Recent results from neutrino oscillation experiments

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Invisibles Workshop 14
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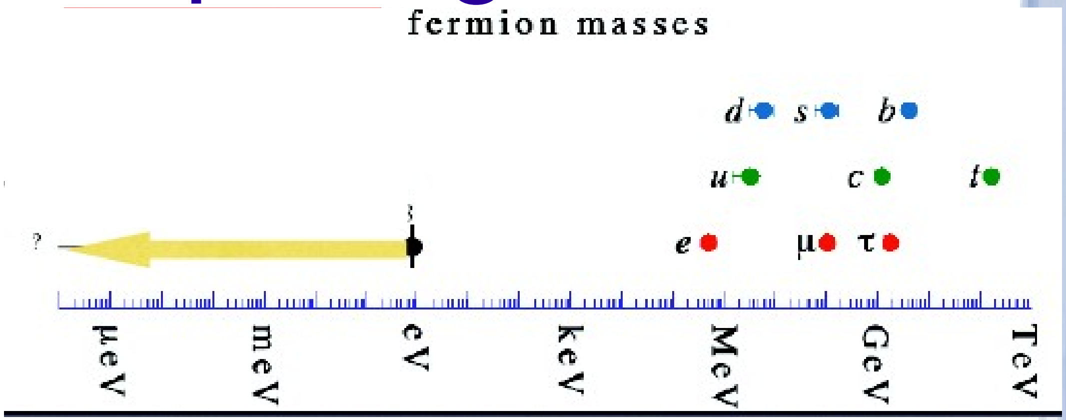
Outline

- Introduction
- New oscillation results (tau nu appearance, day-night effect)
- Results from reactor experiments
- Results from accelerator experiments

- Unless explicitly noted, all talks are from the ICHEP parallel sessions

Neutrino physics: surprising results

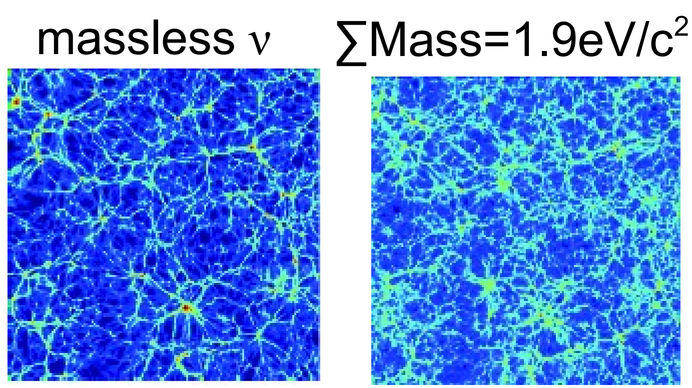
- The unbearable lightness of neutrino masses begs a compelling explanation



- The neutrino mixing angles are large, at variance with the quark mixing angles: large CP violation effects are allowed

$$V_{PMNS} = \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \quad V_{CKM} = \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$

- Neutrinos play a fundamental role in the evolution of the Universe. Can they explain matter-antimatter asymmetry ?



Baryon density

Agarwal, Feldman 2010

The Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix

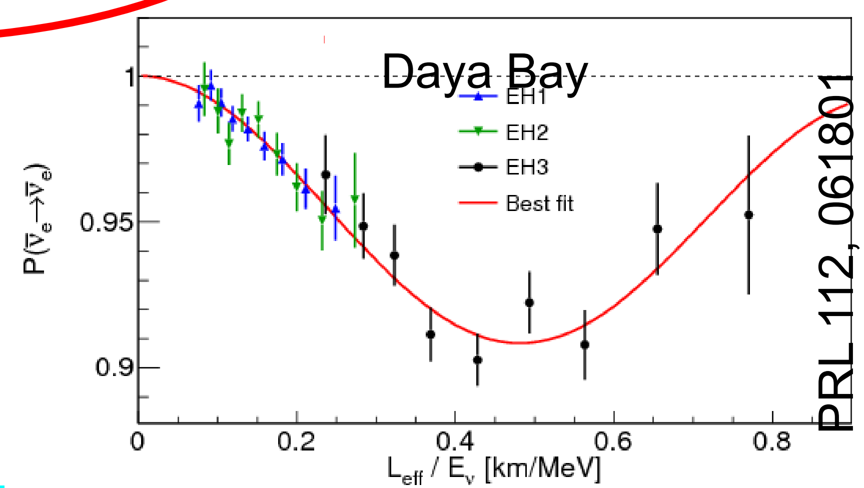
$s_{ij}=\sin\theta_{ij}$

This talk

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3}\\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3}\end{pmatrix}=\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 0\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

- The oscillation phenomena have been convincingly observed using solar, atmospheric, reactor and accelerator neutrinos, establishing the three neutrino SM paradigm
- Currently unveiling three-neutrino subleading effects

$\nu_\mu \rightarrow \nu_\tau,\ \nu_\mu,\ \nu_e$ +CP conj. $\quad \bar{\nu}_e \rightarrow \bar{\nu}_e$



Parameter	Value	Precision (%)
Δm^2_{21}	$7.5\ 10^{-5}\ eV^2$	2.6
θ_{12}	34°	5.4
Δm^2_{32}	$2.4\ 10^{-3}\ eV^2$	2.6
θ_{23}	42°	~10
θ_{13}	9°	8.5

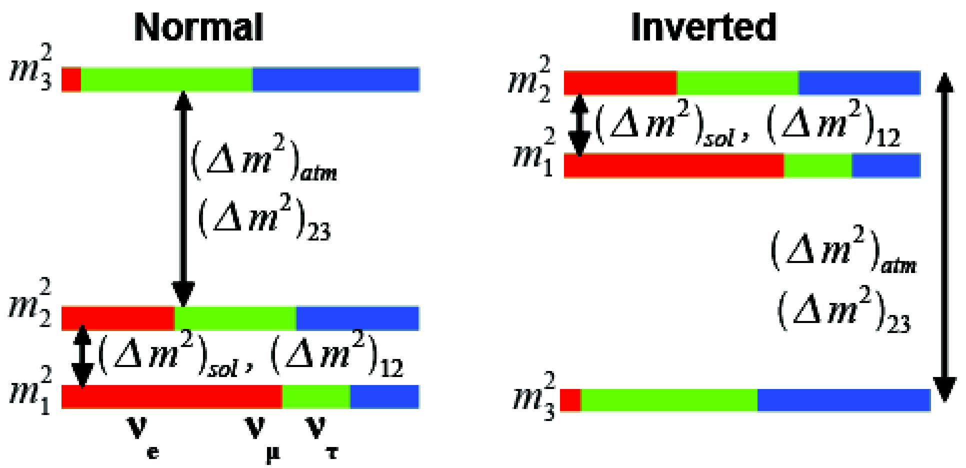
Capozzi et al.
ArXiv:1312.2878

Next steps in neutrino oscillation studies

1) Is θ_{23} =45°? which octant ?
2) Determine the mass hierarchy
3) Measure the CP violation parameter δ
4) Precision tests of the PMNS paradigm (ideally at the % level, as for the CKM matrix)
5) Are there any new neutrino states ?

→

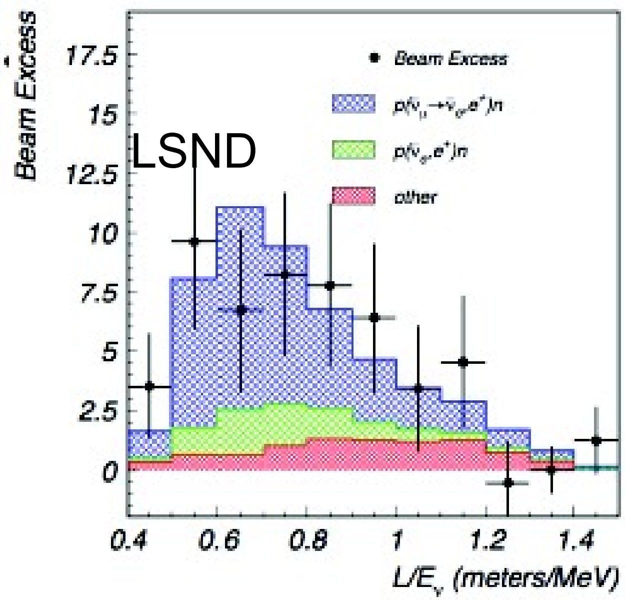
1) Is there a symmetry between ν_μ and ν_τ ?
2) Help model builders. Impact on cosmology.
3) Link with leptogenesis. Are we born out of (heavy) neutrinos ?
4) How different are neutrinos ?
5) Potential to alter the whole picture



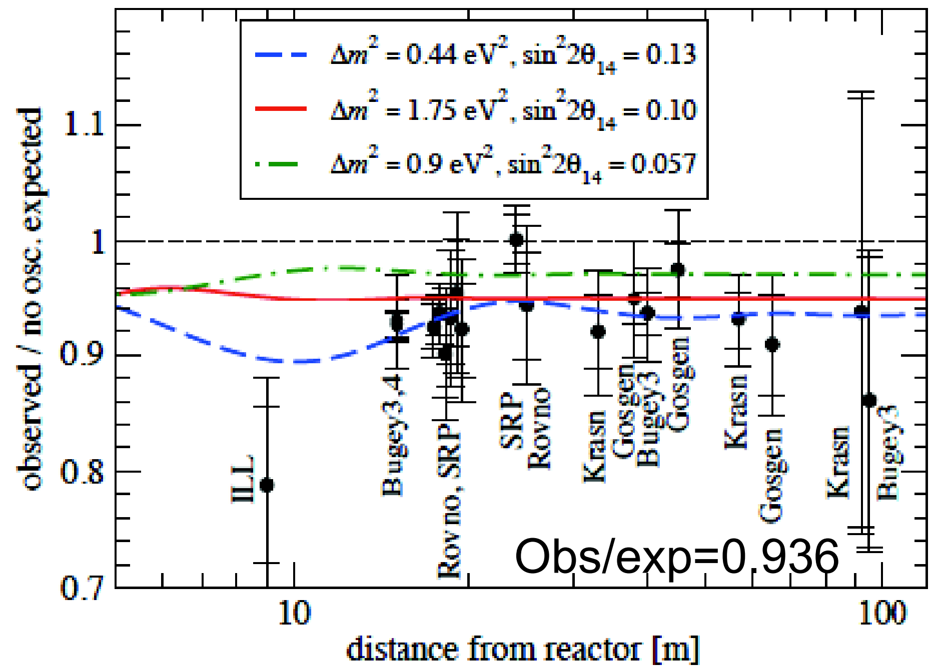
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ $\bar{\nu}_e \rightarrow \bar{\nu}_?$

Short baseline neutrino anomalies

PRD64 (2001) 112007

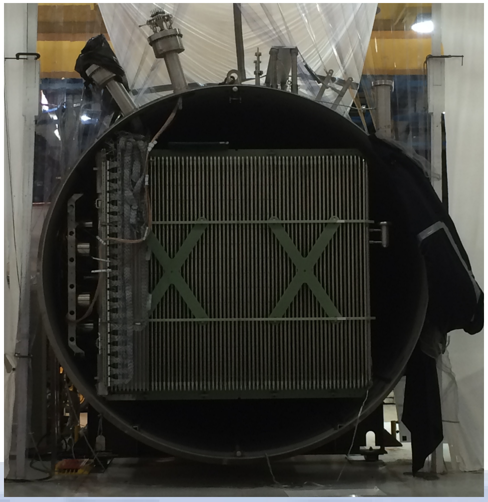


J. Kopp et al, arXiv:1303.3011v3



Original ref:G. Mention et al. PRD83:073006 (2011)

MicroBooNE



Talk by W. Ketchum

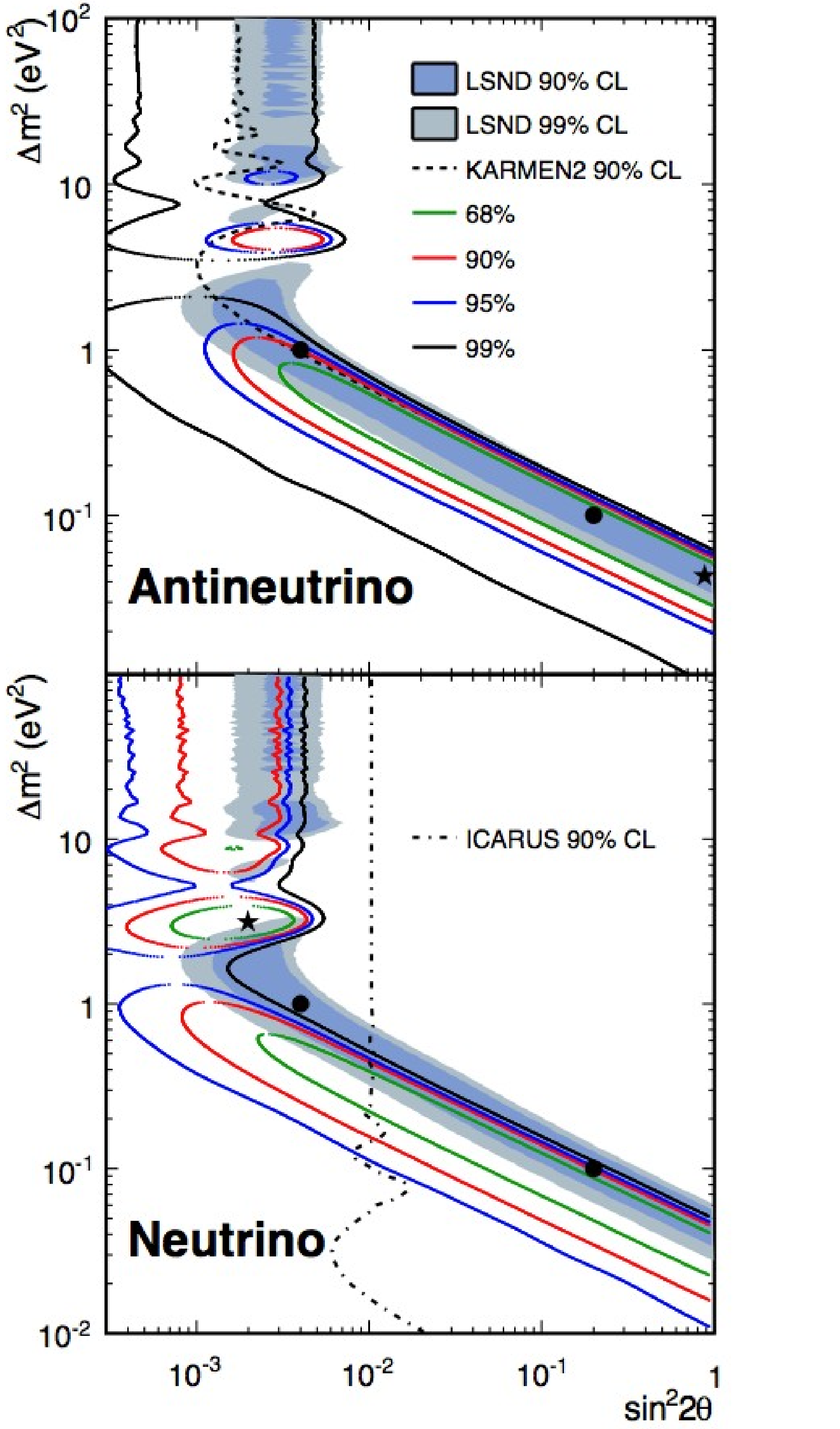
- Short baseline experiments (LSND, MiniBooNE, reactors, Ga source) have revealed anomalies that could be interpreted as oscillations with Δm~eV
- No global satisfactory interpretation due to tensions within the data
- A full parallel session was dedicated to the new experimental effort, at accelerators (MicroBooNE), reactors and using intense sources (SOX)

