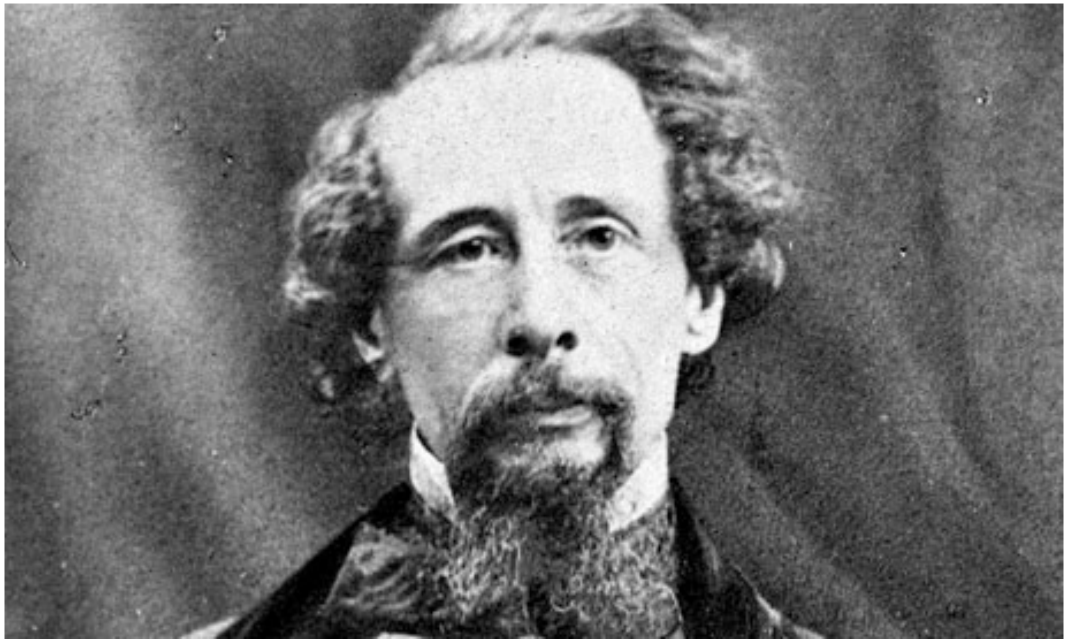
Neutrino Physics at the Crossroads

Higgs-Maxwell Meeting
8 February 2012
Royal Society of Edinburgh
Paul Soler

University of Glasgow

On the 200th anniversary of the birth of Charles Dickens:

A Tale of Two Earthquakes (and one tsunami)



Neutrino Physics

- Neutrino Physics always seems to deliver surprising and important results
  - It supplied the first evidence for electroweak unification – the discovery of neutral currents
  - Neutrinos from the sun were first direct evidence of nuclear fusion reactions in the core of stars
  - Three neutrino families (no more, no less!)
  - Neutrinos from cosmic rays, from the sun and from reactors showed evidence for neutrino oscillations – first evidence for neutrino mass and physics beyond the Standard Model
  - Other surprises and controversies – sterile neutrinos (LSND)?, Majorana neutrinos (double beta decay)?, superluminal neutrinos (Opera)?

Outline

- Current and future neutrino oscillation experiments
  - Neutrino mixing and oscillations
  - Atmospheric neutrinos, K2K and MINOS
  - Solar neutrinos, KamLand
  - T2K and recent MINOS results on θ_{13}
  - Reactor experiments: Double Chooz, RENO, Daya Bay
  - LSND, MiniBoone and sterile neutrinos
  - Future long baseline experiments: NOVA, LBNE, Beta Beams and Neutrino Factories
- Superluminal neutrinos

I will not say anything about direct neutrino mass or double beta decay – a talk in its own right!

Neutrino Oscillations

- Weak eigenstates do not coincide with mass eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \Rightarrow U_{PMNS} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i?} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix}$$

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

Neutrino mixing matrix (Pontecorvo-Maki-Nakagawa-Sakata, PMNS matrix) similar to CKM matrix of quark sector.

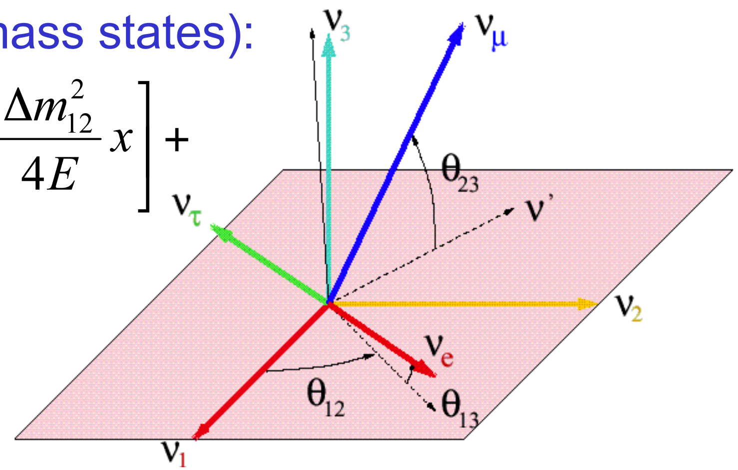
- Neutrino mixing predicts neutrino oscillation and CP violation:

States: $|\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle$ where $\alpha = e, \mu, \tau$ and $i = 1,2,3$

Probability of mixing (rotation between flavour and mass states):

$$P_{\nu_e\nu_\mu(\bar{\nu}_e\bar{\nu}_\mu)}(x) = s_{23}^2 \sin^2 2\theta_{13} \sin^2\left[\frac{\Delta m_{13}^2}{4E} x\right] + c_{23}^2 \sin^2 2\theta_{12} \sin^2\left[\frac{\Delta m_{12}^2}{4E} x\right] +$$

$$+ \tilde{J} \cos\left[\pm\delta - \frac{\Delta m_{13}^2}{4E} x\right]\left(\frac{\Delta m_{12}^2}{4E} x\right)\sin\left[\frac{\Delta m_{13}^2}{4E} x\right]$$

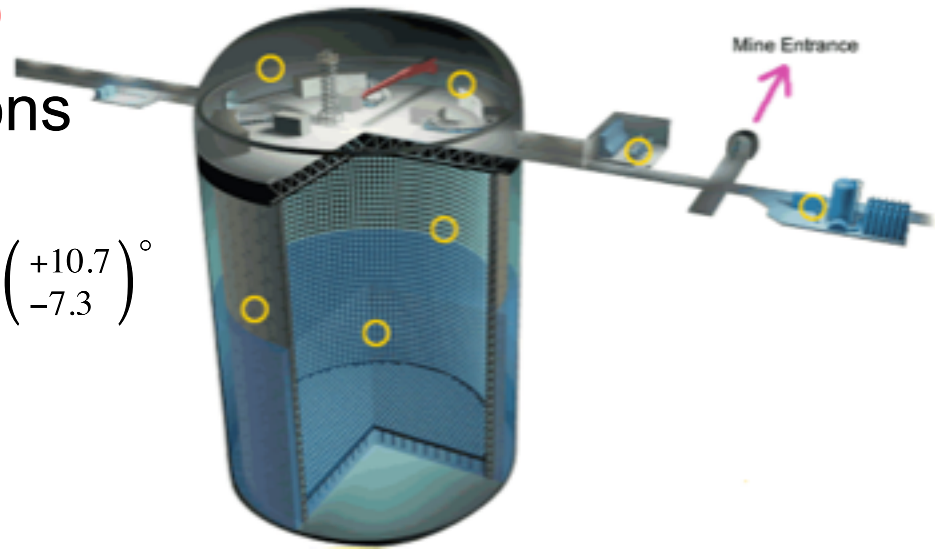


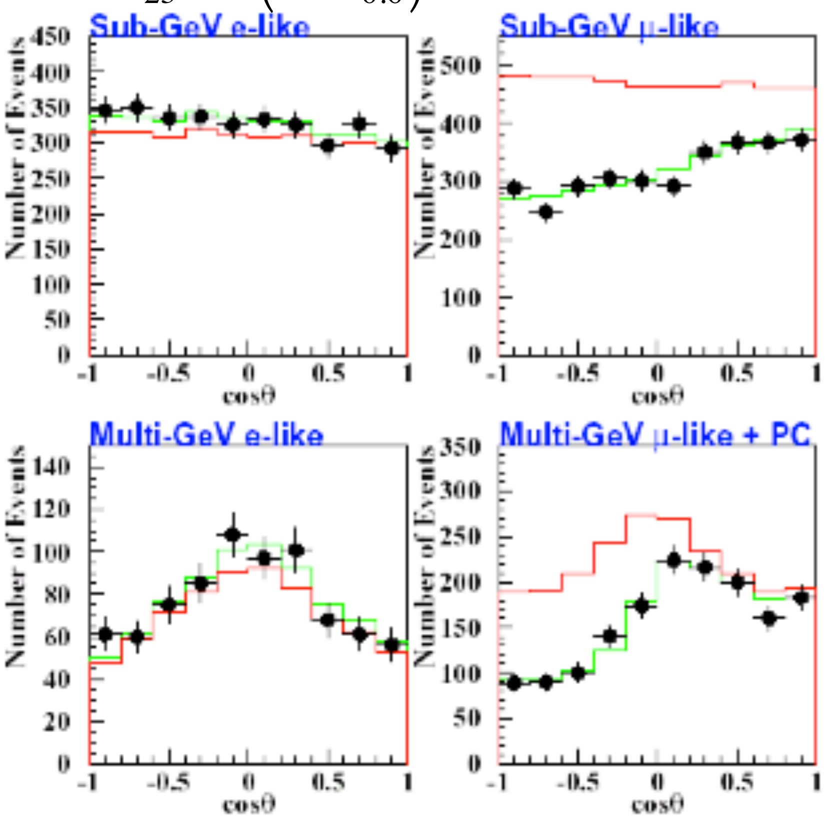
Atmospheric Neutrinos

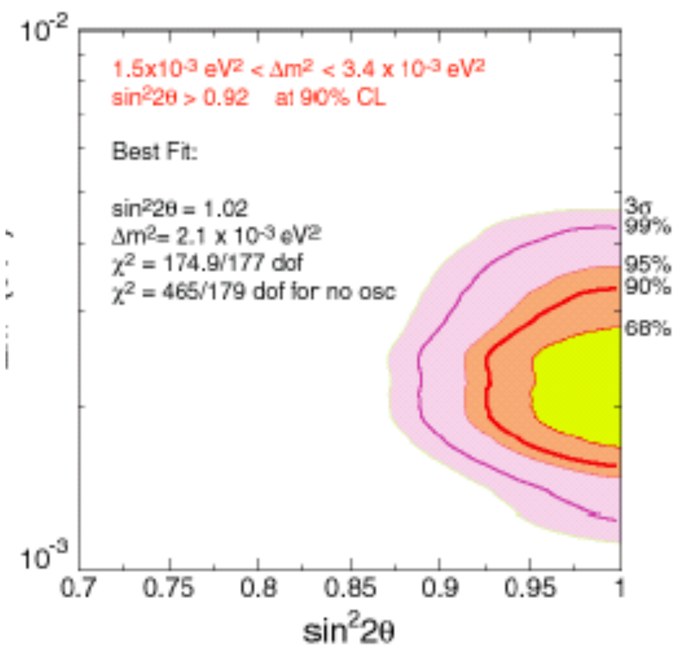
- Super-Kamiokande (1998)
  - Discovery neutrino oscillations
  - Neutrino mixing maximal?

$$\sin^2(2\theta_{23}) > 0.9 \Rightarrow \theta_{23} = 42.8^{+4.7}_{-2.9}\left(^{+10.7}_{-7.3}\right)^\circ$$

$$\Delta m_{23}^2 = \left(2.1^{+1.9}_{-0.6}\right) \times 10^{-3}\ eV^2$$



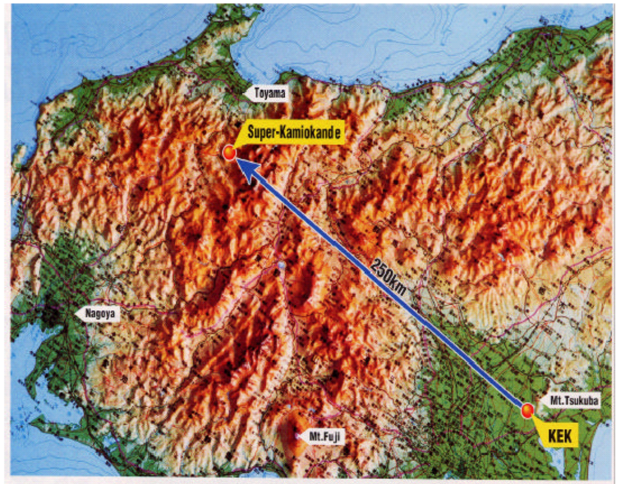


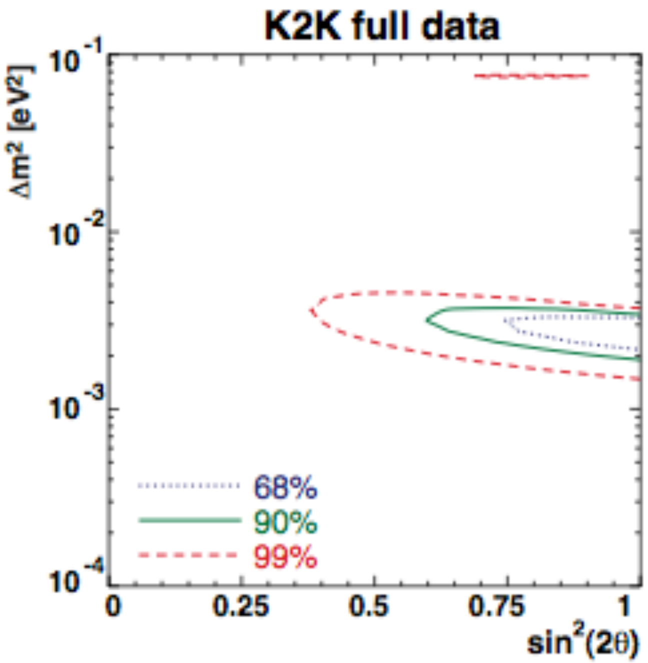


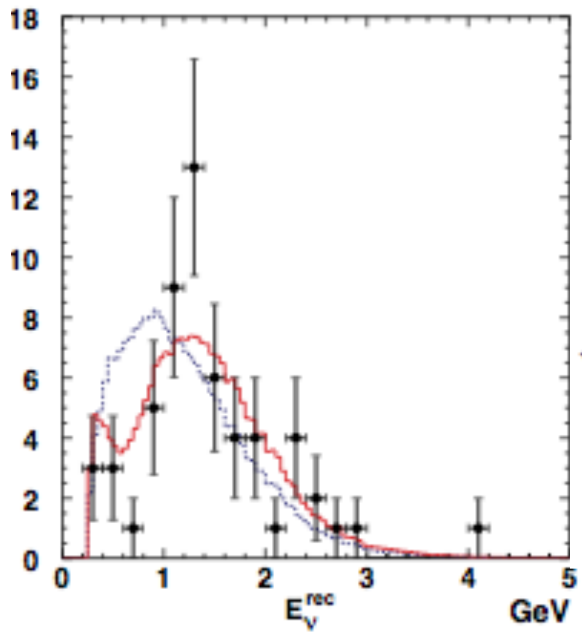
Long Baseline Accelerator Data

- K2K Long Baseline:
  - Confirmation neutrino oscillations
    - Observed: 112 events in Super-K
    - Expected (no oscillation): $158.1^{+9.2}_{-8.6}$
    - **4.3σ**
  - Same parameters as atmospheric:

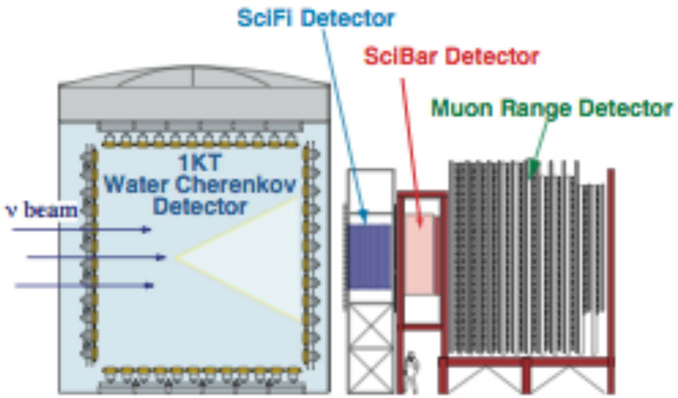
$$\sin^2(2\theta_{23}) = 1 \qquad \Delta m_{23}^2 = 2.75 \times 10^{-3}\ eV^2$$





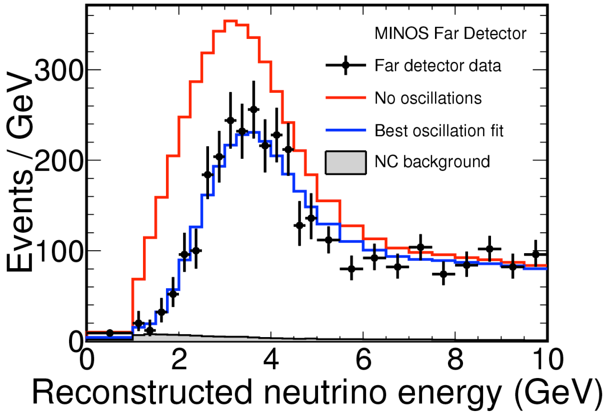


K2K Front Detector



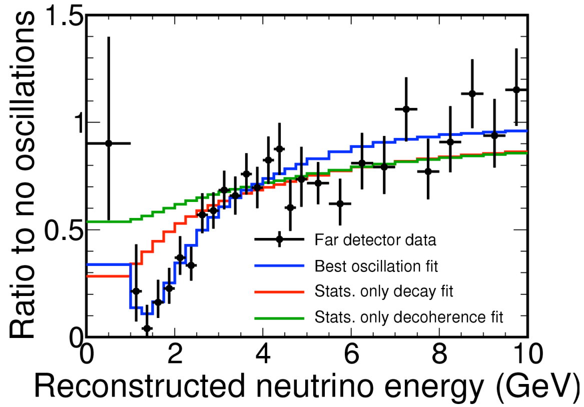
Long Baseline Accelerator Data

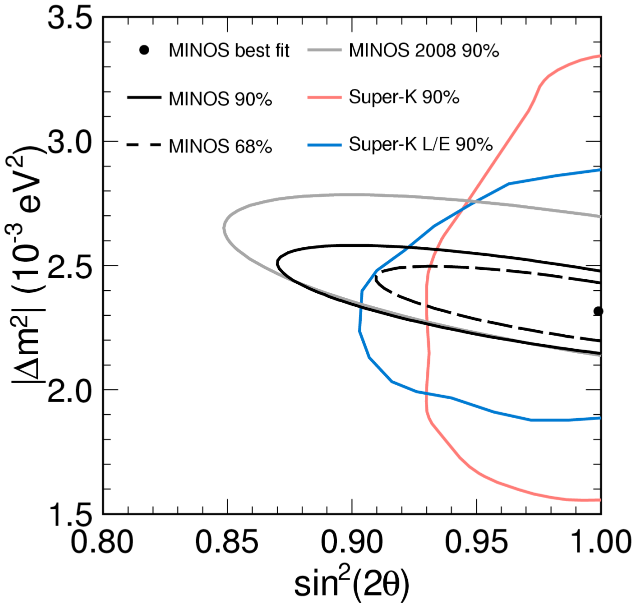
- MINOS Long Baseline:
  - More sensitive measurement oscillations
    Observed: 1986 events (FC), 2017 (PC)
    Expected (no oscillation): 2451 events (FC), 2206 (PC)
  - Agreement with SupeK, K2K



$$\Delta m_{23}^{\ 2} = \left(2.32^{+0.12}_{-0.08}\right) \times 10^{-3}\ eV^2$$

$$\sin^2(2\theta_{23}) > 0.90 @ 90\% CL$$





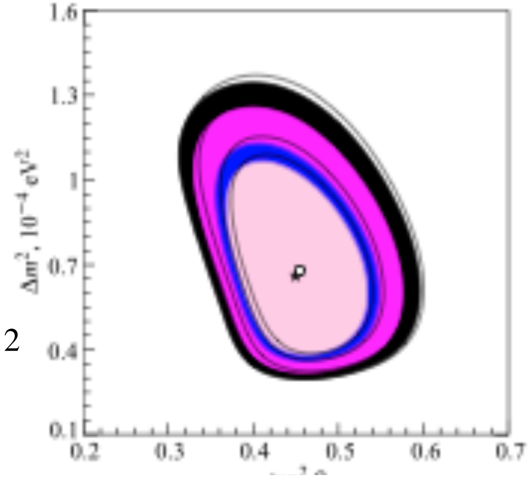
MINOS FD

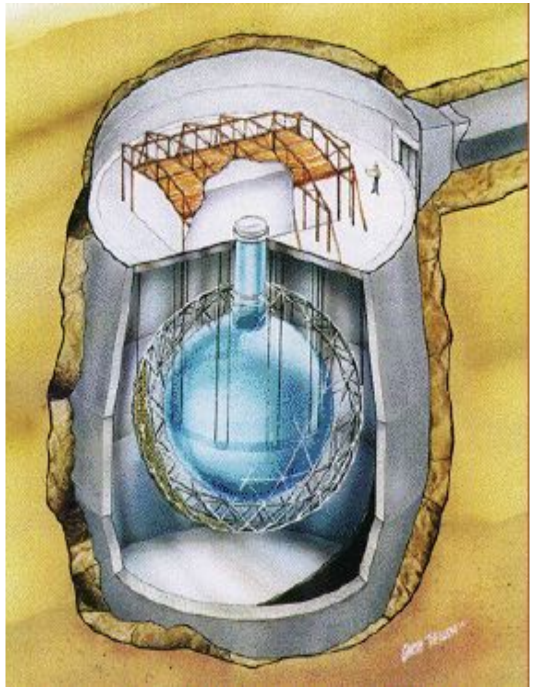
Solar Neutrinos

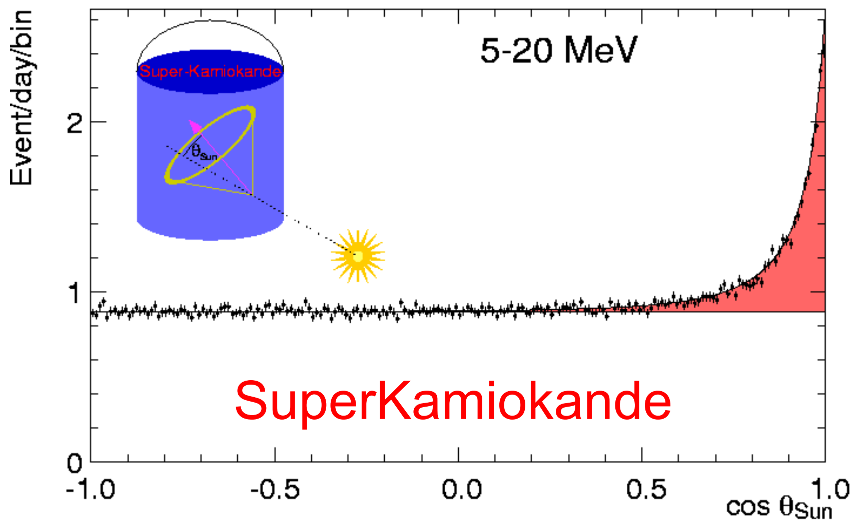
- Combination solar neutrino experiments also established neutrino oscillations through adiabatic MSW effect in matter
  - Chlorine, Gallium
  - Super-Kamiokande
  - Sudbury Neutrino Observatory

