Recent results in neutrino oscillation studies

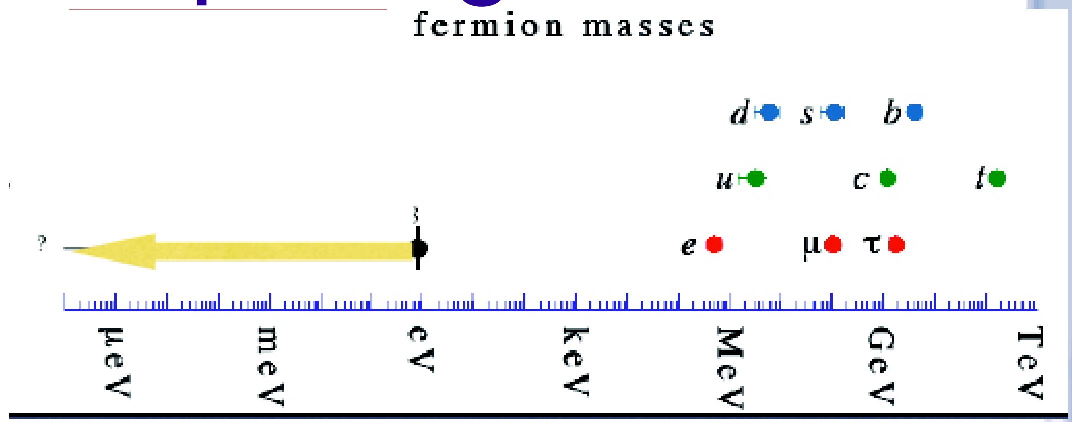
Marco Zito
IRFU/SPP CEA Saclay

ICPPA
Moscow, October 12th 2016

Outline

- Introduction - the PMNS neutrino oscillation framework
- Recent results with reactor experiments and short baseline anomalies
- Long baseline experiments, present and future

Neutrino physics: surprising results

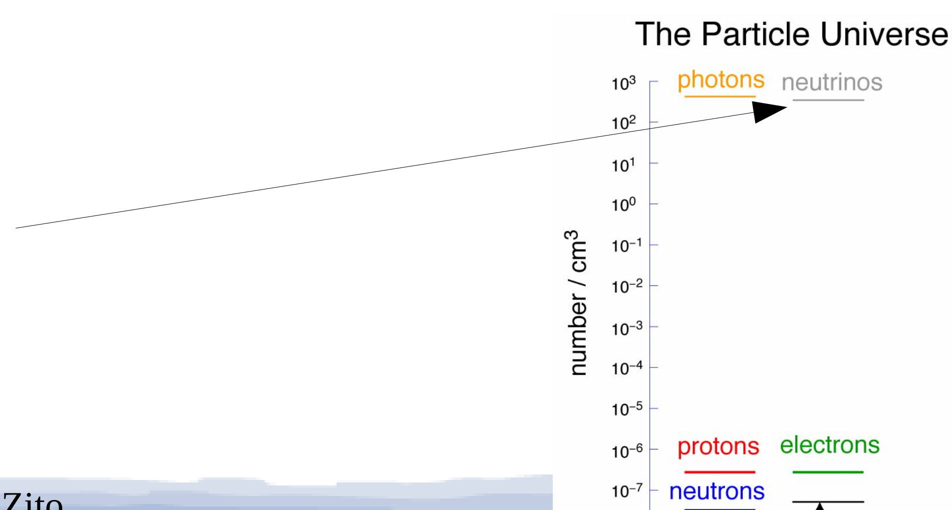


- The extreme lightness of neutrino masses begs a compelling explanation

- 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 an important role in the evolution of the Universe. Can they explain matter-antimatter asymmetry ?



Neutrino oscillations

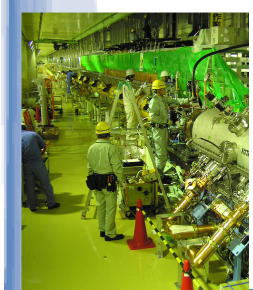
$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

If neutrino flavor eigenstates are different from mass eigenstates, propagation induces a phase shift with the appearance of a new flavor

$\nu_\mu = -\sin\theta\,\nu_1 + \cos\theta\,\nu_2$

Propagation

Source



W ν_μ μ

$\nu_1 \rightarrow \exp(-ip_1x)\,\nu_1$

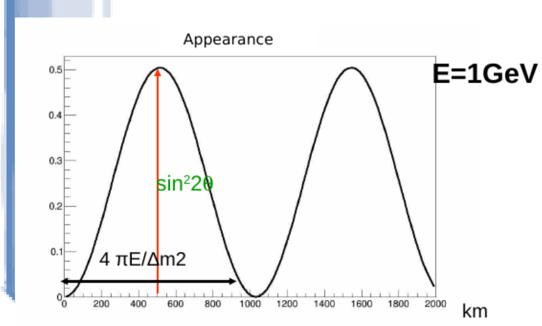
$\nu_2 \rightarrow \exp(-ip_2x)\,\nu_2$

$\Delta\varphi = \Delta m^2 L/(4E)$

ν_e e

Detector

L



$\mathrm{Prob}(\nu_\mu \rightarrow \nu_e) = \sin^2(2\theta)\,\sin^2(\Delta m^2 L/4E)$

This is a simplified two neutrino scenario

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

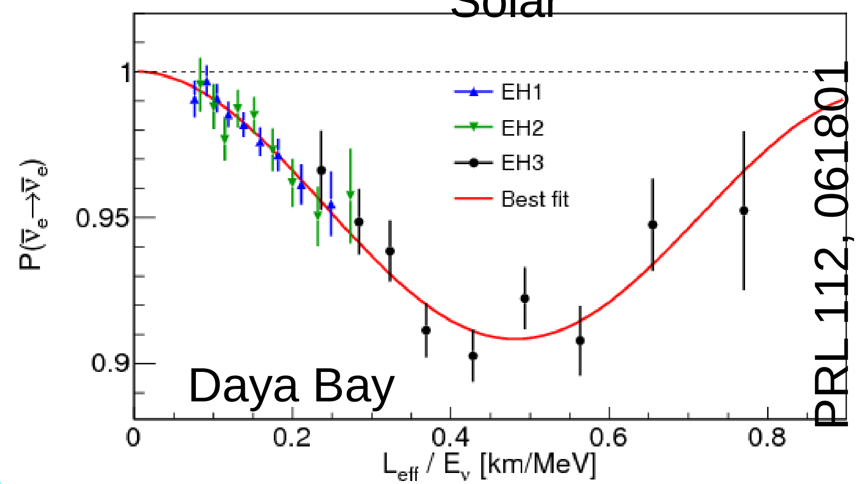
$s_{ij}=\sin\theta_{ij}$

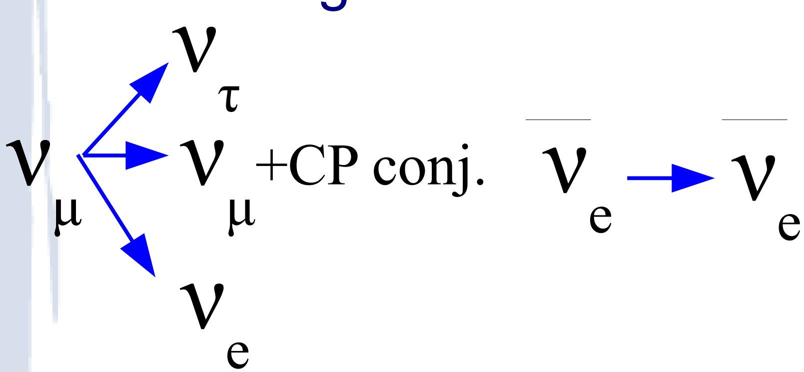
$c_{ij}=\cos\theta_{ij}$

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

Atmospheric　　　　　　　　　　Solar

- The oscillation phenomena have been convincingly observed using solar, atmospheric (Nobel prize 2015), reactor and accelerator neutrinos, establishing the three neutrino SM paradigm
- Currently studying three-neutrino subleading effects





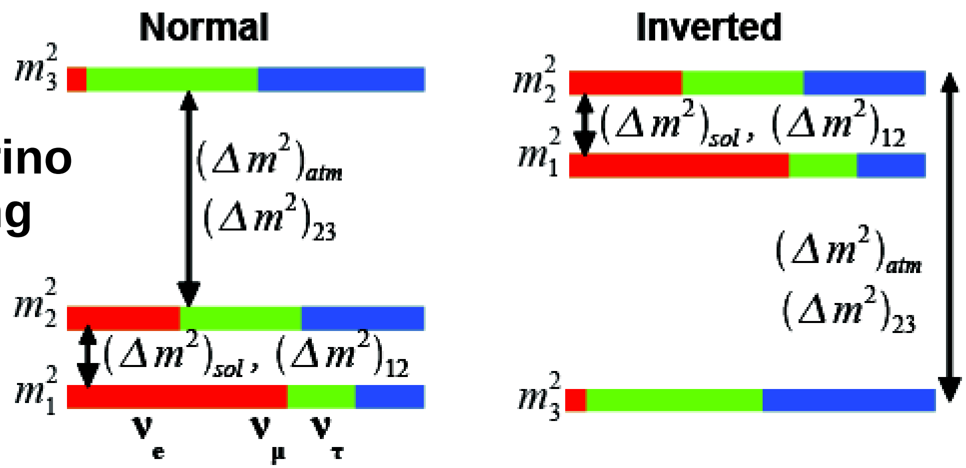
Parameter	Value	Precision (%)
Δm^2_{21}	$7.5\ 10^{-5}\ eV^2$	2.6
θ_{12}	34°	5.4
Δm^2_{32}	$2.4\ 10^{-3}\ eV^2$	2.6
θ_{23}	42°	~10
θ_{13}	9°	6 (Daya Bay 2014)

Capozzi et al.
ArXiv:1312.2878
Talk by M. Tortola

Open questions in neutrino physics

1) Is θ_{23} =45°? which octant ?
2) Determine the mass ordering (often incorrectly called 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 ?
6) Dirac or Majorana ?
7) Absolute mass scale

Normal neutrino mass ordering



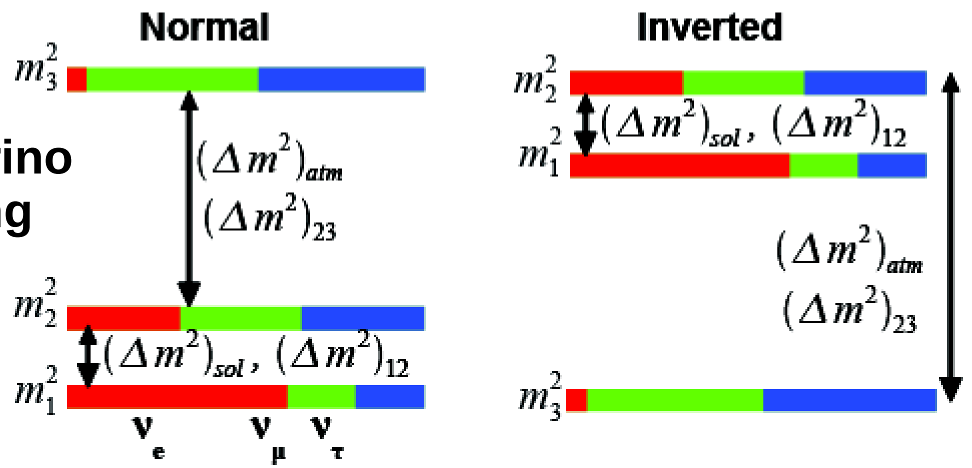
Inverted neutrino mass ordering

Open questions in neutrino physics

1) Is $\theta_{23}=45°$? which octant ?
2) Determine the mass ordering
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 ?
6) Dirac or Majorana ?
7) Absolute mass scale