Notice also the SHIP proposal at CERN: search for heavier sterile neutrinos in a beam dump

MiniBooNE Plots from arXiv:1303.2588
Phys.Rev.Lett. 110 (2013) 161801

MiniBooNE allowed regions in antineutrino mode (top) and neutrino mode (bottom) for events with EQE > 200 MeV within a two-neutrino oscillation model. Also shown are the ICARUS (before update shown at ICHEP14) and KARMEN appearance limits for neutrinos and antineutrinos, respectively. The shaded areas show the 90% and 99% C.L. LSND $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ allowed regions. The black stars show the MiniBooNE best fit points, while the circles show the example values for several oscillation parameter sets

Notice severe tensions with short baseline disappearance experiments (like CDHS)

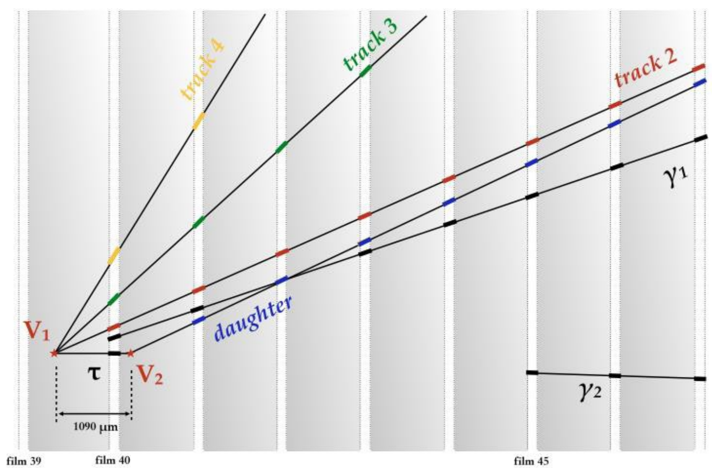


$\nu_\mu \rightarrow \nu_\tau$

Tau neutrino appearance

OPERA performed a search for ν_μ to ν_τ appearance with a baseline of 732 km (CERN to Gran Sasso) using the Emulsion Cloud Chamber technique. It has recently observed a fourth ν_τ candidate (tot bkg = 0.23). The null hypothesis is excluded at the 4.2 σ CL.

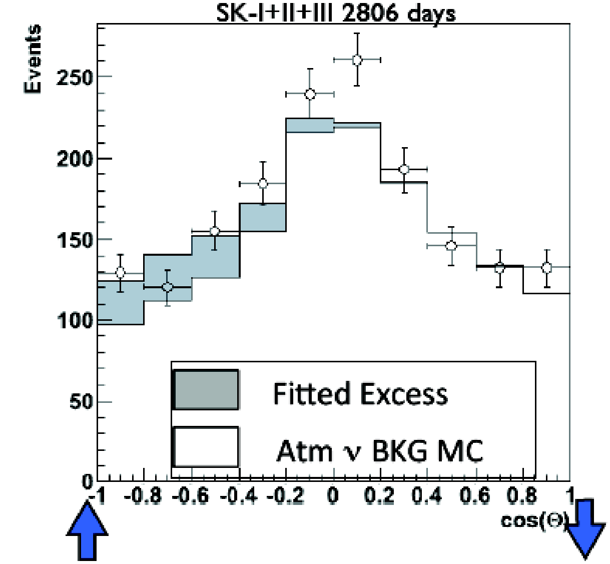
Talk by M. Komatsu



Decay channel	Expected signal $\Delta m^2_{23} = 2.32$ meV²	Total background	Observed
$\tau \rightarrow h$	0.41 ± 0.08	0.033 ± 0.006	2
$\tau \rightarrow 3h$	0.57 ± 0.11	0.155 ± 0.030	1
$\tau \rightarrow \mu$	0.52 ± 0.10	0.018 ± 0.007	1
$\tau \rightarrow e$	0.62 ± 0.12	0.027 ± 0.005	0
Total	2.11 ± 0.42	0.233 ± 0.041	4

Super-Kamiokande has searched for ν_τ-like events in atmospheric neutrinos and found an excess with 3.8 σ significance.

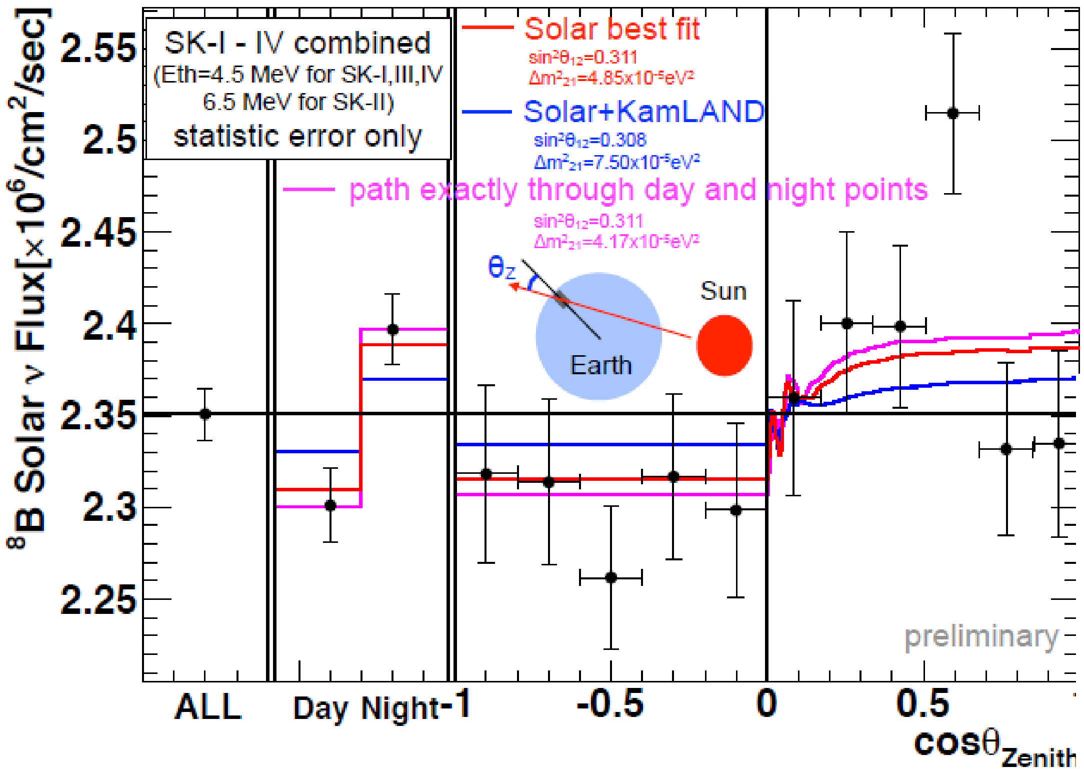
PRL, 2013 vol. 110 (18) p. 181802



Talk by M. Shiozawa

PRL 112, 091805 (2014) Y. Koshio at NEUTRINO 2014

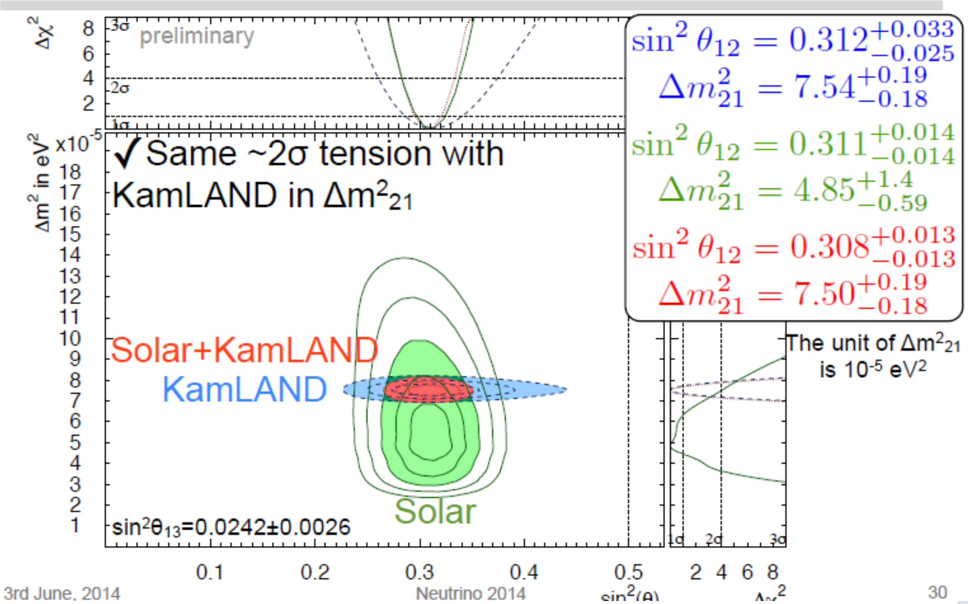
Solar neutrino: day-night effect



(For Solar neutrino analysis)

Phase	Period	Livetime (days)	Fiducial vol. (kton)	# of PMTs	Energy thr.(MeV)
SK-I	1996.4 ~ 2001.7	1496	22.5	11146 (40%)	4.5
SK-II	2002.10 ~ 2005.10	791		5182 (20%)	6.5
SK-III	2006.7 ~ 2008.8	548	22.5 (>5.5MeV) 13.3 (<5.5MeV)	11129 (40%)	4.5
SK-IV	2008.9 ~	1669	22.5 (>5.5MeV) 13.3 (4.5<E<5.5) 8.8 (<4.5MeV)		3.5

total 4504 days (coverage) (Kinetic energy)



SK has lowered the threshold on the electron recoil energy to 3.5 MeV

^{8}B day-night effect observed at 2.8-3 sigmas

Neutrino oscillations : observables

Reactor experiments

$\bar{\nu}_e \longrightarrow \bar{\nu}_e$

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \underbrace{\left(\cos^2\theta_{12} \sin^2 \frac{\Delta m^2_{31} L}{4E} + \sin^2\theta_{12} \sin^2 \frac{\Delta m^2_{32} L}{4E}\right)}_{\sin^2 \frac{\Delta m^2_{ee} L}{4E}} - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2 \frac{\Delta m^2_{21} L}{4E}$$

$\nu_\mu \longrightarrow \nu_\mu$

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - (\cos^4\theta_{13} \sin^2 2\theta_{23} - \sin^2 2\theta_{13} \sin^2\theta_{23}) \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$

Accelerator experiments

$\nu_\mu \longrightarrow \nu_e$

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) - \frac{\sin 2\theta_{12} \sin 2\theta_{23}}{2 \sin\theta_{13}} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right) \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) \sin\delta_{CP}$$

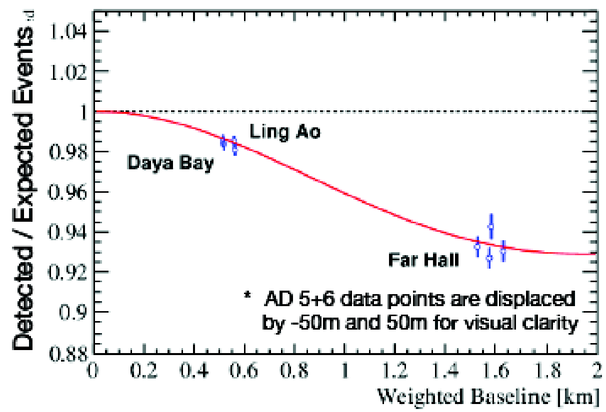
Disappearance channel : sensitivity to θ_{23} and (subleading) to the octant

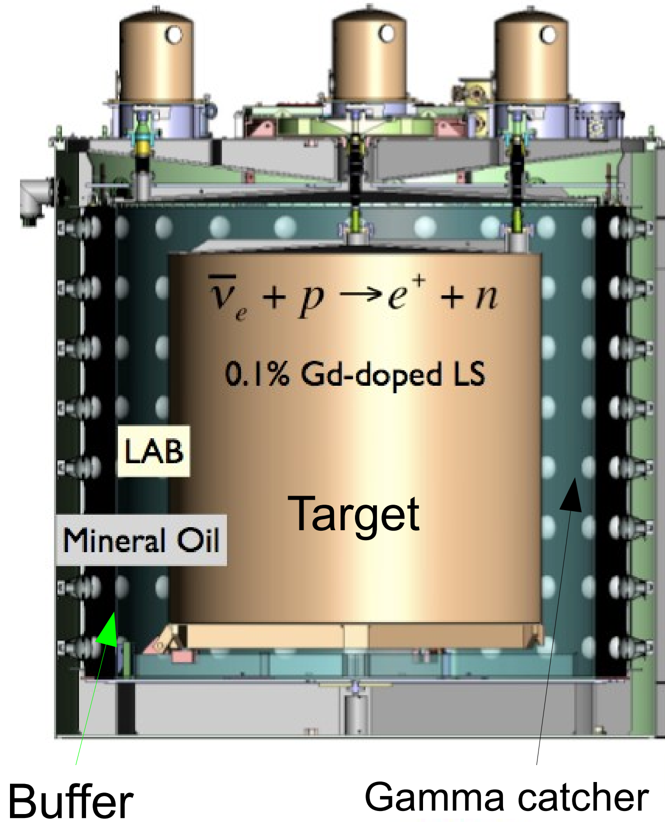
Appearance channel : sensitivity to θ_{13} and (subleading) to the CP phase