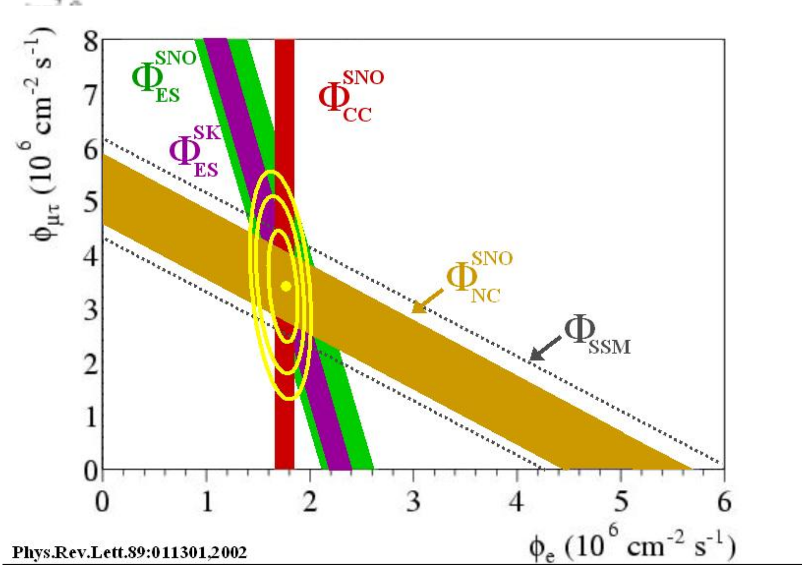
$$\Delta m_{21}{}^{2} = (7.59 \pm 0.20) \times 10^{-5}\ eV^{2}$$

$$\theta_{21} = 34.4^{\circ} \pm 1^{\circ} \pm 3^{\circ}$$









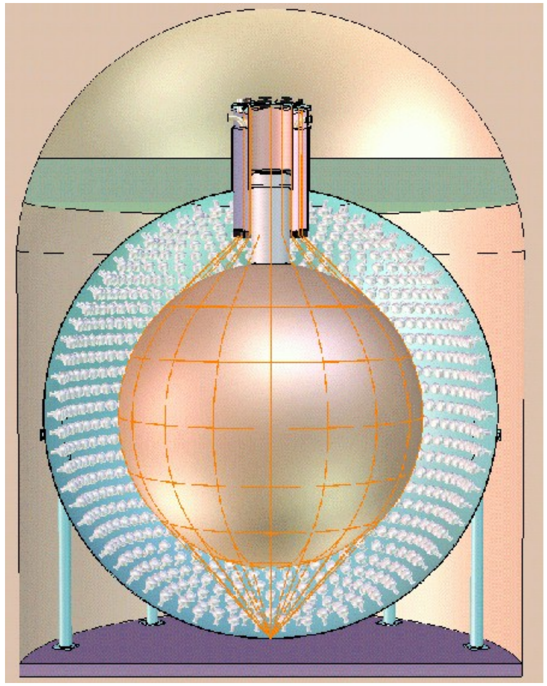
KamLAND

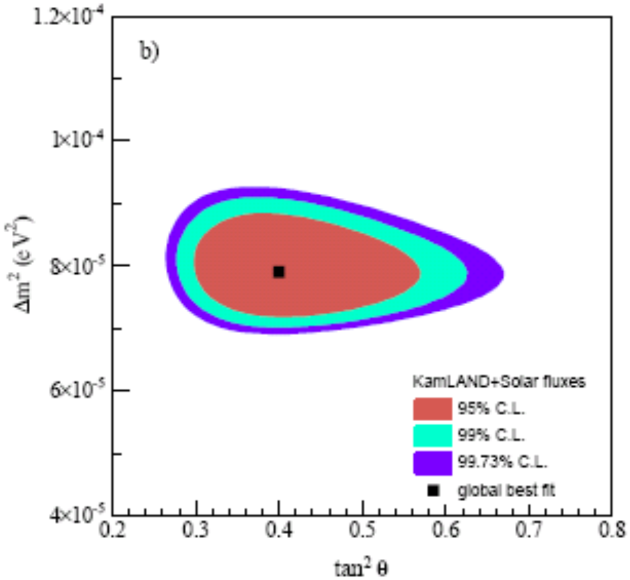
- Long baseline reactor experiment in Japan
  - Average distance (L) to reactors: 175±35 km

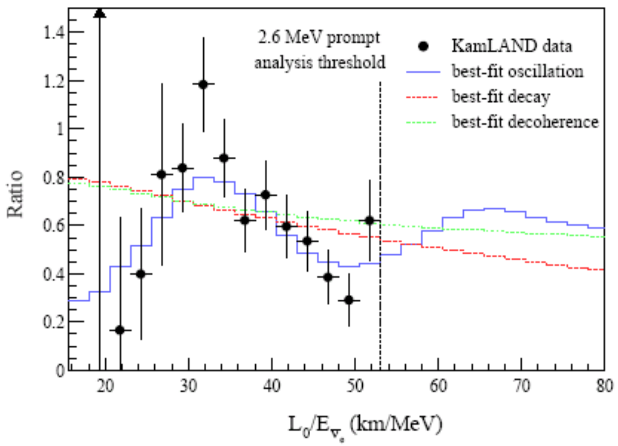
$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = \cos^4\theta_{13}\left[1 - \sin^2 2\theta_{12}\sin^2\frac{\Delta m^2_{12} L}{4E_\nu}\right]$$

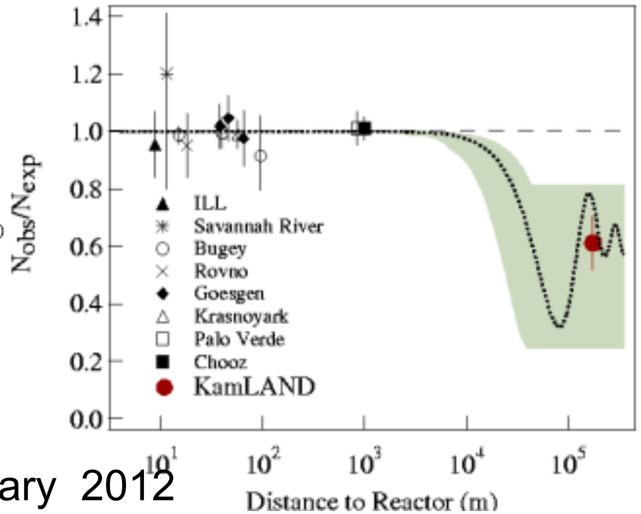
$$\Delta m^2_{12} = 7.9^{+0.6}_{-0.5}\times 10^{-5}\ eV^2 \quad \tan^2\theta_{12} = 0.46^{+0.10}_{-0.07} \Rightarrow \theta_{12} = 34.1^\circ$$

Confirmation of solar neutrino results with antineutrinos



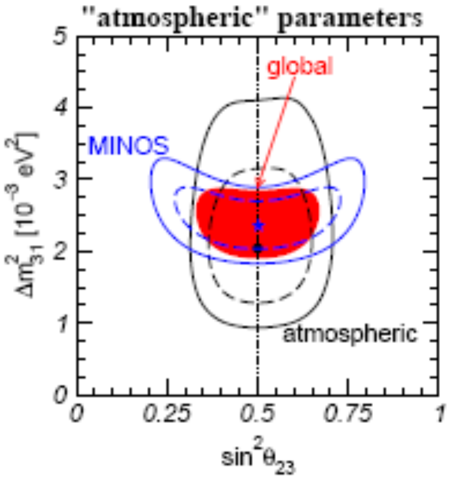


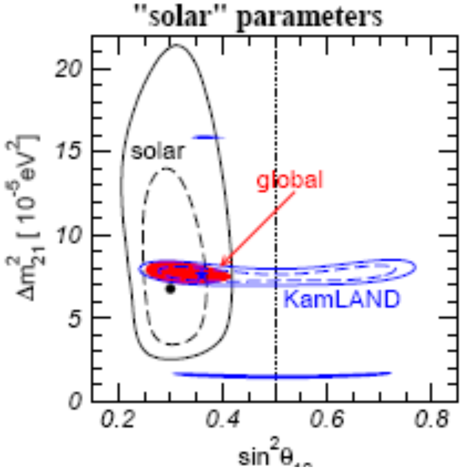


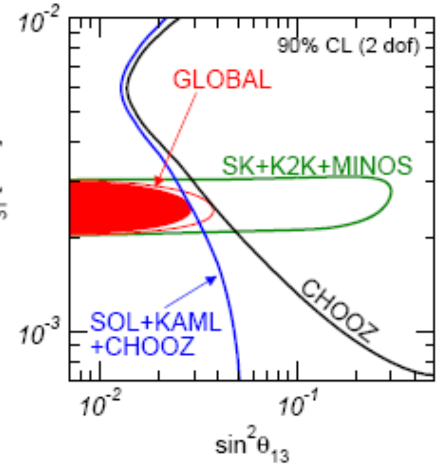


Global fits

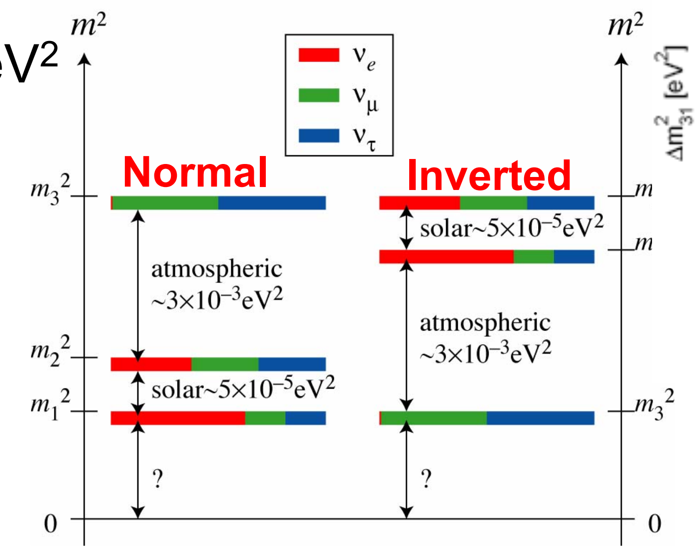
- Consistent picture emerging:
  - Atmospheric+MINOS/K2K
  - Solar+KamLand
  - Reactor limits (Chooz)
- Global fit provides:
  - $\sin^2\theta_{12}=0.312\pm0.017$
  - $\Delta m_{12}^2 = 7.59\pm0.20\times10^{-5}$ eV^2
  - $\sin^2\theta_{23}=0.51\pm0.06$
  - $\Delta m_{23}^2=2.45\pm0.09\times10^{-3}$ eV^2
- Unknown quantities:
  - $\sin\theta_{13}<0.224$ (@3σ),
  - Is $\theta_{23}=\pi/4, <\pi/4$ or $>\pi/4$?
  - Mass hierarchy: sign Δm_{13}^2
  - CP violation phase δ





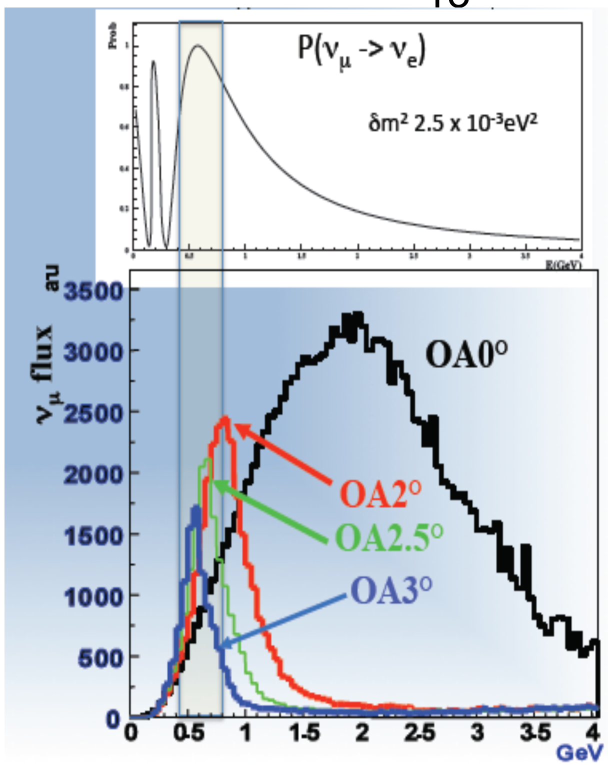


Schwetz

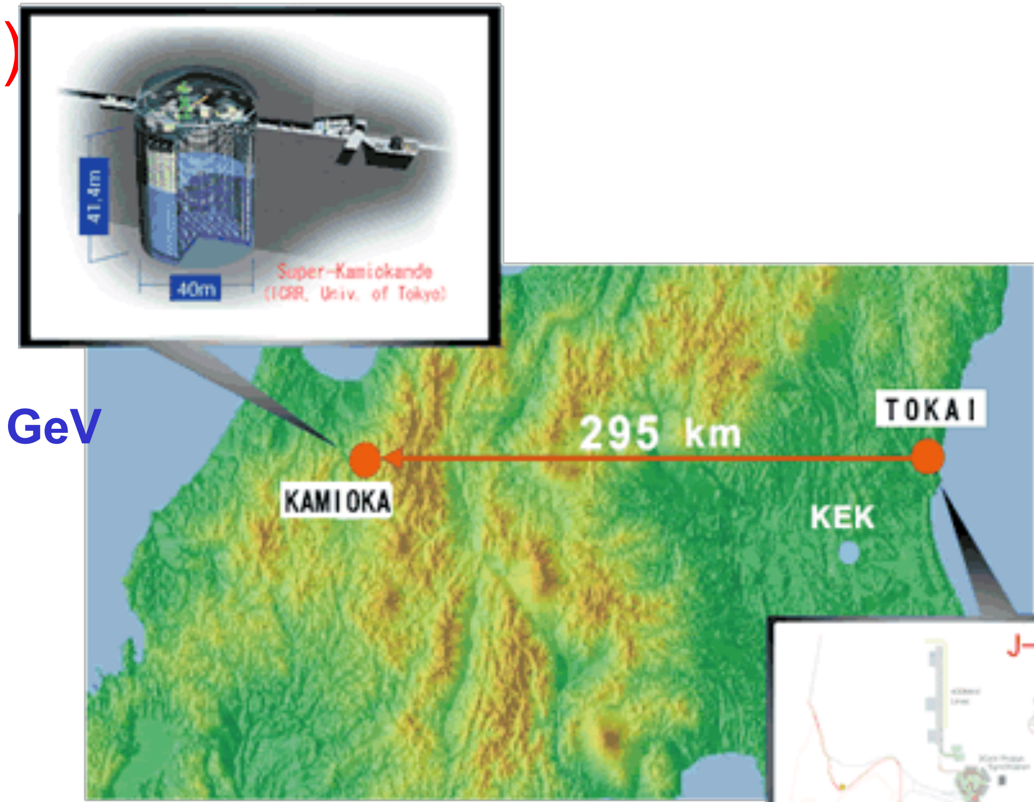


The search for θ_{13}

- The next goal in neutrino oscillation physics is the discovery of θ_{13} – first step towards CP violation
- T2K (Tokai-to-Kamioka)
  - First off-axis beam to discover θ_{13}: 2.5°



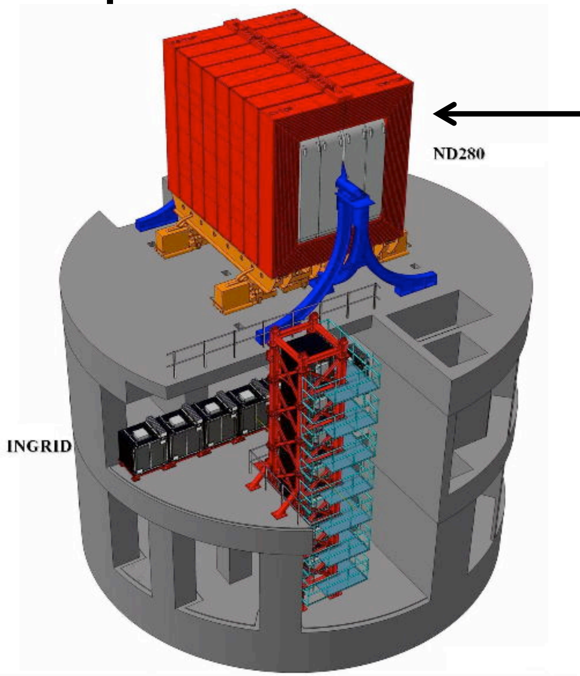
E_ν=0.6 GeV

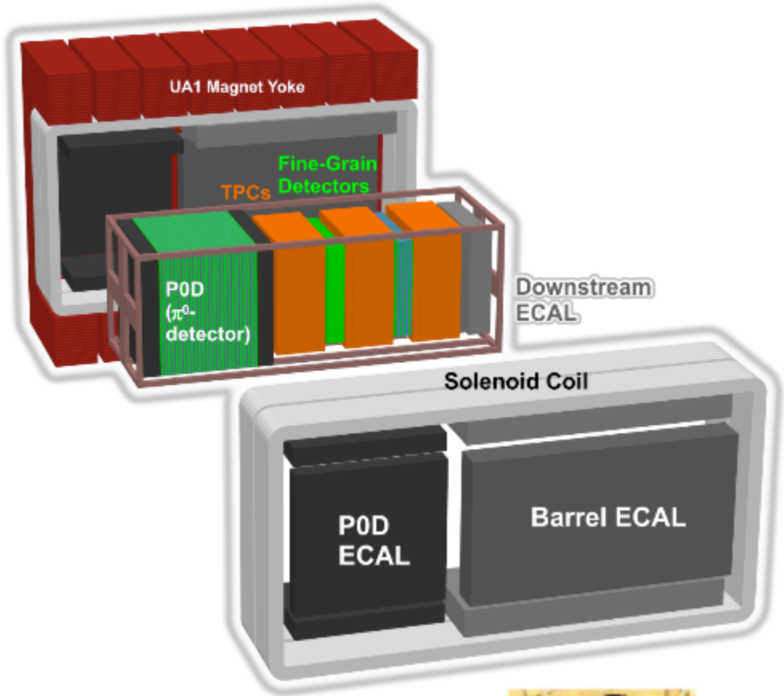


Off-axis: narrower energy band: $E_\nu = \dfrac{m_\pi^2 - m_\mu^2}{2\left(E_\pi - p_\pi \cos\theta\right)}$

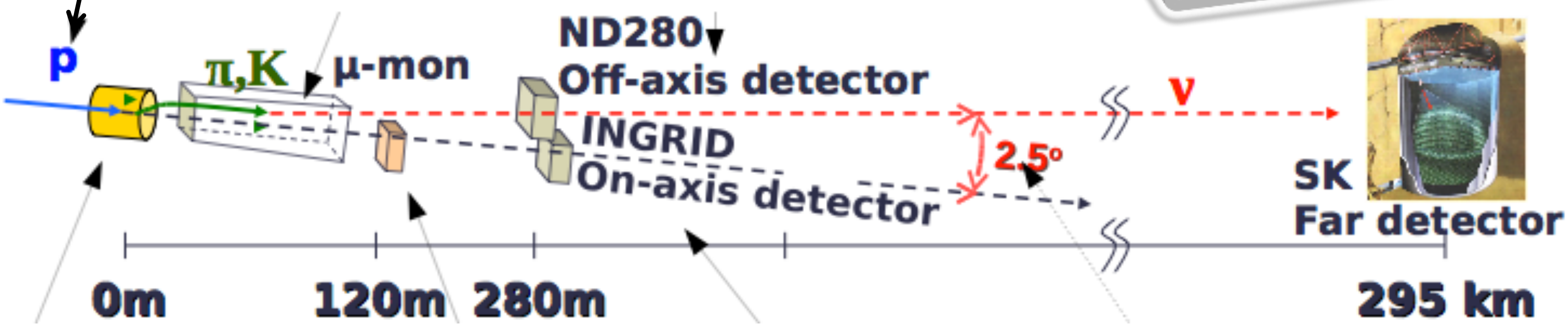
T2K Detectors

- Near detectors: μ-mon, INGRID and ND280
- Far detector: Super-Kamiokande (295 km)



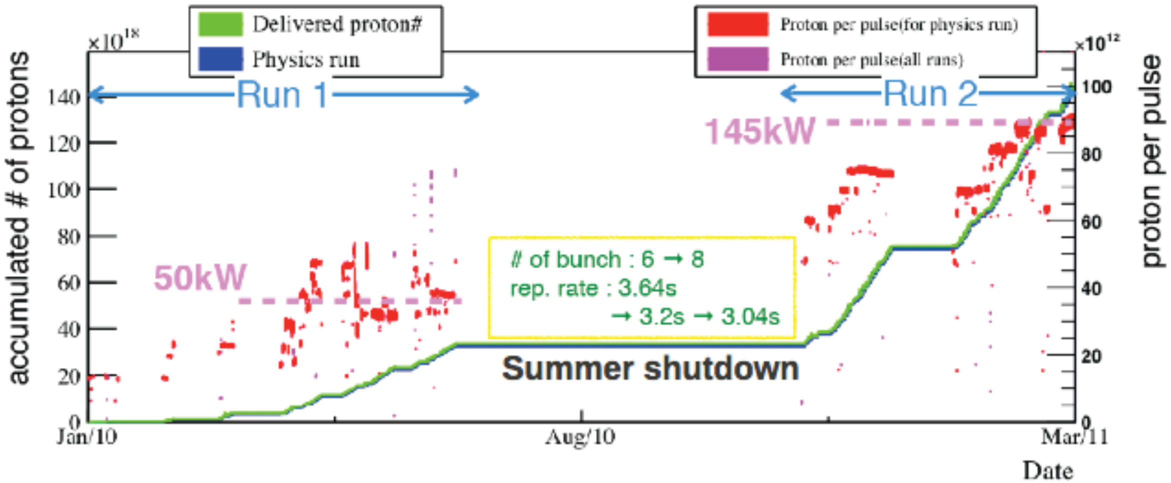


30 GeV protons from J-PARC

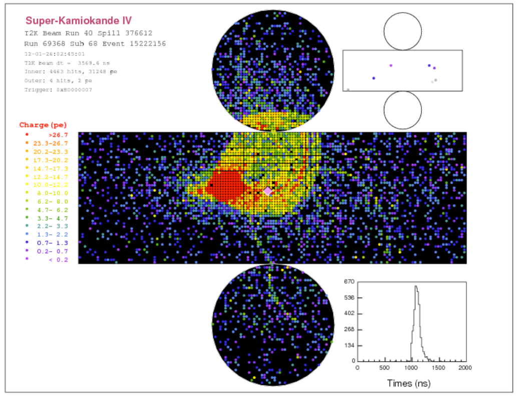


T2K Detectors

- Data taking: $1.43x10^{20}$ POT (2% expected data)



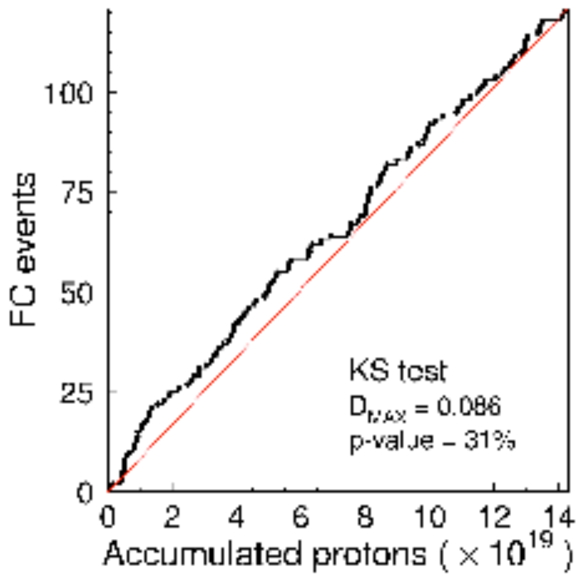
- Run cut short by devastating earthquake and tsunami that hit Japan on 11 March 2011
- Accelerator damaged and repaired
- Facility was recovered and T2K started data taking again on 24 Dec 2011 (without horn)
- One event Jan 2012
- Resumption full data taking March 2012



