Long Baseline Neutrino Oscillation Projects

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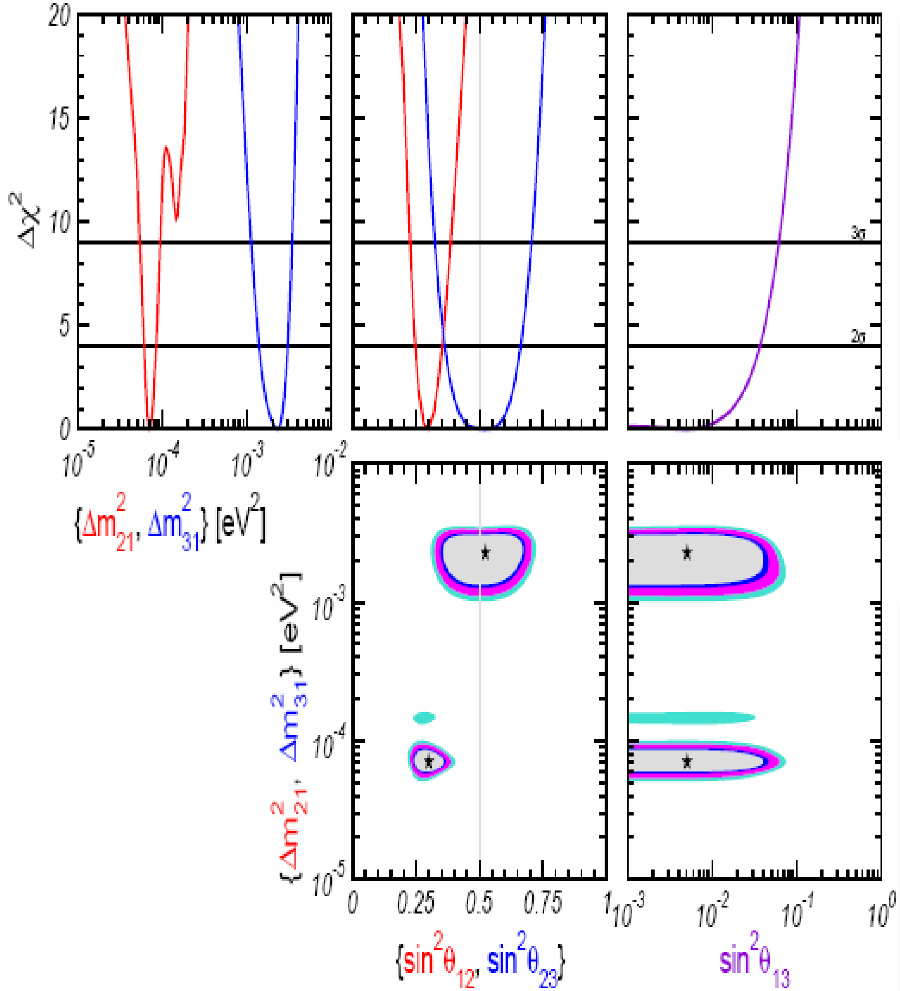
RAL/CCLRC

CCLRC
Rutherford Appleton Laboratory

Overview

- Current status
  - see S. King's talk
  - global fits
- Experiments coming soon
  - MINOS
  - OPERA
  - IKARUS
- Experiments coming not so soon
  - T2K
  - NOvA

Results of Global Fits



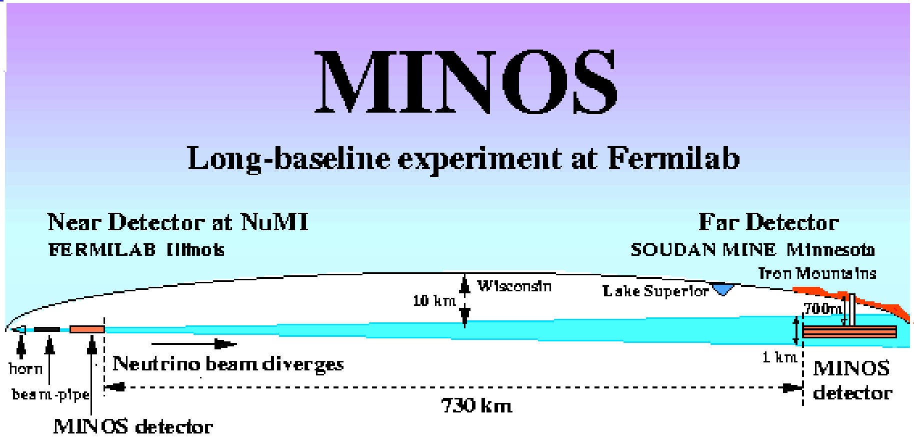
- 3σ range: 3-flavour analysis

Δm^2_{31} = 1.1 -3.4 $\times 10^{-3}$ eV^2
$\sin^2\theta_{23}$ = 0.32 -0.7
Δm^2_{21} = 5.4 -9.4 $\times 10^{-5}$ eV^2
$\sin^2\theta_{12}$ = 0.23 -0.39

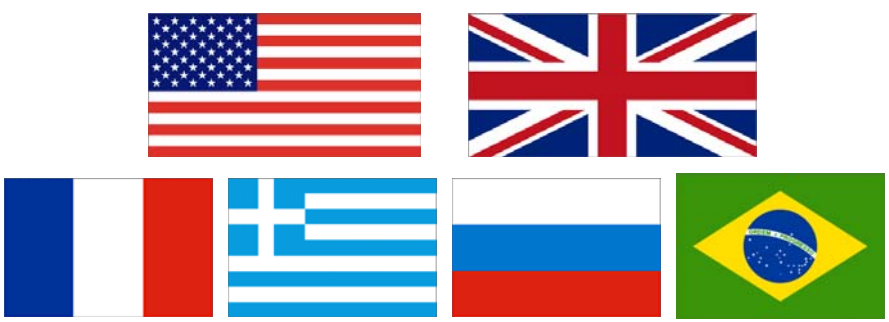
- 3σ range: 2-flavour analysis

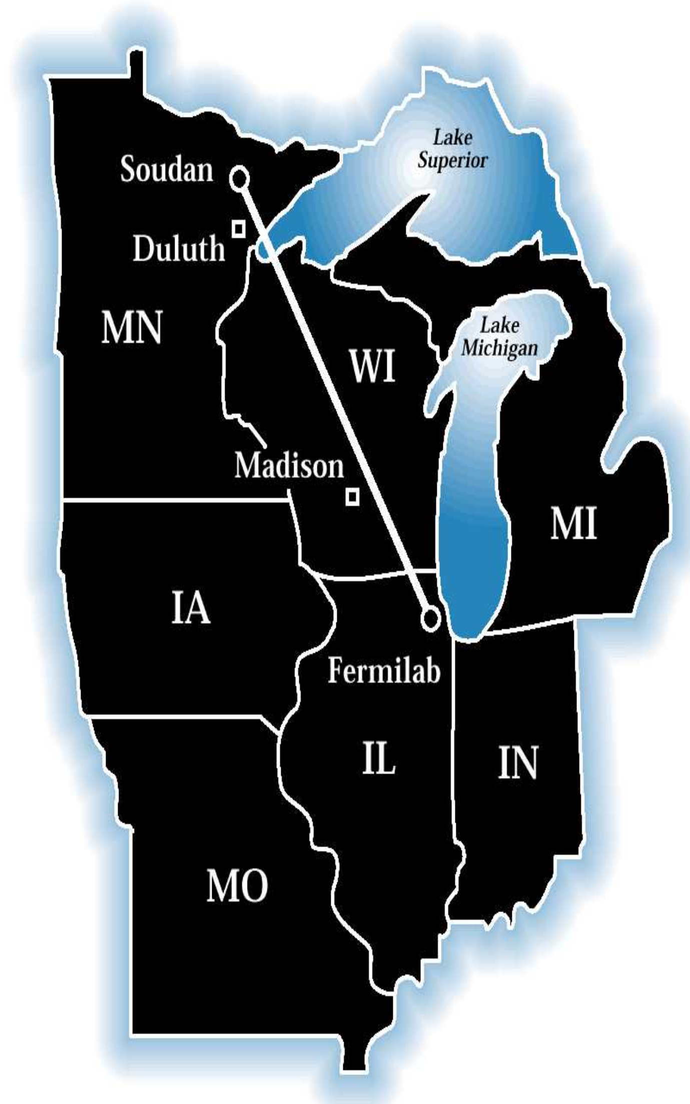
Δm^2_{31} = 1.1 -3.4 $\times 10^{-3}$ eV^2
$\sin^2\theta_{23}$ = 0.32 -0.68
Δm^2_{21} = 5.4 -9.4 $\times 10^{-5}$ eV^2
$\sin^2\theta_{12}$ = 0.23 -0.39

The MINOS Experiment



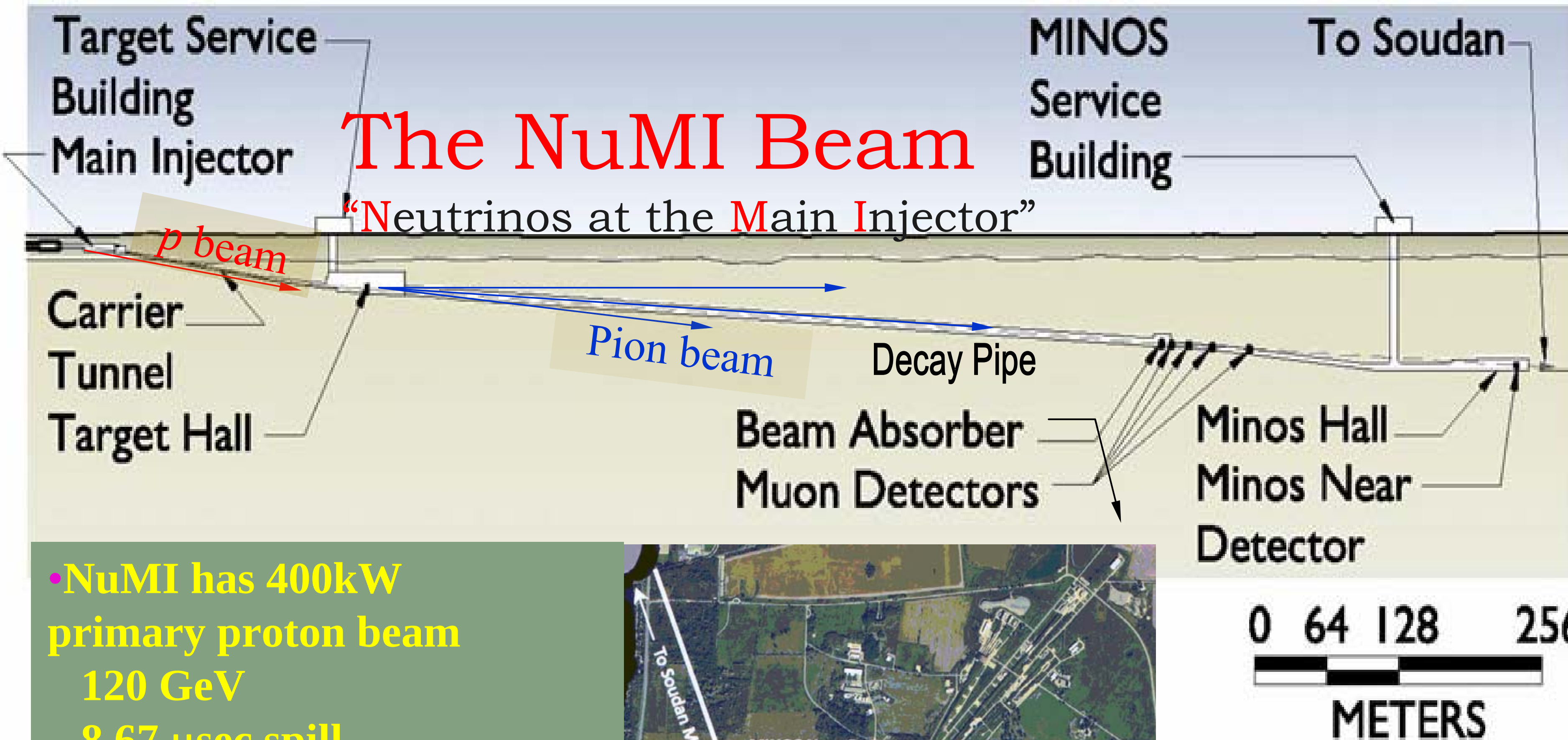
- NuMI beam to Soudan in MN (distance 735 km)
- Sagitta:10 km
- >1 km wide at destination



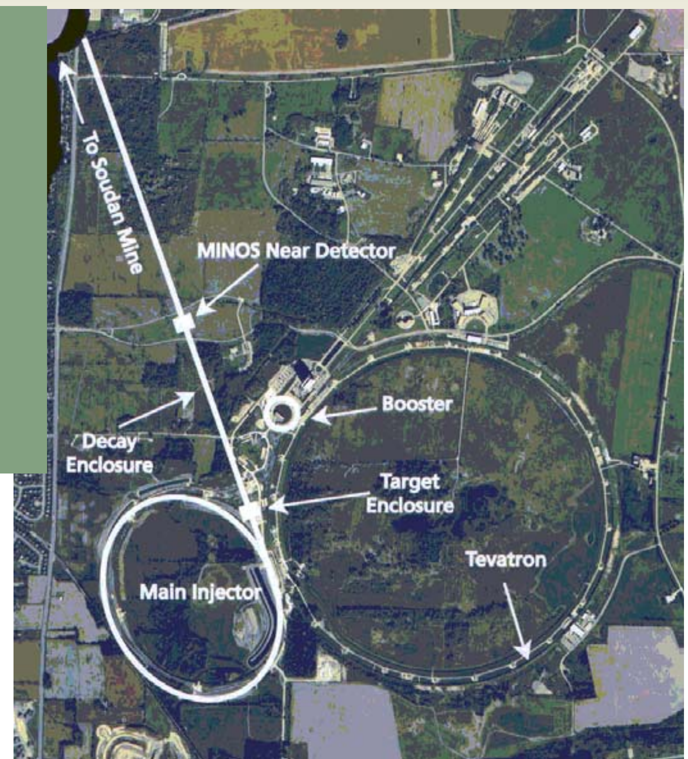


The NuMI Beam

"Neutrinos at the Main Injector"



- **NuMI has 400kW primary proton beam**
  - **120 GeV**
  - **8.67 μsec spill**
  - **1.9 sec rep rate**
  - **5 Booster batches**
    - **(2.5×10^{13} prot/spill)**



