

Current and future status of θ_{13}

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October 17th 2011
IDS-NF

Outline

* Implication of θ_{13} results

- * for CP violation
- * for mass hierarchy

* Current θ_{13} results

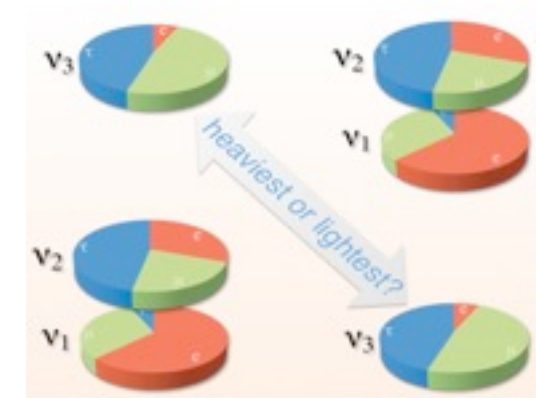
- * Accelerators
- * Global fit

* Future θ_{13} results

- * Reactors
- * Nova

* What if θ_{13} is big ?

* Summary



Very inspired from T. Kobayashi at ICFA 2011

Where does θ_{13} matter?

$$\begin{aligned}
 P[\nu_\mu(\bar{\nu}_\mu) \rightarrow \nu_e(\bar{\nu}_e)] = & \left. \begin{aligned} & \sin^2 2\theta_{13} s_{23}^2 \sin^2(\phi_{31}) - 1/2 s_{12}^2 \sin^2 2\theta_{13} s_{23}^2 (2\phi_{21}) \sin(2\phi_{31}) \\ & + 2J_r \cos\delta (2\phi_{21}) \sin(2\phi_{31}) \mp 4J_r \sin\delta (2\phi_{21}) \sin^2(\phi_{31}) \end{aligned} \right\} \text{Vacuum terms} \\
 & \pm \cos 2\theta_{13} \sin^2 2\theta_{13} s_{23}^2 \frac{(4Ea(x))}{(\Delta m_{31}^2)} \sin^2 \phi_{31} \\
 & \mp \frac{(a(x)L)}{2} \sin^2 2\theta_{13} \cos 2\theta_{13} s_{23}^2 \sin(2\phi_{31}) \left. \vphantom{\frac{(4Ea(x))}{(\Delta m_{31}^2)}} \right\} \text{Matter Effect terms} \\
 & + c_{23}^2 \sin^2 2\theta_{12} (\phi_{21})^2 \left. \vphantom{\frac{(4Ea(x))}{(\Delta m_{31}^2)}} \right\} \text{Solar term}
 \end{aligned}$$

$$\phi_{ij} = \frac{(\Delta m_{ij}^2 L)}{(4E)}$$

$$a(x) = \sqrt{(2)} G_F N_e(x)$$

 CP terms.

 Mass hierarchy terms.

$$J_r \left(= c_{12} s_{12} c_{13}^2 s_{13} c_{23} s_{23} \right)$$

Mass hierarchy



CP terms



Measuring θ_{13} ?

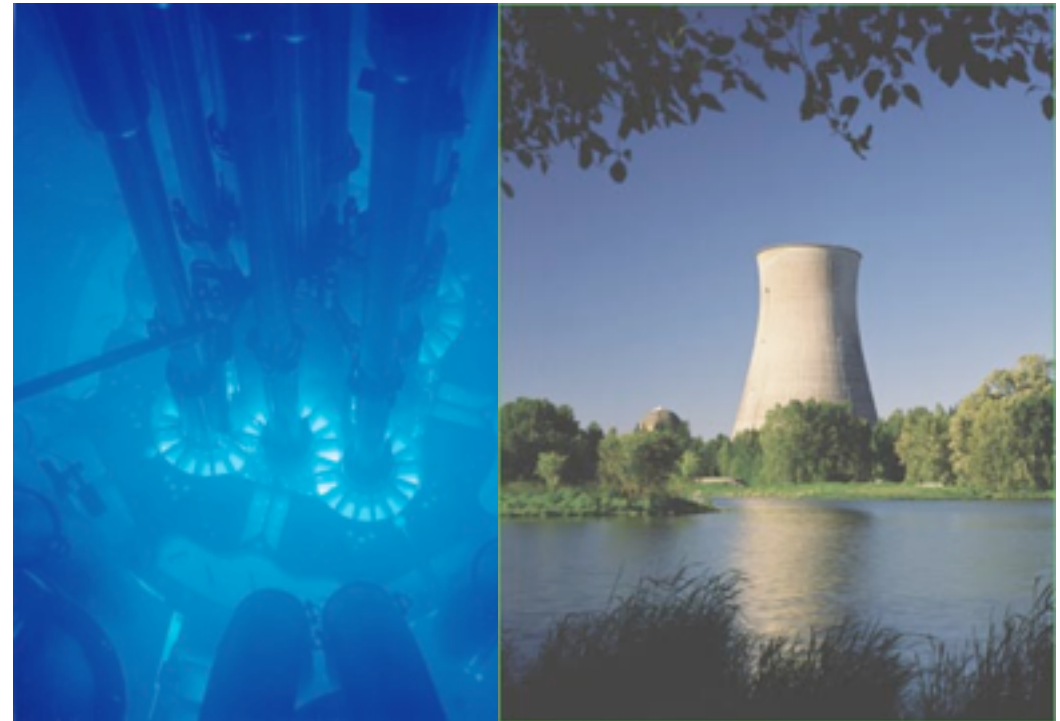
- * Reactor experiments

- * Reno
- * Double Chooz
- * Daya Bay

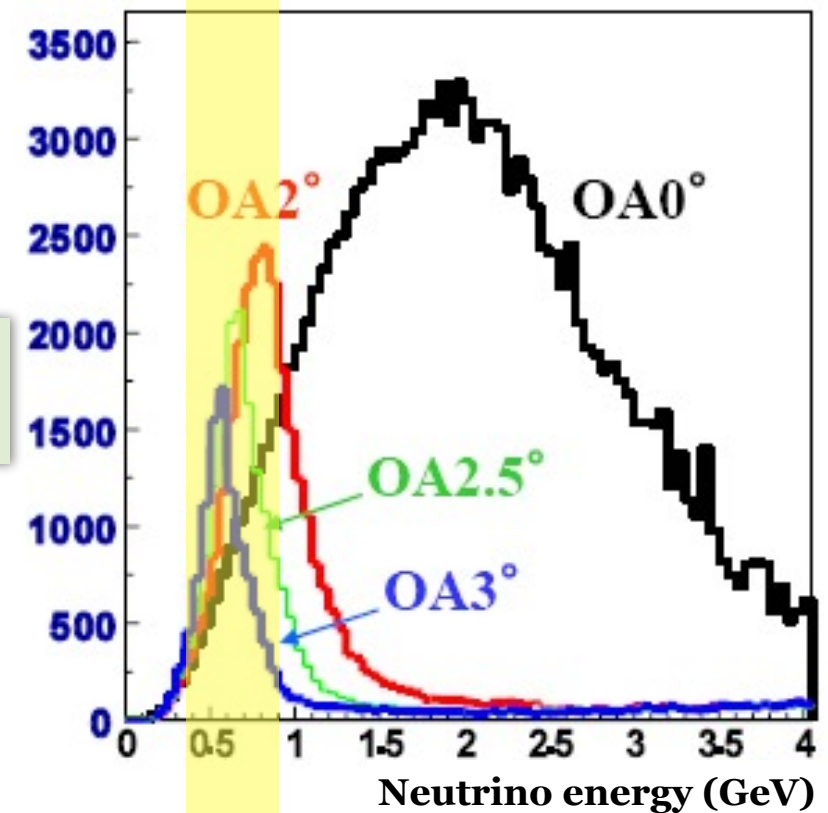
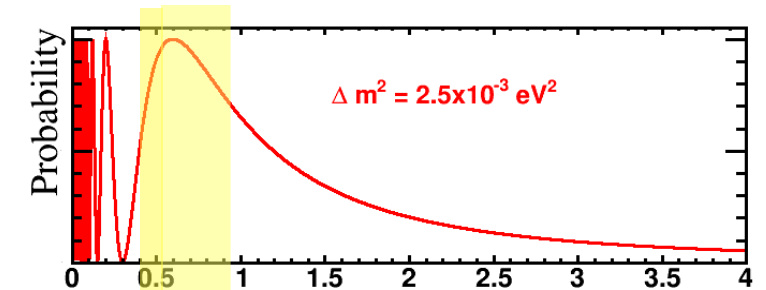
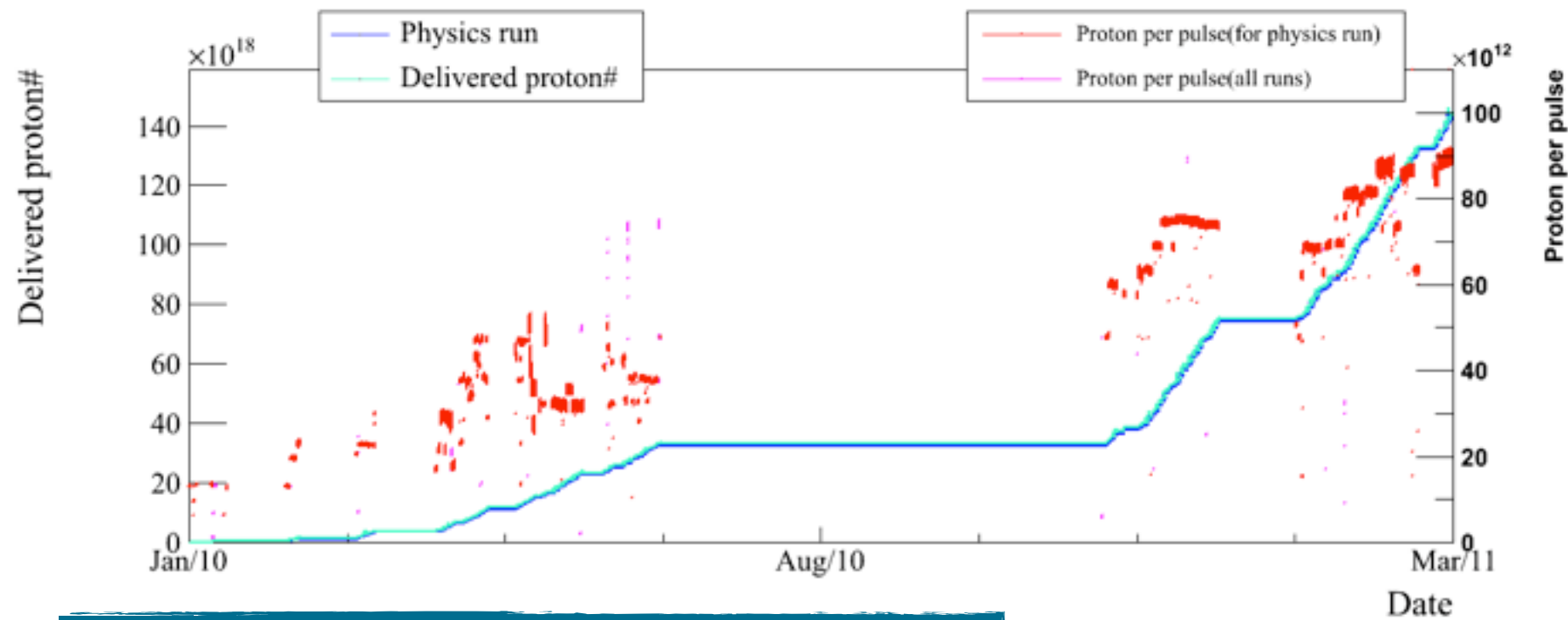
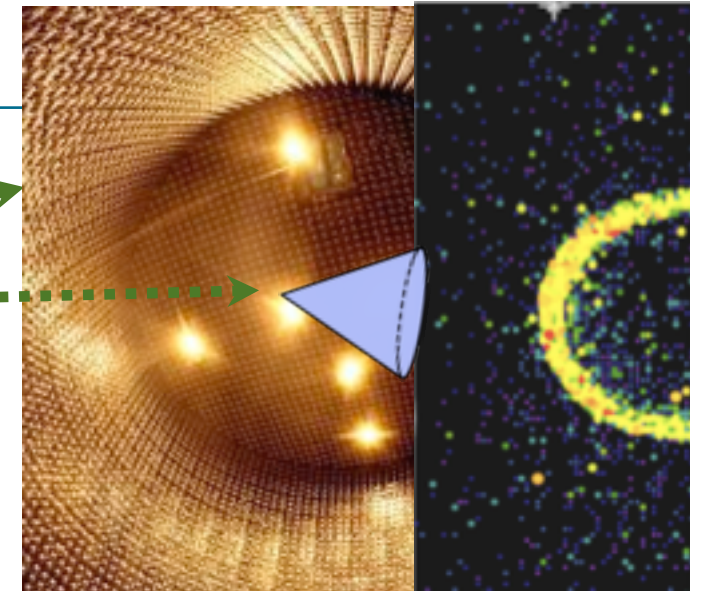
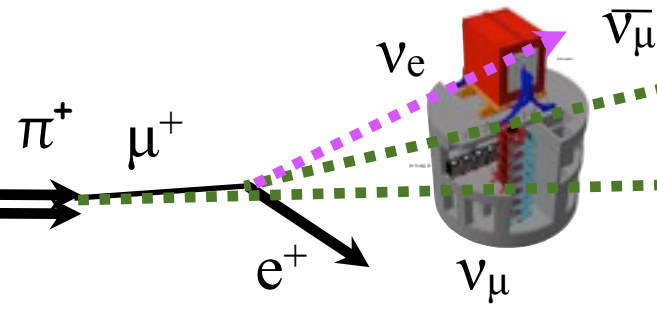
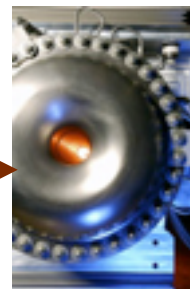
- * Accelerator experiments