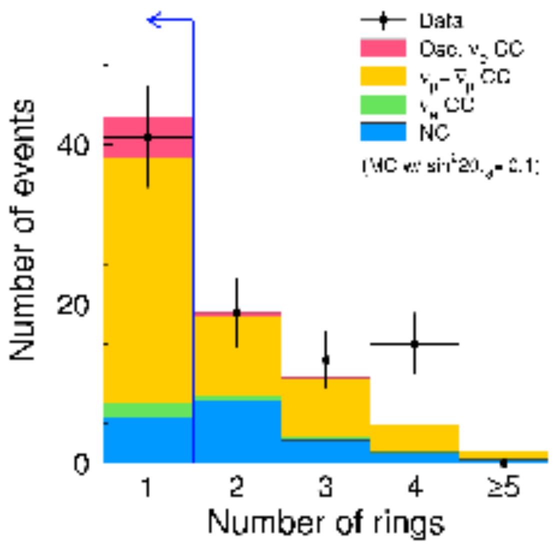
T2K electron neutrino appearance

- Data selection:

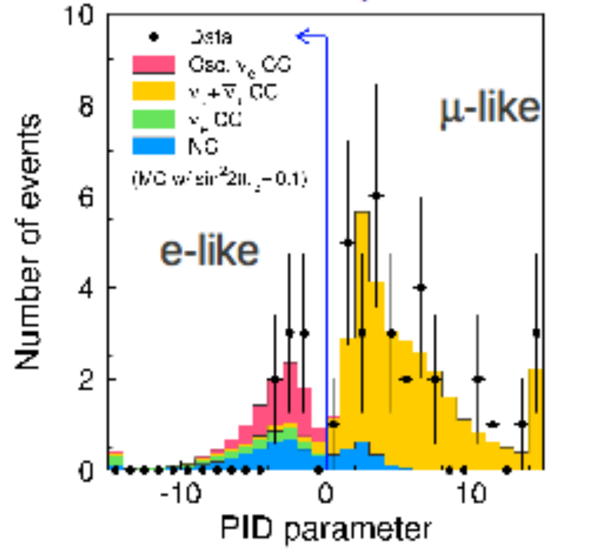
88 FCFV events



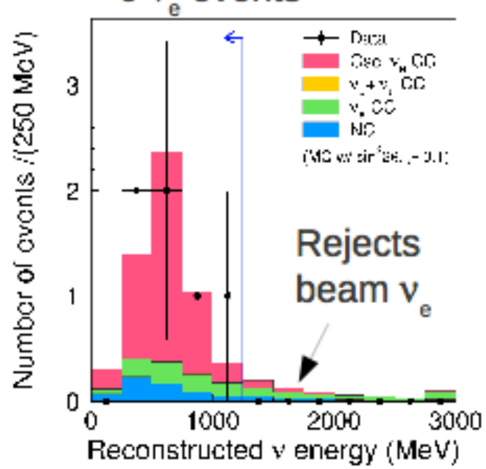
41 single ring events



8 e-like events, 33 μ-like events



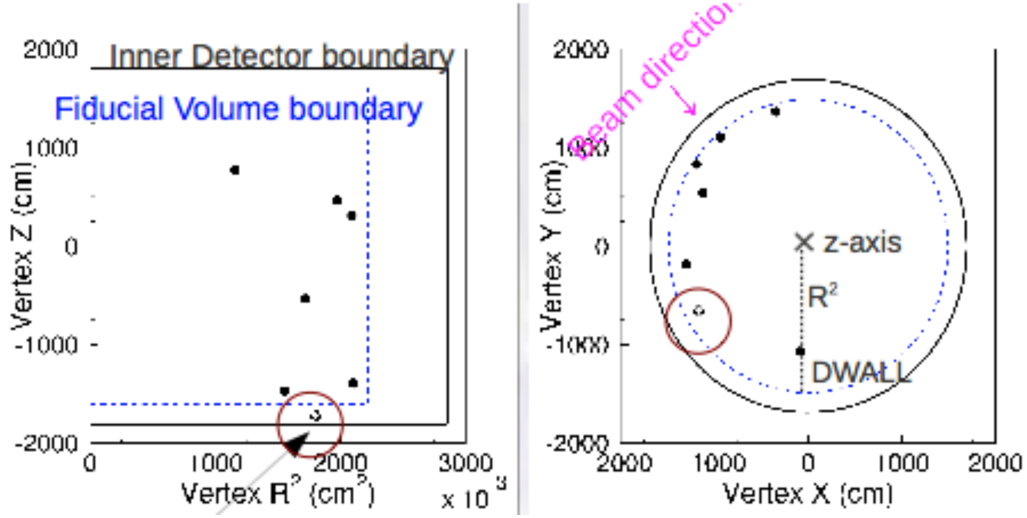
6 ν_e events



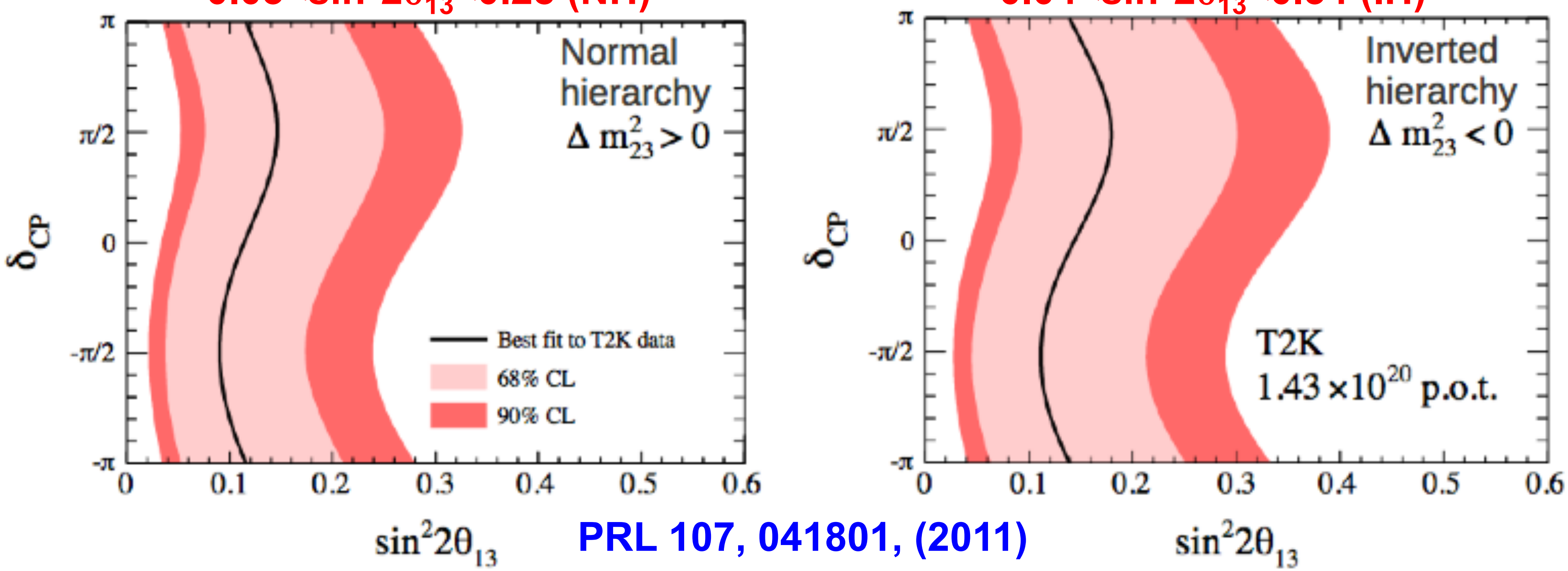
  - Finally, 6 events survive cuts(1.5±0.3) unoscilllated background
  - If $\sin^2 2\theta_{13}$=0.1 then 5.5 events would have survived cuts

T2K electron neutrino appearance

- Some issue with events being close to fiducial volume edge, but no evidence for bias
- Final sensitivity of θ_{13} as a function of CP phase δ:

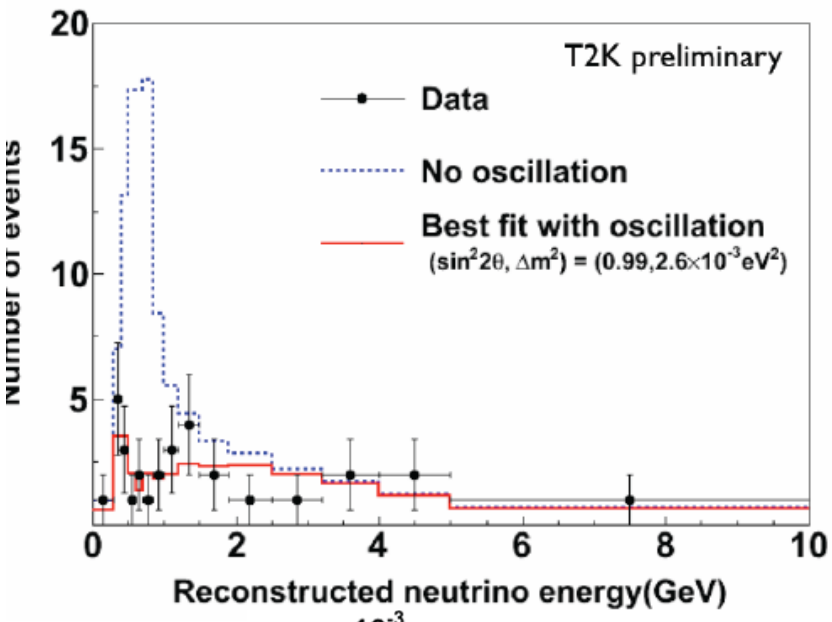


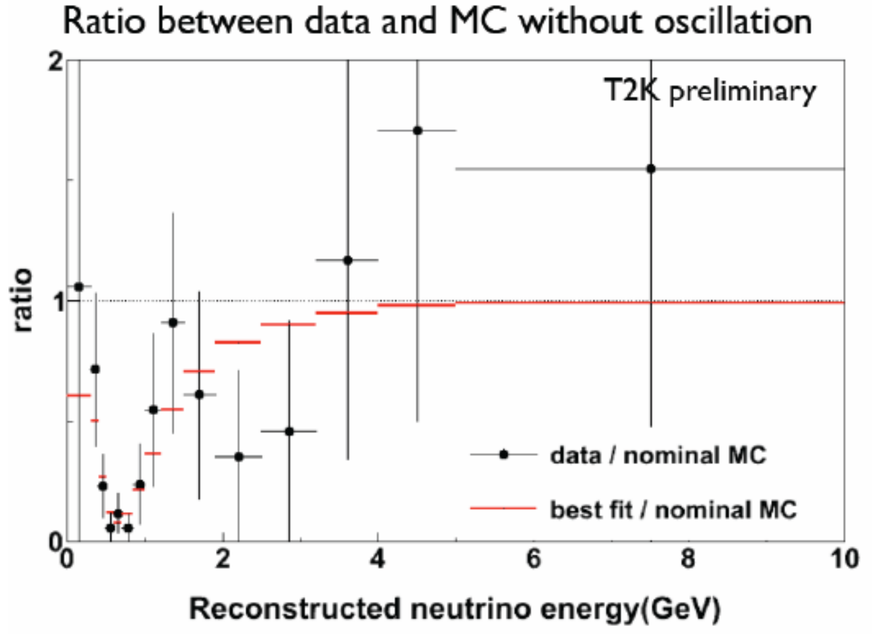
$0.03 < \sin^2 2\theta_{13} < 0.28$ (NH) **$0.04 < \sin^2 2\theta_{13} < 0.34$ (IH)**

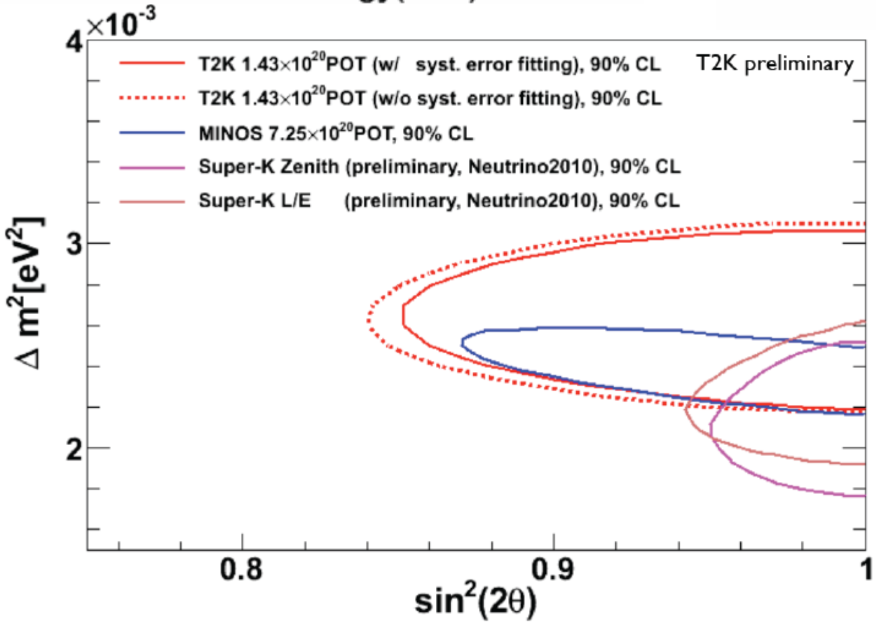


PRL 107, 041801, (2011)

T2K ν_μ disappearance







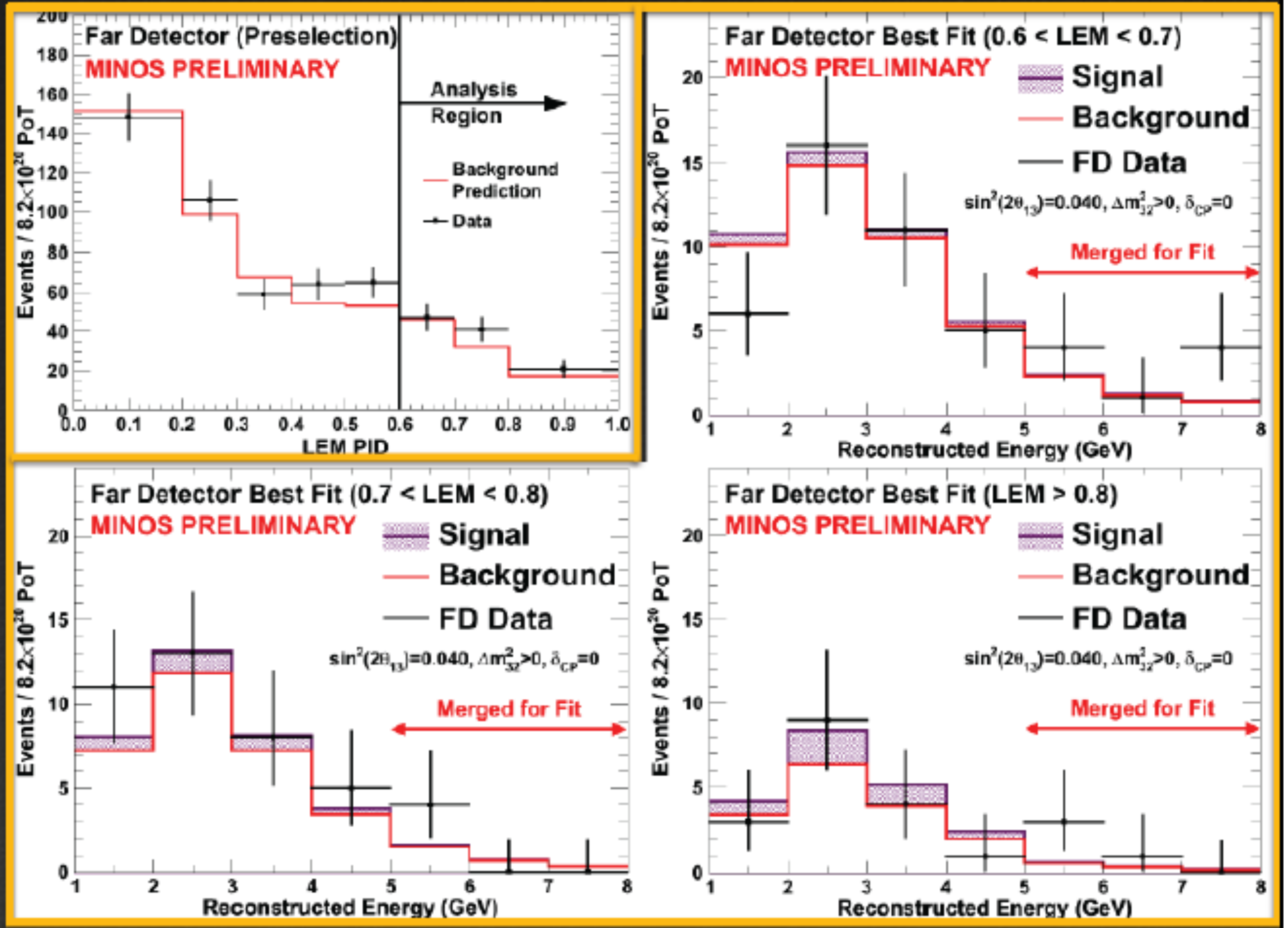
Recent published paper:
Arxiv: 1201.1386

$\sin^2 2\theta_{13}=0.99$
$\Delta m^2_{32}=2.63\text{x}10^{-3}$

MINOS ν_e results

Appearance Result for 15-Bin Fitting

The fit uses 15 bins – three in PID and 5 in reconstructed energy.



Best Fit:

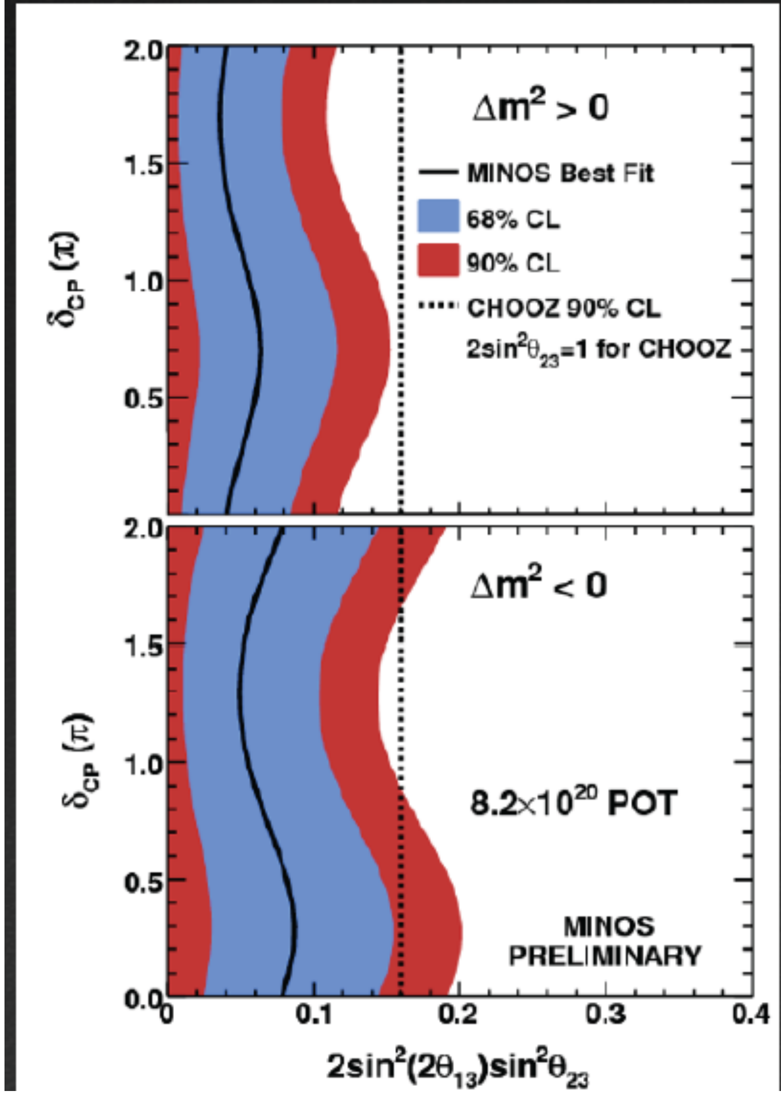
$\sin^2 2\theta_{13} = 0.040$

for $\delta=0$ and $\sin^2 2\theta_{23}=1$, normal mass hierarchy

Signal enhanced region LEM>0.7:
expect $49.5 \pm 7.0(\text{stat.}) \pm 2.8(\text{syst.})$, observed 62 events in the FD

MINOS ν_e results

Region Allowed by Fit



MINOS has updated its electron neutrino appearance analysis **for an exposure of 8.2×10^{20} POT, with shape fitting and a new selection variable**

$\sin^2(2\theta_{13})<0.12$ for normal mass hierarchy, <0.19 for inverted hierarchy, at 90% C.L., for $\delta=0$

$\sin^2(2\theta_{13})=0.04$ (0.08) are the best fit values

$\sin^2(2\theta_{13})=0$ excluded at 89% C.L.