ν_μ CC Energy Analysis

- Select ν_μ charge current events

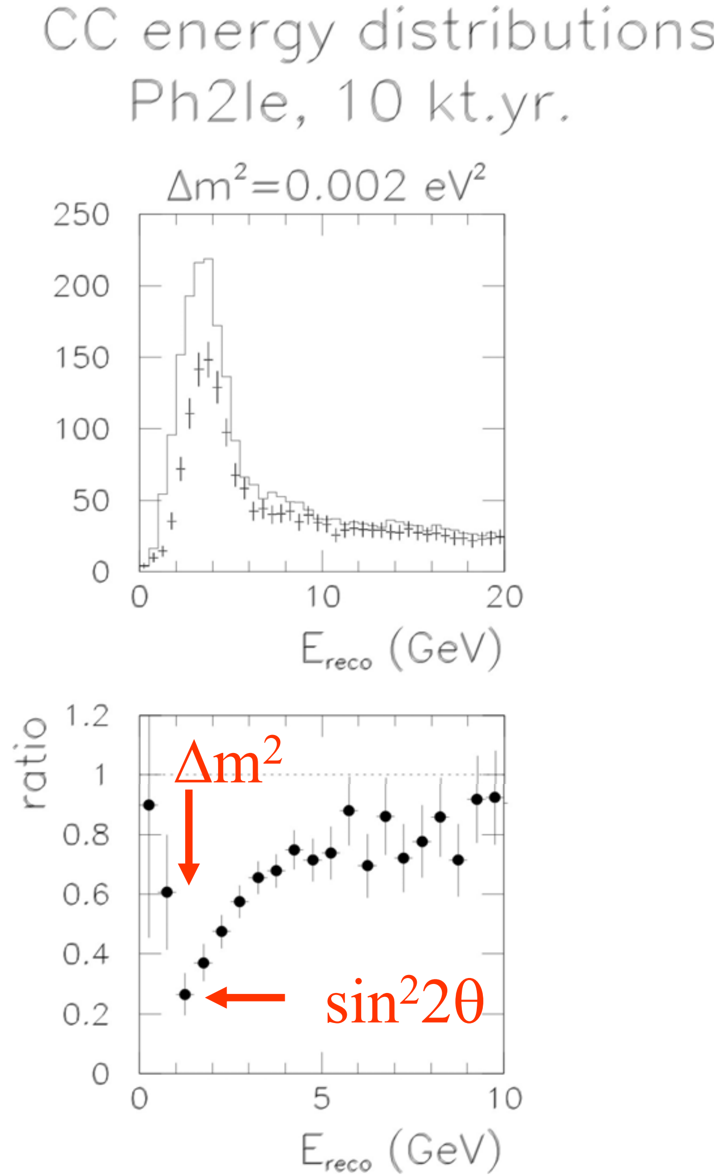
$$E_\nu = E_\mu + E_h$$

range, B field (→ E_μ) **calorimetric** (→ E_h)

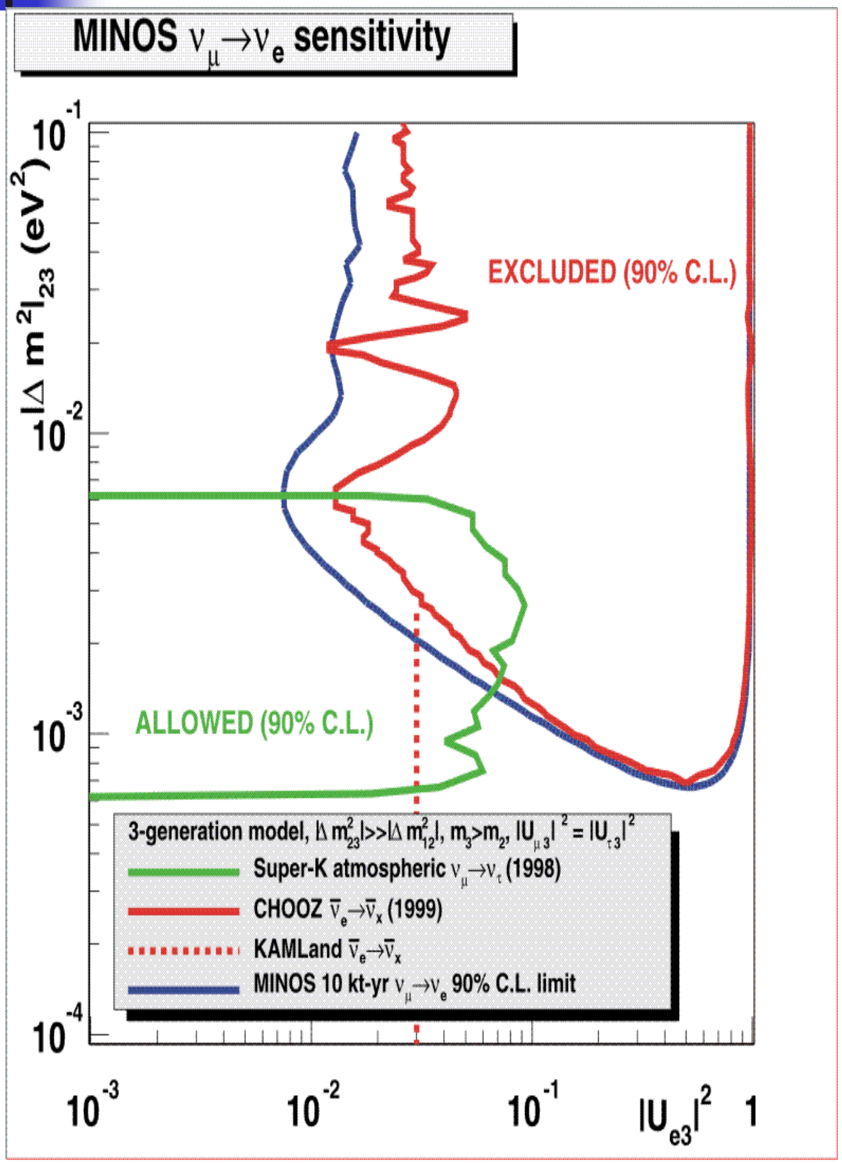
- Energy resolution:

$$\Delta p_\mu / p_\mu = 10\%$$
$$\Delta E_h / E_h = 60\% / \sqrt{E}$$

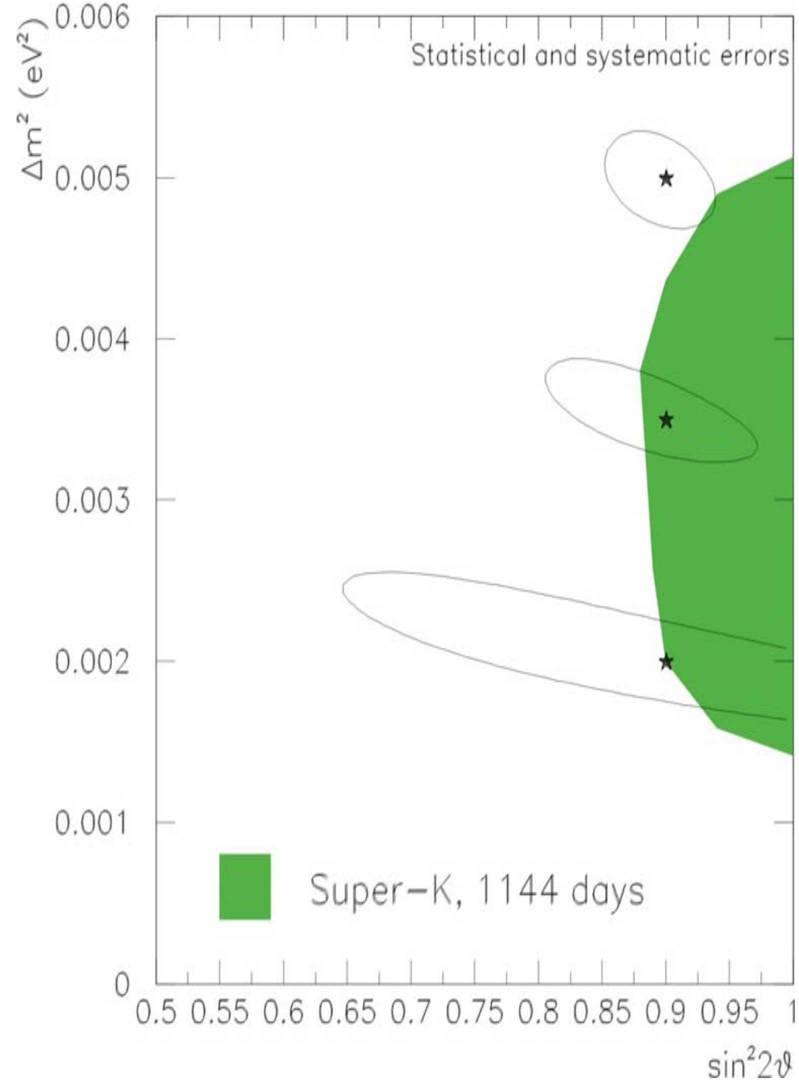
- Compare energy spectrum in near and far detector
- Measure Δm^2 and $\sin^2 2\theta$



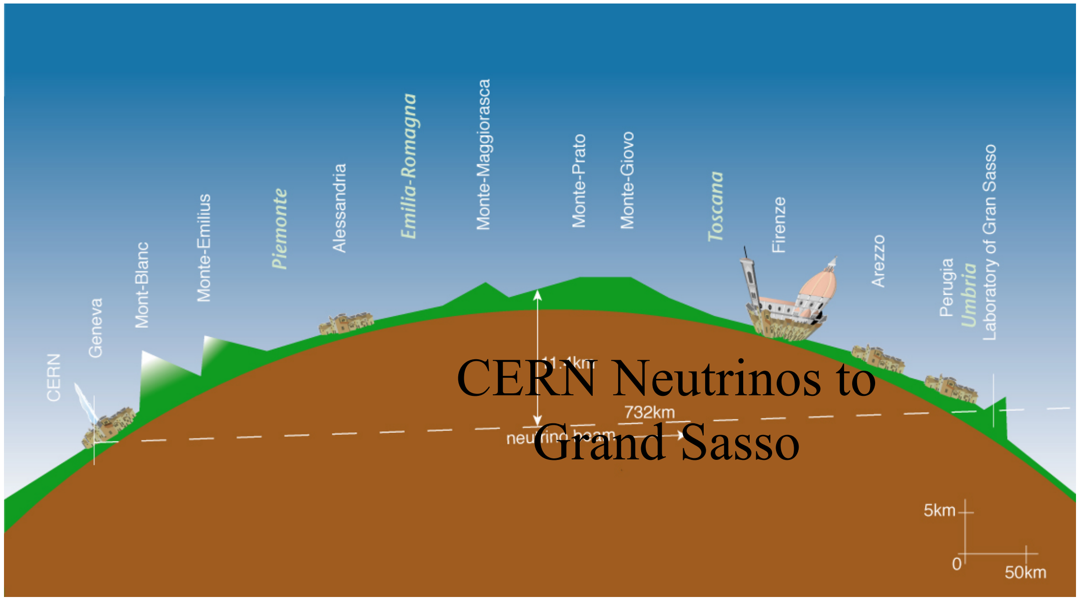
MINOS Sensitivity



Muon Disappearance Measurement



CNGS Beam



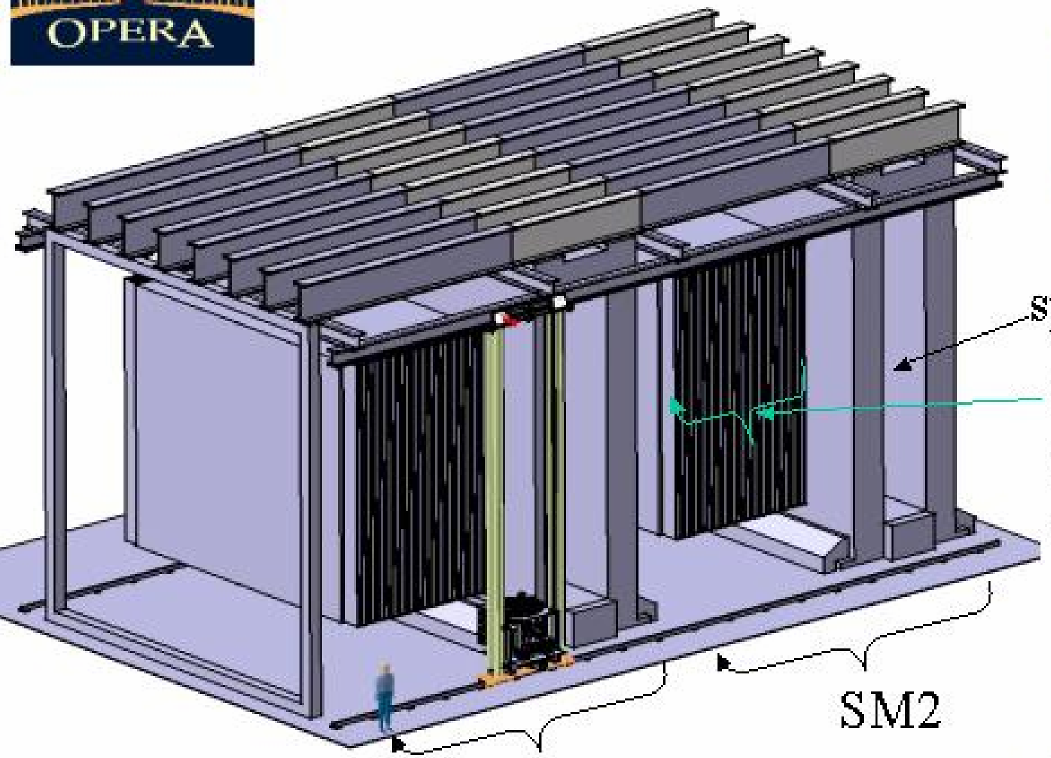
- Baseline: 730 km
- $<E_\nu>$ = 17 GeV
- optimised for τ appearance

- CERN SPS
  - E_p = 400 GeV
  - $4.8*10^{13}$ ppp
  - cycle 6 - 27.6 sec
  - $7.6*10^{19}$ pot/year

