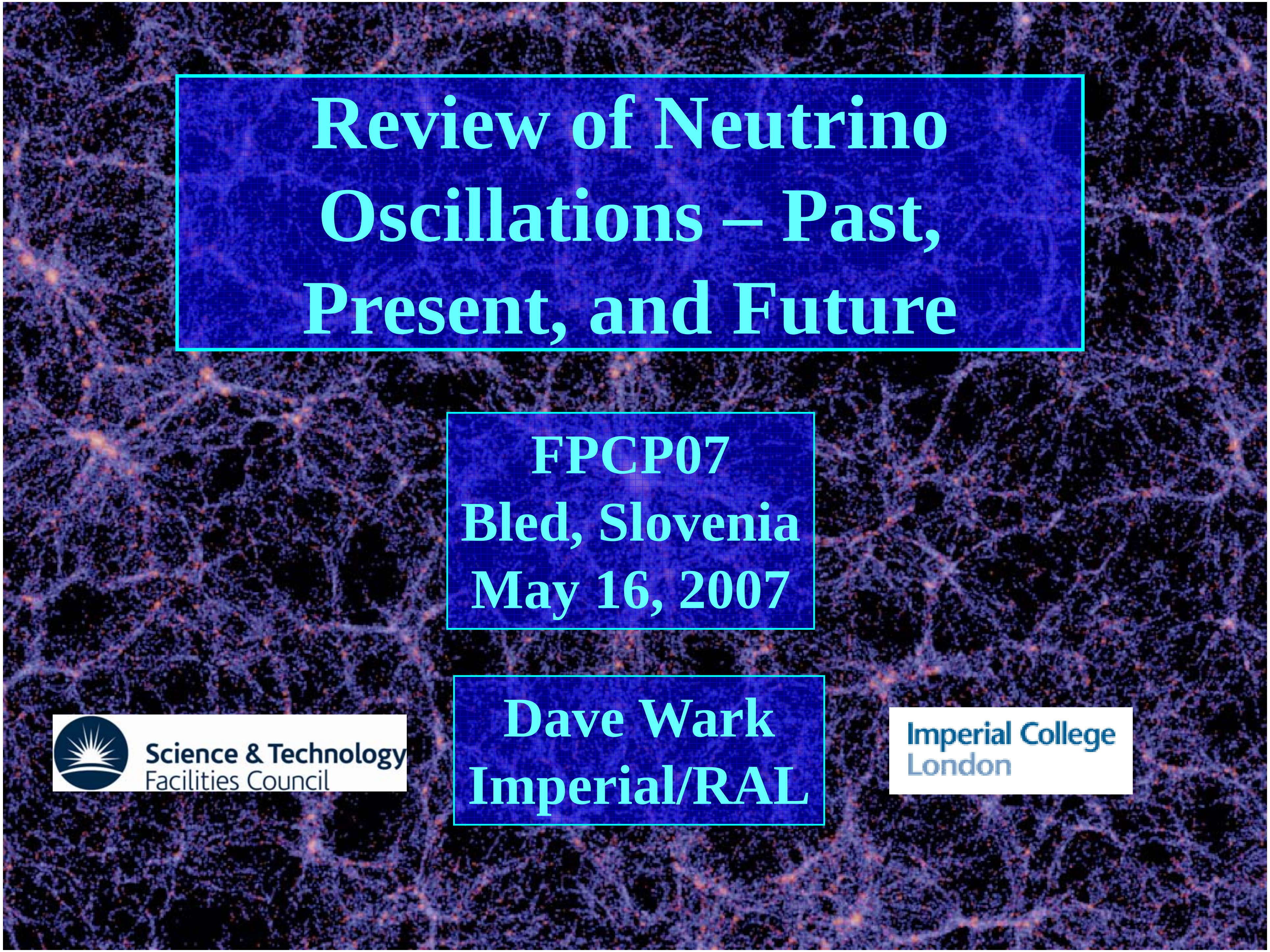
Review of Neutrino Oscillations – Past, Present, and Future

FPCP07
Bled, Slovenia
May 16, 2007

Dave Wark
Imperial/RAL

Science & Technology
Facilities Council

Imperial College
London



The Maki-Nakagawa-Sakata-Pontecorvo Matrix

If neutrinos have mass: $|\nu_l\rangle = \sum U_{li} |\nu_i\rangle$

For three neutrinos:

$$U_{li} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$where\ c_{ij} = \cos\theta_{ij},\ and\ s_{ij} = \sin\theta_{ij}$$

Three Angles

$$P(v_\mu \rightarrow v_e) = \sin^2 2\theta \sin^2 (1.27 \frac{\Delta m^2 L}{E})$$

The MNSP Matrix

If neutrinos have mass: $$|\nu_l\rangle = \sum U_{li}|\nu_i\rangle$$

For three neutrinos:

$$U_{li} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$where\ c_{ij} = \cos\theta_{ij},\ and\ s_{ij} = \sin\theta_{ij}$$

Two mass differences - each has a sign

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \sin^2 (1.27 \frac{\boxed{\Delta m^2} L}{E})$$

$$\sin^2 2\theta_m = \frac{\sin^2 2\theta}{(\omega - \cos 2\theta)^2 + \sin^2 2\theta}$$

$$\omega = -2\sqrt{2} G_F N_e E / \Delta m^2$$

The MNSP Matrix

If neutrinos have mass: $|\nu_l\rangle = \sum U_{li}|\nu_i\rangle$

For three neutrinos:

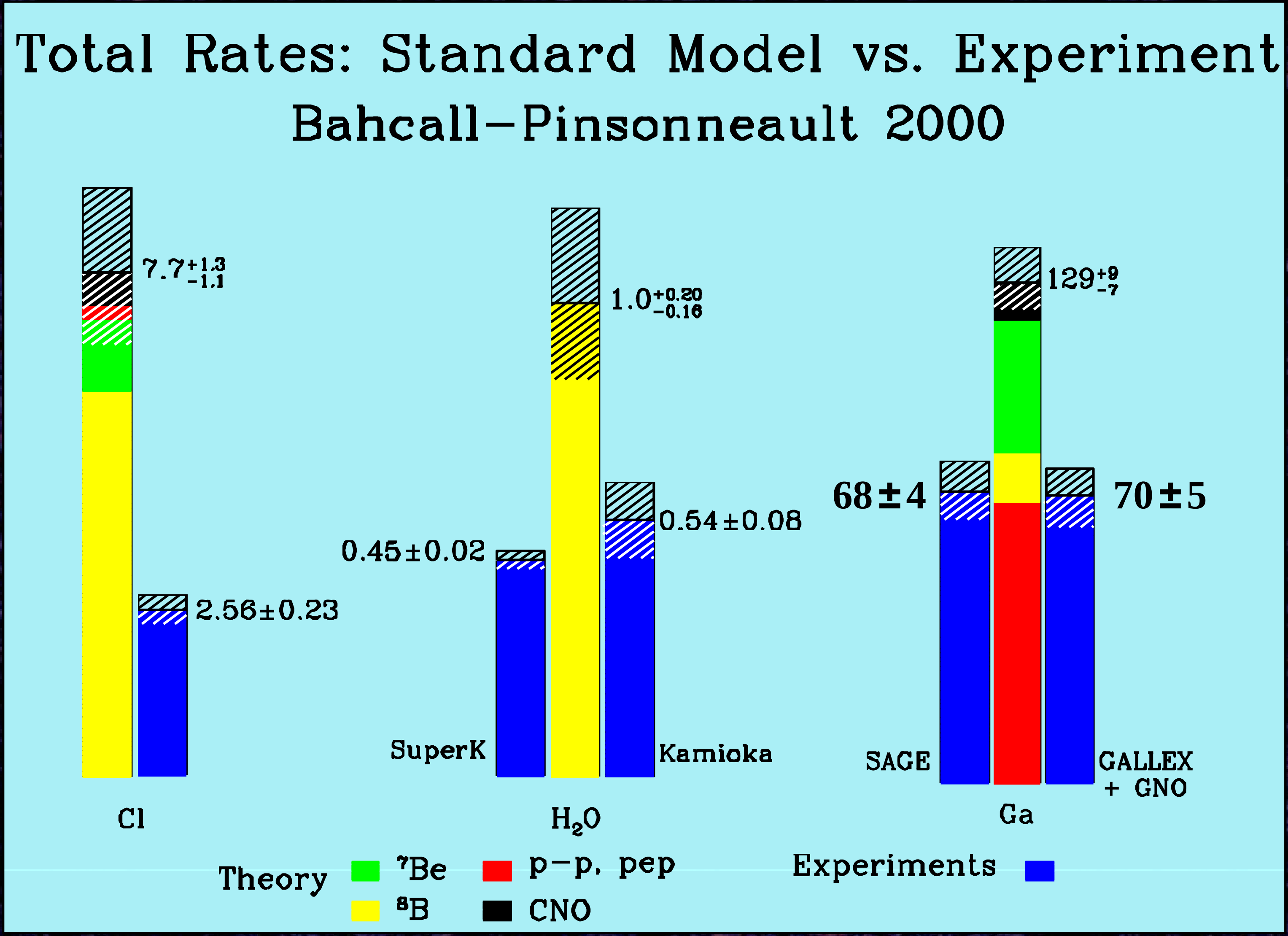
$$U_{li} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$where\ c_{ij} = \cos\theta_{ij},\ and\ s_{ij} = \sin\theta_{ij}$$

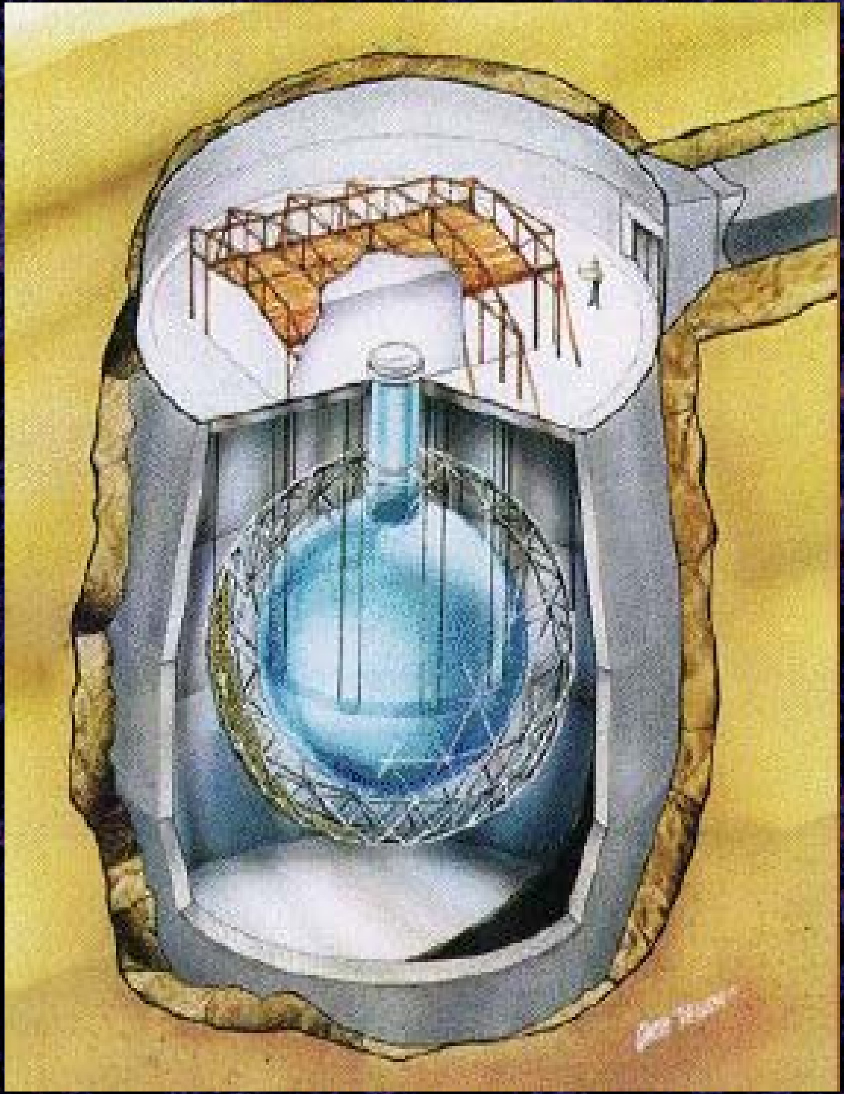
CP violating phase δ

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta \sin^2 (1.27 \frac{\Delta m^2 L}{E})$$

Measuring θ_{12}, Δm_{12}^2 – Solar Neutrinos



Measuring θ_{12}, Δm_{12}^2 - SNO



CC $\nu_e + \mathrm{d} \rightarrow \mathrm{p} + \mathrm{p} + \mathrm{e}^-$

- Q = 1.445 MeV
- good measurement of ν_e energy spectrum
- some directional info ∝ (1 – 1/3 cosθ)
- ν_e only

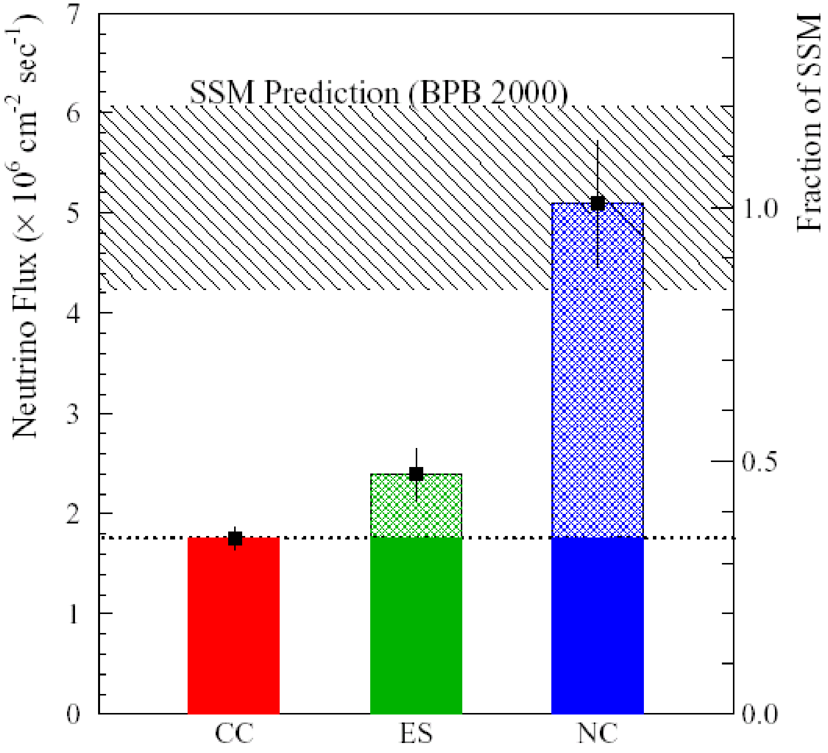
NC $\nu_x + \mathrm{d} \rightarrow \mathrm{p} + \mathrm{n} + \nu_x$

- Q = 2.22 MeV
- measures total ^{8}B ν flux from the Sun
- equal cross section for all ν types

ES $\nu_x + \mathrm{e}^- \rightarrow \nu_x + \mathrm{e}^-$

- low statistics
- mainly sensitive to ν_e, some ν_μ and ν_τ
- strong directional sensitivity

Measured SNO Fluxes



Assuming ^{8}B energy spectrum ...

Fluxes ($\times 10^6$ cm^{-2} sec^{-1})

$$\phi_{CC} = 1.76^{+0.06}_{-0.05}\ (\text{stat.}) \pm 0.09\ (\text{sys.})$$

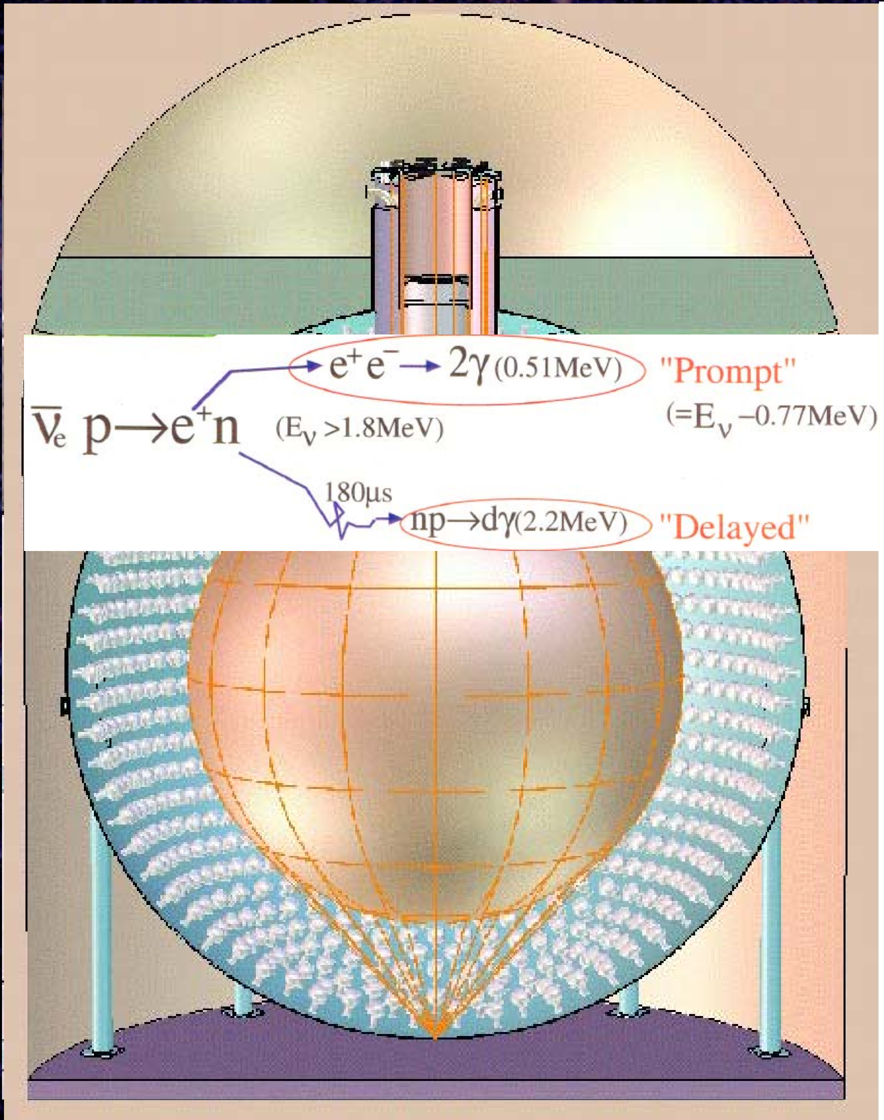
$$\phi_{ES} = 2.39^{+0.24}_{-0.23}\ (\text{stat.}) \pm 0.12\ (\text{sys.})$$

$$\phi_{NC} = 5.09^{+0.44}_{-0.43}\ (\text{stat.})^{+0.46}_{-0.43}\ (\text{sys.})$$

Repeated with NaCl to enhance NC signal, blind analysis

→All results agreed.