For the first time, an experiment has been able to exclude beyond the Chooz limit in all of the parameter space for the normal mass hierarchy

MINOS ν_μ results

Muon Neutrino Disappearance

Muon neutrinos are observed to disappear as they travel. The most precise result in Δm^2 was obtained by MINOS:

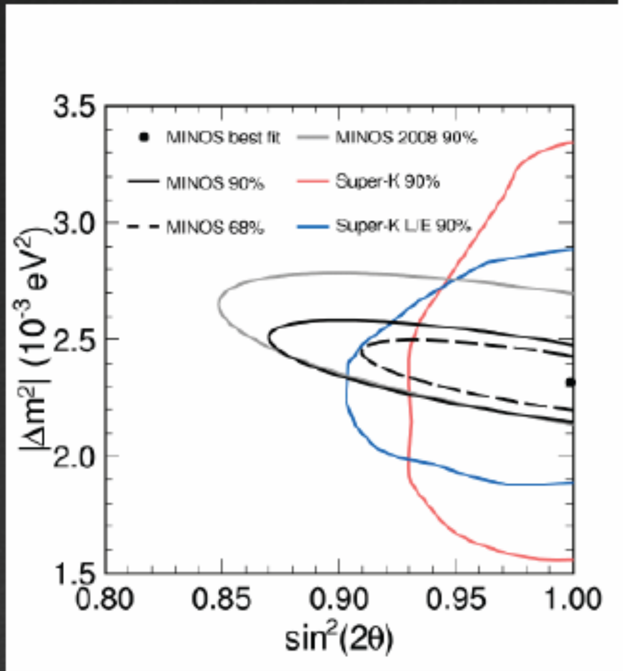
$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2(1.27 \Delta m^2_{32} L/E)$$

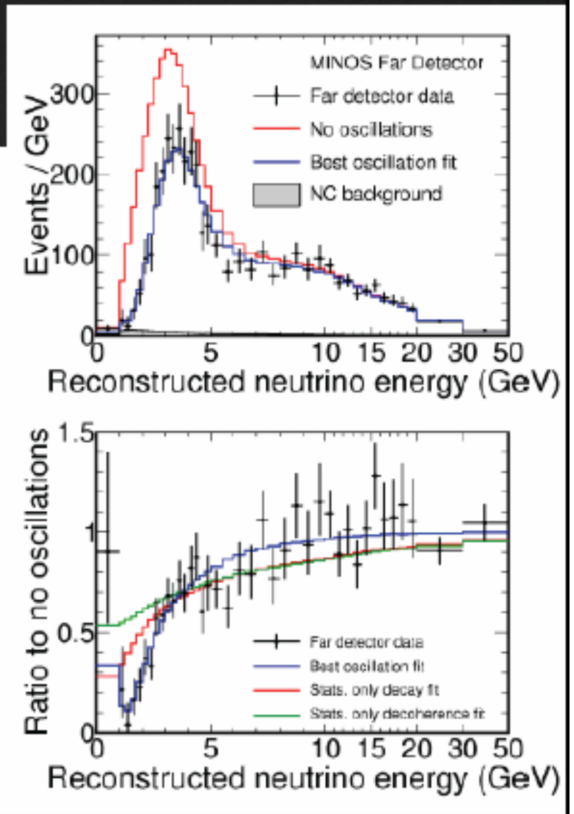
$$|\Delta m^2| = 2.32^{+0.12}_{-0.08} \times 10^{-3} eV^2$$

$$\sin^2(2\theta) > 0.90 (90\% C.L.)$$

Expected 2451 events
Observed 1986 events

Exclude decay at 7 σ
Exclude decoherence at 9 σ





Phys. Rev. Lett. 106, 181801 (2011)

MINOS anti-ν_μ results

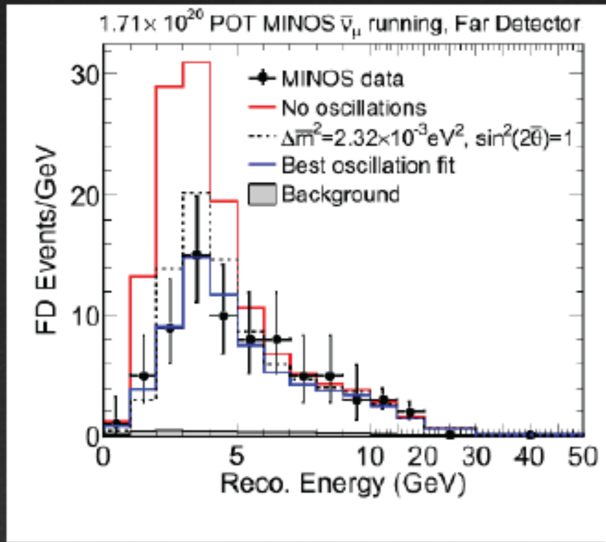
Muon Anti-Neutrino Disappearance

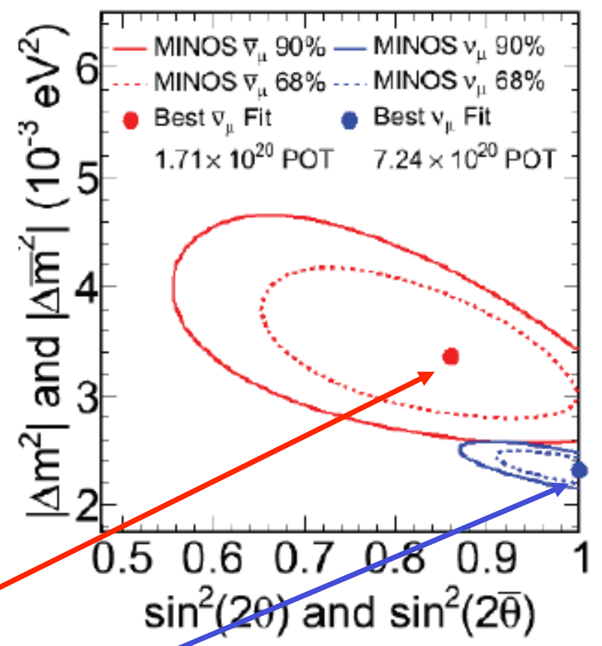
By reversing the horn current, NuMI can create an anti-neutrino beam, can analyze the resulting data in a similar way to the neutrino data

No oscillation Prediction: **156 events**

Observe: **97 events**

No oscillations disfavored at 6.3 σ





$$\left|\overline{\Delta m^2}\right| = (3.36^{+0.46}_{-0.40}(stat.) \pm 0.06(syst.)) \times 10^{-3}\,\mathrm{eV}^2$$

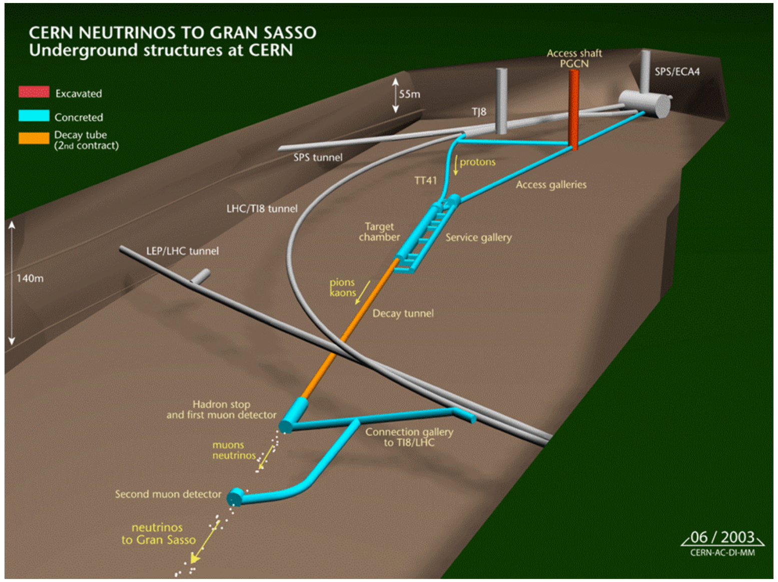
$$\sin^2(2\bar{\theta}) = 0.86^{+0.11}_{-0.12}(stat.) \pm 0.01(syst.)$$

Phys. Rev. Lett. 107, 021801 (2011)

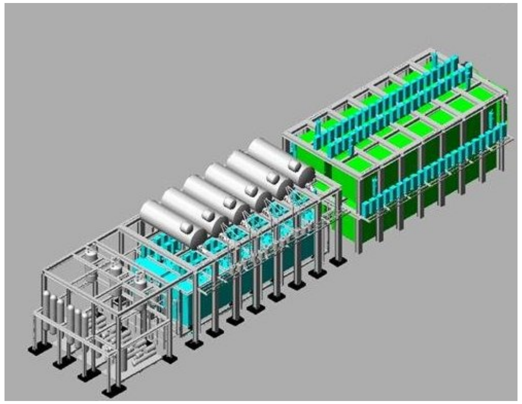
Tension antineutrino-neutrino results: ~2σ

OPERA at Gran Sasso

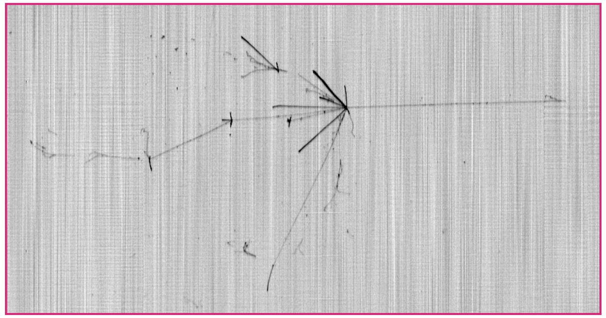
- CNGS: CERN to Gran Sasso (Italy). L= 732 km, <E> = 30 GeV. Started in 2006.



- ICARUS (600 ton liquid argon TPC): kinematic selection of ν_τ



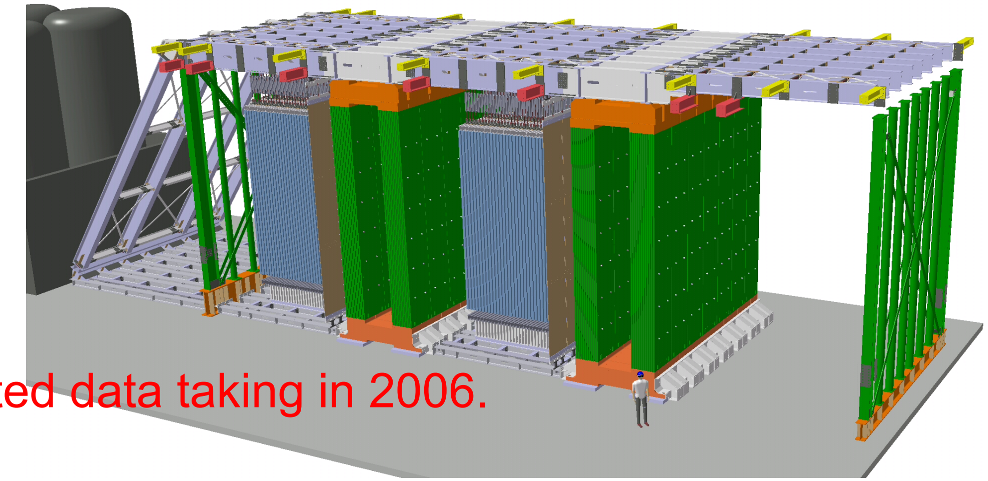
Started data taking 2010



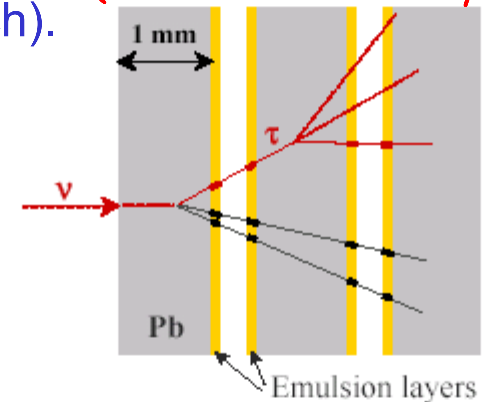
206,336 "ECC bricks"
(56 Pb/Emulsion layers)

- OPERA (1.8 kton emulsion based ν_τ appearance search).

ν beam



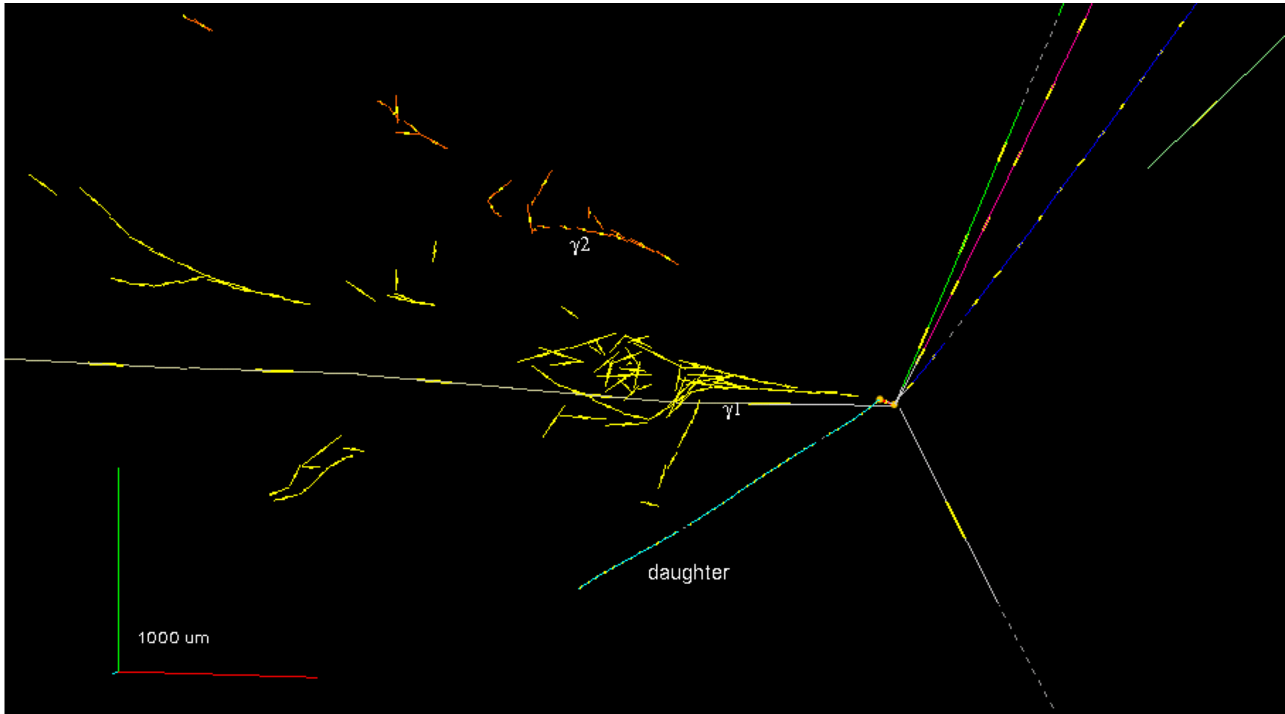
Started data taking in 2006.



6.6 ν_τ signal events
(Δm^2=1.9x10^{-3}eV^2)

OPERA at Gran Sasso

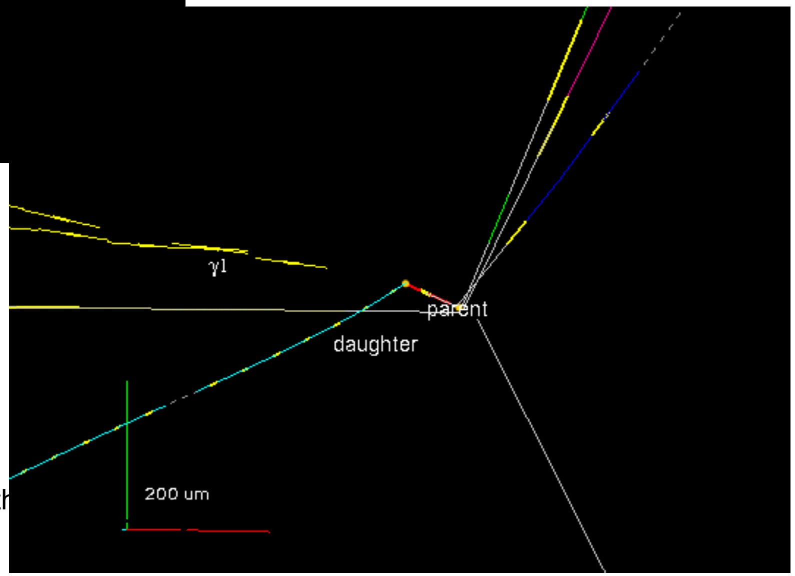
- OPERA: first tau candidate found in 2010



Consistent with τ decay to ρ:

$$\nu_\tau + N \rightarrow \tau^- + X$$

$$\tau^- \rightarrow \rho(\pi^-\pi^0) + \nu_\tau$$



Background: 0.045±0.020

Significance: 2.36σ

New OPERA ν_τ results

Updated OPERA sensitivity

Including all the improvements in the analysis

Decay channel	Number of signal events expected for $Dm^2 = 2.5\times10^{-3}\ eV^2$	
	22.5×10^{19} p.o.t.	Analysed sample
$\tau \to \mu$	1.79	0.39
$\tau \to e$	2.89	0.63
$\tau \to h$	2.25	0.49
$\tau \to 3h$	0.71	0.15
Total	7.63	1.65

In the analyzed sample (92% of '08+'09 data) one ν_τ observed in the $\tau \to h$ channel compatible with the expectation of 1.65 signal events.

Summary of background

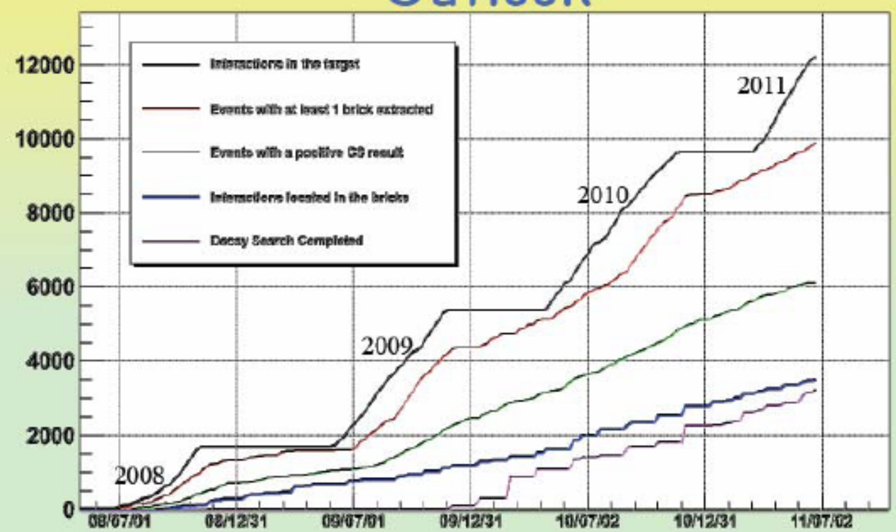
Very clean channel

Decay channel	Number of background events for:							
	22.5×10^{19} p.o.t.				Analysed sample			
	Charm	Hadron	Muon	Total	Charm	Hadron	Muon	Total
$\tau \to \mu$	0.025	0.00	0.07	0.09±0.04	0.00	0.00	0.02	0.02±0.01
$\tau \to e$	0.22	0	0	0.22±0.05	0.05	0	0	0.05±0.01
$\tau \to h$	0.14	0.11	0	0.24±0.06	0.03	0.02	0	0.05±0.01
$\tau \to 3h$	0.18	0	0	0.18±0.04	0.04	0	0	0.04±0.01
Total	0.55	0.11	0.07	0.73±0.15	0.12	0.02	0.02	0.16±0.03

The expected background in the $\tau \to h$ channel is 0.05 ± 0.01
The probability of a background fluctuation up to at least one event is 5%.
The total expected background is 0.16 ± 0.03 and the probability a background fluctuation is 15%.

EPS-HEP 2011 - Grenoble S.Dusini - INFN Padova 17

Outlook



1 ν_τ event observed

1.65 ν_τ events expected

0.16±0.03 background expected

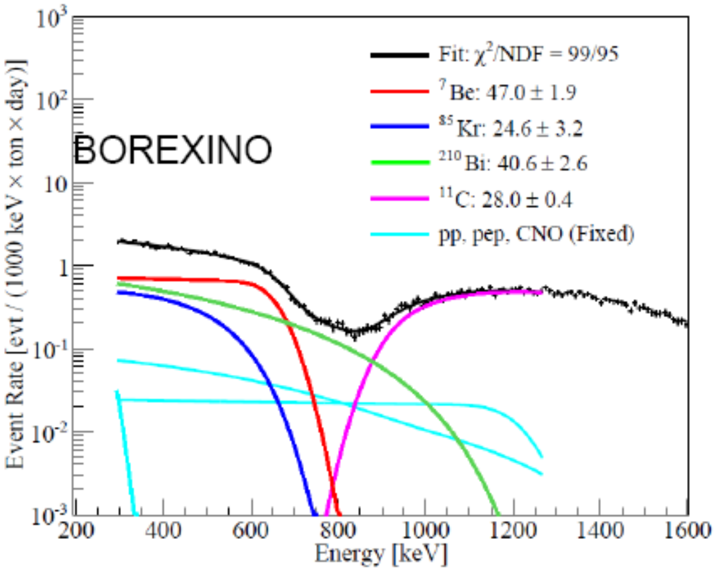
Full OPERA sample expectation:

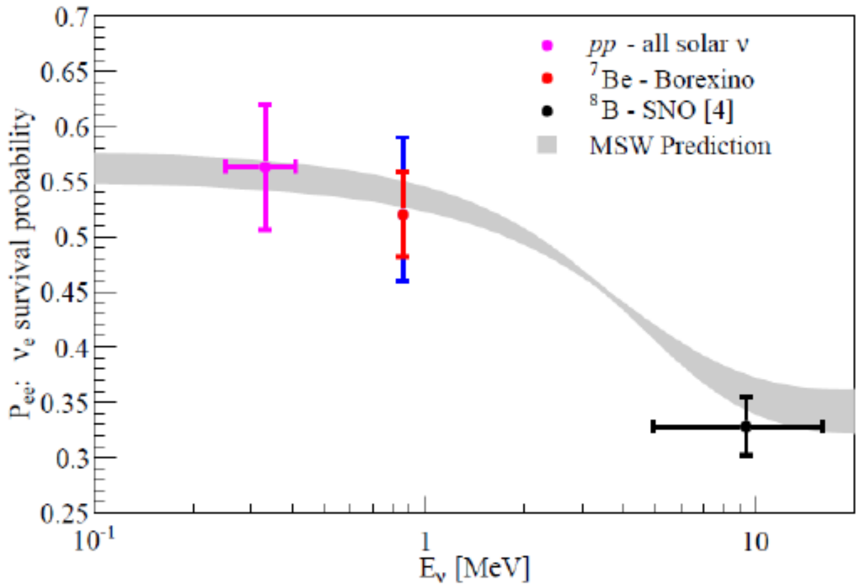
7.63 ν_τ events expected

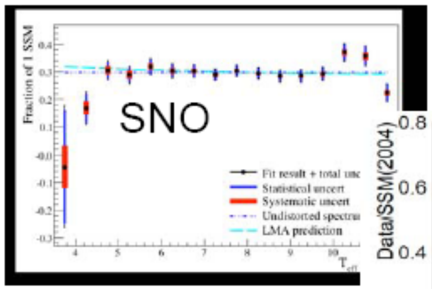
0.73±0.15 background expected

Borexino

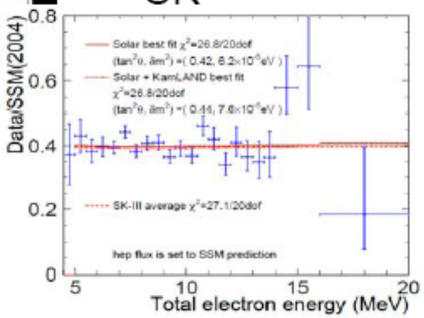
Precision measurement of solar ^{7}Be with Borexino







SK



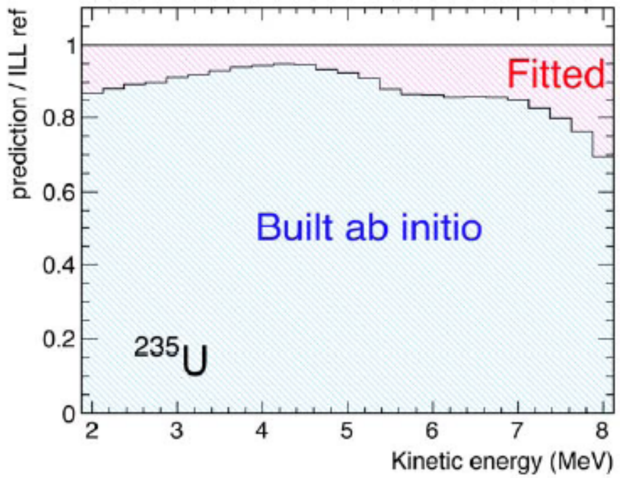
Mapping the MSW suppression:

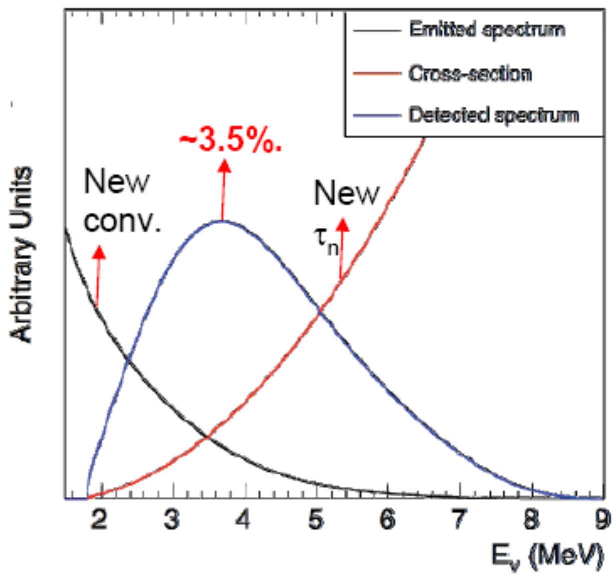
Transition region is sensitive to NSI:
Lower B threshold required to map
Expected up-turn

Reactor anomaly

Revised reactor neutrino spectra & VSBL reactor ν-anomaly

T. Mueller et al. Phys. Rev. D83, 073006, 2011





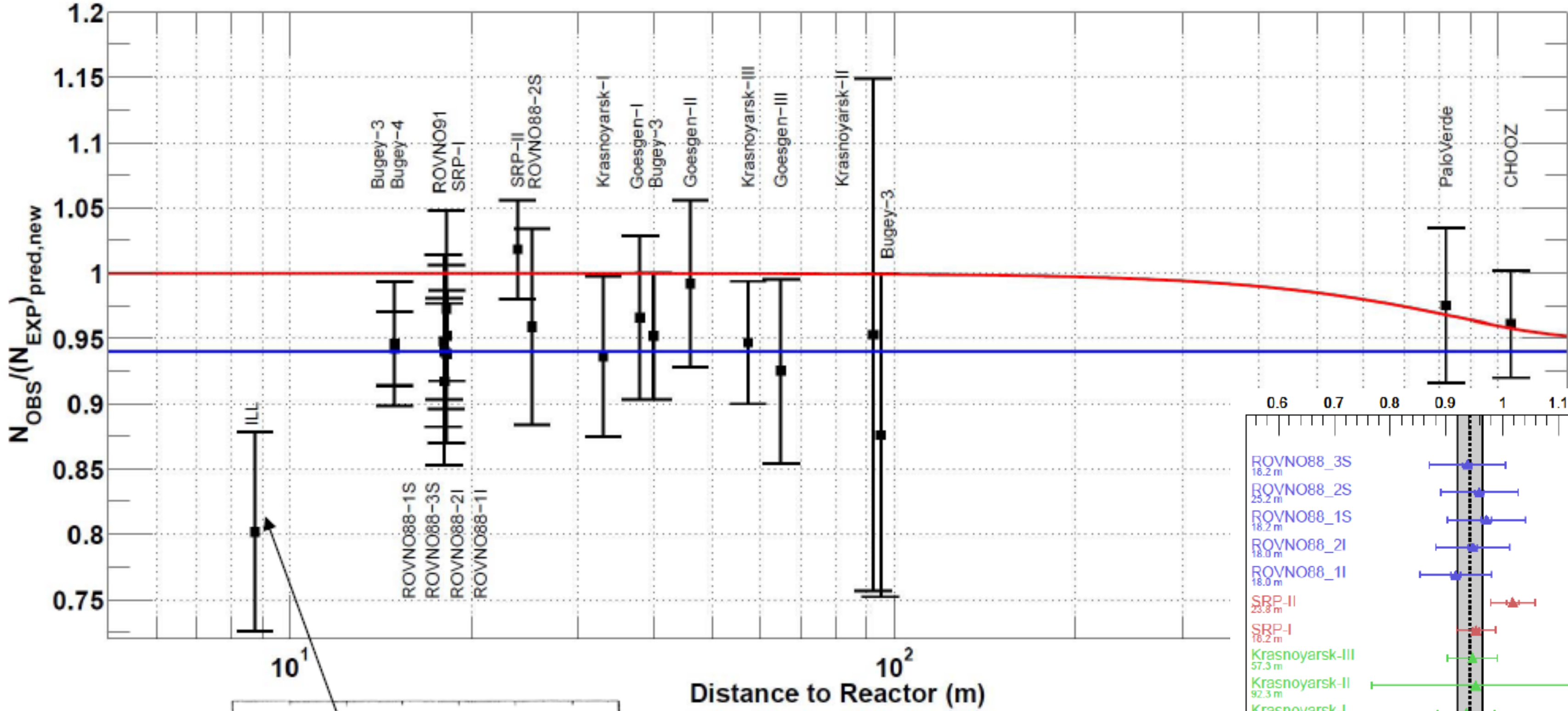
- Triggered by evaluation for DC far-detector phase
- Improved conversion from β to $\bar{\nu}_e$ spectra:
  - Anchored to experimentall ILL BILL-spectra of fission products
  - Conversion at individual β-branch level; residuals fitted as in original ILL conversion
  - Off-equilibrium effects included
- Improved (& increased) neutron life time measurement; also improved weak magnetism and radiative corrections

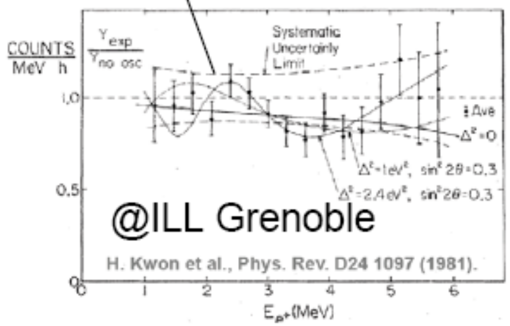
$$\sigma_f^{pred} = \int_0^\infty S_{tot}(E_\nu)\sigma_{V-A}(E_\nu)dE_\nu = \sum_k f_k \sigma_{f,k}^{pred}$$

	old [3]	new	new/old
$\sigma^{pred}_{f,^{235}U}$	6.39±1.9%	6.61±2.11%	+3.4%
$\sigma^{pred}_{f,^{239}Pu}$	4.19±2.4%	4.34±2.45%	+3.6%
$\sigma^{pred}_{f,^{238}U}$	9.21±10%	10.10±8.15%	+9.6%
$\sigma^{pred}_{f,^{241}Pu}$	5.73±2.1%	5.97±2.15%	+4.2%

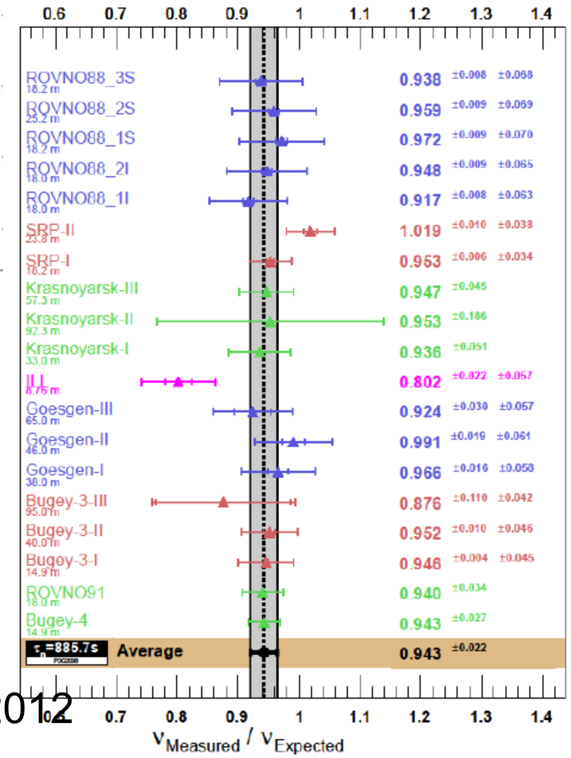
Reactor anomaly

G. Mention et al. arXiv:1101.2755v4



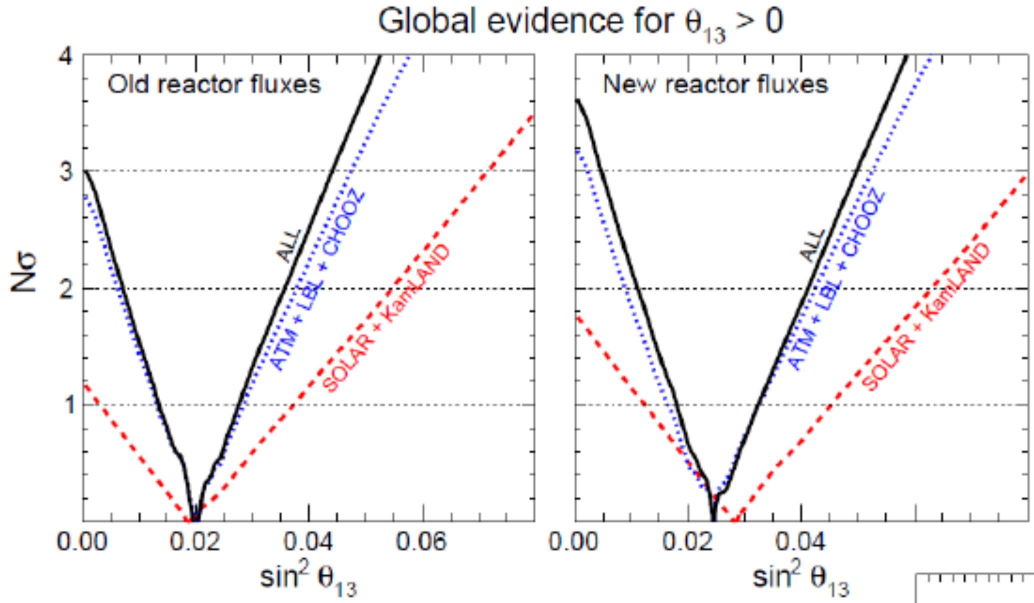


Revisisiting reactor fluxes means all previous experiments showed deficit: 0.943±0.023 (2.5σ)

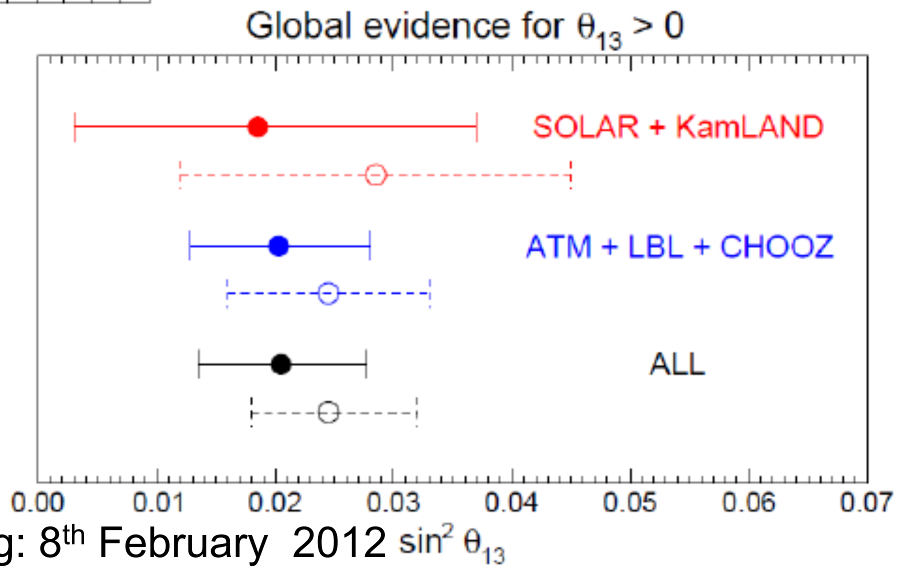


New global fits

Global 3ν analysis inclusive T2K and Minos results



Fogli, Lisi, Marrone, Palazzo, Rotunno, arXiv:1106.6028 [hep-ph]

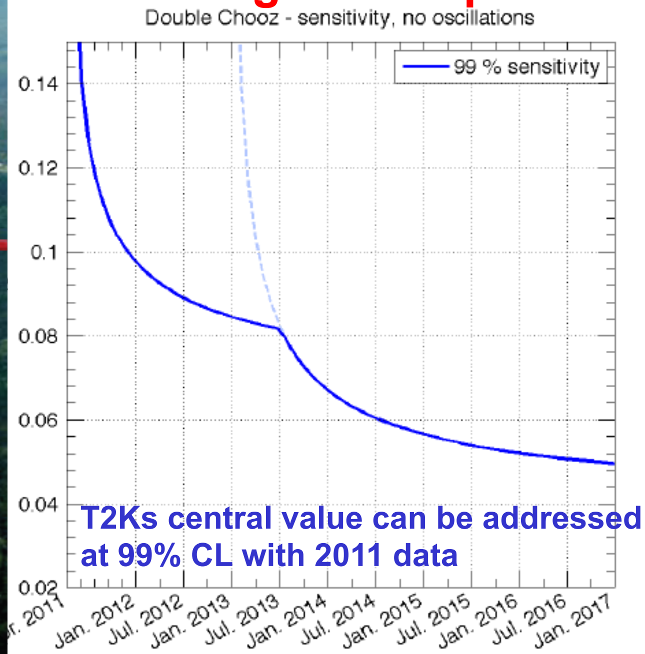


With old reactor fluxes: 3.0 sigma

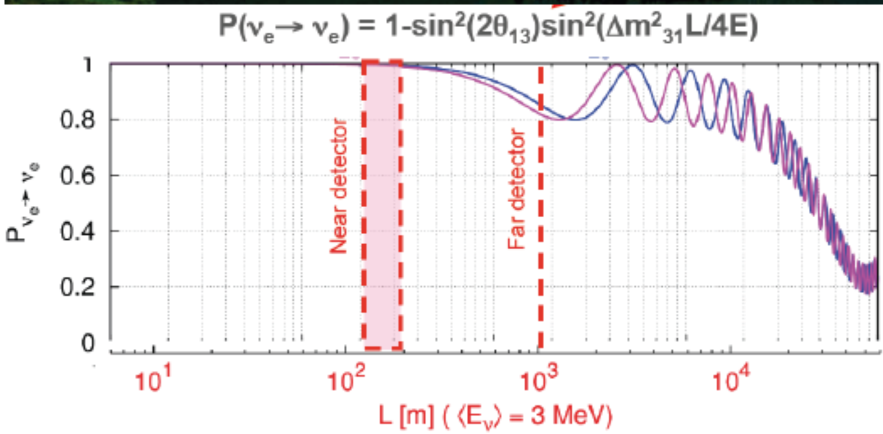
(With new reactor fluxes: 3.6 sigma)

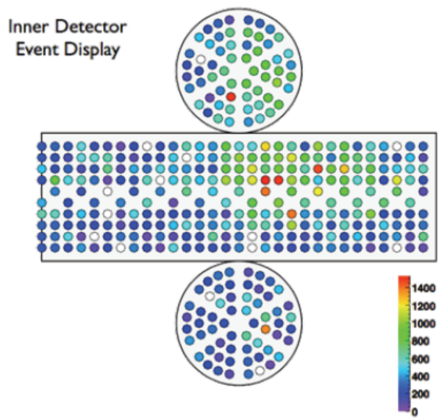
Reactor experiments

Double Chooz (France)
Data taking since April 2011



T2Ks central value can be addressed at 99% CL with 2011 data





Reactor experiments

RENO

Site: Youngwang, Korea

Tunnel + halls ready

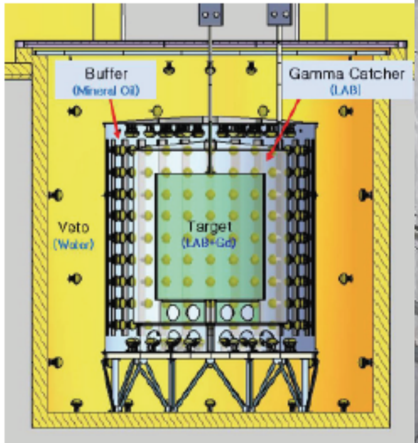
6 cores, 16 GW

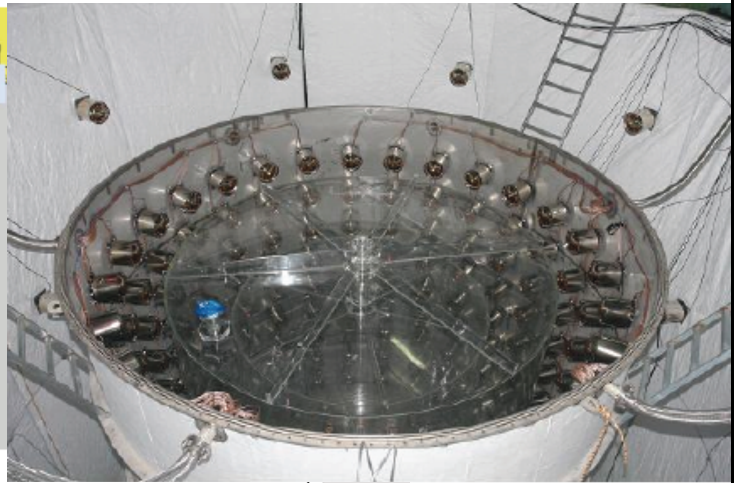
Daya Bay

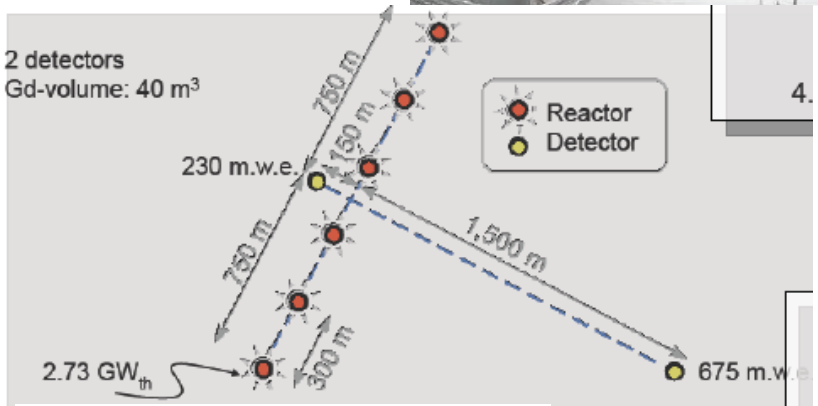
Site: Daya Bay Plant (11.6+6 GWth), China

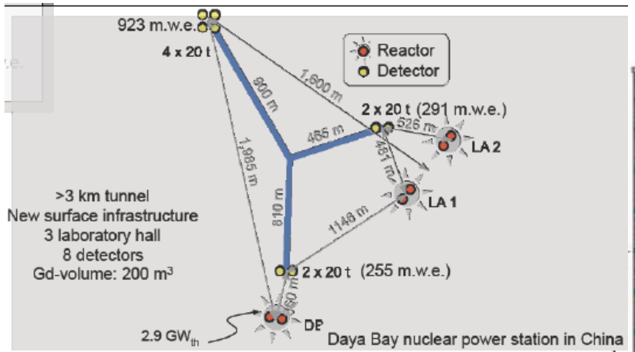
Near: 1 km tunnel + laboratory

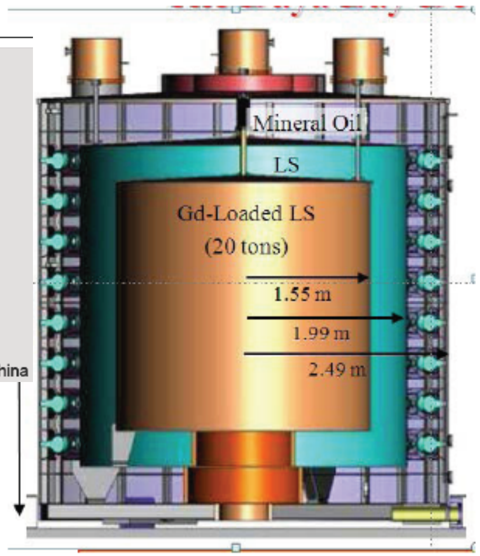
Far: 2 km tunnel + laboratory











Status

Two detector filled

Data taking by August 2011

Status

2 near det. running by Summer 2011

4 far detectors deployment in 2012

LSND and sterile neutrinos

- Accelerator experiments in 1990s: $\nu_\mu \leftrightarrow \nu_e$ $\quad \bar{\nu}_\mu \leftrightarrow \bar{\nu}_e$
  - LSND: Liquid Scintillator Neutrino Detector (Los Alamos)
  - KARMEN: Karlsruhe Rutherford Medium Energy Neutrino (RAL)

$$\begin{cases} \pi^+ \to \mu^+ + \nu_\mu & \textbf{(in flight or at rest)} \\ \mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e & \textbf{(at rest)} \end{cases}$$

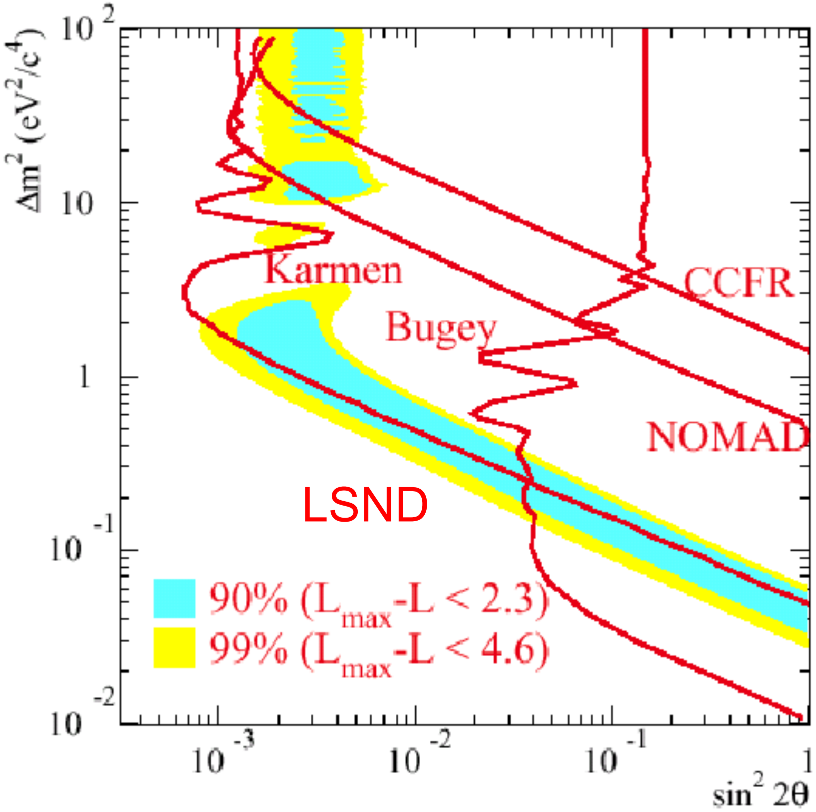
$$\begin{cases} \pi^- \to \mu^- + \bar{\nu}_\mu & \textbf{(in flight)} \\ \mu^- \to e^- + \nu_\mu + \bar{\nu}_e & \textbf{(at rest)} \end{cases}$$

Claim by LSND of $\bar{\nu}_\mu \leftrightarrow \bar{\nu}_e$ oscillations:

$$P(\bar{\nu}_\mu \leftrightarrow \bar{\nu}_e) = (3.3 \pm 0.9 \pm 0.5) \times 10^{-3}$$

Not confirmed by KARMEN:

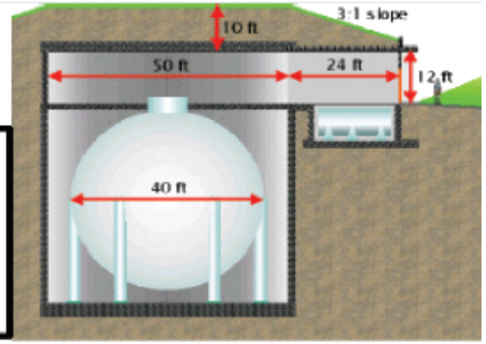
$$P(\bar{\nu}_\mu \leftrightarrow \bar{\nu}_e) < 4.2 \times 10^{-3} \; (90\% \; CL)$$

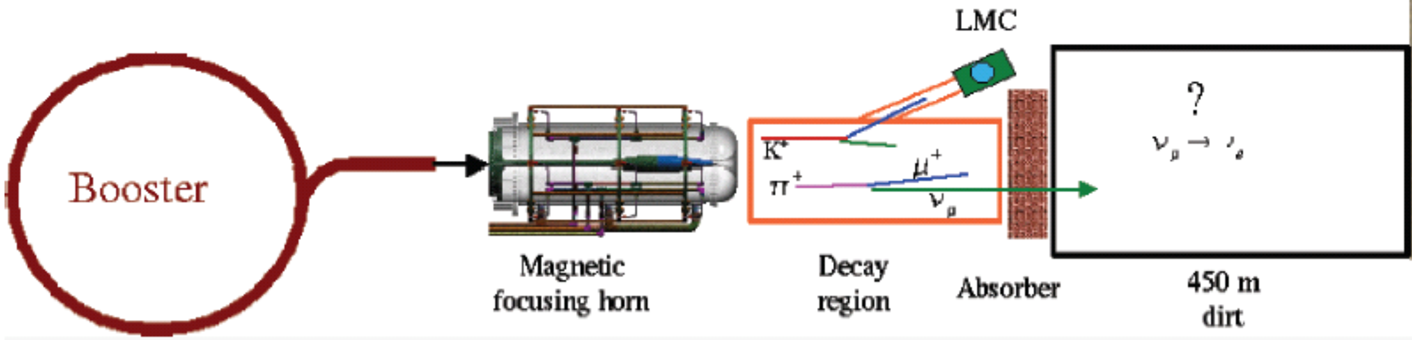


MiniBoone

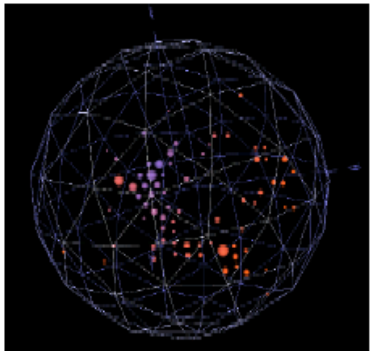
- MiniBoone (Fermilab) to confirm or deny LSND claim. Started data taking in 2002.