- Experiments
  - OPERA
  - ICARUS

The OPERA Detector

Total target ~ 1.8 kton
= 206336 bricks



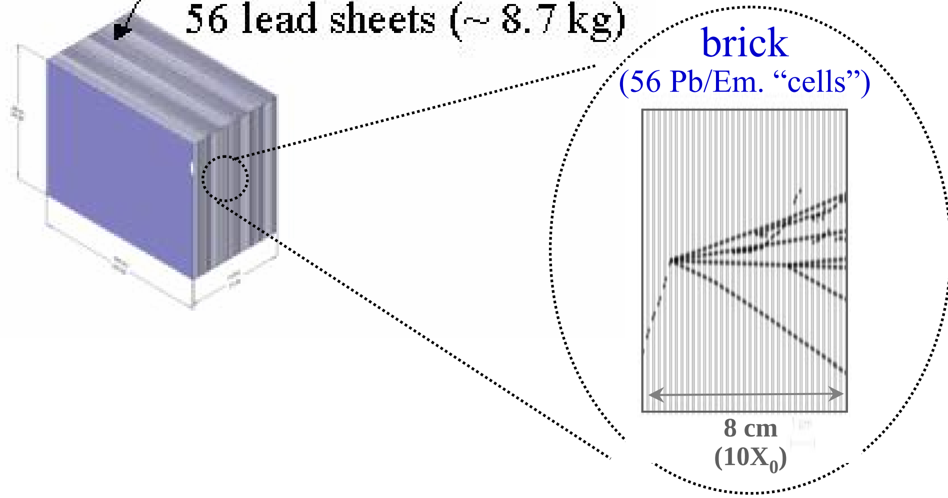
spectrometer

31 Walls
(each containing
3328 bricks)

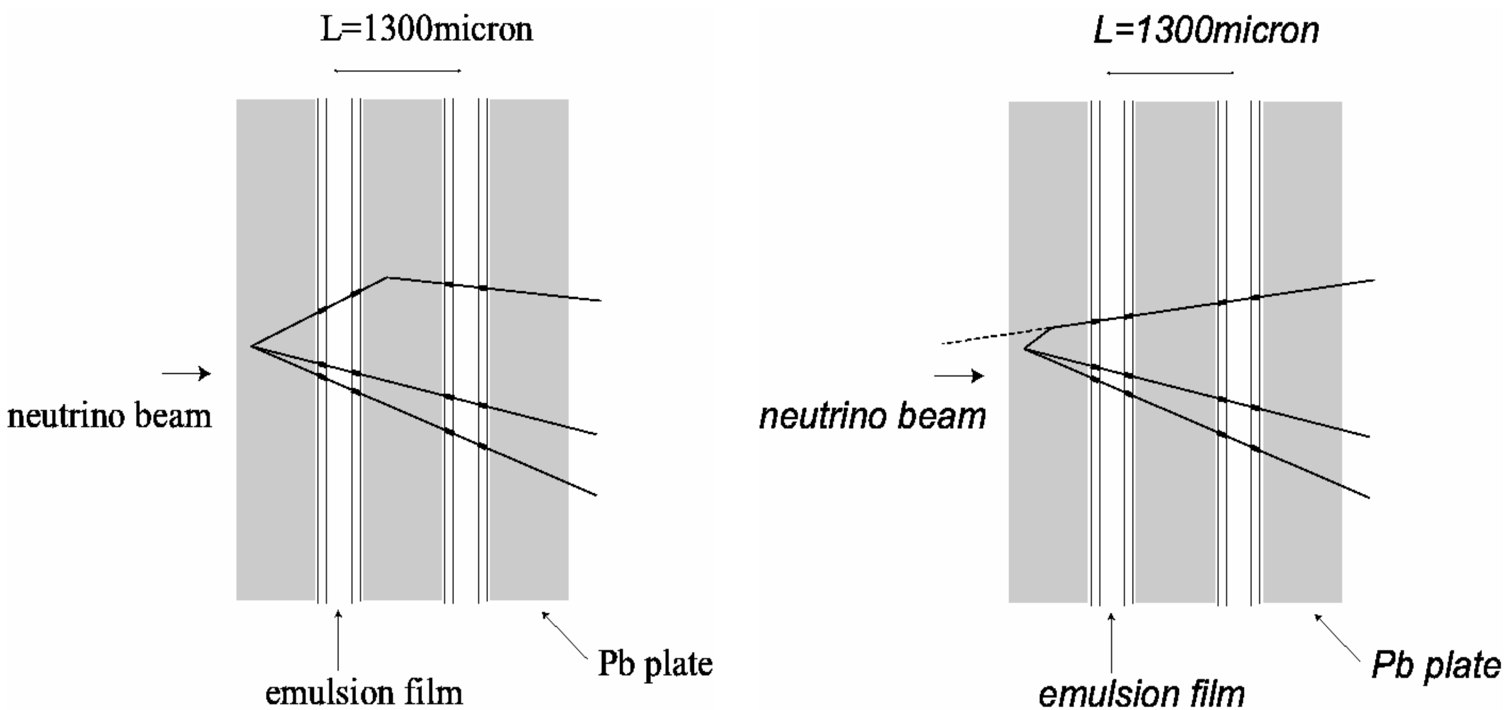
SM2

SM1
31 walls (brick walls+TT)
+ 1 spectrometer

1 brick is made of
57 nuclear emulsions and
56 lead sheets (~ 8.7 kg)



OPERA ν_τ Candidates



"Long decays"
reconstruct kink topology

"Short decays"
detect large impact parameter track

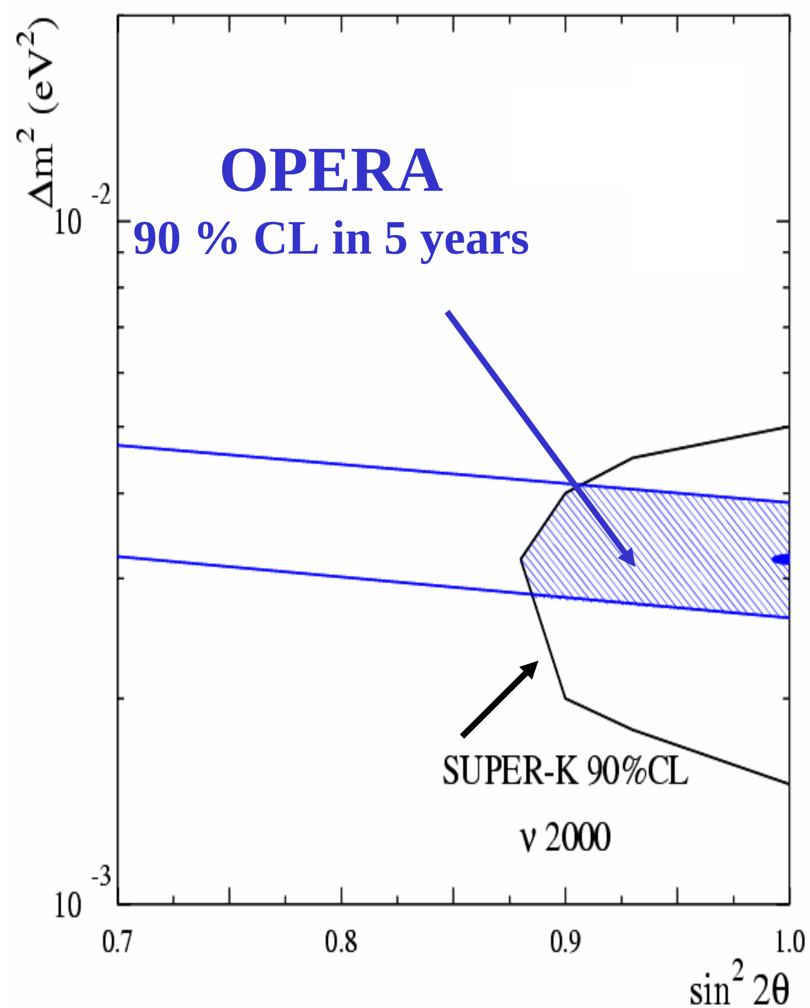
Loose cut to reject low momentum tracks

OPERA: Δm2

90 % CL limits *	Δm^2 (10^{-3} eV^2)		
	1.5	3.2	5.0
Upper limit	2.1	3.8	5.6
Lower limit	0.8	2.6	4.3
(U - L) / (2*True)	41 %	19 %	12 %
N_τ / year	0.82	2.82	3.66

*** assuming the observation of a number of events corresponding to those expected for the given Δm^2**

(mixing constrained by SuperK)

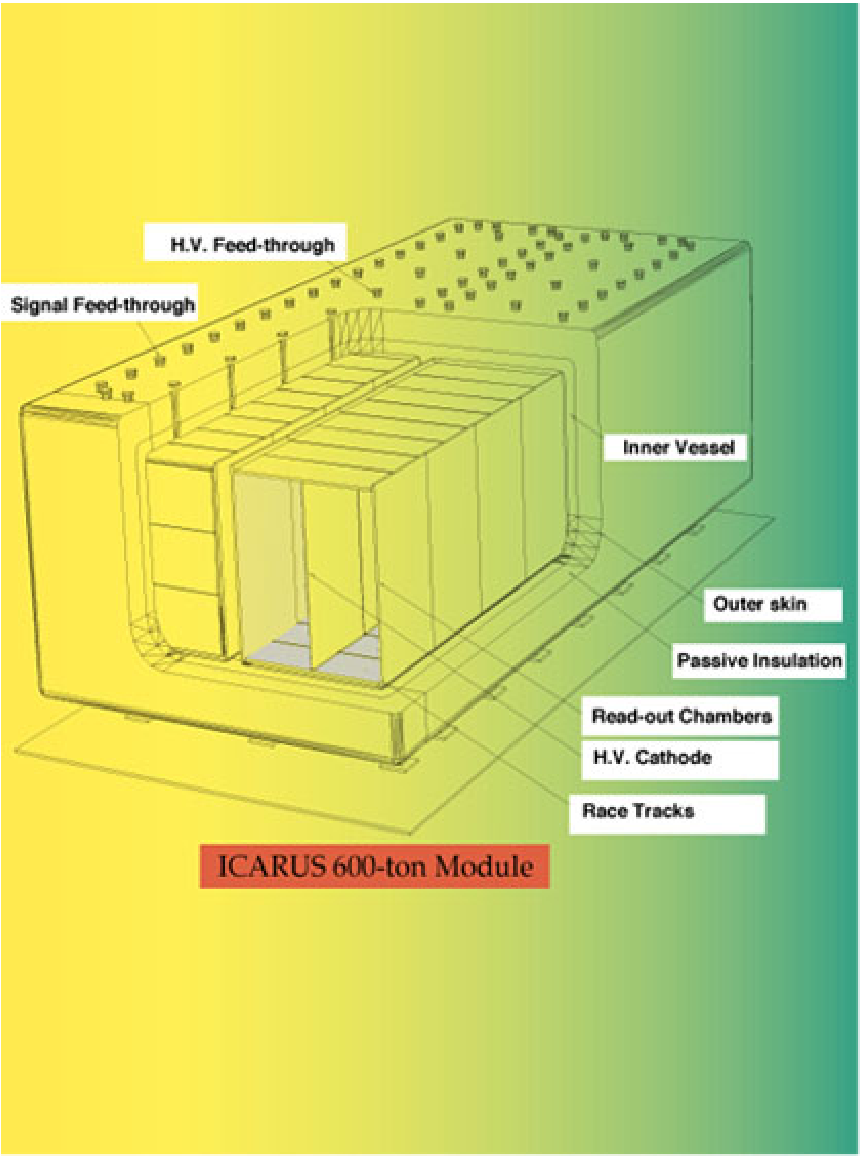


Probability to observe SuperK signal

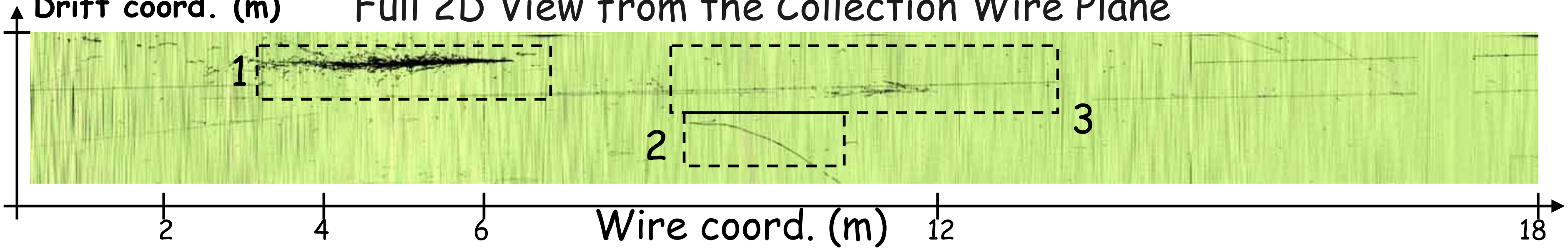
years	$P_{3\sigma}$	$P_{4\sigma}$
3	93%	83%
5	96%	91%

ICARUS

- Liquid Argon TPC
- Physics Program
  - Nucleon Decay
  - Atmospheric Neutrinos
  - Solar Neutrinos
  - Beam Neutrinos
- Electronic bubble chamber

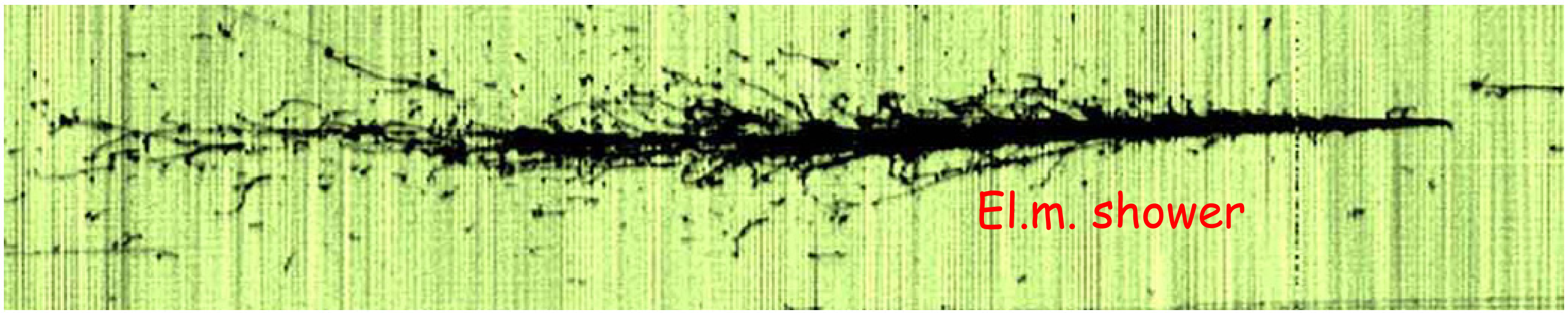


Full 2D View from the Collection Wire Plane



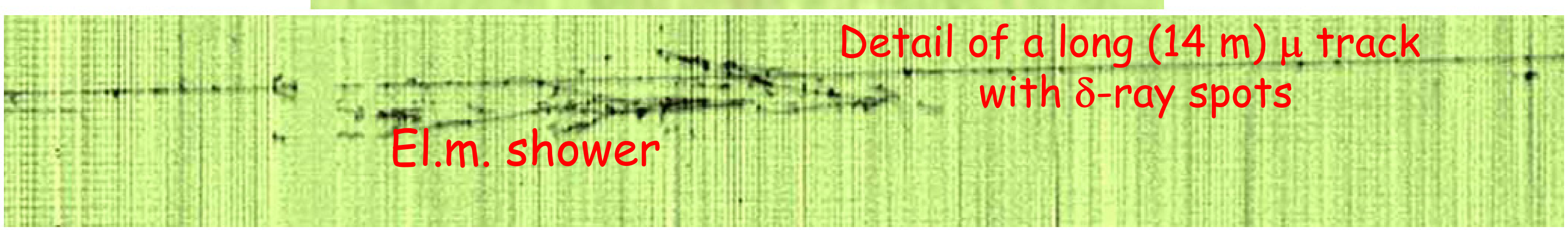
Zoom views

1



2

3



T600 test @ Pv: Run 201 - Evt 12

The Status so far

- Solar Neutrinos $\nu_e \rightarrow \nu_\mu$ or ν_τ
  - good measurement

$$\theta_{12} \approx 30^0$$

$$\Delta m_{12}^2 \approx 7 \times 10^{-5}\,\mathrm{eV}^2$$

- Atmospheric Neutrinos $\nu_\mu \rightarrow \nu_\tau$
  - initial measurement

$$\theta_{23} \approx 45^0$$

$$\Delta m_{23}^2 \approx 2 \times 10^{-3}\,\mathrm{eV}^2$$

  - Precision measurement to follow soon
    - MINOS
- What is missing?