- * T2K
- * Minos

- * Global fits

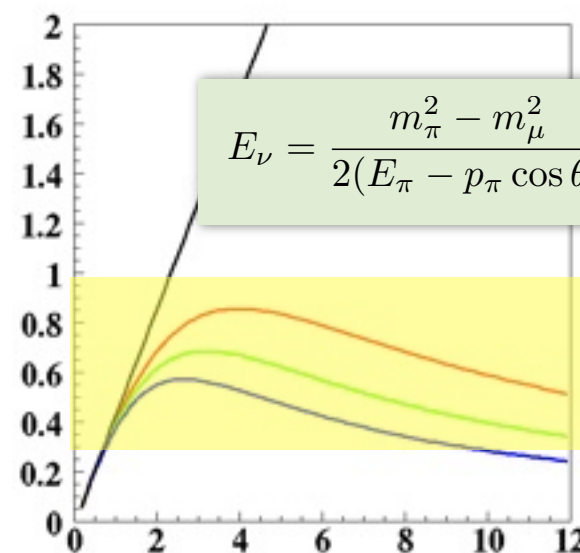


T2K - Overview



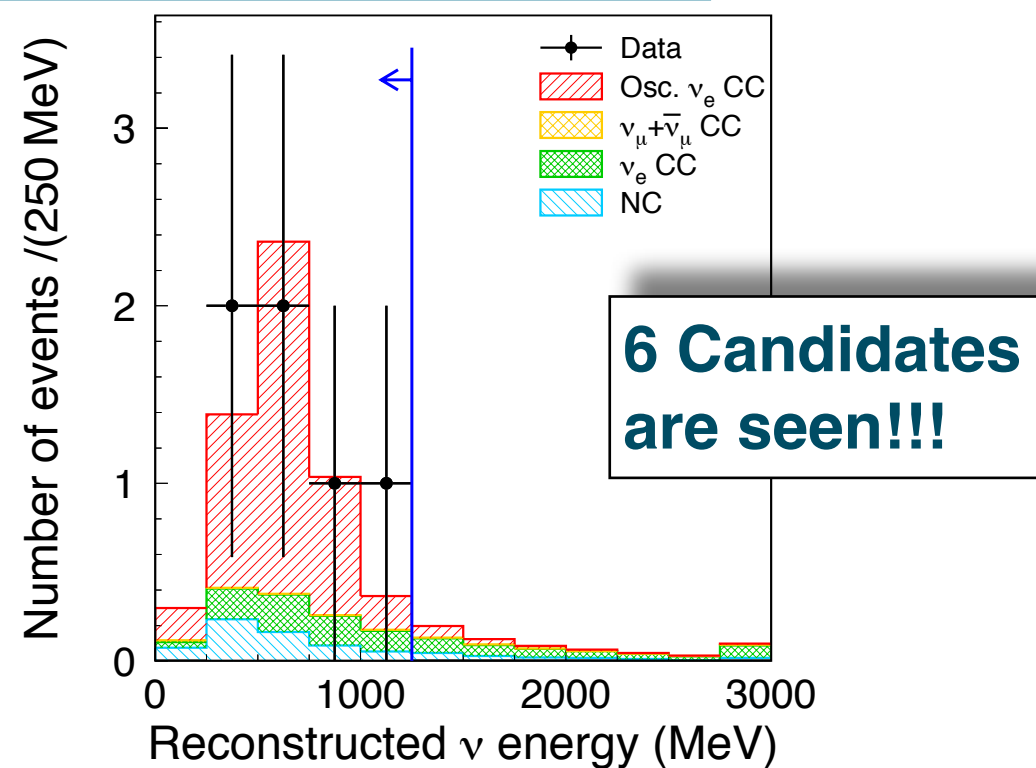
Main facts:

- 1.43 x 10²⁰ POT accumulated from January 2010 to March 2011.
- Reached 145 kW.
- Beam will start again in December, new data coming this winter.



$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{2(E_\pi - p_\pi \cos \theta)}$$

T2K results - 6 candidates



All data analysed

Event selection:

Signal Efficiency = 66%

Background Rejection:

77% for beam ν_e

99% for NC

6 candidate events remain

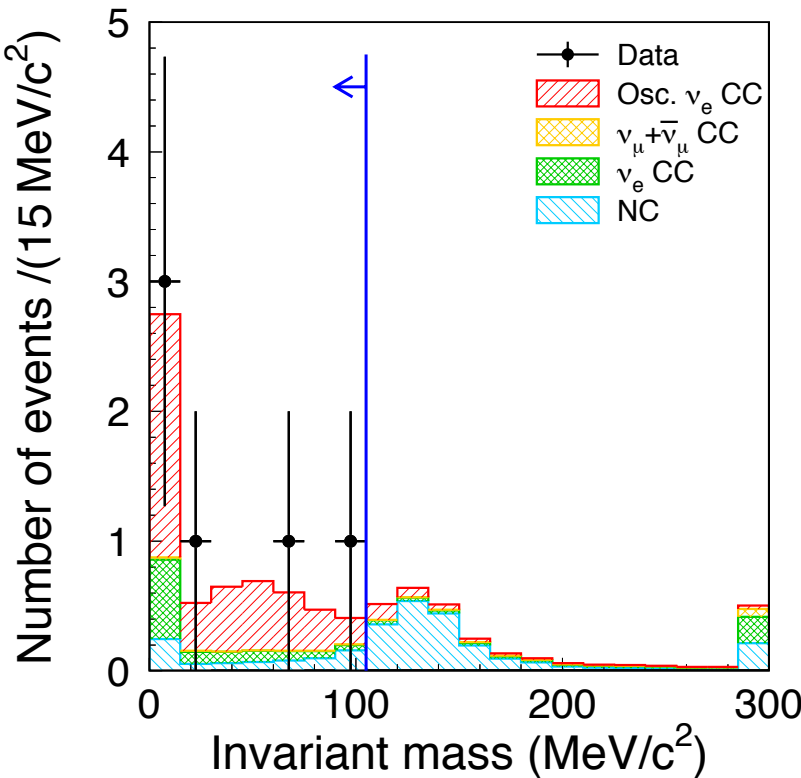
1.5 ± 0.3 BG expected

Probability to observe ≥ 6 evts w/ $\sin^2 2\theta_{13}=0$: **0.7%**

2.5 σ excess observed

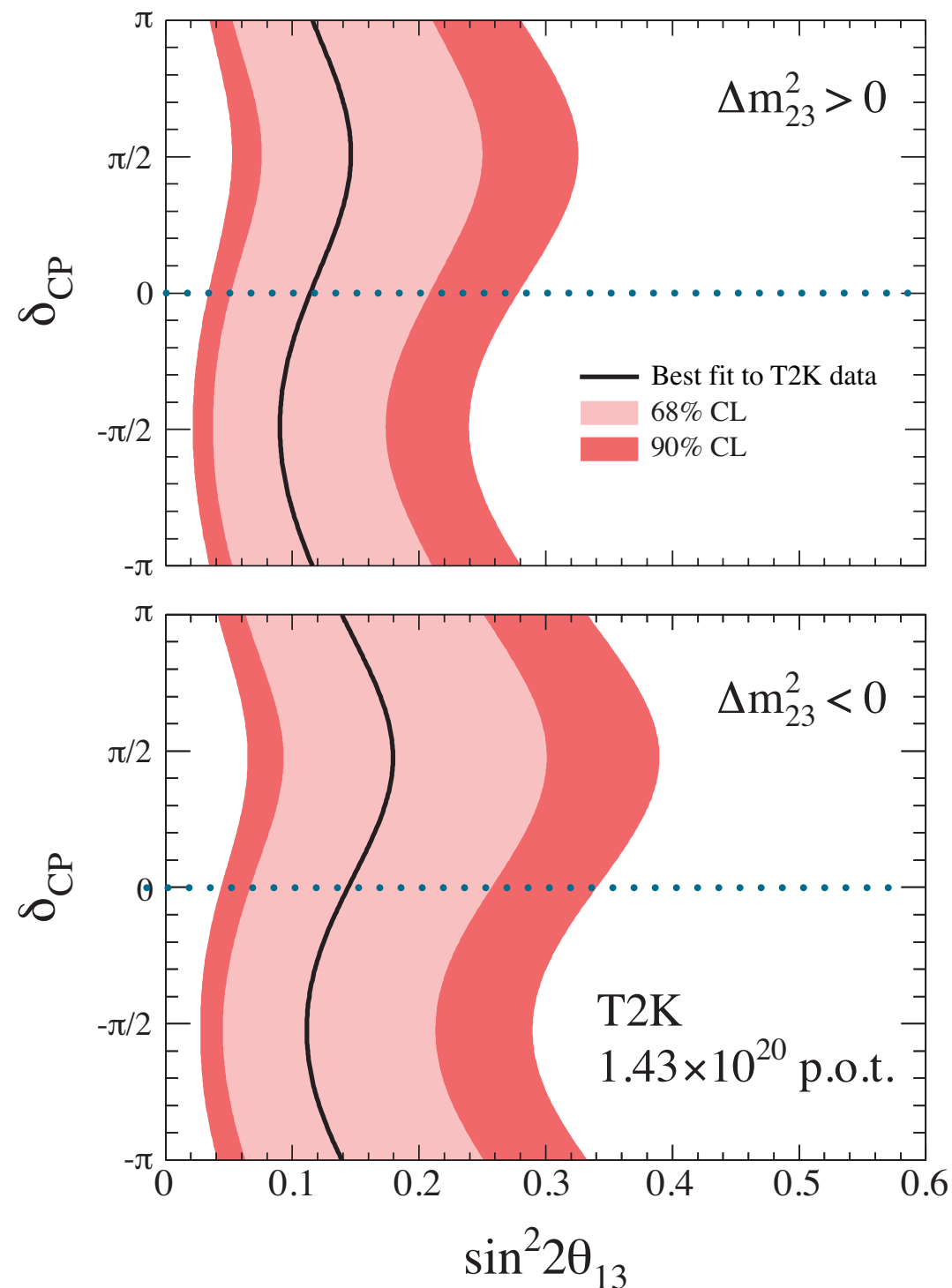
$$\sin^2 2\theta_{13} = 0$$

Selection Step	Background			Observation
	ν_μ CC	Beam ν_e	NC	
No OD signal (fully contained: FC)	-	-	-	121
Vertex in SK fiducial volume (distance from ID wall > 2m)	52	3.0	18	88
One ring	31	1.9	5.7	41
e-like ring	1.0	1.9	3.7	8
Electron energy > 100MeV	0.7	1.9	3.2	7
No delayed electron signal	0.1	1.6	2.8	6
Invariant mass of 1 e-like ring + additional forced-reconstructed e-like ring $M_{\text{inv}} < 105 \text{ MeV}/c^2$	0.04	1.1	0.8	6
Reconstructed neutrino energy $E_\nu < 1250 \text{ MeV}$	0.03	0.8	0.6	6



T2K - Allowed regions

PRL 107, 041801 (2011)



Best fit results is right around Chooz 90% CL upper bound ($\sin^2(2\theta_{13}) = 0.15$)

at $\delta_{CP} = 0$:

$\sin^2(2\theta_{13}) = 0.11$ for normal mass hierarchy
 $0.03 < \sin^2(2\theta_{13}) < 0.28$

$\sin^2(2\theta_{13}) = 0.14$ for inverted mass hierarchy
 $0.04 < \sin^2(2\theta_{13}) < 0.34$

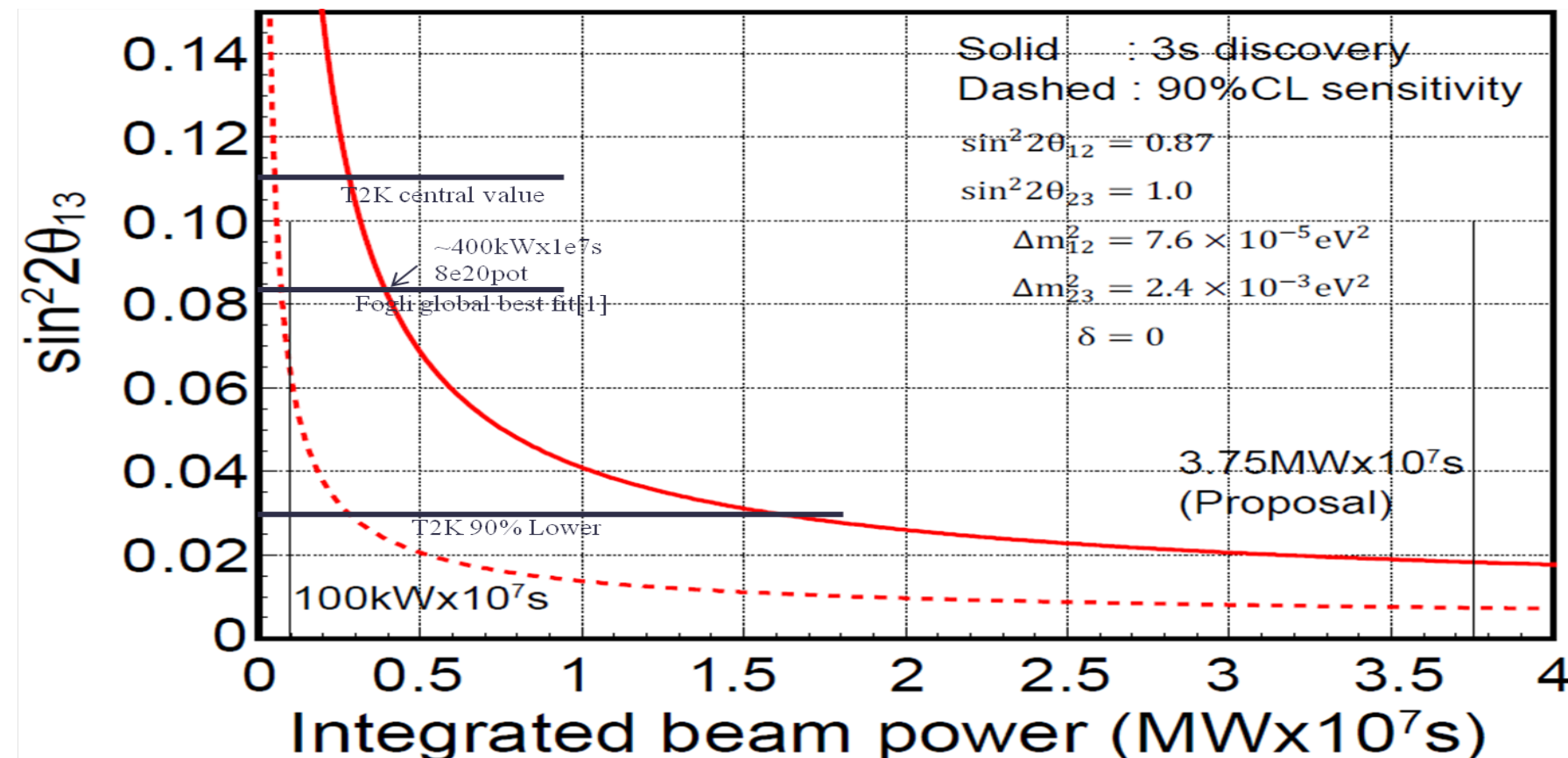
T2K - Sensitivities

We aim to have:

By Summer 2013: **~0.5** [MWx10⁷s] ~ 1e21pot
Conclude non-zero θ_{13}
> 5 sigma for present T2K central value

Within a few years : **~1** [MWx10⁷s] ~ 2e21pot
> 3 sigma for $\sin^2 2\theta_{13} > 0.04$

Approved goal : **3.75** [MWx10⁷s] ~ 8e21pot
> 3 sigma for $\sin^2 2\theta_{13} > \sim 0.02$