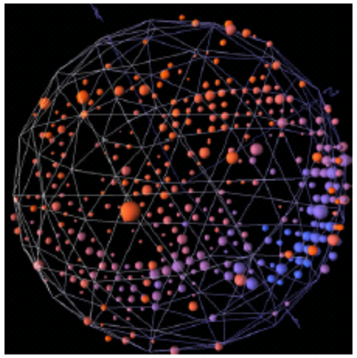
Search for $\nu_\mu \leftrightarrow \nu_e$ oscillations **(ν_e appearance in ν_μ beam)**

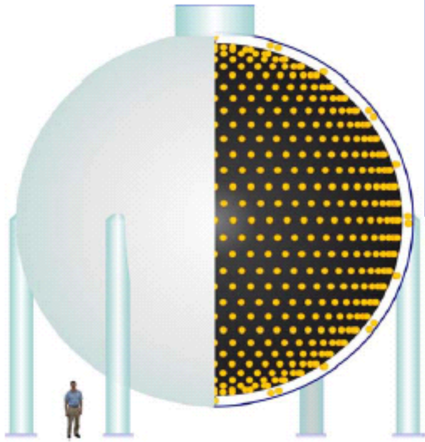


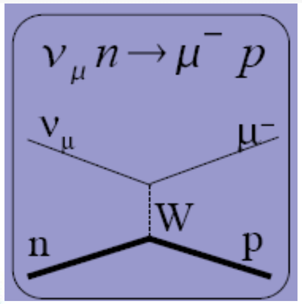


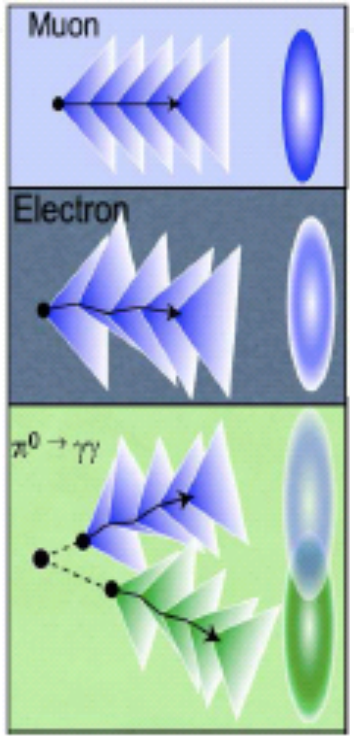
Michel electron **π^0 event**







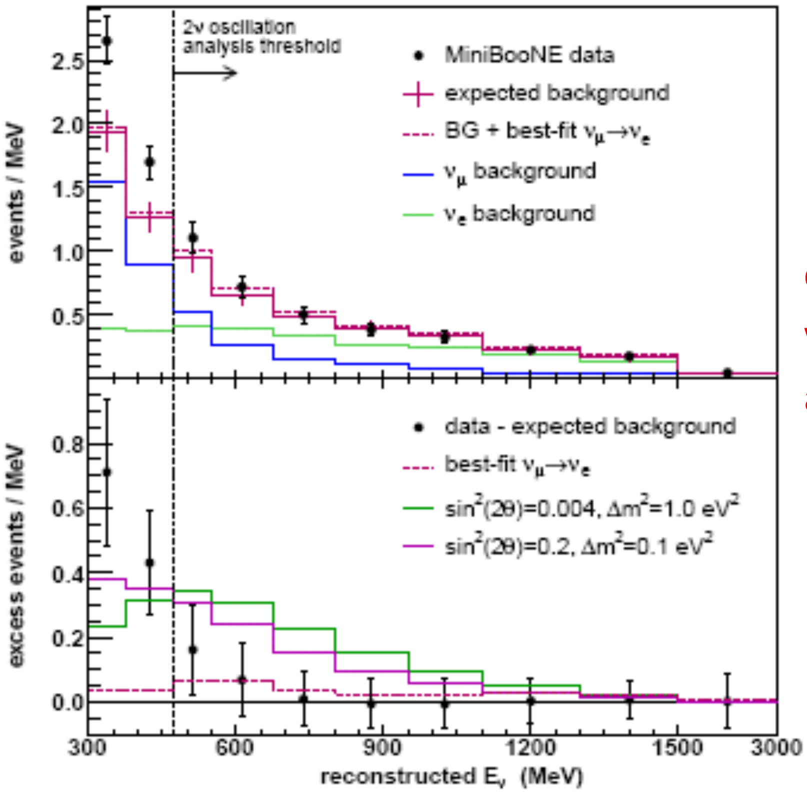




MiniBoone

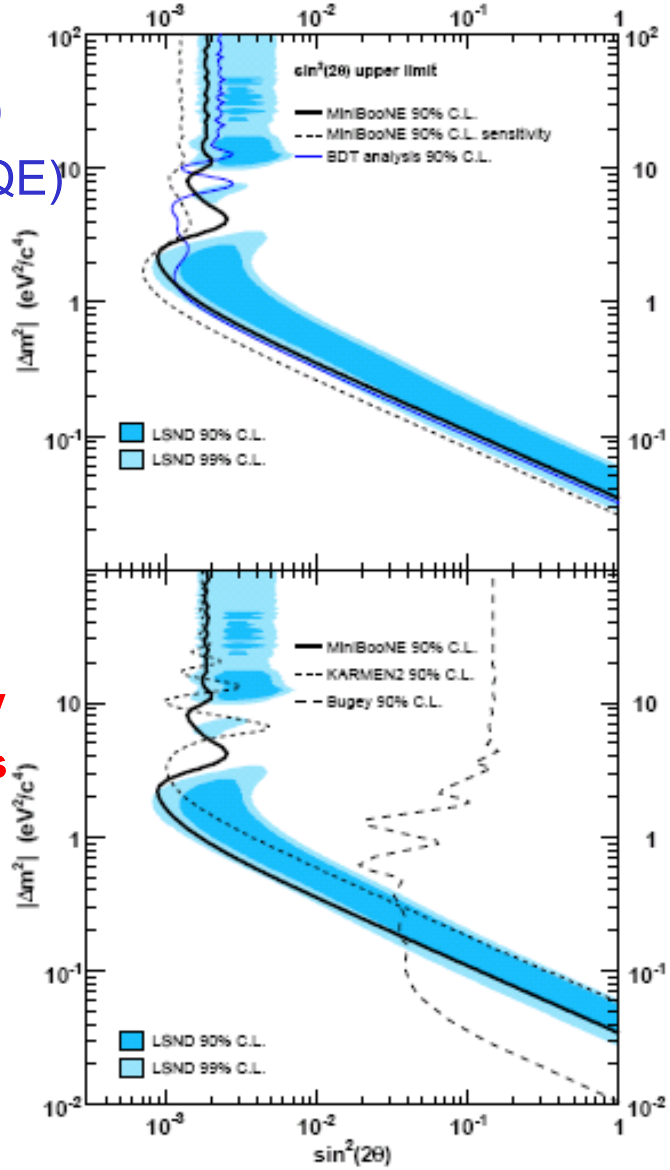
- MiniBoone analysis relies on knowing:
  - Flux of neutrinos from accelerator (hadron yields)
  - Charged current quasi-elastic cross-section (CCQE)
  - ν_e background from μ, π and K decay
  - NC backgrounds (eg: π^0, Δ resonance)

Search for $\nu_\mu \leftrightarrow \nu_e$ oscillations



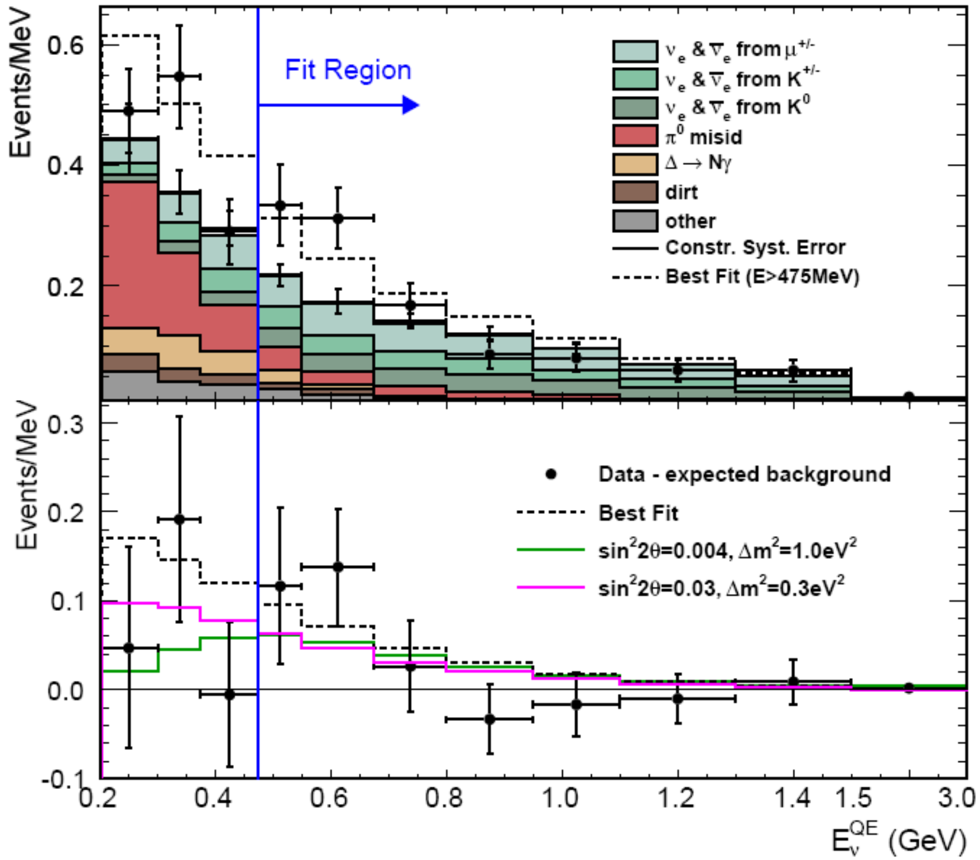
Results published June 2007.

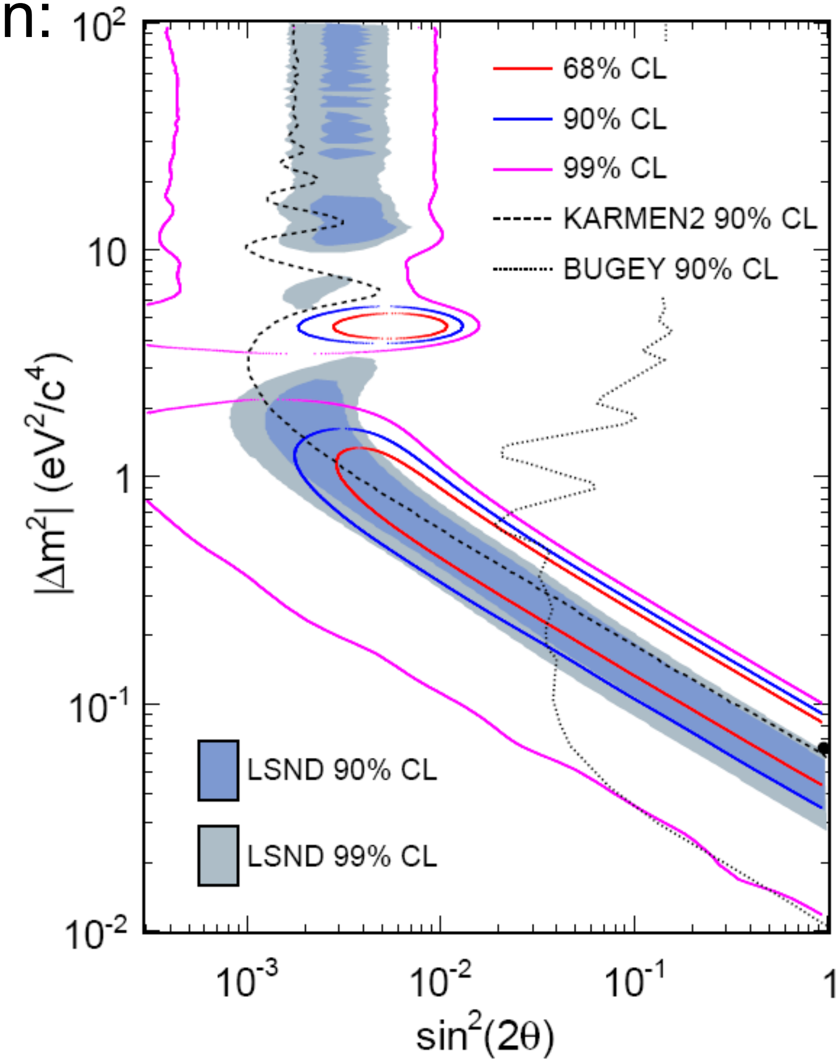
No excess of ν_e events in ν_μ energy window but excess at low energy



MiniBoone

- MiniBoone recent antineutrino run:





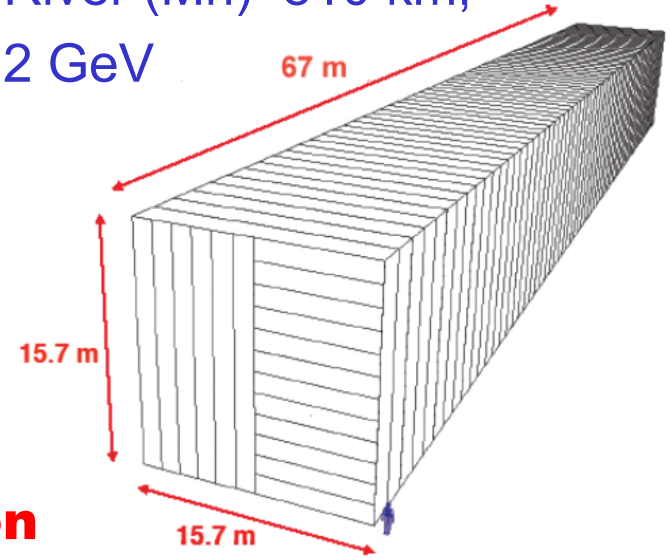
- Agreement with LSND?

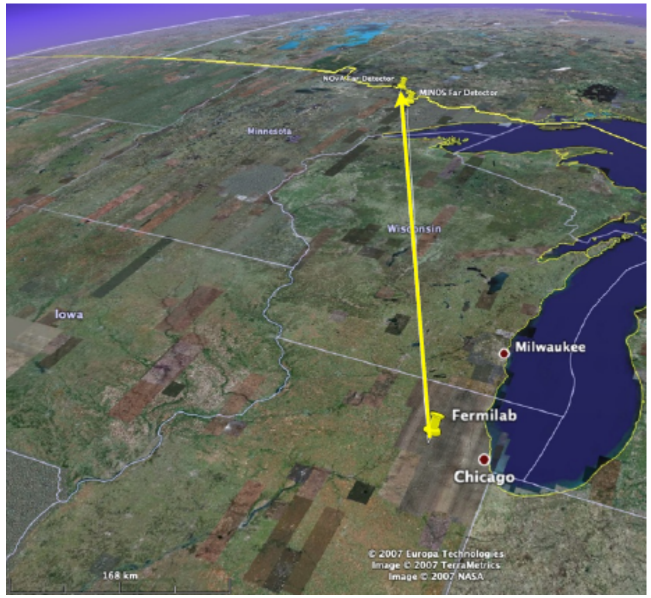
NOVA neutrino appearance

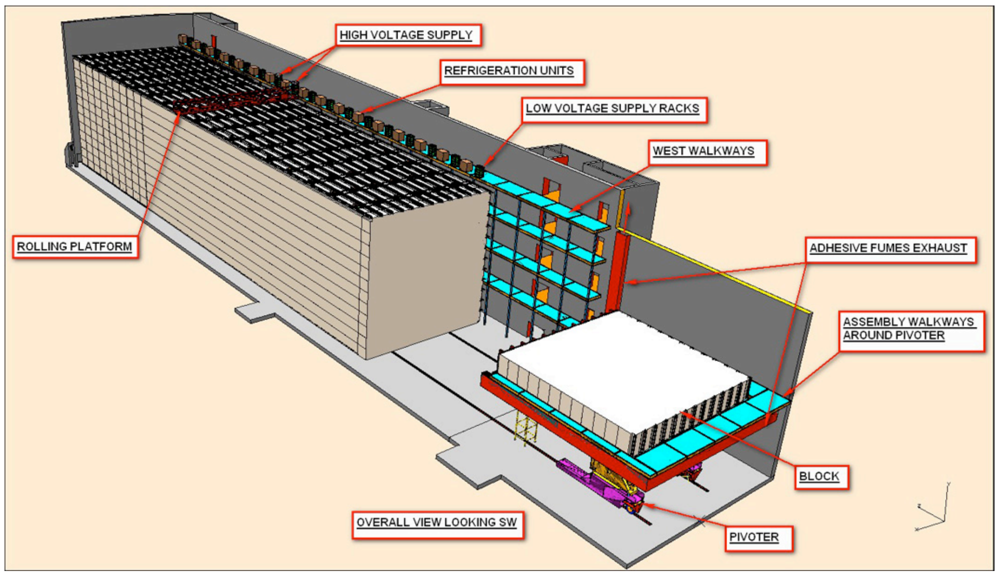
- Fermilab to Ash River (Mn) 810 km,
  - 14 mrad, ~2.2 GeV

14 kt liquid scintillator detector

Under construction

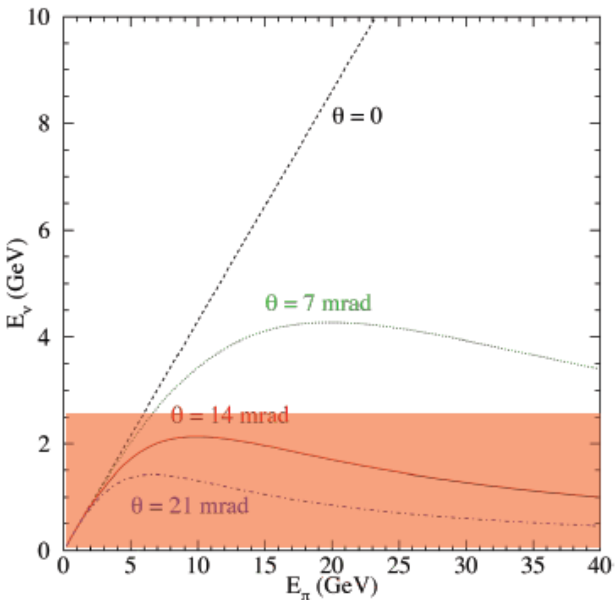




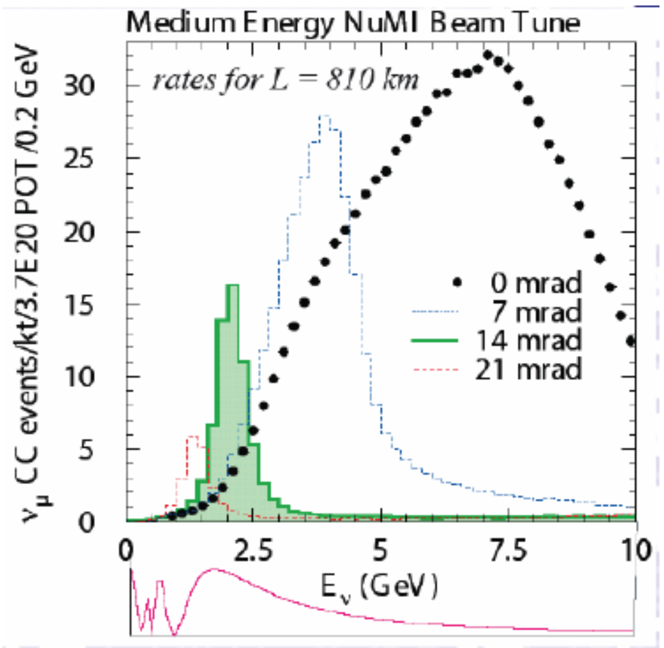


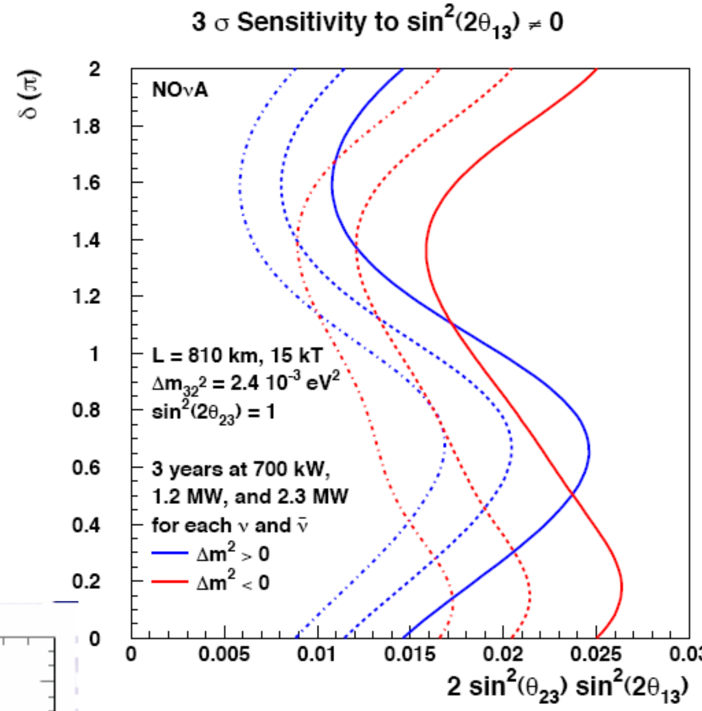
NOVA neutrino experiment

- Fermilab to Ash River (Mn) 810 km,
  - 14 mrad, ~2.2 GeV



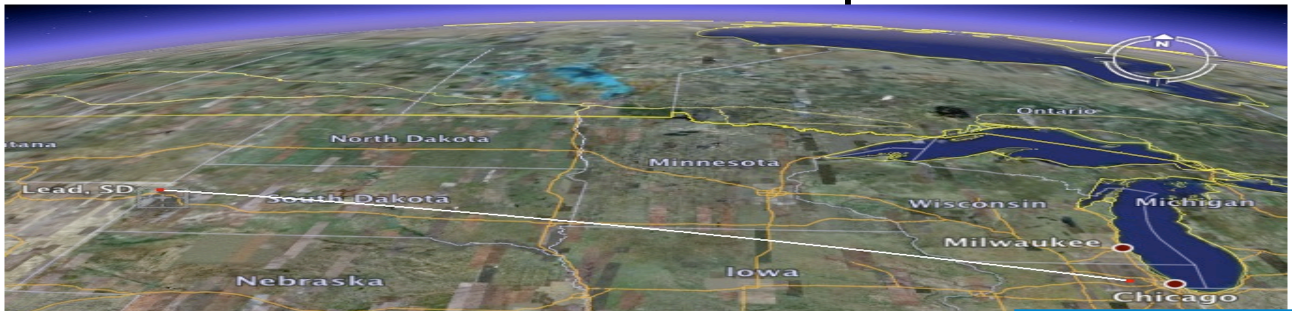
Main goals: θ_{13}, mass hierarchy and CP violations

