Current Status and Future Prospects of Neutrino Oscillations

Yifang Wang
Institute of high energy physics
Invisibles 15， June 24， 2015

Neutrino Oscillation

- **If the neutrino mass eigenstate is different from that of the weak interaction, neutrinos can oscillate: from one type to another during the flight:**

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

Oscillation probability:

$$P(\nu_e \to \nu_\mu) = \sin^2(2\theta)\,\sin^2(1.27\Delta m^2 L/E)$$

Oscillation amplitude (θ) · **Oscillation frequency** (Δm^2)

Oscillation matrix for 3 generations:

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}V_{e1} & V_{e2} & V_{e3}\\ V_{\mu1} & V_{\mu2} & V_{\mu3}\\ V_{\tau1} & V_{\tau2} & V_{\tau3}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

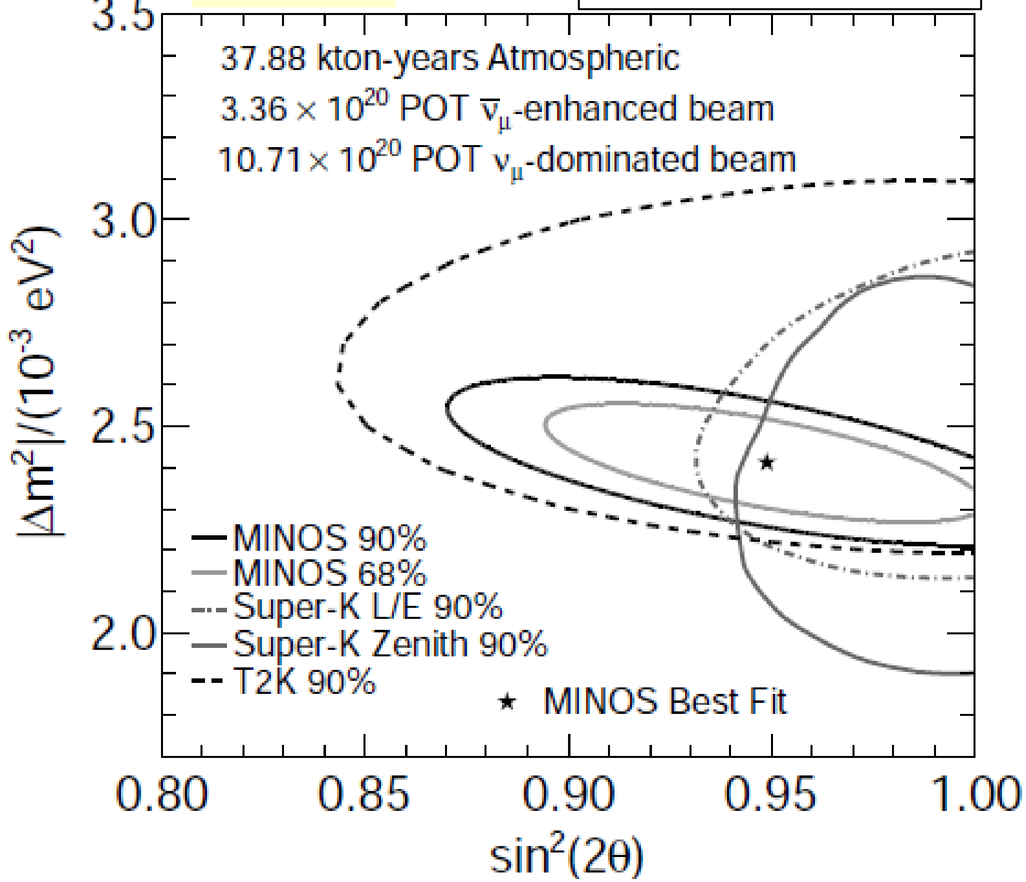
- **Known parameters:** θ_{23}, θ_{12}, $|\Delta M^2_{23}|$, ΔM^2_{12}
- **Recent progress:** θ_{13}
- **Unknown parameters:** mass hierarchy(ΔM^2_{23}), CP phase δ

Atmospheric Neutrinos

- **Determination of θ_{23} & $|\Delta M^2_{23}|$**
- **Current experiment: SuperK, Icecube**
  - ⇨ **Still improves θ_{23} & $|\Delta M^2_{23}|$**
  - ⇨ **3 flavor analysis for**
    - ✓ **θ_{23} octant**
    - ✓ **mass hierarchy**
    - ✓ **CP phase**
- **Future experiments**
  - ⇨ **INO, PINGU/Icecube, HyperK**

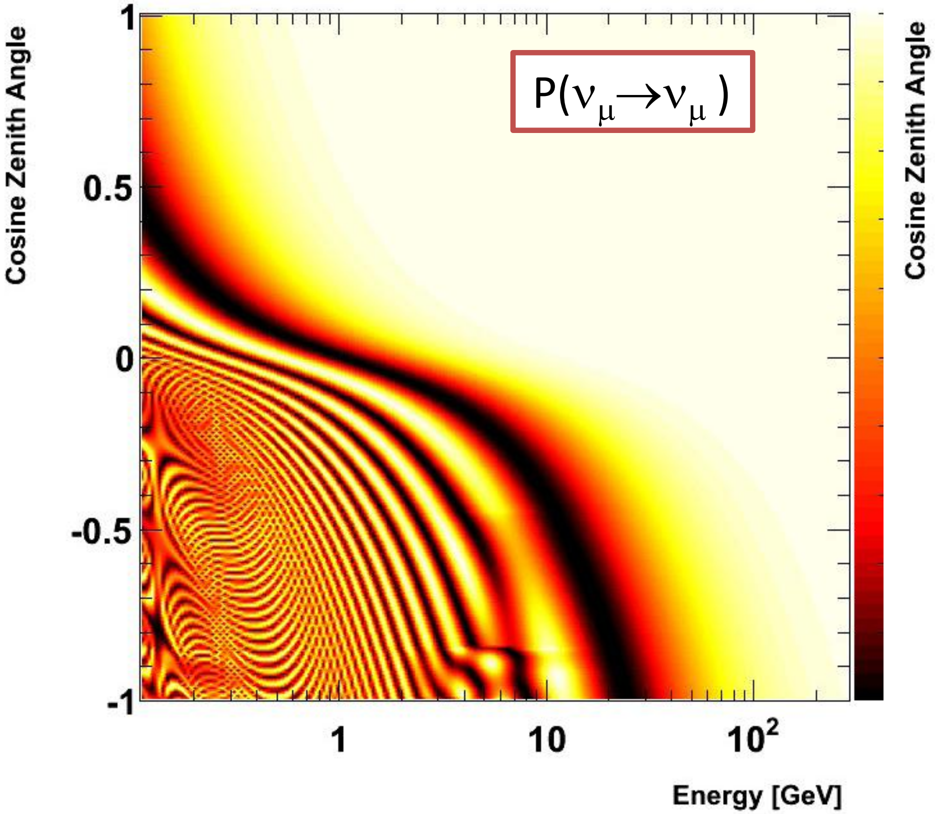
MINOS

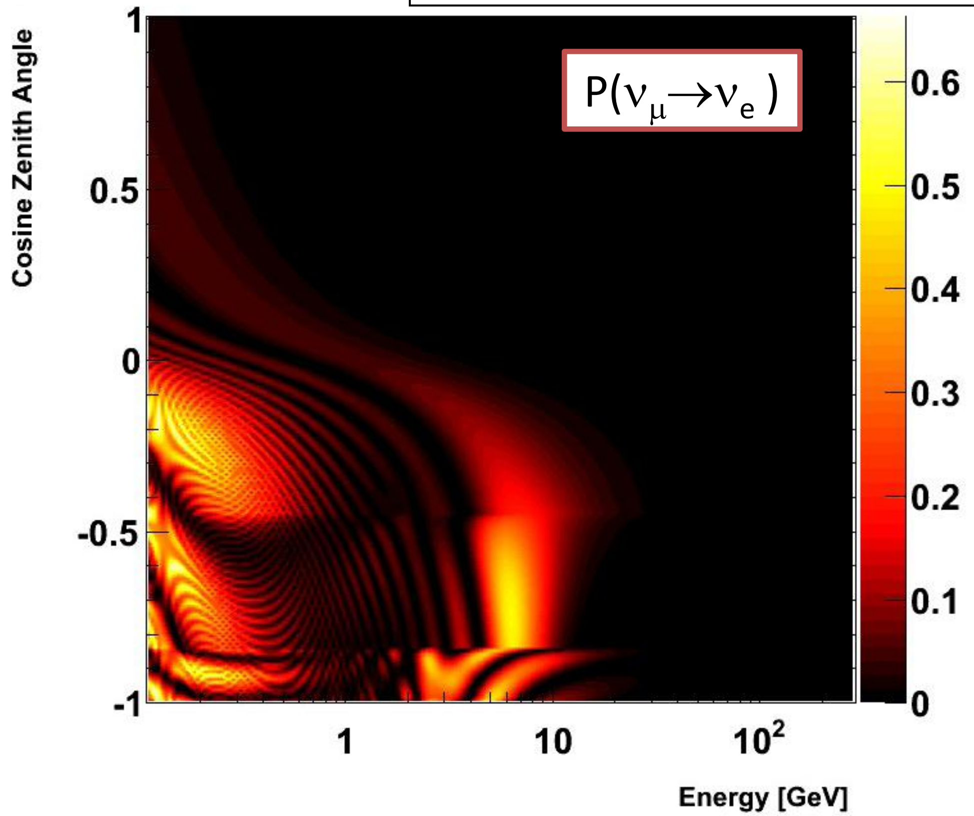
ArXiv:1304.6335



Three Flavor analysis: Sub-leading Effects

Roger Wendell@Neutrino 2014

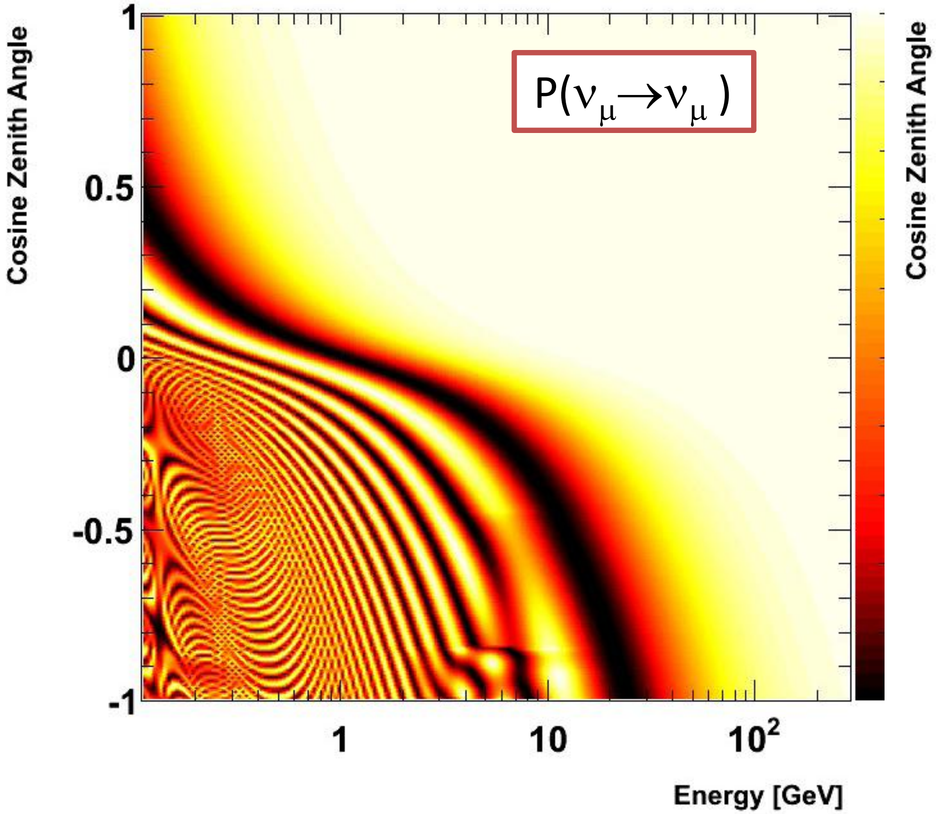


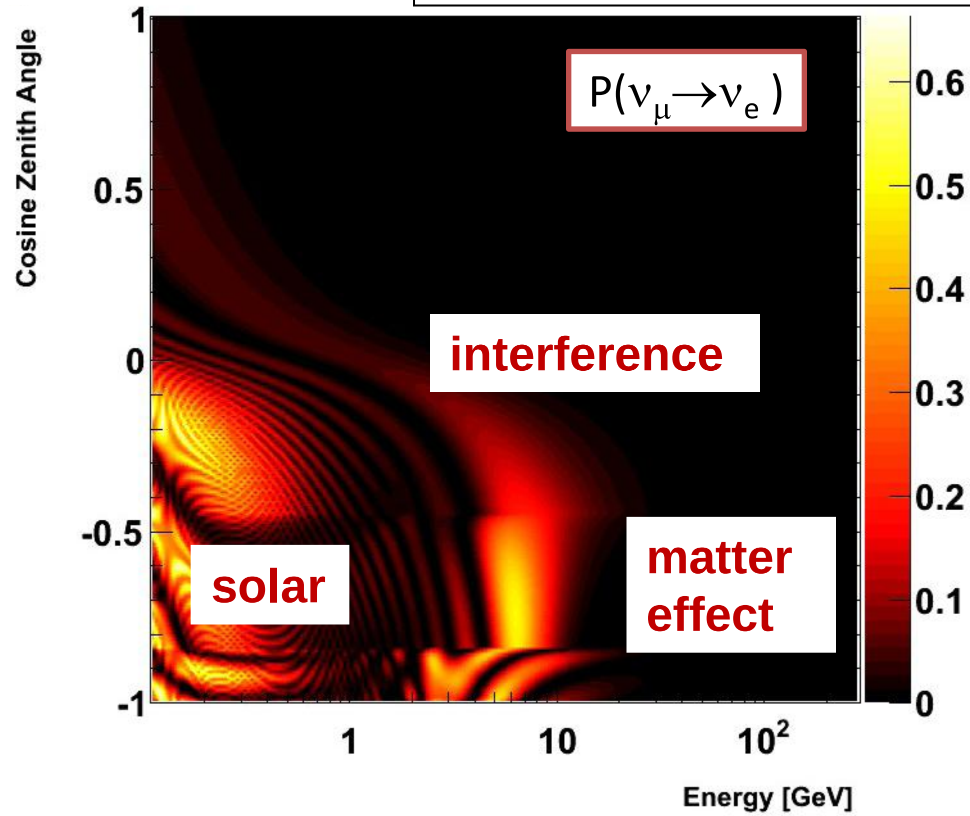


- Thanks to the huge statistics and large θ_{13}, we can look for:
  - Mass hierarchy: enhanced high E upward going ν_e due to the matter effect
  - Octant of oscillation: enhanced low energy ν_e due to the solar term
  - CP phase δ: interference between these two