Measuring θ_{12}, Δm_{12}^2 - KamLAND

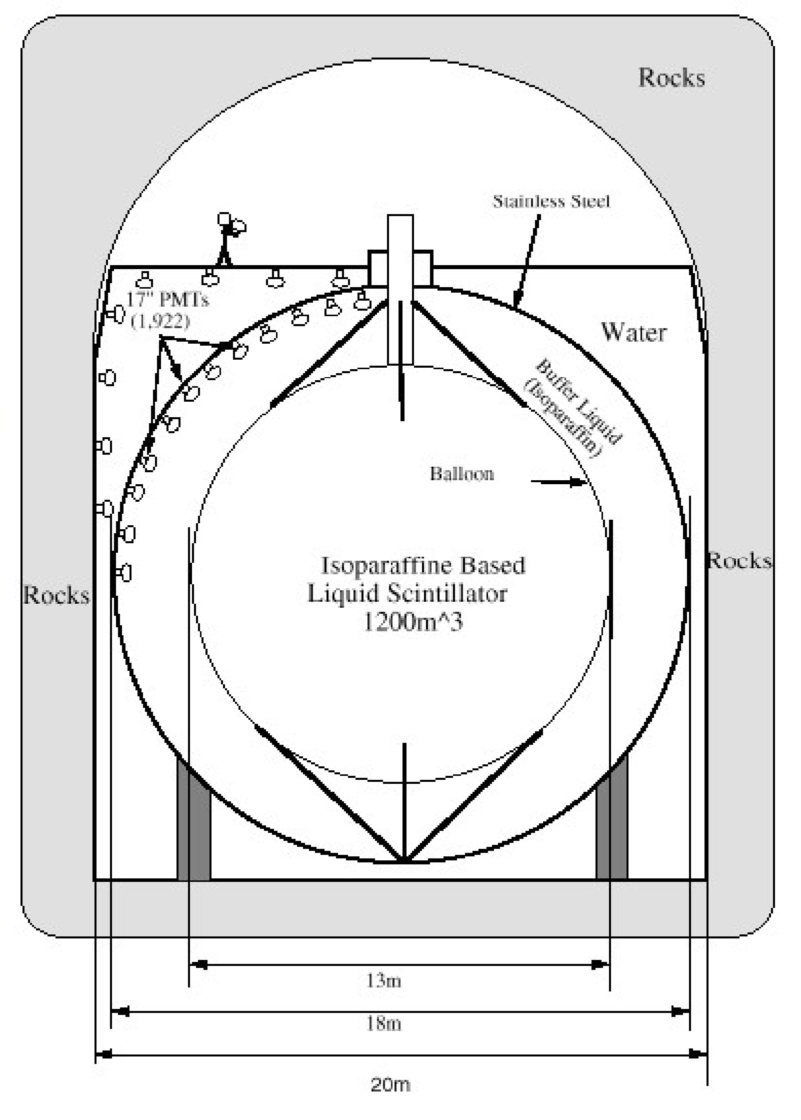


$\overline{\nu}_e\, p \rightarrow e^+ n$ ($E_\nu > 1.8$MeV)

$e^+ e^- \rightarrow 2\gamma$ (0.51MeV) "Prompt" ($= E_\nu - 0.77$MeV)

180μs

$np \rightarrow d\gamma$ (2.2MeV) "Delayed"

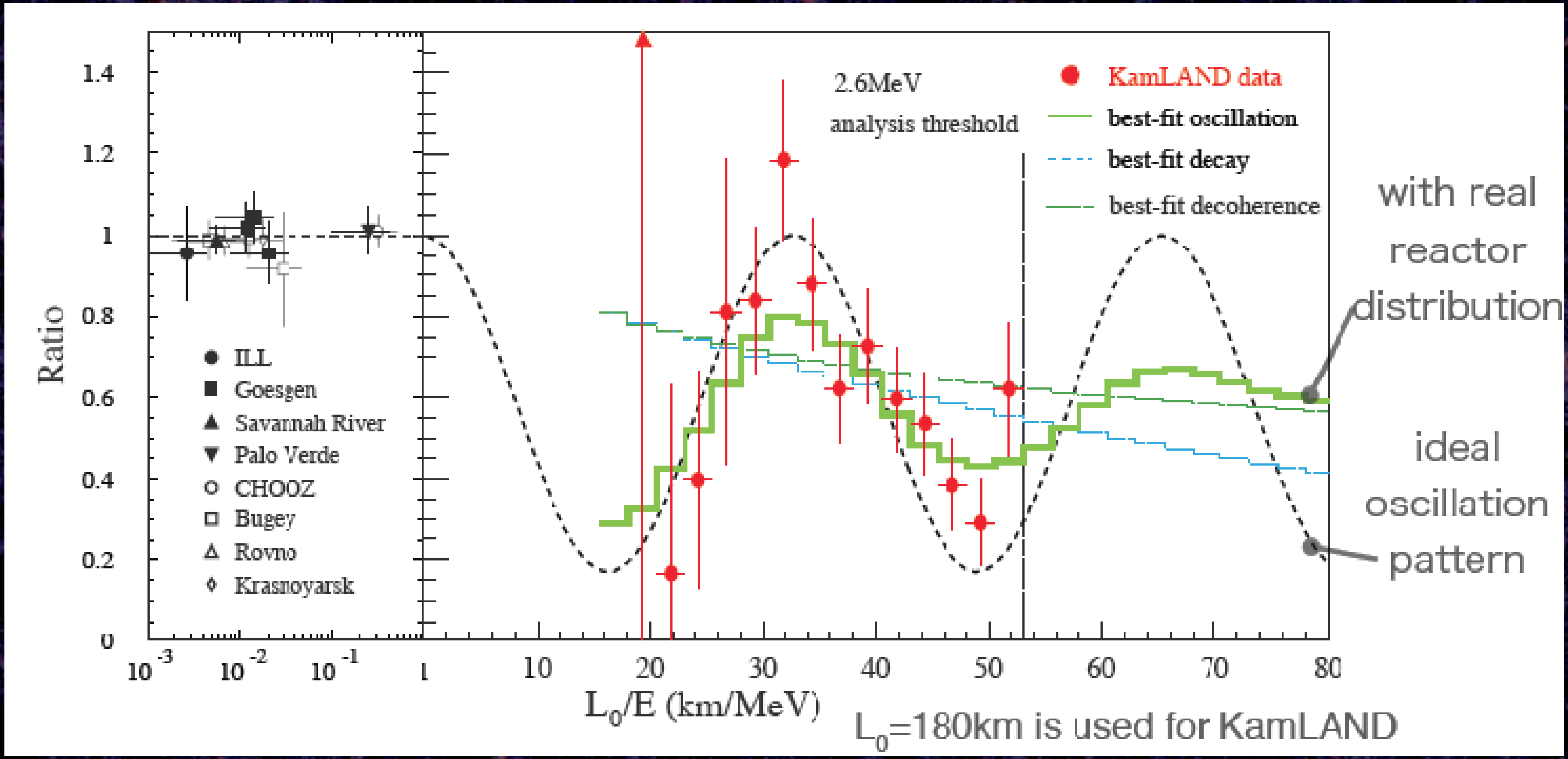


Sum over all Japanese power reactors...

Measuring θ_{12}, Δm_{12}^2 - KamLAND

Total Rates: Standard Model vs. Experiment

Slides from S. Enomoto's talk at WIN05



with real reactor distribution

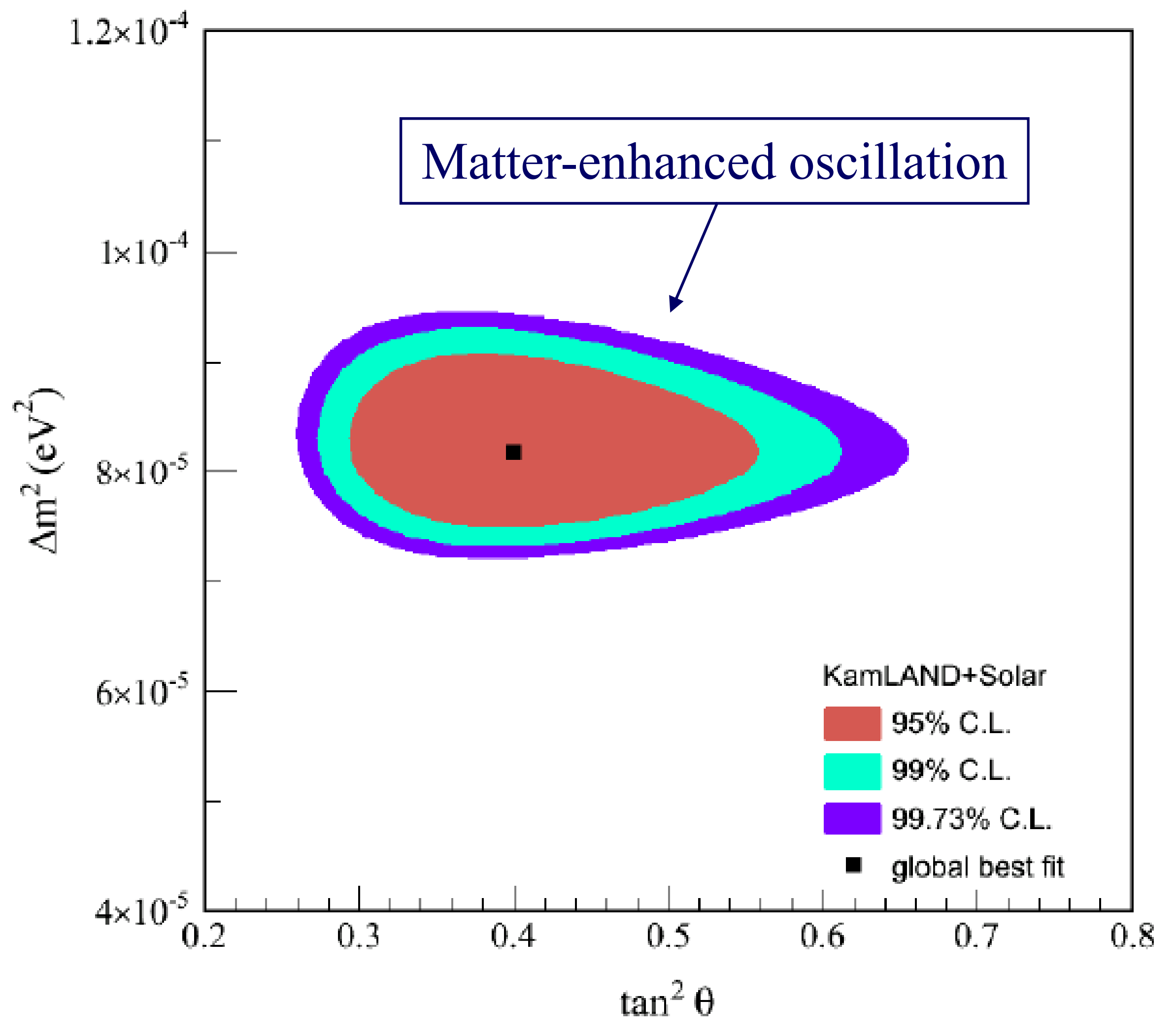
ideal oscillation pattern

L_0=180km is used for KamLAND

Proved (with other results) that neutrinos oscillate…

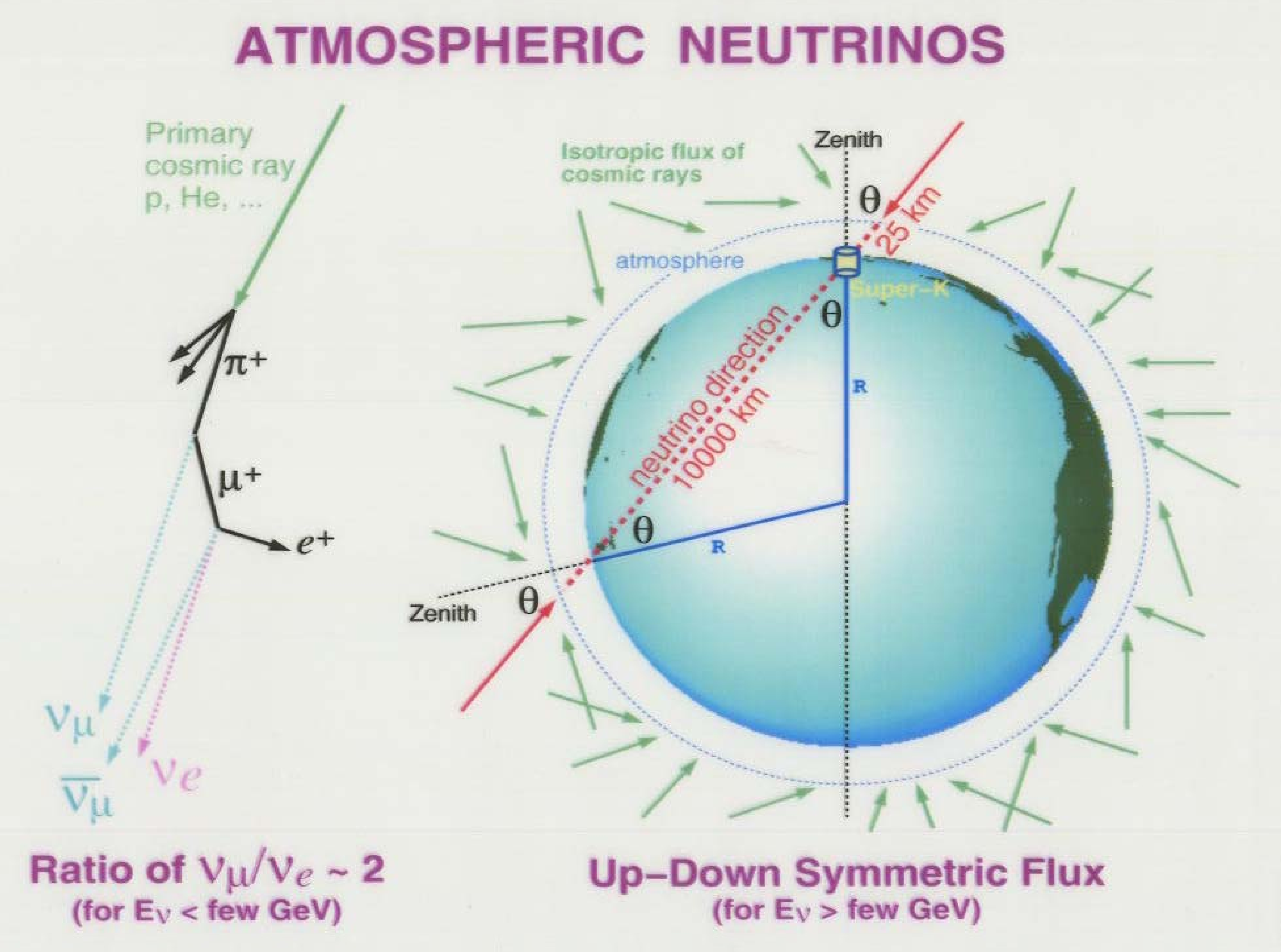
…or at least do a damned fine impression.