Can be answered with Long Baseline experiments

Normal neutrino mass ordering

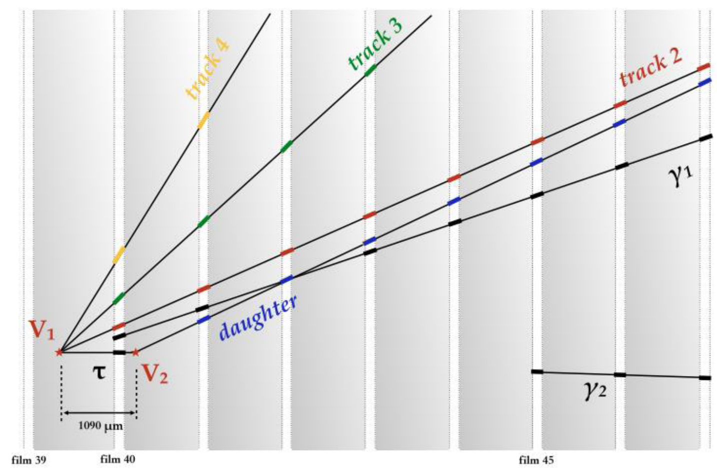


Inverted neutrino mass ordering

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

Tau neutrino appearance

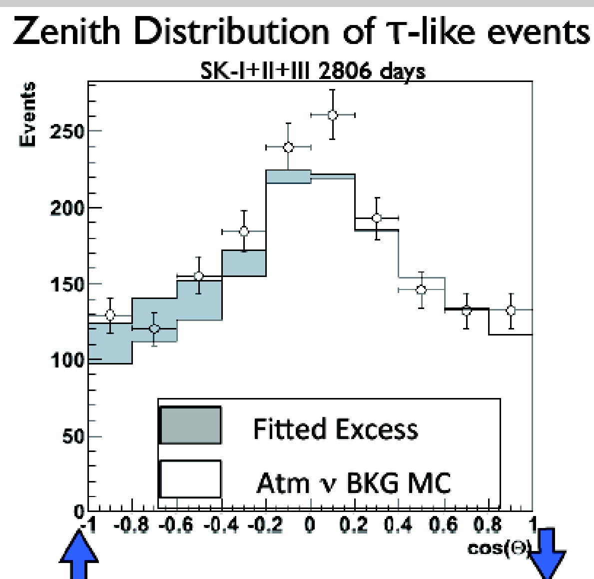
OPERA performed a search for ν_μ to ν_τ appearance with a baseline of 732 km (CERN to Gran Sasso) using the Emulsion Cloud Chamber technique. It has observed five ν_τ candidates (tot bkg = 0.25). The null hypothesis is excluded at the 5.1 σ CL.



Decay channel	Bck	Exp sig	Obs.
τ→1h	0.04	0.52	3
τ→3h	0.17	0.73	1
τ→μ	0.004	0.61	1
τ→e	0.03	0.78	0
Tot	0.25±0.05	2.64±0.53	5

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

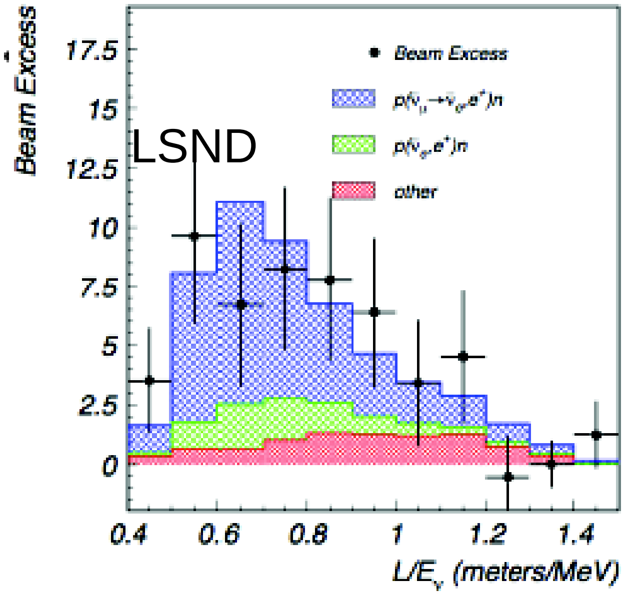


$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

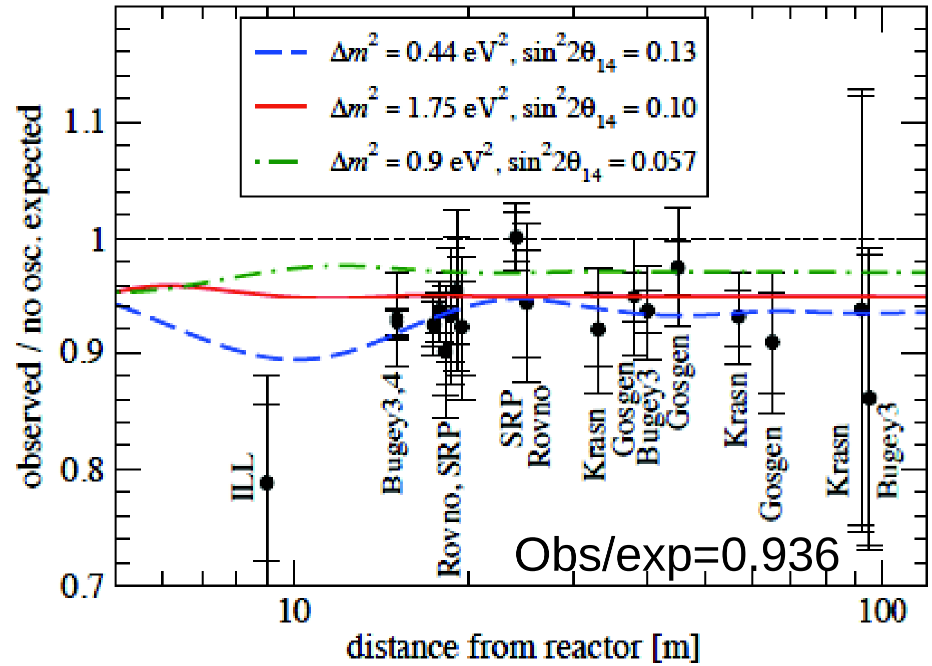
$\bar{\nu}_e \rightarrow \nu_?$

Short baseline neutrino anomalies

PRD64 (2001) 112007

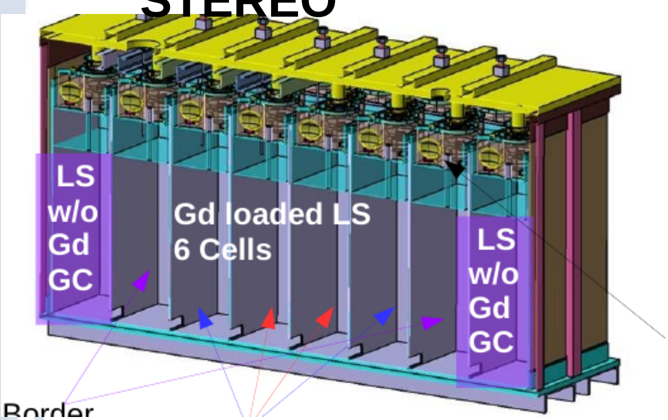


J. Kopp et al, arXiv:1303.3011v3



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

STEREO

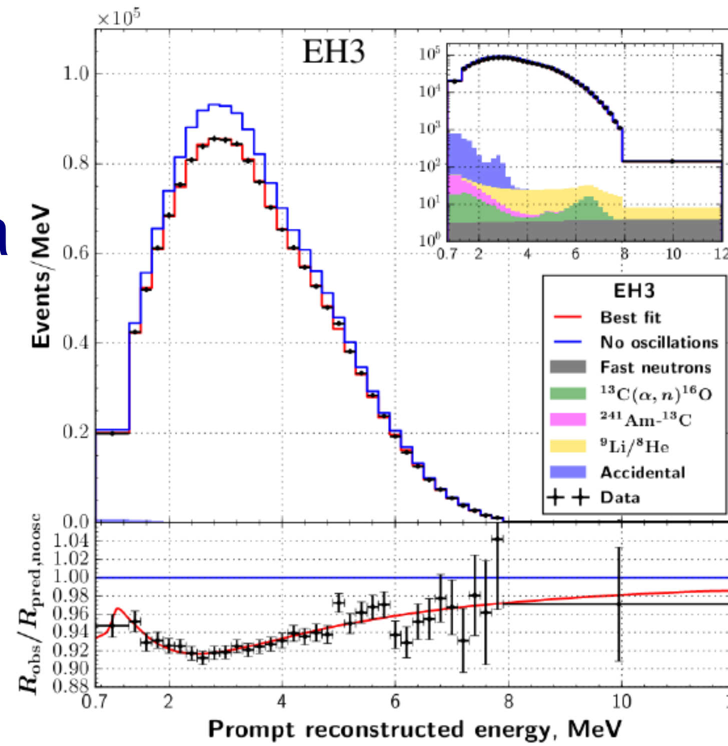


- Short baseline experiments (LSND, MiniBooNE, reactors, Ga source) have revealed anomalies that could be interpreted as oscillations with Δm~eV
- No globally satisfactory interpretation due to tensions within the data
- A new generation of very short baseline (<~10m) reactor experiments (Neutrino4, Stereo, Solid, Prospect …) are (very close to) taking data
- Short baseline program at Fermilab
- New results by IceCube

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

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

- 1230 days of data
- Over 2.5 M (300K) IBD candidates in tota
- Consistent neutron capture result



$$\sin^2 2\theta_{13} = [8.41 \pm 0.27(\text{stat.}) \pm 0.19(\text{syst.})] \times 10^{-2}$$
$$|\Delta m^2_{ee}| = [2.50 \pm 0.06(\text{stat.}) \pm 0.06(\text{syst.})] \times 10^{-3}\text{eV}^2$$
$$\chi^2/\text{NDF} = 232.6/263$$

- New result by Double Chooz
  $\sin^2(2\,\theta_{13}) = 0.119 \pm 0.016$ (A. Cabrera, CERN seminar sept 2016)

Experiment	$\sin^2 2\theta_{13}$	Value
Daya Bay		0.0841±0.0033
RENO		0.082±0.010
D-CHOOZ		0.111±0.018