The Missing Pieces

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & c_{13}s_{12} & s_{13} \\ -c_{23}s_{12}e^{i\delta} - c_{12}s_{13}s_{23} & c_{12}c_{23}e^{i\delta} - s_{12}s_{13}s_{23} & c_{13}s_{23} \\ s_{23}s_{12}e^{i\delta} - c_{12}c_{23}s_{13} & -c_{12}s_{23}e^{i\delta} - c_{23}s_{12}s_{13} & c_{13}c_{23} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- One mixing angle largely unknown: θ_{13}
  - Small, only limits exist
  - Results in sub-dominant $\nu_\mu \rightarrow \nu_e$ oscillations
- CP violating phase δ
  - Possible large CP violation in lepton sector
  - May give hints towards GUT
  - Why are we here?
    - matter vs. anti-matter asymmetry

Sub-Dominant Oscillations

- Some Math:

$$P(\nu_\mu \to \nu_e) = P_1 + P_2 + P_3 + P_4$$

$$P_1 = \sin^2\theta_{23}\sin^2\theta_{13}\left(\frac{\Delta_{13}}{B_\pm}\right)^2 \sin^2\frac{B_\pm L}{2}$$

$$P_2 = \cos^2\theta_{23}\sin^2\theta_{12}\left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\frac{AL}{2}$$

$$P_3 = J\cos\delta\left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right)\cos\frac{\Delta_{13}L}{2}\sin\frac{AL}{2}\sin\frac{B_\pm L}{2}$$

$$P_4 = J\sin\delta\left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right)\sin\frac{\Delta_{13}L}{2}\sin\frac{AL}{2}\sin\frac{B_\pm L}{2}$$

$$\Delta_{ij} = \frac{\Delta m_{ij}^2}{2E_\nu};$$

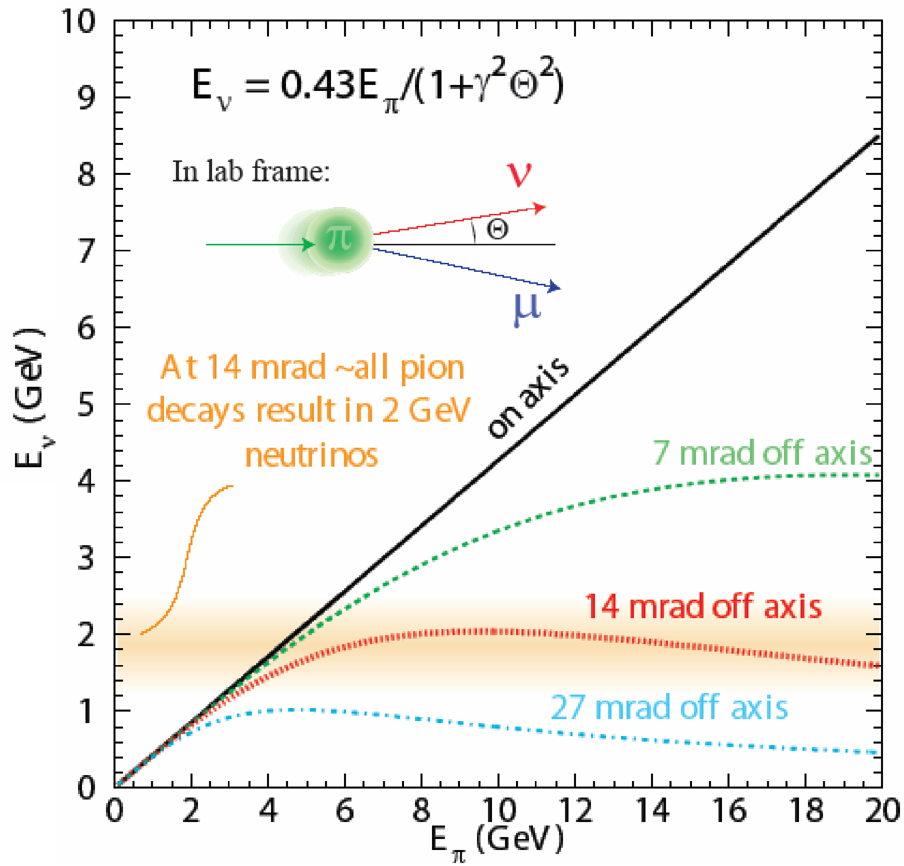
$$A = \sqrt{2}G_F n_e;$$

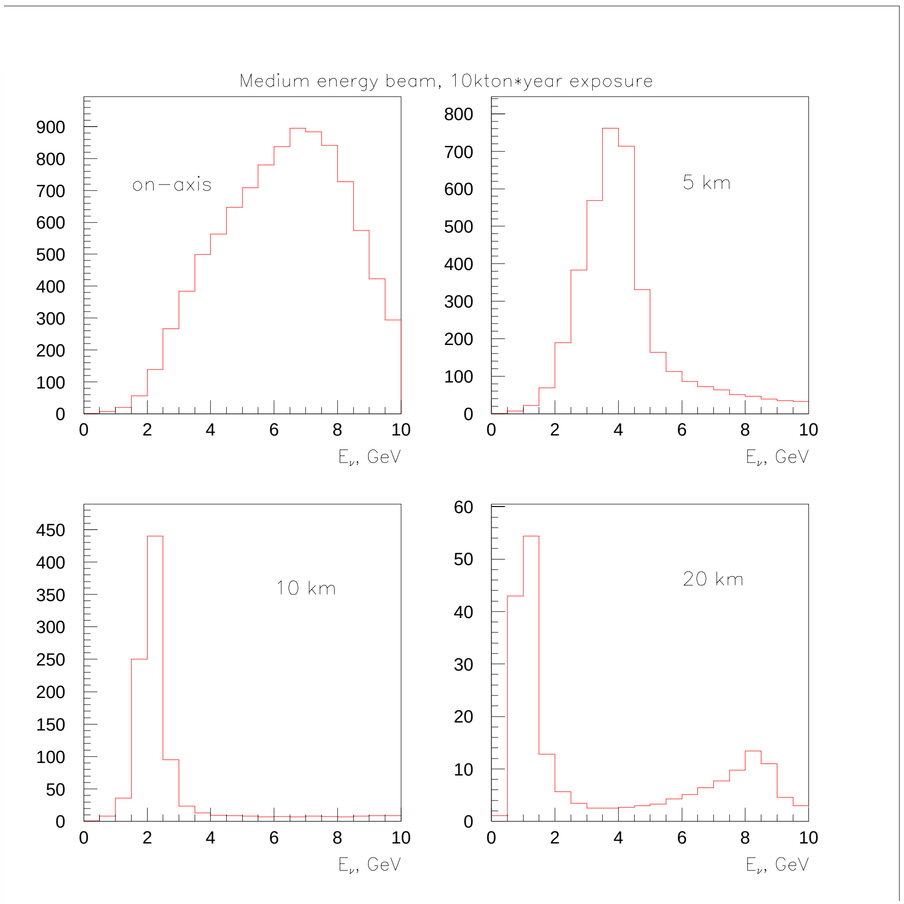
$$B_\pm = |A \pm \Delta_{13}|;$$

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

A. Cervera et al., Nuclear Physics B 579 (2000) 17 – 55, expansion to second order in $\theta_{13}, \frac{\Delta_{12}}{\Delta_{23}}, \frac{\Delta_{12}}{A}, \Delta_{12}L$

Why Off-Axis?


$E_\nu = 0.43E_\pi/(1+\gamma^2\Theta^2)$
In lab frame:
ν
π
Θ
μ
At 14 mrad ~all pion decays result in 2 GeV neutrinos
on axis
7 mrad off axis
14 mrad off axis
27 mrad off axis
E_ν (GeV)
E_π (GeV)


Medium energy beam, 10kton*year exposure
on-axis
5 km
10 km
20 km
E_ν, GeV

Next generation LBL experiments in Japan

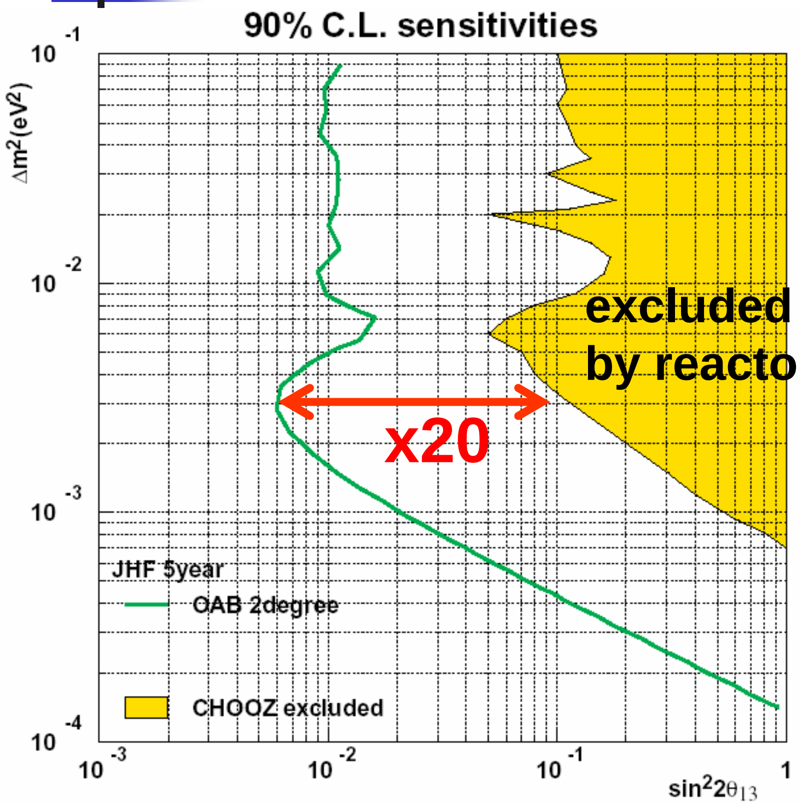
"T2K neutrino project"

- Baseline ~295 km
- Energy ~ 1 GeV
- Sensitive to
  - Θ_{13} and δ

	Beam power	Far detector	Physics
1st phase	0.75MW	Super Kamiokande(50kt)	disappearance $\nu_\mu \to \nu_X$ appearance $\nu_\mu \to \nu_e$ NC measurements
2nd phase	~4MW	Hyper Kamiokande(1Mt)	CP violation Proton decay

Sensitivities in first phase(5yrs)

Search for ν_e appearance

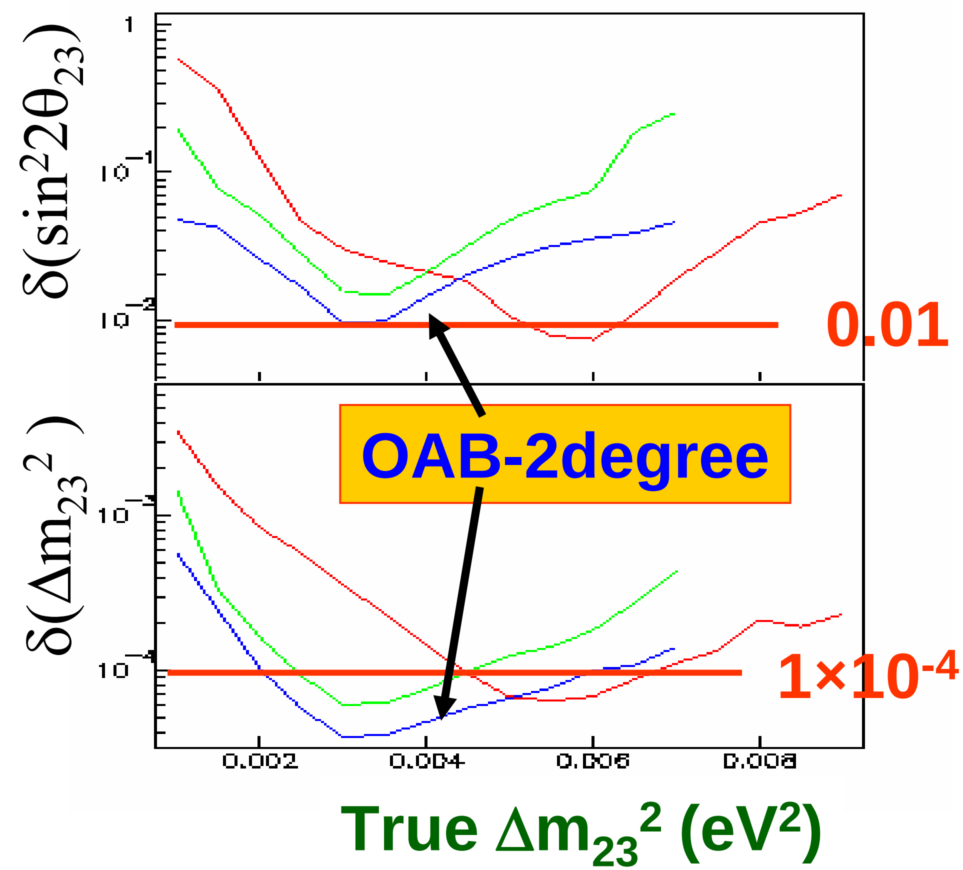


$$\sin^2 2\theta_{\mu e} \equiv \sin^2 \theta_{23} \cdot \sin^2 2\theta_{13}$$

~0.5

Sensitive $\sin^2 2\theta_{13} > 0.006$ (90%)
$\sin^2 2\theta_{13} > 0.018$ (3σ)