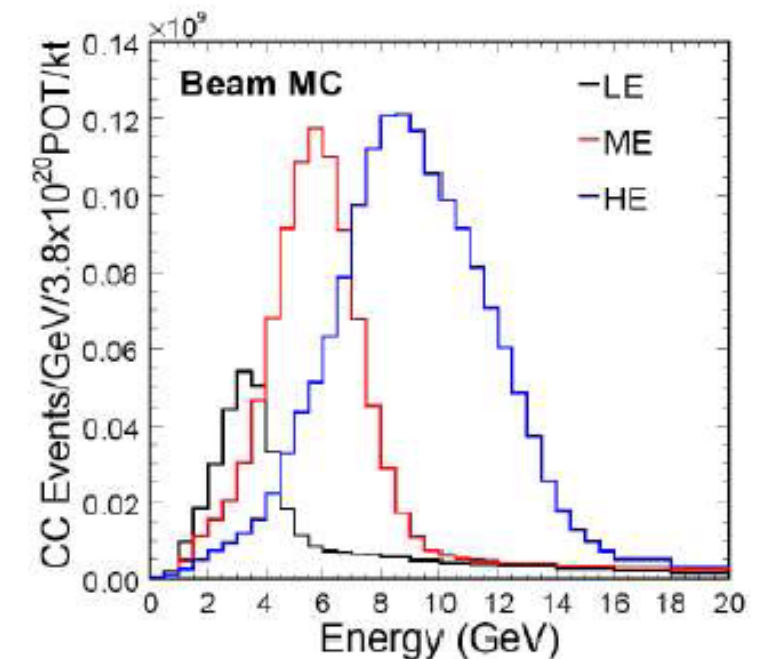
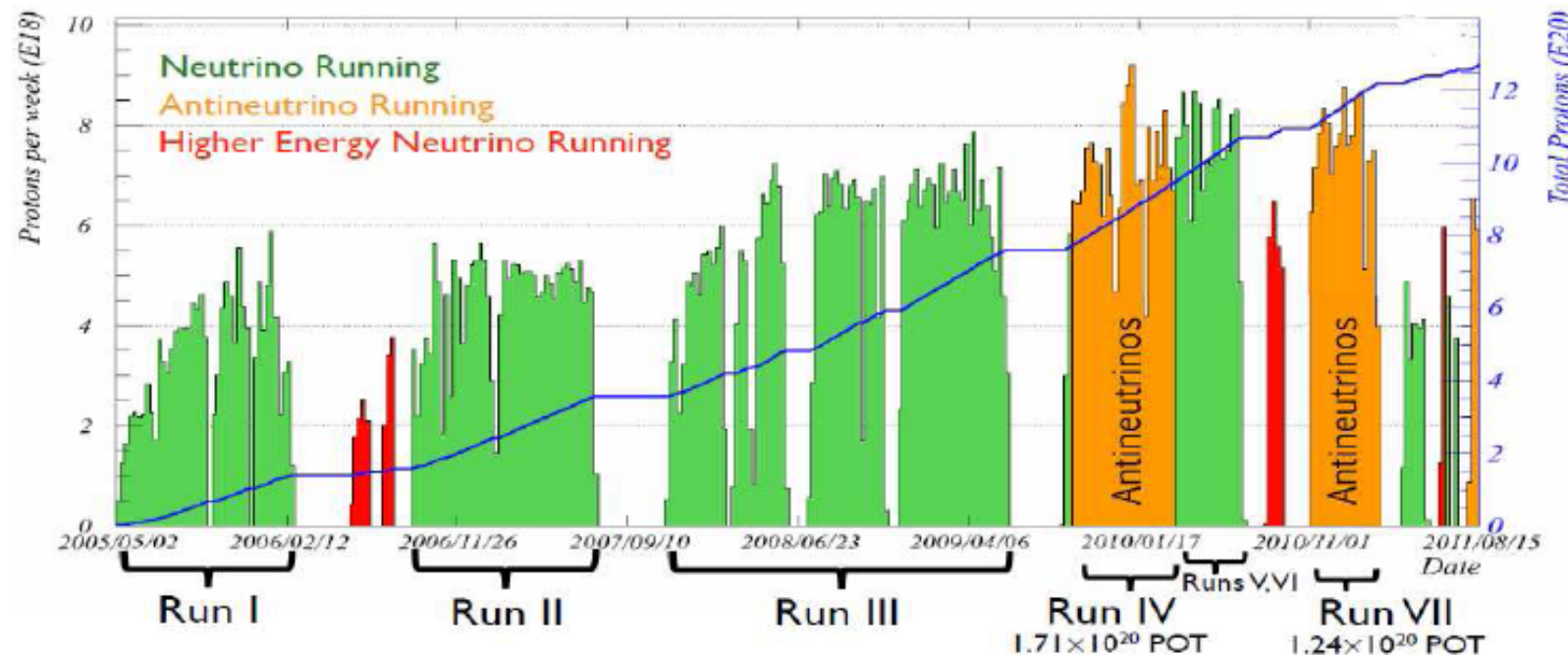
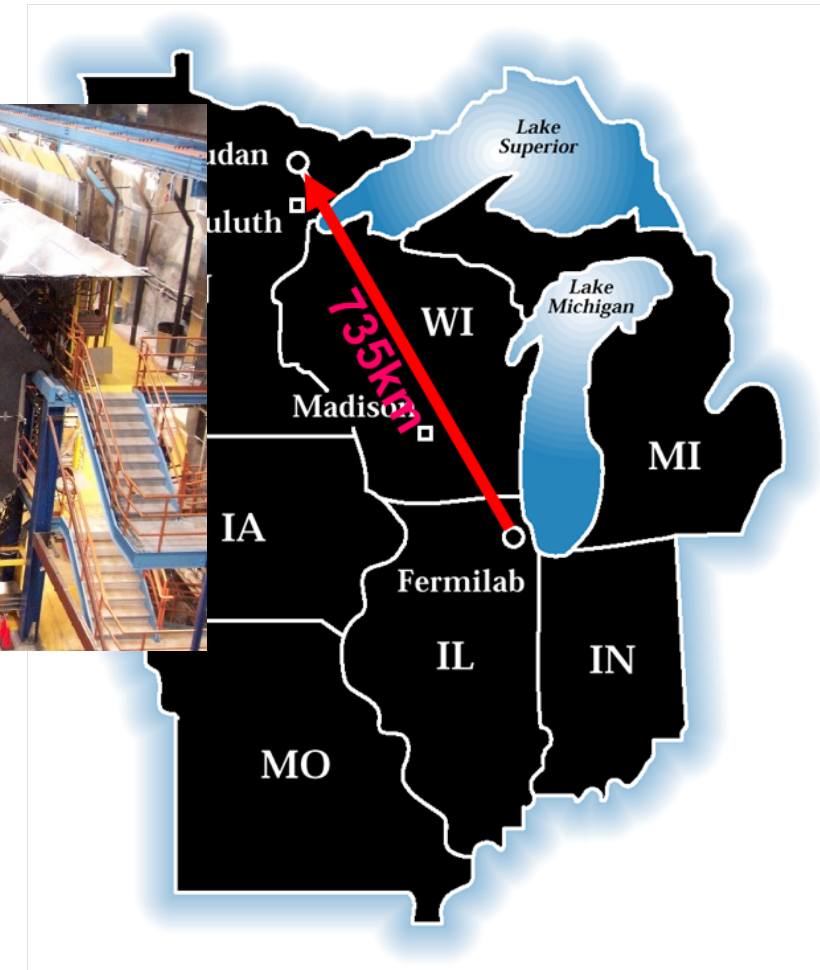


T2K - Status & Plan

- * J-PARC has not been operated since Mar. 11, 2011 because of the earthquake.
- * Intensive recovery works are on-going
- * We will resume J-PARC operation in Dec. 2011
 - * First, LINAC will start operation on Dec. 12, 2011
- * We plan to have >2 “cycle”(~month) beam for users within JFY2011 (by the end of March 2012)
- * In FY2012 (April 2012 - March 2013) J-PARC plan to operate fully (~9month) (budget requested)
- * LINAC energy recovery from 181MeV to 400MeV originally scheduled in 2012 was delayed to start July 2013
 - * User's needs to take longer beam after long shutdown by the earthquake
 - * Delay of preparation caused by earthquake

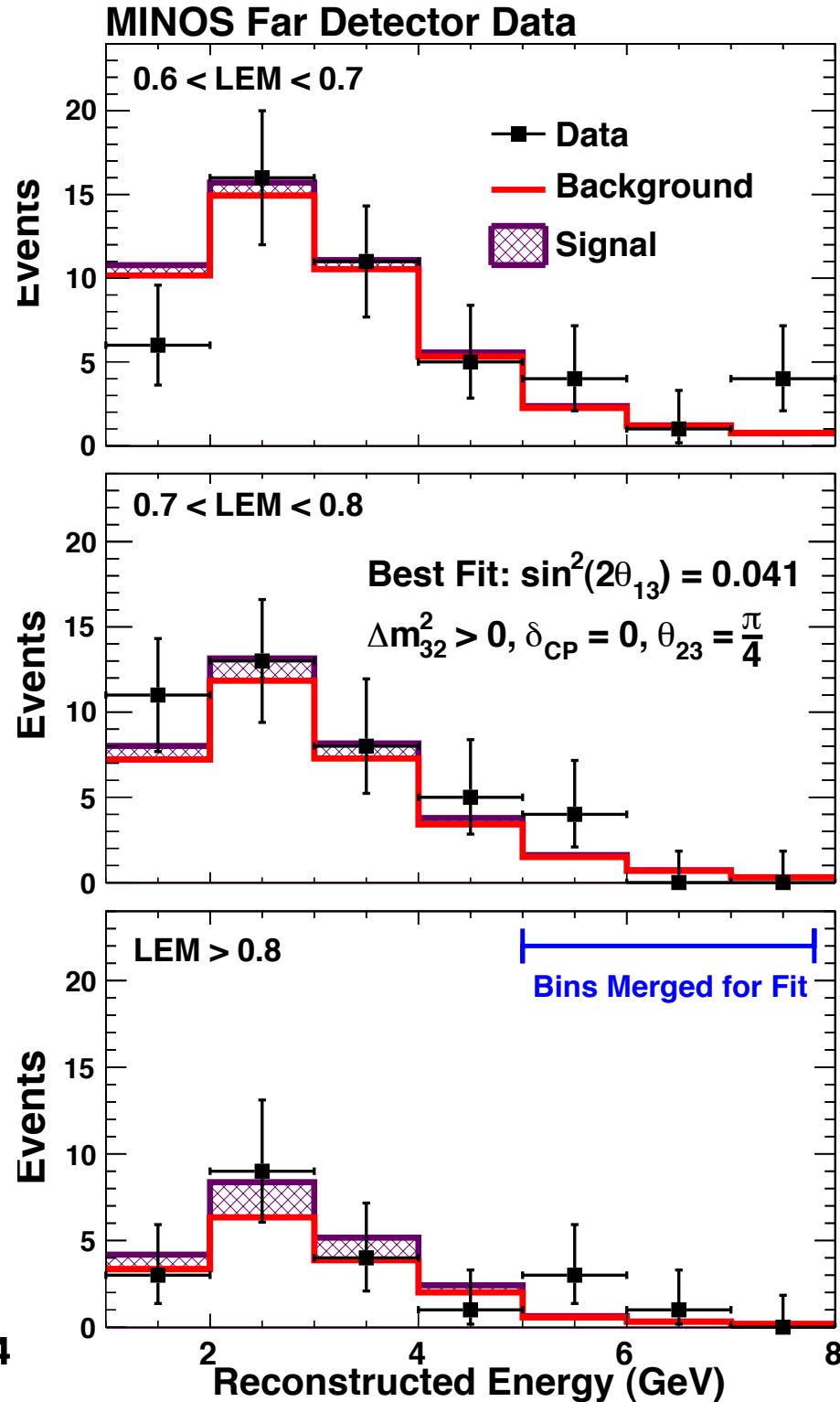
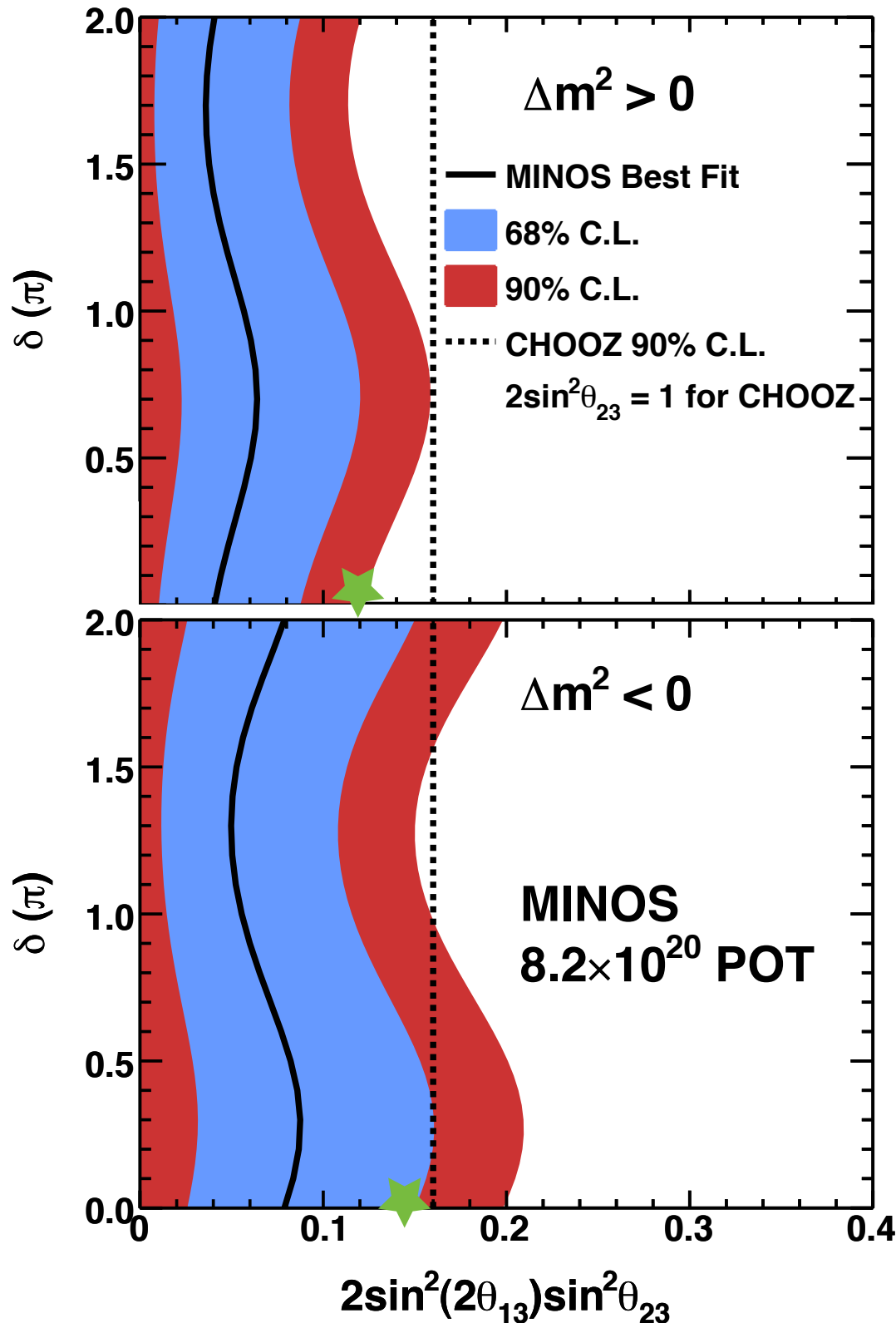
MINOS - Overview