Towards CP violation: $\nu_\mu \to \nu_e$ beyond the leading term

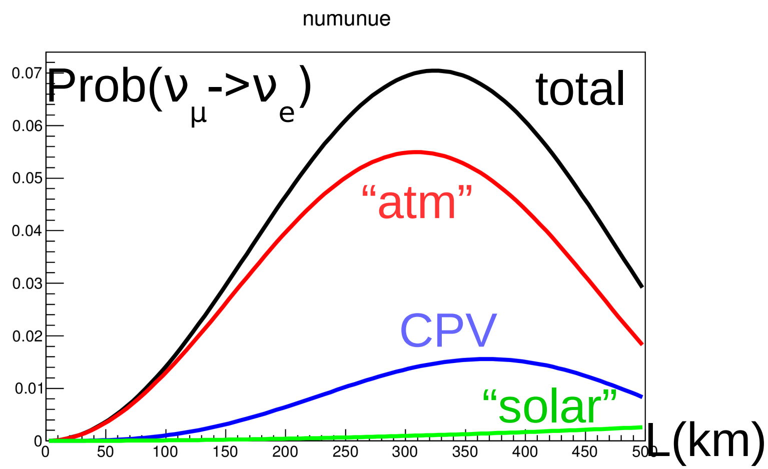
$$P(\nu_\mu \to \nu_e) \approx 4 C^2_{13} S^2_{13} S^2_{23} \sin^2 \Phi_{31}$$ "Atmospheric" term

$$\mp 8 C^2_{13} C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin\Phi_{32} \sin\Phi_{31} \sin\Phi_{21}$$ CP violating term

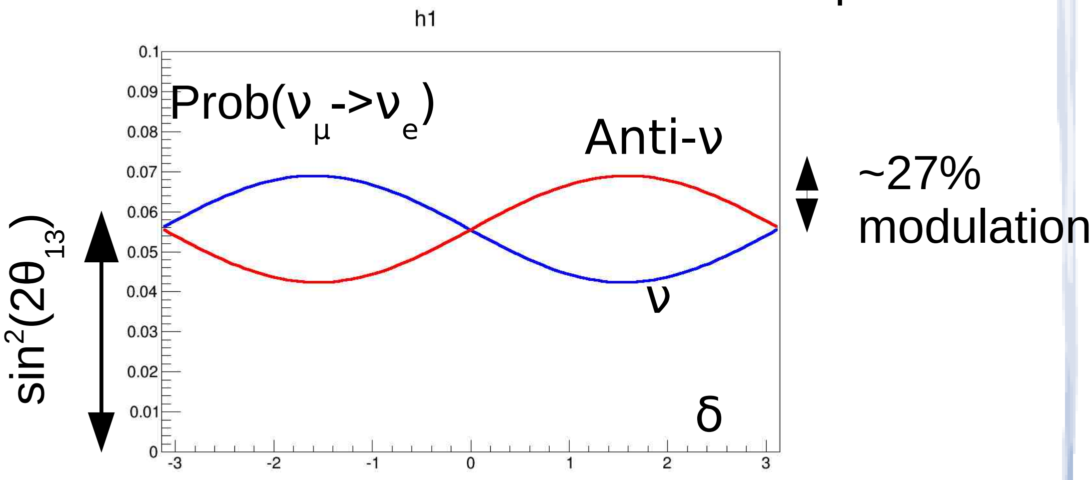
$$+4 S^2_{12} C^2_{13} \left(C^2_{12} C^2_{23} + S^2_{12} S^2_{23} S^2_{13} - 2 C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta\right) \sin^2 \Phi_{21}$$ "Solar" term

$$C_{ij} = \cos(\theta_{ij})$$
$$\Phi_{ij} = \Delta m^2_{ij} L / 4E$$

Change sign from ν to anti-ν! An accelerator based neutrino beam is ideal to study this, as either neutrinos or antineutrinos can be produced

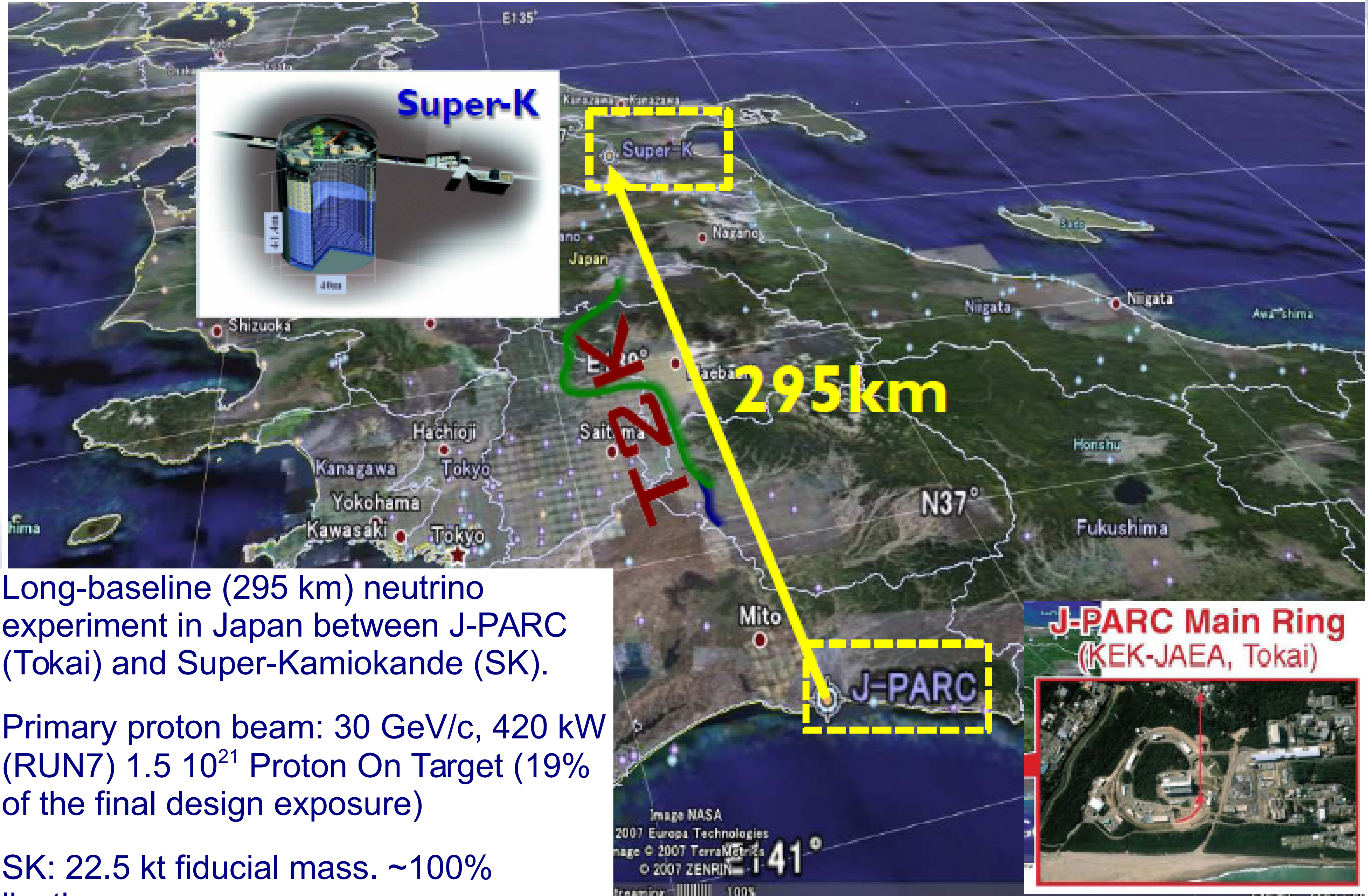


E=0.6 GeV



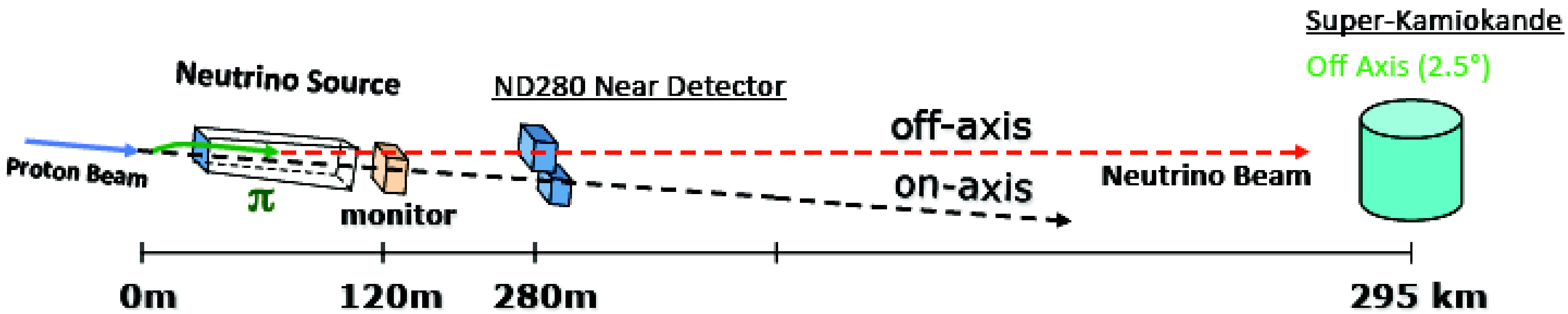
Caution: indicative plots !!

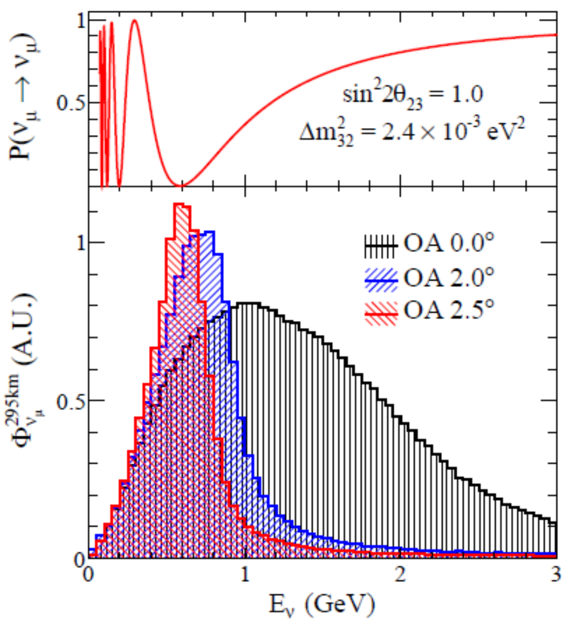
The Tokai to Kamioka (T2K) experiment



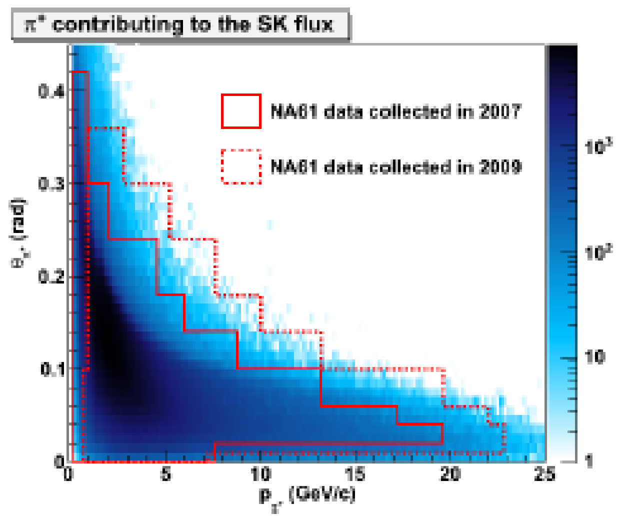
- Long-baseline (295 km) neutrino experiment in Japan between J-PARC (Tokai) and Super-Kamiokande (SK).
- Primary proton beam: 30 GeV/c, 420 kW (RUN7) 1.5 10^{21} Proton On Target (19% of the final design exposure)
- SK: 22.5 kt fiducial mass. ~100% livetime