ν_μ disappearance



$d(\sin^2 2\theta) \sim 0.01$
$d(\Delta m^2) \sim< 1\times10^{-4}$ in 5 years

w/ beam MC, & full SK det. simulation

NOvA: Potential Sites

Vermilion Bay, Ontario,CN
980 km, 18 km up

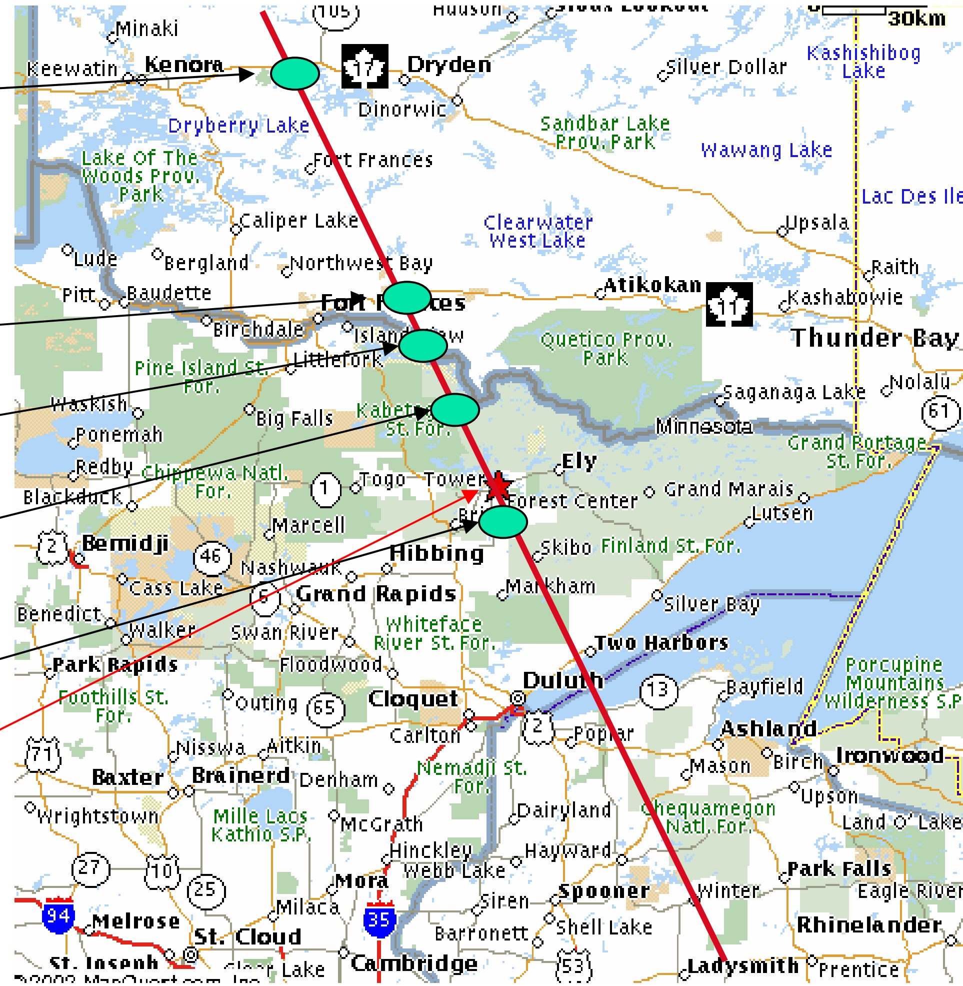
Fort Frances, Ontario,CN
875 km, 9 km up

Ash River, MN
825 km, 5 km up

Buyck, MN
775 lm, 2 km up

LTV site, MN
715 km, 1 km down

MINOS Location
735 km



NOvA (TASD)

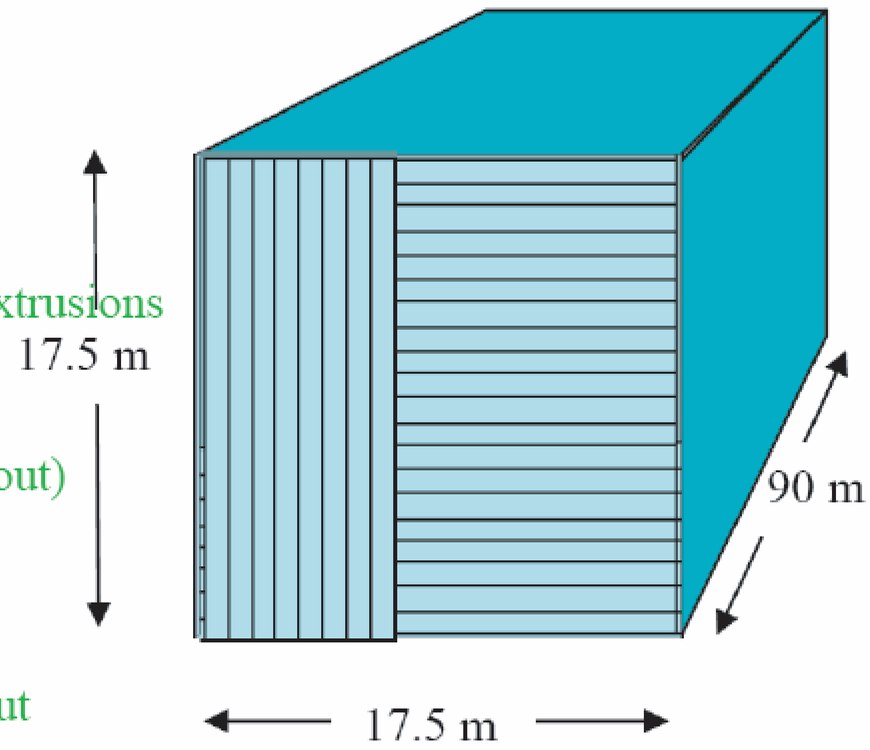
- Totally Active Scintillator Detector

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

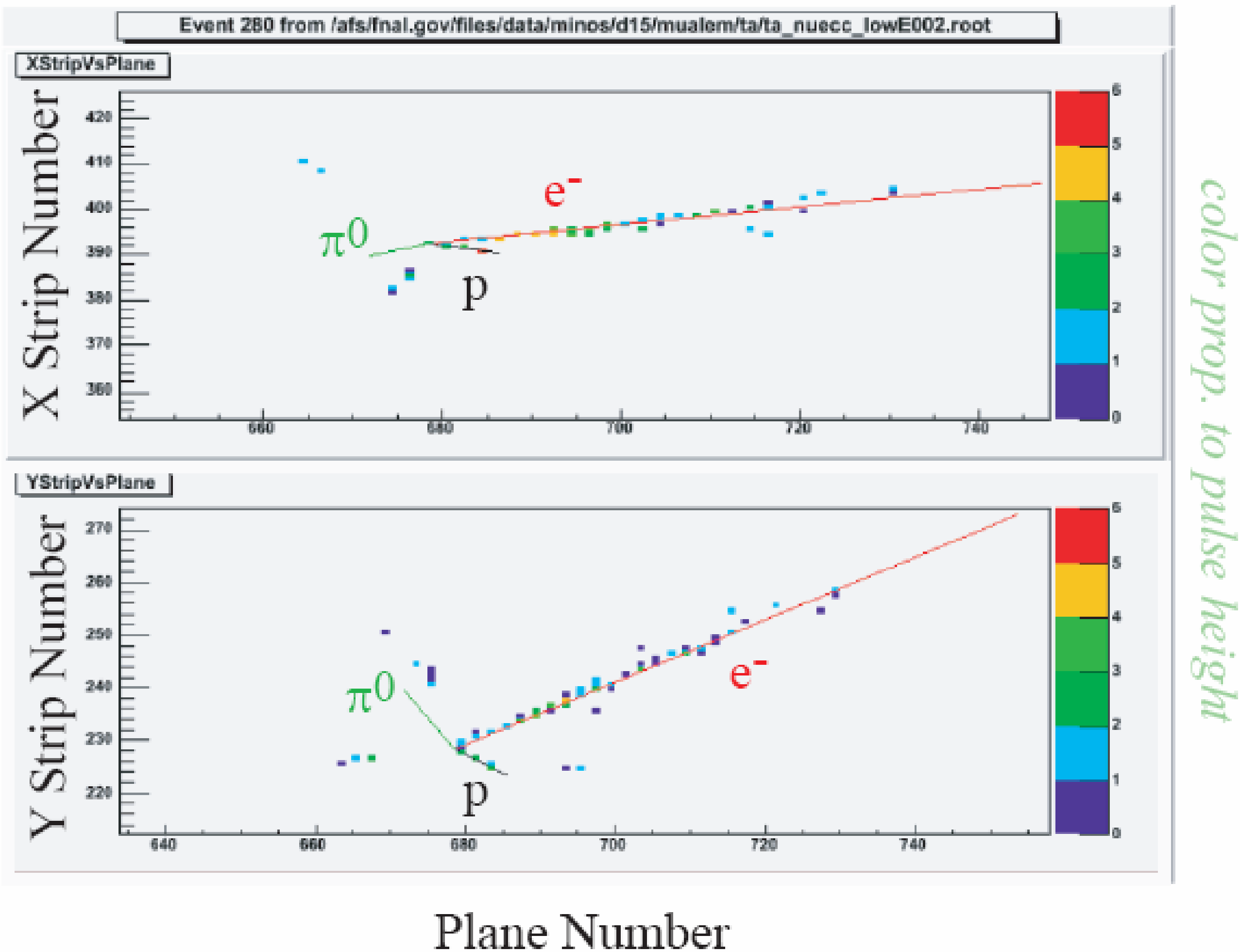
No absorber



NOvA (TASD) Performance

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

$$E_\nu = 1.65\ GeV$$

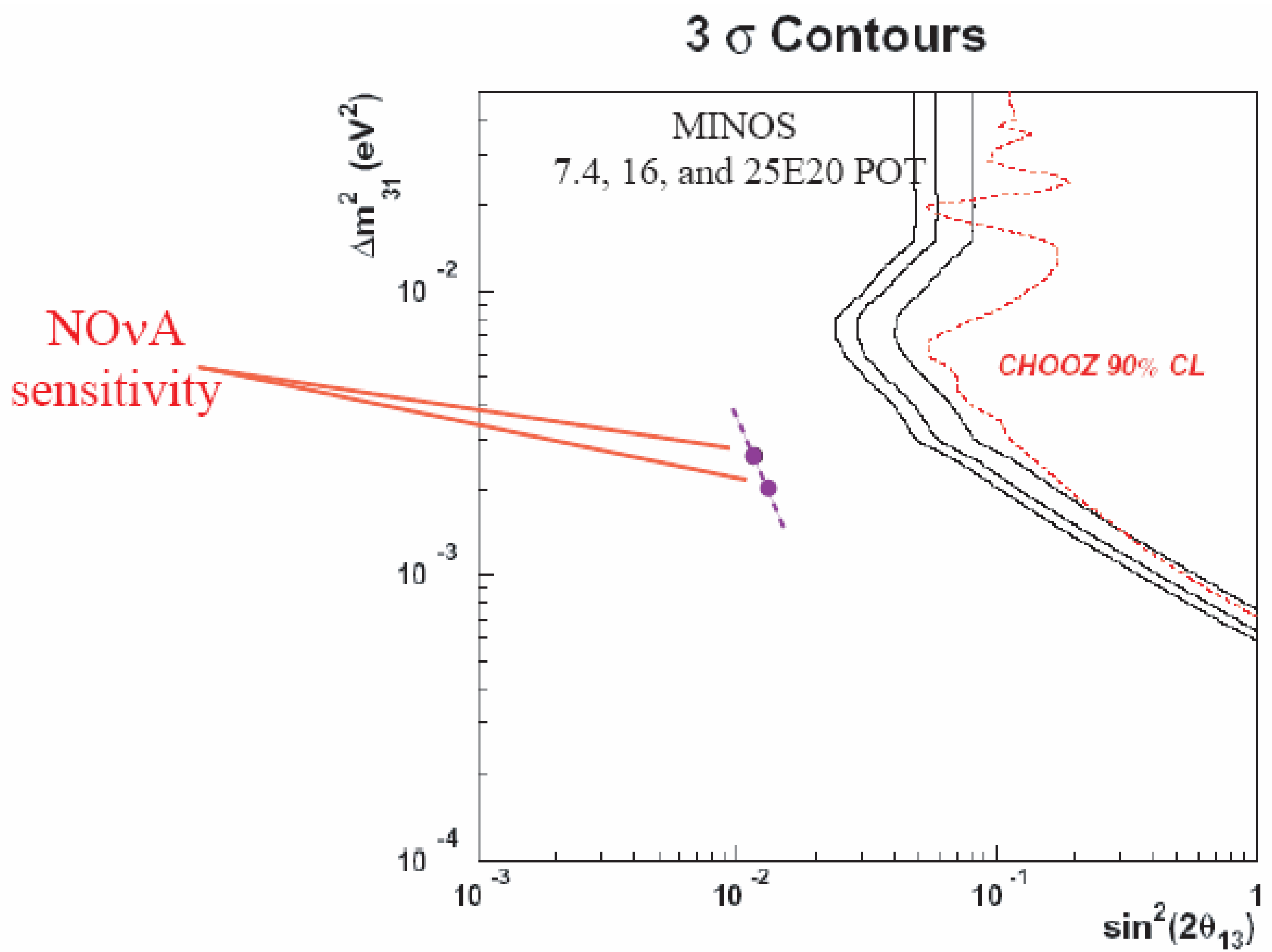


Signal efficiency
32% (18% baseline)