Three Flavor analysis: Sub-leading Effects

Roger Wendell@Neutrino 2014

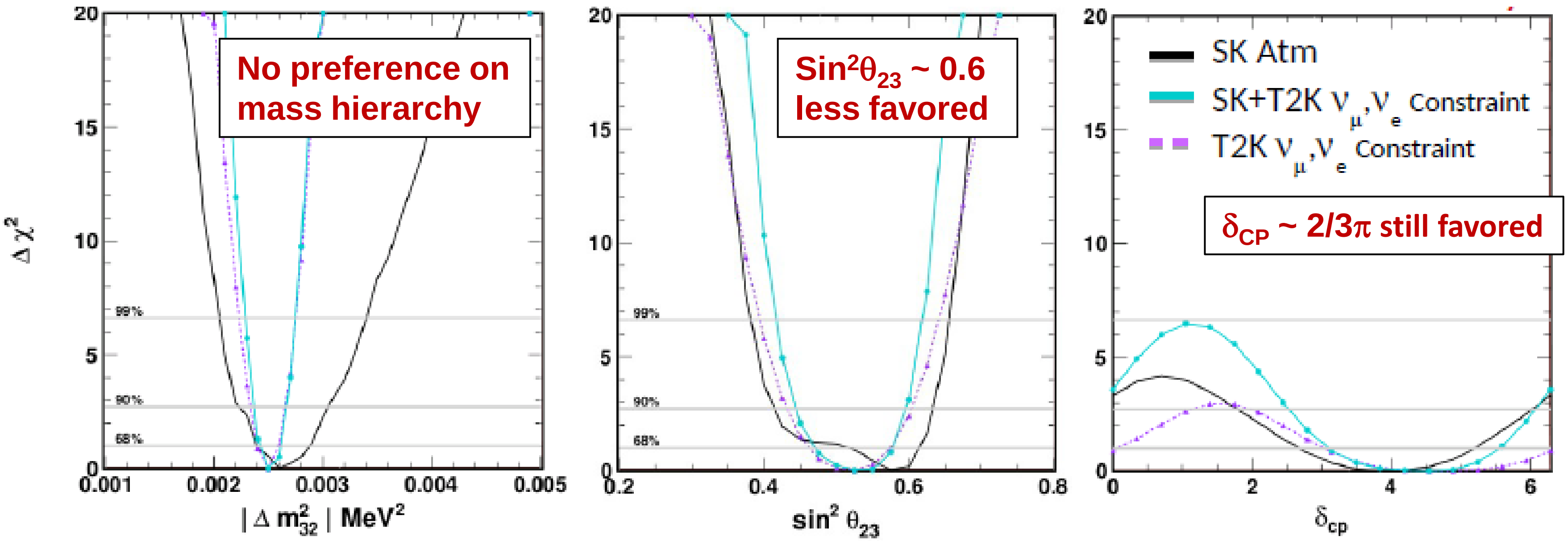




- Thanks to the huge statistics and large θ_{13}, we can look for:
  - Mass hierarchy: enhanced high E upward going ν_e due to the matter effect
  - Octant of oscillation: enhanced low energy ν_e due to the solar term
  - CP phase δ: interference between these two

Fitting Results: SuperK + T2K

R. Wendall@neutrino2014



Fit (543 dof)	χ^2	θ_{13}	δ_{cp}	θ_{23}	$\Delta m_{23}(x10^{-3})$
SK + T2K (NH)	578.2	0.025	4.19	0.55	2.5
SK + T2K (IH)	579.4	0.025	4.19	0.55	2.5

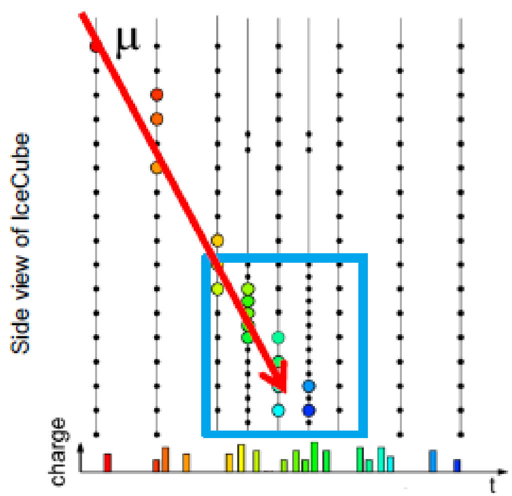
- $\chi^2_{IH} - \chi^2_{NH}$ = **-1.2** (-0.9 SK only)
- CP Conservation ($\sin\delta_{cp}$ = 0) allowed at (at least) 90% C.L. for both hierarchies

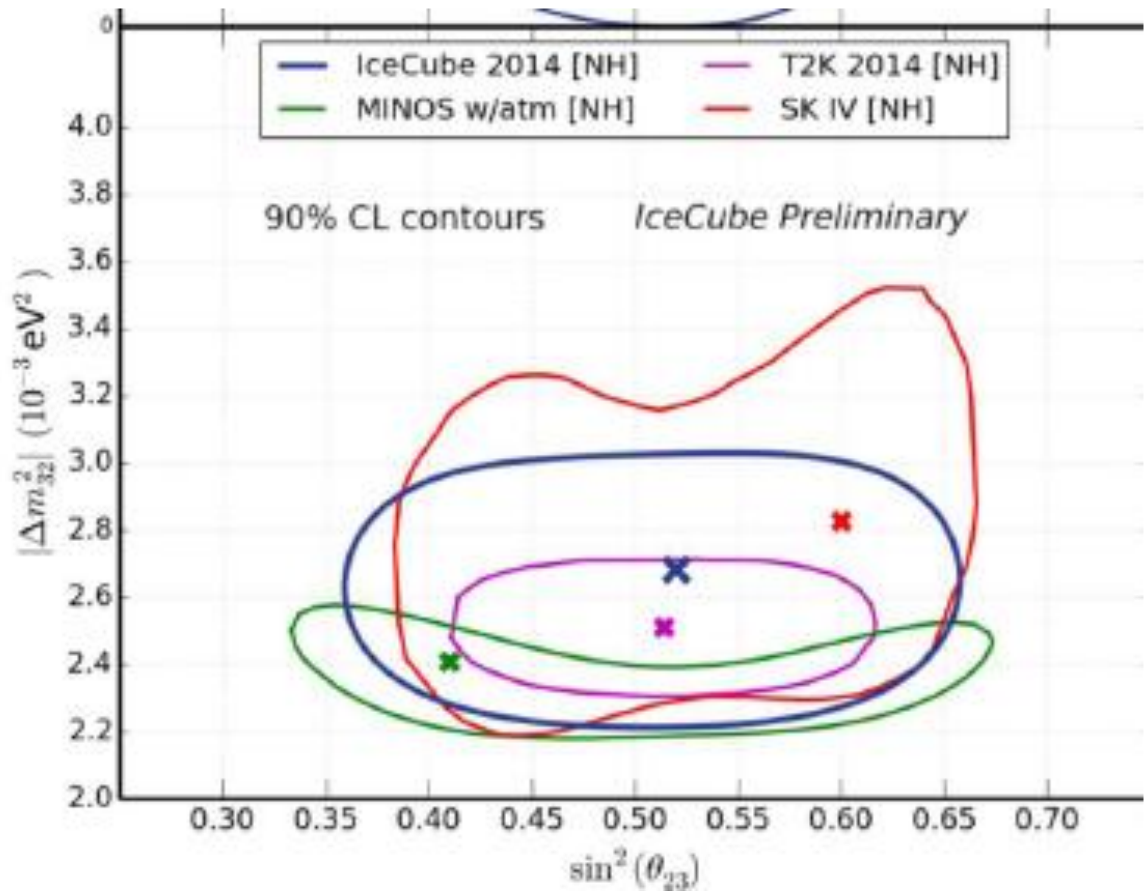
Same detector, generator and reconstruction: easy for systematic error correlation
MINOS is not included yet

IceCube/DeepCore

- IceCube: 5160 PMTs over 1 km^3,DeepCore: 600 PMTs over 0.02 km^3
- Sensors separation: 7-70 m, Light yield： a few p.e. @ 10 GeV
- Cosmic-μ rate is 10^6 higher than ν
- Already better than SuperK !

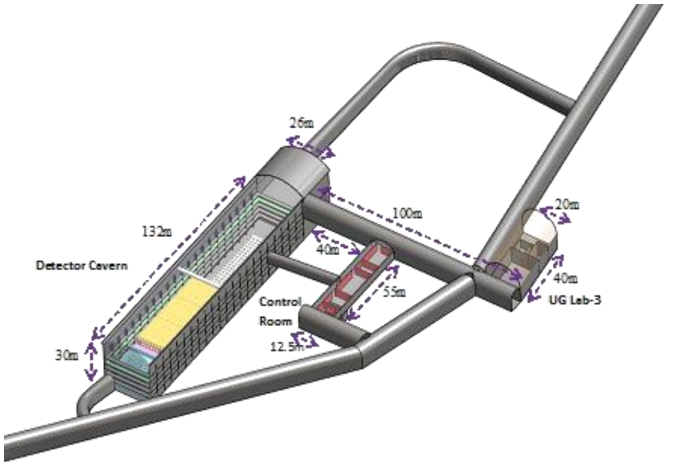
J.P. Yáňez@neutrino2014

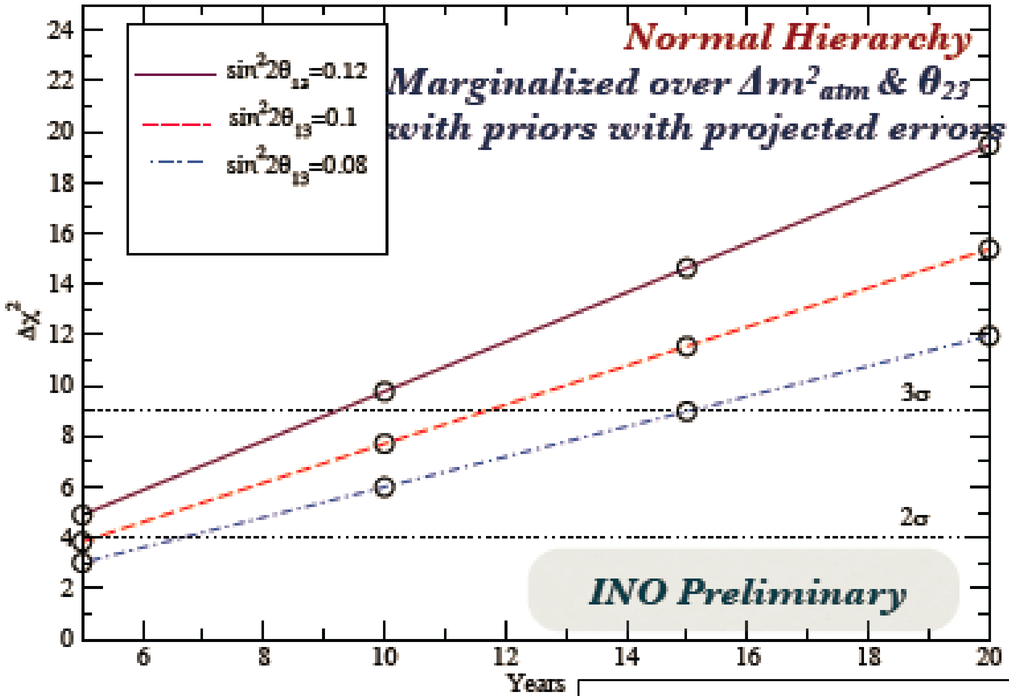




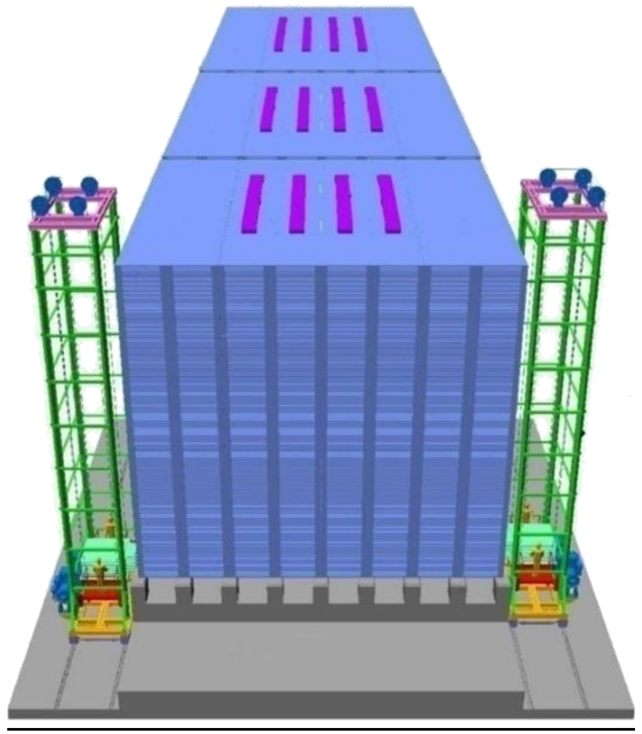
Future experiment: INO

- INO(India-based Neutrino Observatory): 50kt magnetized iron plates interleaved with RPCs: Sign sensitive
- Construction started, operational: 2018
- Sensitivity to mass hierarchy: ~3σ after 10 years running



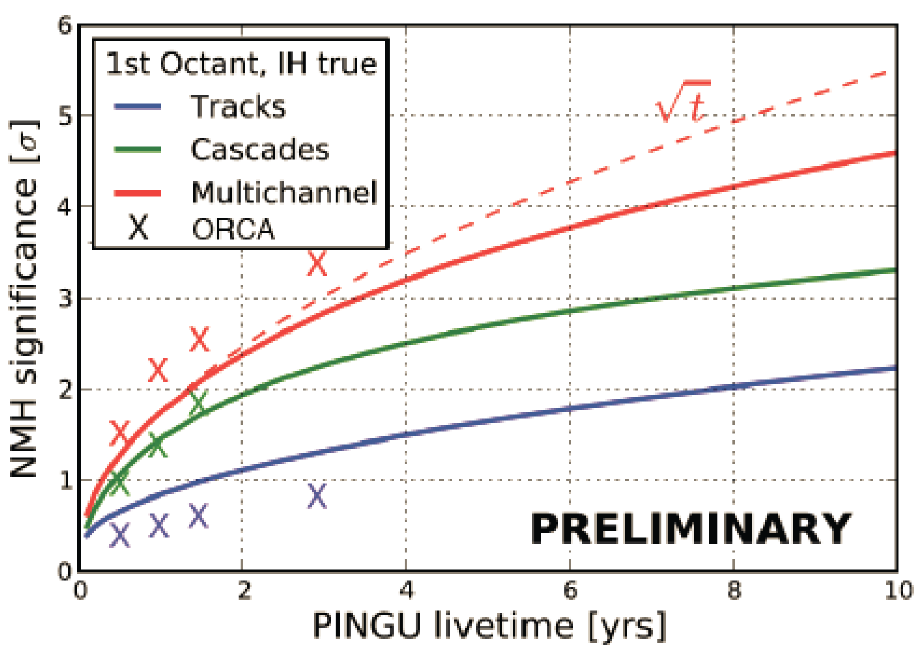


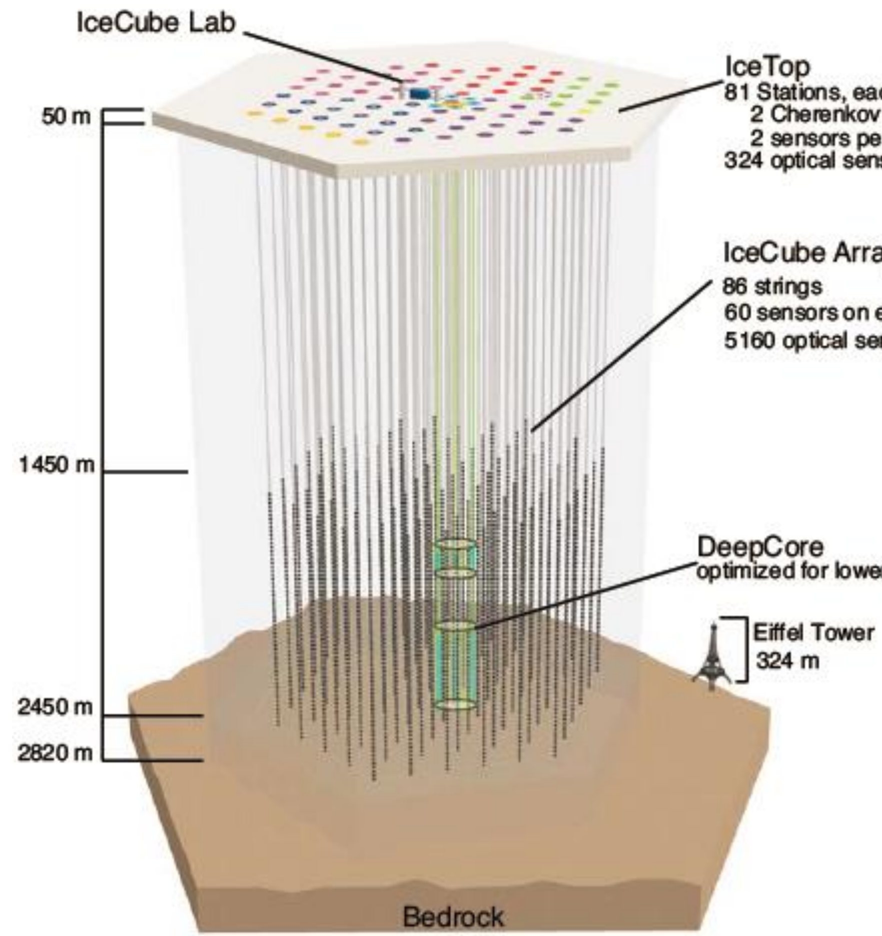
Choubey@neutrino'12



Future experiments: PINGU(& ORCA)