T2K: Main Experimental Features

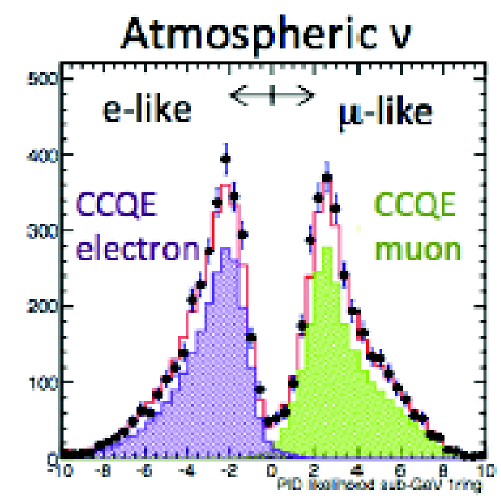




Off-axis beam.
Flux has a narrow peak tuned for the first oscillation maximum



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

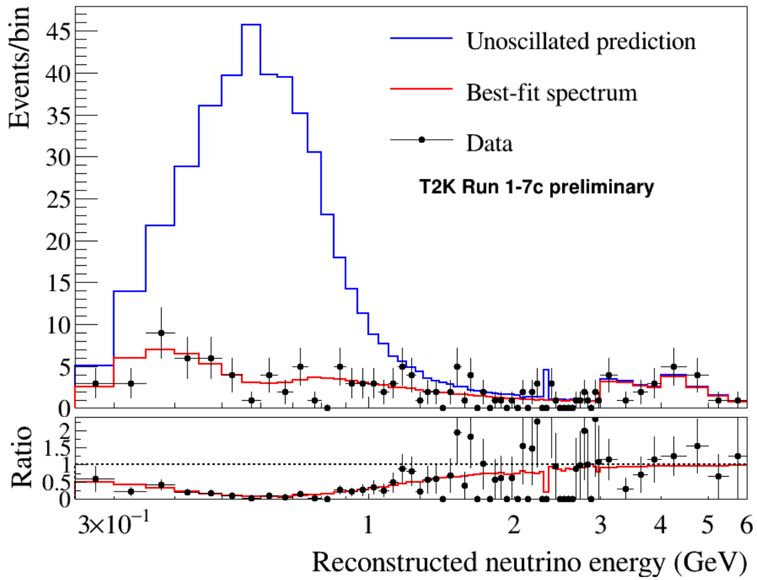


Excellent particle identification capabilities in SK (misid <1%)