Reactor neutrino experiment: schematic

Nuclear reactor: $>10^{20}$ ν/s

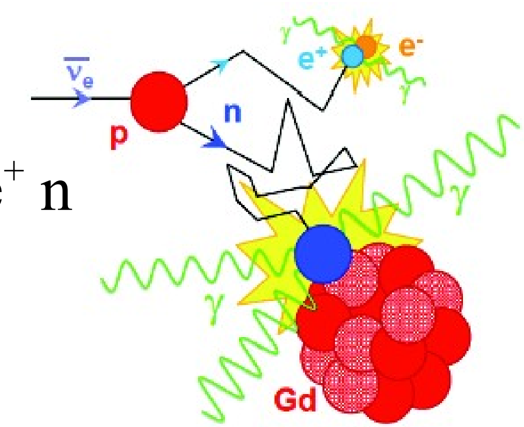
$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{31} L}{4E}$$





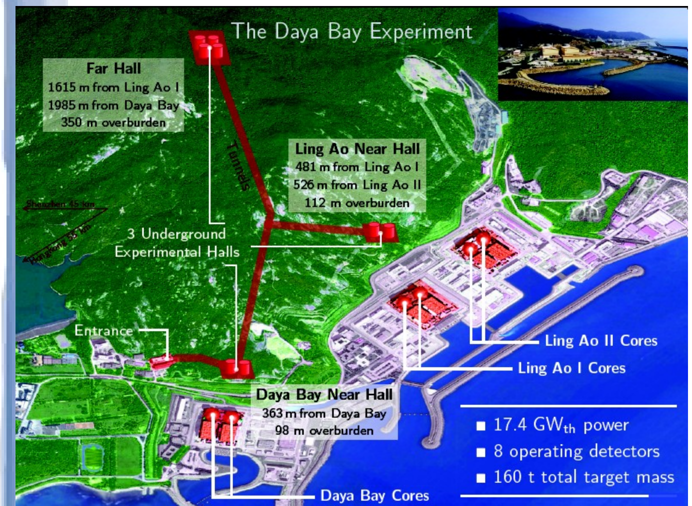
- The detection technique is based on the Inverse Beta Decay reaction followed by a neutron capture on Gadolinium (delayed coincidence).
- The reactor flux is measured by near detector(s).
- Control of the backgrounds and of the systematic uncertainties is crucial.

$$\nu_e\, p \rightarrow e^+\, n$$



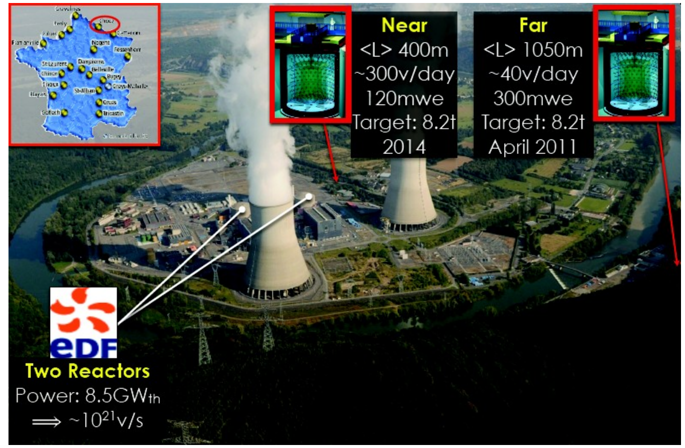
Reactor neutrino experiments

Daya Bay



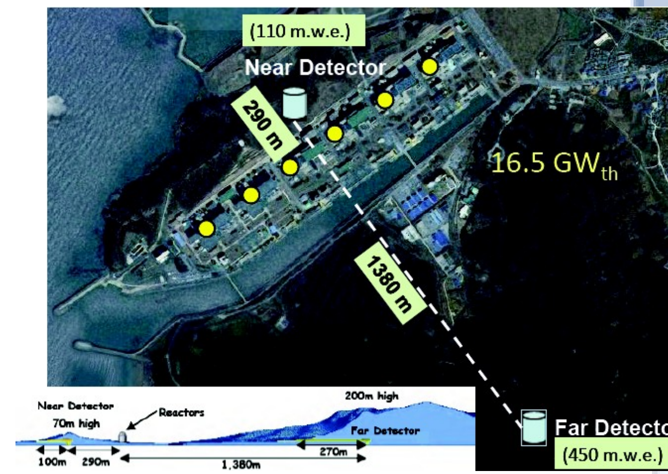
China
6 reactors, 17 GWth
8 detectors,
363-1985m baselines
621 live days
1M neutrino detected

Double Chooz



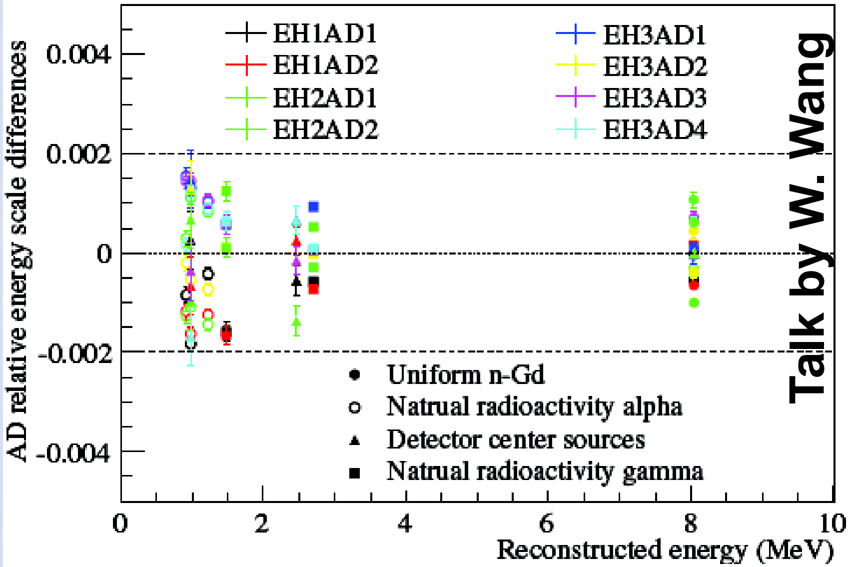
France
2 reactors, 8.5 GWth
2 detectors,
400-1050m baselines
460 live days
17351 neutrinos detected
<u>Near detector ready in the autumn</u>

RENO



South Korea
6 reactors, 16.5 GWth
2 detectors,
290-1380m baselines
794 live days
1M neutrino detected

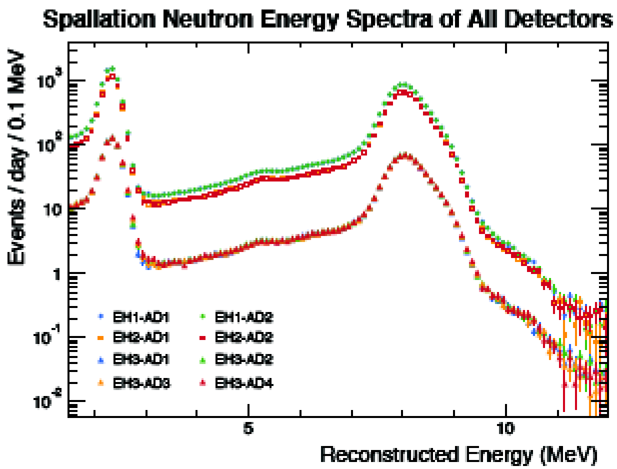
Reactor experiments: control of uncertainties

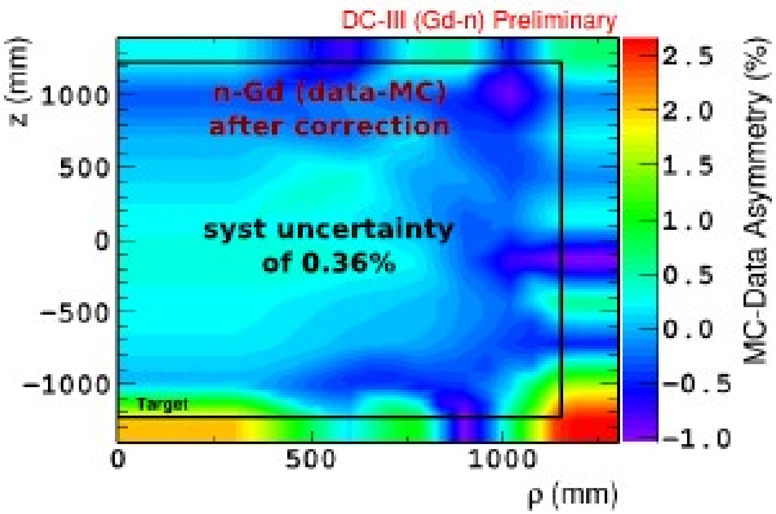


Talk by W. Wang

Daya Bay: relative energy scale uncertainty within 0.2% (was 0.35%) for the 8 detectors

Neutron energy spectra





Talk by J. Haser

Double Chooz: uniformity correction using muon-produced neutrons

$\bar{\nu}_e \rightarrow \bar{\nu}_e$

Daya Bay $\bar{\nu}_e$ disappearance

- Four times more statistics (621 days) than the previously published result
- Over 1 million antineutrinos detected (150k in the far detectors)
- Most precise measurement of $\sin^2(2\theta_{13})$ (6%)
- Shape distortion agrees with oscillation prediction

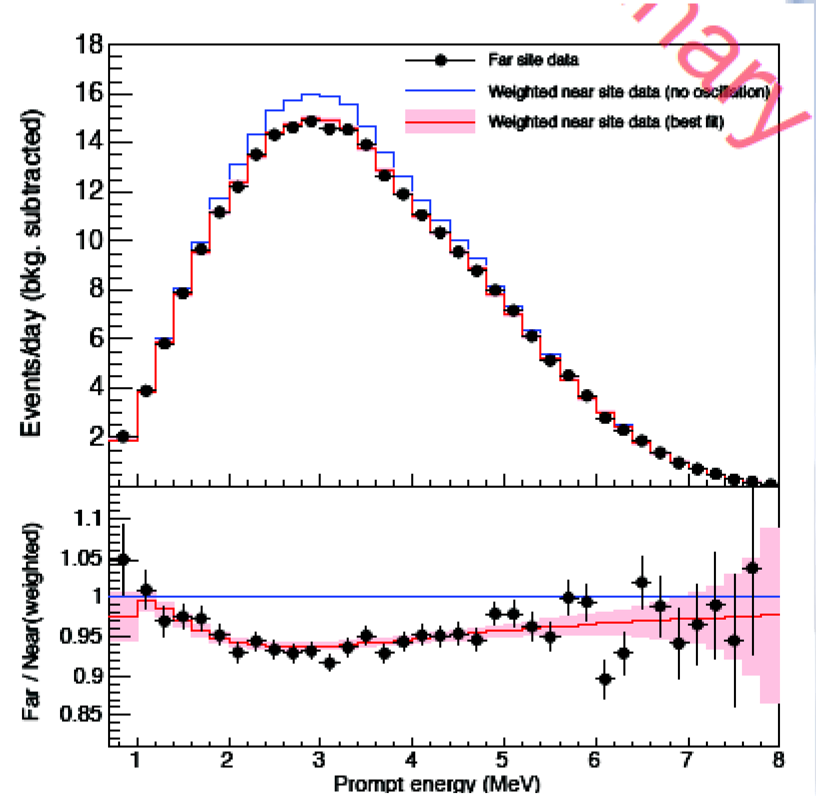
$$\sin^2 2\theta_{13} = 0.084^{+0.005}_{-0.005}$$

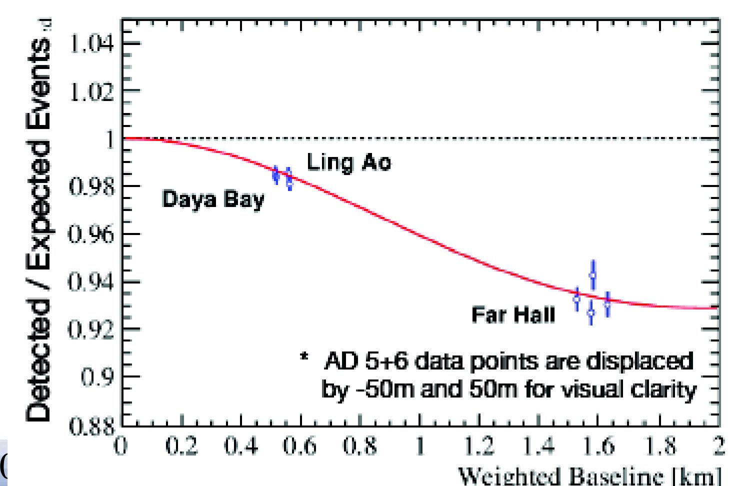
$$|\Delta m^2_{ee}| = 2.44^{+0.10}_{-0.11} \times 10^{-3}\mathrm{eV}^2$$

$$\chi^2/NDF = 134.7/146$$

RENO $\sin^2 2\theta_{13} = 0.101 \pm 0.013$

Double Chooz $\sin^2 2\theta_{13} = 0.090^{+0.032}_{-0.029}$

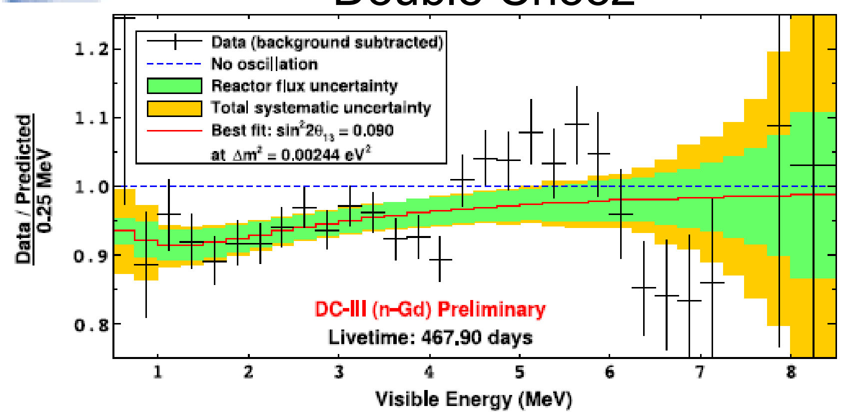




Understanding the reactor neutrino flux

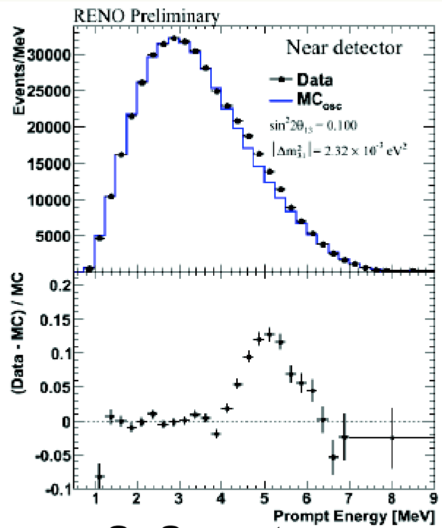
- A distortion in the spectrum was observed by Double Chooz, RENO and Daya Bay
- Preliminary studies disfavor background and energy-scale as an explanation
- According to preliminary studies the θ_{13} measurement is not affected thanks to the near detectors