- **A large ice Cerenkov detector with E_{thresh} < 10 GeV**
  - ⇨ **Add 40 strings with 20 m spacing**
  - ⇨ **~ 20× photocathode density**
  - ⇨ **Existing IceCube as the VETO**
- **Equivalent target mass: +10 Mt**
- **Sensitivity: ~ 3σ in ~ 3 years**



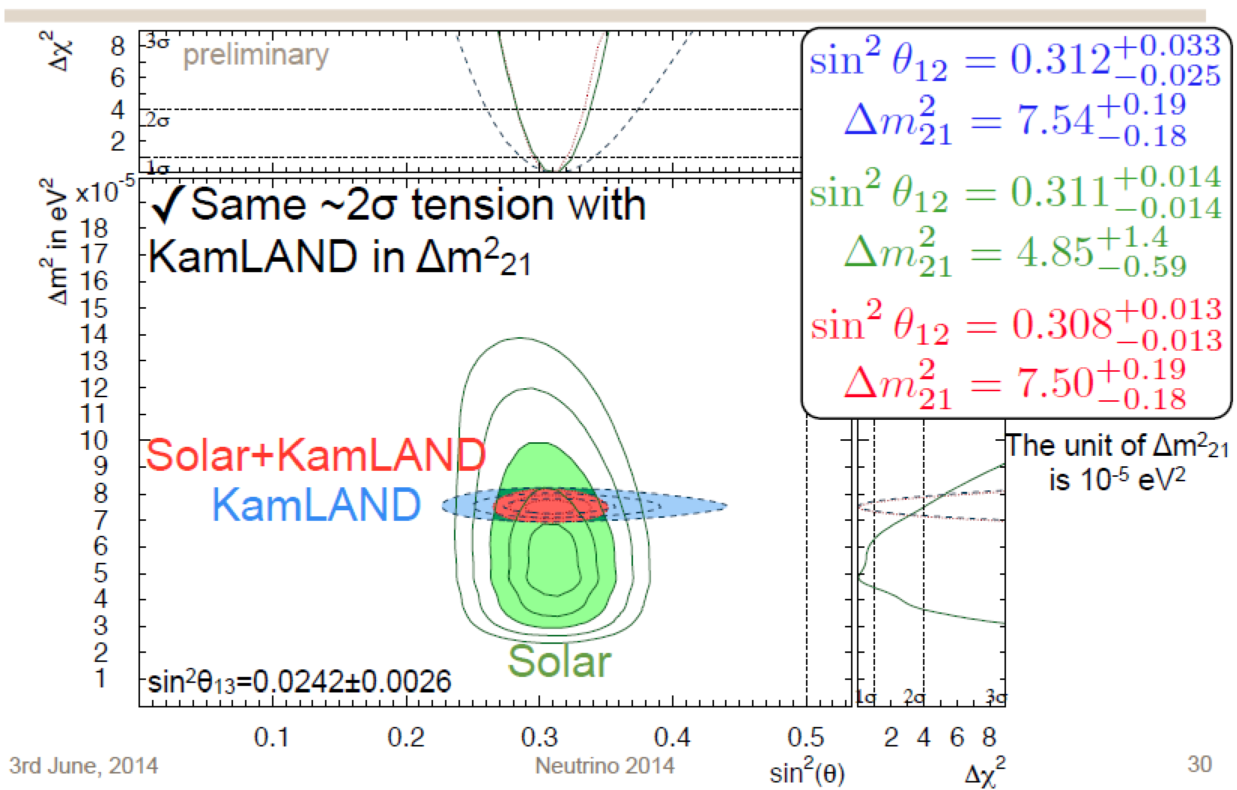


D. Grant@neutrino 2014

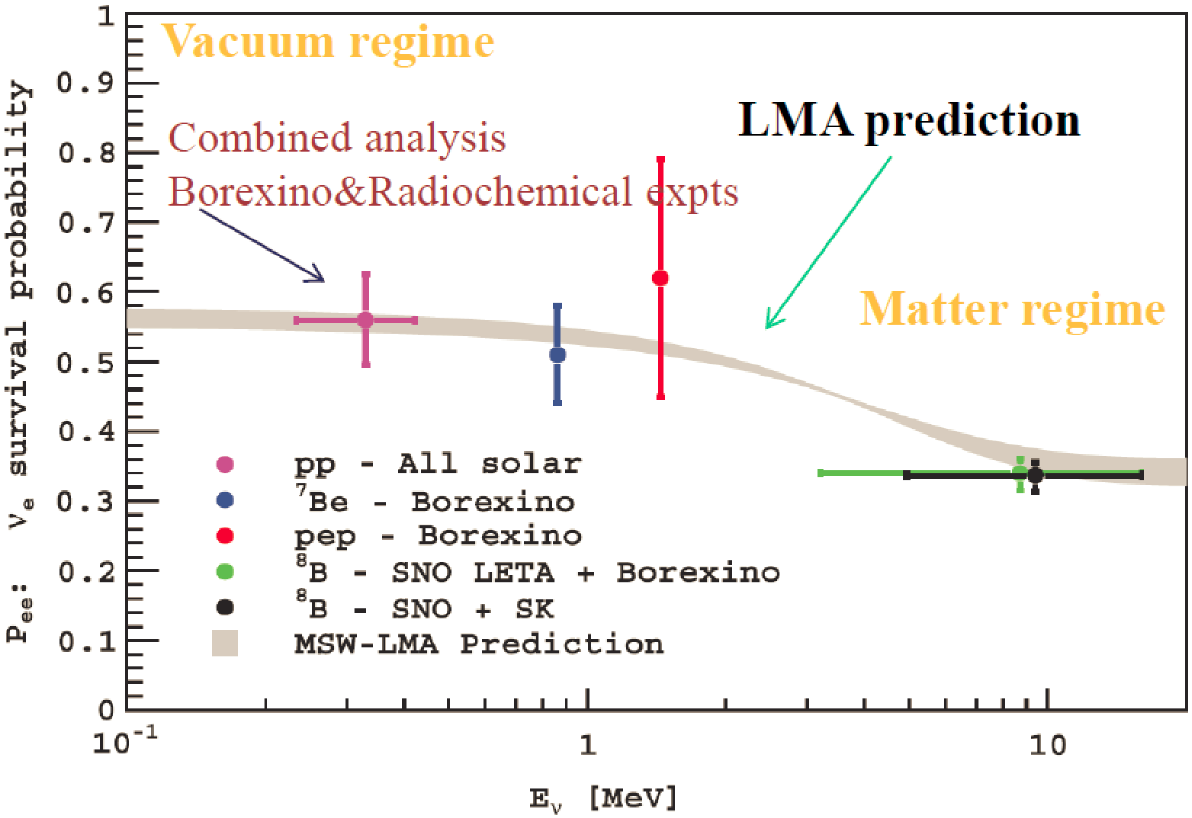
Solar neutrinos

- **Measurement of θ_{12} & ΔM^2_{21}**
- **Current experiments: Borexino, SuperK**
- **Future experiment:**
  - **SNO+, XMASS, LENA, JUNO…**

Koshio@neutrino 2014



Confirmation of the Solar Model and the Neutrino Oscillation



Ranucci @ neutrino 2014

- Accomplished:
  - ^{7}Be flux
  - ^{8}B flux down to 3 MeV
  - pep flux & limit on CNO
- Future:
  - pp neutrinos
  - CNO

Future

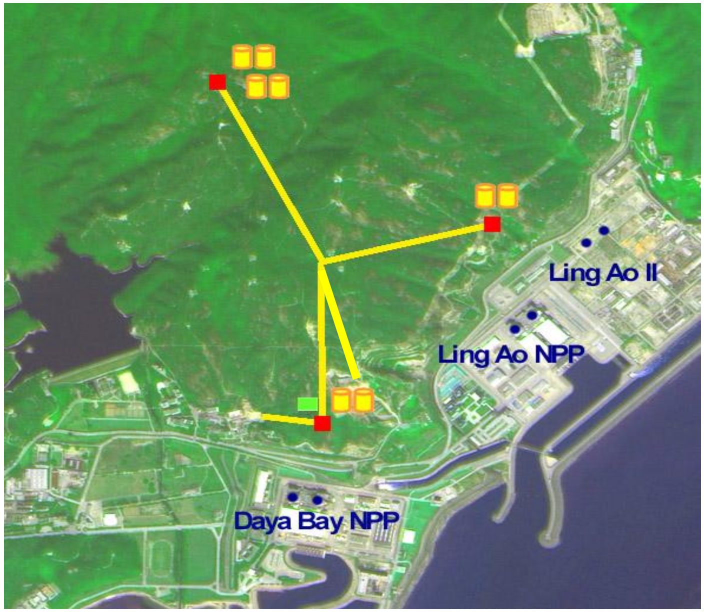
- Better oscillation measurements
  - Seasonal variations
  - Spectrum distortion
  - Day-night effect
- Non-standard interactions
  - Flavor changing NC
  - Sterile neutrinos
  - Mass varying neutrinos
- Solar physics:
  - Understand the stellar formation by measuring the metallicity of the Sun's core
    - Precision 8B flux
    - CNO flux

- SuperK
- Borexino
- SNO+
- XMASS
- JUNO
- HyperK
- LENA
- ...

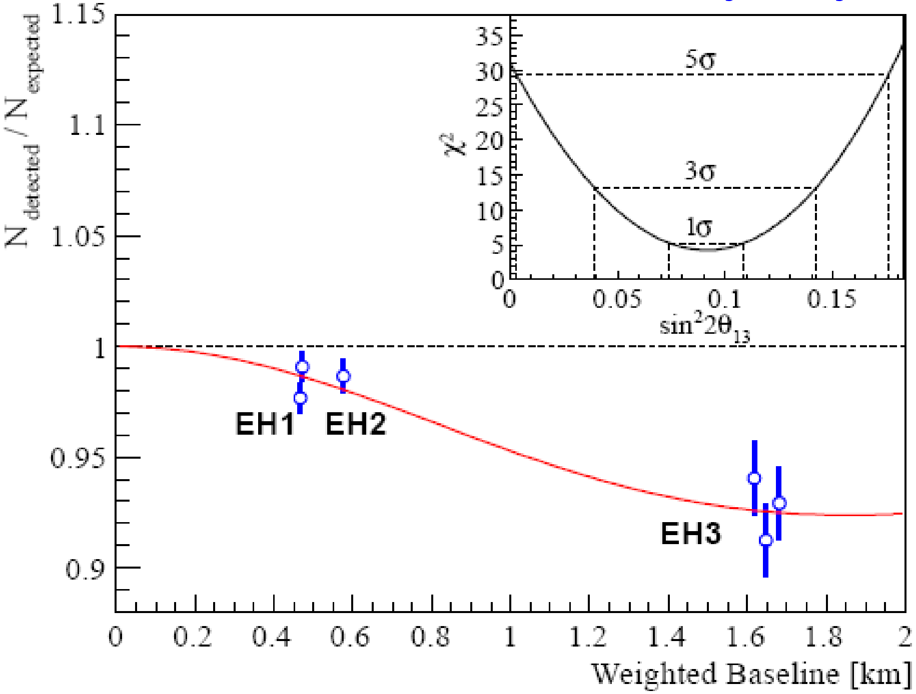
Reactor neutrinos

- **Established θ_{13} Oscillation**
- **Future: Mass hierarchy**
  - ⇨ **JUNO, RENO-50**