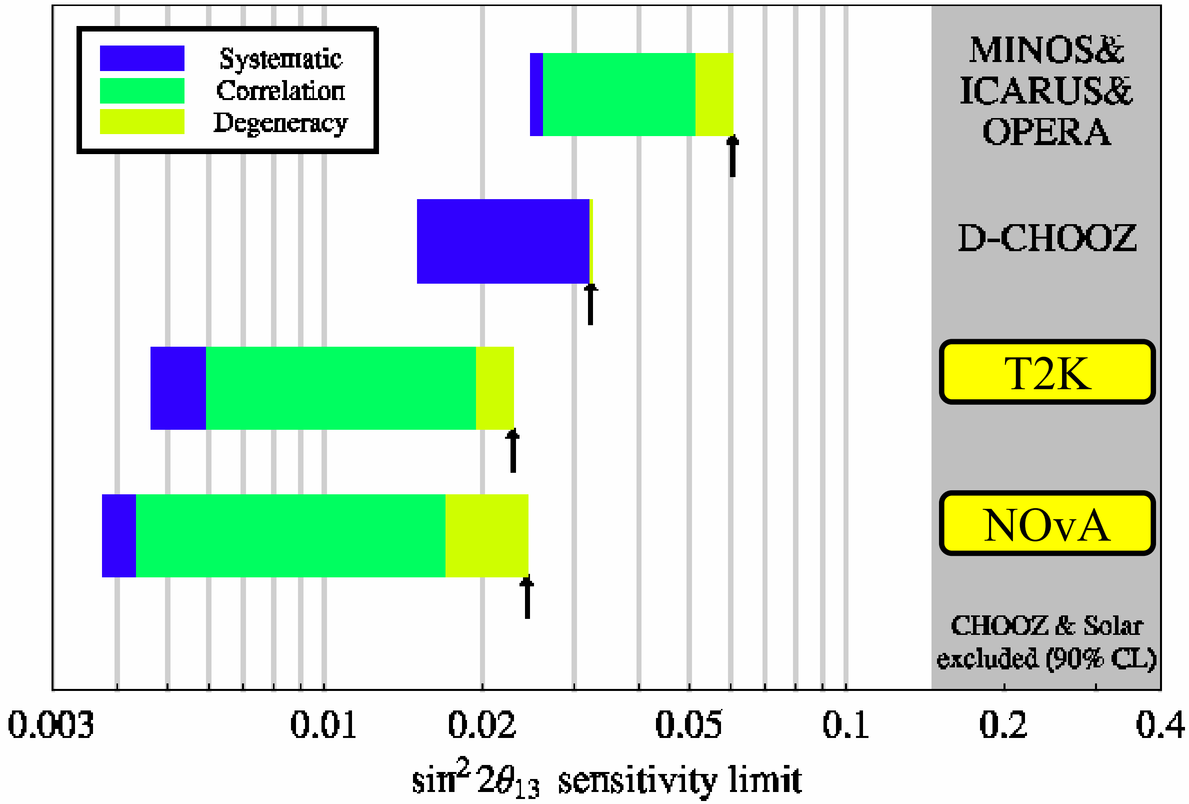
signal/background
7.7 (4.6 baseline)

signal/sqrt(bg.)
26 (24.5 baseline)

Physics Reach



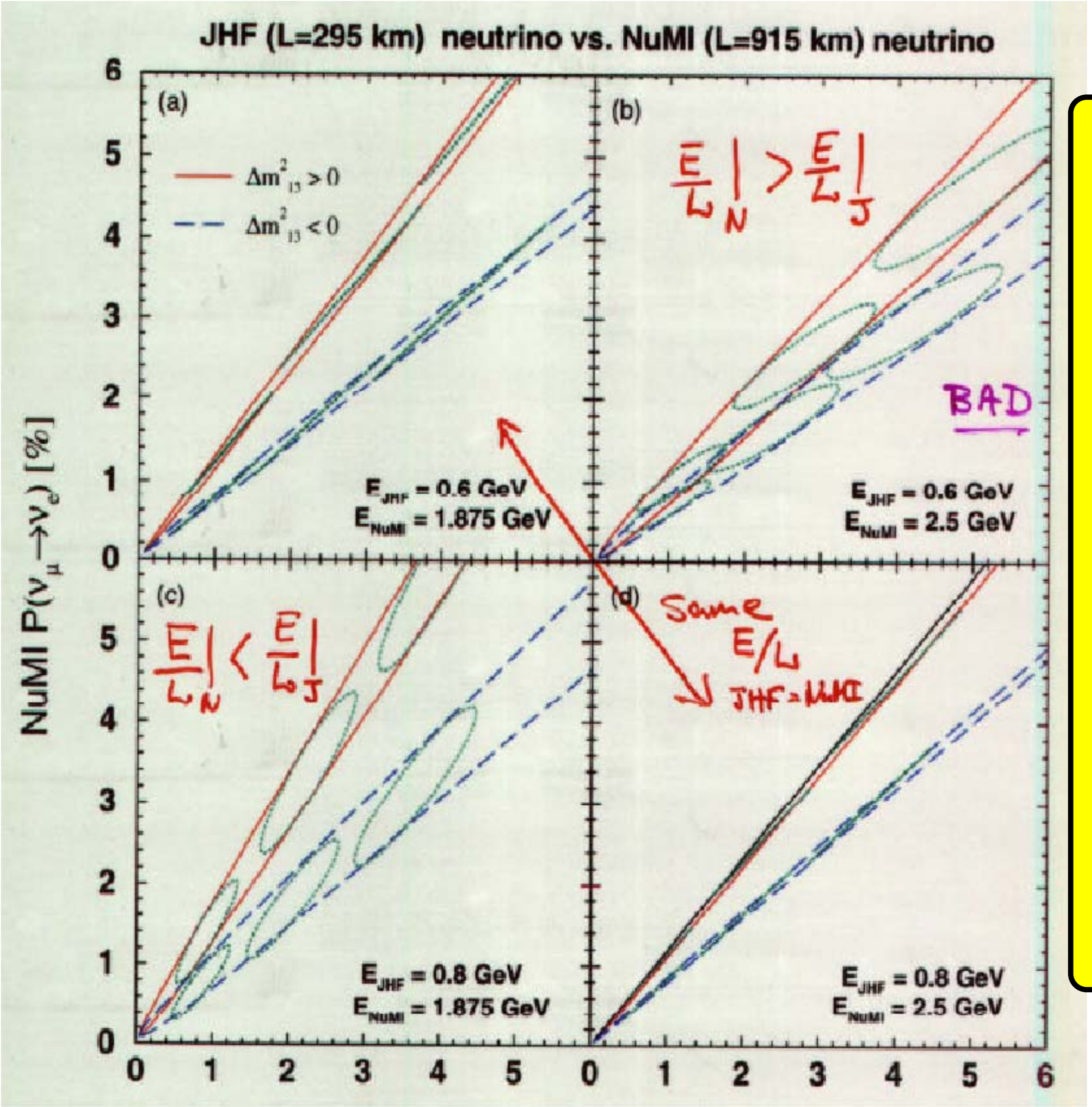
Comparison



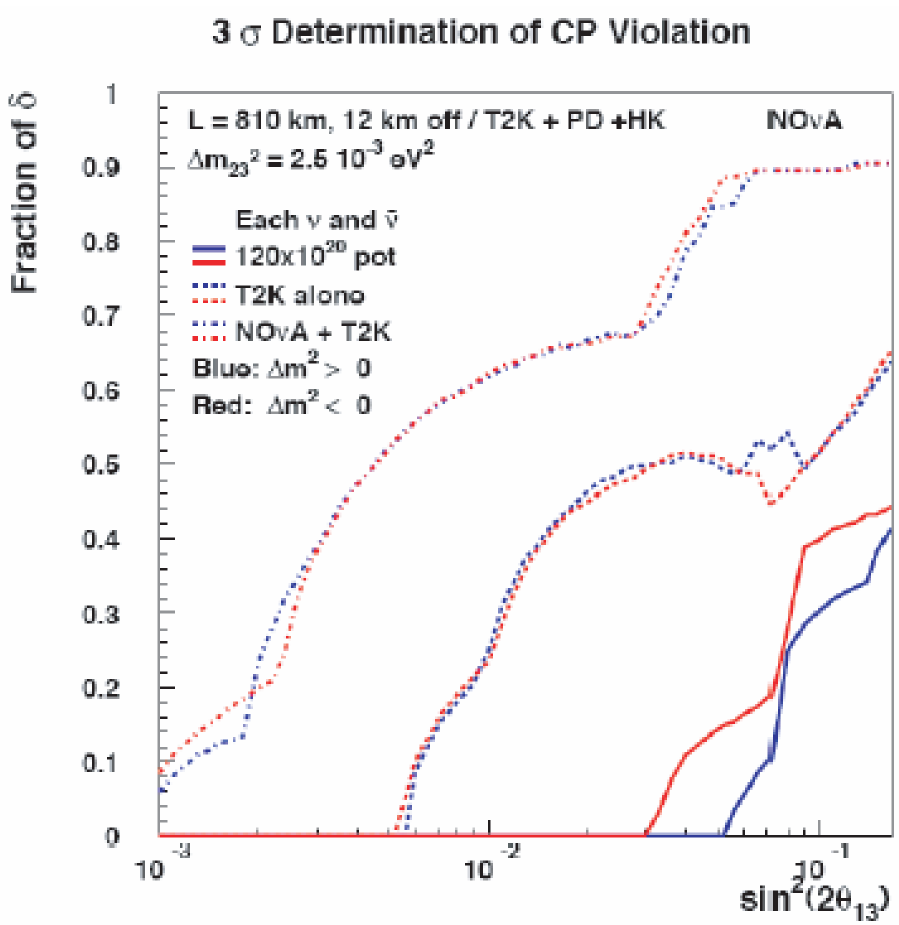
P. Huber et al. hep-ph/0403068

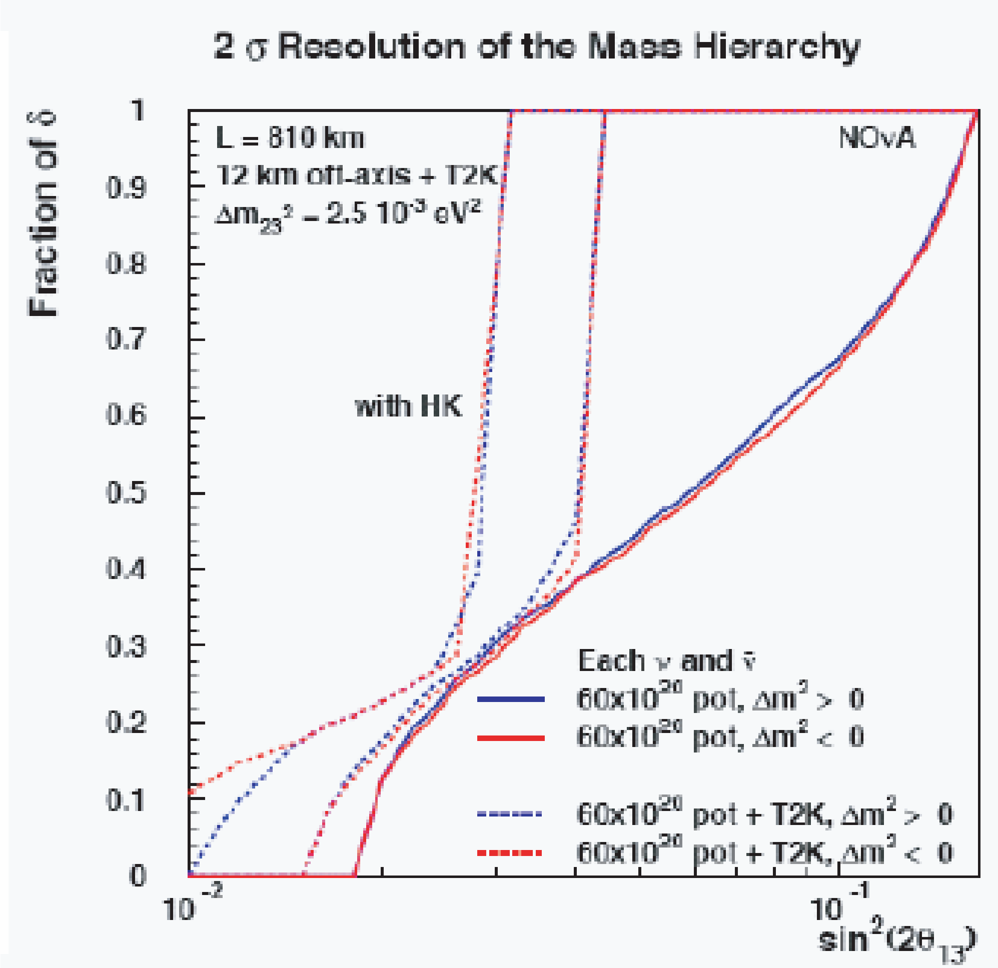
Mass Hierarchy (sign of Δm^2_{13})

- Combine
  - T2K
  - NOvA
- Use right baseline to determine sign of Δm^2_{13}
- best, if E/L is the same!