Double Chooz



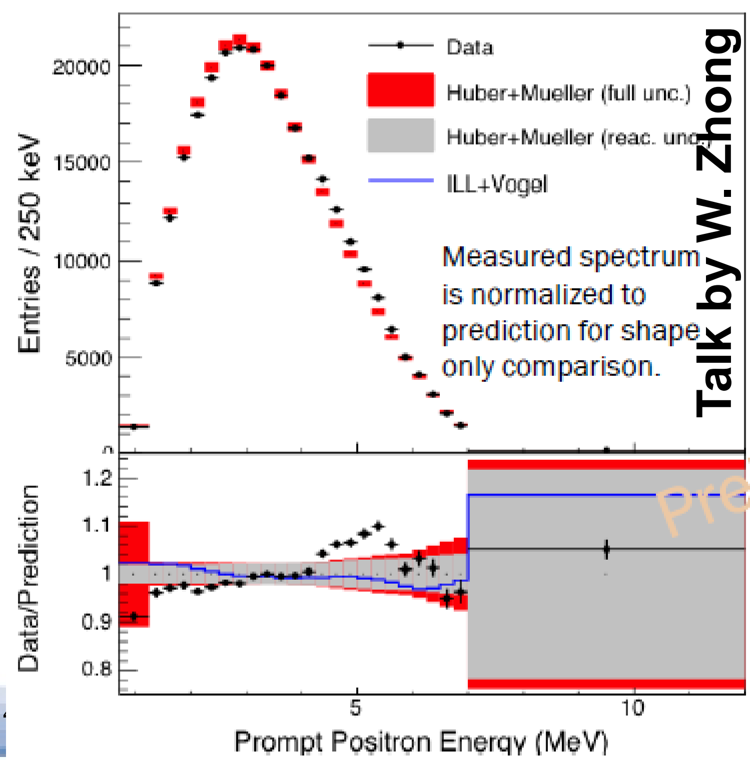
arXiv:1406.7763

RENO



S. Seo at NEUTRINO2014

Daya Bay

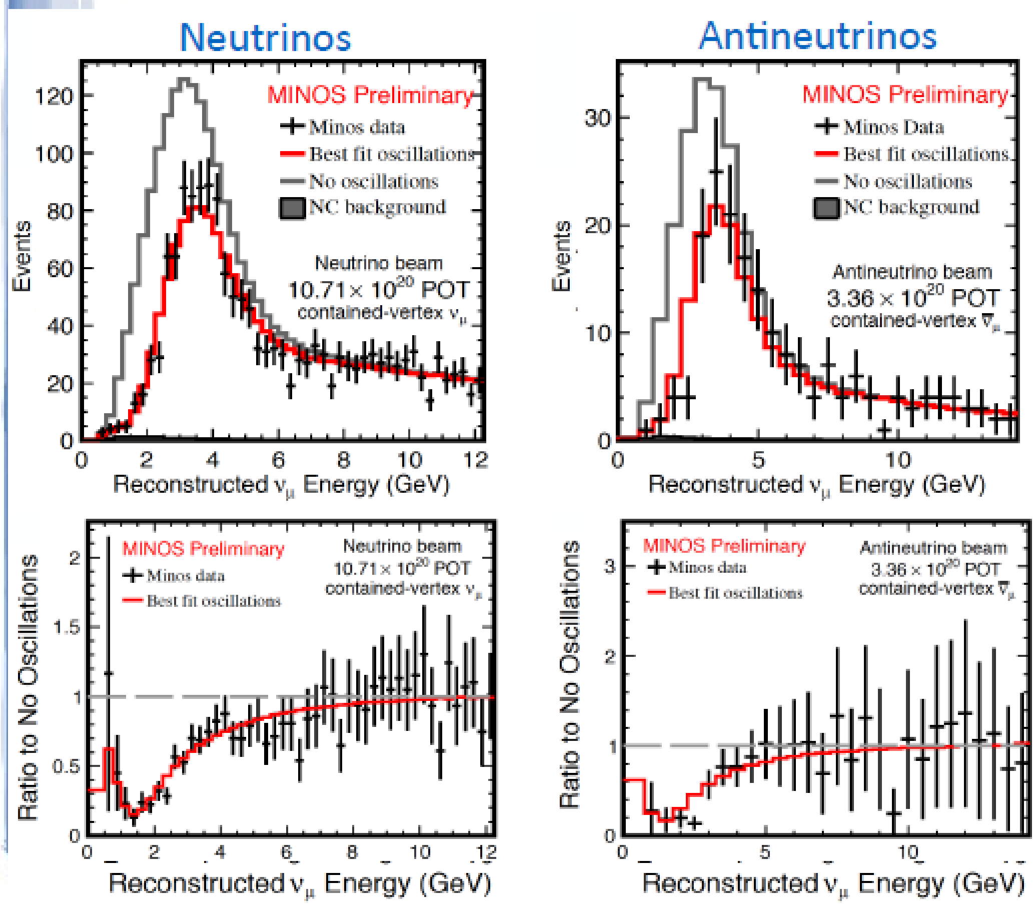


Talk by W. Zhong

See also D. Dwyer, T. Langford arXiv:1407.1281

MINOS/MINOS+

- Long baseline experiment (735 km) from Fermilab to Soudan mine, 5.4 kt magnetized iron/scintillator, on NUMI beamline
- Combined three flavor fit to neutrino beam data (10.71 10^{20} POT) antineutrino beam data (3.36 10^{20} POT), MINOS+ and atmospheric neutrino
- Most precise determination of the atmospheric mass splitting |Delta m^2_{32}|



Three-Flavor Oscillations Best Fit

Inverted Hierarchy

$|\Delta m^2_{32}| = 2.37^{+0.11}_{-0.07} \times 10^{-3}\mathrm{eV}^2$

$\sin^2\theta_{23} = 0.43^{+0.19}_{-0.05}$

$0.36 < \sin^2\theta_{23} < 0.65$ (90% C.L.)

Normal Hierarchy

$|\Delta m^2_{32}| = 2.34^{+0.09}_{-0.09} \times 10^{-3}\mathrm{eV}^2$

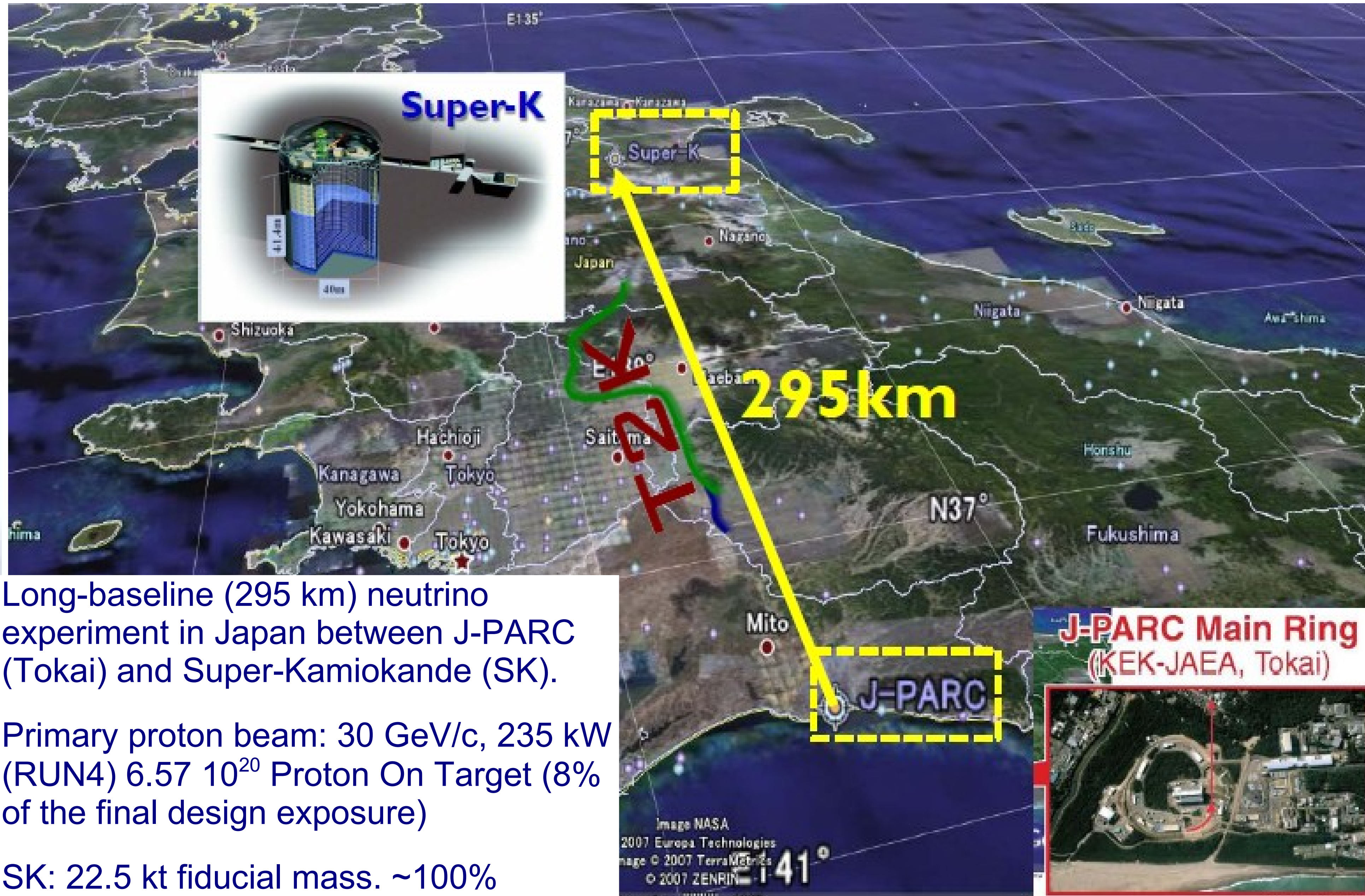
$\sin^2\theta_{23} = 0.43^{+0.16}_{-0.04}$

$0.37 < \sin^2\theta_{23} < 0.64$ (90% C.L.)

PRL 112 191801 (2014)

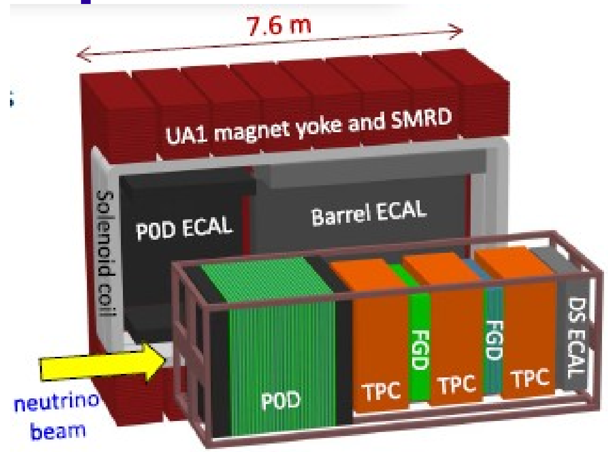
Talk by A. Sousa at NEUTRINO2014

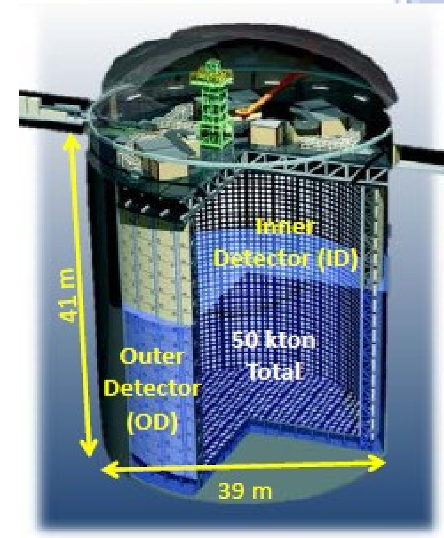
The Tokai to Kamioka (T2K) experiment

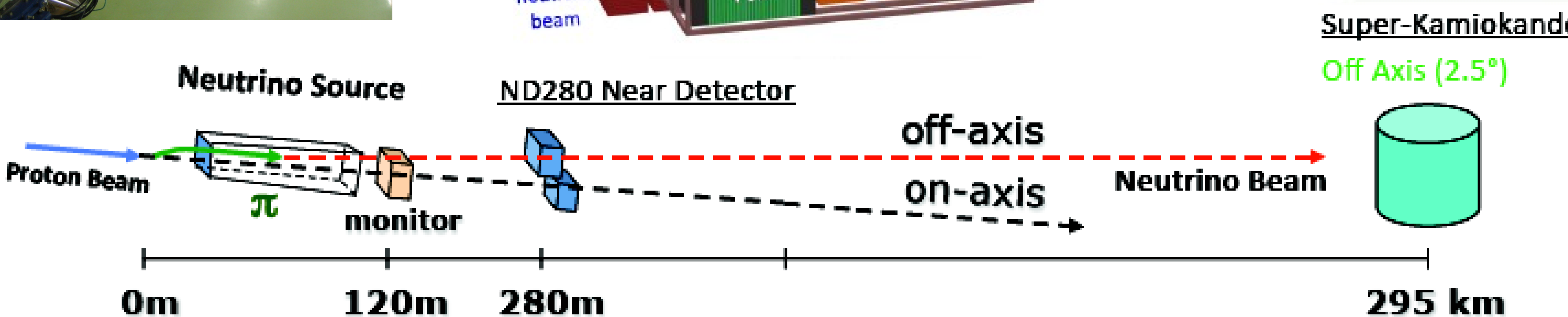


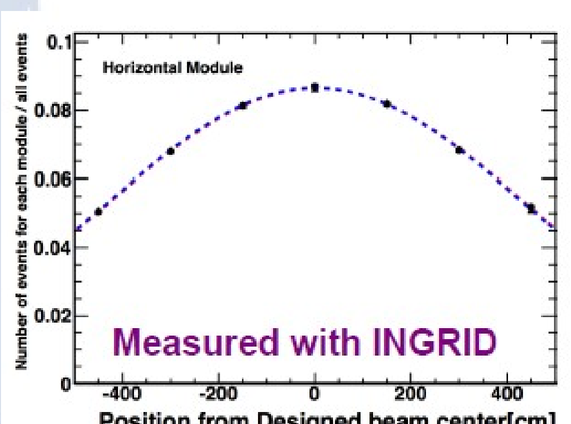
- Long-baseline (295 km) neutrino experiment in Japan between J-PARC (Tokai) and Super-Kamiokande (SK).
- Primary proton beam: 30 GeV/c, 235 kW (RUN4) 6.57 10^{20} Proton On Target (8% of the final design exposure)
- SK: 22.5 kt fiducial mass. ~100% livetime