Daya Bay

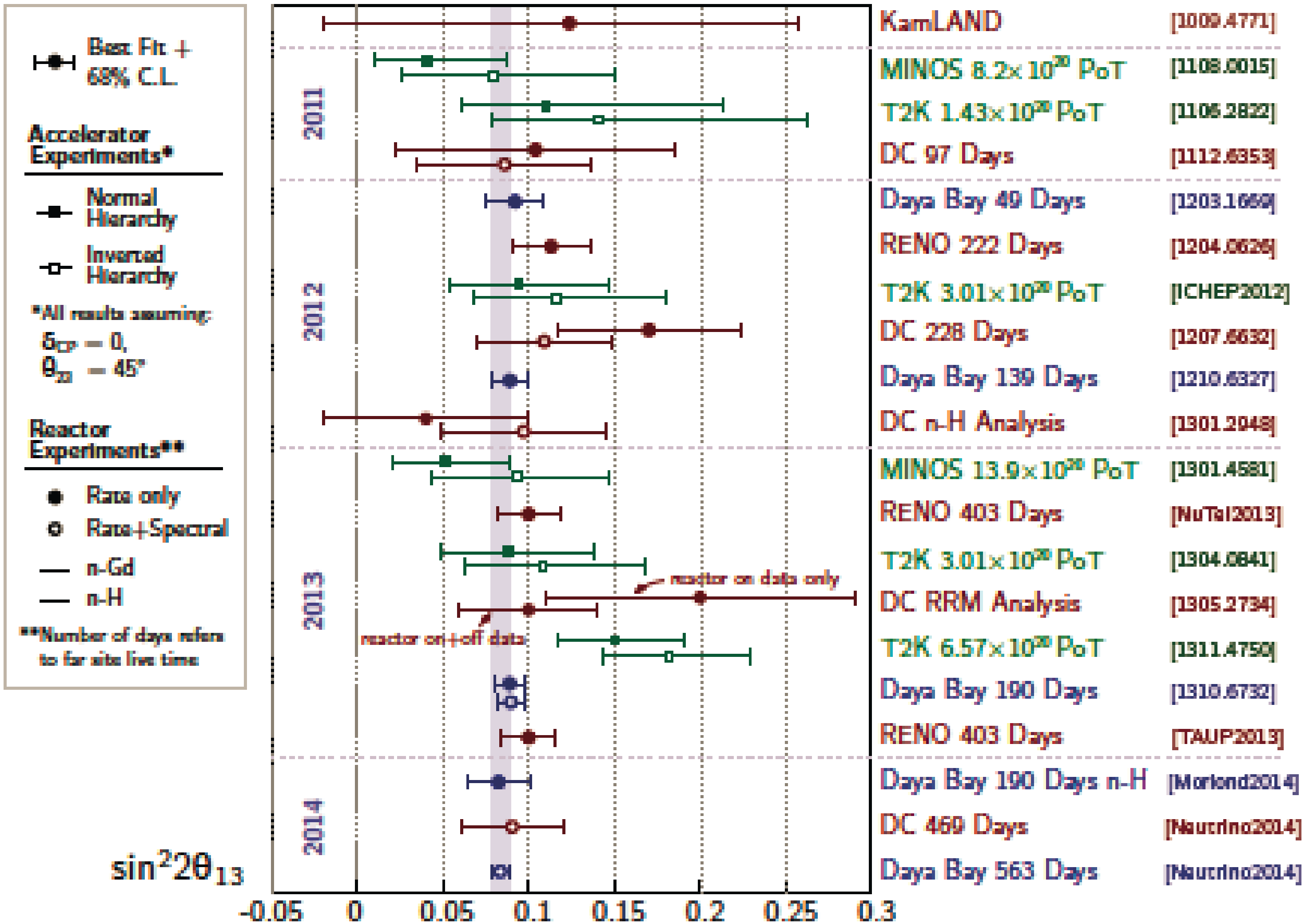


Daya Bay



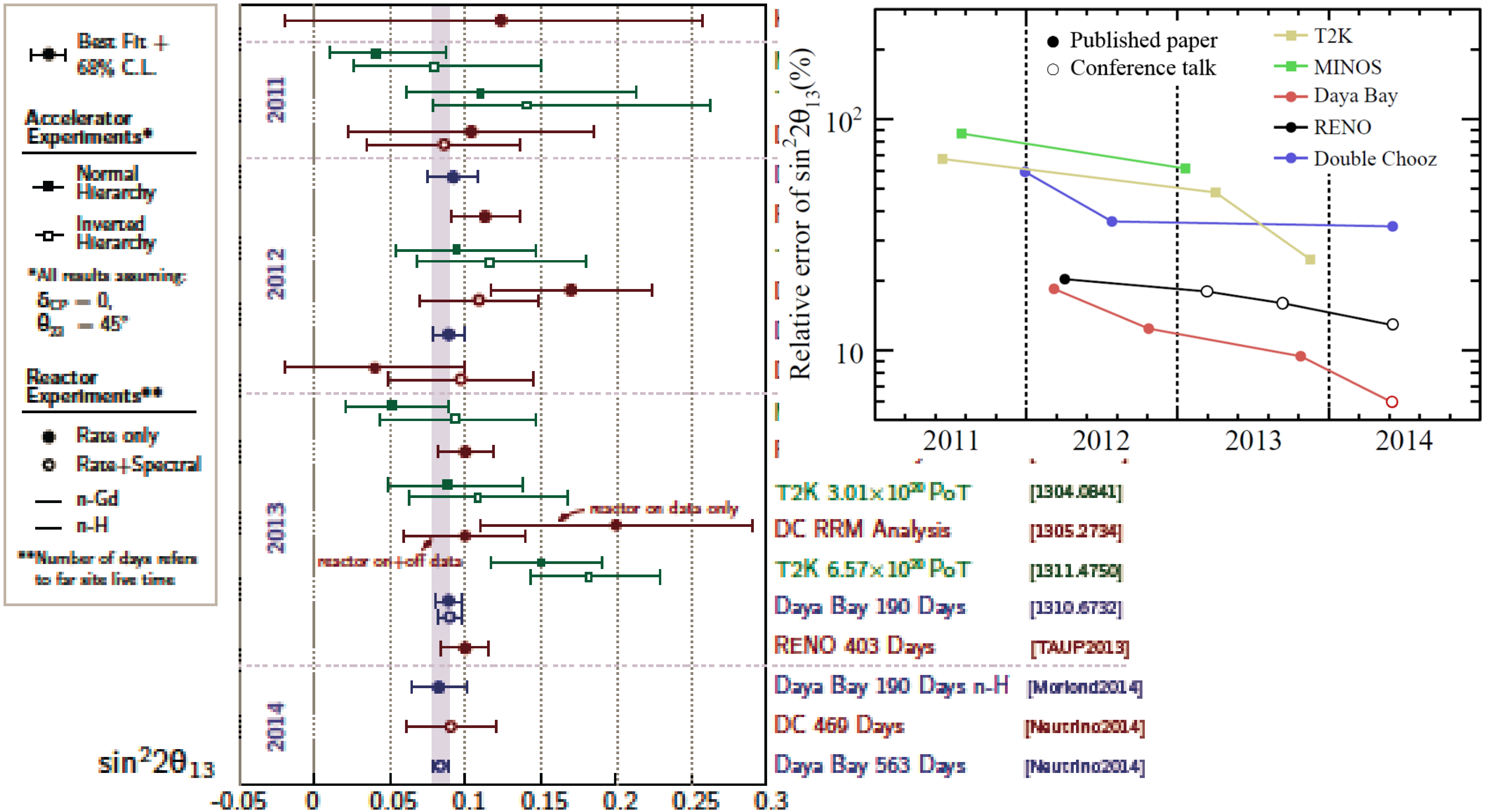
F.P. An et al., NIM. A 685(2012)78
F.P. An et al., Phys. Rev. Lett. 108, (2012) 171803, citation > 1200

Comparison of θ_{13} Measurements



Accelerator experiments assuming δ_{CP}=0, θ_{23}=45°

Comparison of θ_{13} Measurements



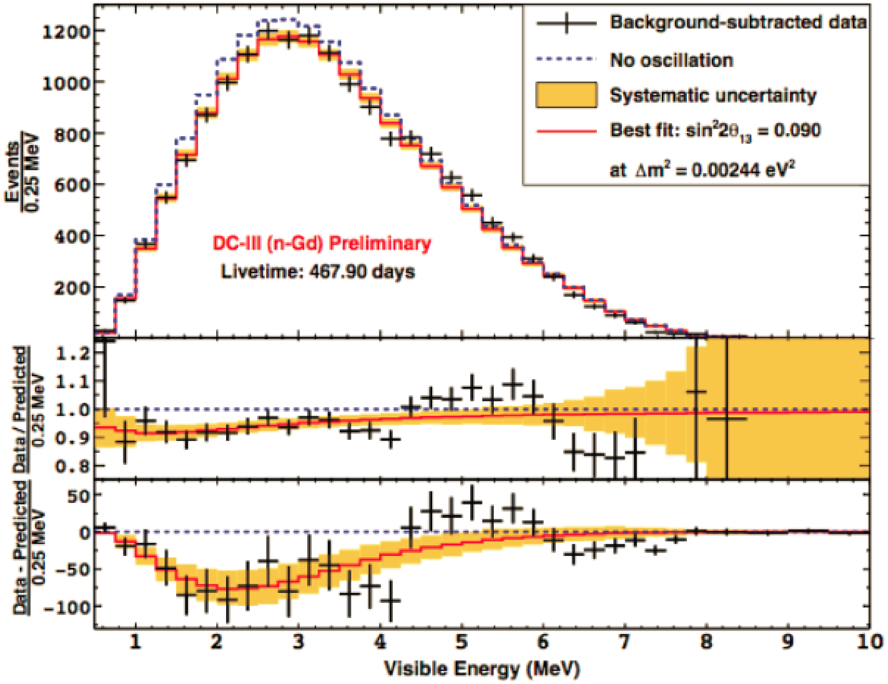
Accelerator experiments assuming δ_{CP}=0, θ_{23}=45°

Double Chooz: Results and Prospect

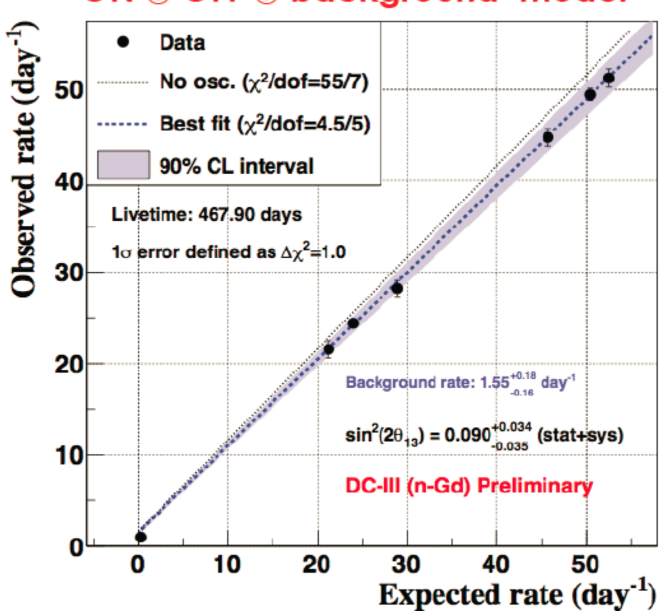
- **Reactor rate modulation: background measurement**
- **nGd rate+shape analysis for far detector only**

$\sin^2(2\theta_{13})=(0.09\pm0.03)$

$(\chi^2/n.d.f. = 51.4/40)$



ON ⊕ OFF ⊕ background model



- **Near detector ready**
- **Expected final precision on $\sin^2 2\theta_{13}$: ~ 10-15%**

RENO: Results and Prospects

- ✓ Also reactor rate modulation analysis
- ✓ New results on nGd & nH rate analysis
- ✓ Shape analysis is on the way
- ✓ Reduced systematics but ^{252}Cf contamination worsened the uncertainty
- ✓ Future prospects: 7% precision

◆ nGd rate analysis

$\sin^2(2\theta_{13}) = 0.101 \pm 0.008$ (stat.) $\pm$ 0.010 (sys.)

- Data before ^{252}Cf contamination: previous **0.012 (sys.)** → 0.007 (sys.)
- Data after ^{252}Cf contamination: → 0.018 (sys.)

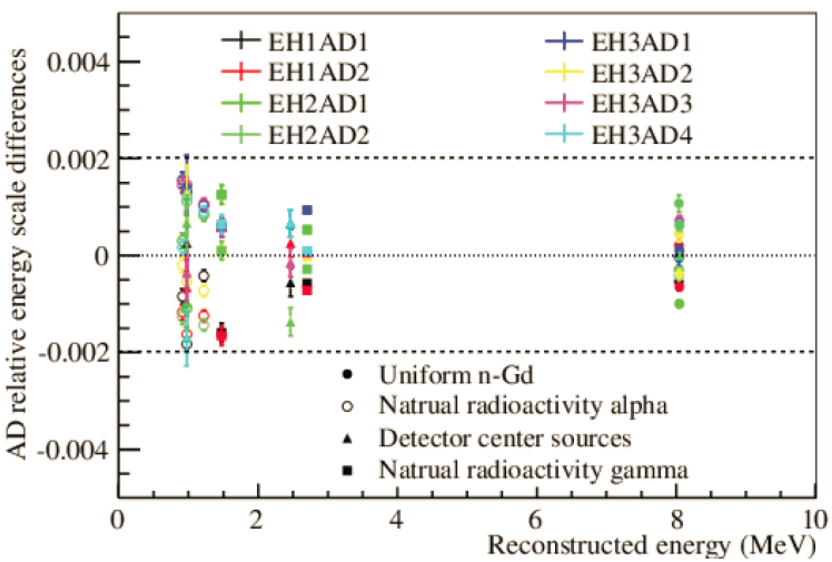
◆ nH rate analysis

$\sin^2(2\theta_{13}) = 0.095 \pm 0.015$ (stat.) $\pm$ 0.025 (sys.)

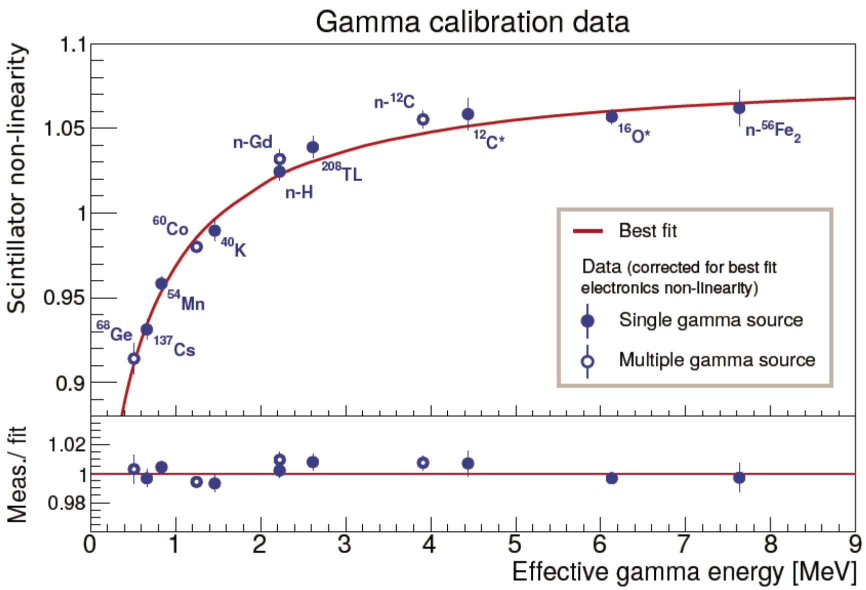
Daya Bay

- Detailed and precise corrections for non-linearity
- Continue to improve: reduced backgrounds and systematics
- Rate + Shape analysis for nGd events
- Rate analysis for nH events

Relative energy scale difference: <0.2%

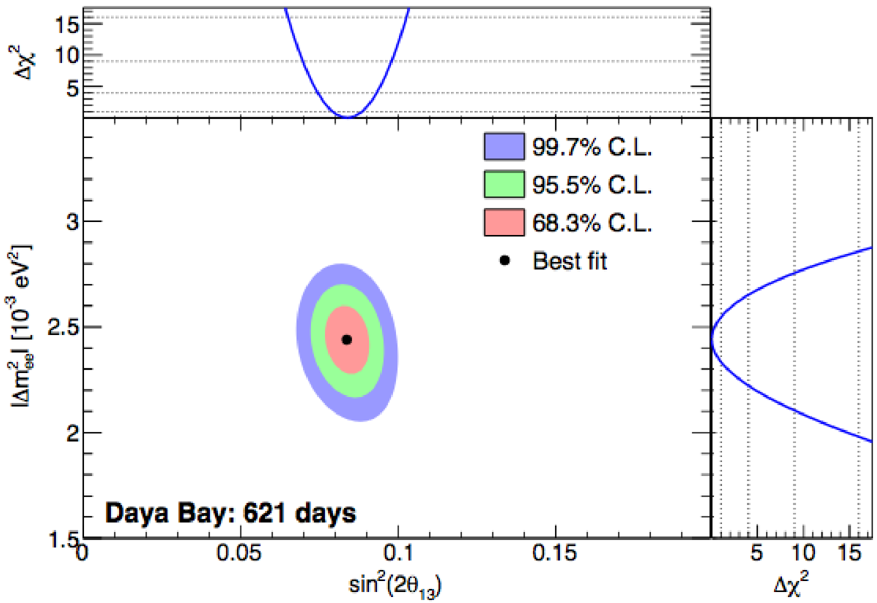


Non-linearity uncertainty < 1%

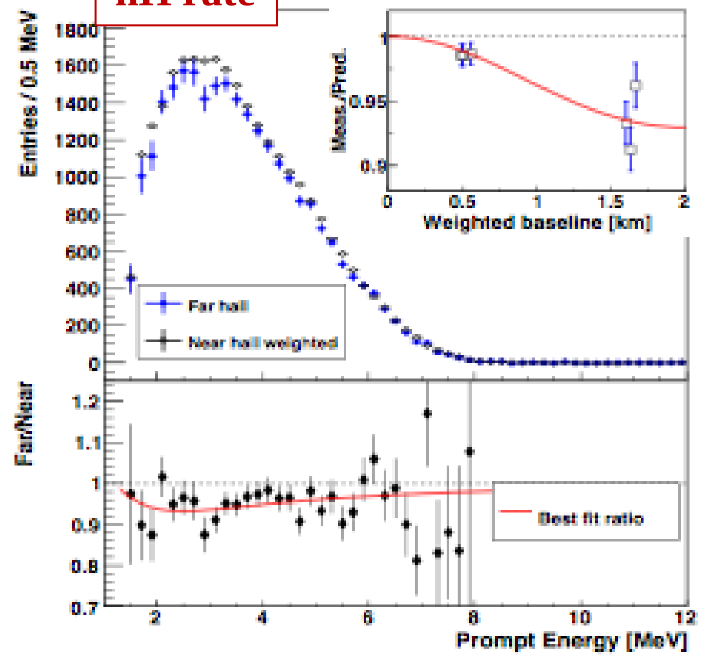


Recent Results

nGd rate+shape



nH rate



$\sin^2 2\theta_{13} = 0.083 \pm 0.018$

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

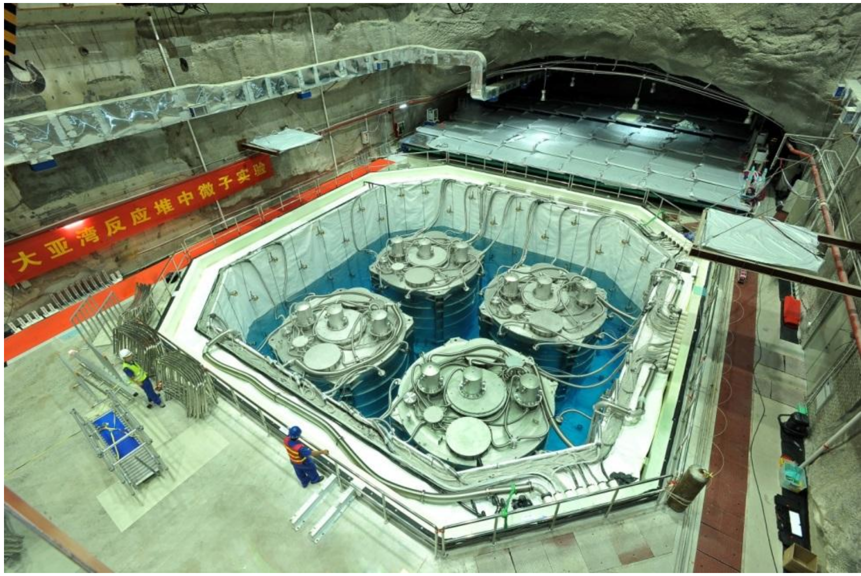
$$|\Delta m^2_{ee}| = 2.44^{+0.10}_{-0.11} \times 10^{-3} \mathrm{eV}^2$$