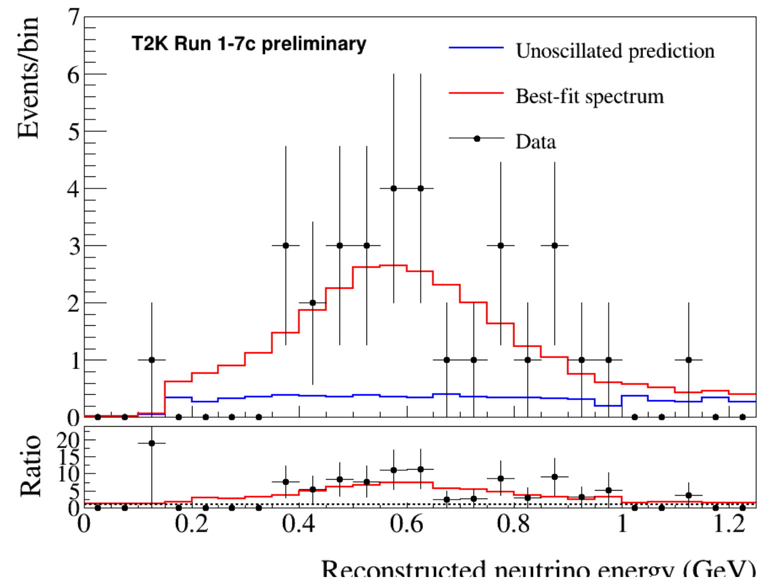
19% of full data set: nu/antinu=1

T2K combined ν_e, ν_μ, $\bar{\nu}_e$, $\bar{\nu}_\mu$ analysis

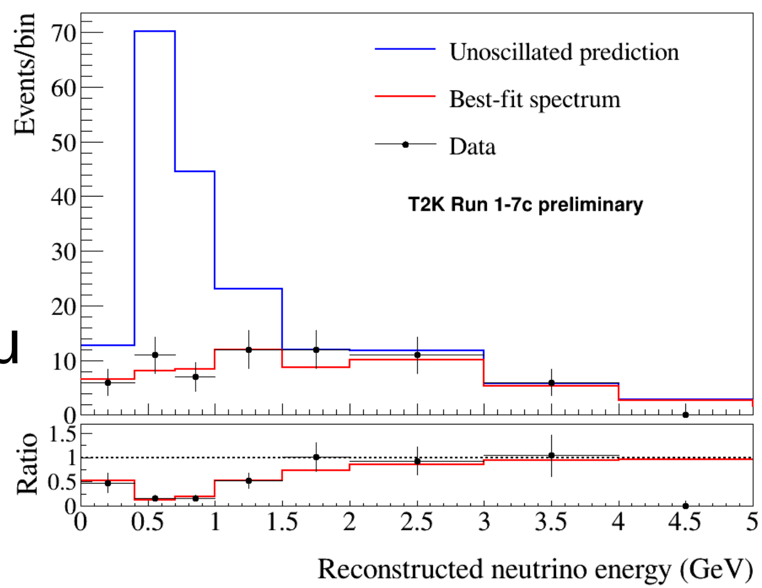
ν_μ



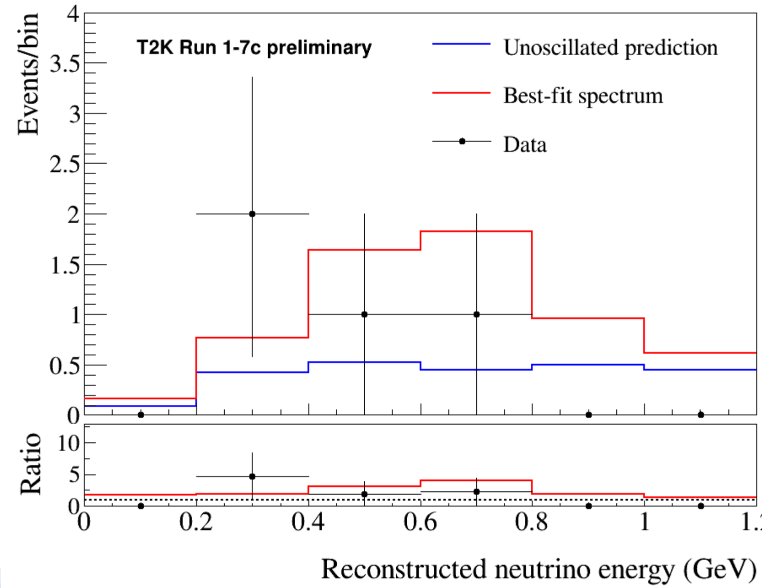
ν_e



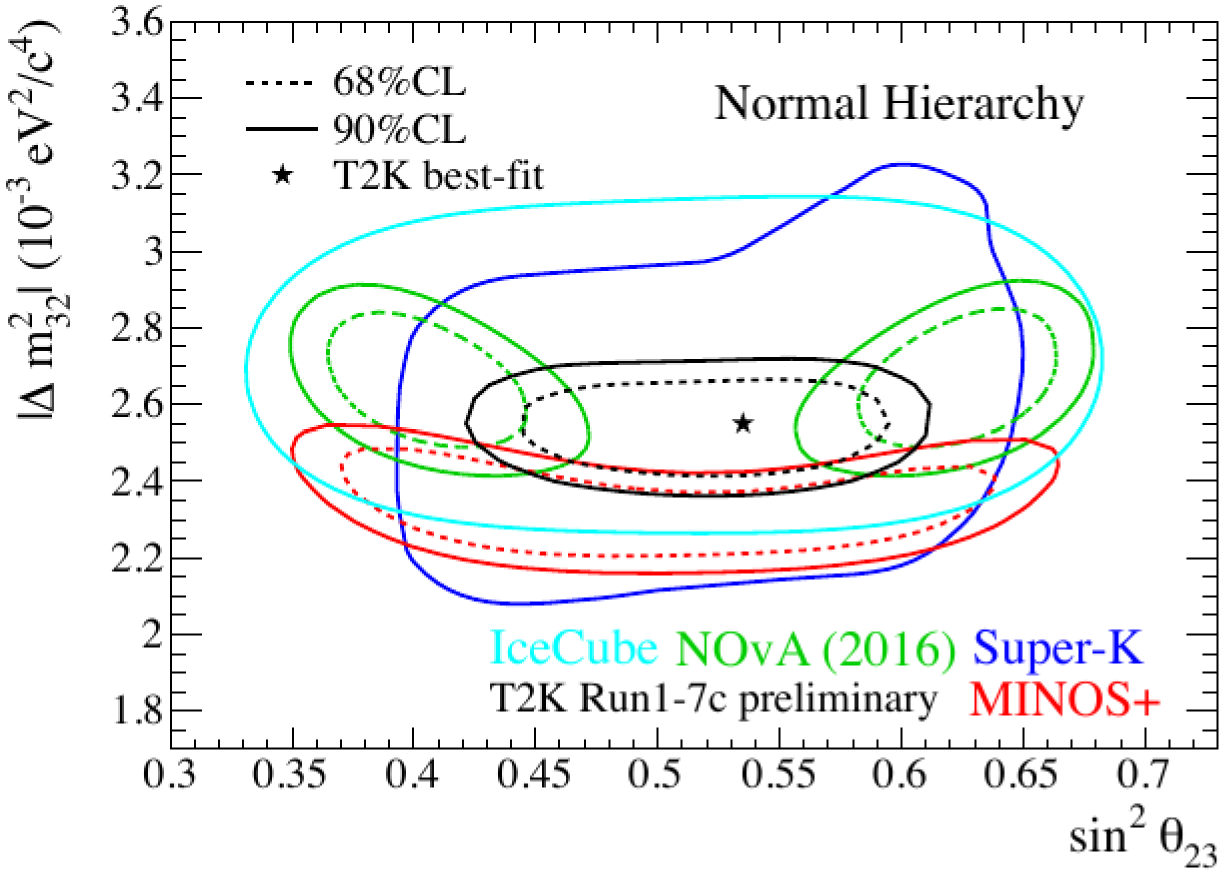
$\bar{\nu}_\mu$



$\bar{\nu}_e$



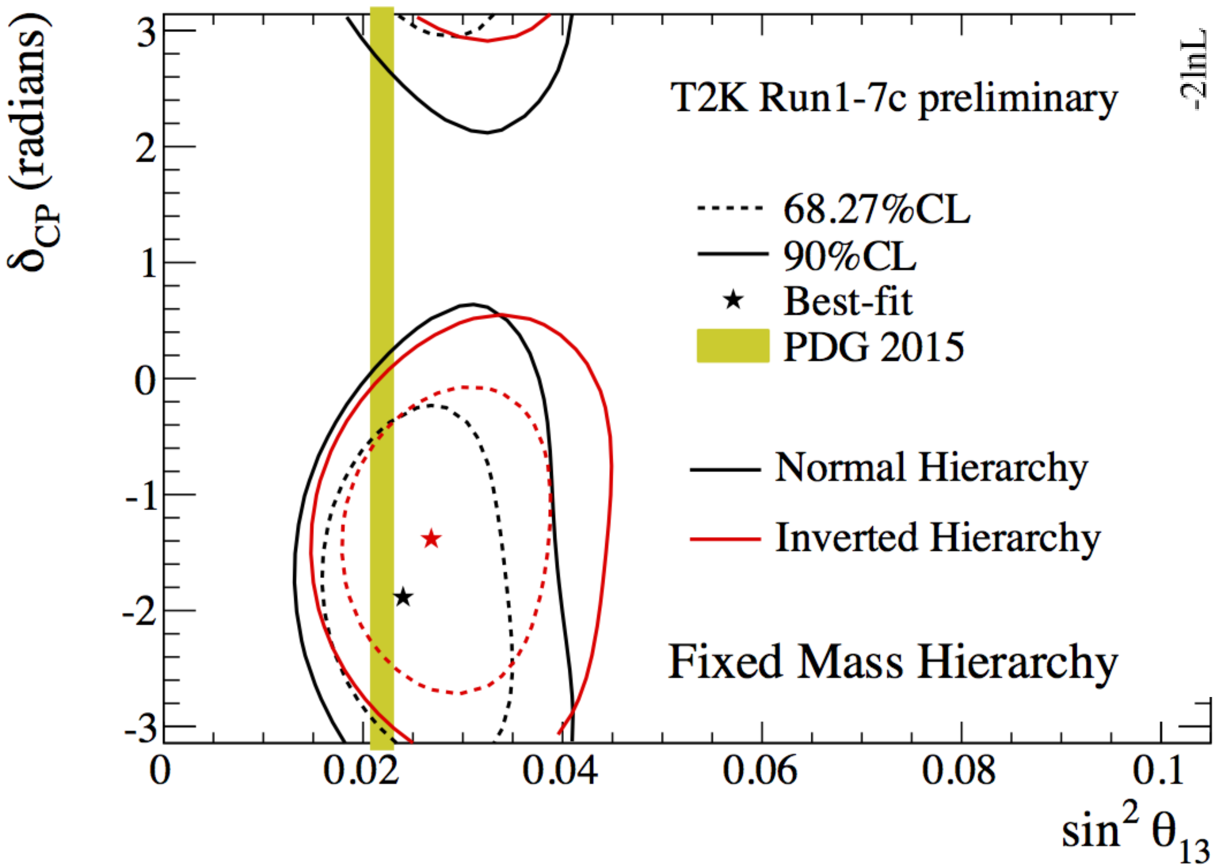
T2K ν_μ disappearance

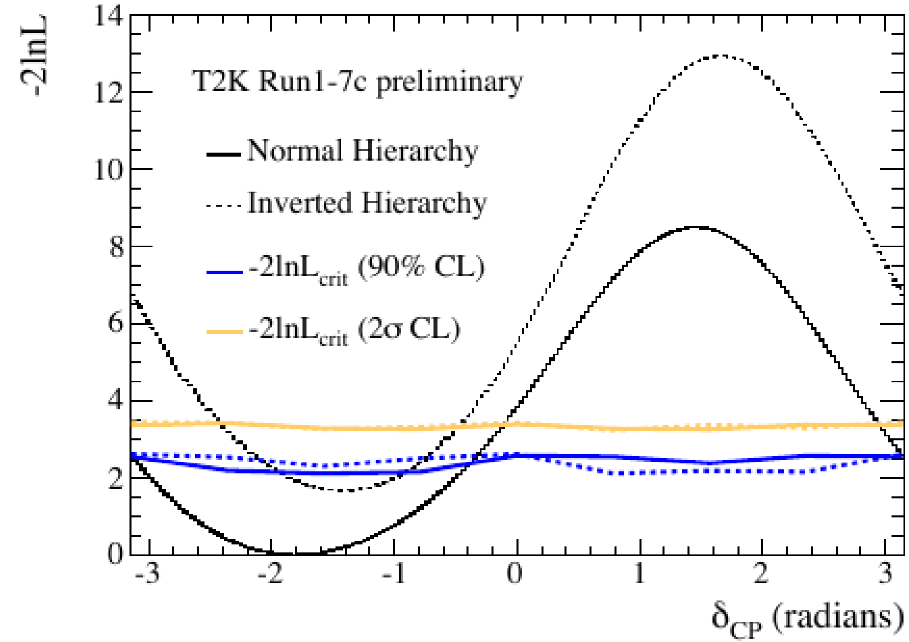


19% of full data set: 50 %nu, 50%antinu

$\nu_\mu \to \nu_e$

T2K first search for CP violation

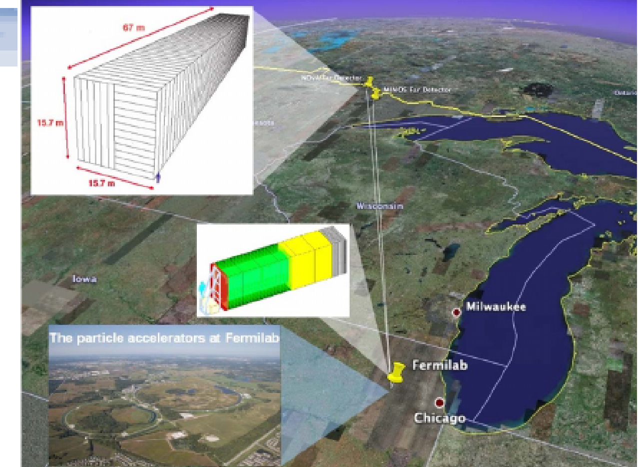




	$\delta_{cp} = -\pi/2$ (NH)	$\delta_{cp} = 0$ (NH)	$\delta_{cp} = +\pi/2$ (NH)	$\delta_{cp} = \pi$ (NH)	Observed
ν_e	28.7	24.2	19.6	24.1	32
$\bar{\nu}_e$	6.0	6.9	7.7	6.8	4

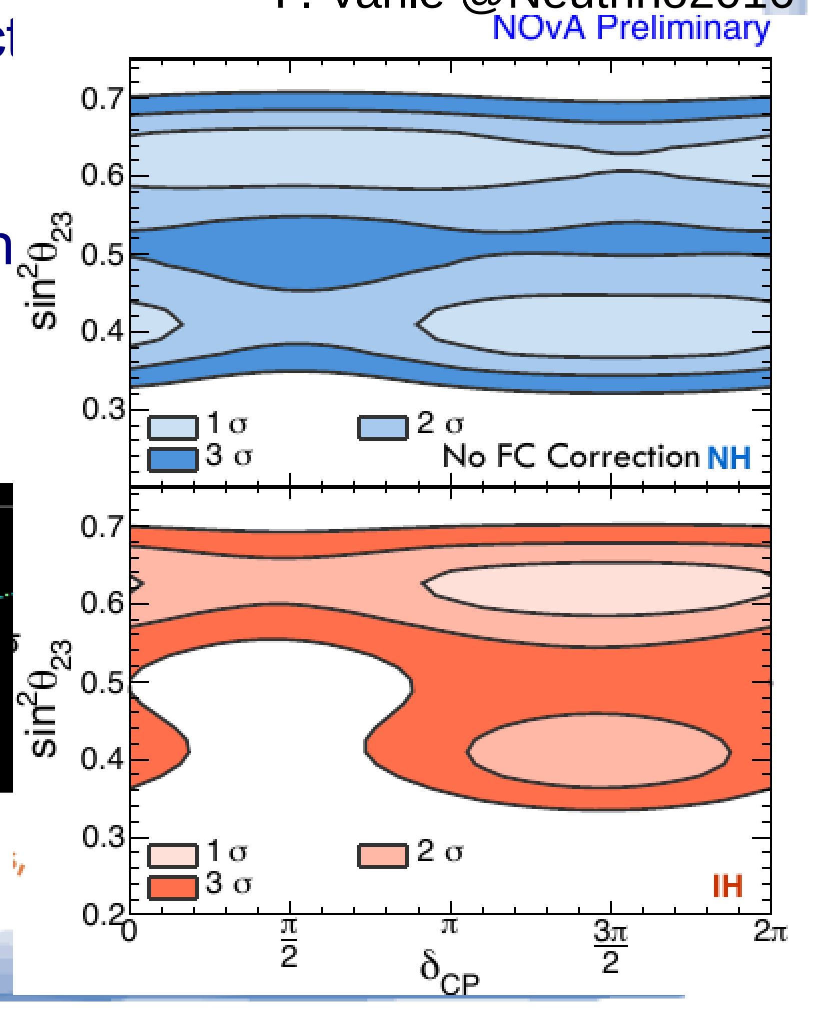
$\nu_\mu \rightarrow \nu_e$

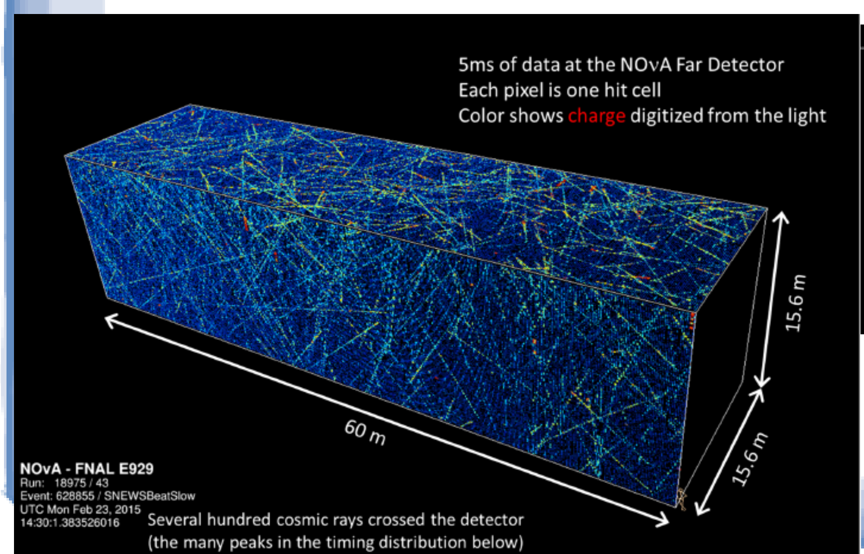
NOvA

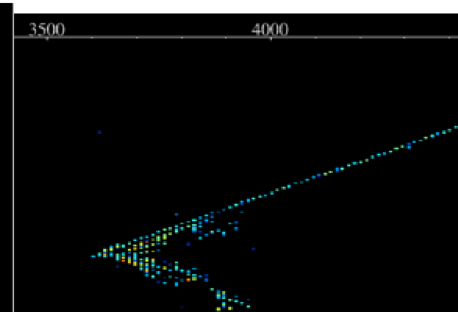


- L=810 km from FNAL to Ash River (Minnesota)
- Off-axis NUMI beam (2 GeV) with 500->700 kW
- 14kt surface liquid scintillator segmented detect
- Weak preference for NH
- Region around delta=π/2 IH excluded, indicatin the same global minimum as T2K