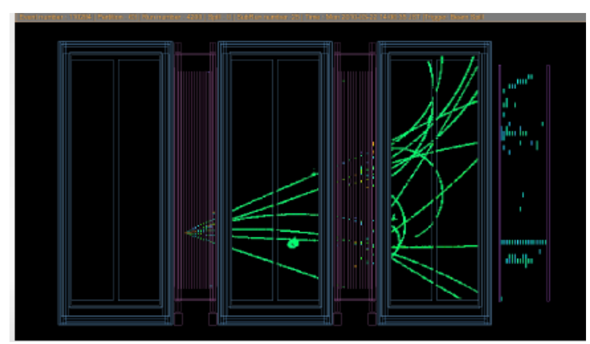
T2K Experimental Setup

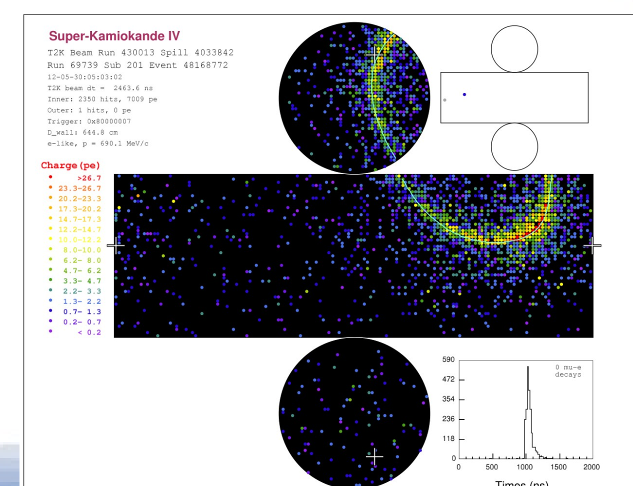




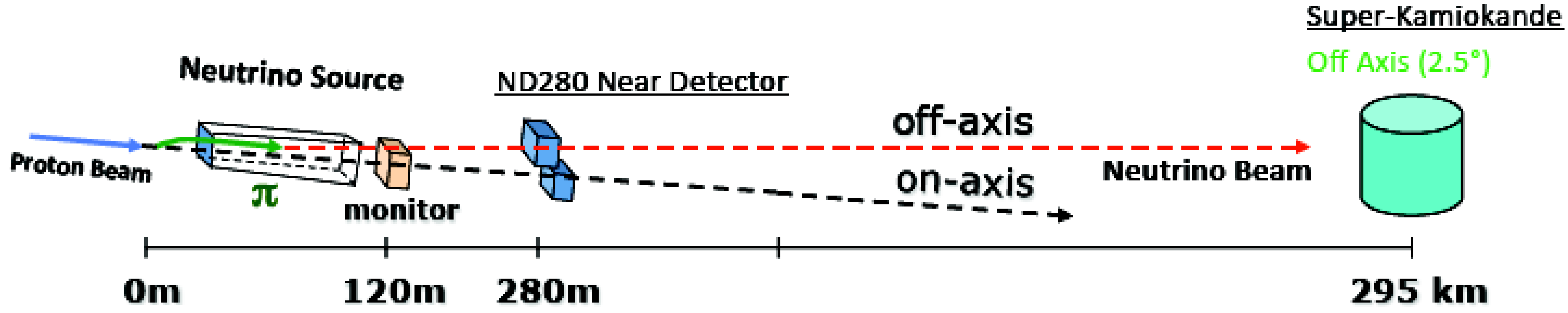


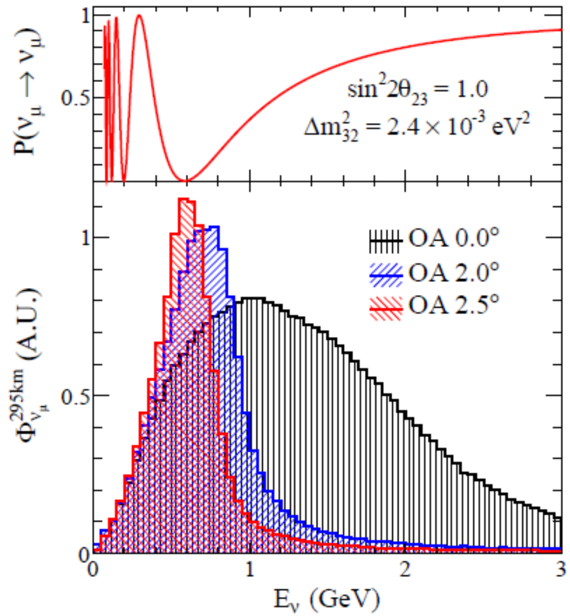


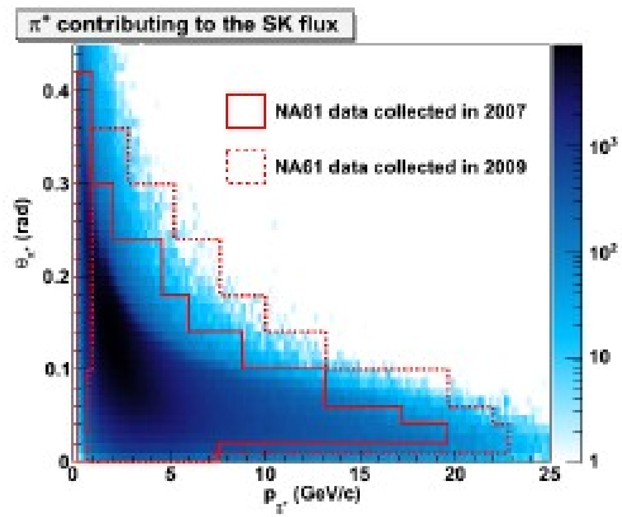


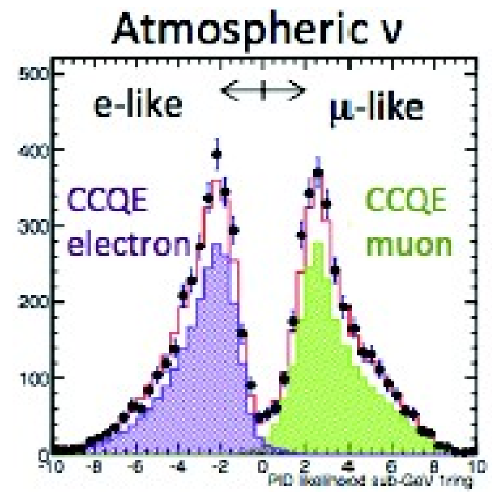


T2K: Main Experimental Features







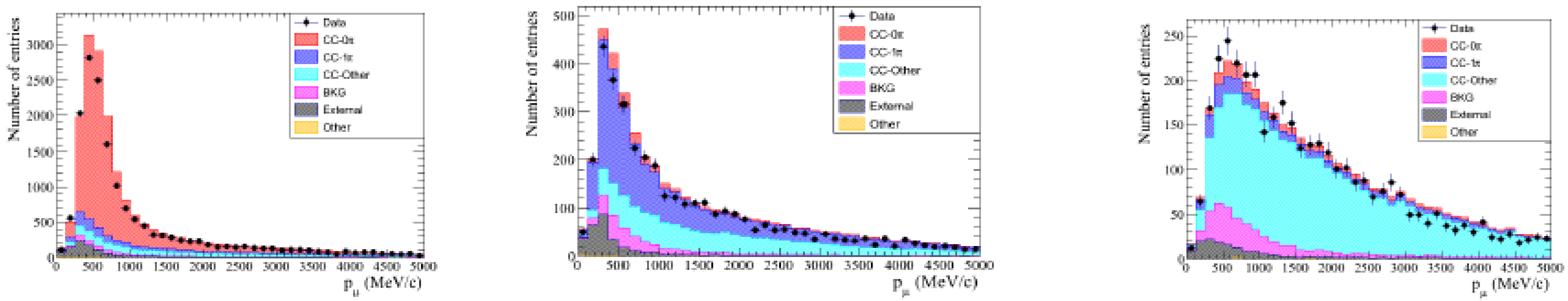


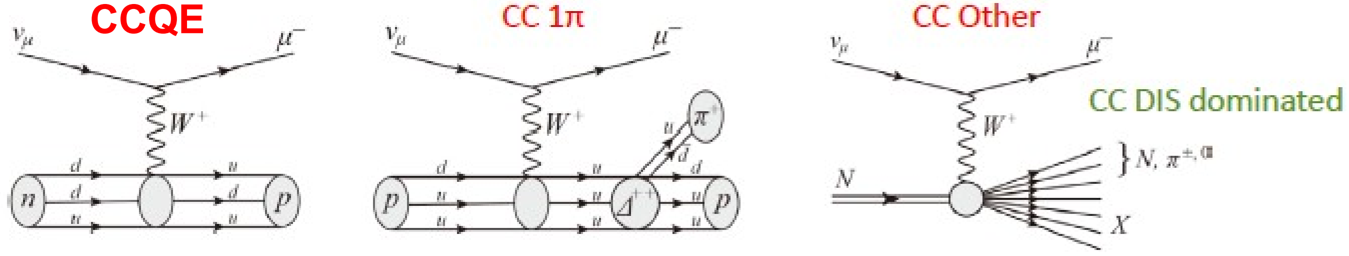
Off-axis beam.
Flux has a narrow peak tuned for the first oscillation maximum

Pion and kaon production measured by the NA61 exp. at CERN

Excellent particle identification capabilities in SK (misid <1%)

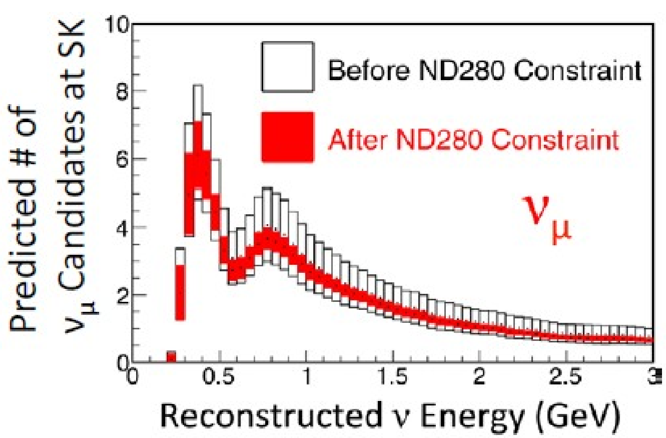
T2K Near detector constraint

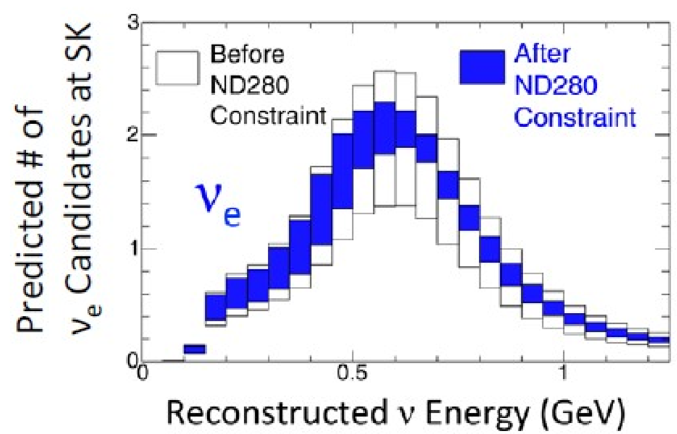




Talk by A. Hillairet

Flux and cross-section systematic uncertainty on N_{SK} significantly reduced to ~7%