Measuring θ_{12}, Δm_{12}^2



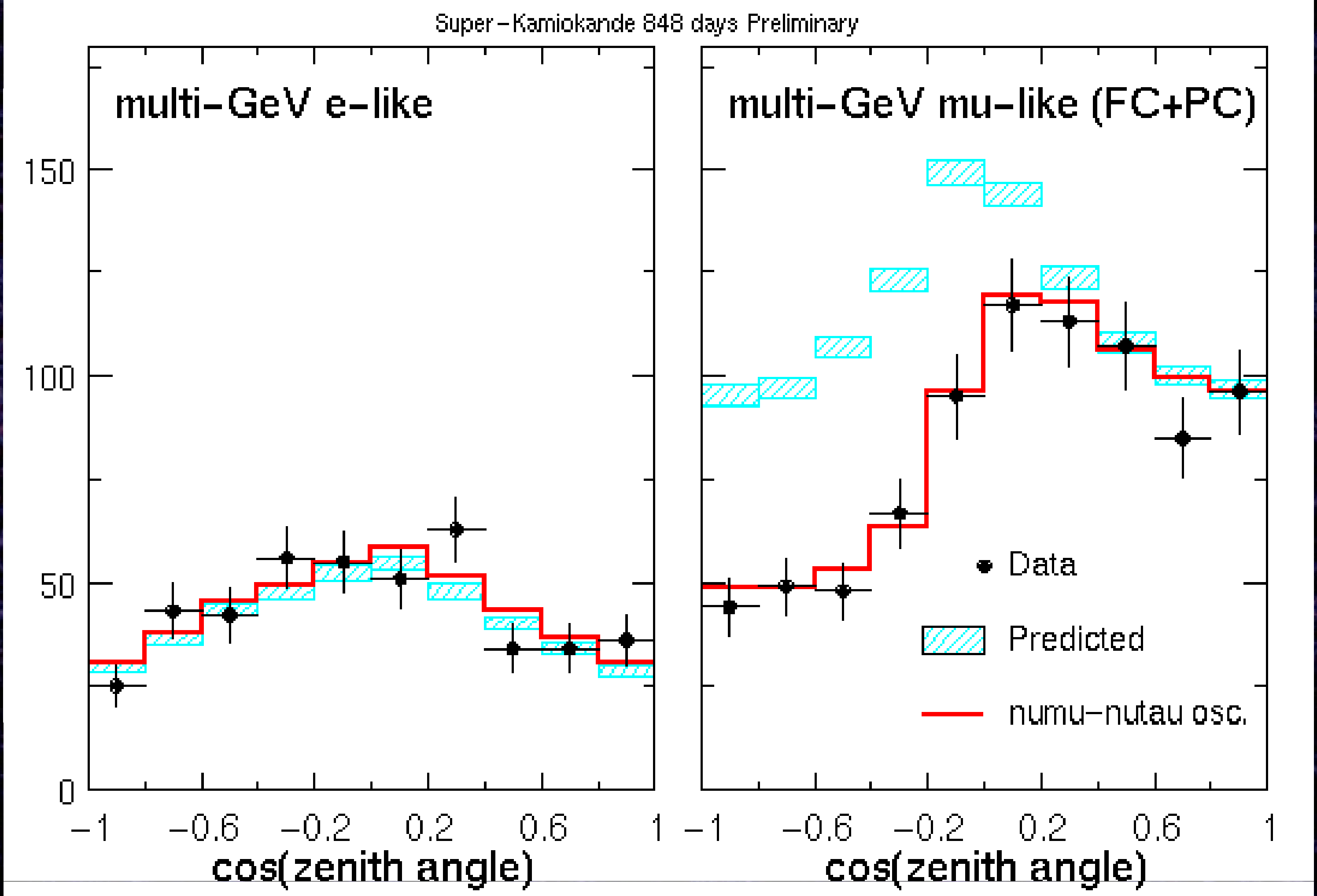
Solar + KamLAND

1^{st} Smoking Gun – SK Atmospheric

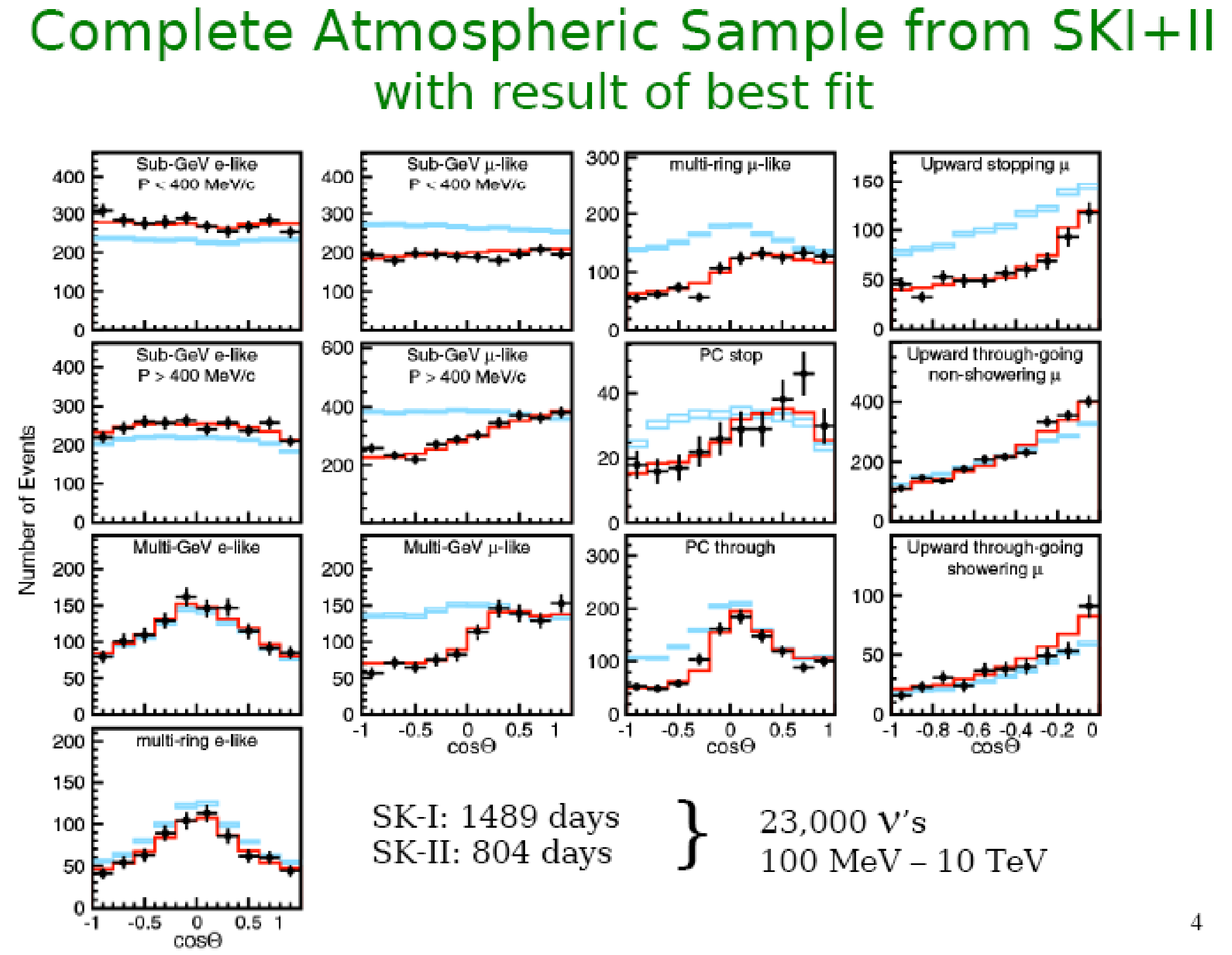


Observed ratio ~1, Look at zenith angle distributions…

SK data as a function of zenith angle



1st Smoking Gun – SK Atmospheric



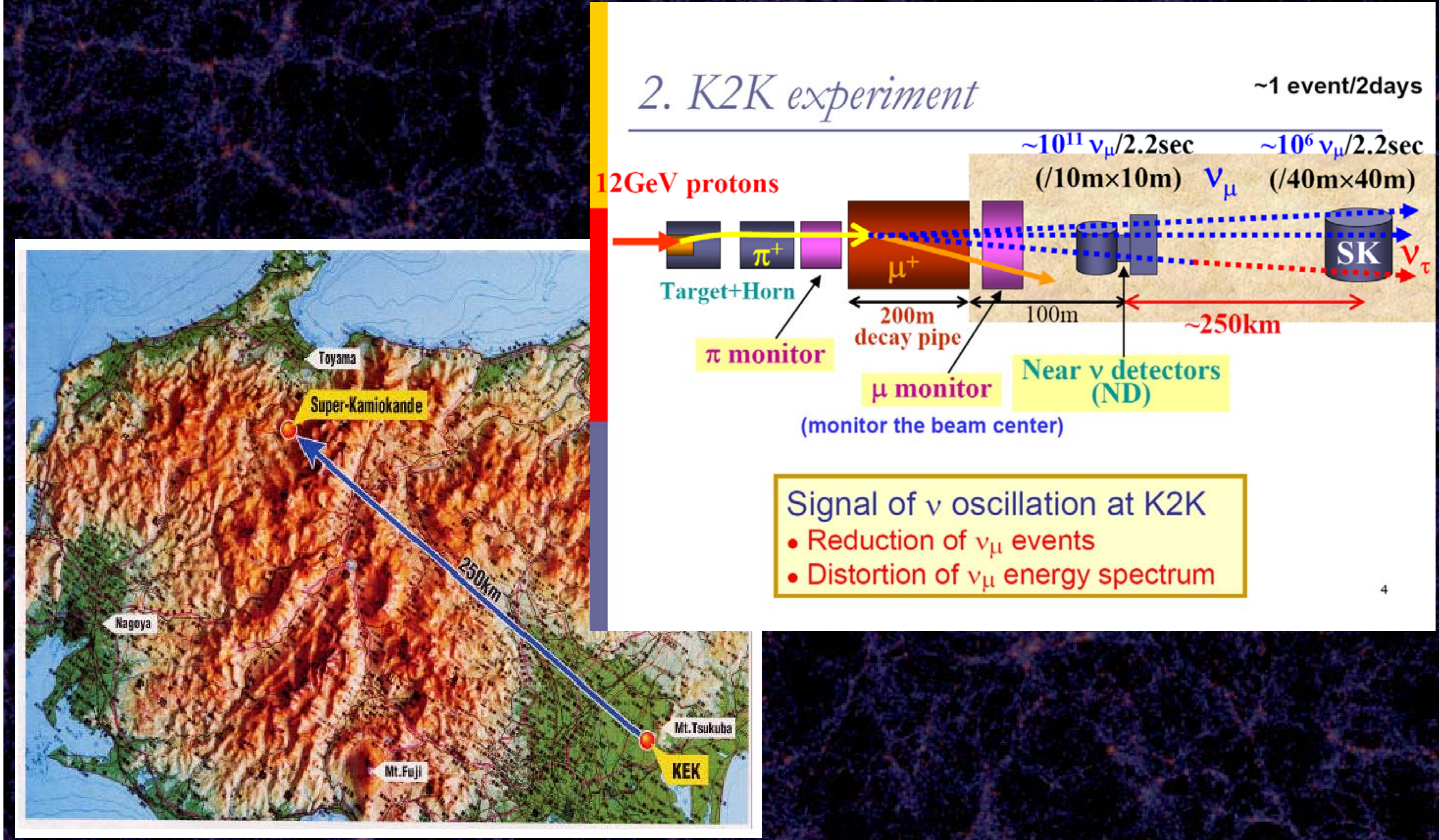
Complete Atmospheric Sample from SKI+II
with result of best fit

SK-I: 1489 days
SK-II: 804 days } 23,000 ν's
100 MeV – 10 TeV

4

Latest analysis from Chris Walter, ICHEP06.

First Accelerator Confirmation – K2K

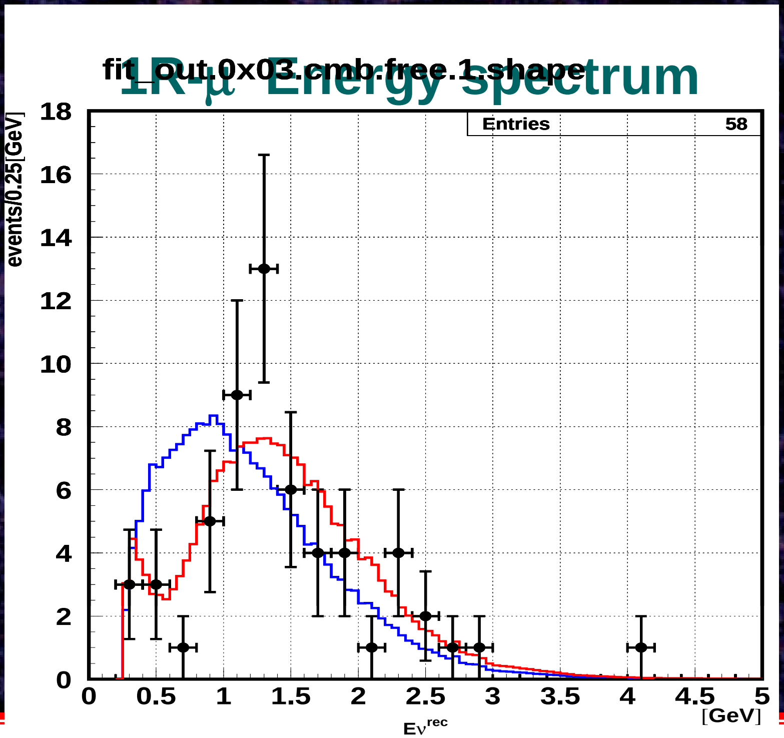


2. K2K experiment

Signal of ν oscillation at K2K
- Reduction of ν_μ events
- Distortion of ν_μ energy spectrum

4

Final K2K Statistics



	N_{sk}^{obs}	N_{sk}^{pred}
All	112	155.9
1 ring	67	99.0
μ-like	58	90.8
e-like	9	8.2
multi-ring	45	56.8

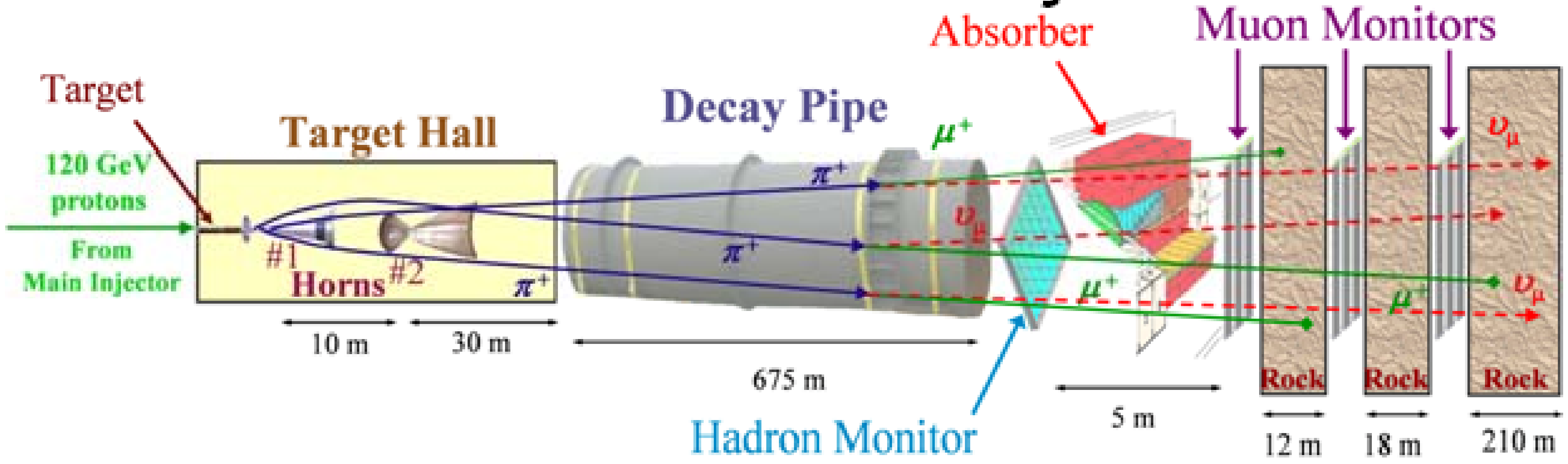
Oscillation – disappearance – two flavors analysis

$\sin^2 2\theta = 1.19 \pm 0.23$ $\Delta m^2 = (2.55 \pm 0.40)\times 10^{-3}\,\mathrm{eV}^2$

$1.88\times 10^{-3} \leq \Delta m^2 \leq 3.48\times 10^{-3}\,\mathrm{eV}^2$ (90%CL) for $\sin^2 2\theta = 1$

Plots from Pier Loverre's talk.