- * FNAL 120GeV Main Injector Soudan mine (735km)
- * Horn-focused wide band ν_μ beam
- * (magnetized) Iron-scintillator sampling calorimeter
5,400tons @ far, 980tons @ near
- * Taking data > 6yrs
- * $8.2e20$ pot data w/ neutrino run is used for $\bar{\nu}_e$ appearance search



MINOS - Results

★ T2K Central values



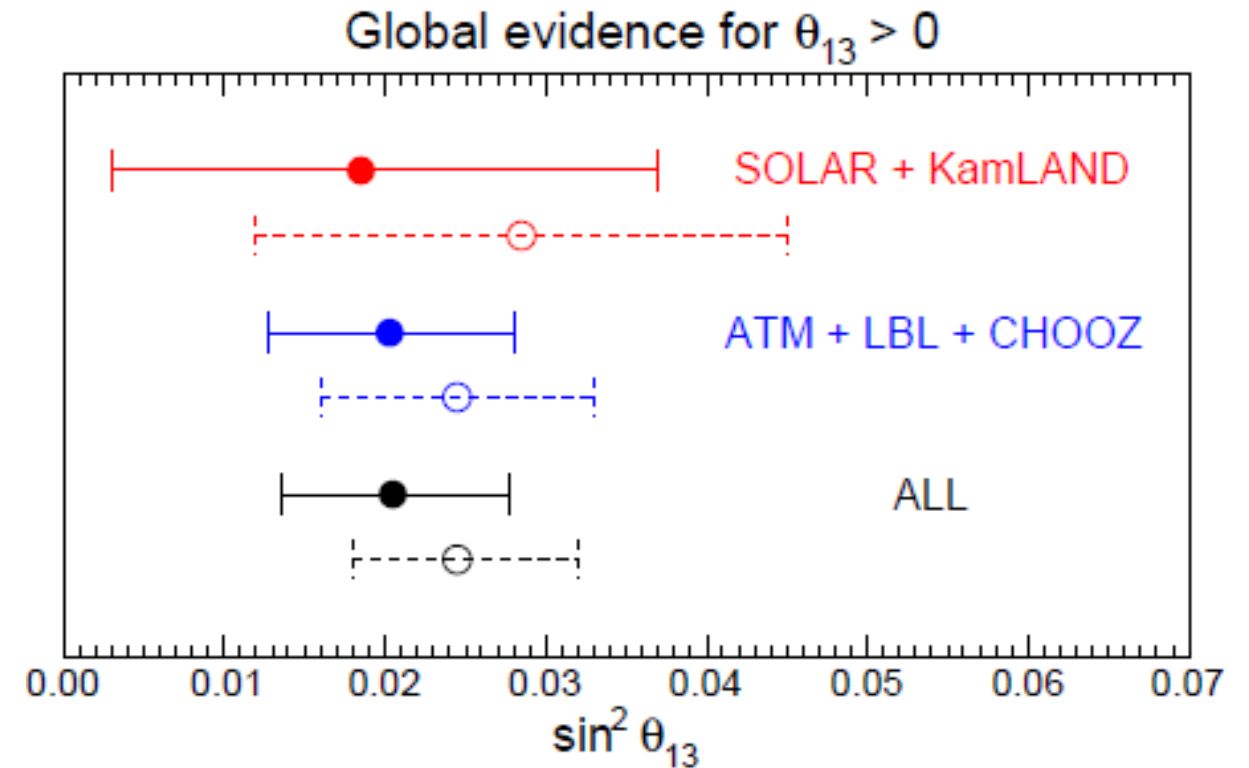
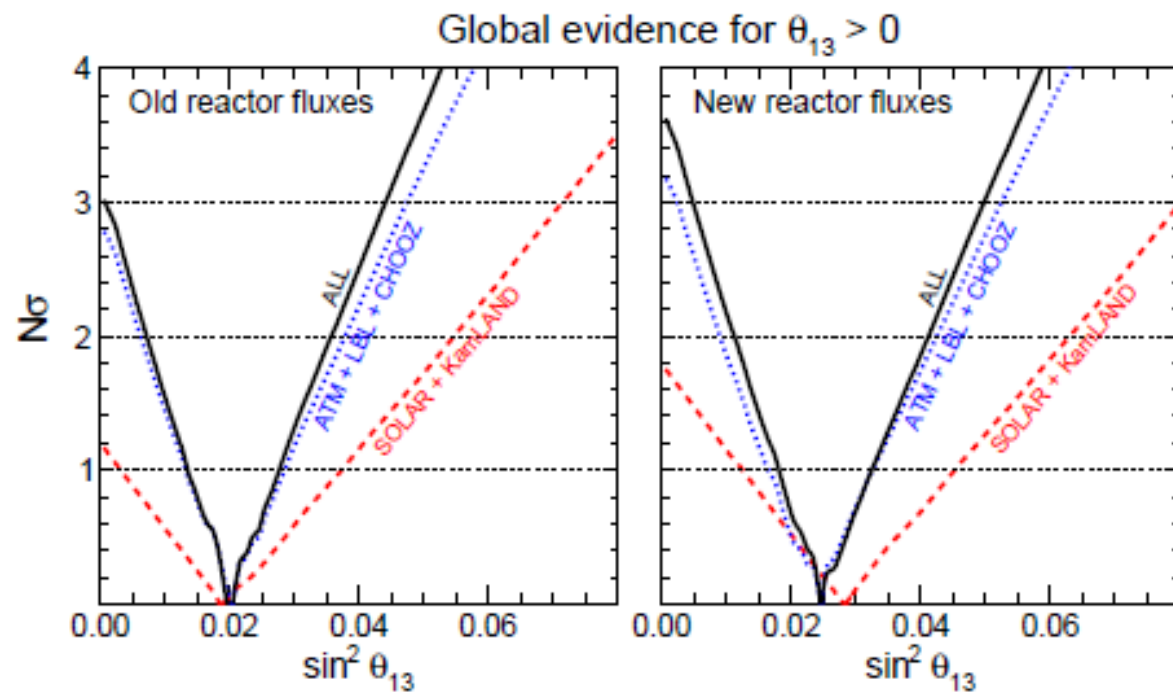
For $\text{LEM} > 0.7$

Exp BG events:
 49.5 ± 2.8 (sys) ± 7.0 (stat)

Observed events in FD data:
 62

This is a 1.7σ excess

Global fit



G.L.Fogli, et.al, arXiv:1106.6028v1 [hep-ph]