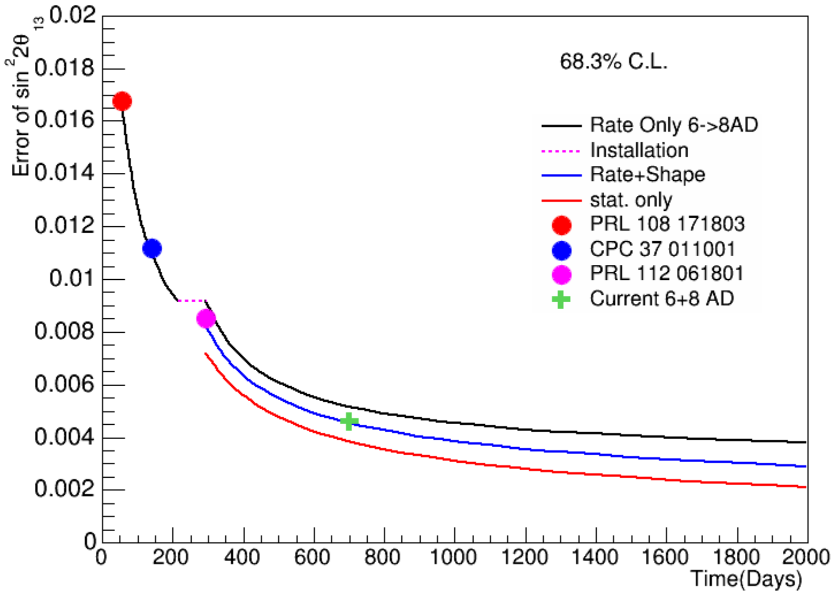
$$\chi^2/NDF = 134.7/146$$

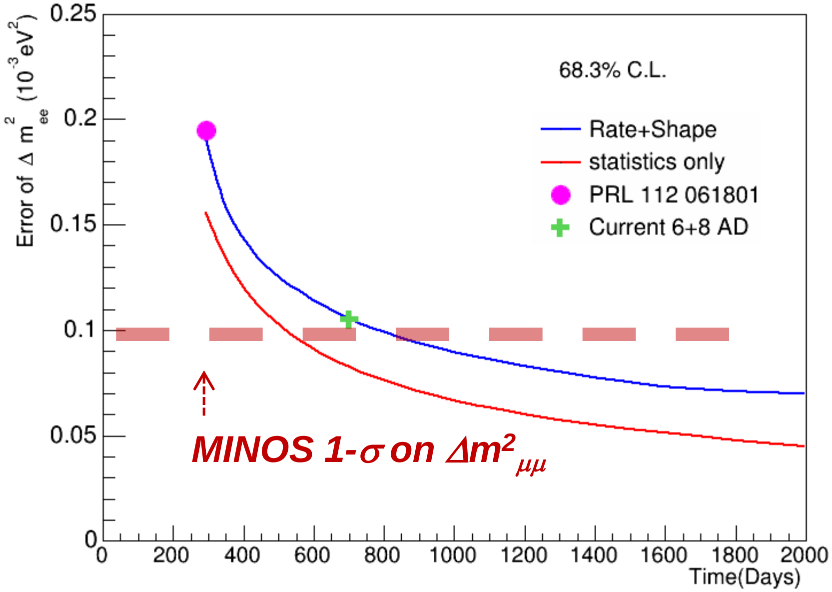
- **$\Delta(\sin^2 2\theta_{13})/\sin^2 2\theta_{13}$ ~ 6%, the best among all mixing angles**
- **$\Delta(\Delta M^2_{ee})/\Delta M^2_{ee}$ ~ 5%, similar to that of MINOS**
- **nH results ~4.5σ, independent check**

Future Prospects

- Precision still dominated by statistics
- Continue to improve systematics
- Data taking until 2017
- Precision expected:
  - ⇨ $\Delta(\sin^2 2\theta_{13}) \sim 0.003$ ➔ ~ 3%
  - ⇨ $\Delta(\Delta M^2_{ee}) \sim 0.07$ ➔ ~3%

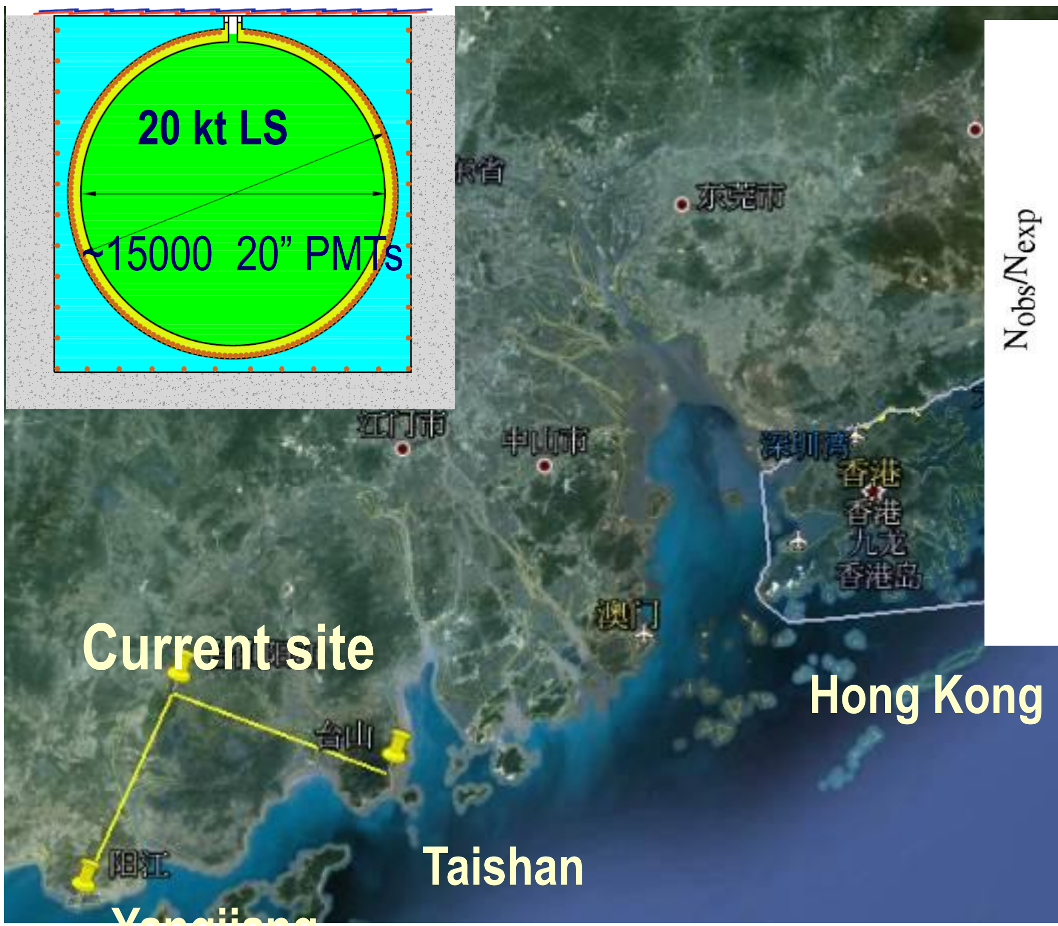


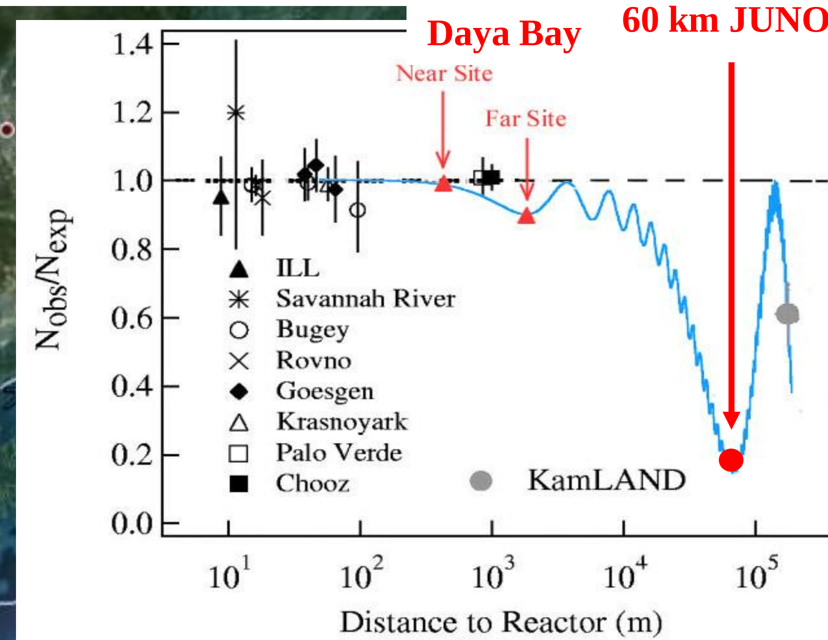




Future Experiment: JUNO

	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	running	planned	approved	Construction	construction
power/GW	17.4	17.4	17.4	17.4	18.4





Talk by YFW at ICFA seminar 2008, Neutel 2011; by J. Cao at NuTurn 2012 ;

Paper by L. Zhan, YFW, J. Cao, L.J. Wen, PRD78:111103,2008; PRD79:073007,2009

Physics Reach

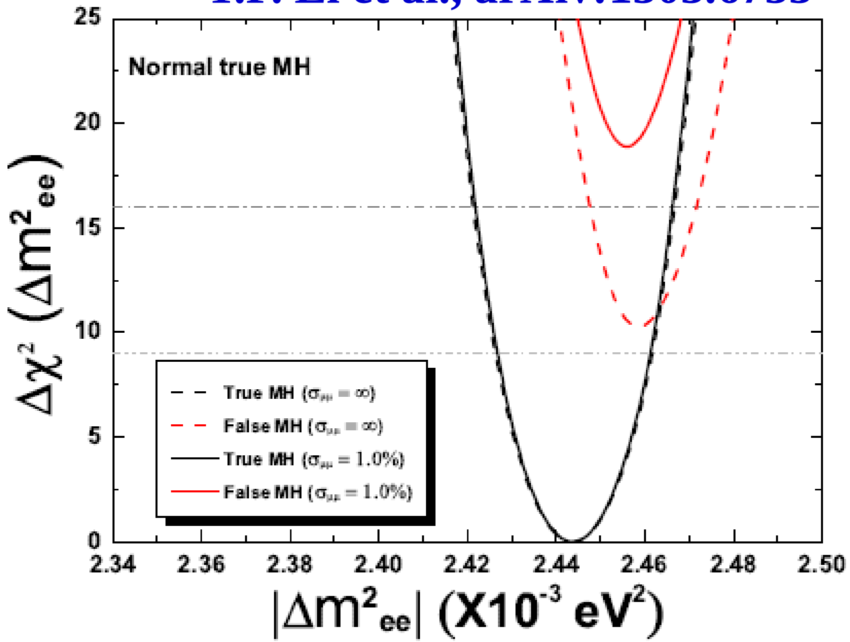
Thanks to a large θ_{13}

- **Mass hierarchy**
- Precision measurement of mixing parameters
- Supernova neutrinos
- Geoneutrinos
- Sterile neutrinos
- ……

	Current	Daya Bay II
Δm^2_{12}	3%	0.6%
Δm^2_{23}	5%	0.6%
$\sin^2\theta_{12}$	5%	0.7%
$\sin^2\theta_{23}$	10%	N/A
$\sin^2\theta_{13}$	14% → 4%	~ 15%

Detector size: 20kt
Energy resolution: 3%/√E
Thermal power: 36 GW

Y.F. Li et al., arXiv:1303.6733

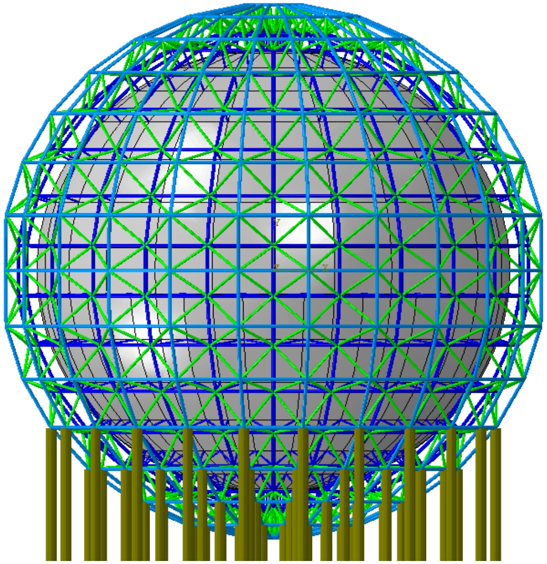


For 6 years, mass hierarchy cab be determined at 4σ level, if $\Delta m^2_{\mu\mu}$ can be determined at 1% level

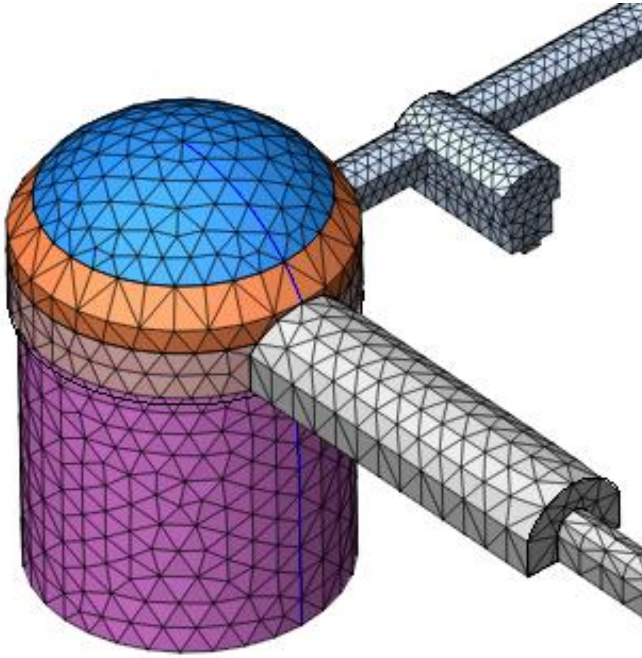
Status of JUNO

Schedule:

- Civil preparation：2013-2014
- Civil construction：2015-2017
- Detector component production：2016-2017
- PMT production：2016-2019
- Detector assembly & installation：2018-2019
- Filling & data taking：2020

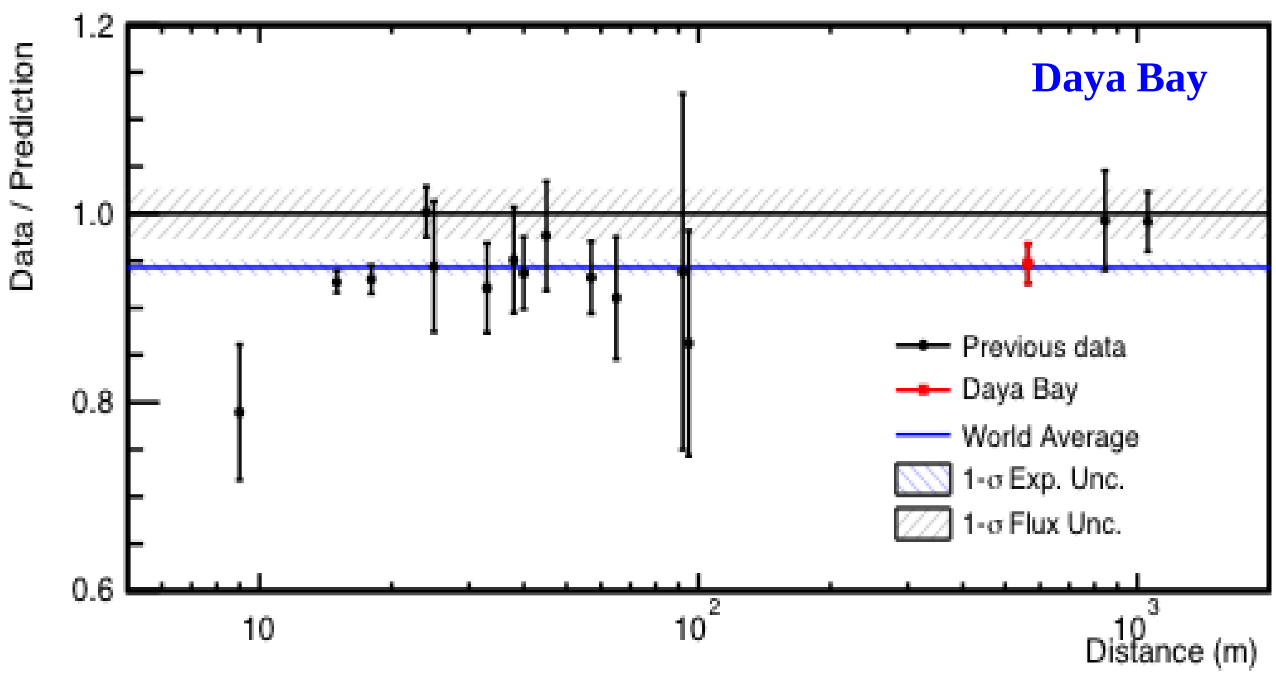


Grounding breaking on Jan. 10, 2015



Reactor neutrino anomaly

- **By a new flux calculation, there may exist a reactor neutrino flux deficit: 0.943±0.023. A 3σ effect ?**
- **Confirm by other calculations and measurements**
- **Oscillation with sterile neutrinos ? Many experiments:**
  - **Radioactive sources: CeLAND(^{144}Ce in KamLAND), SoX(^{51}Cr in Borexino),…**
  - **Accelerator beams: IsoDAR, Icarus/Nessie, …**
  - **Reactors: Nucifer, Stereo, Solid, SCARR, …**



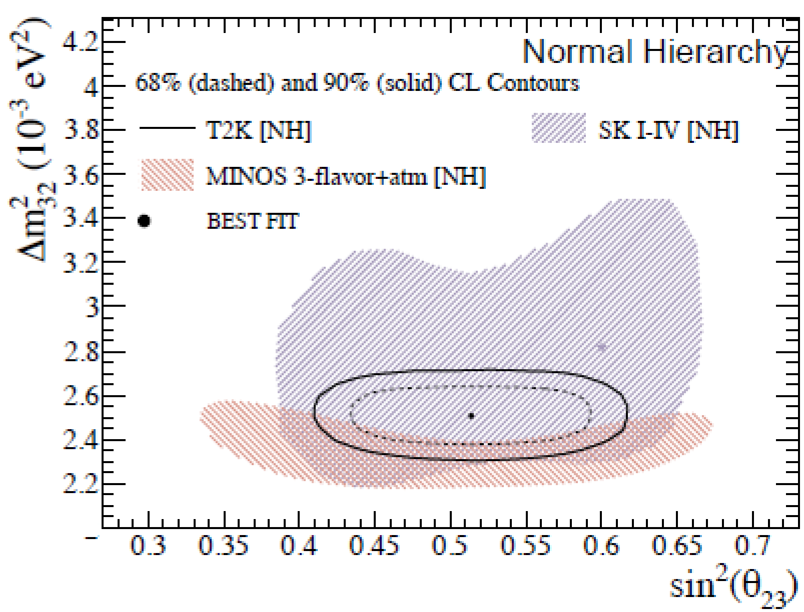
Accelerator Neutrinos

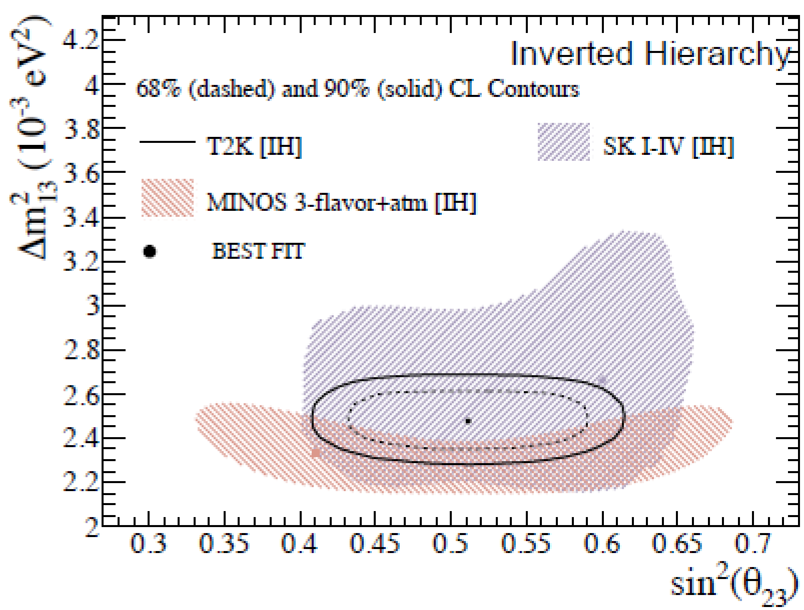
- Determination of θ_{23} and $|\Delta M^2_{23}|$
- Current experiments: T2K
- Future experiment:
  - DUNE, T2HK, INO, …
  - Neutrino factories

C. Water@neutrino2014

		Best-fit ± FC 68% CL (Δm^2 units 10^{-3} eV^2/c^4)
NH	$\sin^2\theta_{23}$	$0.514^{+0.055}_{-0.056}$
	Δm^2_{32}	2.51 ± 0.10
IH	$\sin^2\theta_{23}$	0.511 ± 0.055
	Δm^2_{13}	2.48 ± 0.10

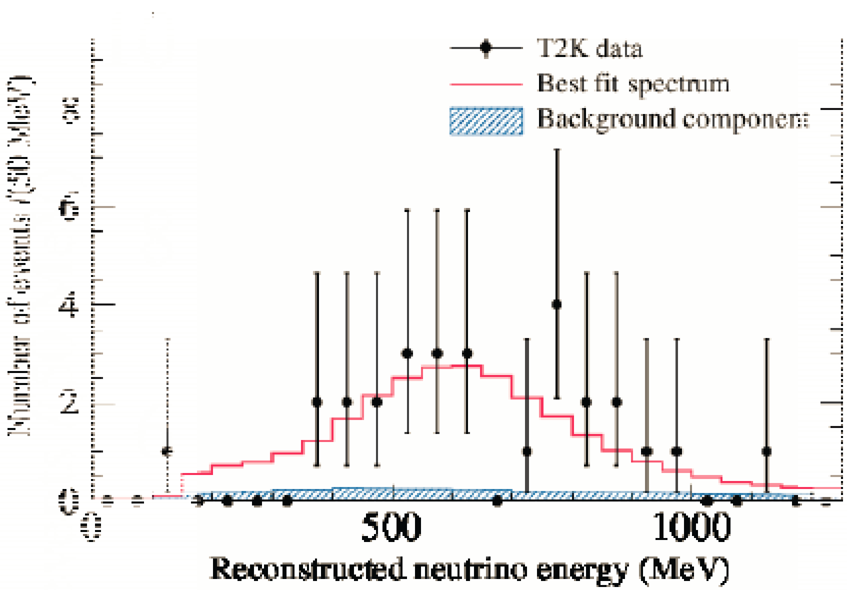
Phys. Rev. lett. 112(2014)181801

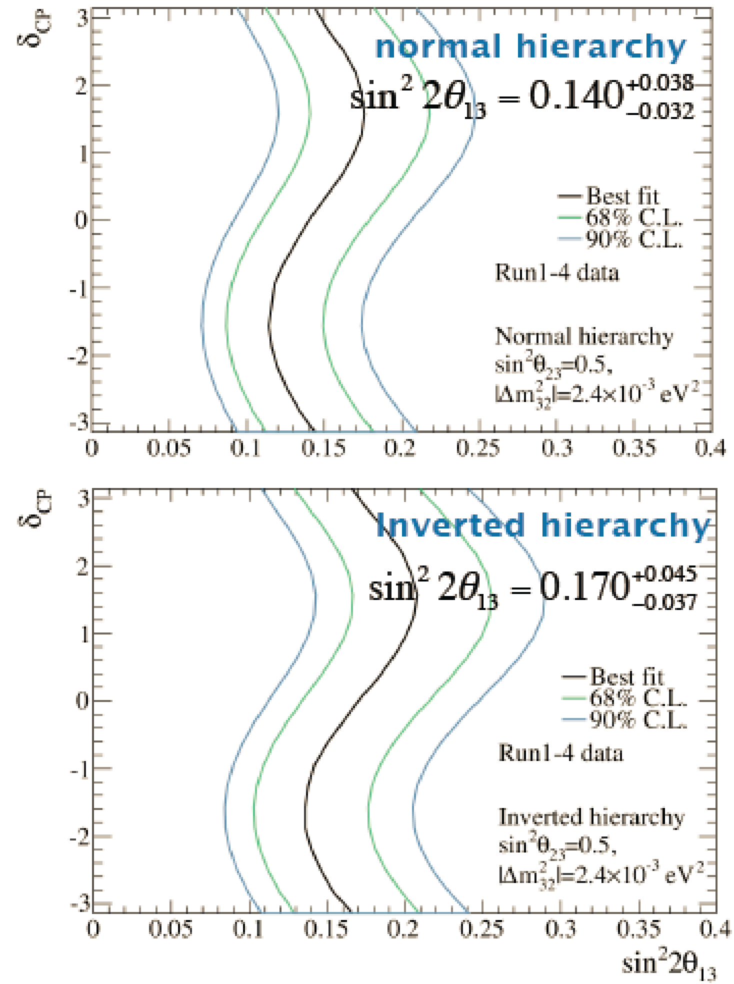




Phys. Rev. Lett. 112, 061802 (2014)

T2K observation of ν_e Appearance





4.92 ± 0.55 events expected background

28 events observed

21.6 events expected @ $\sin^2 2\theta_{13}$= 0.1

δ_{CP}= 0, $\sin^2\theta_{23}$= 0.5

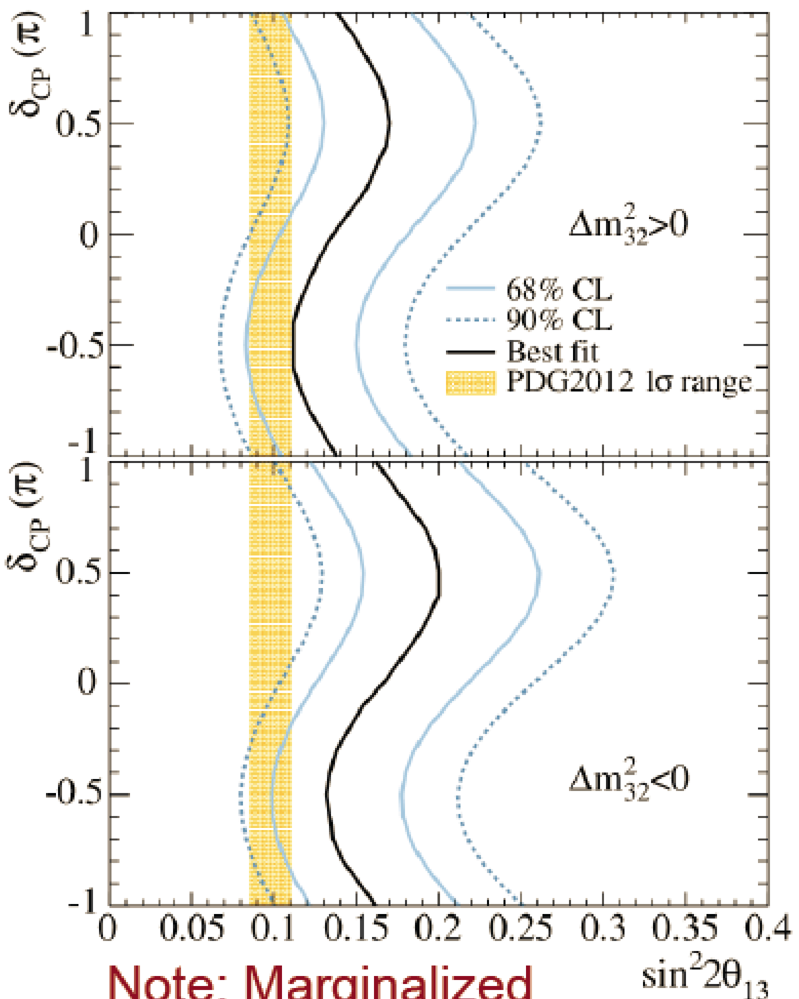
7.3 σ significance for non-zero θ_{13}

First ever observation (>5σ) of an explicit ν appearance channel

CP Phase is known ?

- Taking reactor θ_{13} results, CP phase is constrained to be close to $-\pi/2$
- This is a very lucky value for NOVA and other accelerator experiments
- Mass hierarchy and CP phase will be known soon ?