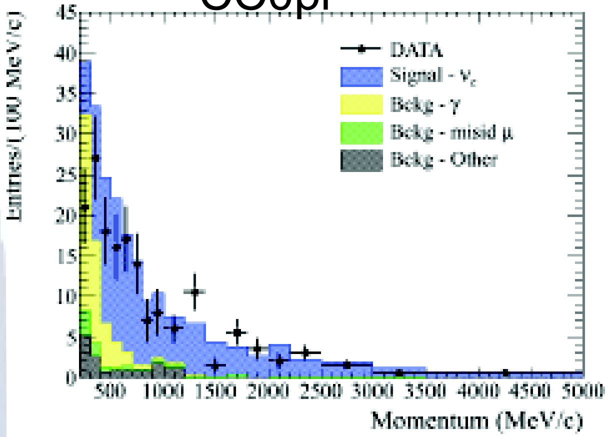




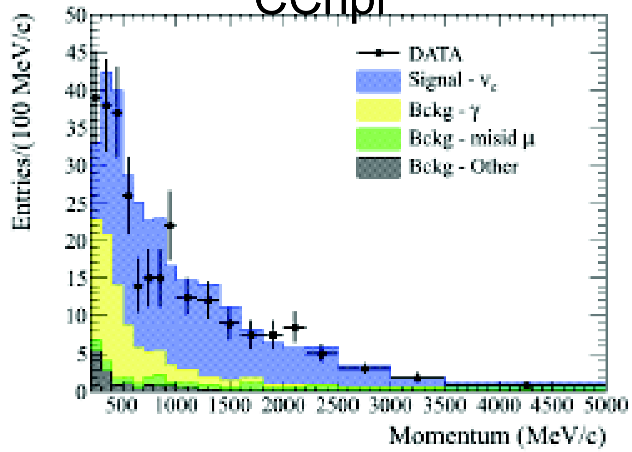
Phys. Rev. D 89, 092003

Intrinsic electron neutrino background

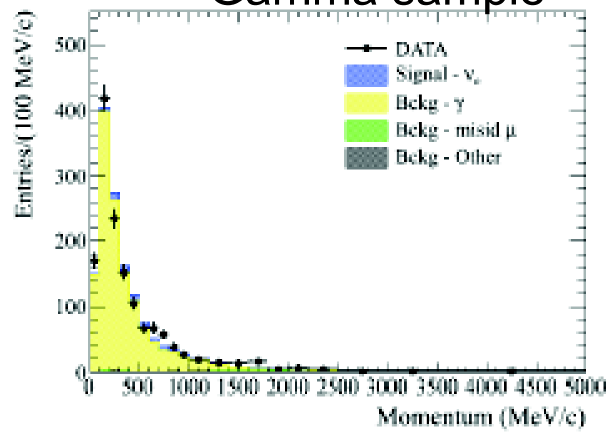
CC0pi



CCnpi



Gamma sample



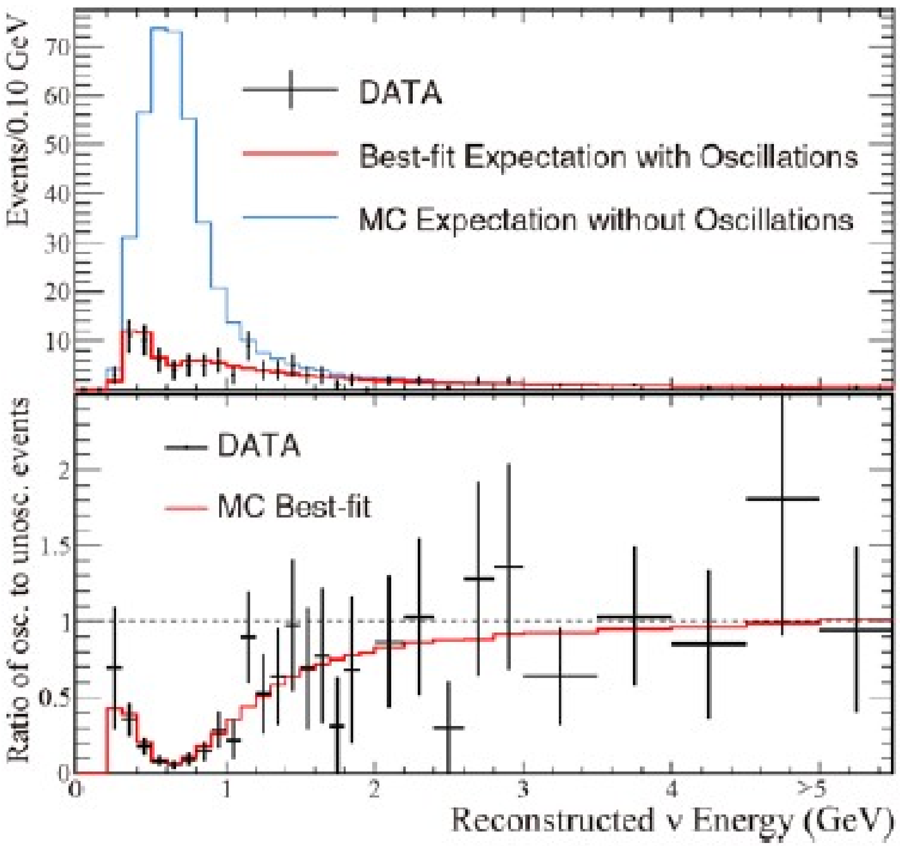
- Measured at near detector thanks to the excellent particle identification in the TPC of the T2K near detector
- Background (mainly γ from π^0 produced by neutrino outside near detector) constrained by control sample

$$\frac{Meas.\,\nu_e\,flux}{Predicted\,\nu_e\,flux} = 1.01 \pm 0.06\,(stat) \pm 0.08\,(syst)$$

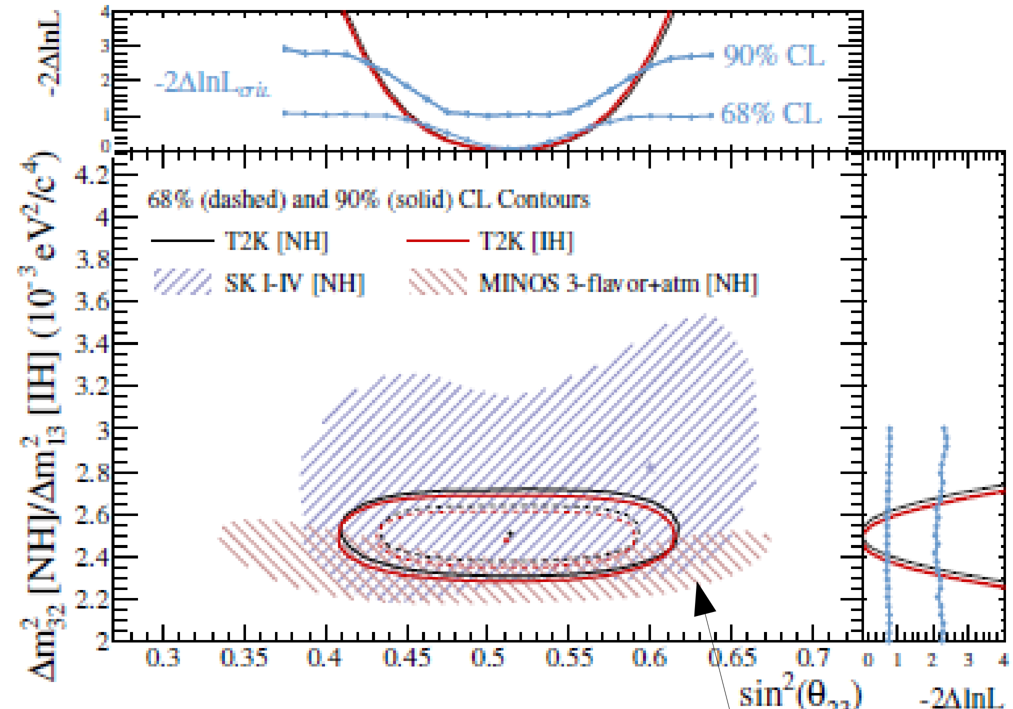
$\nu_\mu \longrightarrow \nu_\mu$

Phys. Rev. Lett. 112, 181801 (2014)

T2K ν_μ disappearance measurement



Talk by A. Himmel



Notice recent MINOS 3-flavor result

Oscillation parameters		Best-fit value
NH	$\sin^2(\theta_{23})$	$0.514^{+0.055}_{-0.056}$
	Δm^2_{32} (10^{-3} eV^2)	2.51 ± 0.10
IH	$\sin^2(\theta_{23})$	0.511 ± 0.055
	Δm^2_{13} (10^{-3} eV^2)	2.48 ± 0.10

$N_{obs} = 120$

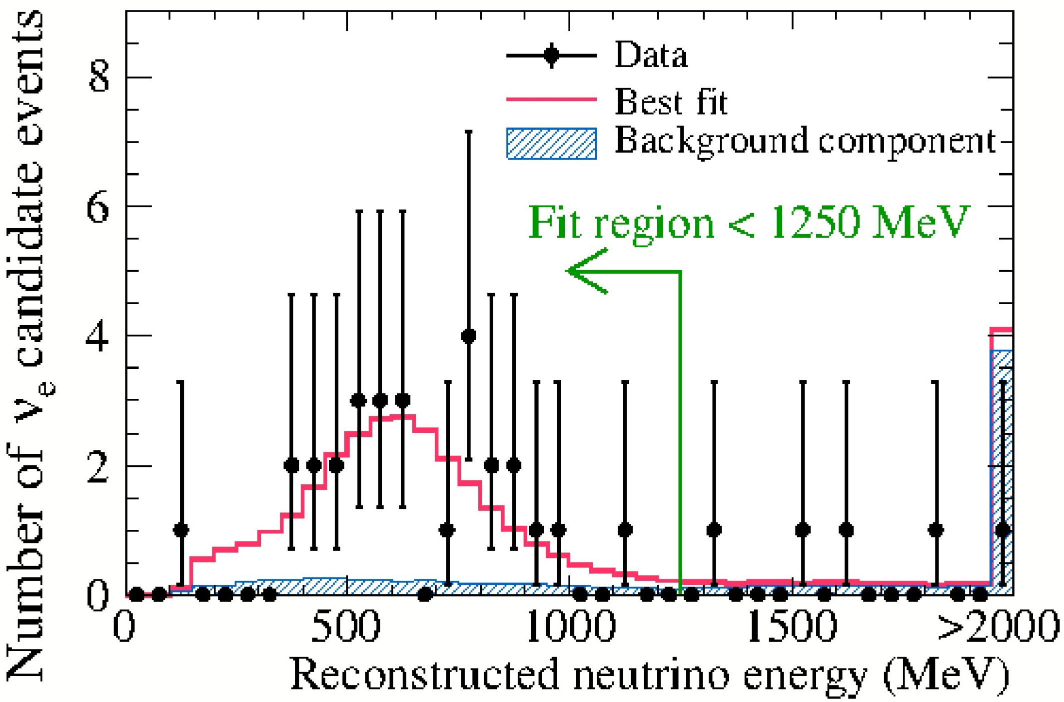
N_{exp} (no osc) = 446±23(syst.)

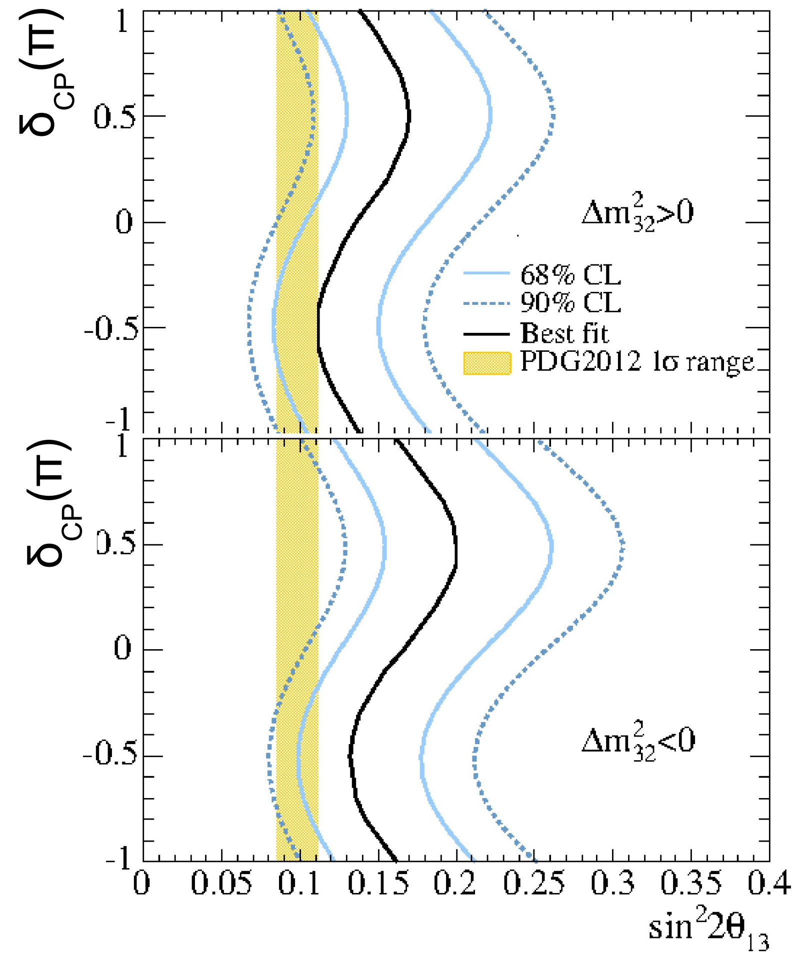
Data favor maximum disappearance.