Neutrinos at the Main Injector



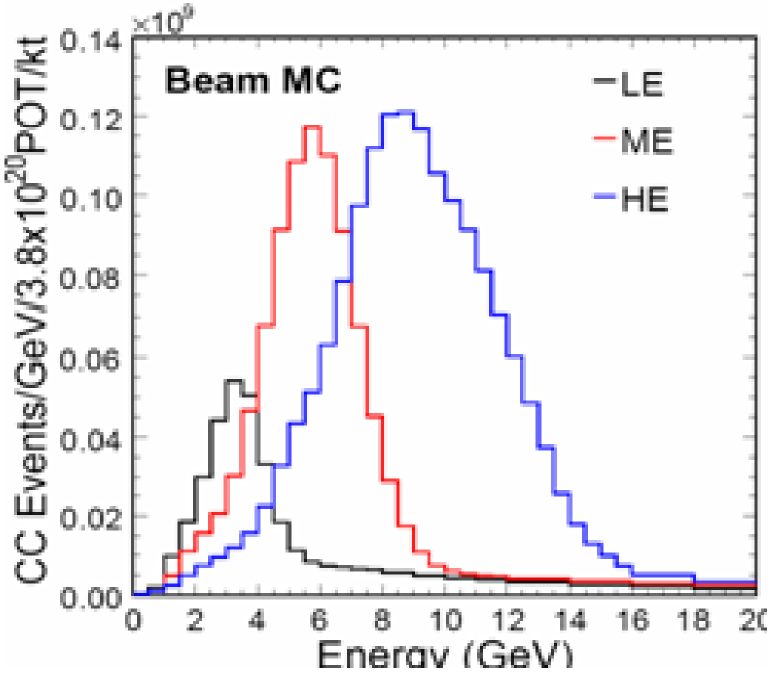
- 120 GeV protons strike 0.9m graphite target
- 2 focusing horns: 180kA, each is 3m long
- 2m diameter evacuated decay pipe (<0.5Torr)
- 4 Rad-hard monitoring planes see remnant p, μ
- Target position adjusts to change beam energy
- 10 µs spills at up to 0.5Hz

On Axis:

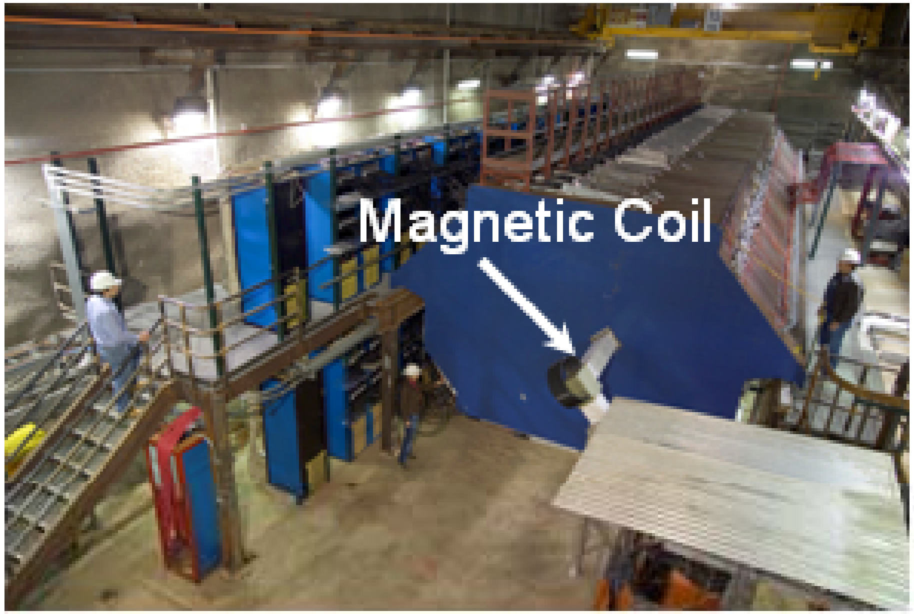
ν_μ = 92.9%

$\bar{\nu}_\mu$ = 5.8%

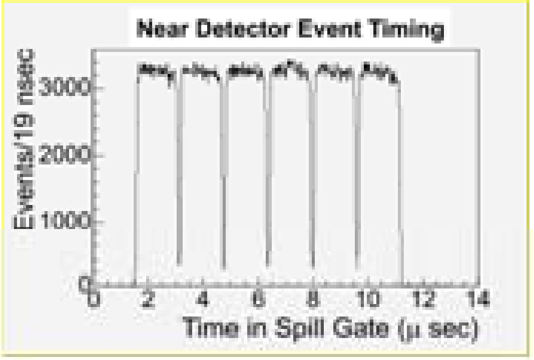
$\bar{\nu}_e + \nu_e$ = 1.5%

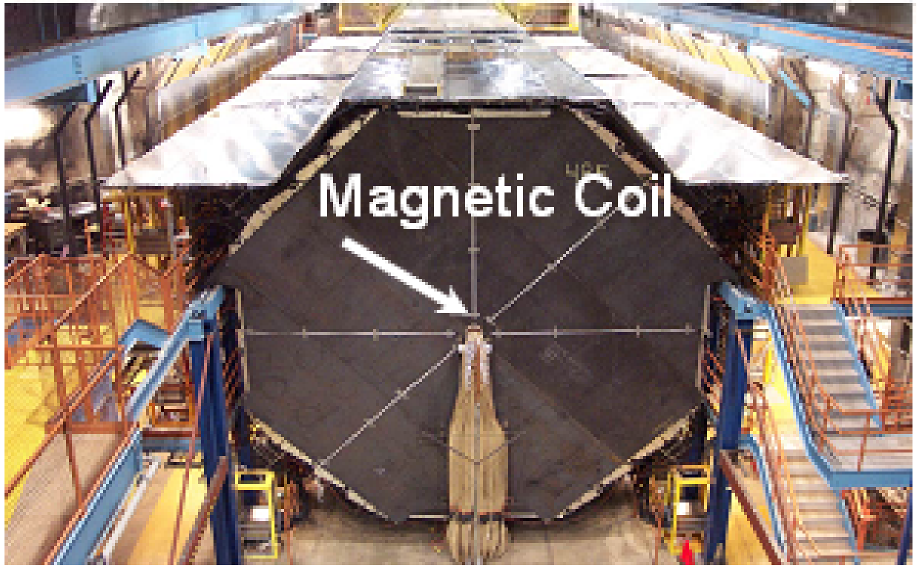


MINOS Detectors

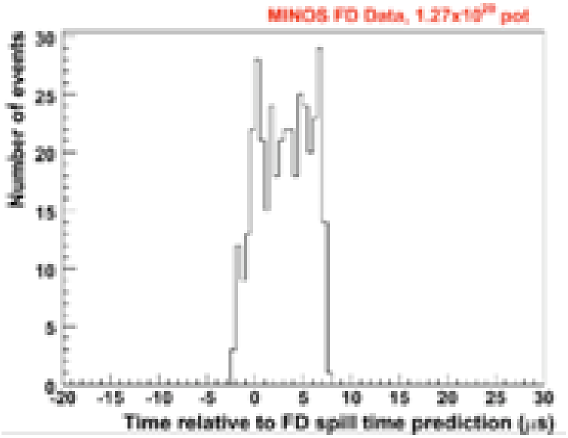


- 980 tons, 1 km from target
- Data used to predict ν spectrum at far detector
- 4.8 m x 3.8 m, 15 m long
- Front end electronics read out every 19nsec

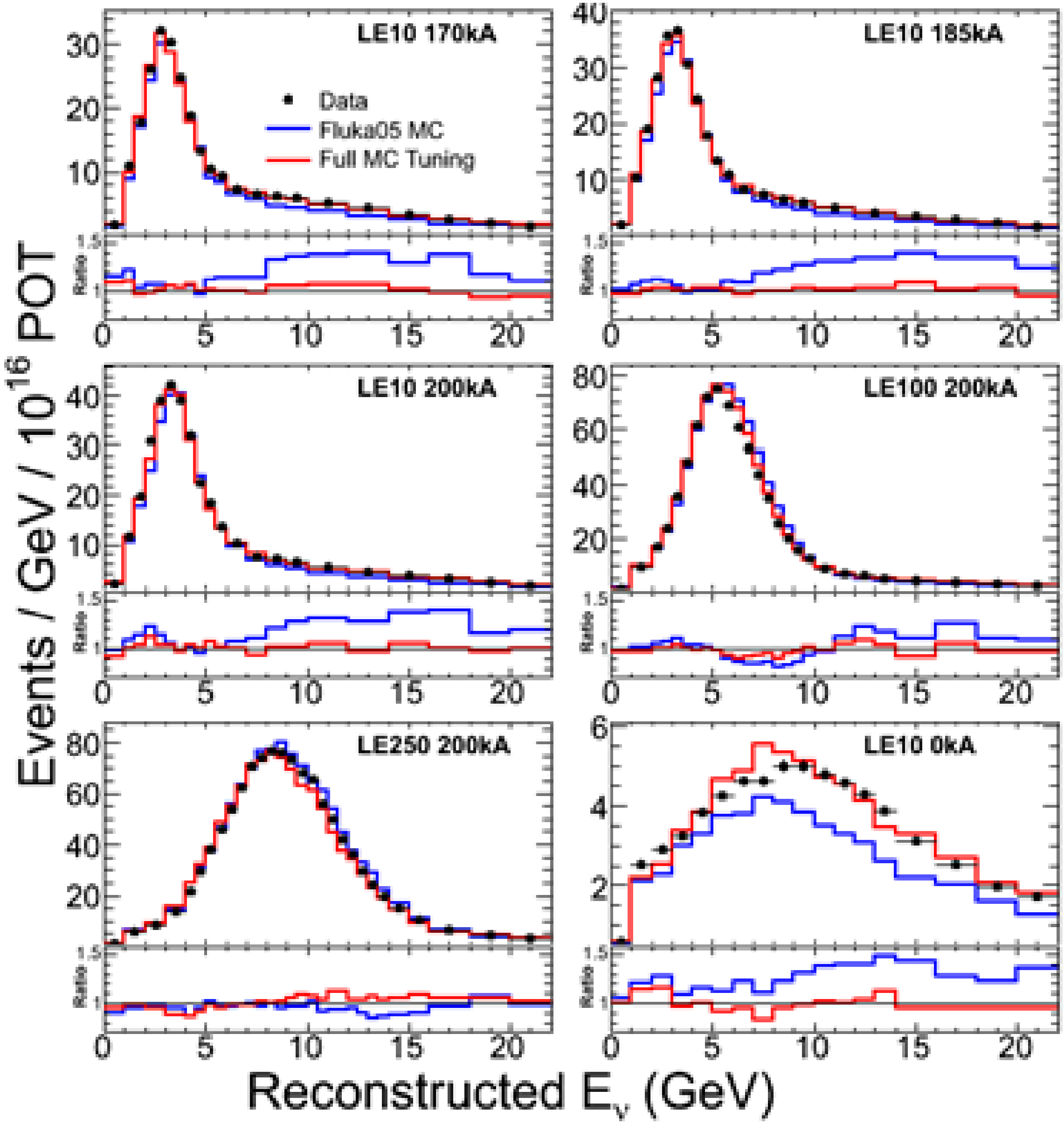




- 5.4 kT, 735 km
- 8 m octagon, 30 m long
- Front end electronics capable <1μsec timing resolution



Energy Spectrum Tuning

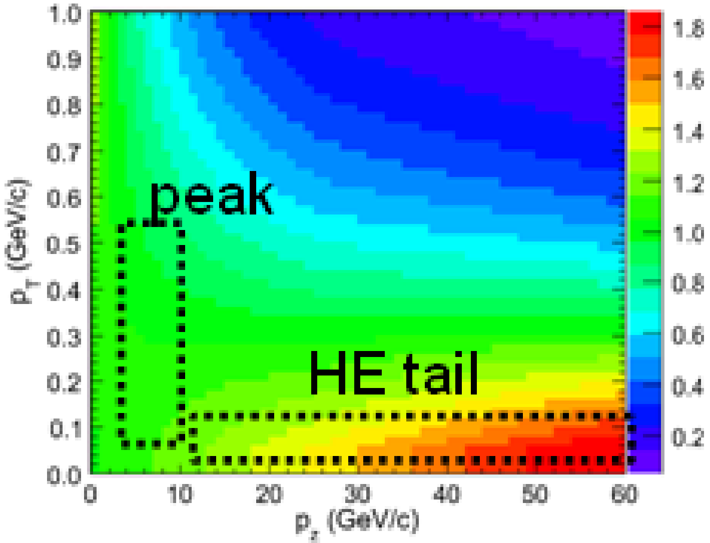


Reweight pion x_F and p_T to improve data/MC agreement

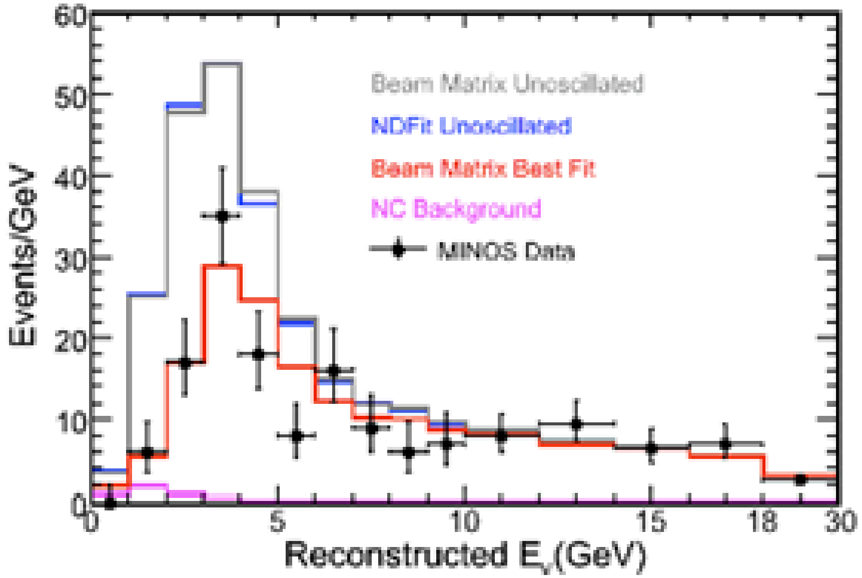
Include horn focusing, NC norm and energy scale as nuisance parameters

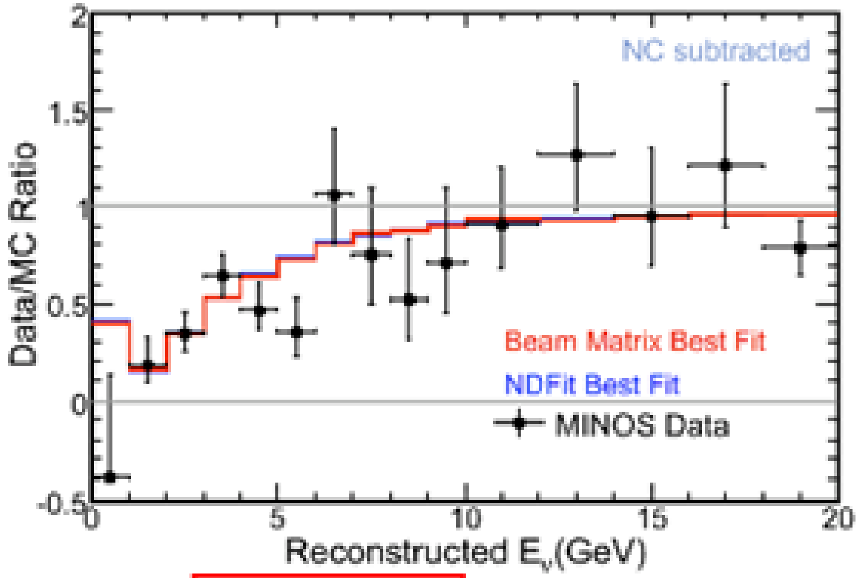
Osc. analyses use these weights

P_T v P_z weights



Fit for Oscillation Parameters





$$\chi^2 = \sum_{i=1}^{\text{nbins}}\left[2(e_i - o_i) + 2o_i\ln(o_i/e_i)\right] + \boxed{\sum_{j=1}^{\text{nsys}}\Delta s_j^2/\sigma_{s_j}^2}$$

Penalty terms for systematic uncertainties

$$\left|\Delta m^2_{32}\right| = 2.74^{+0.44}_{-0.26}\ (\text{stat}+\text{syst})\times 10^{-3}\,\text{eV}^2$$

$$\sin^2 2\theta_{23} = 1.00_{-0.13}\ (\text{stat}+\text{syst})$$

$$\text{Normalization} = 0.98$$

Fit constrained to physical region

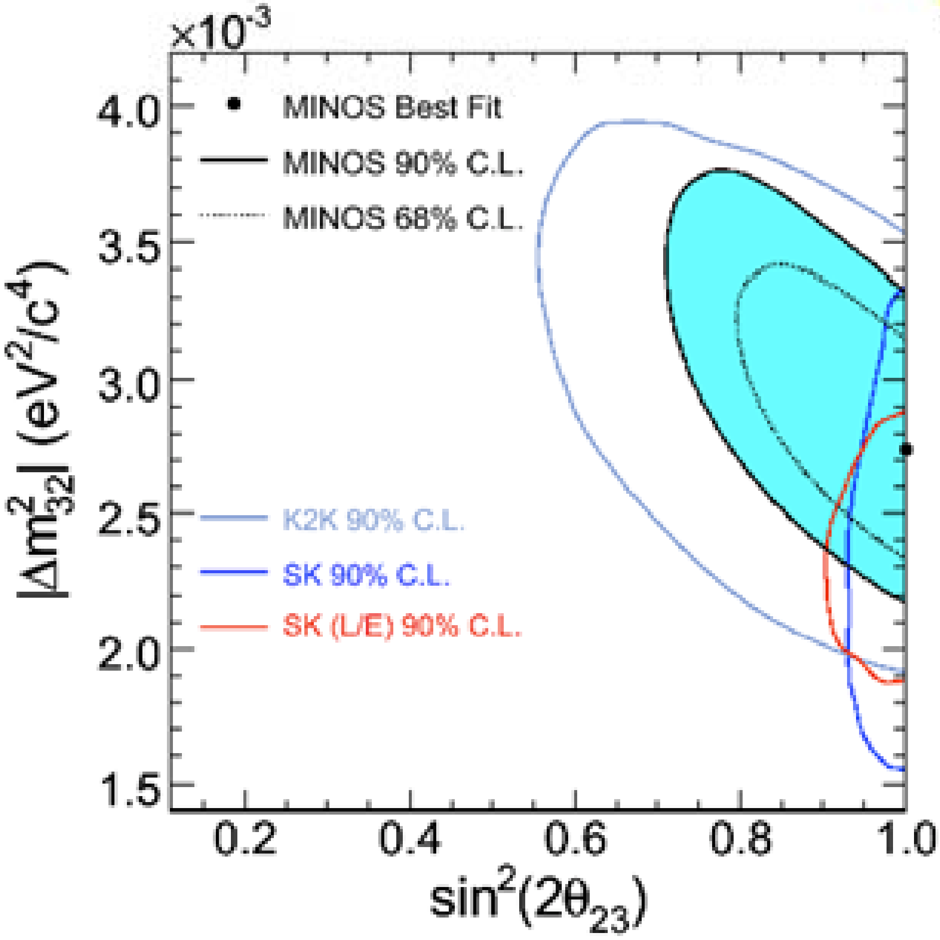
Best Fit Confidence Intervals

- Contours are for the matrix method and include fit for nuisance parameters
- Other methods give consistent best fit points
- MINOS results already competitive with other experiments