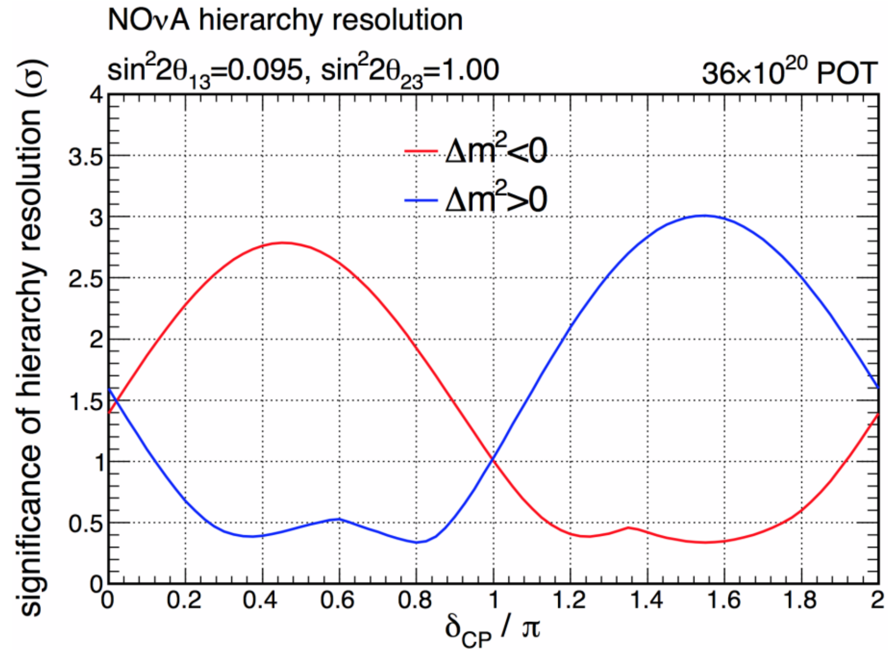
C. Water@neutrino2014

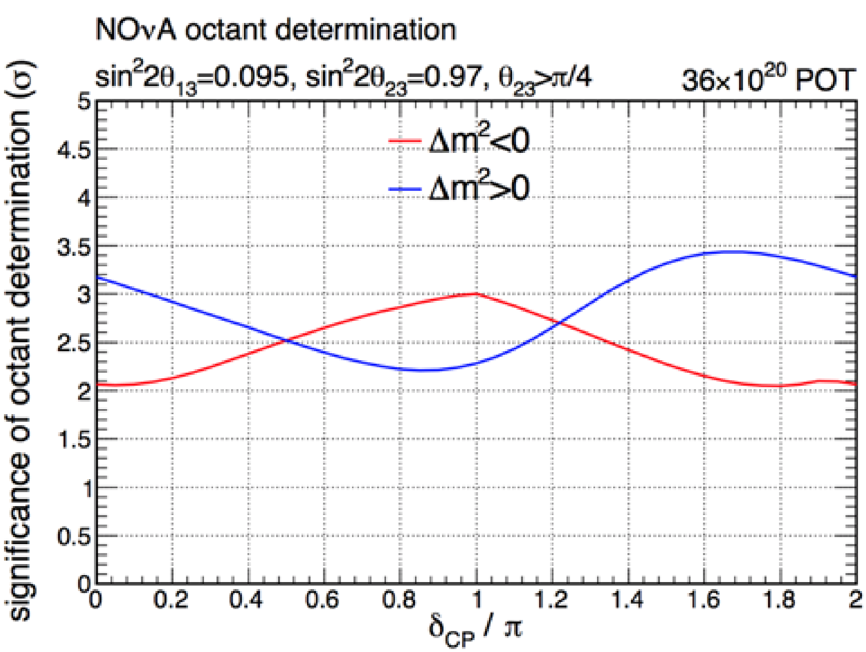


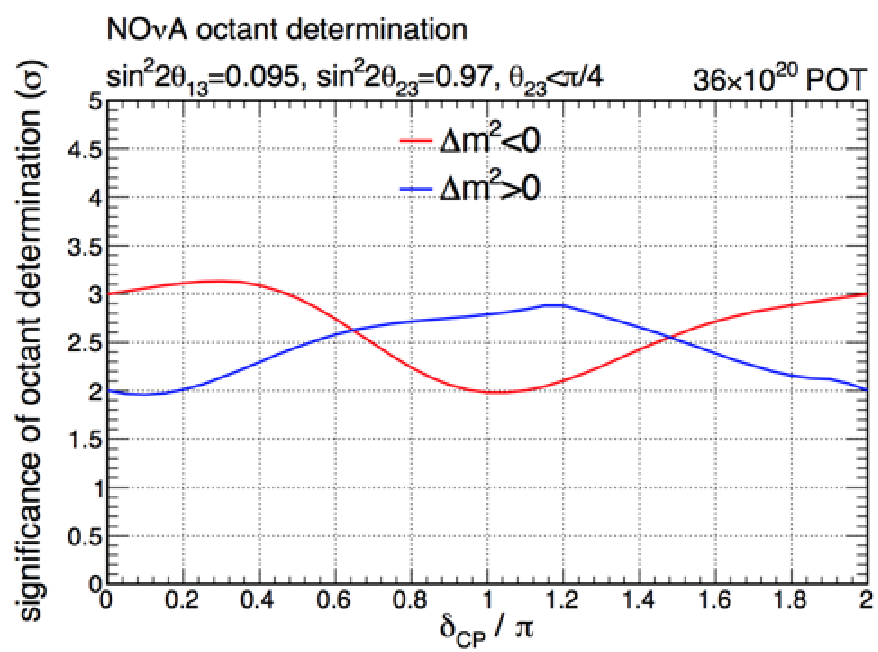
Note: Marginalized over θ_{23} and Δm^2_{32}

Nova： Physics Reach

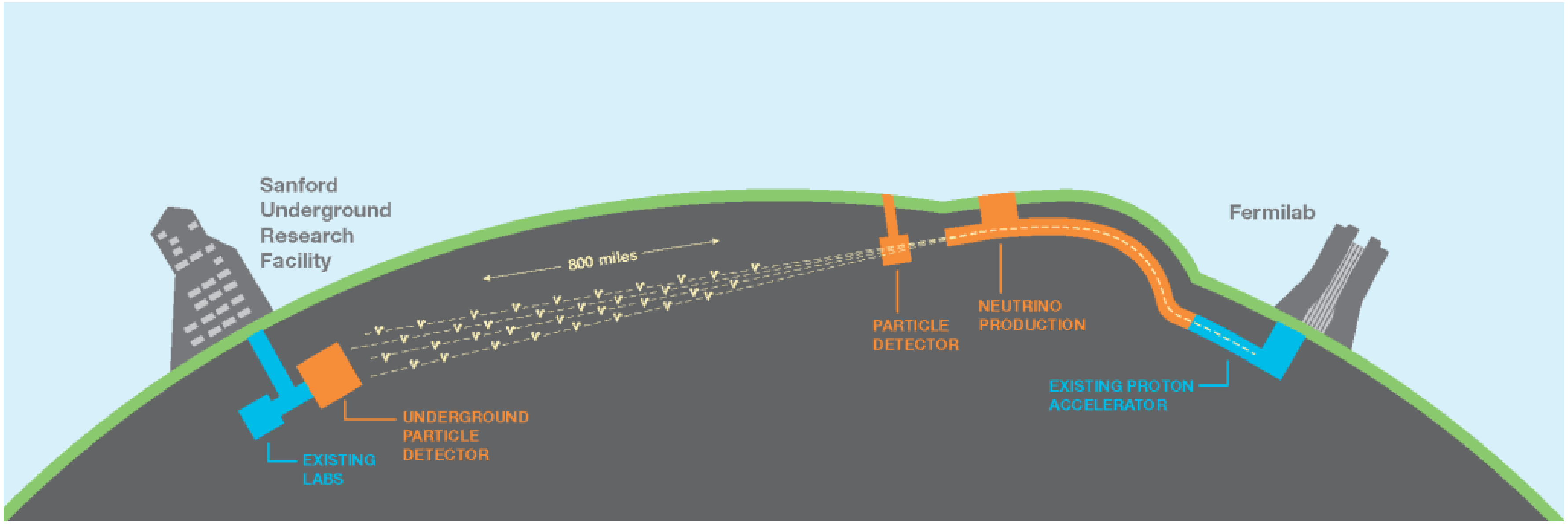
- May get mass hierarchy if lucky
- For non-maximal θ_{23} octant determination: > 95% CL for all δ_{CP} @ $\sin^2 2\theta_{23}$ = 0.97