$\nu_\mu \rightarrow \nu_e$

Phys. Rev. Lett. 112, 061802 (2014)

T2K observation of $\nu_\mu \rightarrow \nu_e$ appearance

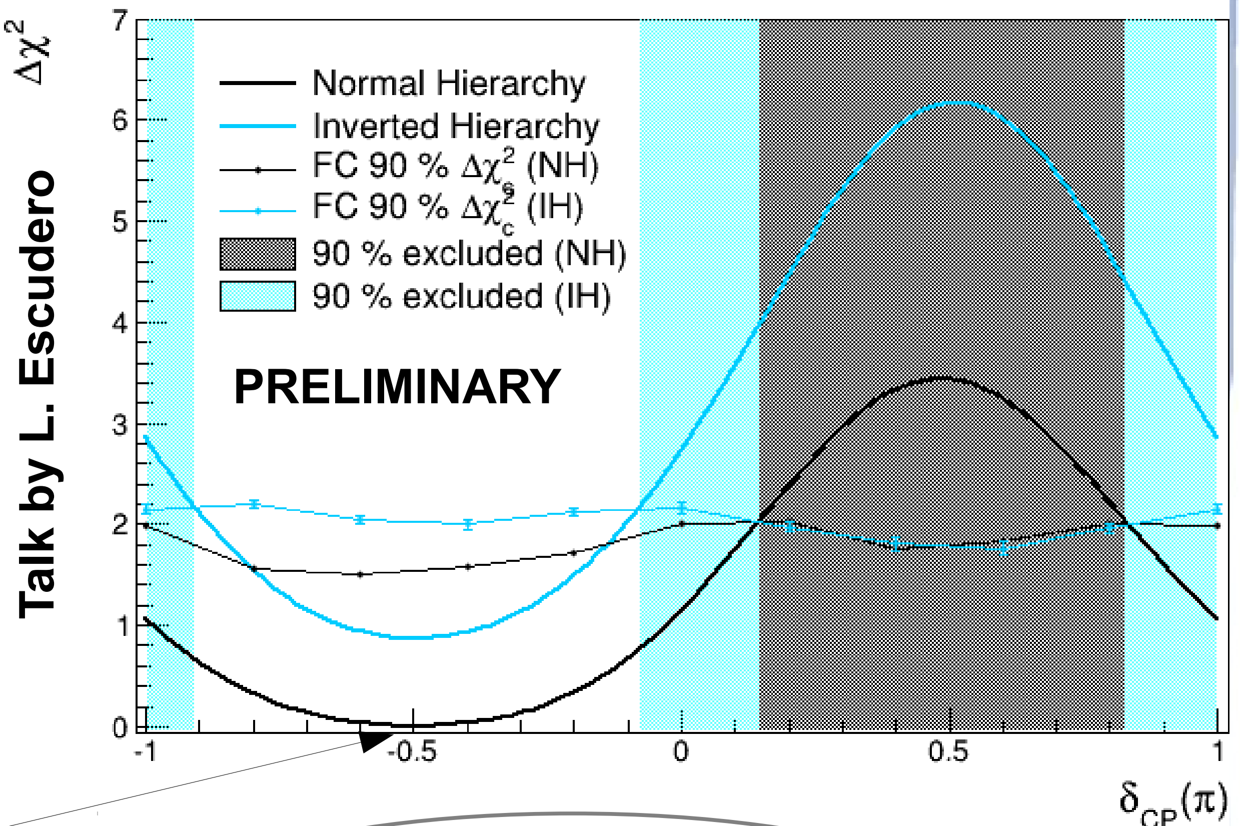




- N_{obs} = 28
- N_{exp} (bck. only) = 4.9±0.6(syst.)
- N_{exp} ($\sin^2 2\theta_{13}$=0.1) = 21.6
- 7.3 σ evidence of non-zero θ_{13}
- First direct observation of a new flavor appearance
- Opens the way to the determination of the CP violation parameter δ

T2K combined fit to appearance and disappearance data

- Combined fit to the ν_μ and ν_e samples
- Using PDG 2013 θ_{13} T2K obtains an indication favoring $\delta = -\pi/2$
- Similar results from an independent analysis using Markov chain MC producing Bayesian credible intervals
- If nature has chosen this happy spot: a) a generous help to experiments b) a solution that satisfies the leptogenesis bound with no additional CP violation



Leptogenesis bound

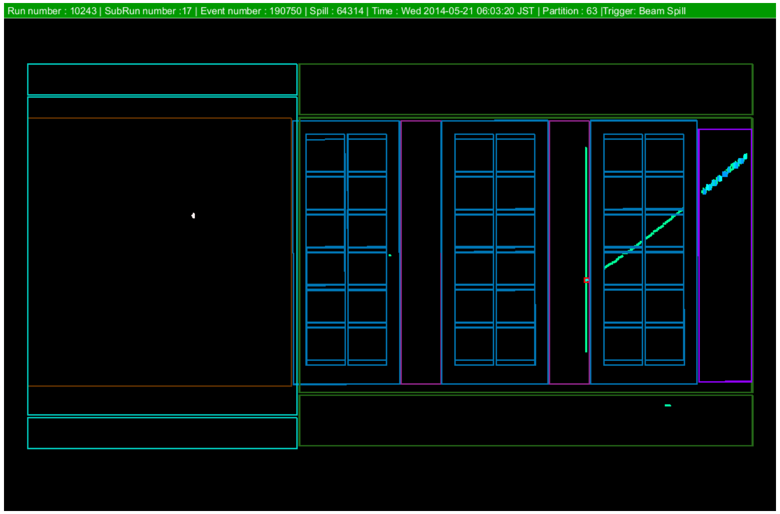
$$|\sin\theta_{13}\sin\delta| \geq 0.11$$

Pascoli Petcov Riotto 2007

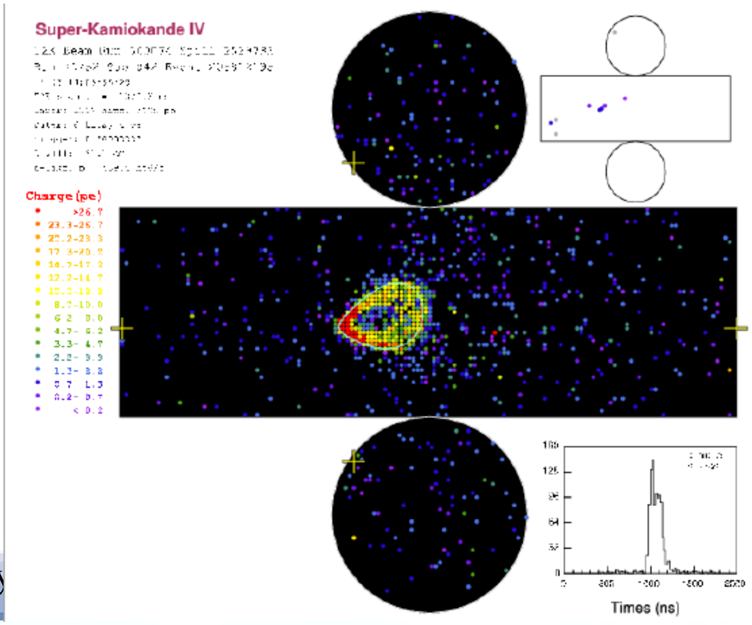
T2K status

- T2K has recently resumed data-taking (0.7 10^{20} POT in 2014) mostly in anti-neutrino mode
- Beam power : ~220 kW
- Looking forward to more data for increased precision in neutrino oscillation results

ND280 event

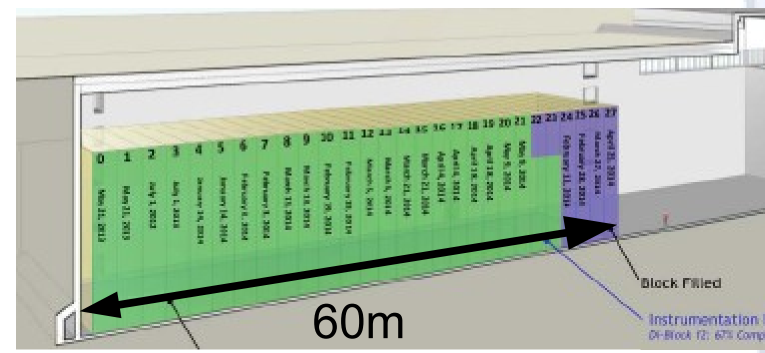


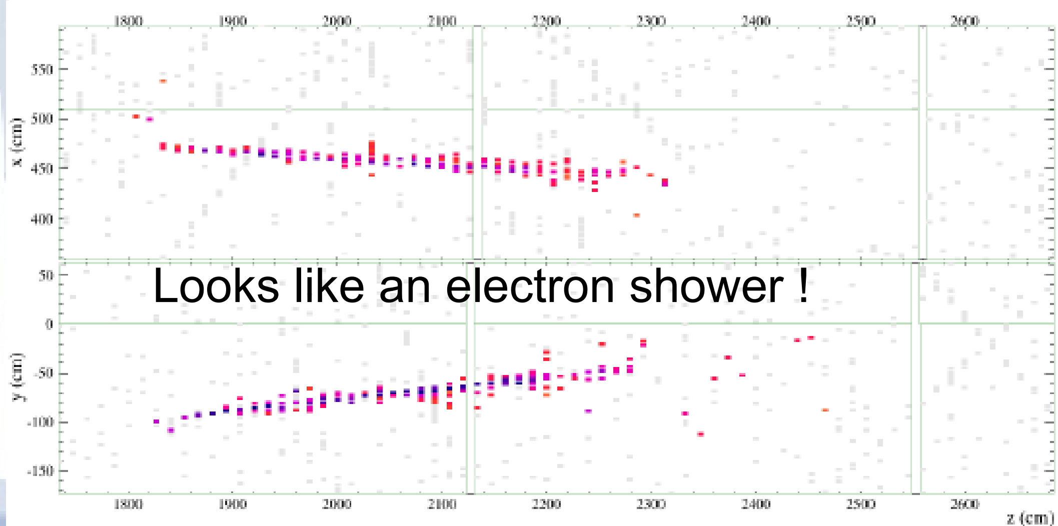
SK event



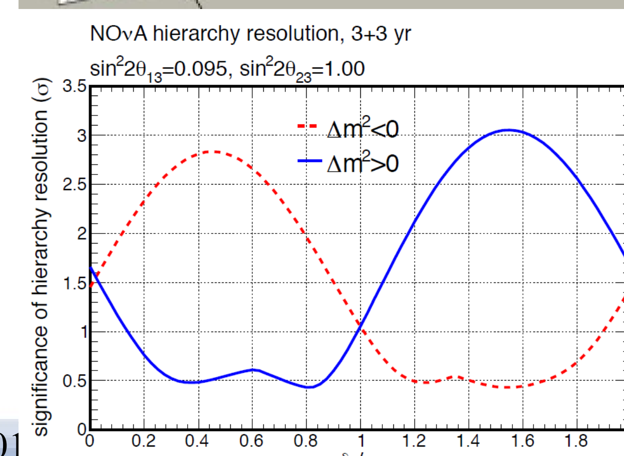
First neutrinos in NOvA

- NOvA is an off-axis experiment from Fermilab to Ash River (810 km) on the NUMI beam
- The far detector is a 14 kt totally active liquid scintillator filled structure
- First neutrino events observed
- Sensitivity to CP violation and mass hierarchy
- MINOS+ also started data-taking





Talk by J. Musser

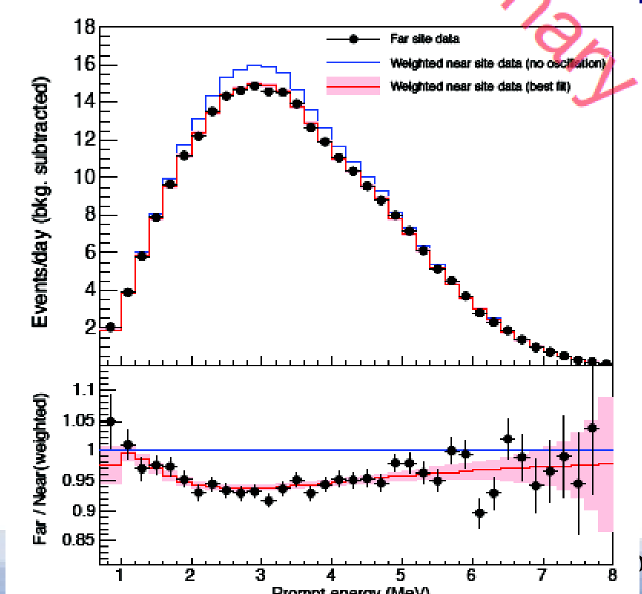


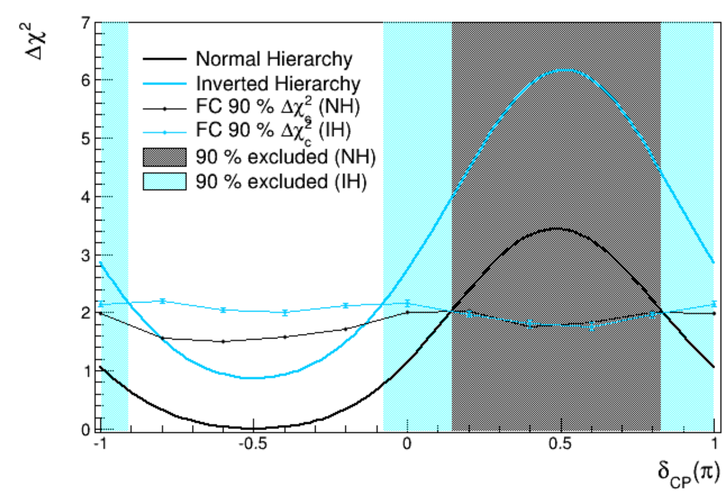
Future experiments

- Reactor experiments : expected future precision to 3%
- Now->2020: T2K and NOvA
- New experiments attempting to determine mass hierarchy: INO, JUNO, PINGU, ORCA (See talk by T. Schwetz)
- ~2025(?) next generation of long baseline neutrino experiments (proposals: HyperKamiokande, LBNO, LBNE) dedicated to mass hierarchy and CP violation

Conclusions

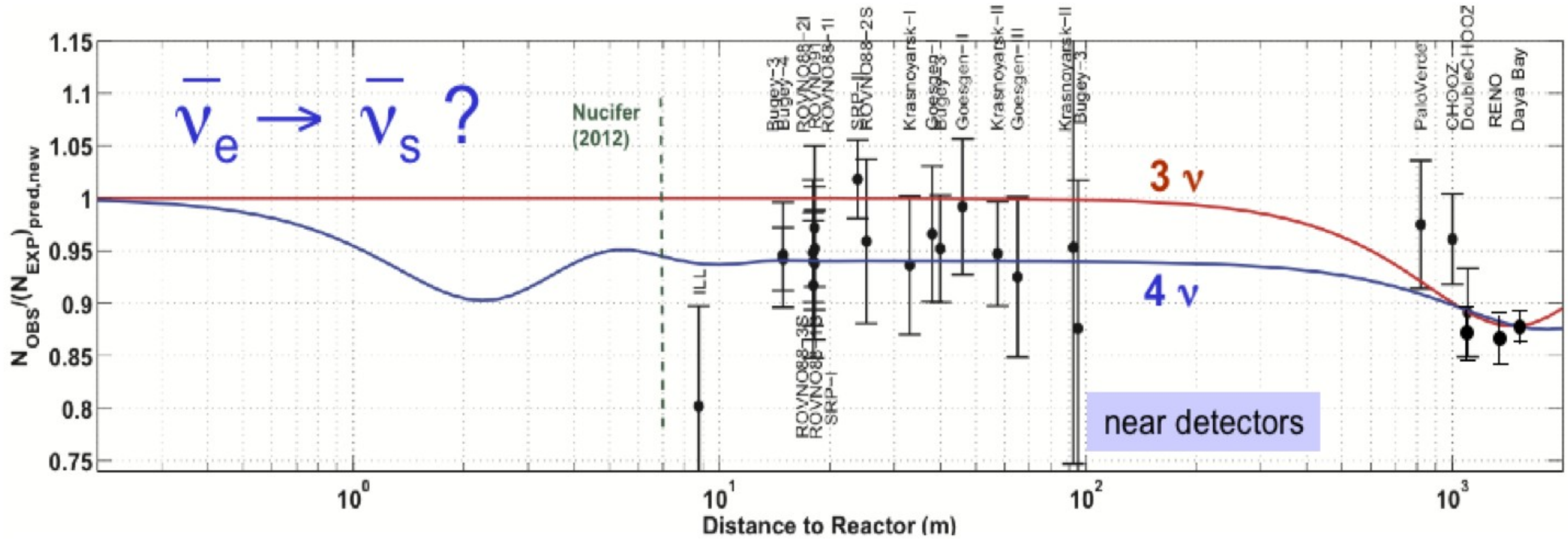
- The study of neutrino oscillations has provided many surprising discoveries in the last 15 years, establishing the three neutrino mixing paradigm, implying Physics beyond the SM
- The field is approaching the few % precision era due to dedicated experimental efforts
- The experiments begin to be sensitive to CP via the interplay of accelerator and reactor observables
- Major efforts are ongoing towards answering the remaining open questions and providing precision tests