* Exclude $\theta_{13}=0$ at more than 3σ level

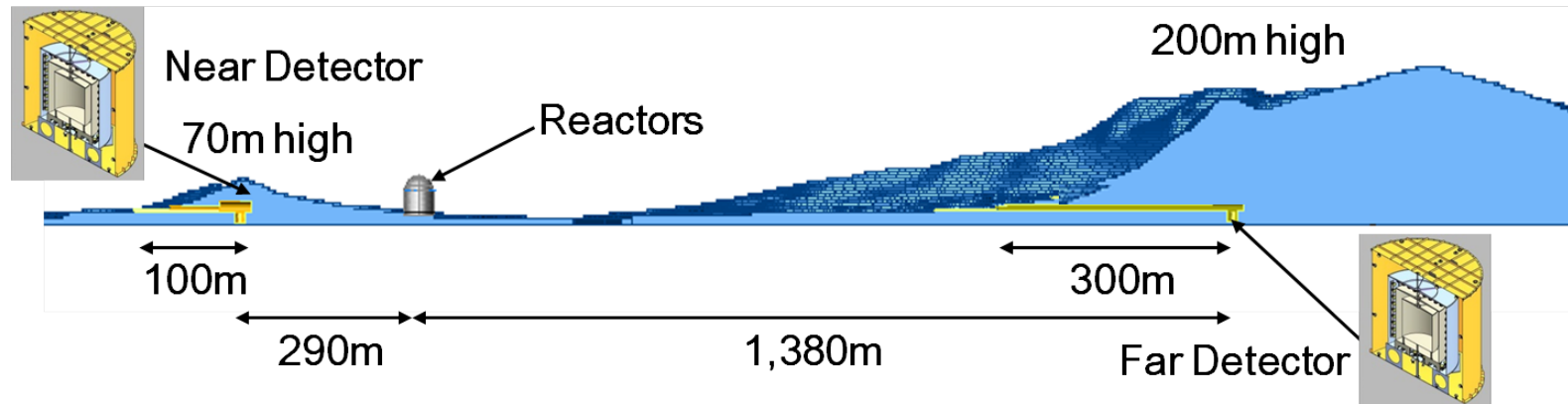
* Best fit : $\sin^2 \theta_{13}=0.021$

Overall: most urgent & important task: **EXPERIMENTALLY** DEFINITELY conclude

Future results

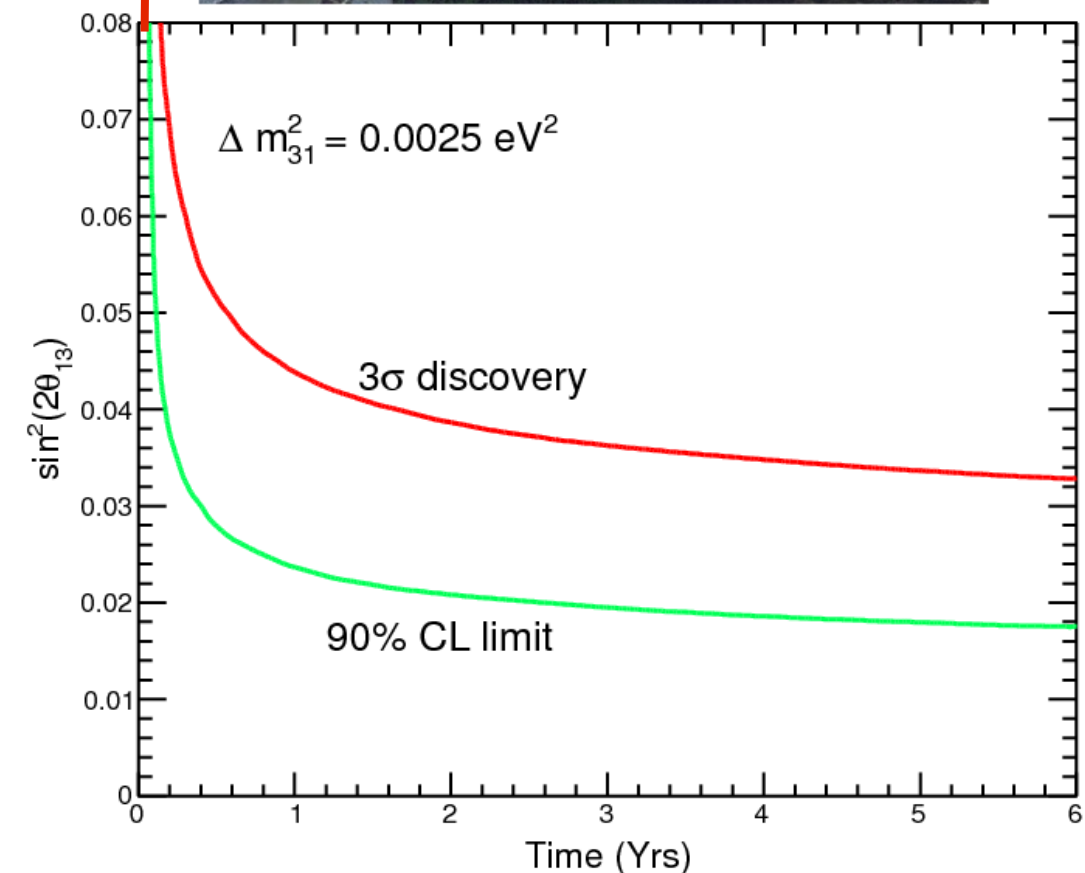


Reno



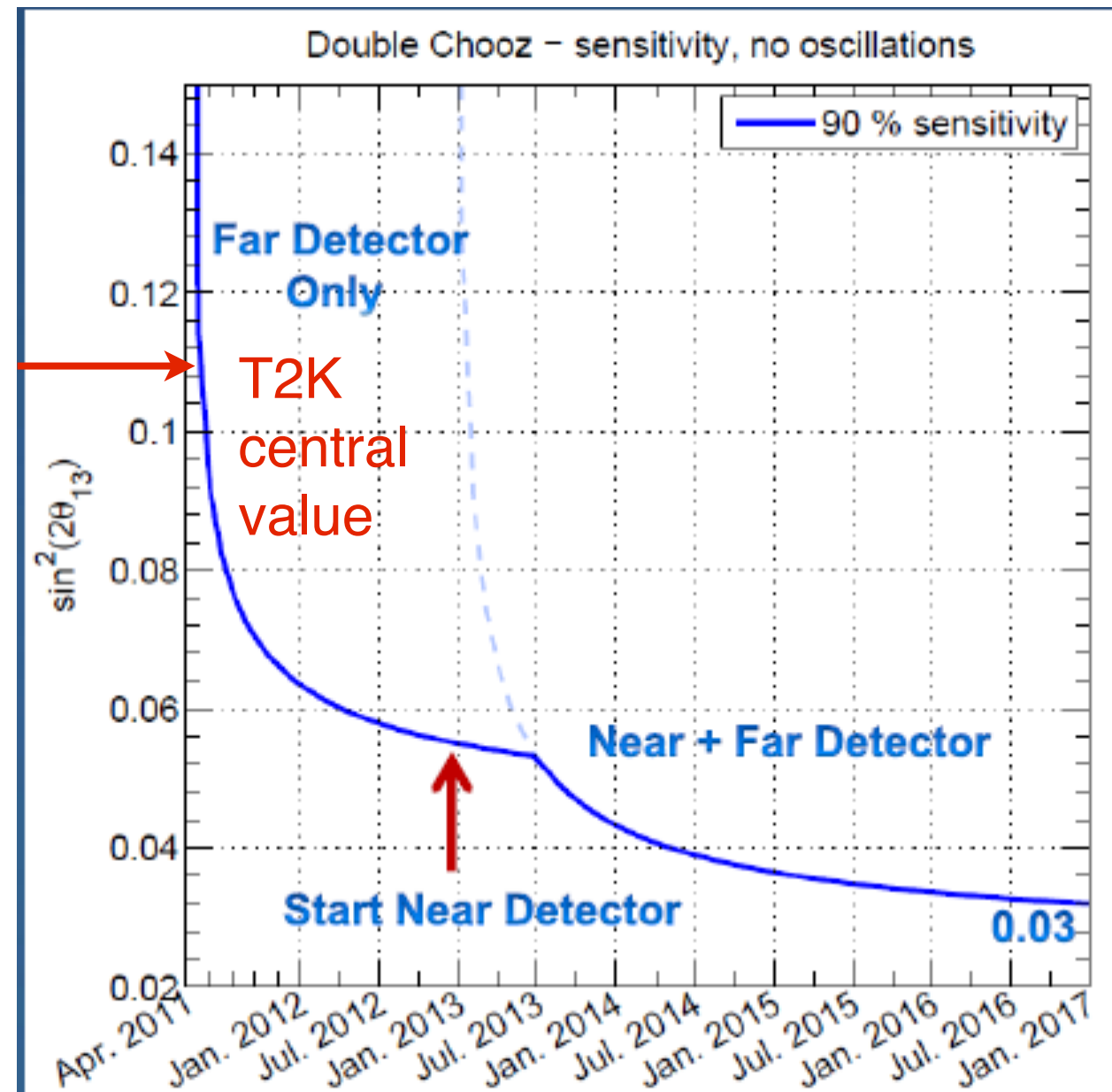
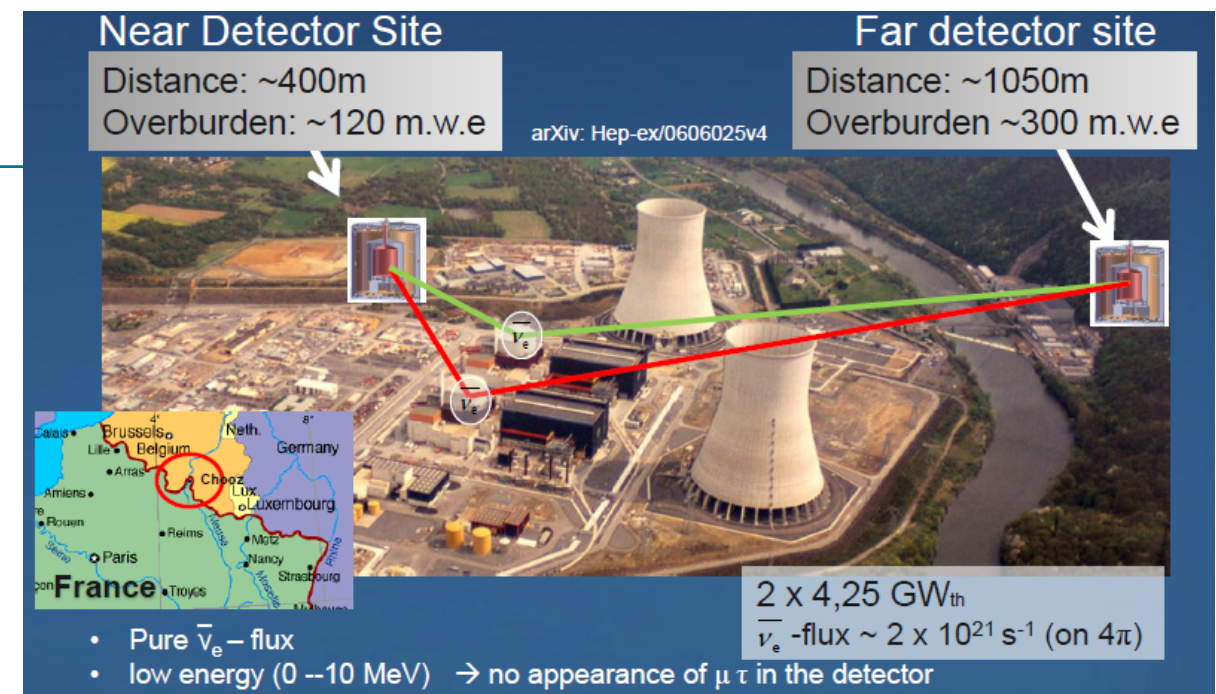
- * 16.1GW reactor & 2x16ton detectors (1.4km)
- * Started data taking with both near & far detectors from Aug. 1, 2011.
- * First results on $\sin^2(2\theta_{13}) \sim 0.5$ are expected to be available within a half year.
- * $\sin^2(2\theta_{13}) > 0.02$ at 90% within ~ 3 yrs