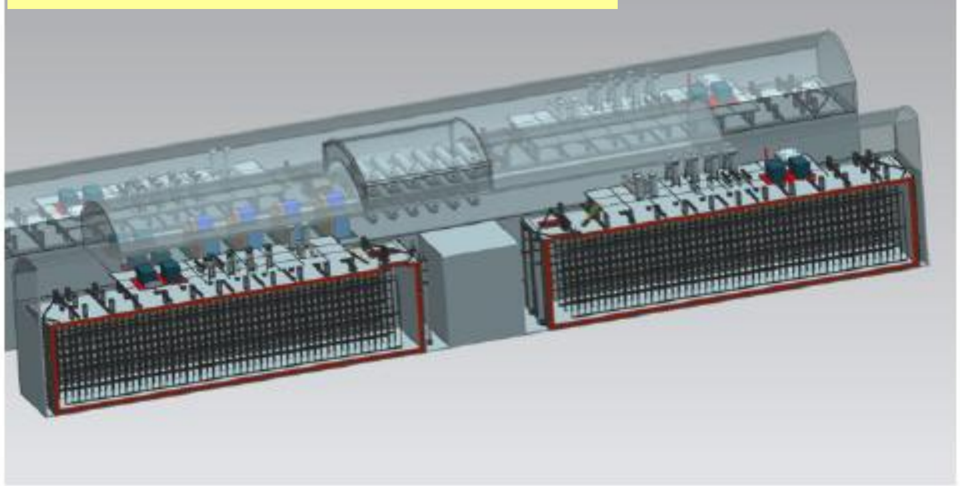


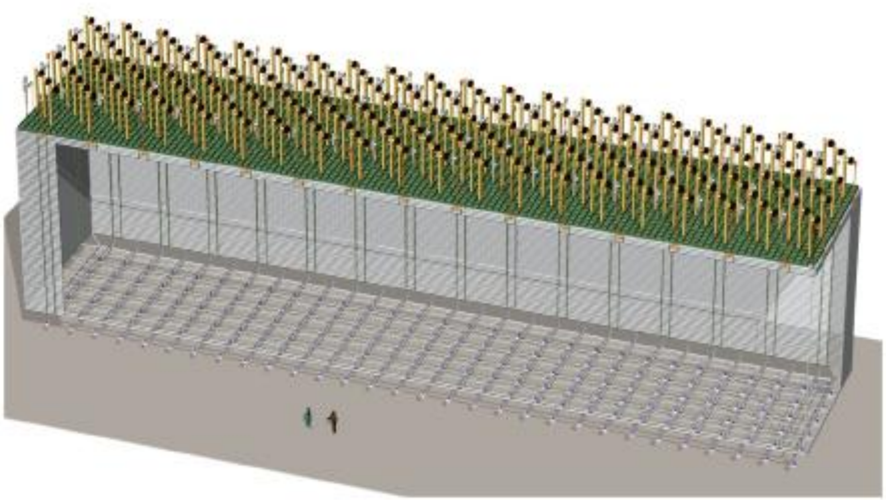


LBNF/DUNE



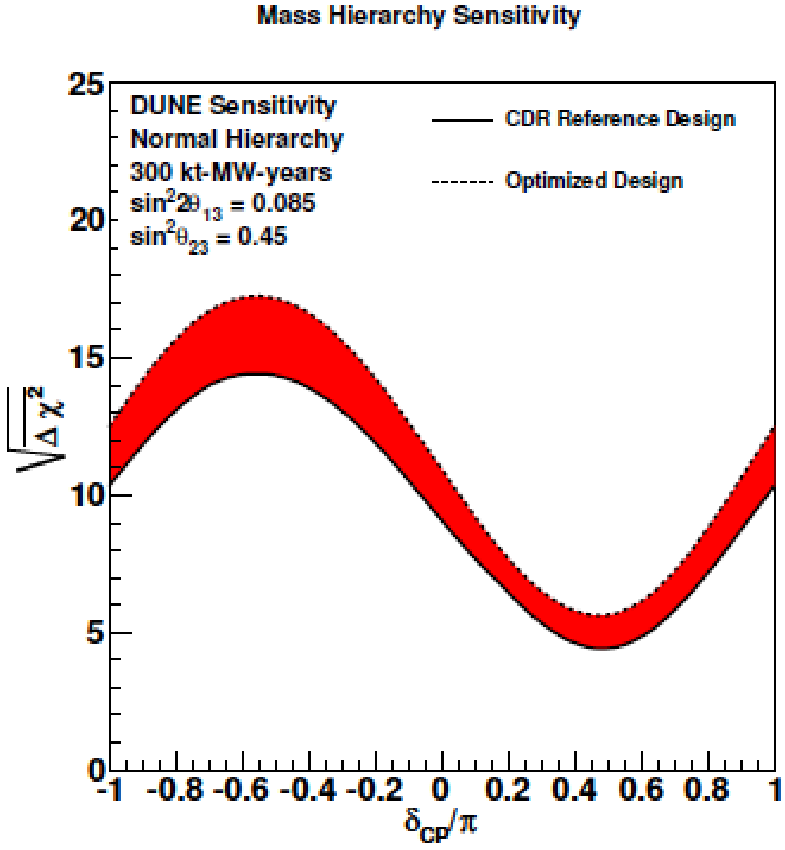
LAr detector: two options

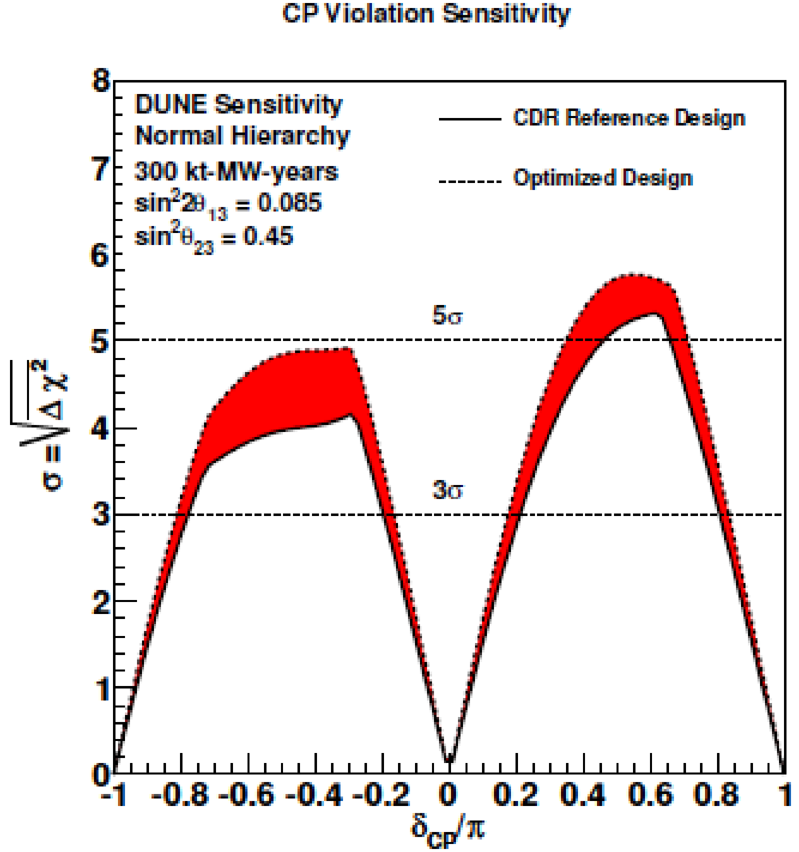




Physics at DUNE

Exposure: 300 kt·W

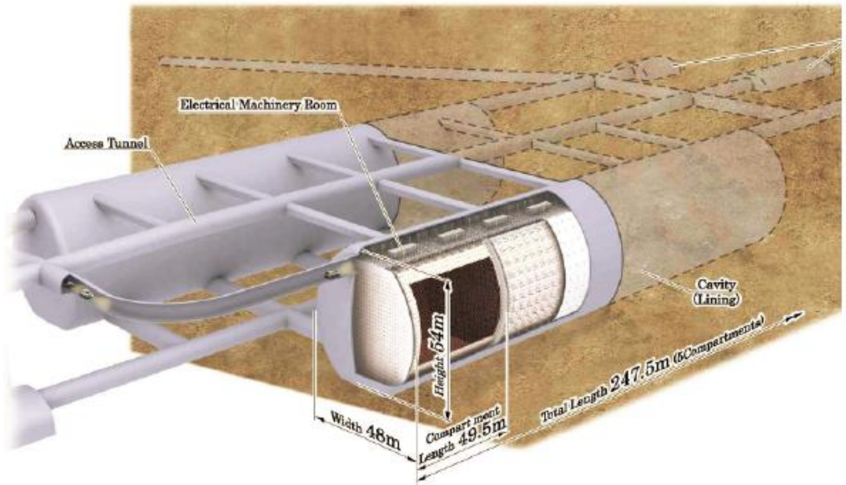


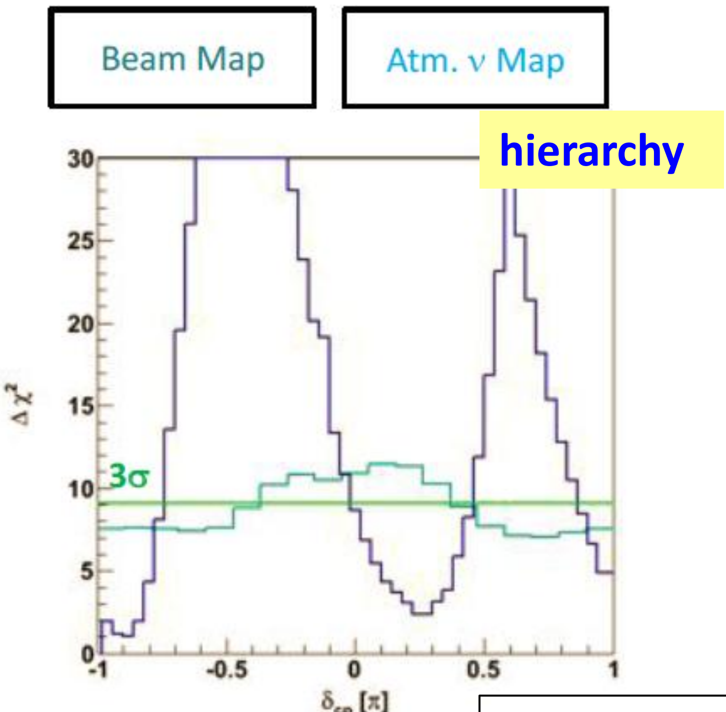


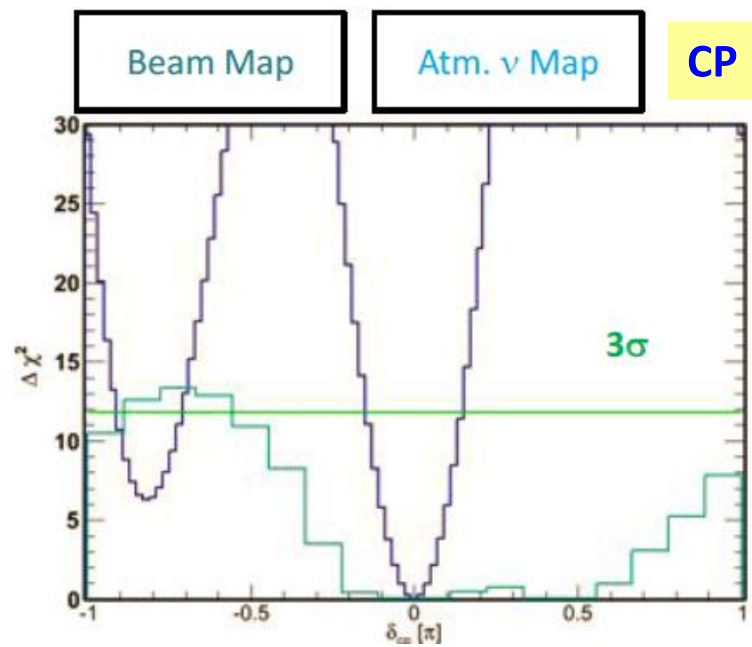
- First phase: Two 10 kt detector with a 1.2 MW proton power
- Future: 40 kt with a 2.4 MW proton power
- Goal: 850 kt·W

Future experiment: T2HK

- **1 Mt water Cerenkov detector**
- **99000 20” PMT, 20% coverage**
- **Octant issue: $\Delta \sin^2\theta_{23} < 1\%$**
- **Mass hierarchy: complementary to T2HK**
- **CP: T2HK much better**





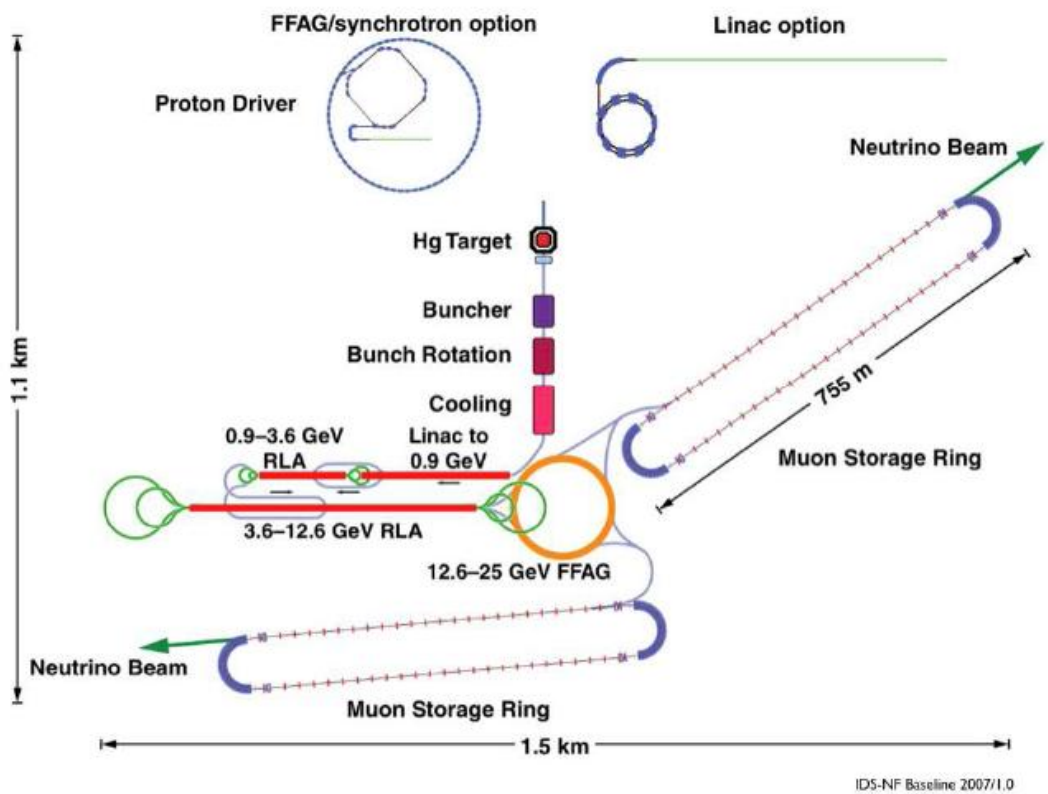


Wendell@HyperK open meeting 2012

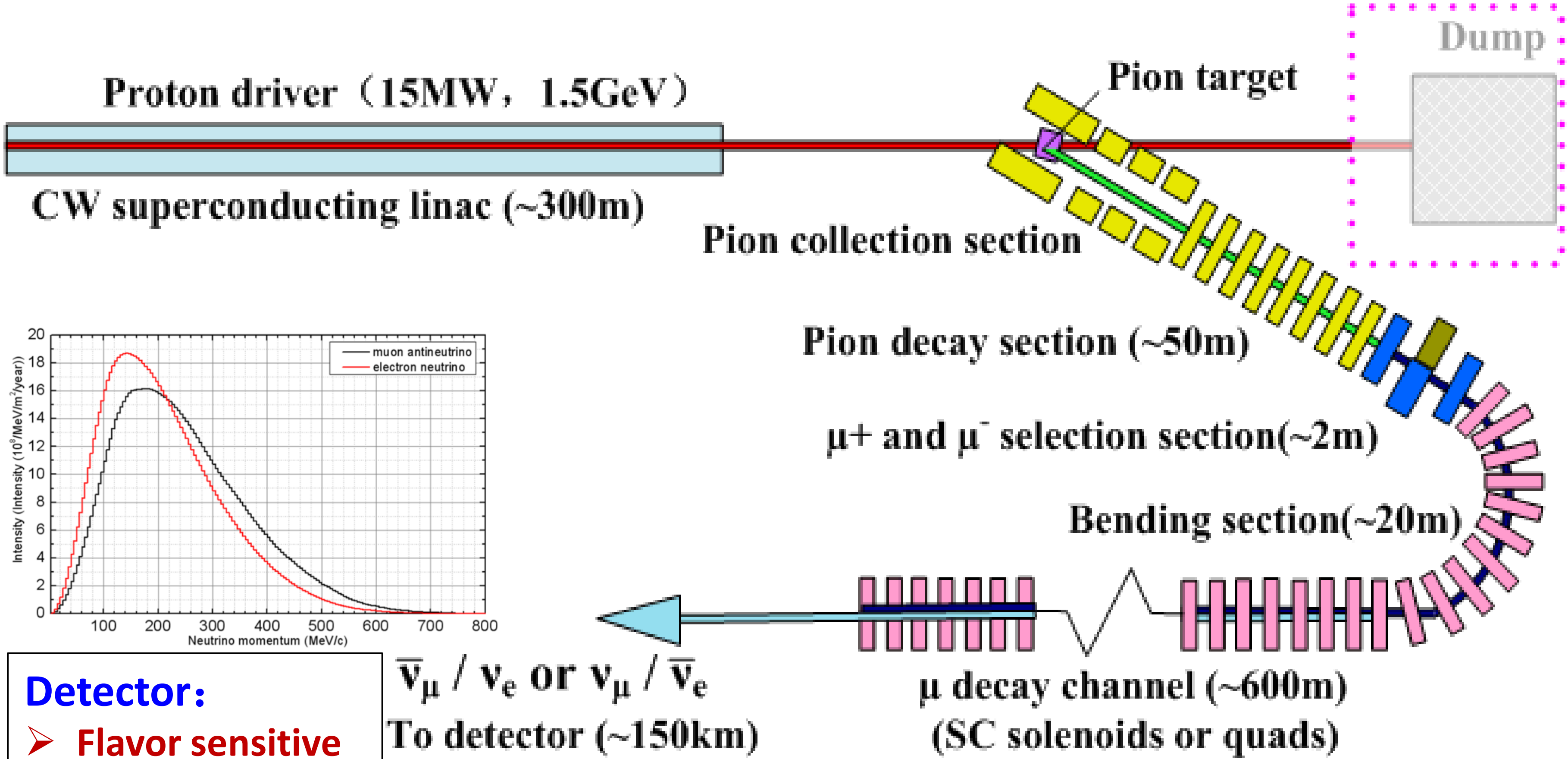
Neutrino Factory

Stored $\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$	
Disappearance	**Appearance**
$\bar{\nu}_e \rightarrow \bar{\nu}_e \rightarrow e^+$	$\bar{\nu}_e \rightarrow \bar{\nu}_\mu \rightarrow \mu^+$ $\bar{\nu}_e \rightarrow \bar{\nu}_\tau \rightarrow \tau^+$
$\nu_\mu \rightarrow \nu_\mu \rightarrow \mu^-$	$\nu_\mu \rightarrow \nu_e \rightarrow e^-$ $\nu_\mu \rightarrow \nu_\tau \rightarrow \tau^-$

- All channel available
  - Large ν_e (ν_e bar) flux
  - High energy ν_e (ν_e bar) flux
- Rate $\propto E_n$ @ fixed L/E
  - Optimize event rate@L/E
  - Optimize MH
  - Optimize CP sensitivity
- Our dream machine:
  - CP phase δ at 10-15% level



A New Type of Neutrino Beam for CP (MOMENT)



Detector:

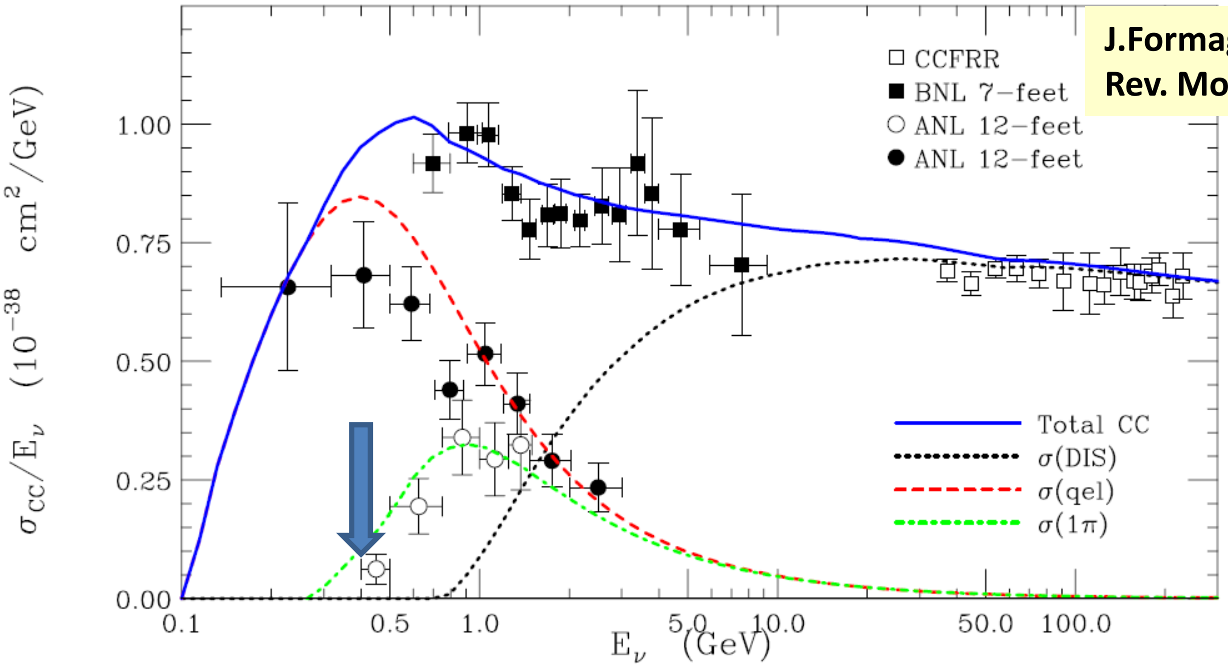
- Flavor sensitive
- Charge sensitive
- NC/CC sensitive

Cao et al., arXiv:1401.8125

Neutrinos after the target/ collection/decay: ~ 5×10^{21} ν/year

Why MOMENT ?

- Easier and cheaper in comparison with neutrino factories, by abandoning muon cooling and acceleration stage.
- Its CW mode makes the target system slightly easier.
- The lower beam energy at ~ 300 MeV maybe optimal: free from pi0 background



J.Formaggio and G.Zeller, Rev. Mod.Phys. 84.3(2012)1307

Summary

- Atmospheric neutrinos are improving the precision of θ_{23} & ΔM^2_{23}; sub-leading effects can be used to determine the **mass hierarchy & CP phase.**
- Solar neutrinos continue to provide improved measurements of θ_{12} & ΔM^2_{12}; solar-related and other astrophysics issues require much larger detectors.
- Reactor neutrinos provided precise measurements of θ_{13} & ΔM^2_{13}; next generation experiments can measure precisely θ_{12} & ΔM^2_{12} & ΔM^2_{23}, determine the **mass hierarchy,** and study many astrophysics issues.
- Sterile neutrino issues will be settled by experiments at reactors and/or using radioactive sources & accelerators, sooner or later.

Mass hierarchy and **CP phase** will be known in a not too far future