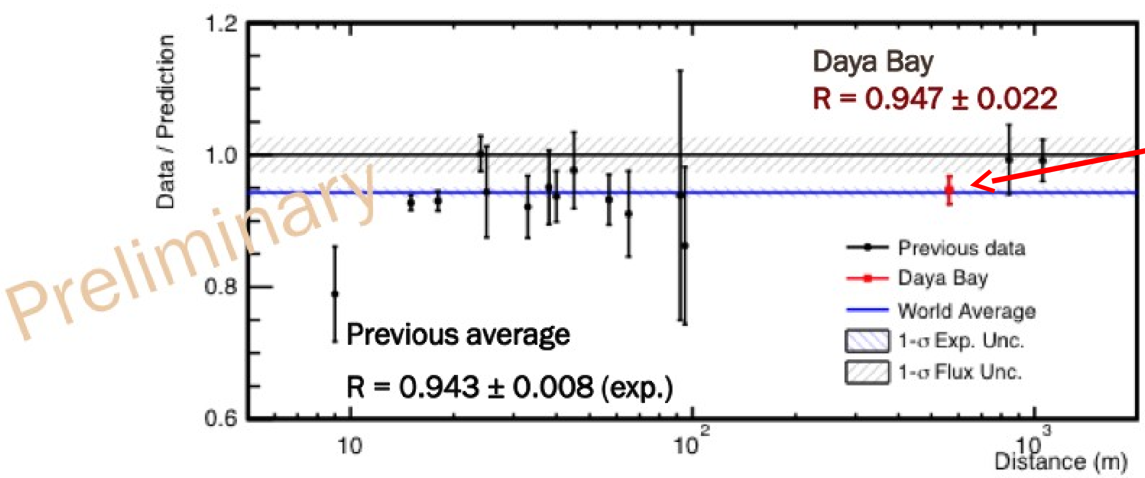




Back-up slides

Reactor Anomaly Plot:

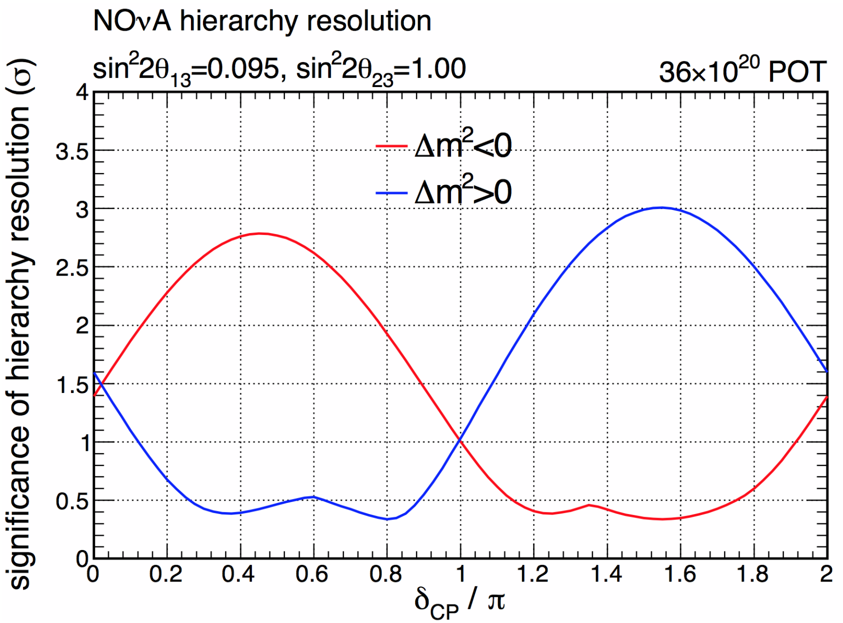




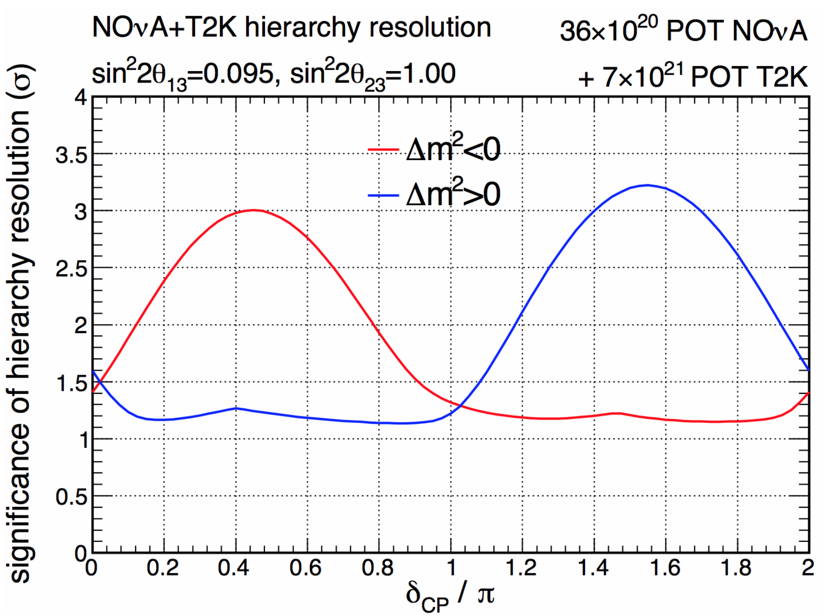
Daya Bay (with use of 3 Near Detectors only): plot shown by Weili Zhong at ICHEP14

NOvA (material shown at Neutrino2014)

NOvA Mass Hierarchy Sensitivity



NOvA alone

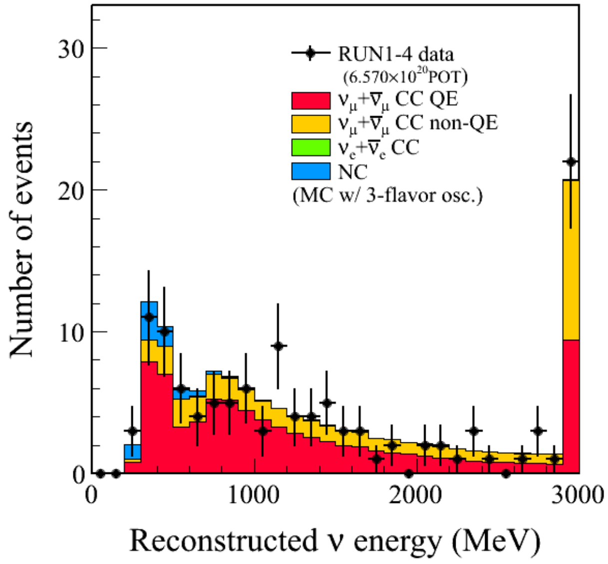


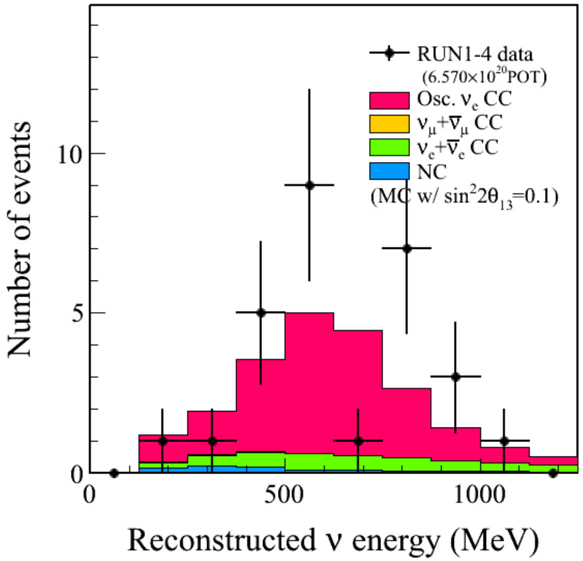
Combined NOvA+T2K

T2K Event selection

- ν_μ event selection
  - Fully contained fiducial volume
  - Single ring μ like event
  - P > 200 MeV/c
  - N decay electron ≤1

- ν_e event selection
  - Fully contained fiducial volume
  - Single ring e like event
  - E_{vis} > 100 MeV/c
  - N decay electron =0
  - π_0 rejection cut
  - E_{rec} < 1250 MeV

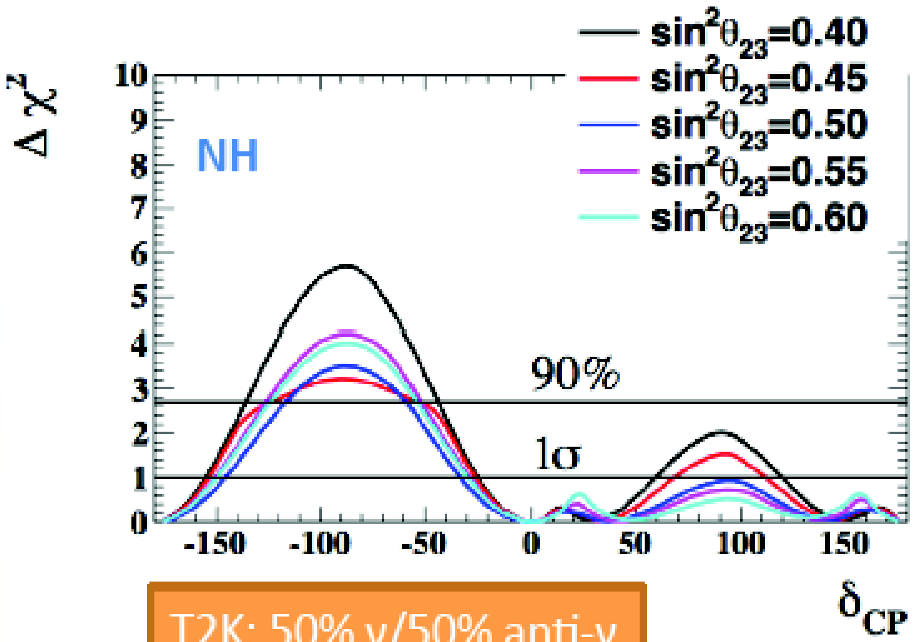




T2K systematic uncertainties

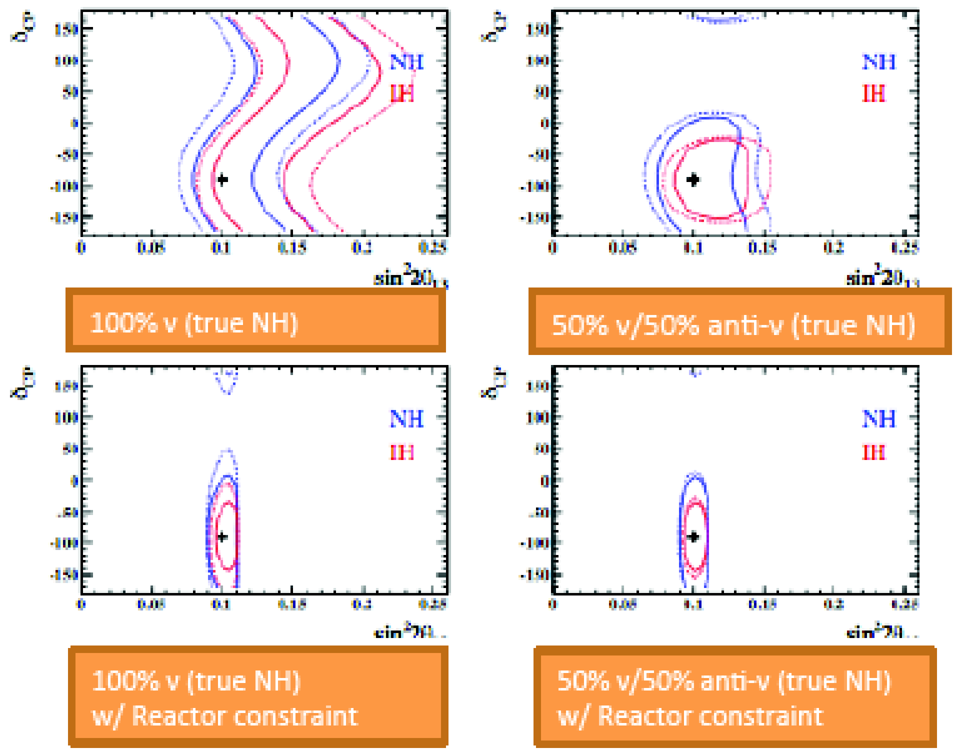
Systematic Source	Relative Uncertainty in # of ν_e Candidates (%)	Relative Uncertainty in # of ν_μ Candidates (%)
Flux + cross section (ND280 constrained)	3.1	2.7
Cross section (ND280-independent)	4.7	5.0
π Hadronic Interactions	2.3	3.5
SK Detector	2.9	3.6
Total	**6.8**	**7.6**

Future Sensitivity to CPV using T2K



T2K: 50% ν/50% anti-ν

"Lucky! (+: $Sin^2 2\theta$=0.1, δCP=-90)"



No systematics

5% error on signal, 10% on background

T2K studies indicate our best sensitivity will be for 50% ν/50% anti-ν running. Anti-nu running also opens a large new physics program.