P. Vahle @Neutrino2016







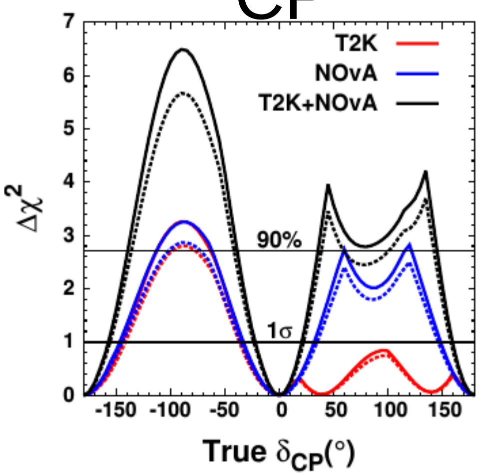
$\nu_\mu \rightarrow \nu_e$

1409.7469

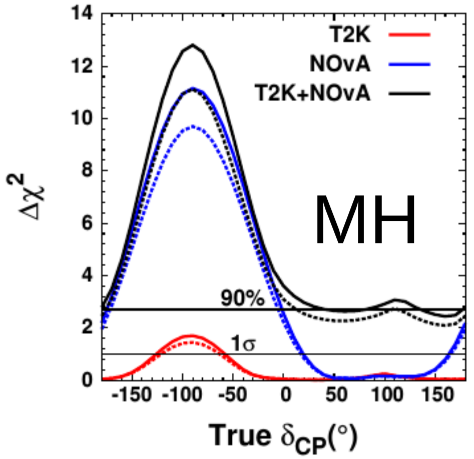
Final reach of T2K and NOvA

- Presently weak indications favoring NH
- Similar sensitivity to CP for T2K and NovA, better sensitivity to MH for NOvA (larger baseline)
- Best sensitivity for δ=-π/2 and NH
- Need more data for a measurement of δ

CP



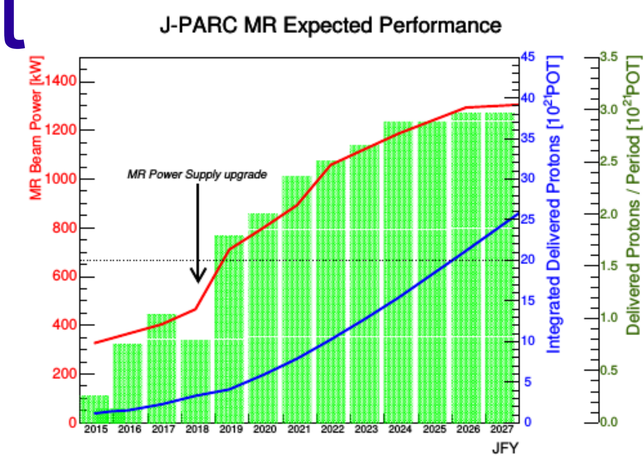
(b) 1:1 T2K, 1:1 NOνA $\nu:\bar{\nu}$, NH

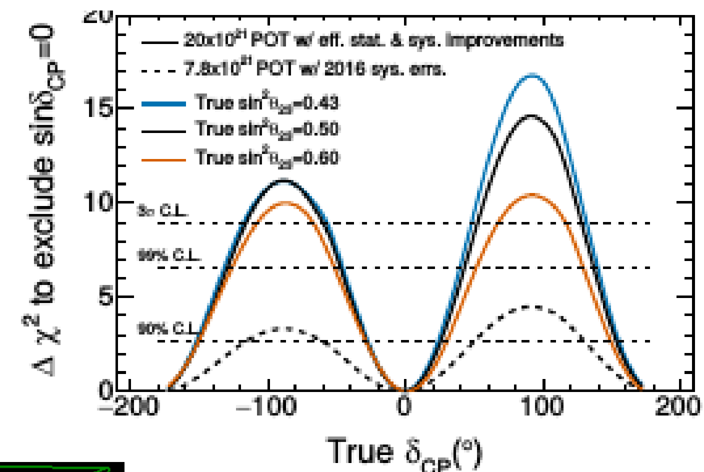


(b) 1:1 T2K, 1:1 NOνA $\nu:\bar{\nu}$, NH

The T2K-II project

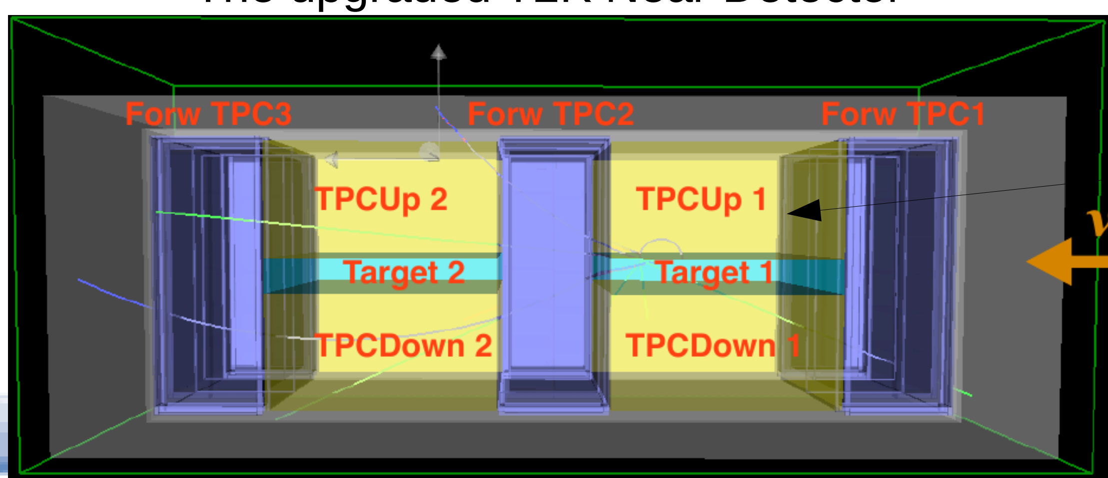
- JPARC MR upgrade approved: beam power up to 1.3 MW
- T2K-II proposal: extend the data taking from 2021 to 2026 with 20 10^{21} POT (~3 times T2K-I)
- 400 nue appearance events, 100 anti-nue, reach 3 σ for δ_{CP}
- Upgrade of the near detector is foreseen with state of the art new TPCs and other detectors, CERN workshop https://indico.cern.ch/event/568177/





The T2K TPC

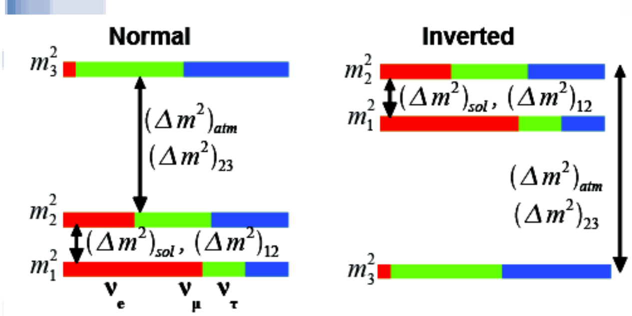
The upgraded T2K Near Detector

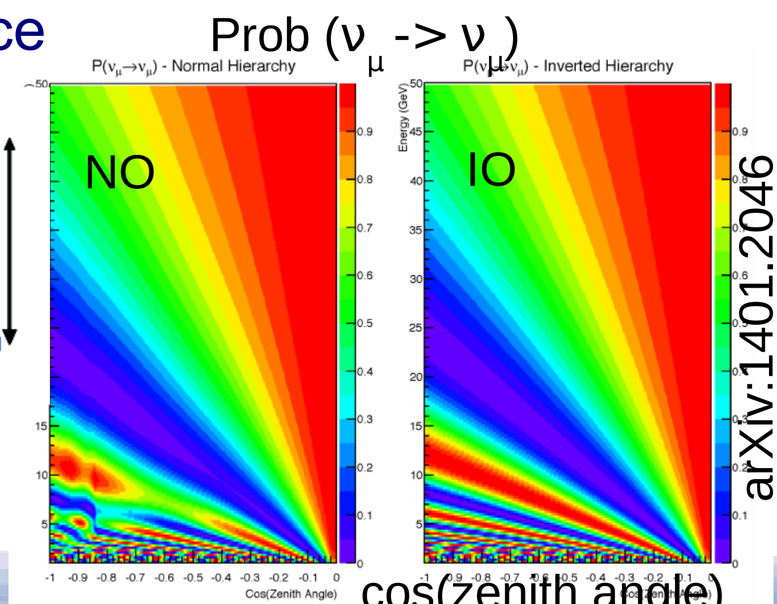


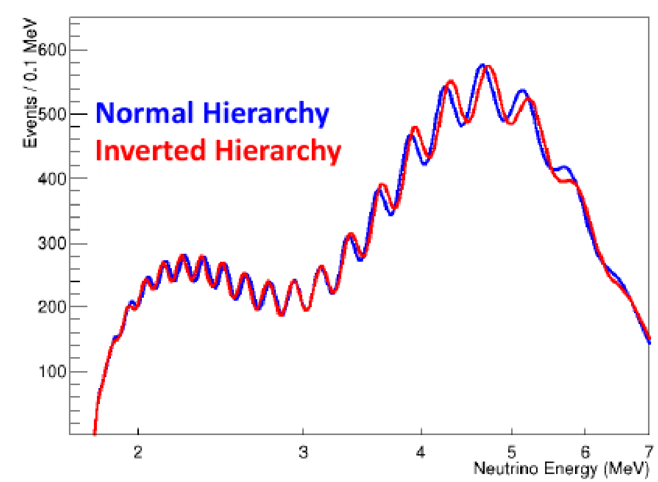
New TPCs to be built with MPGD devices

The neutrino mass ordering

- This fundamental question, with implication for neutrino mass models, cosmology, 0-nu double beta decays etc. is still open
- Neutrino propagation in the Earth matter enhances $\nu_\mu \to \nu_e$ or $\bar{\nu}_\mu \to \bar{\nu}_e$ depending on the ordering (MSW effect)
- This effect can be observed with long baseline experiments (NOvA, DUNE) or with atmospheric neutrinos (PINGU, Orca, INO, HK)
- The 20 kt Liquid Scintillator JUNO experiment under construction will attempt to measure this ordering with reactor neutrinos at 50 km from the source





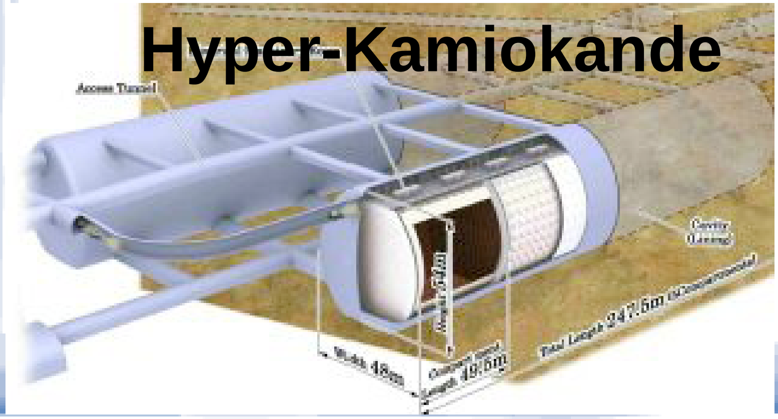


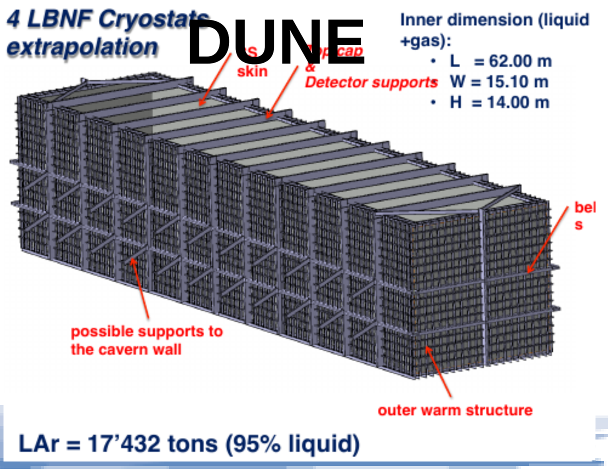
Neutrino energy, JUNO, before energy resolution smearing