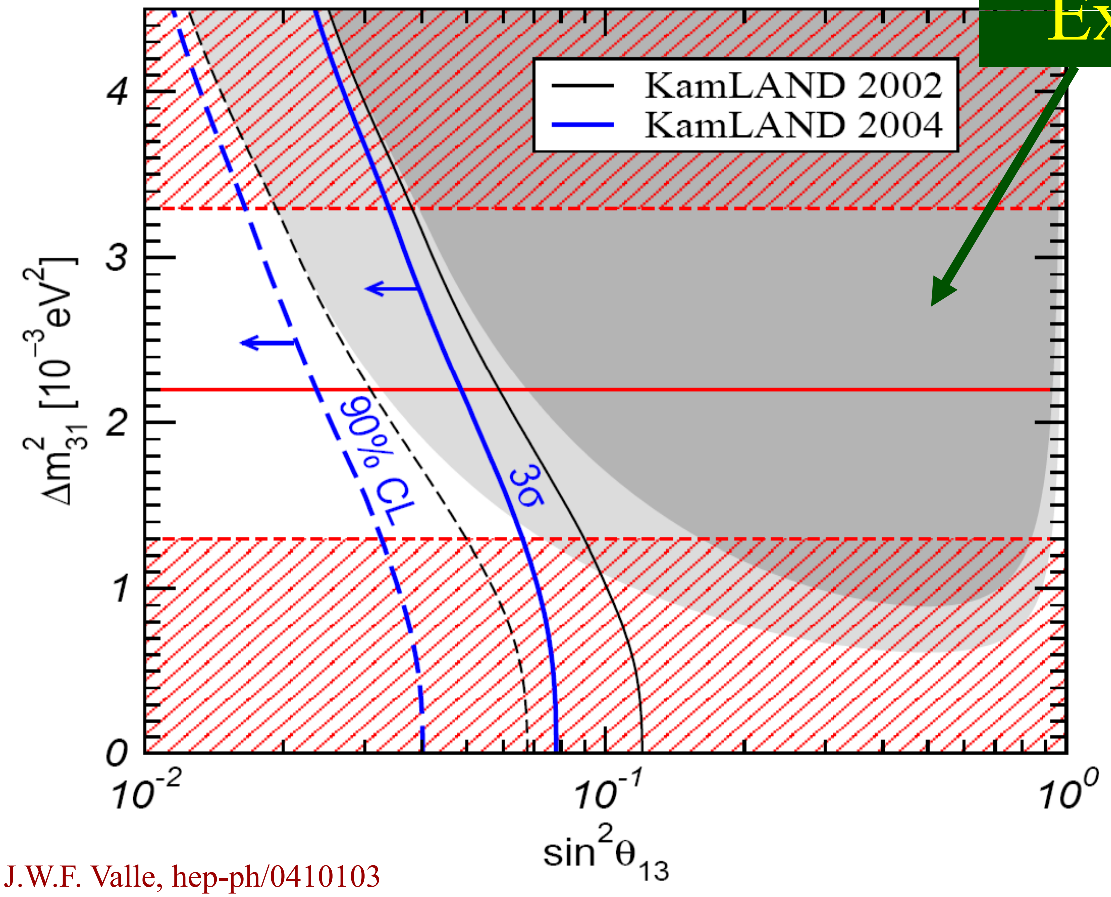
$$\left|\Delta m^2_{32}\right| = 2.74^{+0.44}_{-0.26}\ (\mathrm{stat+syst})\times 10^{-3}\,\mathrm{eV}^2$$

$$\sin^2 2\theta_{23} = 1.00_{-0.13}\ (\mathrm{stat+syst})$$

$$\mathrm{Normalization} = 0.98$$



What about θ_{13}?



Excluded by Chooz Reactor Experiment

J.W.F. Valle, hep-ph/0410103

All we have at present are limits, showing θ_{13} is small…

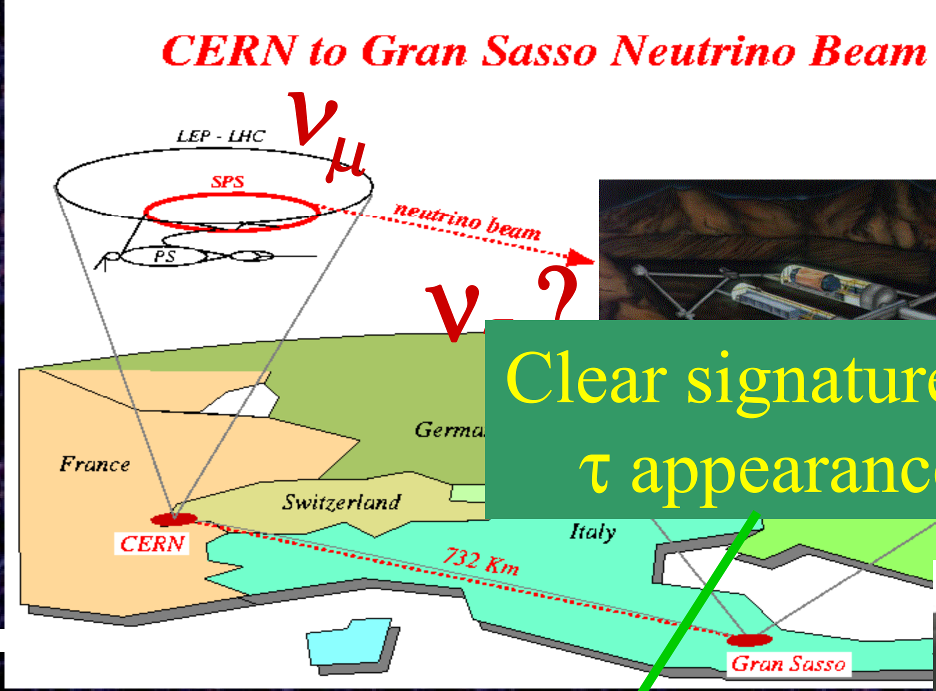
What are the experimental targets for new accelerator experiments?

Total Rates: Standard Model vs Experiment

- More accurate determinations of already measured parameters (better than CKM?) ⇒ is $\theta_{23} = 45°$?
- Other signatures of oscillations – ν_τ appearance.
- θ_{13} – look for $\nu_\mu \rightarrow \nu_e$,
- The sign of Δm_{23}^2 (or Δm_{31}^2)
- The CP-violating phase δ
- First, however, resolve the LSND anomaly.

Has now been done! See talk by H. Tanaka. We don't know what happened to LSND, but it doesn't appear to be oscillations…

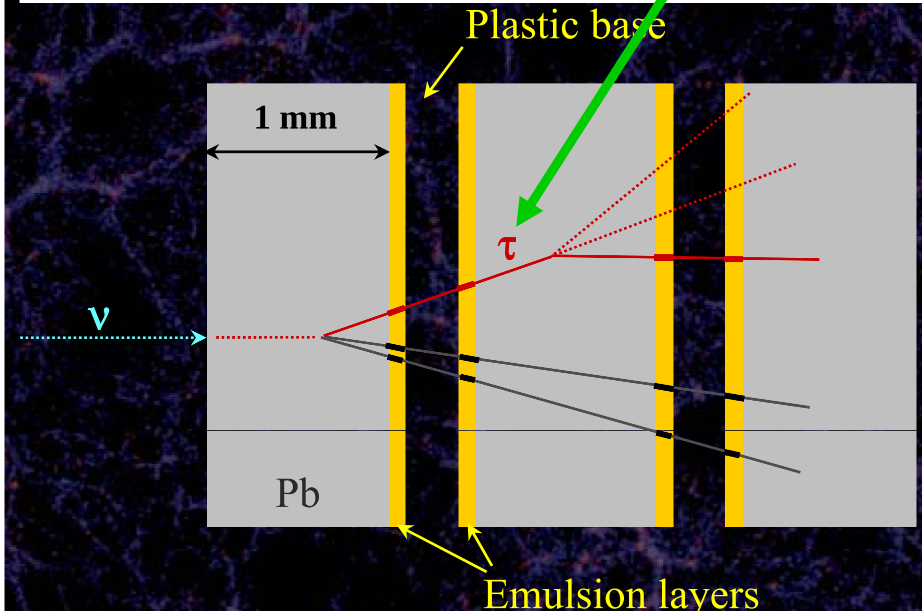
The near future – CNGS and OPERA

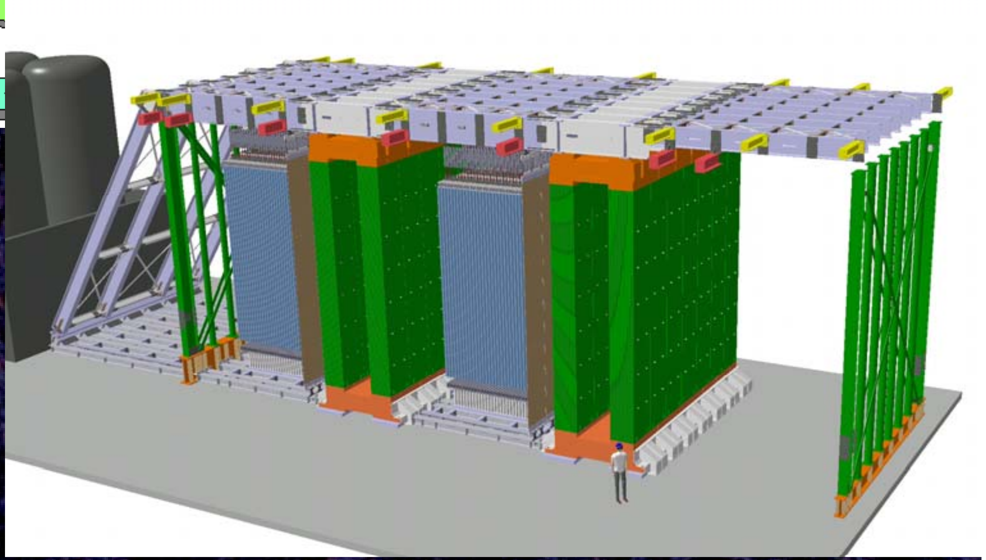


Clear signature of τ appearance

OPERA

5 yrs nominal running, best-fit SK
~12 signal events, ~1 background





Ready for data taking
autumn 2007

Dave Wark
Imperial College/RAL

Three neutrino mixing.

If neutrinos have mass: $|\nu_l\rangle = \sum U_{li}|\nu_i\rangle$

$$U_{li} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

where c $\cos\theta$ *and* s $\sin\theta$

$$\begin{aligned} P_{e\mu} \cong{} & \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2 \Delta \\ & \mp \alpha \sin 2\theta_{13} \sin\delta \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin^3 \Delta \\ & - \alpha \sin 2\theta_{13} \cos\delta \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos\Delta \sin 2\Delta \\ & + \alpha^2 \cos^2 \theta_{23} \sin^2 2\theta_{12} \sin^2 \Delta \end{aligned}$$

where $\alpha =$ ~0.03 and $\Delta =$ ~π/4

And $\sin^2 2\theta_{13} <$ ~0.14

Three neutrino mixing.

- Until limit is improved by a factor of a few the first term dominates.
- Optimal situation for CP measurement is when all terms are ≈ equal, or when $\sin^2 2\theta_{13} \sim 0.01$.

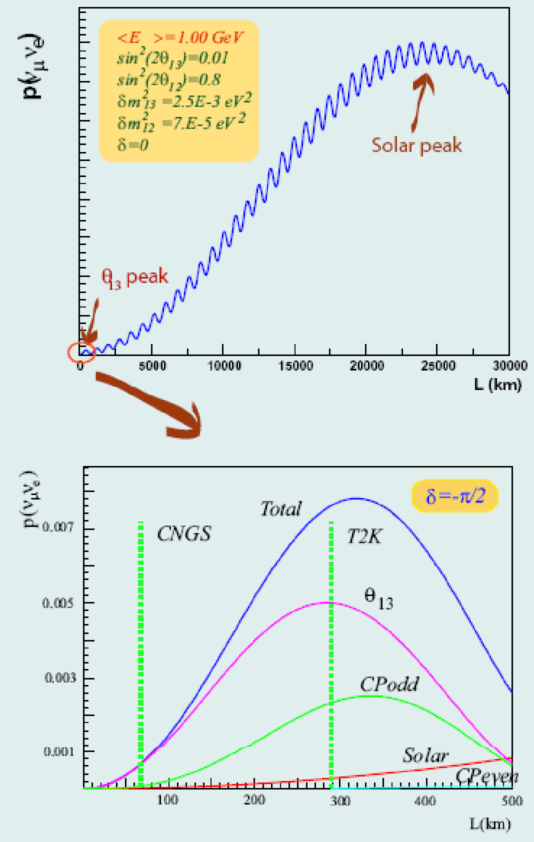
$$
\begin{aligned}
P_{e\mu} \cong\ & \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2 \Delta \\
& \mp \alpha \sin 2\theta_{13} \sin\delta \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin^3 \Delta \\
& - \alpha \sin 2\theta_{13} \cos\delta \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos\Delta \sin 2\Delta \\
& + \alpha^2 \cos^2 \theta_{23} \sin^2 2\theta_{12} \sin^2 \Delta
\end{aligned}
$$

where $\alpha =$ ~0.03 and $\Delta =$ ~π/4

And $\sin^2 2\theta_{13} < \sim 0.14$

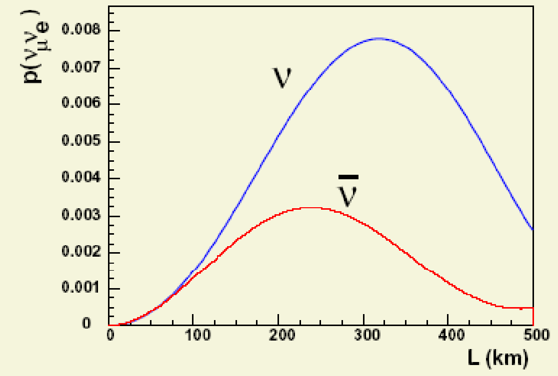
Three neutrino mixing.

Sub leading $\nu_\mu - \nu_e$ oscillations



$$
\begin{aligned}
p(\nu_\mu \to \nu_e) = {} & 4c^2_{13}s^2_{13}s^2_{23}\sin^2\frac{\Delta m^2_{13}L}{4E} && \theta_{13}\ \text{driven}\\
& + 8c^2_{13}s_{12}s_{13}s_{23}(c_{12}c_{23}cos\delta - s_{12}s_{13}s_{23})\cos\frac{\Delta m^2_{23}L}{4E}\sin\frac{\Delta m^2_{13}L}{4E}\sin\frac{\Delta m^2_{12}L}{4E} && \text{CPeven}\\
& - 8c^2_{13}c_{12}c_{23}s_{12}s_{13}s_{23}\sin\delta\sin\frac{\Delta m^2_{23}L}{4E}\sin\frac{\Delta m^2_{13}L}{4E}\sin\frac{\Delta m^2_{12}L}{4E} && \text{CPodd}\\
& + 4s^2_{12}c^2_{13}\{c^2_{13}c^2_{23} + s^2_{12}s^2_{23}s^2_{13} - 2c_{12}c_{23}s_{12}s_{23}s_{13}cos\delta\}\sin\frac{\Delta m^2_{12}L}{4E} && \text{solar driven}\\
& - 8c^2_{12}s^2_{13}s^2_{23}\cos\frac{\Delta m^2_{23}L}{4E}\sin\frac{\Delta m^2_{13}L}{4E}\frac{aL}{4E}(1-2s^2_{13}) && \text{matter effect (CP odd)}
\end{aligned}
$$

θ_{13} discovery requires total probability greater than solar driven probability



Leptonic CP discovery requires

$$A_{CP} = \frac{P(\nu_\mu\to\nu_e) - P(\overline{\nu}_\mu\to\overline{\nu}_e)}{P(\nu_\mu\to\nu_e) + P(\overline{\nu}_\mu\to\overline{\nu}_e)} \neq 0$$

Three neutrino mixing.

- Most experiments make essentially one measurement of $P(\nu_\mu \to \nu_e)$.
- There are correlations between parameters, including ones that cannot be measured at accelerators.
- There are degenerate solutions from the sign of Δm_{31}^2 and whether θ_{23} is greater or smaller than $\pi/4$.