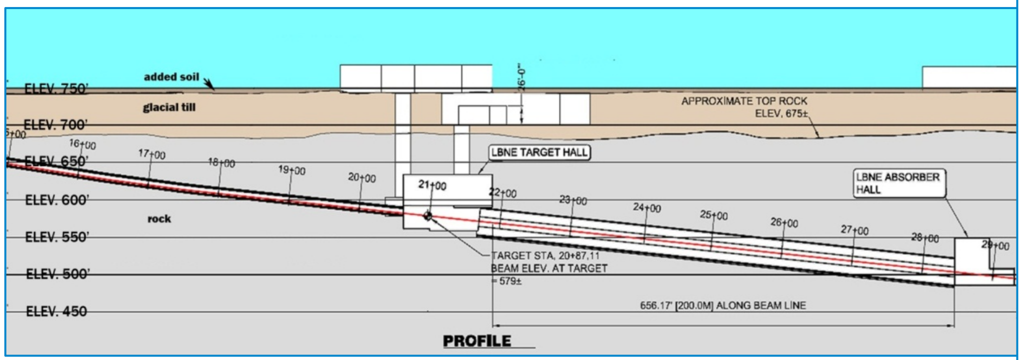


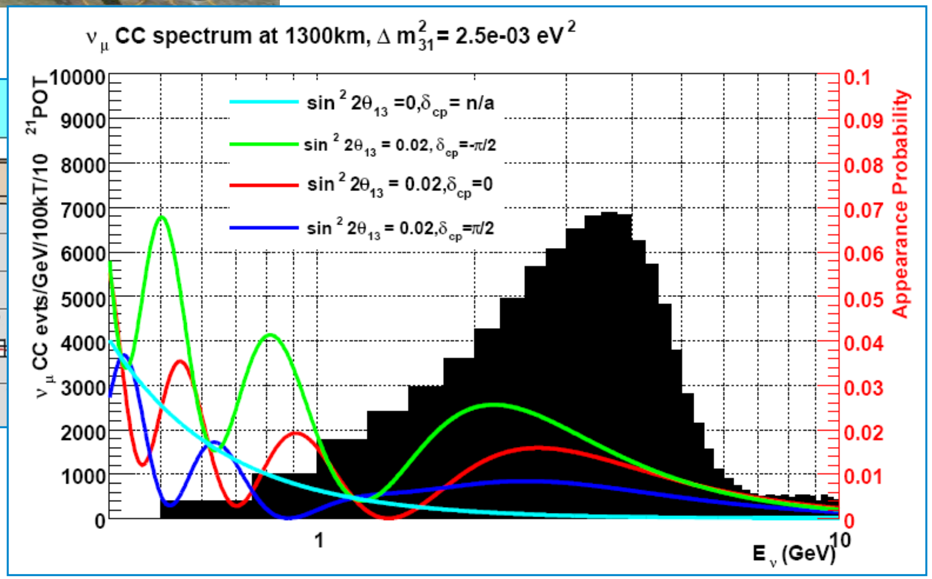


LBNE

- Long Baseline Neutrino Experiment (LBNE): Fermilab-Sanford Lab, SD (formerly Homestake or DUSEL)
  - CD0 approval Jan 2010
  - Wide band beam: multiple oscillation maxima ν_e appearance

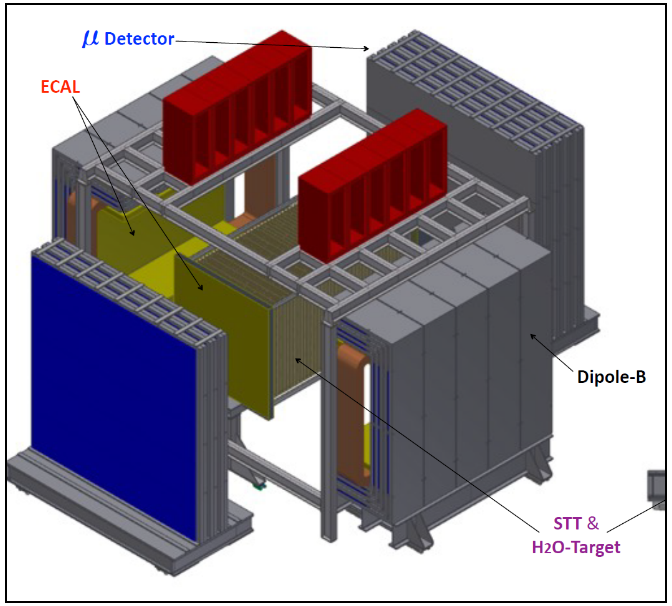


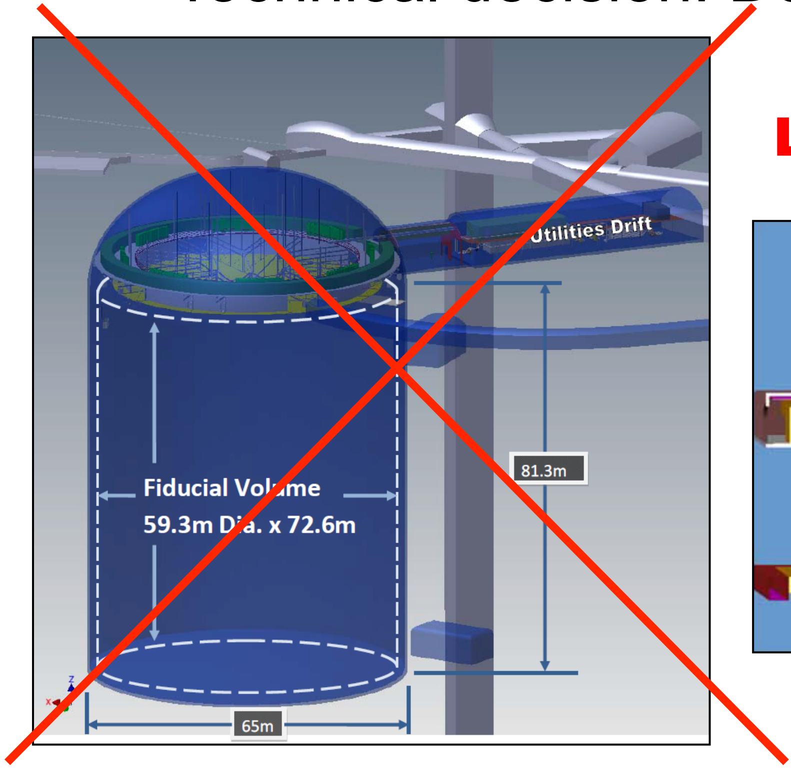




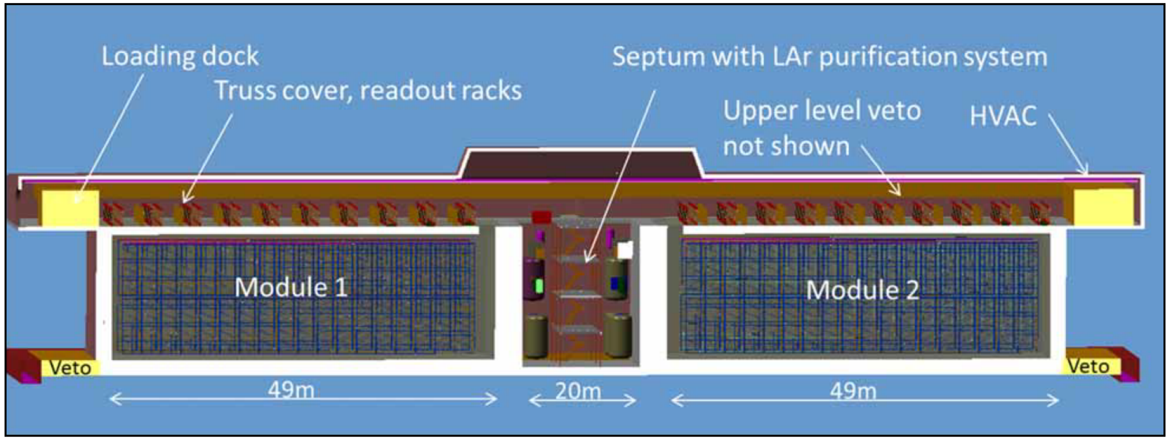
LBNE

- Fine grained near detector:
- Far detector: 200 kton water Cherenkov or 33 kton Liquid Argon TPC
  - Technical decision: Dec 2011





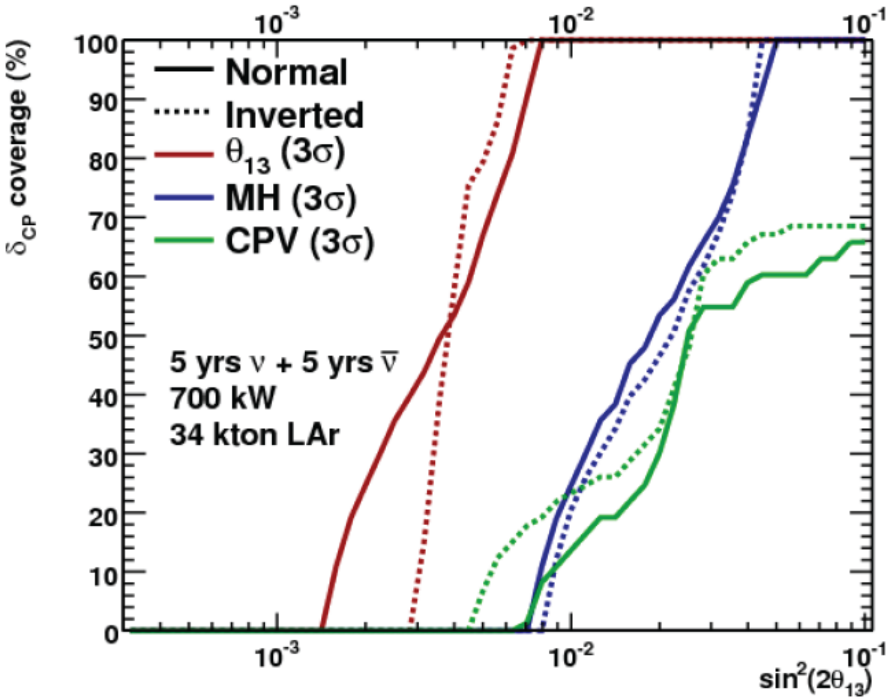
Liquid Argon



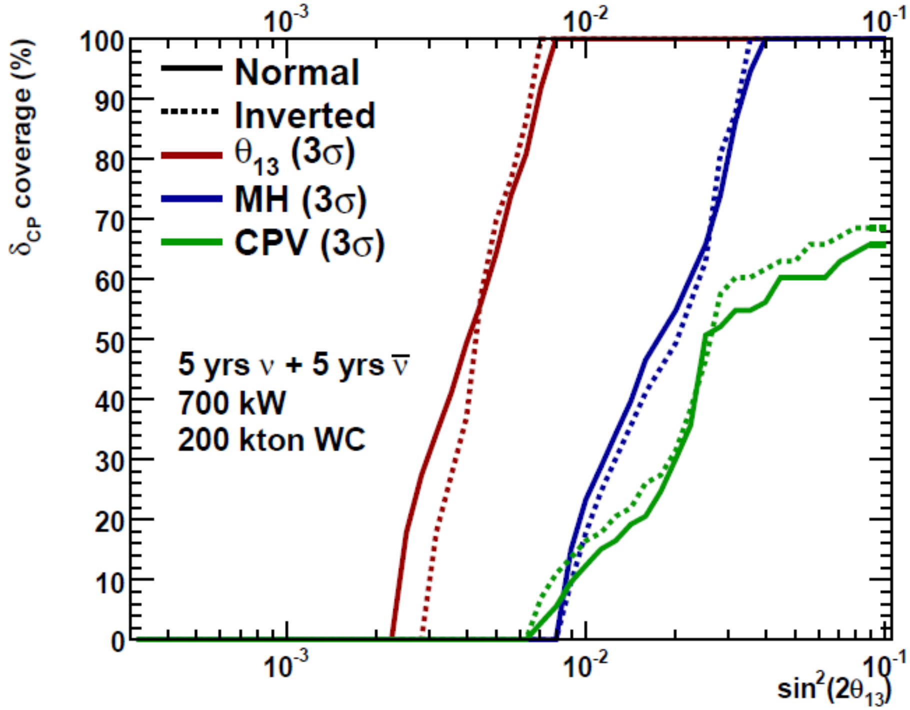
LBNE Physics Coverage

- Far detector: 200 kton Water Cherenkov or 33 kton Liquid Argon – factor of 7 in mass for equivalent sensitivity

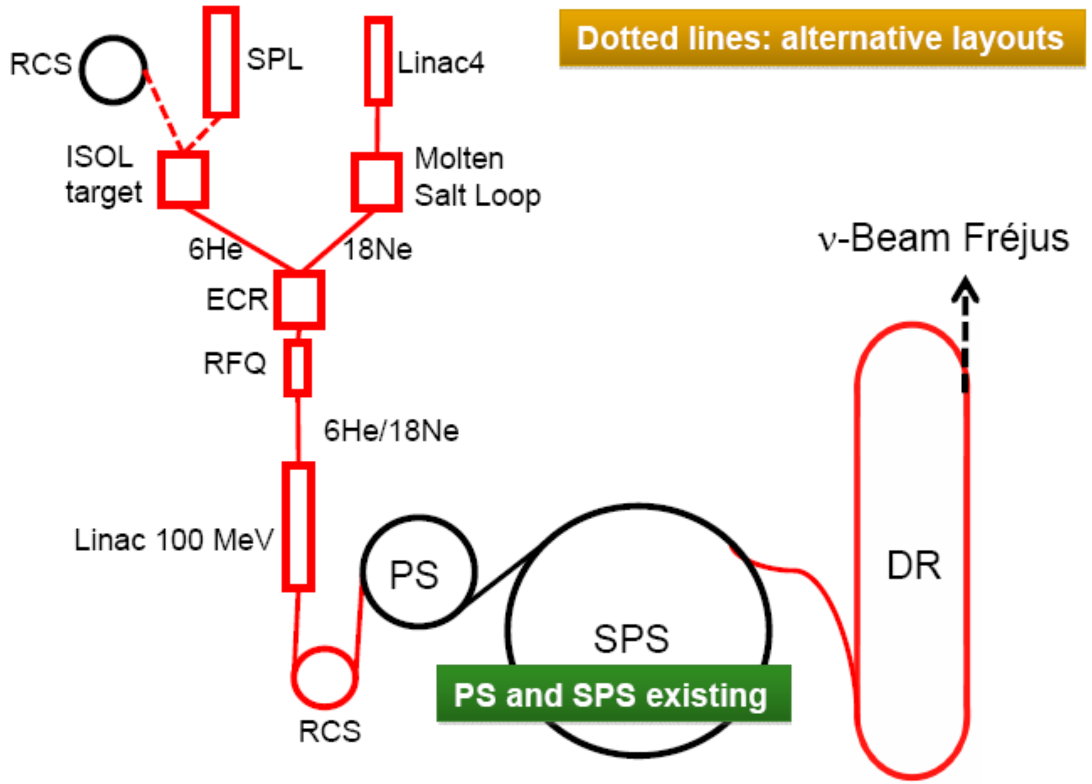
34 kt LAr TPC



200 kt WCD



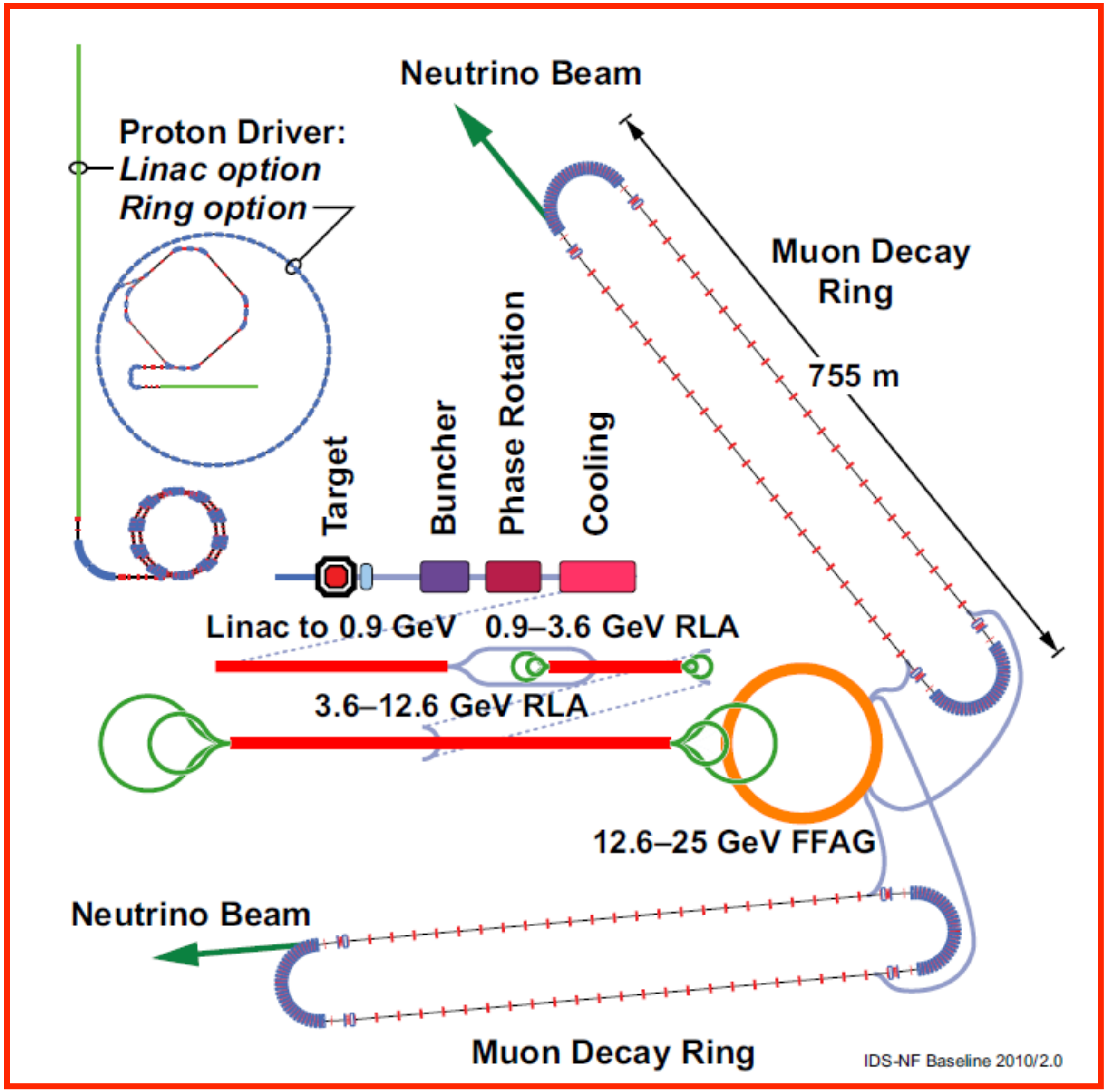
Future: Beta Beams?



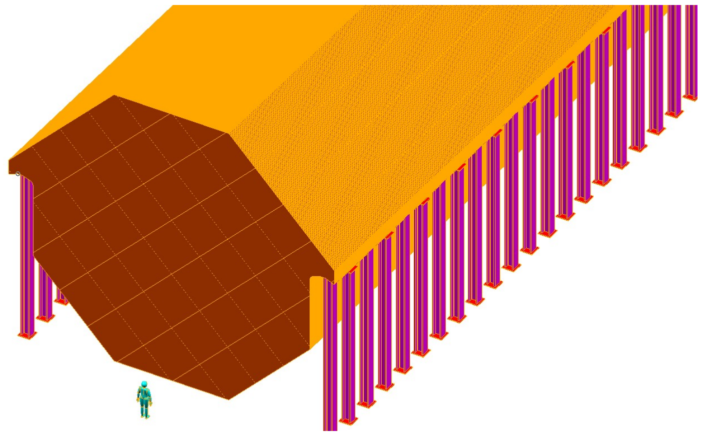
$B\rho$ ~ 500 Tm, B = ~6 T, C = ~6900 m, L_{ss}= ~2500 m, γ = 100, all ions

- SF in Decay Ring (CERN, Cockroft)
  - RF hardware seems feasible
- 60 GHz Ion Source (LPSC, CNRS, Grenoble)
  - Tests of magnetic field for plasma containment ok
  - Tests of assembly with 28 GHz (emmittances and efficiencies)
  - 60 GHz gyrotron: awaiting reception 2012
- Collection of high-Q ions from production ring (UCL, Louvain)
  - Collection ok
  - Efficiencies now measured
- Measurements of x-sections 8B and 8Li (INFN, Legnaro)
  - Analysis of results available in September
- Decay Ring Redesigned (CEA)
  - Collective effects less important
- Collimation in Decay Ring (CERN)
  - Needs good solution

Future: Neutrino Factory?