T2K
central
value



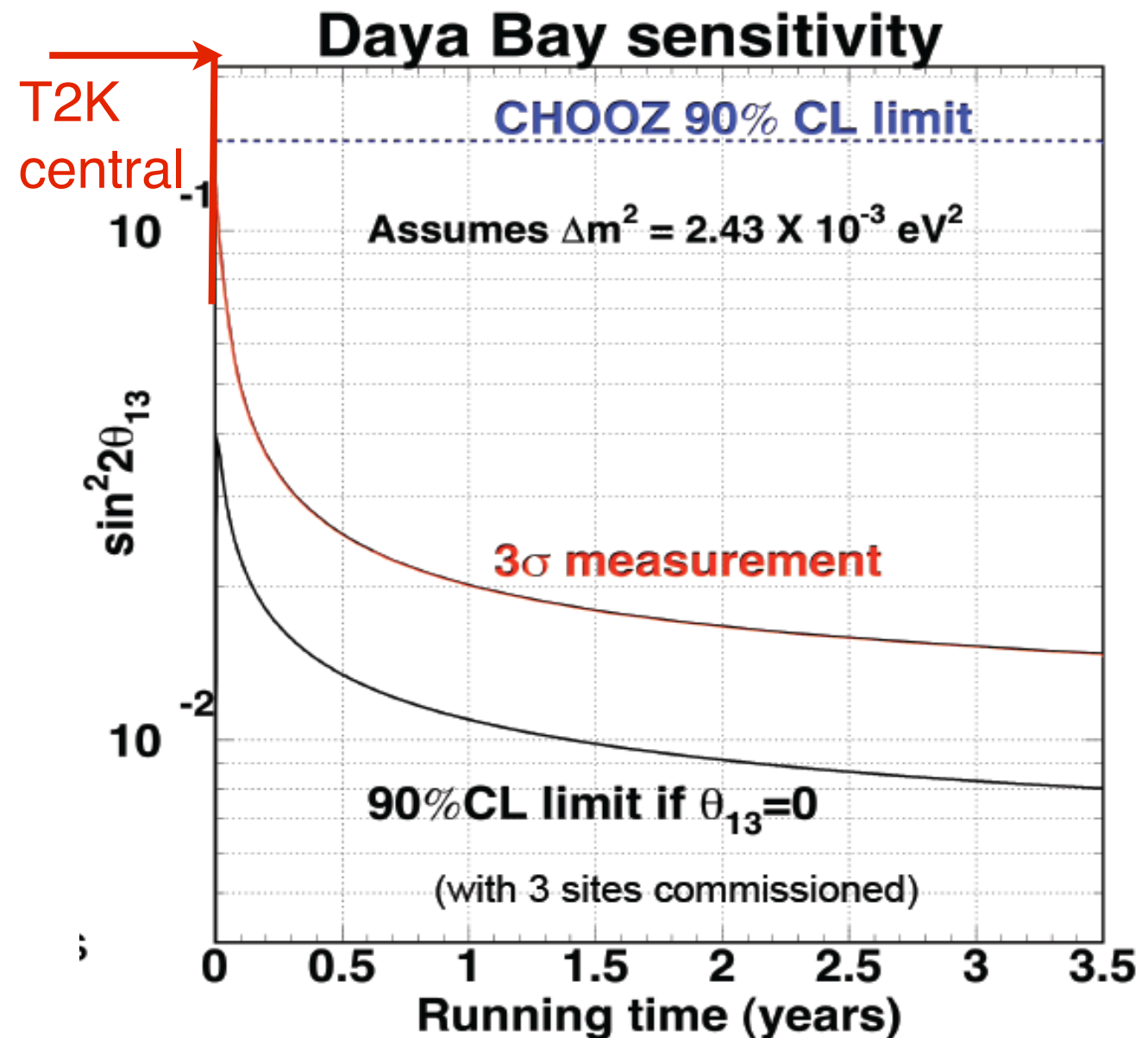
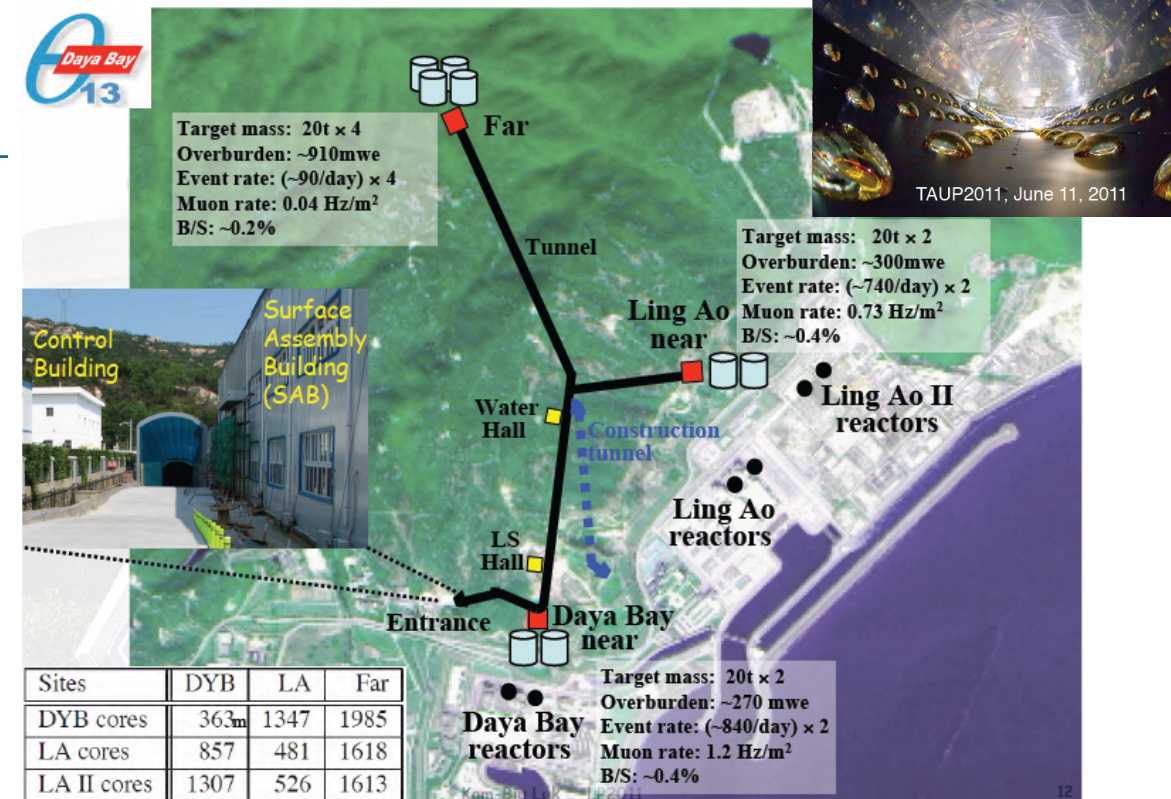
Double Chooz

- * 8.2GW reactor & 2x8ton detector (1.05km)
- * **Far detector completed, started data taking since Apr. 13, 2011, >120 days w/ 75% physics data live**
- * Data taking w/ near det expected from early 201
- * $\sin^2 2\theta_{13}$ sensitivity (90%CL) ~0.08 in half year, 0.03 ultimately

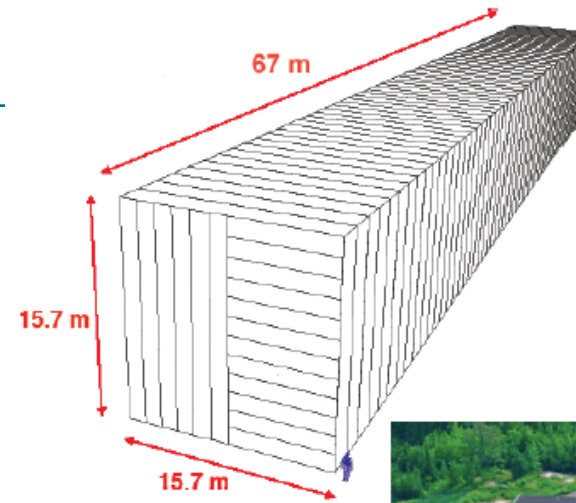
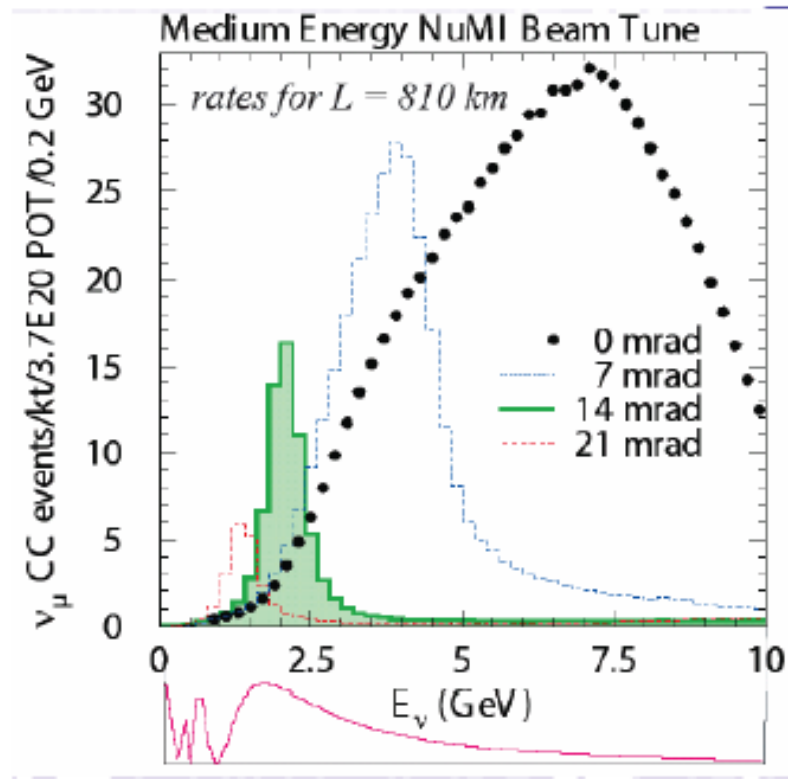


Daya Bay

- * $6 \times 2.95 = 17.4 \text{ GW}$ & $4 \times 20 \text{ t}$ far/ $4 \times 20 \text{ t}$ near detectors's (1.6~2km)
- * **4/8 detectors filled, 2 detector taking data**
- * Data taking with all detectors from Summer 2012
- * $\sin^2 2\theta_{13} < 0.03 (0.02)$ at 3σ in 1(3) years



NOvA



- 14 kt total mass, 70% scintillator
- 930 planes
- ~3 m water equivalent earth overburden of barite and concrete



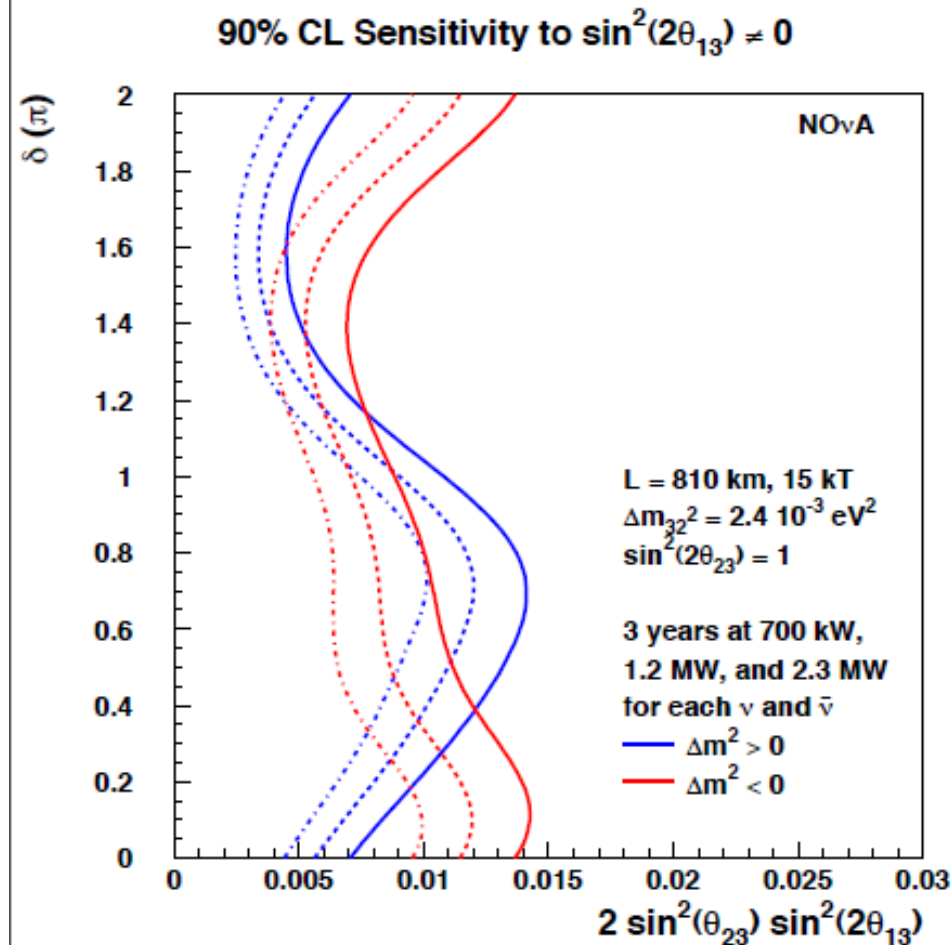
- * FNAL NuMI off-axis beam
- * Power upgrade 320 kW $\rightarrow$ 700 kW
 - * Recycler: anti-proton $\rightarrow$ proton
 - * Rep cycle 2.2s $\rightarrow$ 1.33s
- * New 14 kton liquid scintillator fine grained detector @810km
- * Far detector will complete and start full operation in 2014