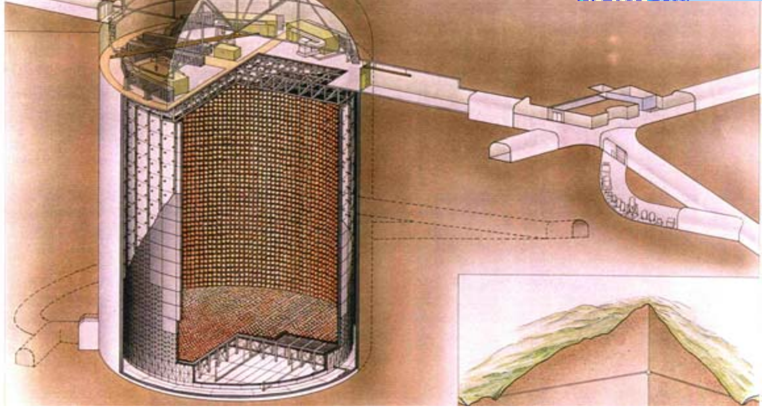
$$
\begin{aligned}
P(\nu_\mu \to \nu_e) &= 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2 \frac{\Delta m_{31}^2 L}{4E} \times \left(1 + \frac{2a}{\Delta m_{31}^2} \left(1 - 2S_{13}^2\right)\right) \\
&+8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E} \\
&-8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E} \\
&+4S_{12}^2 C_{13}^2 \left\{C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta\right\} \sin^2 \frac{\Delta m_{21}^2 L}{4E} \\
&-8C_{13}^2 S_{13}^2 S_{23}^2 \cos \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \frac{aL}{4E} \left(1 - 2S_{13}^2\right)
\end{aligned}
$$

Long Baseline $\nu_\mu \Leftrightarrow \nu_e$ Appearance

- *Modest improvements (factor~2) available from MINOS and OPERA*
- *Major improvements in sensitivity will require major new dedicated experiments.*
- *Superbeams – ν derived from π decay:*
  - *T2KI, T2KII*
  - *NOvA, NOvA + Proton Driver*
  - *CERN → Modanne or LNGS or…*
  - *BNL → Homestake or Henderson*
  - *FNAL → various sites*
- *β Beams – ν_e derived from β-decaying nucleus:*
  - *CERN*
  - *FNAL*
  - *EC beams? – produces "monoenergetic" neutrinos*
- *Neutrino Factories – ν_e/ν_μ derived from μ decay:*
  - *CERN*
  - *RAL*
  - *FNAL*
  - *JPARC*

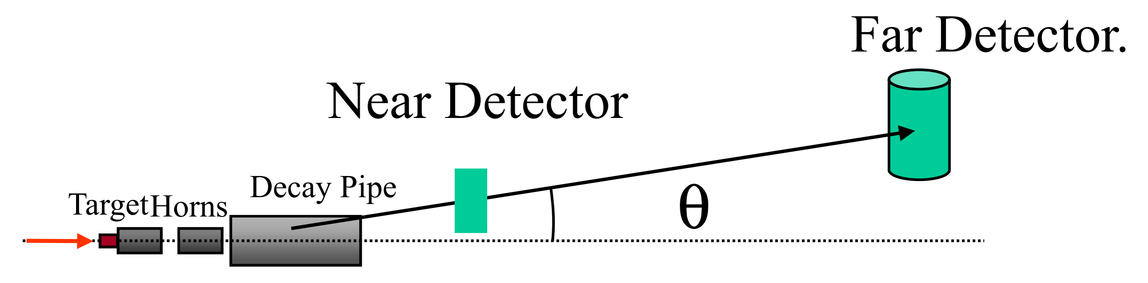
JPARC – SuperK, AKA T2K

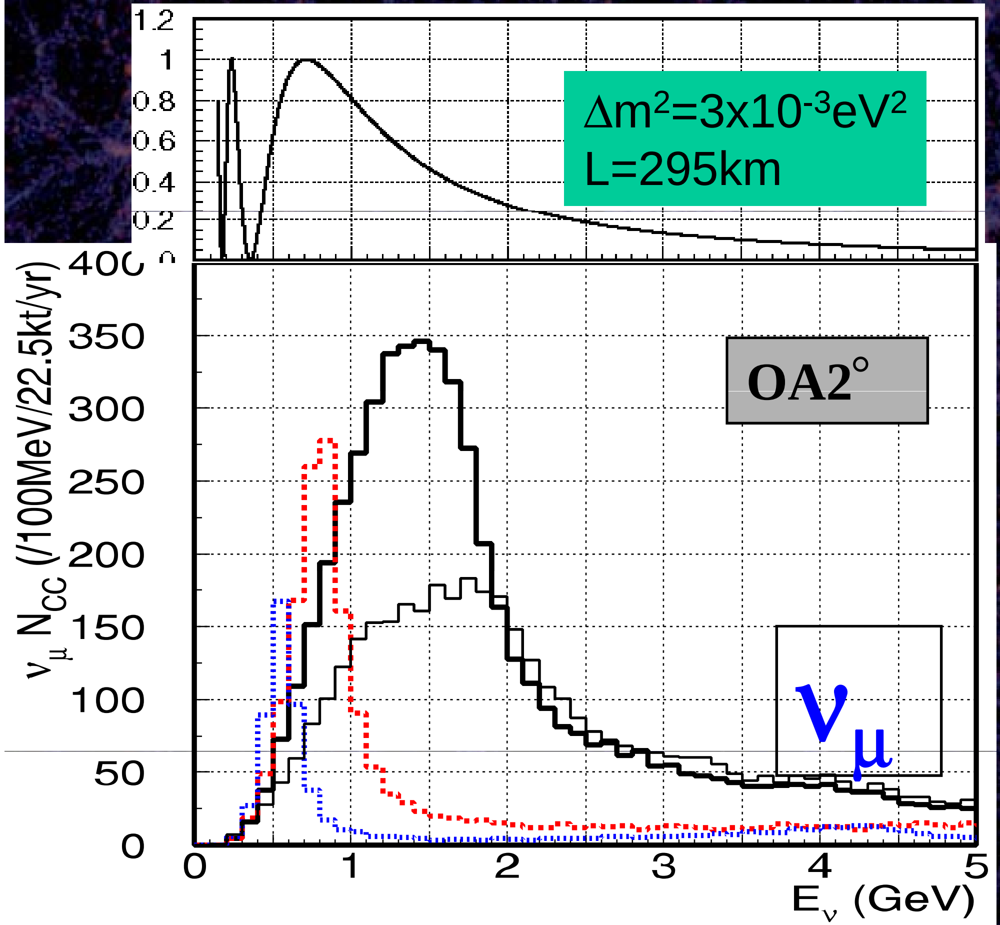
- JPARC Accelerator –
  - Phase I, 0.75 MW @ 50 GeV
  - Phase II, raise power to 4 MW
  - Approved
  - Under const.



- Far Detector – Super Kamiokande
- Rebuild (completed).

Common Features - Off-Axis Beams

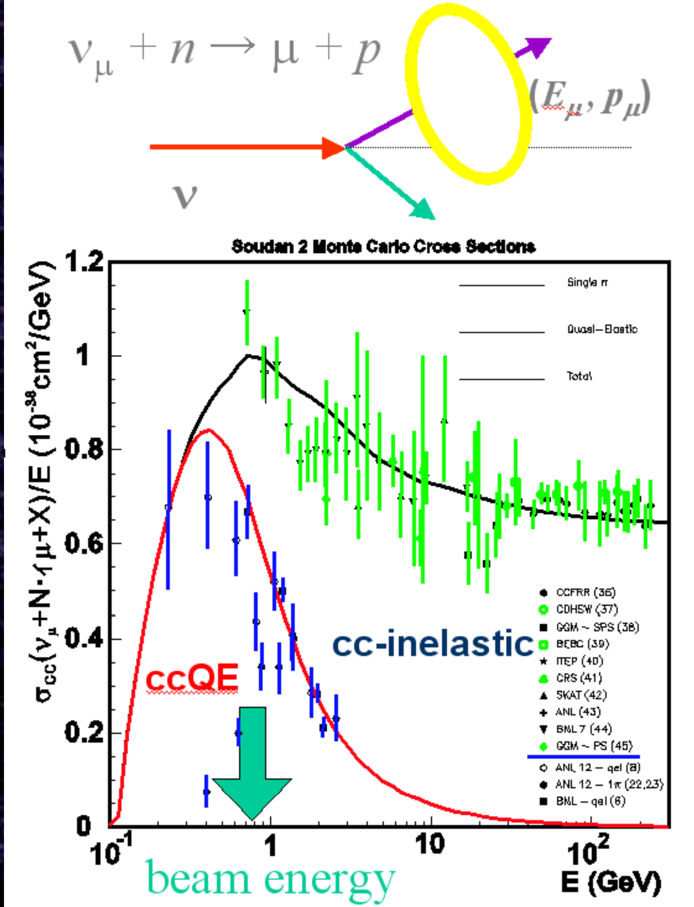


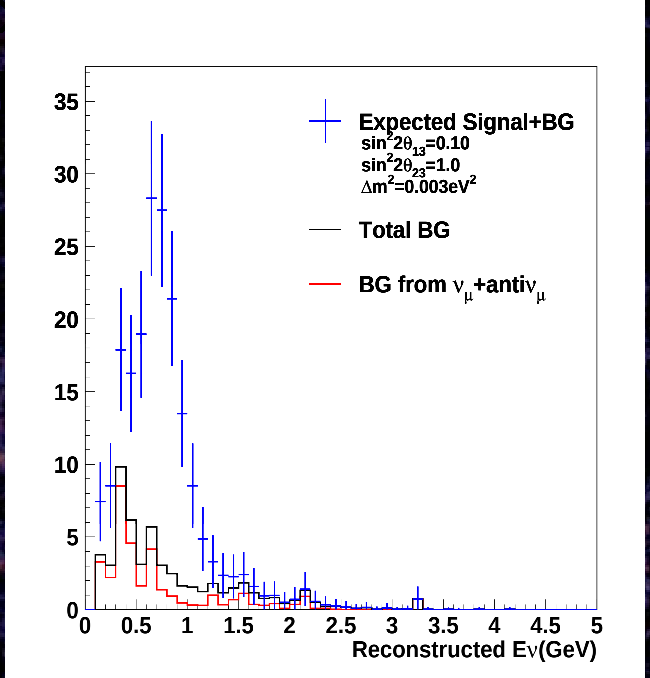


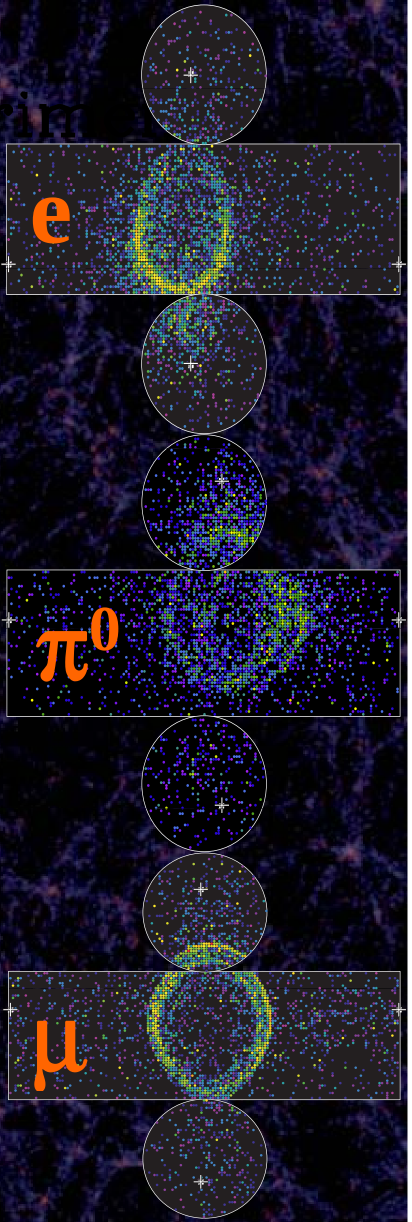
- Pros –
  - Increases flux on osc. max.
  - Reduces high-E tail, and thus NC backgrounds
  - Reduces ν_e contamination from K and μ decay
- Cons –
  - Complicates disappearance measurement
  - Increases near/far differences
  - Have to know angle!

T2K

L/E well-tuned to CCQE,
Critical for untangling
Beam ⊗ Σσ ⊗ detector



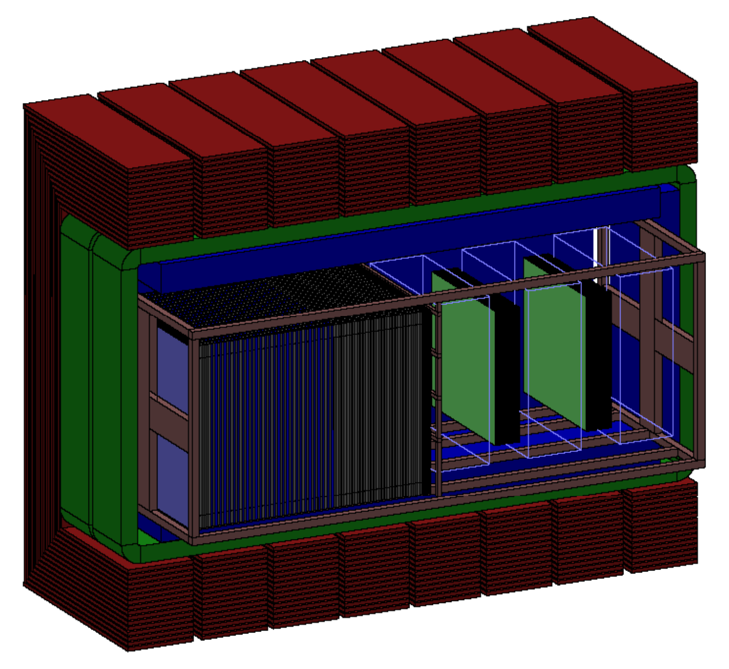


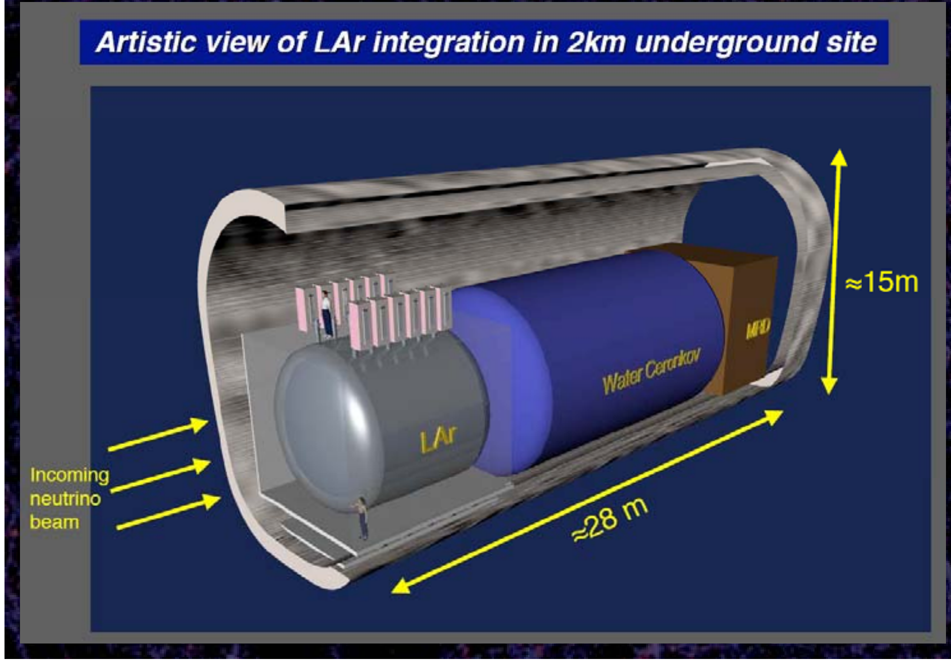


Super Kamiokande
well understood,
Ideal for separating
Electrons, μ, π^0

T2K

- Near Detector @ 280m
  - Built inside UA1/NOMAD magnet for p_μ measurement
  - Sandwich calorimeters/trackers and TPCs for precision beam spectrum and composition measurement.
  - $X(\nu,n)X' \rightarrow X(n,\pi^0)X'$?

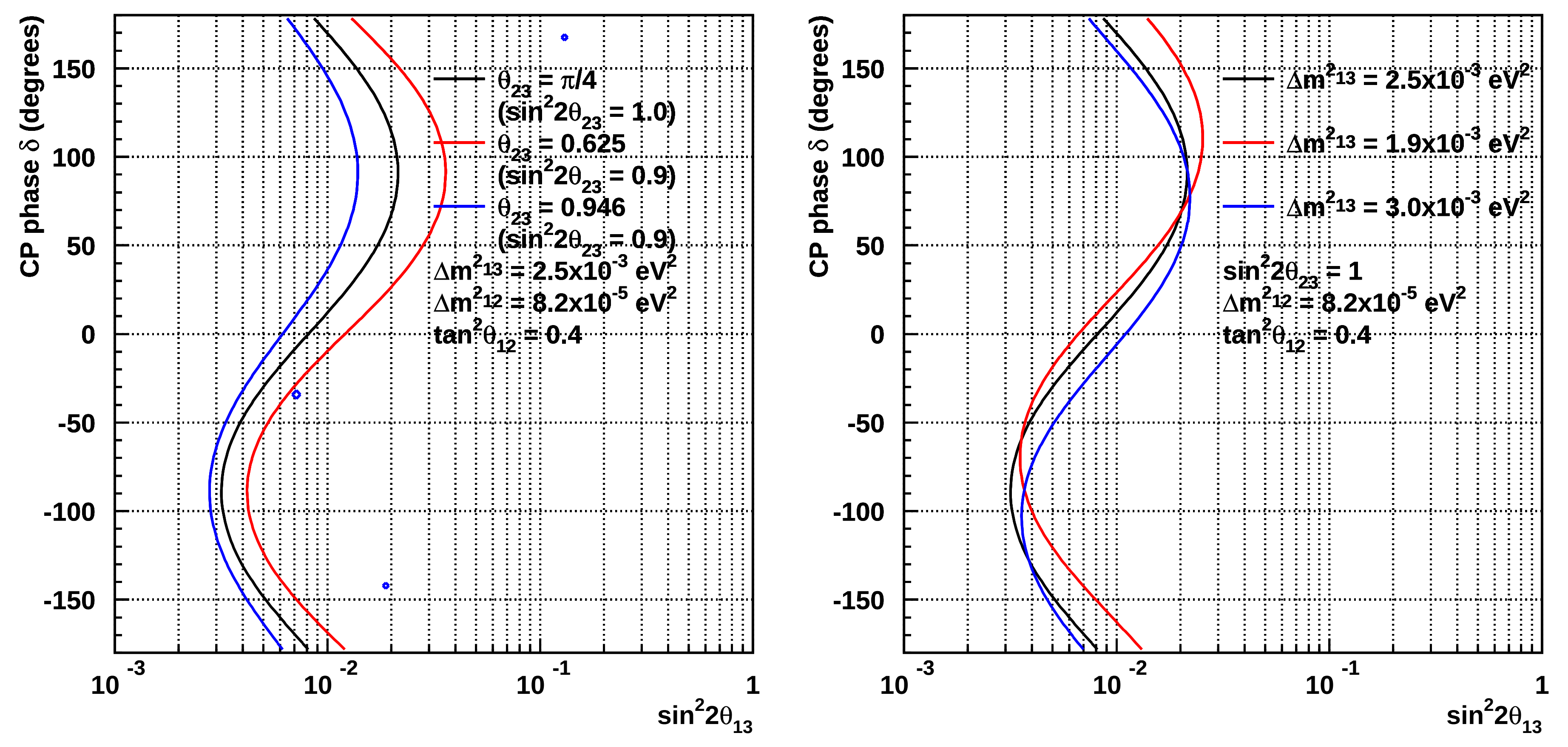




- Near Detector @ 2km
  - Near/far spectral uncertainties negligible
  - Water Cerenkov, MRD, and LAr