New Long Baseline facilities

Strategies for CP

- Short baseline (~100-300 km), lower energy (<1 GeV), narrow beam, large Water Cherenkov (~500 kT). Concentrates on $\nu/\bar{\nu}$ asymmetry around the first oscillation max.
- Longer baseline (>1000 km), higher energy (>1 GeV), wide beam, Liquid Argon TPC (40 kT). All final states accessible, E/L oscillation pattern and second maximum

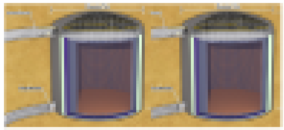


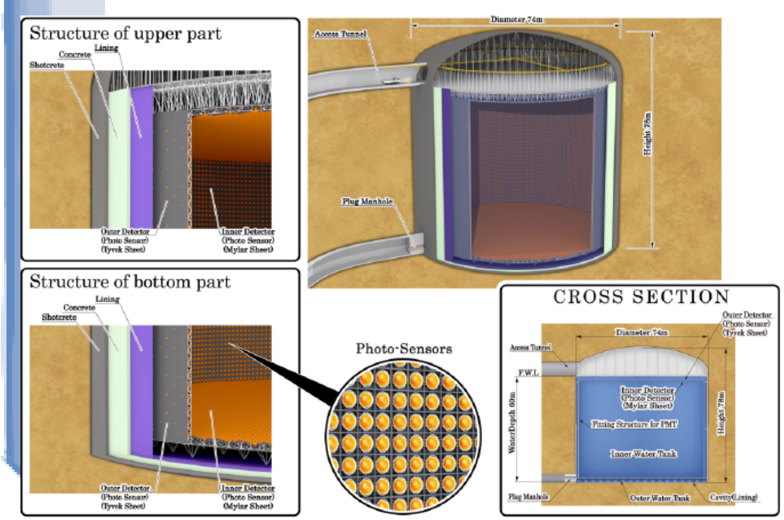


KEK Preprint 2016-21

Hyper-Kamiokande

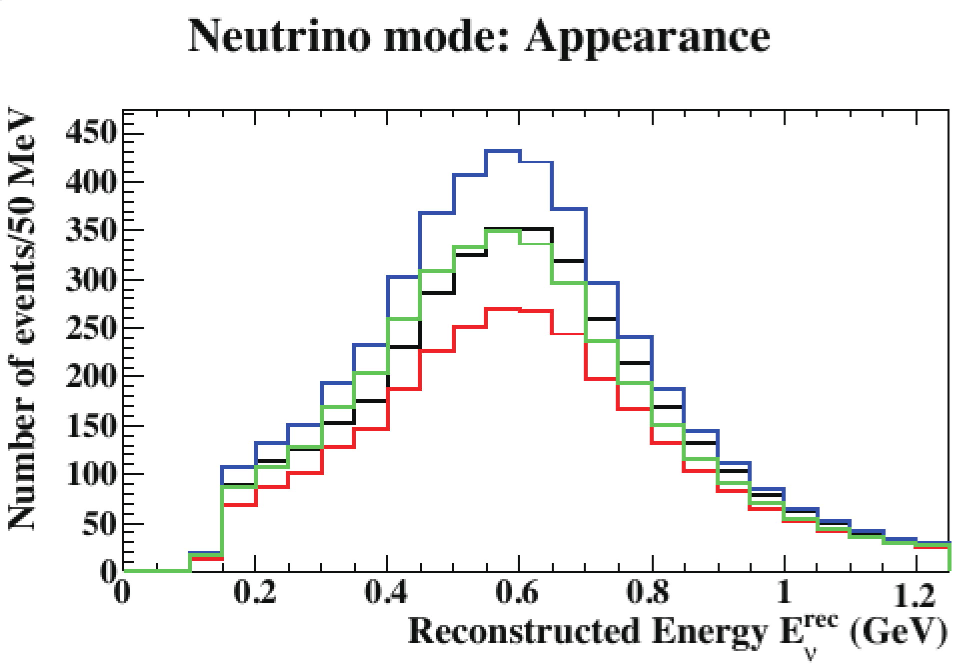
- Tokai to Kamioka 295 km baseline with the same off-axis beam as T2K (upgraded to 1.3 MW)
- 0.19x2 Mt fiducial mass based on the Water Cherenkov technique
- Selected as top priority in Japanese Master Plan of Large Research Project
- Design Report just out
- Timescale: data taking in 2026

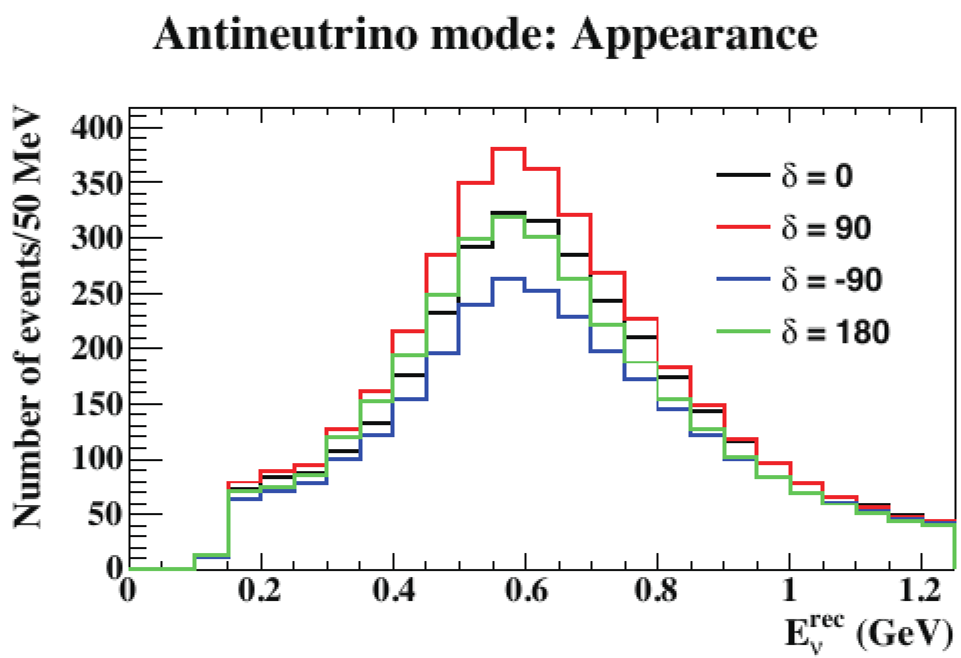
	Super-K (SK)	Letter-of-Intent 2011 (LOI)	2 Tanks w/ High Photodetector density (2HD)
			
Total Volume (Fiducial Volume)	0.05Mton (0.022Mt)	1Mt (0.56Mt)	0.52Mt (0.38Mt)
Dimension	39mΦ × 42m (H)	48 (W) × 54 (H) × 250 (L) m³ ×2	74mΦ × 60m(H) ×2
ID #of Photo-sensors (coverage)	11k (Super-K PMT) (40%)	99k (Super-K PMT) (20%)	80k (B&L) (40%)
Single-photon detection efficiency	12%	12%	24%
Photon-yield	1	0.5	2
single-photon timing resolution	~2nsec	~2nsec	1nsec
Beam power		0.75 MW	1.3 MW

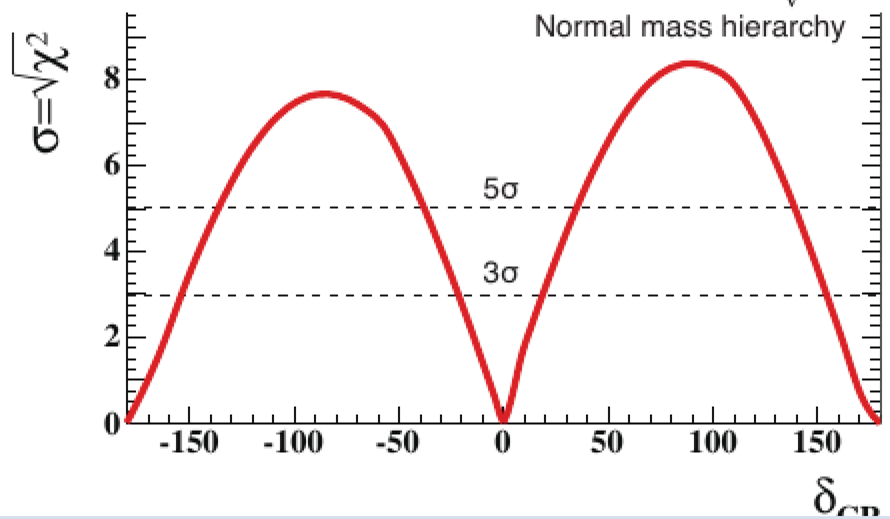


Hyper-Kamiokande CP sensitivity

Arxiv:1502.05199



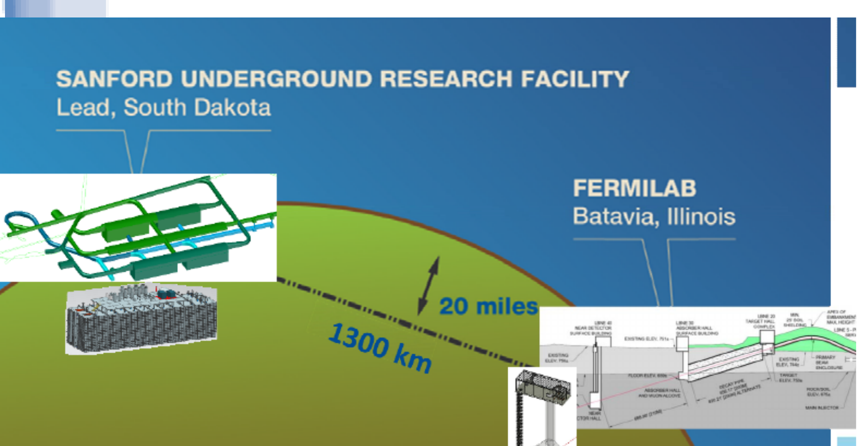




- >3000 ν_e appearance events (nu-mode) with ~700 bck
- Systematics extrapolated from T2K analysis (signal 3% nu mode)
- CPV >3 σ for 76% of δ values

The LBNF/DUNE project

- LBNF DUNE: flagship particle physics project in the US (P5 recommendation)
- 1300 km baseline from FNAL to SURF (South Dakota)
- Based on PIP-II upgrade to FNAL accelerator complex: 1.2 MW at 120 GeV (ultimate beam power 2.4 MW)
- SURF: 4 caverns with 4x10 kt fiducial mass far detector