CP violation & Mass Hierarchy

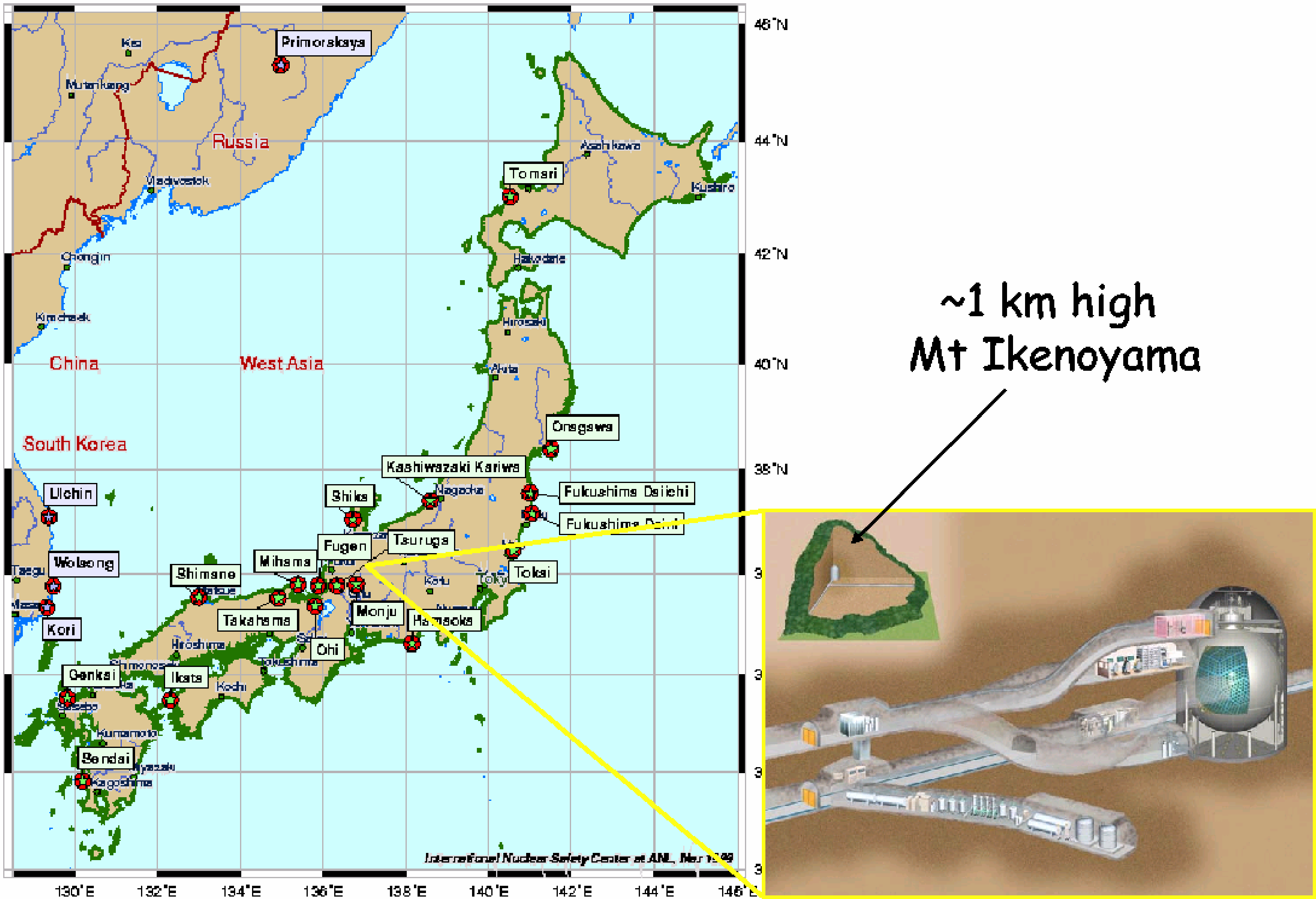




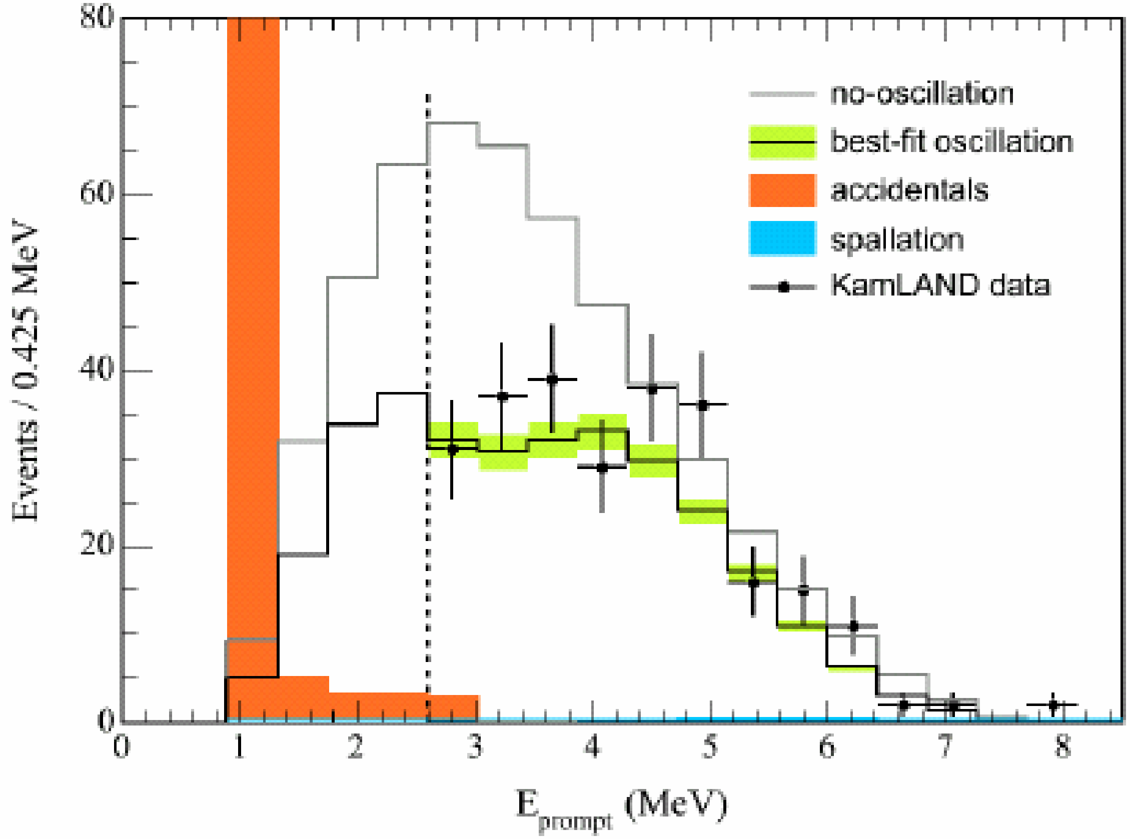
Summary

- In LBL Experiments
  - Neutrino Oscillation well established
- Next generation of detectors
  - precision measurements of some parameters
- New generation of experiments
  - might reveal unknown neutrino parameters
    - Masses & hierarchy
    - Angles
    - CP phase

KamLAND


~1 km high
Mt Ikenoyama
Primorskaya
Russia
China
West Asia
South Korea
Tomari
Asahikawa
Kushiro
Hakodate
Hirosaki
Akita
Onagawa
Kashiwazaki Kariwa
Nagaoka
Fukushima Daiichi
Fukushima Daini
Tokai
Shika
Tsuruga
Fugen
Mihama
Shimane
Takahama
Monju
Hamaoka
Ohi
Ulchin
Wolsong
Kori
Genkai
Ikata
Sendai
Vladivostok
Chongjin
Hiroshima
Kochi
Kumamoto
Kagoshima
Taegu
46°N
44°N
42°N
40°N
38°N
130°E
132°E
134°E
136°E
138°E
140°E
142°E
144°E
International Nuclear Safety Center at ANL

Measured Energy Spectrum



A fit to a simple rescaled reactor spectrum is excluded at 99.89% CL (χ^2=43.4/19)

Best fit to oscillations:

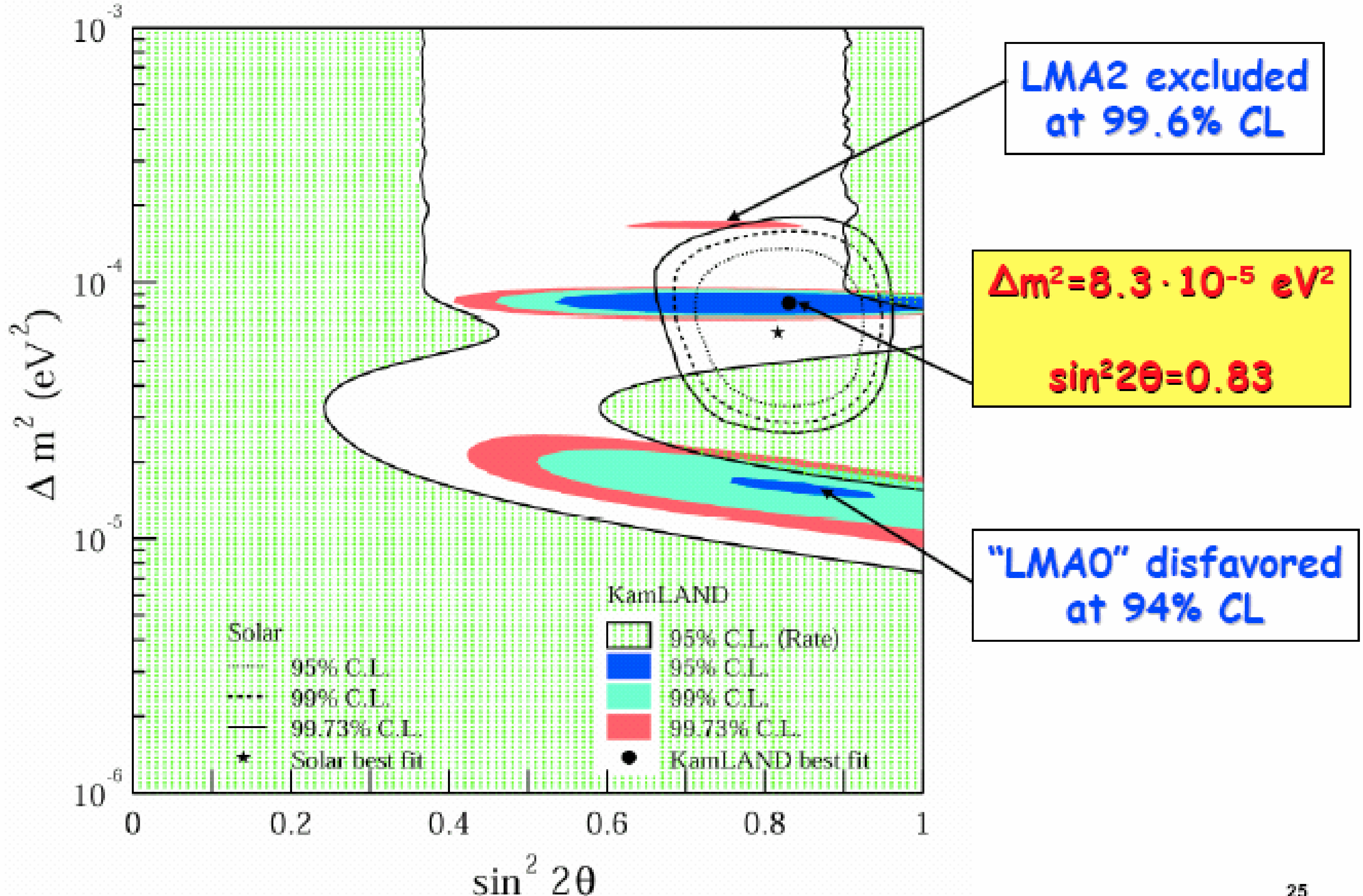
$\Delta m^2 = 8.3 \cdot 10^{-5}$ eV^2

$\sin^2 2\theta = 0.83$

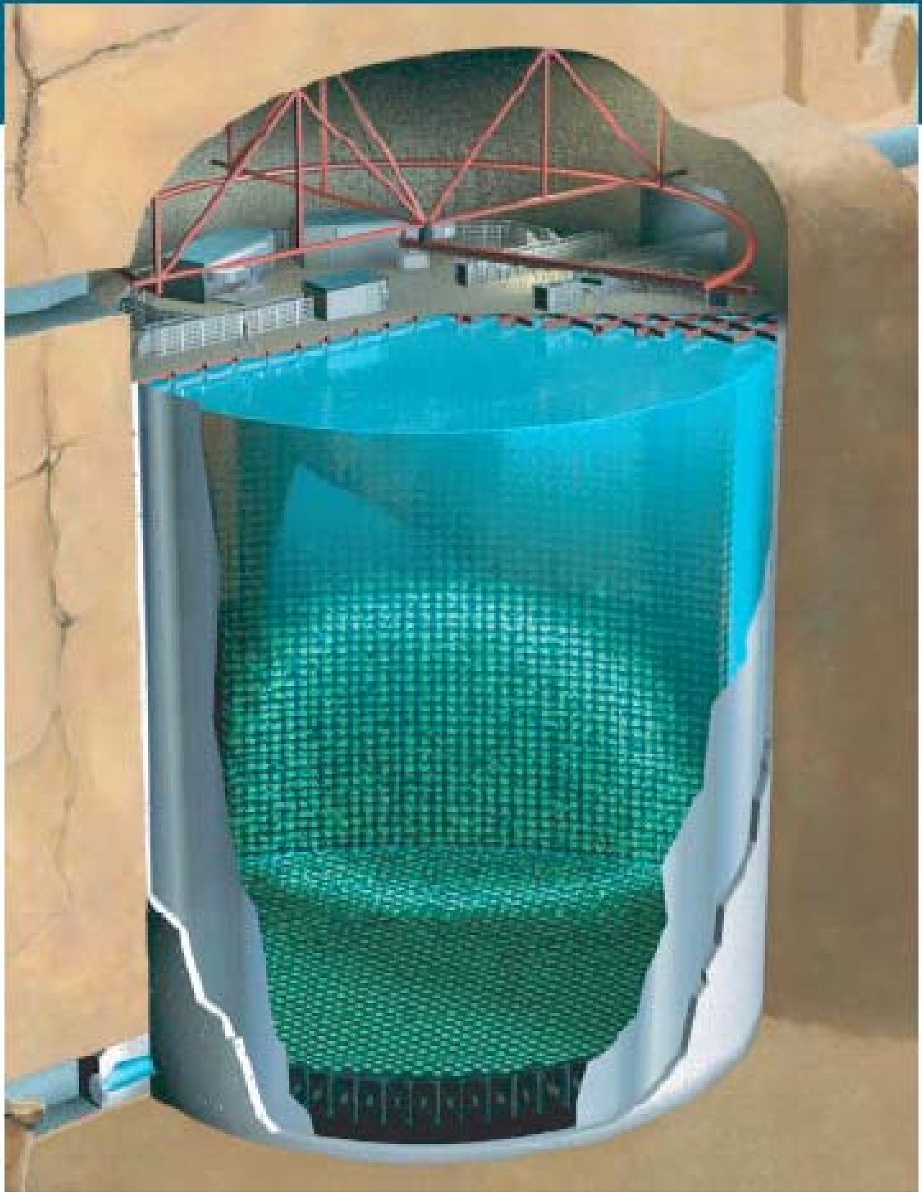
Straightforward χ^2 on the histo is 19.6/11