T2K Sensitivity

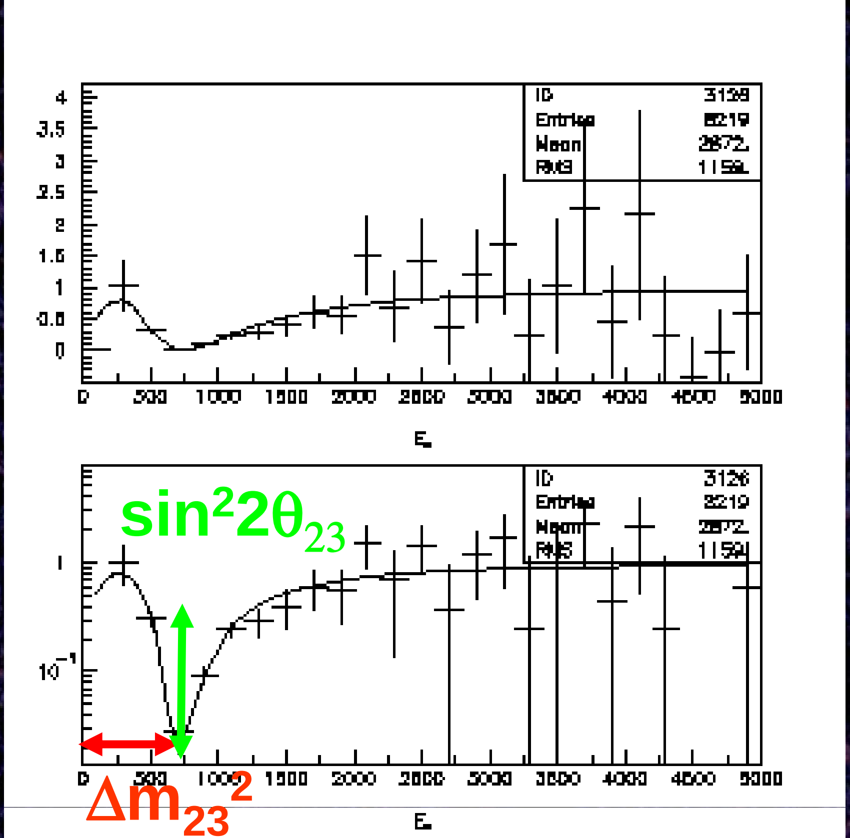
Total Rates: Standard Model vs. Experim



Plot from I. Kato/T2K

Design sensitivity

ν_μ disappearance



NOvA will also be sensitive to ν_u disappearance

$\delta(\sin^2 2\theta)$ ~0.01

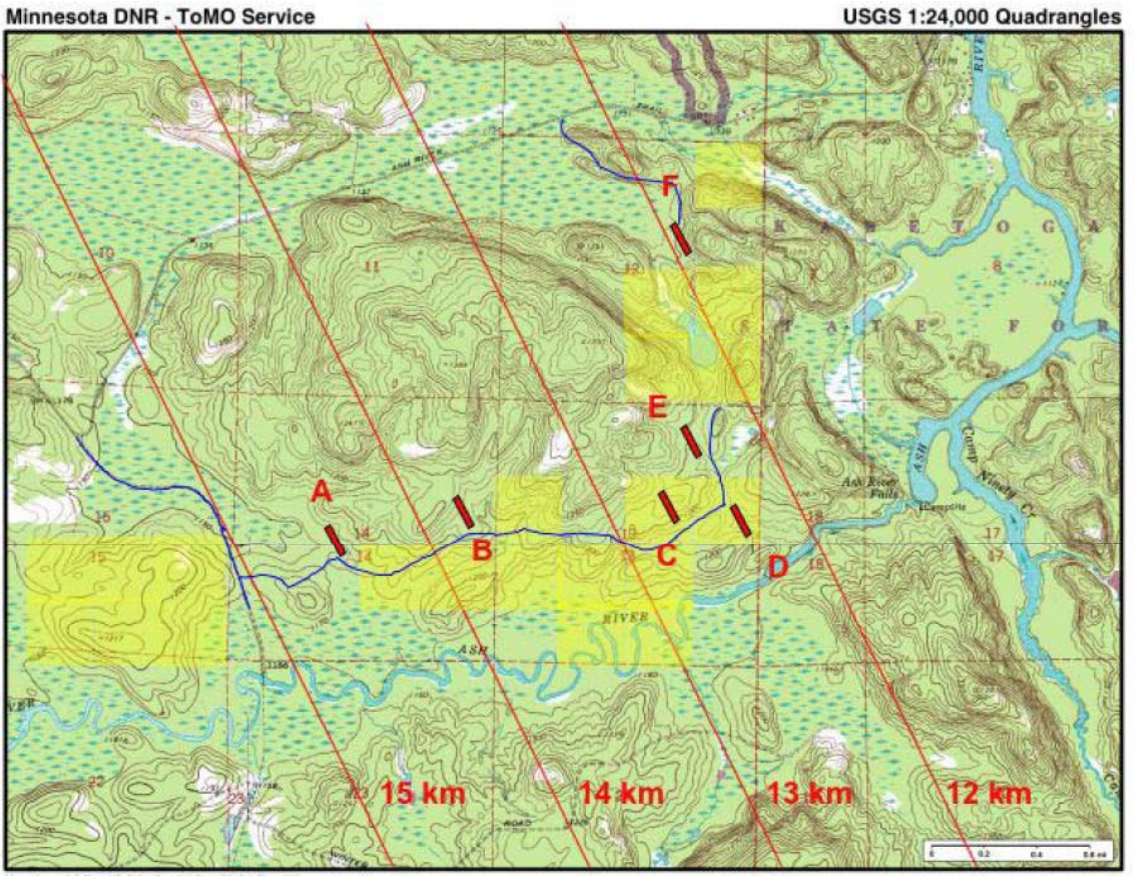
$\delta(\Delta m^2)$ $<1 \times 10^{-4} (eV^2)$

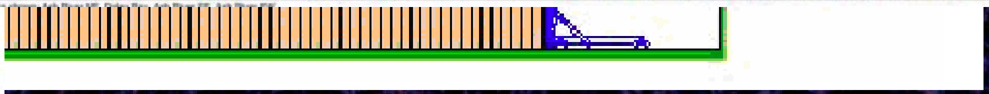
NOvA

Total Rates: Sta

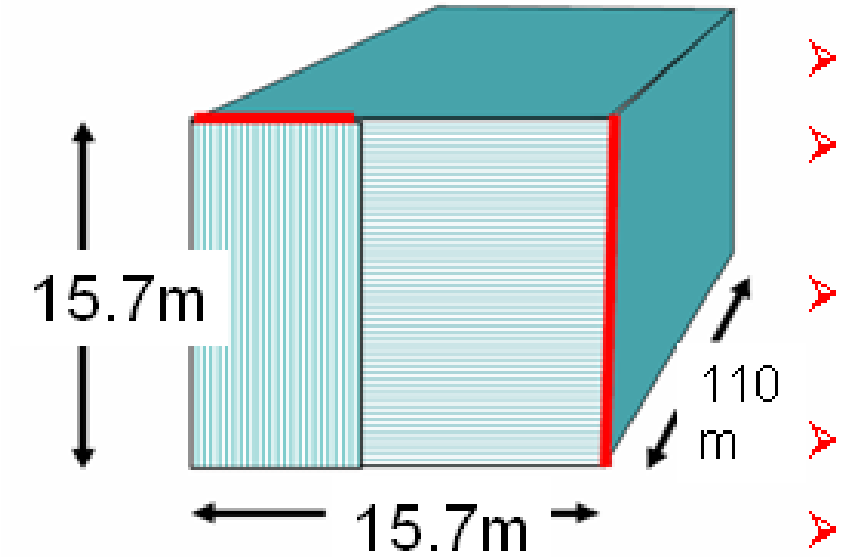
Bathtub for full containment

Ash River

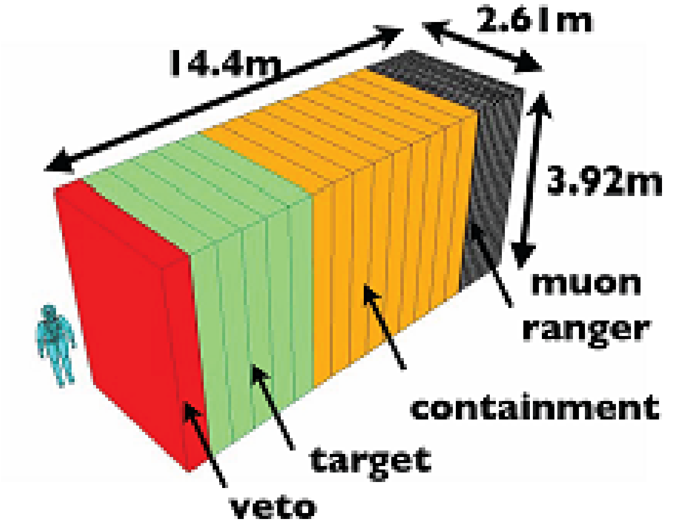




NOvA Detectors

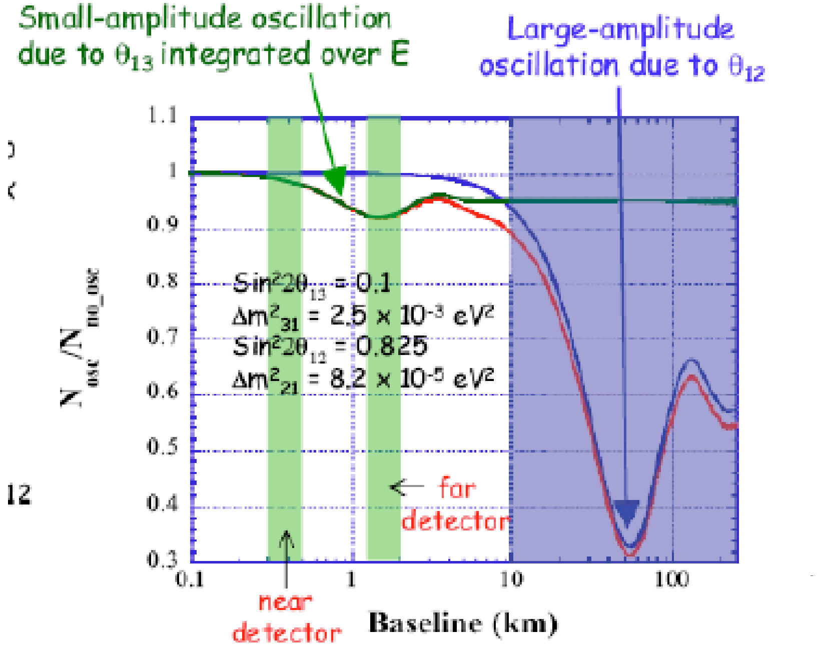


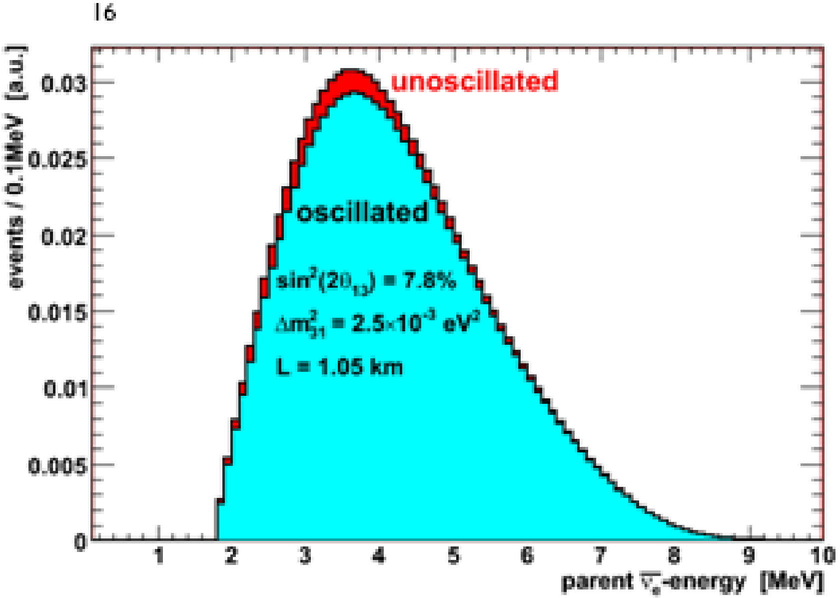
- 25 ktons
- 1984 liquid scintillator planes, no additional absorber (~80% active)
- Scintillator cells
  3.8 x 6.0 x 1570 cm
- Read out from one side per plane with APDs
- Expected minimum signal 20pe



- 126 tons of scintillator, 83 tons of steel
- 23 ton fiducial mass
- 186 liquid scintillator planes in target, 10 in muon ranger, 1m of steel
- Same cell size, same minimum signal
- Read out from one side per plane with APDs plus faster electronics than in far detector

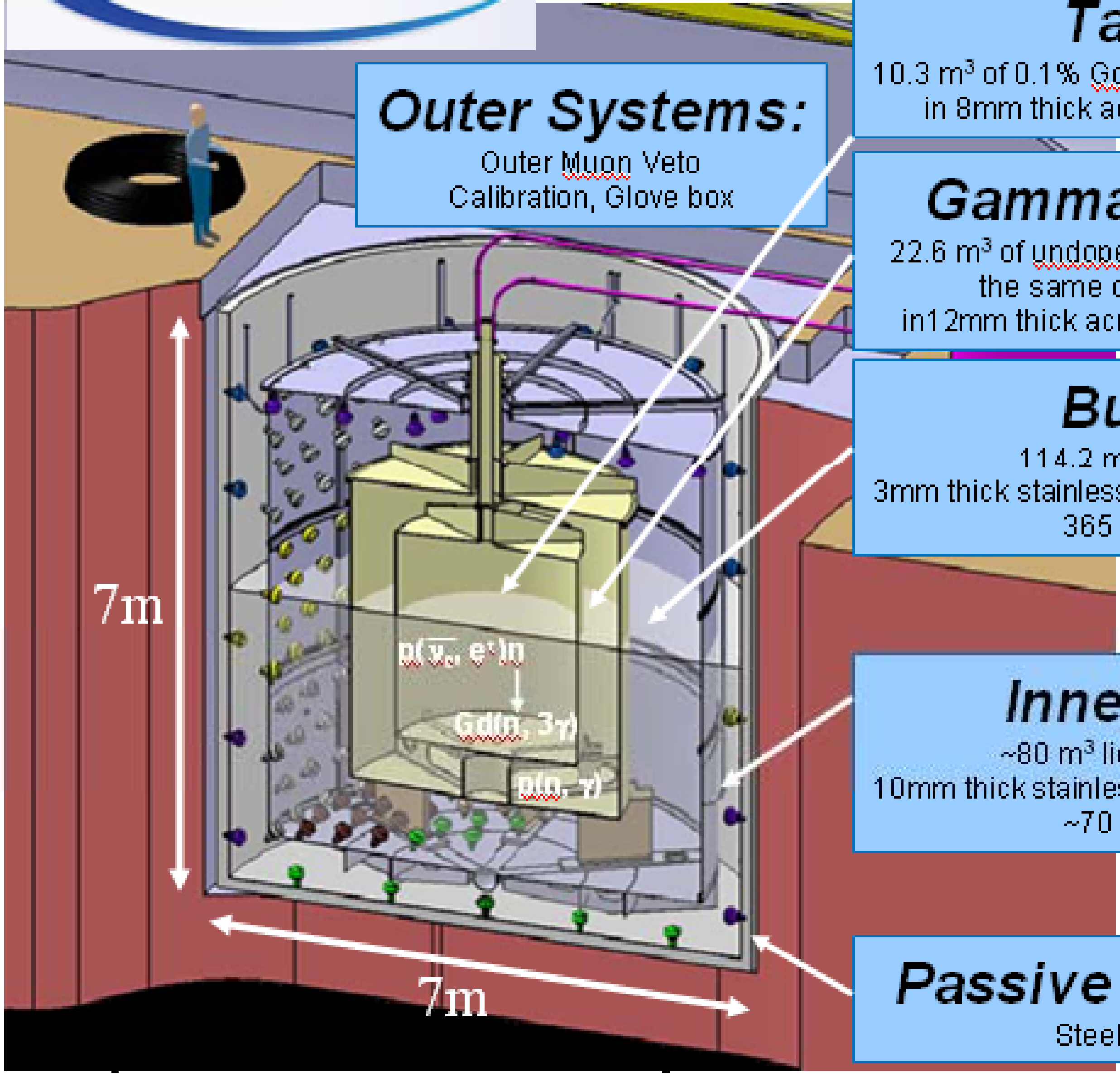
ν-Oscillation at Nuclear Reactors





parent energy-spectrum: $\phi \times d\sigma$

The Detector



Outer Systems:

Outer Muon Veto
Calibration, Glove box

Target:

10.3 m^3 of 0.1% Gd-loaded liquid scintillator
in 8mm thick acrylic vessel (d=2.3m)

Gamma Catcher:

22.6 m^3 of undoped liquid scintillator with
the same optical properties
in12mm thick acrylic vessel (dr=0.55m)

Buffer:

114.2 m^3 mineral oil,
3mm thick stainless steel vessel (dr=1.05m)
365 10'' PMTs

Inner Veto:

~80 m^3 liquid scintillator,
10mm thick stainless steel vessel (dr=0.5m)
~70 PMTs (8'')

Passive Shielding:

Steel (170mm)

Empty detectors: moved to underground halls through access tunnel.
Filled detectors: swapped between underground halls via horizontal tunnels.

