

NUFACT

Muon beams (NUFACT) pose a yet not fully solve technological challenge. However, the needed detectors are massive but straight-forward extrapolations of existing technology. All appearance and disappearance channels are available, thanks to high energy and the simultaneous production of two neutrino beams (however, very good charge separation is necessary). If sufficient luminosity is achieved one can reach ultimately sensitivity to θ_{13}, δ and the neutrino mass hierarchy.

Super(Beta)-Beam

The Super Beam/Beta-Beam offers and alternative/complement to the Neutrino Factory. Different technology, different systematic errors and different E/L. Combination of both facilities is ideal to solve degeneracies. Distances are short and matter effects are difficult to observe. Taus are not produced, thus no silver channel available.

T2K-II/beta-beam will need for ultimate sensitivity 1Mton class detector. Such a detector has a great physics potential (proton decay, supernova observatory) of their own, but it is extraordinarily challenging to build (10-20 times the size of Super-Kamiokande).

Conclusions

First generation Super-Beams (T2K-I) will hopefully observe the subleading transition, measuring or setting a lower bound to θ_{13}.

To measure CP violation very intense beams and massive detectors are needed. A careful assessment of the relative merits of a T2K-II super-beam, a Beta-Beam and muon beams (NuFact) is necessary. Combination of two such facilities would be ideal (different sistematics, matter effects and L/E).