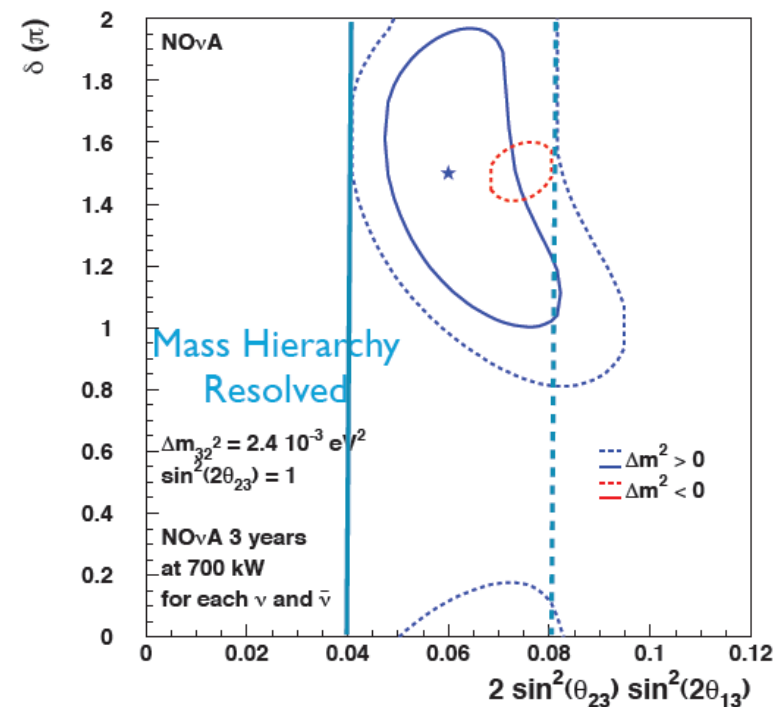
NOvA Sensitivity

- * Can measure large θ_{13} (~T2K center) very soon
- * For smaller θ_{13} good competition
- * Have some sensitivity on mass hierarchy

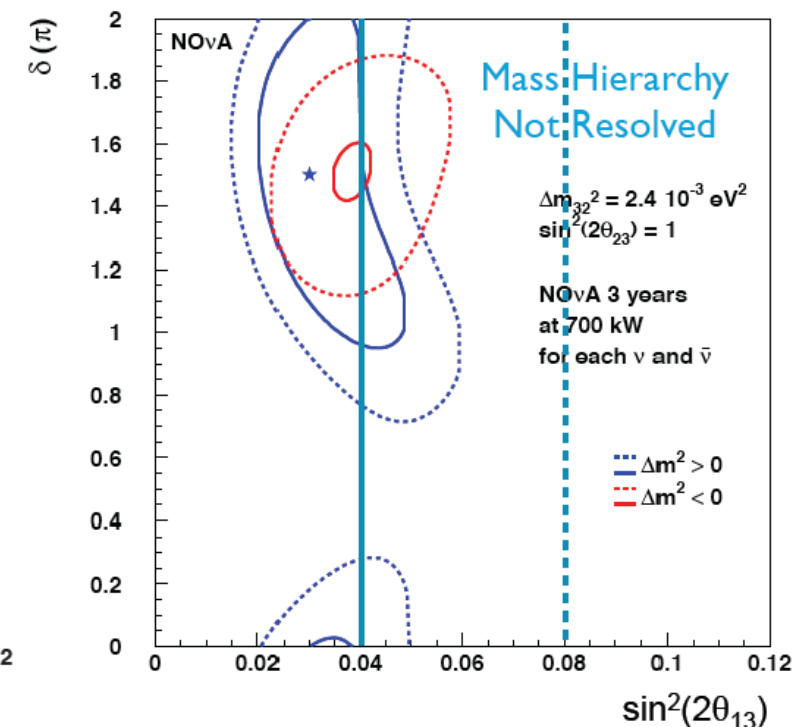
→
T2K
central
value = 0.11



Contours for Starred Point for NOvA



1 and 2 σ Contours for Starred Point for NOvA



What if θ_{13} is big?

If $\sin^2 2\theta_{13} > \sim 0.01$

Make conventional Multi-MW
super beam long baseline
experiments possible to
explore CPV in lepton sector
Although big step needed

IF not

Need “ideal” beam such as
Neutrino Factory or beta beam
to probe CPV

Personal opinion:

It seems until now everyone
was very focus in getting down
to the smallest θ_{13} possible...

Very careful study of
systematics need to be
performed if θ_{13} is as large as
T2K leads to believe.

Alain Blondel: PoS EPS-HEP2009:282,2009.

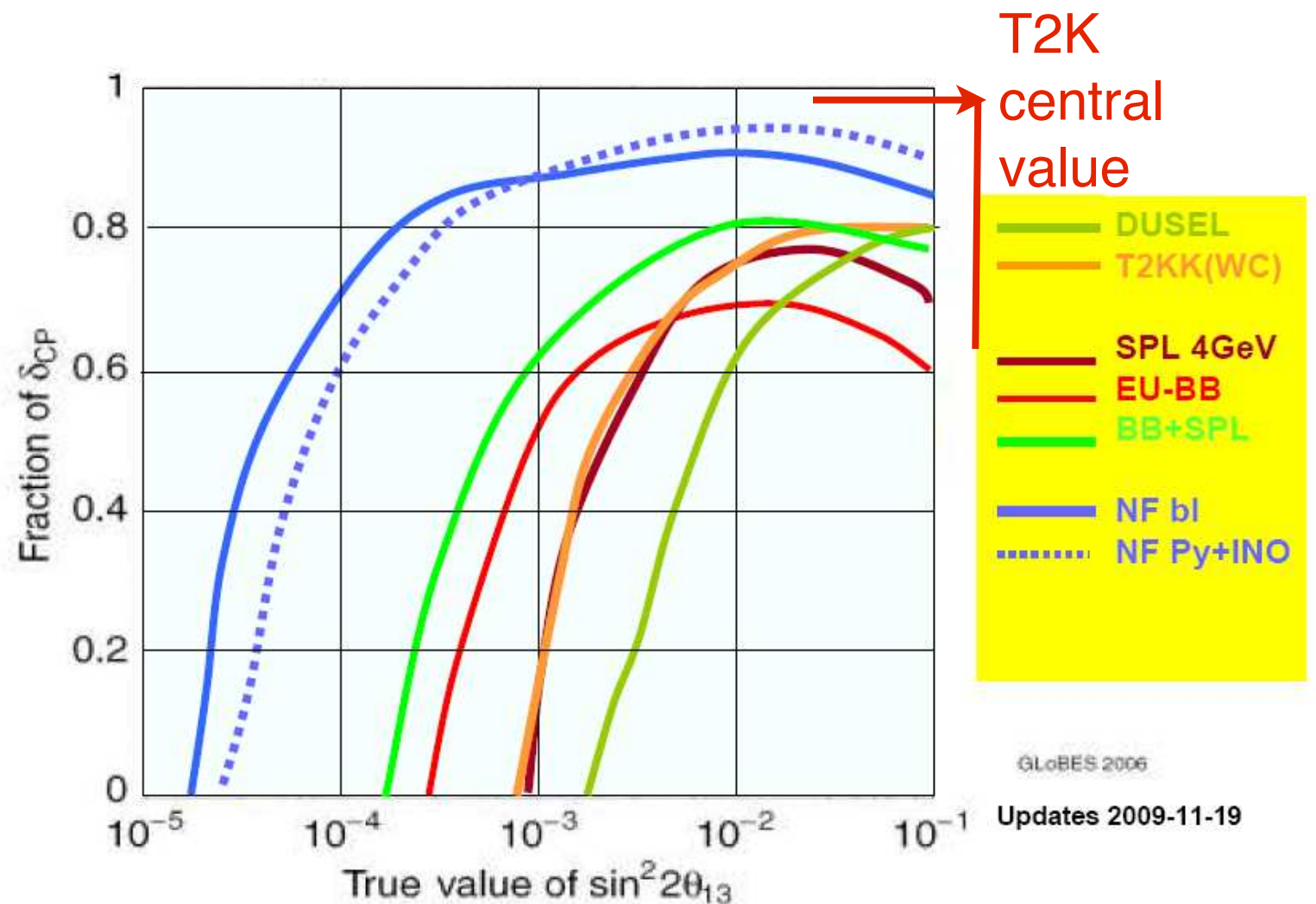


Figure 2 Compilation of 3σ CP sensitivities of future long baseline projects. Here the fraction of δ_{CP} where CP violation can be observed at 3 standard deviations is plotted as a function of θ_{13} . T2KK: T2K 1.66 MW beam to 270 kton fid volume Water Cherenkovs detectors in Japan (295km) and in Korea (1050 km)[10] ; DUSEL: a WBB from Fermilab to a 300 kton WC in DuseL (1300km)[11]; SPL 4 GeV, EU-BB and BB+SPL curves stand for the CERN to Fréjus (130km) project [12]; NF baseline is the Neutrino Factory baseline (4000km and 7000km baselines) and NF Py+INO represents the concrete baseline from CERN to Pyhaslammi mine in Finland (2285 km) and to INO in India (7152 km)[13].

Summary

- * Quest for non-zero θ_{13} is turning around final corner
- * T2K detected first indication of ν_e appearance at 2.5σ significance
 - * $0.03(0.04) < \sin^2 2\theta_{13} < 0.28(0.34)$ (inverted hierarchy)
- * MINOS presented consistent results
- * New reactor experiments are getting online
- * NOvA will come in 2014
- * Discovery of finite θ_{13} will come very soon (hopefully)!
- * Large θ_{13} makes possible to explore CPV with upgraded $>MW$ beam and huge high sensitivity detector BUT precise systematics studies need to be performed