Total length: ~2700 m

Systematic Uncertainties

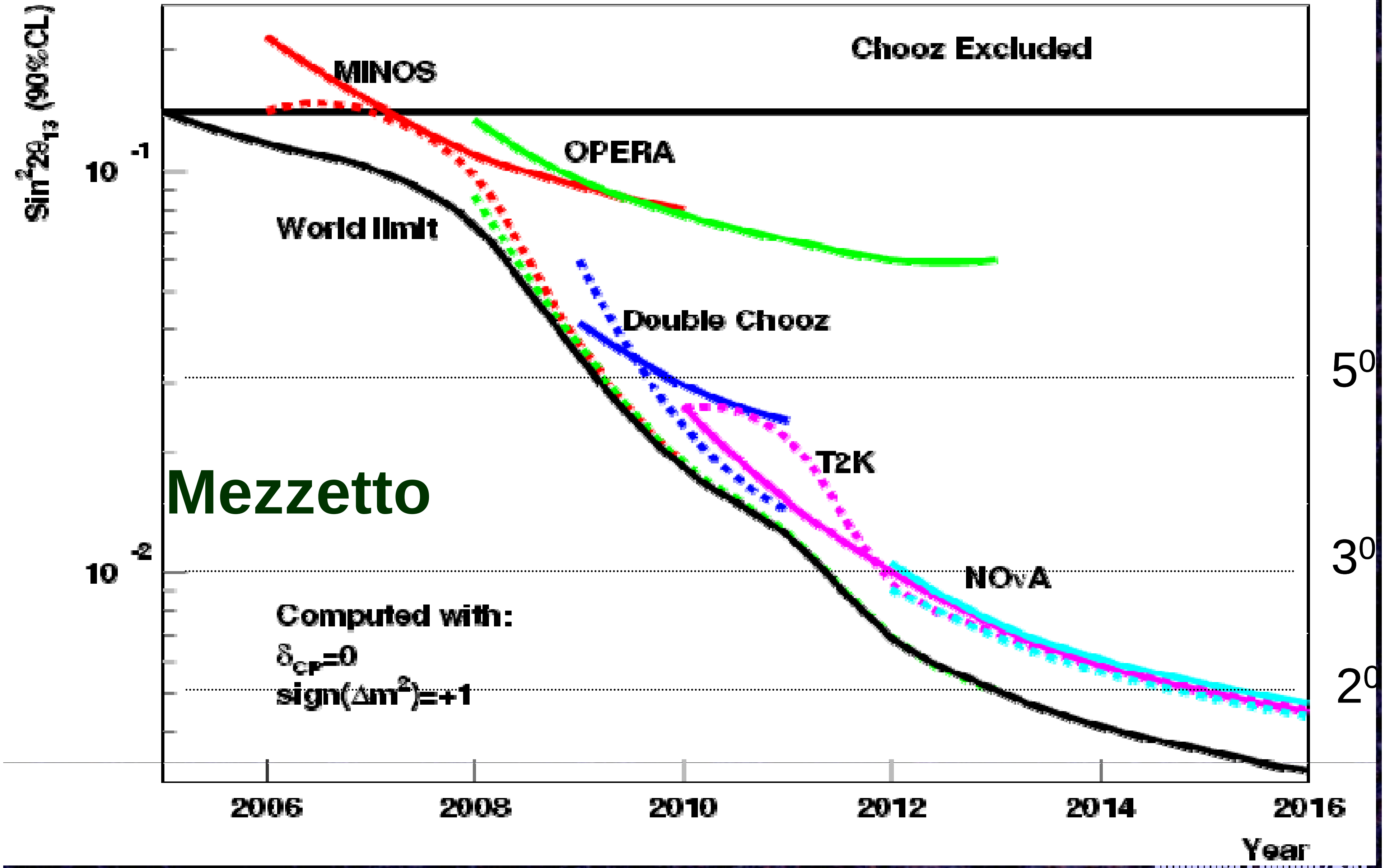
- Reactor-related:

Number of cores	α	σ_ρ(power)	σ_ρ(location)	σ_ρ(total)
4	0.338	0.035%	0.08%	0.087%
6	0.392	0.097%	0.08%	0.126%

- Detector-related:

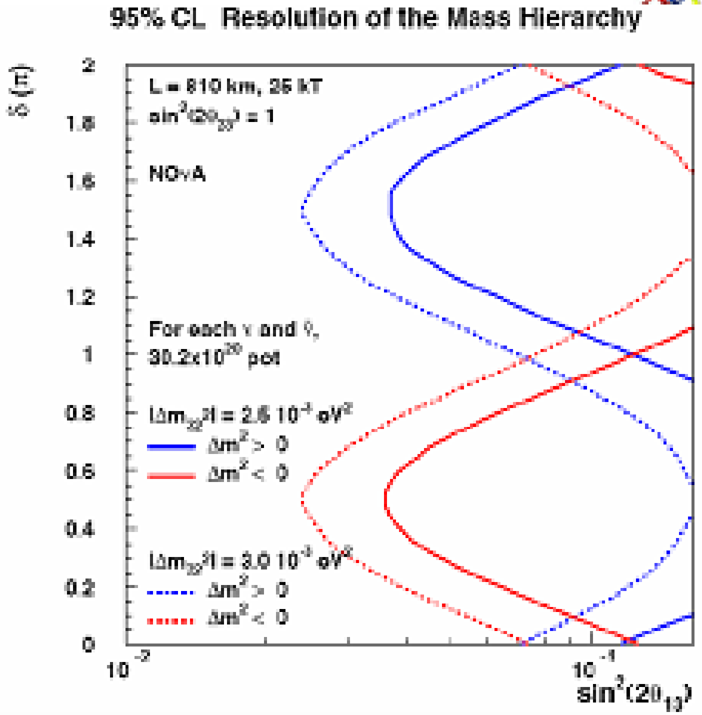
Source of uncertainty		Chooz	Daya Bay (*relative*)		
		(*absolute*)	Baseline	Goal	Goal w/Swapping
# protons	H/C ratio	0.8	0.2	0.1	0
	Mass	-	0.2	0.02	0.006
Detector Efficiency	Energy cuts	0.8	0.2	0.1	0.1
	Position cuts	0.32	0.0	0.0	0.0
	Time cuts	0.4	0.1	0.03	0.03
	H/Gd ratio	1.0	0.1	0.1	0.0
	n multiplicity	0.5	0.05	0.05	0.05
	Trigger	0	0.01	0.01	0.01
	Live time	0	< 0.01	< 0.01	< 0.01
Total detector-related uncertainty		1.7%	0.38%	0.18%	0.12%

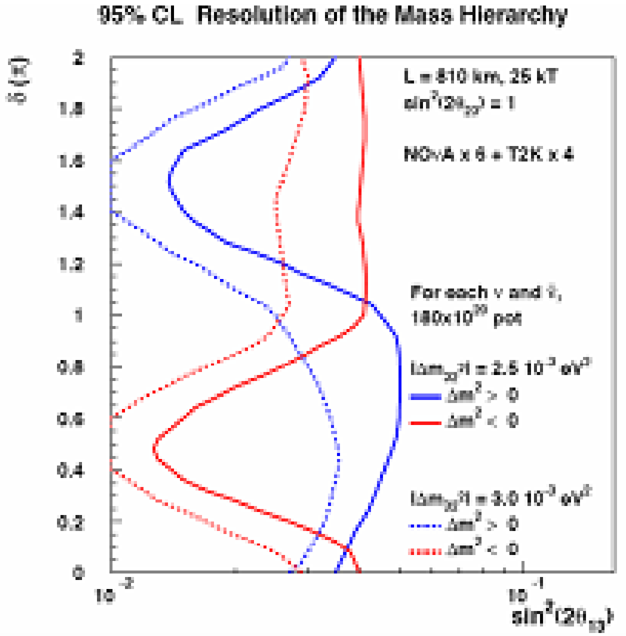
A possible future…



Determining the Mass Hierarchy

- Comparing ν and anti-ν probabilities, there is a region of phase space where NOνA could determine the mass hierarchy



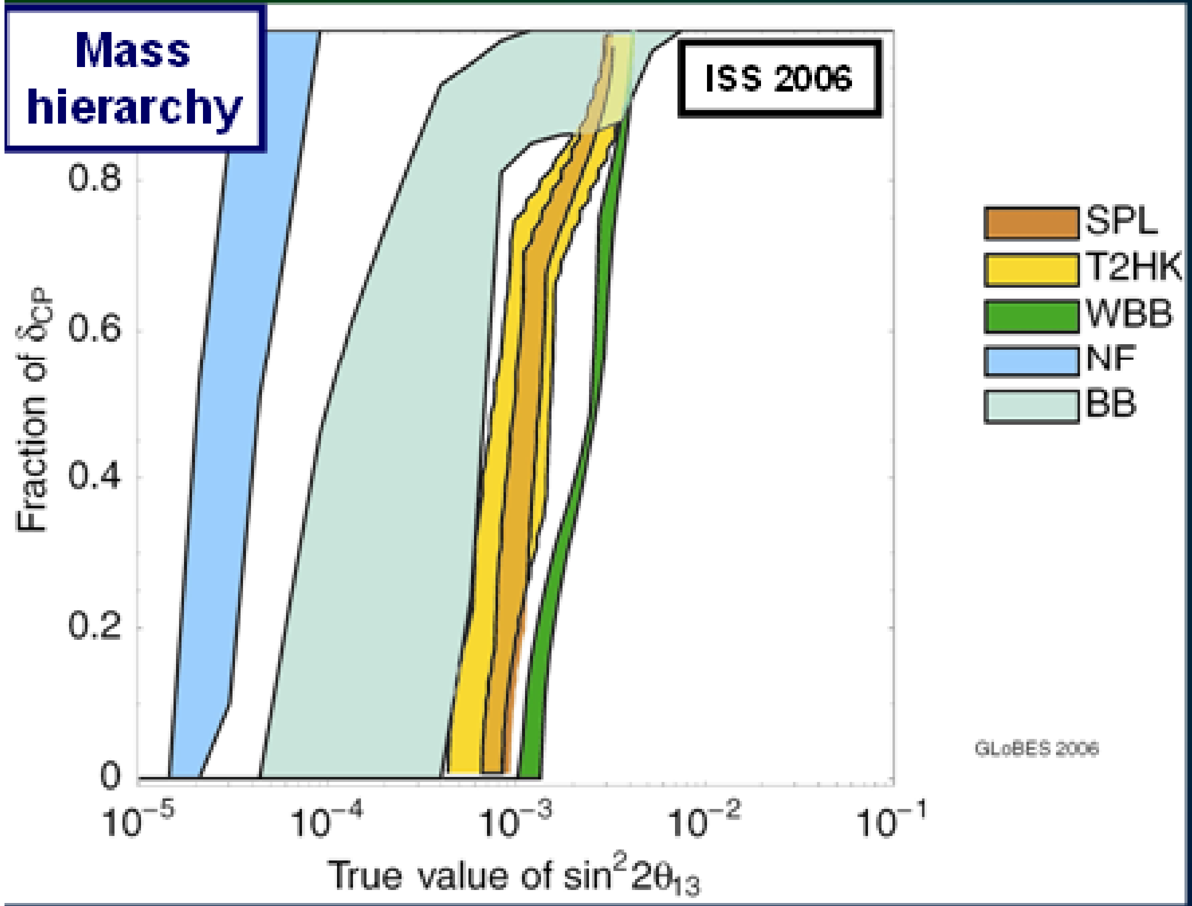


- NOνA and T2K upgrades when combined do even better than just upgrading one by itself

Three Ways Forward?

- Superbeams:
  - ✓ We know how to build them (except for the targets).
  - ✓ The beams are “cheap” (relative to the others).
  - × The beams are not pure, and not well focussed.
  - × The detectors have to be huge.
- β Beams:
  - ✓ Produce pure flavour beams.
  - ✓ Synergies with the nuclear physics programme.
  - × If low γ, need huge detector, if high γ, expensive.
- Neutrino Factory
  - ✓ Most intense source.
  - ✓ Gives two beams at the same time.
  - ✓ Synergies with μ-collider development.
  - × $$$...

Comparison: mass hierarchy



SPL

Systematics: 2% – 5%

T2HK

Systematics: 2% – 5%

WBB

Systematics from proposal

Beta beam

$\gamma = 100$

500 kT H_2O Ç (130 km)

$\gamma = 350$

500 kT H_2O Ç (730 km)

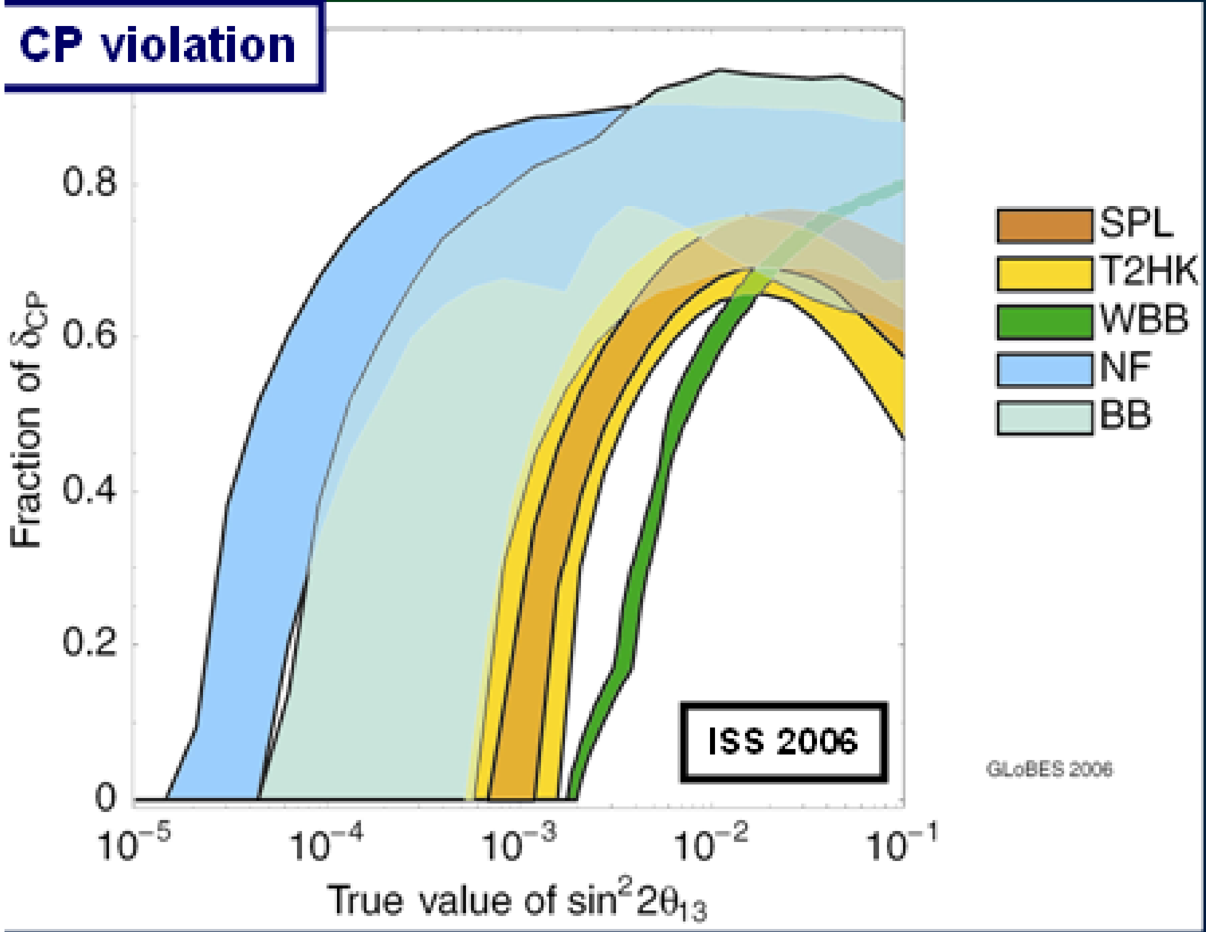
Neutrino Factory

Golden, 4000, E_μ = 50 GeV

Golden* (4000 km), Golden* (7500 km) E_μ = 20 GeV

Slide from Alain Blondel, WIN07

Comparison: CP violation



SPL

Systematics: 2% – 5%

T2HK

Systematics: 2% – 5%

WBB

Systematics from proposal

Neutrino Factory

Golden, 4000, E_μ = 50 GeV

Golden* (4000 km), Golden* (7500 km)

E_μ = 20 GeV

Beta beam

γ = 100

500 kT H_2O Ç (130 km)

γ = 350

500 kT H_2O Ç (730 km)

Slide from Alain Blondel, WIN07

Conclusions

- Neutrino oscillations are an established property of nature (and the first confirmed physics beyond the Standard Model).
- The parameters of the MNSP and ν mass matrices are windows on higher scales, and understanding them is an essential element in developing BSM particle physics.
- The pattern emerging from experiments hints at higher symmetry, but needs better measurement!
- There is no access to this physics except through specialized facilities – the LHC and ILC will not help.
- This game is just beginning and will provide a rich field of particle physics for years to come.
- Join us!

Editorial Comment

- It is commonly stated that science only progresses where there are problems.
- Two of the main CP "problems" (the strong and the SUSY) arise from the failure to observe the electric dipole moment of the neutron.
- Particle EDMs (or rather the lack of them) provide some of the strongest constraints on BSM CP violation.
- No mention at this conference…
- Invite someone to Taiwan to give a talk.