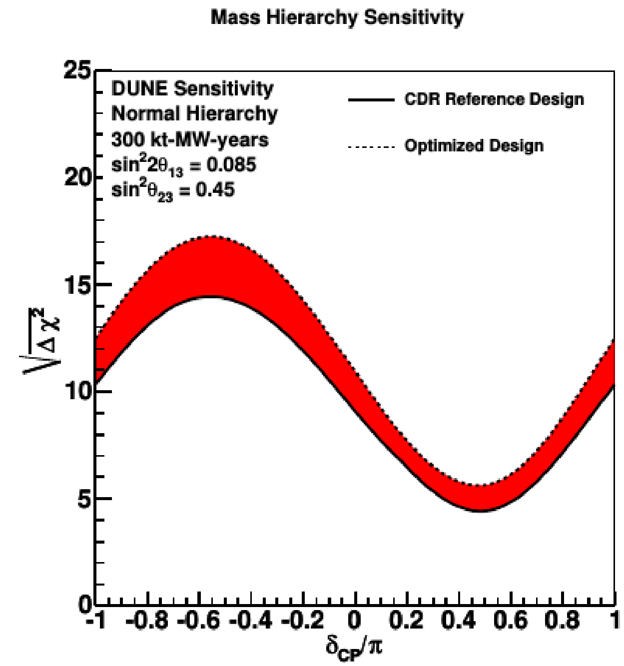


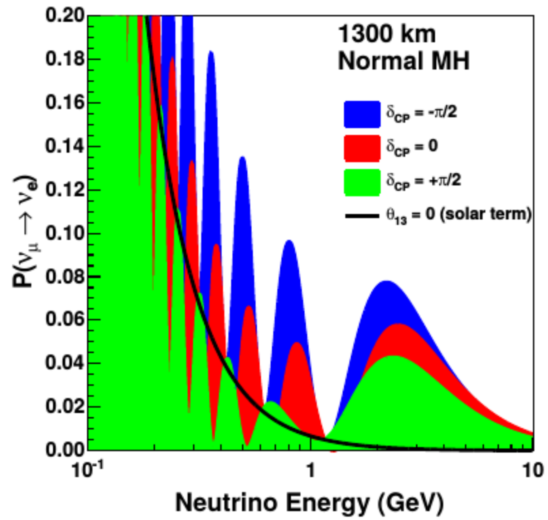
CDR released July 2015: CD1 passed, CD3-a (excavation) approved. CD2 (TDR) in 2019.
LBNF LOI: deployment of first 10kt module in 2021
Collaboration strengthened (>700) and more international (India, CERN, Laguna-LBNO)

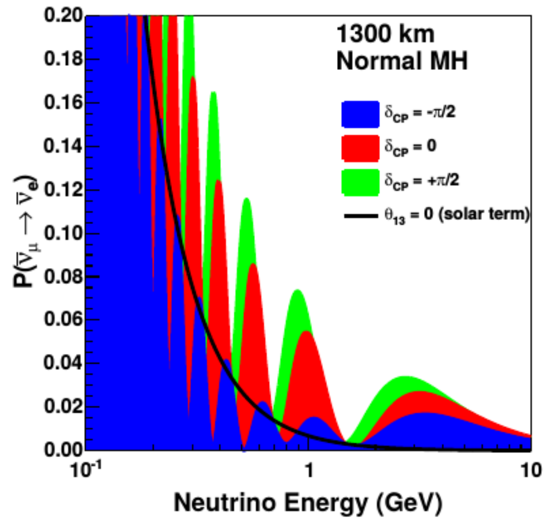
ArXiv:1512.06148

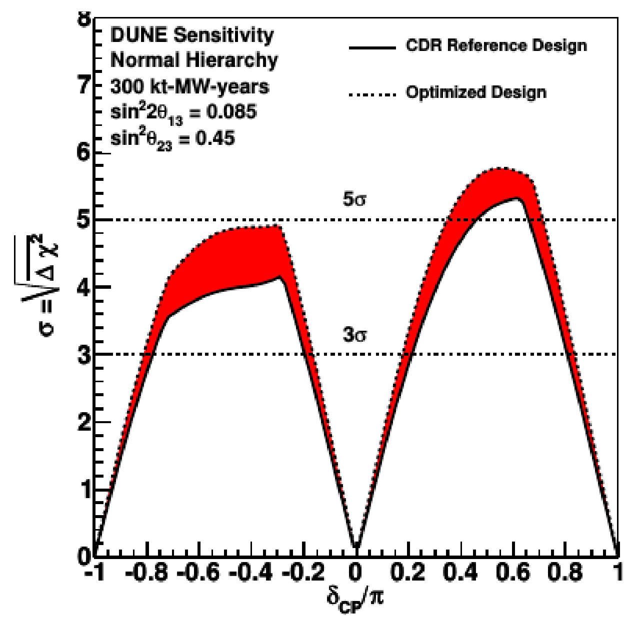
LBNF/DUNE sensitivity

- >3 σ for CP sensitivity over a large fraction of the phase space
- >5 "σ" for Mass Ordering
- 300 kt-MW-years = 3.5 (nu)+3.5 antinu) with 40kt and 1.07 MW beam (80 GeV)





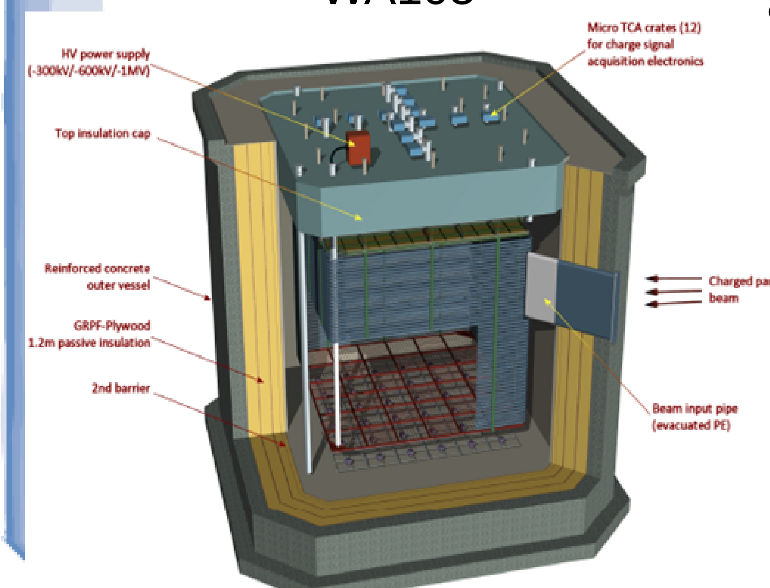




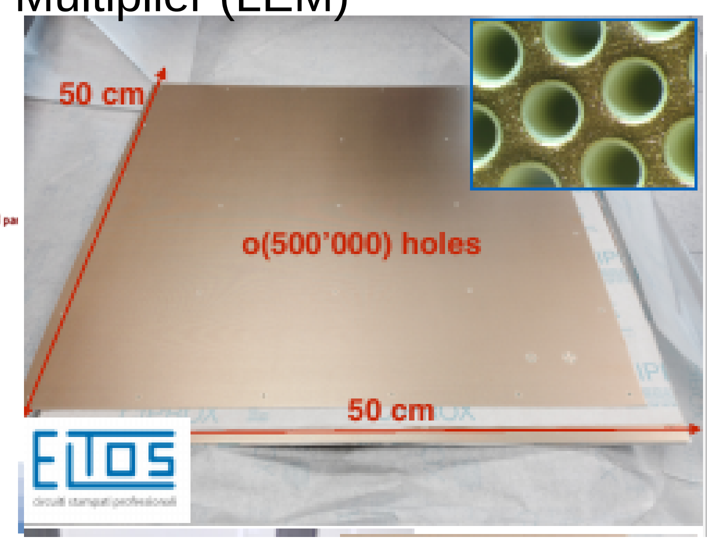
R&D on neutrino detectors at CERN

- After the decision of the European Strategy in 2013, CERN has created a Neutrino Platform for the development of neutrino detectors for DUNE, Hyper-Kamiokande etc.
- The main projects so far are WA104 (Icarus refurbishment), WA105 (demonstrator of double phase Liquid Argon TPC) and ProtoDune-Single Phase. These two will be tested with a charged particle beam in 2018

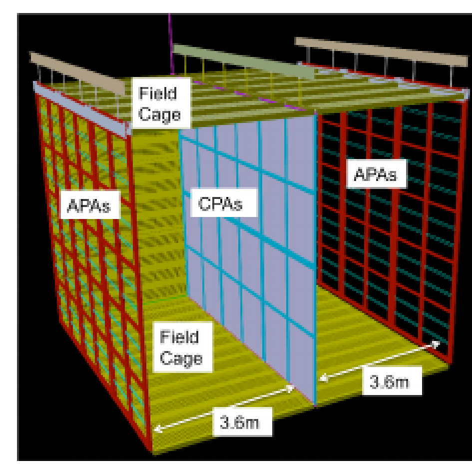
WA105



Double phase concept: gas amplification in Large Electron Multiplier (LEM)



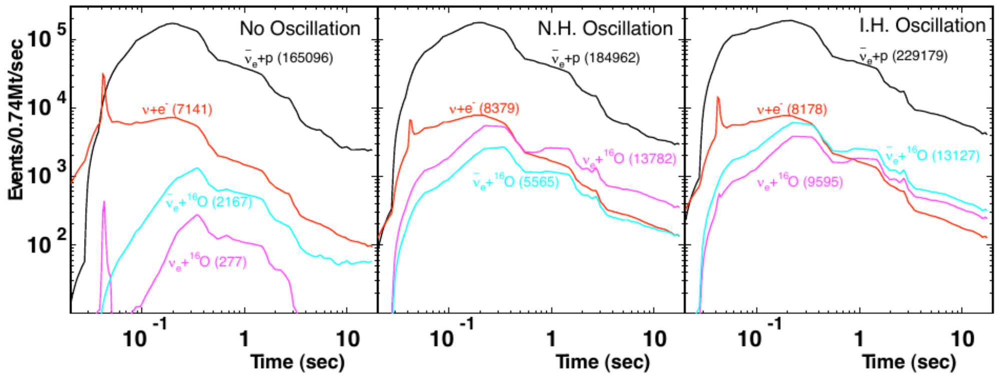
Proto-DUNE-SP



Proton decay studies and neutrinos from the universe

- Large underground detectors like JUNO, DUNE and Hyper-Kamiokande are excellent observatories for a variety of non-accelerator physics studies
- Search for proton decay can attain limit of 10^{35} years
- Neutrinos from Supernova explosions : up to several 10^5 (to be compared to 24 for SN1987A). Liquid argon: tag ν_e with $\nu_e\ {}^{40}Ar \rightarrow e^-\ {}^{40}K^*$
- 200 solar ν/day at HK
- Study of atmospheric neutrinos: mass ordering
- Large complementarity between different detection techniques

SN neutrino burst in the HK detector



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. This requires a matching precision in the control of the beam flux, composition and neutrino cross-sections
- T2K and NOVA give first indications on δ_{CP} (20% of POT), data taking until 2021 (2026 for T2K-II)
- In the next decade new long baseline projects (Hyper-Kamiokande, DUNE) will explore a large fraction of the δ_{CP} parameter with unprecedented precision