Using equal probability bins χ^2/dof=18.3/18 *(goodness of fit is 42%)*

"Solar" Neutrino Results



Super-Kamiokande

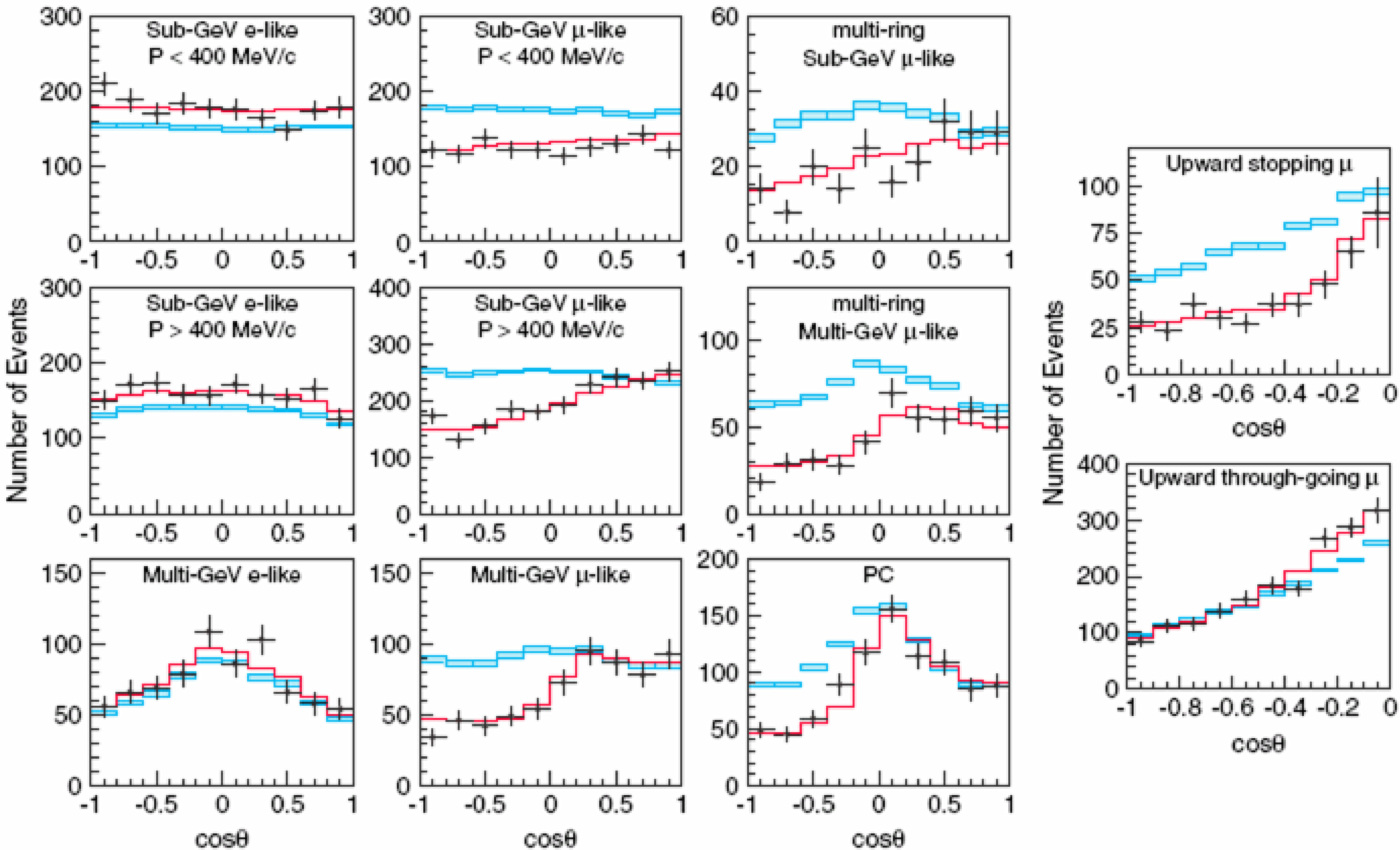


SK-1 1996 - 2001
- 22.5 kton fiducial mass (2m from wall)
- 11146 50-cm photomultiplier tubes
- 40% photocathode coverage
- 1885 20-cm pmts in outer detector

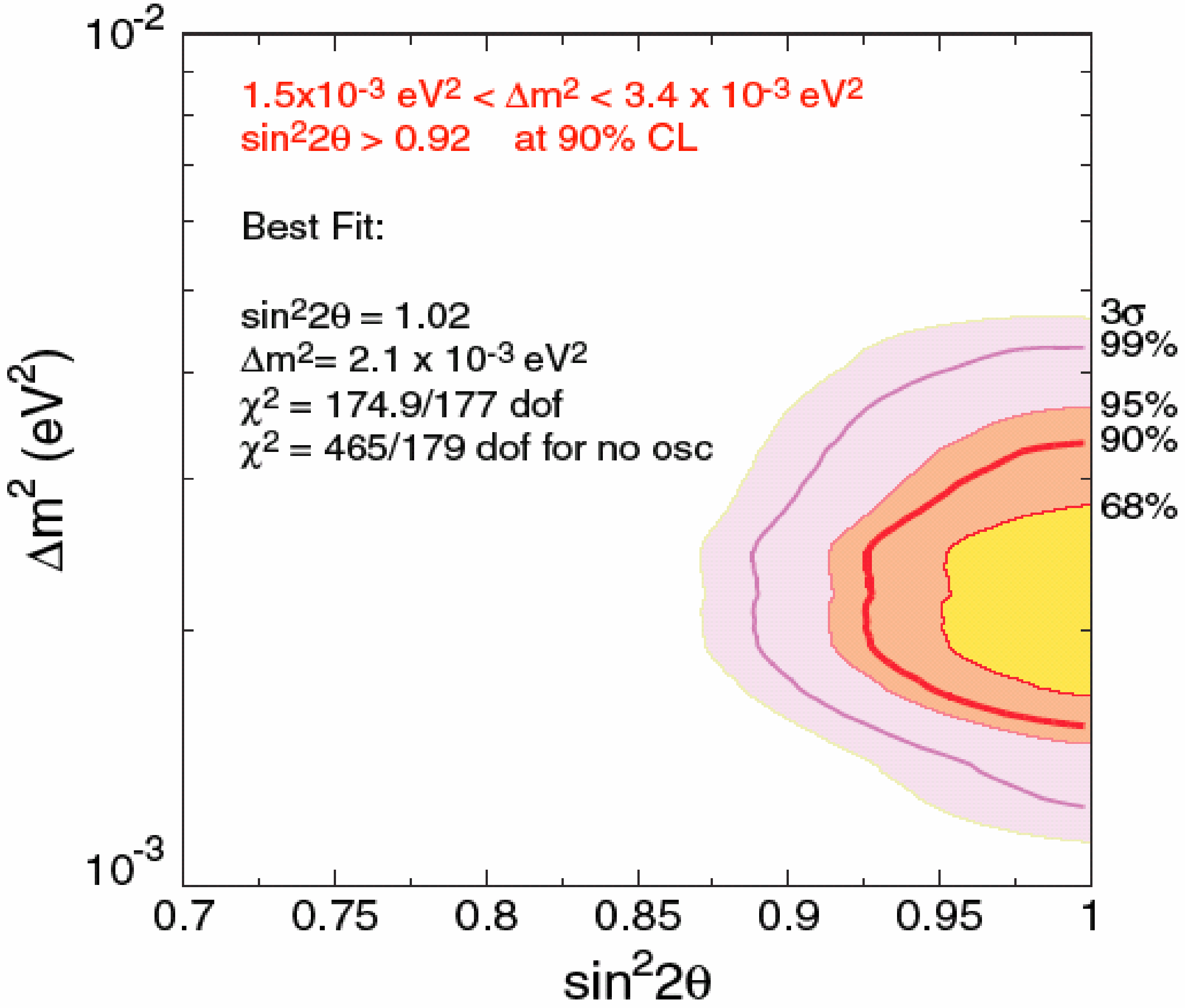
SK-2 January 2003 - October 2005
- 5182 PMTs, mostly recovered from accident
- ~19% coverage with acrylic shields →
- outer detector fully restored
- K2K beam resumed

SK-3 March 2006 +
- original coverage to be restored
- T2K off-axis beam from J-PARC

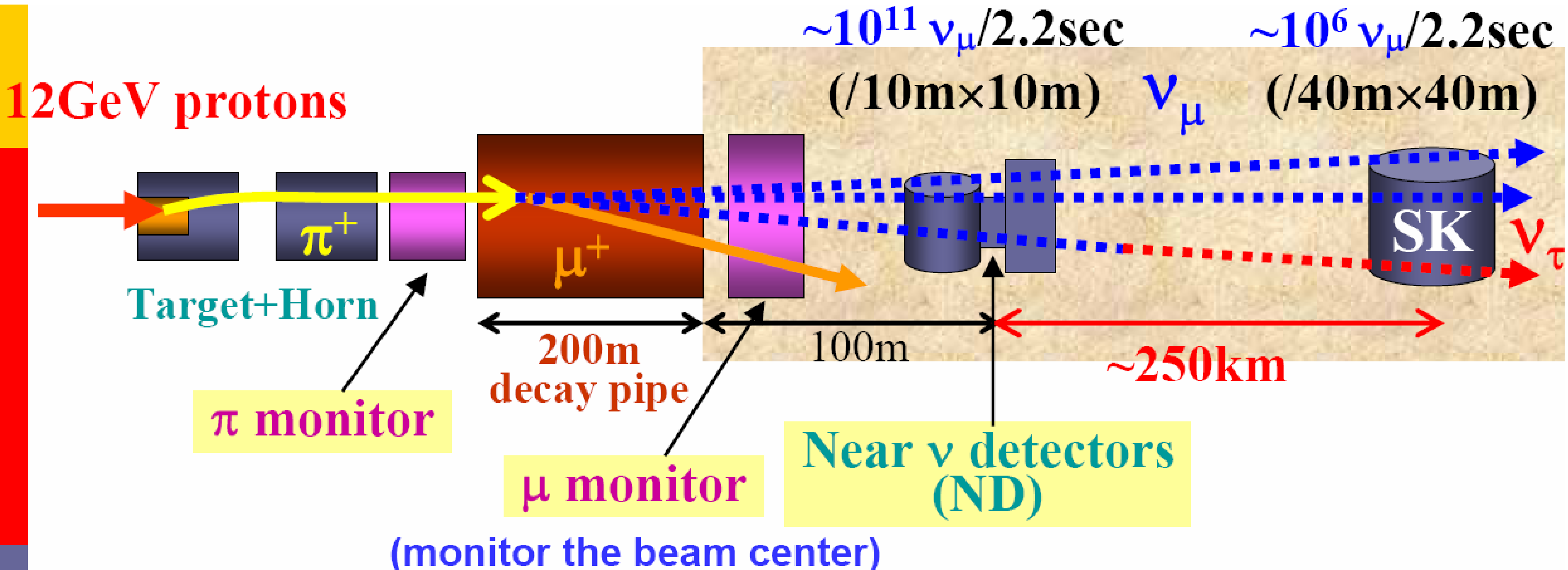
Zenith Angle Distribution



SuperKamiokande Results



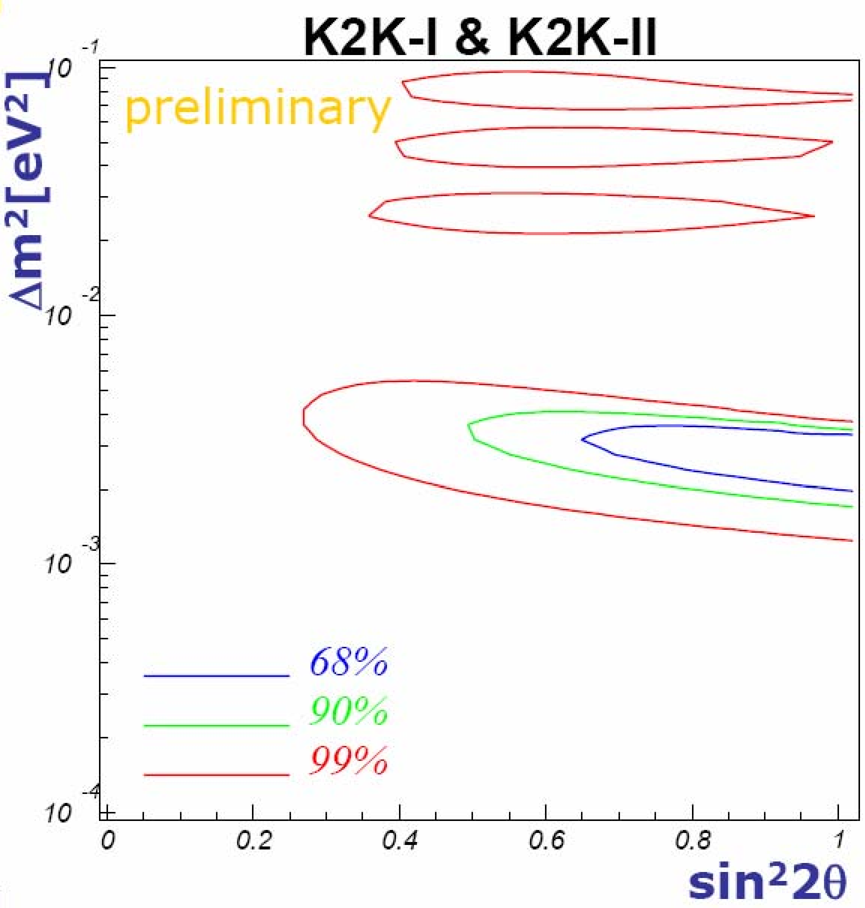
K2K Experiment



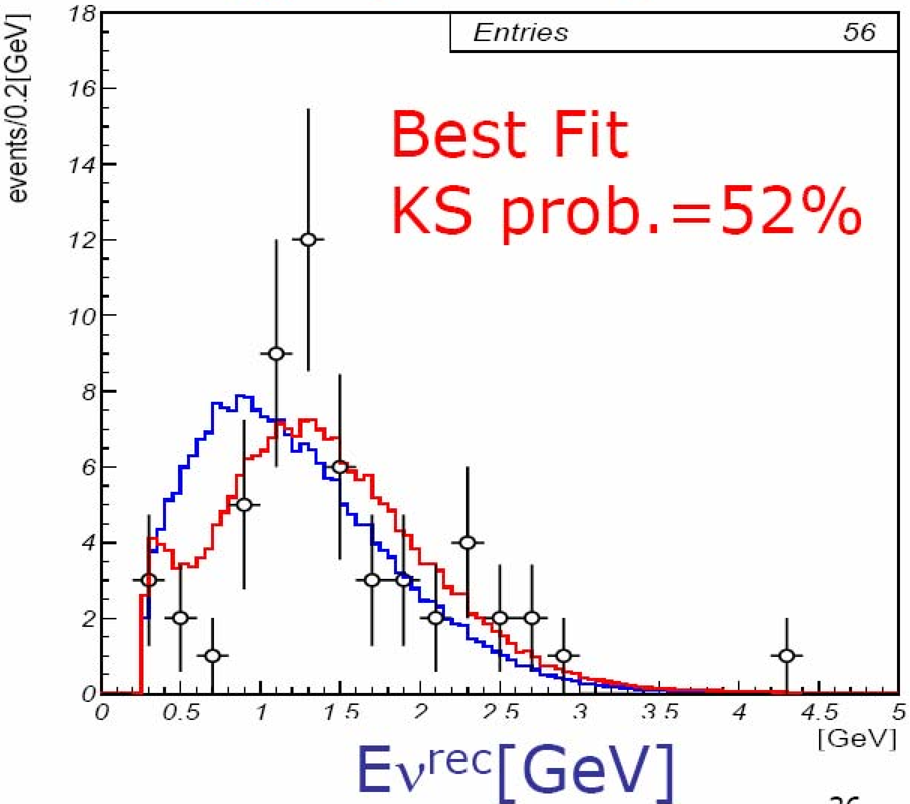
Signal of ν oscillation at K2K

- Reduction of ν_μ events
- Distortion of ν_μ energy spectrum

K2K Results



- $N_{SK}^{obs}=108$
- N_{SK}^{exp} (best fit)=104.8



Based on ΔlnL