- Two Magnetised Iron Neutrino Detectors (MIND):
  - 100 kton at 2500-5000 km
  - 50 kton at 7000-8000 km

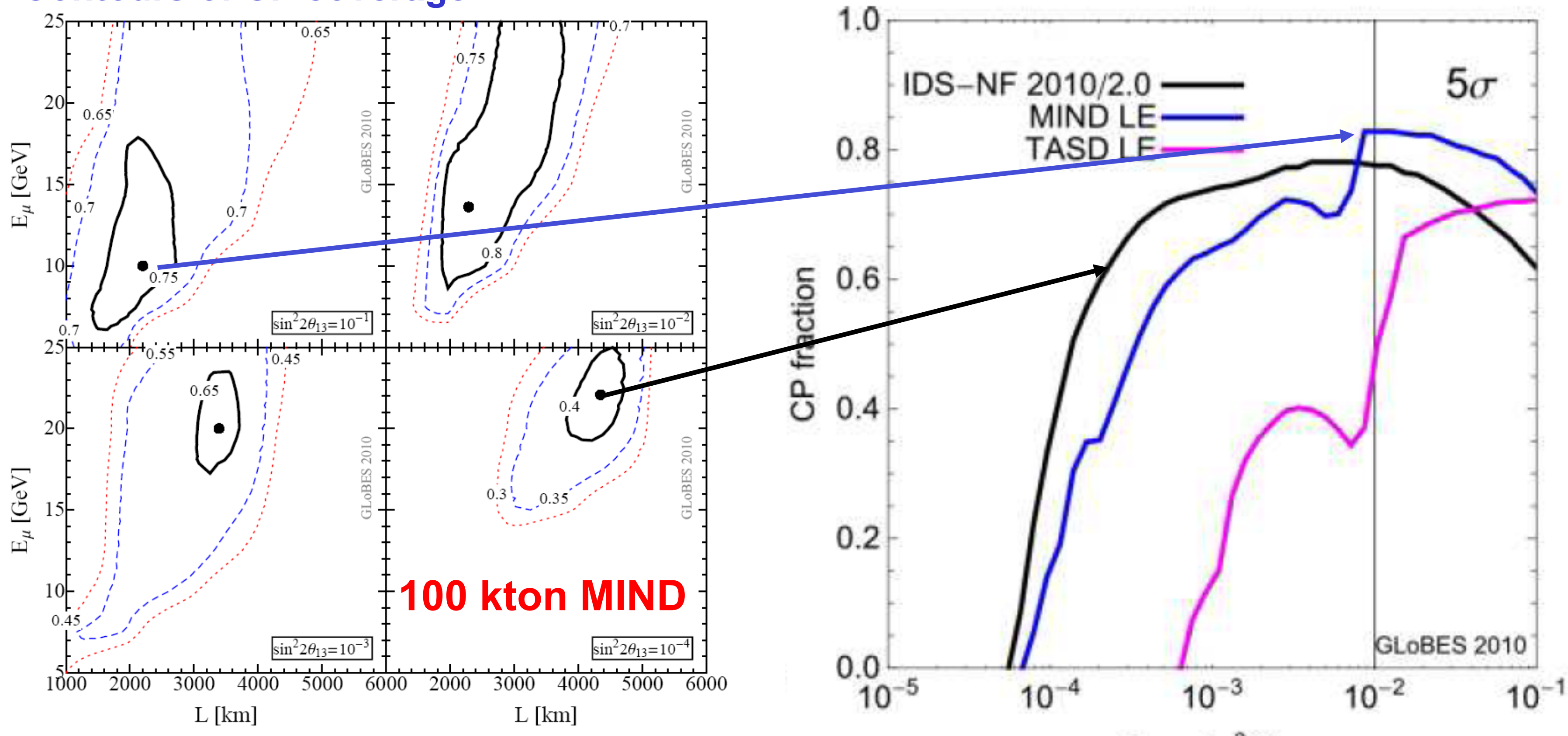


Baseline constantly under review in light of new physics results

Flexible design of Neutrino Factory

- Optimisation as function of θ_{13}

Contours of CP coverage

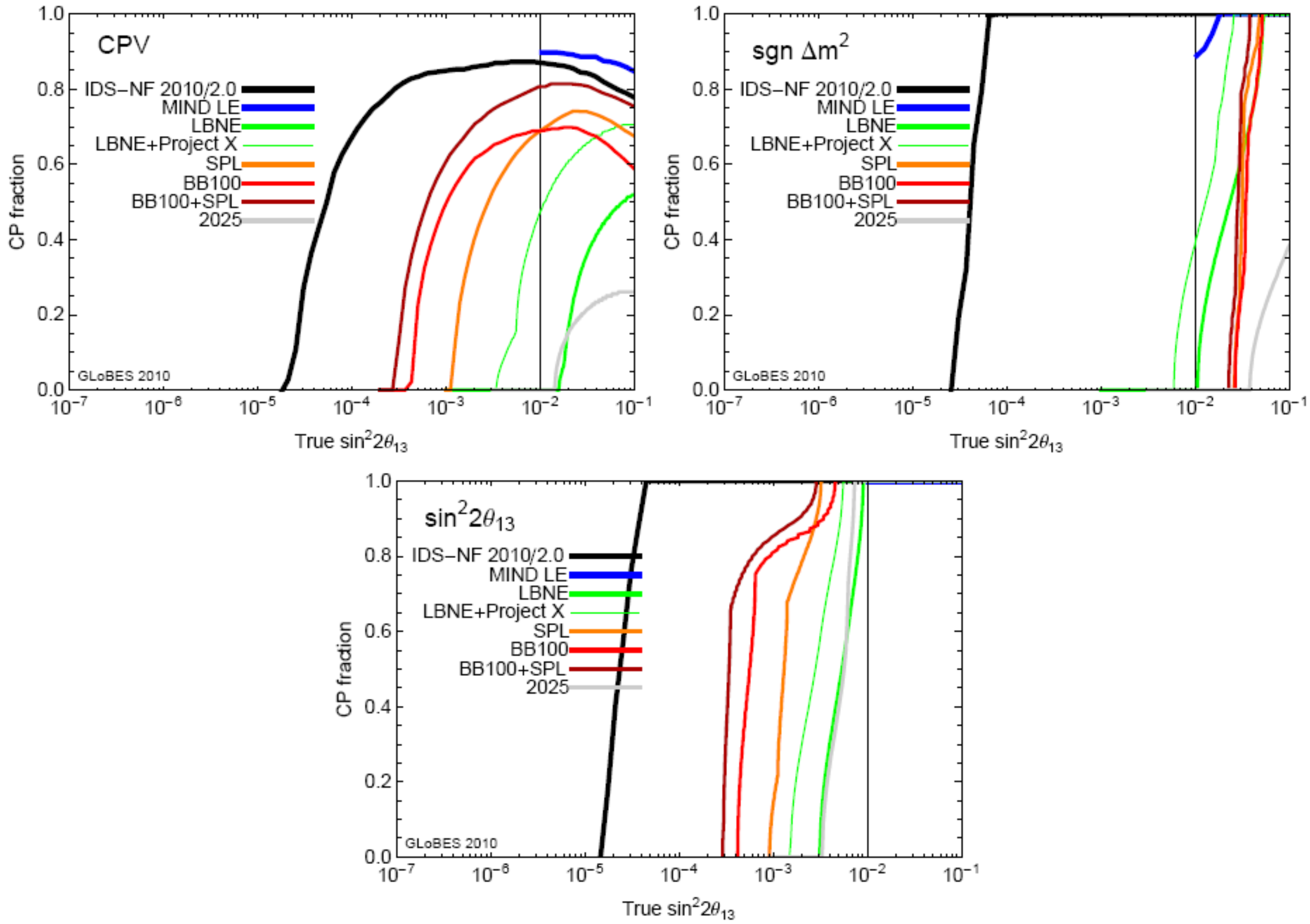


For small θ_{13}: Energy ~25 GeV, Baseline ~4000 km

For large θ_{13}: Energy 10 GeV, Baseline ~2000 km

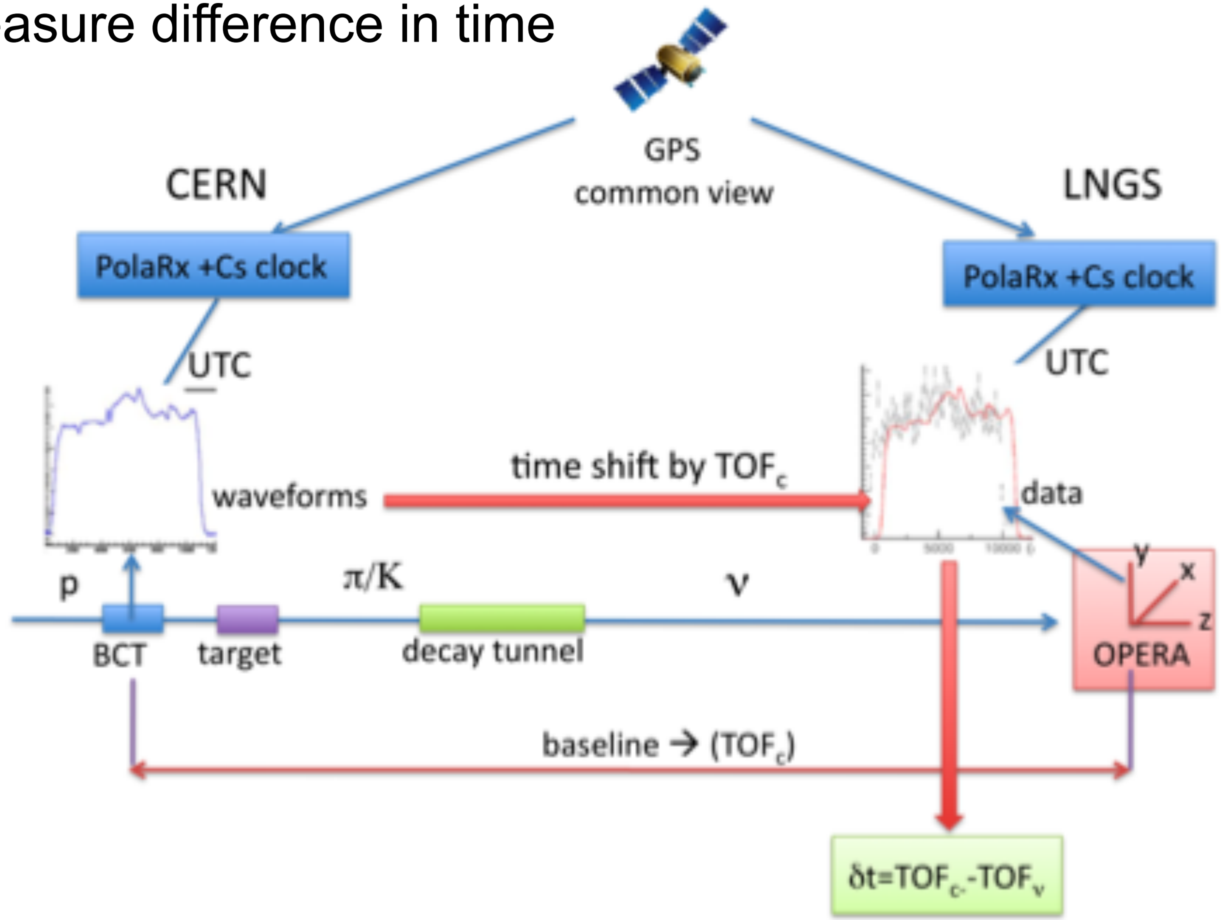
Neutrino Factory performance

- Comparison Neutrino Factory and other facilities
  - **Neutrino Factory outperforms all other facilities**



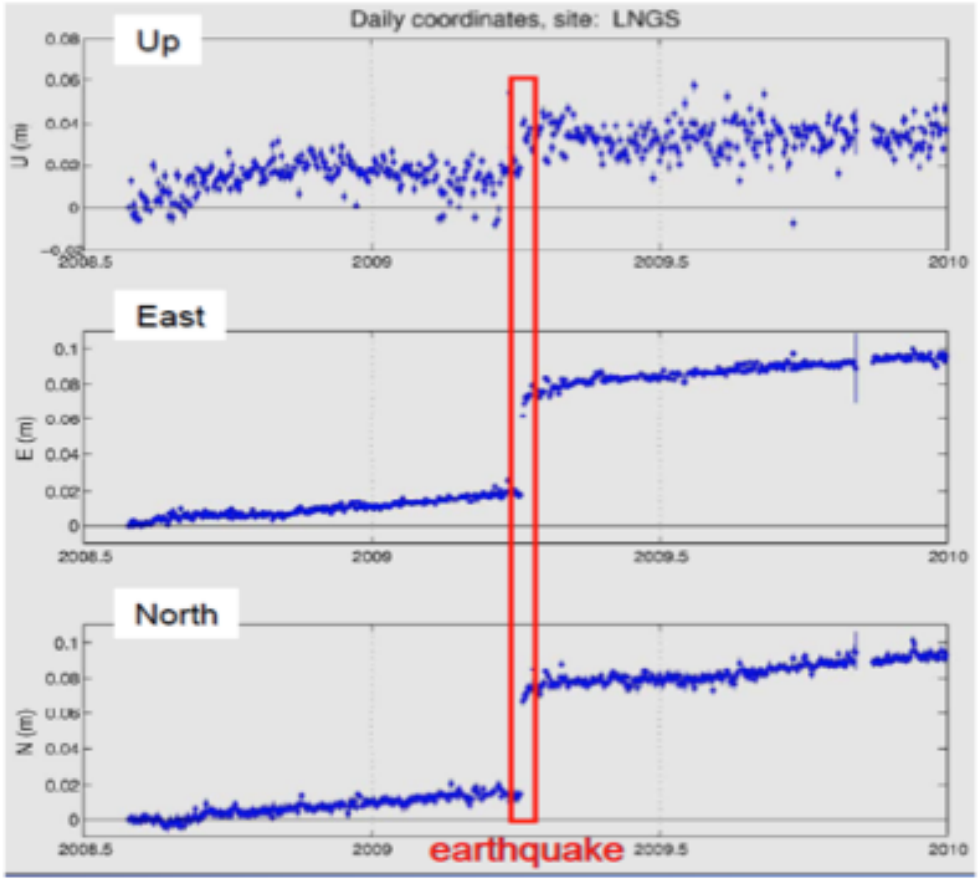
Superluminal neutrinos with OPERA?

- Principle of measurement:
  - Measure proton pulse time picked up by Beam Current Transformer (BCT) with GPS synchronised clock
  - Measure neutrino arrival time with same synchronised clock
  - Measure difference in time



Superluminal neutrinos with OPERA?

- Principle of measurement:
  - Use GPS also to measure distance between BCT and OPERA experiment in Gran Sasso: 731278.0±0.2 m
  - Distance measurement accurate enough to observe 7 cm shift from earthquake on 6 April 2009 in the l'Aquila region



Superluminal neutrinos with OPERA?

- Results:
  - There is 1034.4 ns offset, and 986.6 ns delays, so difference in time is:

$$\Delta t = \left(57.8 \pm 7.8(stat)^{+8.3}_{-5.9}\right) \times 10^{-5}\ ns$$

  - Therefore:

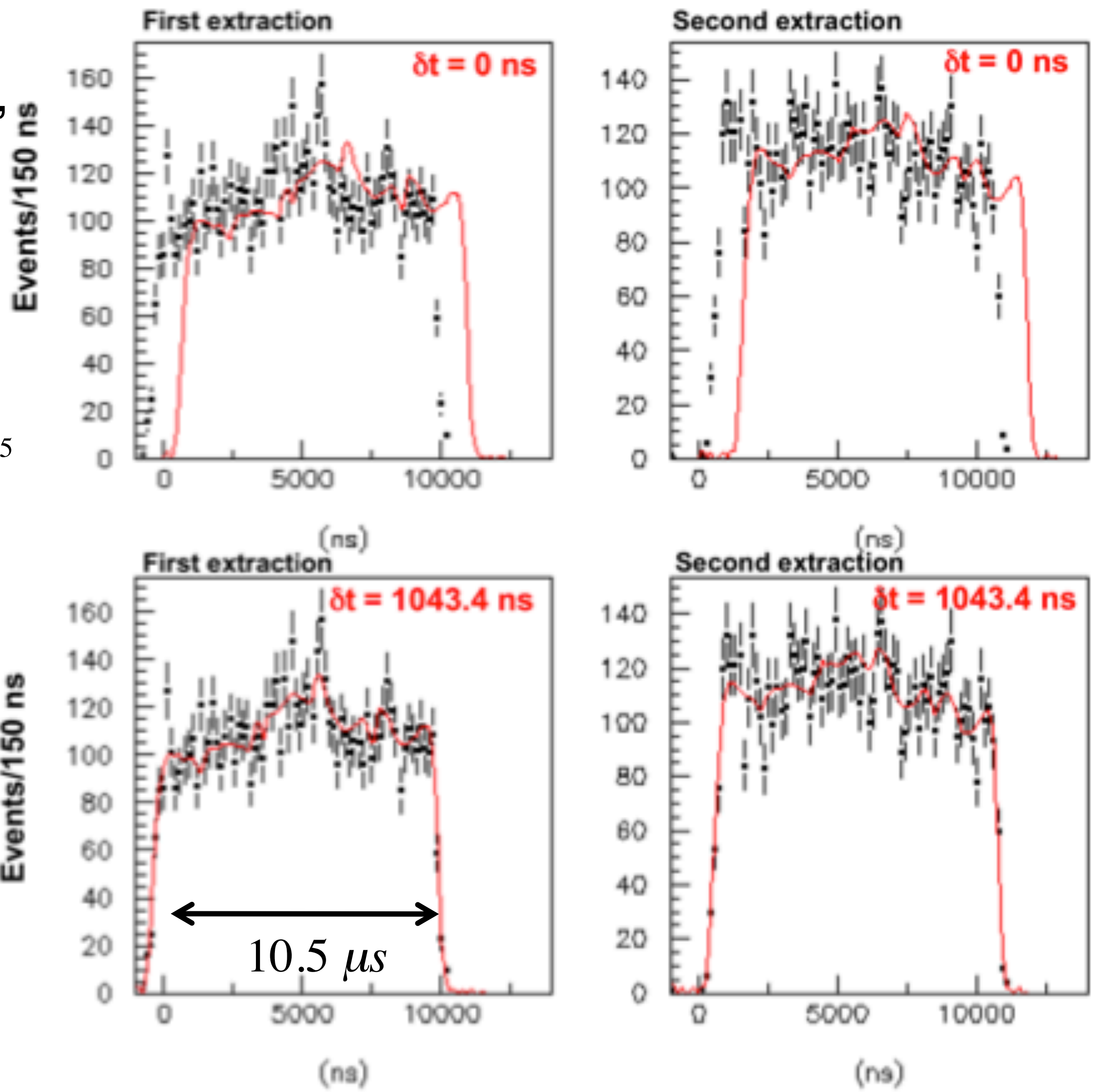
$$\frac{v-c}{c} = \left(2.37 \pm 0.32(stat)^{+0.34}_{-0.24}\right) \times 10^{-5}$$

  - This agrees with MINOS less accurate result in 2007:

$$\frac{v-c}{c} = (5.1 \pm 2.9) \times 10^{-5}$$

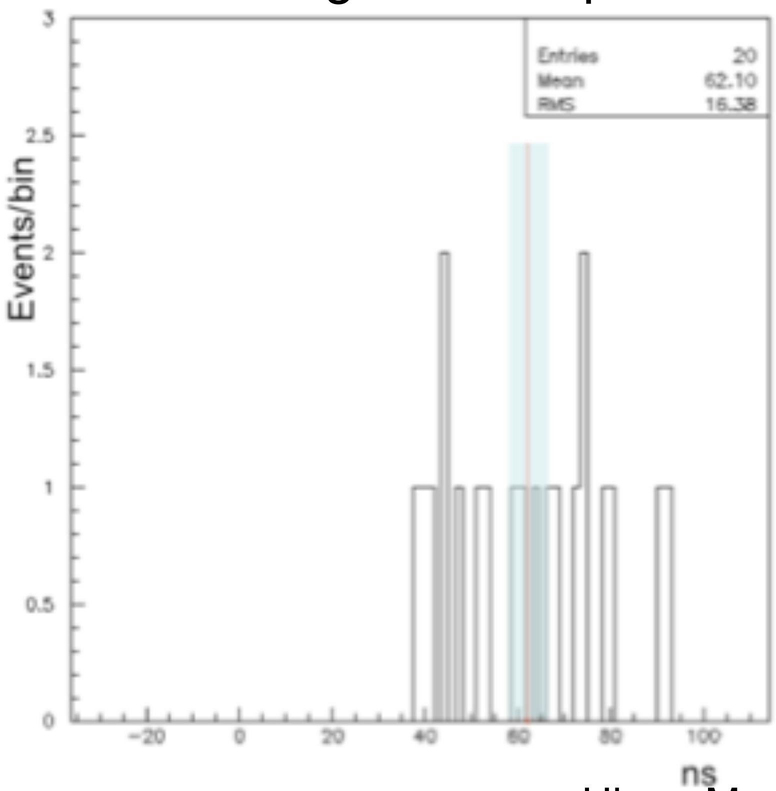
  - It disagrees with SN187a neutrino flight results:

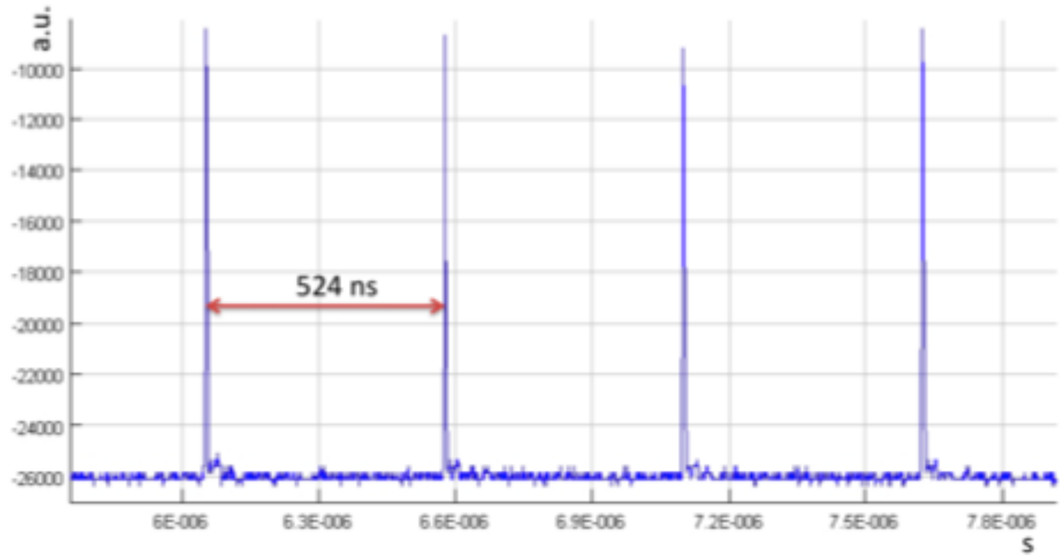
$$\frac{v-c}{c} = 2 \times 10^{-9}$$



Superluminal neutrinos with OPERA?

- Final cross-check with pulsed proton beam with pulses 3 ns wide and 524 ns apart
  - 22 Oct-6 Nov 2011 for $4x10^{16}$ POT – 35 neutrino events
  - Therefore: $\Lambda t = (62.1 \pm 3.7) \times 10^{-5}\ ns$
  - This agrees with previous result





Conclusions

- Neutrino oscillations so far explains all the atmospheric, solar and long baseline neutrino data
- There are hints that θ_{13} is non-zero, and could have large values (between 0.02 and 0.1)
- This opens up the possibility of new long baseline experiments that may discover CP violation
- Which is best: a Super Beam like LBNE, Beta Beam, Neutrino Factory?
- However, short baseline data is conflicted: LBNE and MiniBoone not clarified yet
- Absolute neutrino mass and Majorana nature of neutrino seem to be very difficult, but a major discovery if double beta is found
- The final surprise in the neutrino sector: superluminal velocities or some unknown experimental error?

Quote by Sydney Carton as he is going to the guillotine out of love for the wife of his nemesis Charles Darnay :

"It is a far, far better thing that we do, than we have ever done"

Tale of Two Cities (Charles Dickens)