Reactor Neutrino Physics: What's Beyond Daya Bay?

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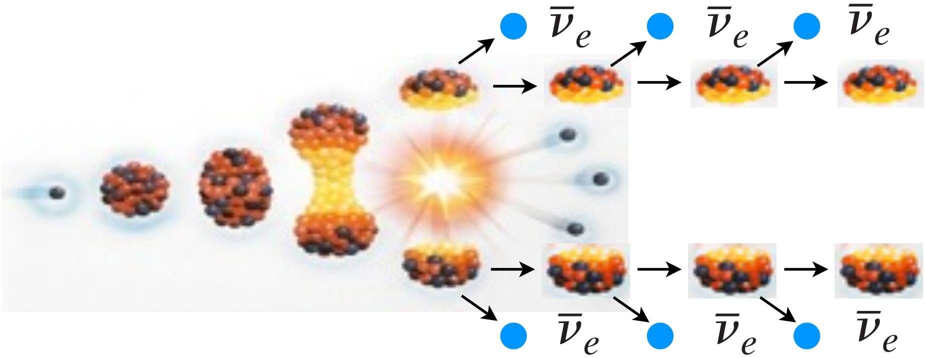
- *A review of the Daya Bay experiment*
- *Mass hierarchy and JUNO*
- *Experiments adapting non-reactor approaches*
- *Summary & conclusion*

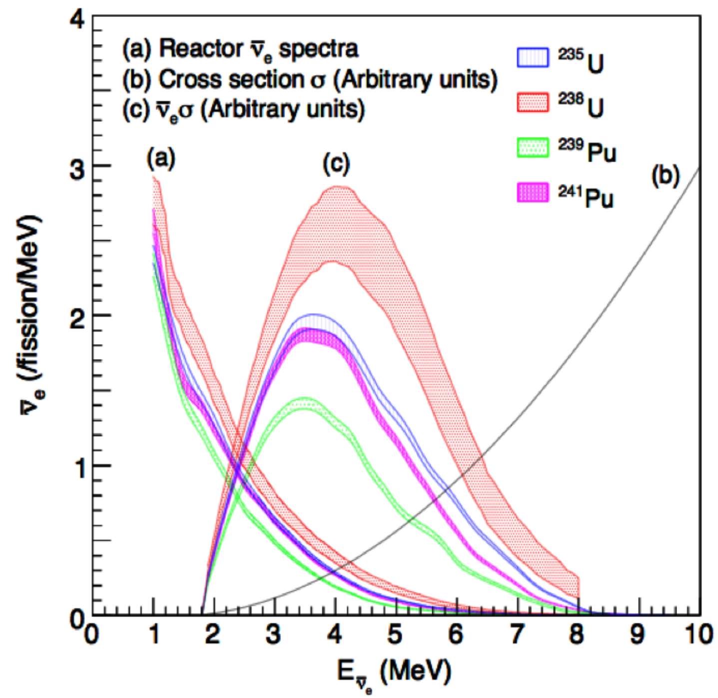
Nuclear Reactors as Antineutrino Sources

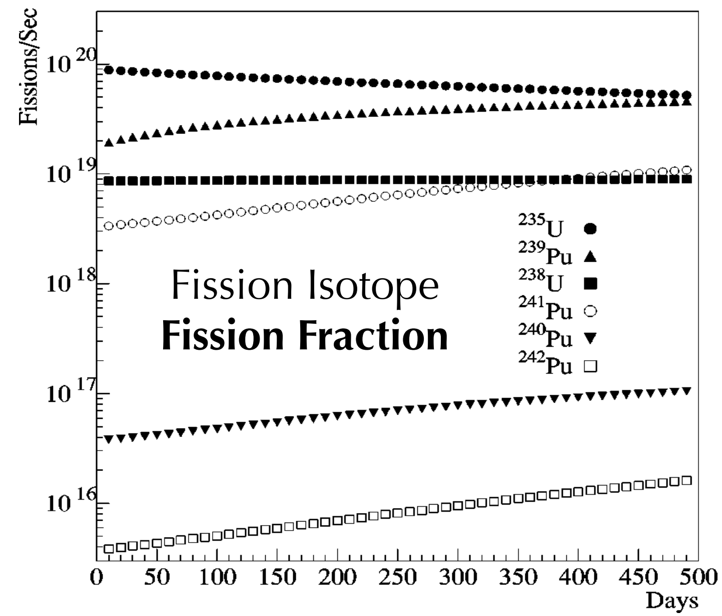
Fission fragments beta decay release antineutrinos



$$S(E_\nu) = \frac{W_{th}}{\sum_i (f_i/F) e_i} \sum_i^{istopes} (f_i/F) S_i(E_\nu)$$

- **Thermal Power, W_{th},** reactor monitoring ~0.5%;
- **Energy Released per Fission, e_i** ~200 MeV, ~0.2%
- **Fission Fractions, f_i/F,** of each isotope evolves as the reactor "burns", ~0.6%
- **Antineutrino Spectra, S_i,** ~2-3.4% if assuming different ^{238}U treatments
  - ^{235}U, ^{239}Pu, ^{241}Pu converted from the electron spectra of measured at BILL in 80's by Feilitzsch et al; Huber, Mueller et al again in 2011
  - ^{238}U antineutrino spectrum is calculated by Vogel in 1980's and Mueller et al in 2011.





Neutrino Physics at Nuclear Reactors

courtesy: Karsten Heeger

2012 - Observation of short-baseline reactor electron antineutrino disappearance

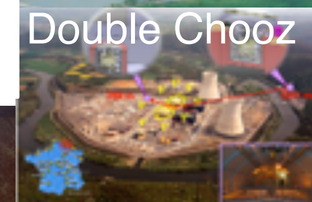
2008 - Precision measurement of Δm_{12}^2. Evidence for oscillation

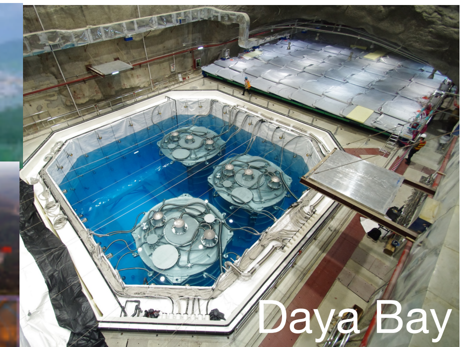
2003 - First observation of reactor antineutrino disappearance

1995 - Nobel Prize to Fred Reines at UC Irvine

1980s & 1990s - Reactor neutrino flux measurements in U.S. and Europe

1956 - First observation of (anti)neutrinos





Past Reactor Experiments
Hanford
Savannah River
ILL, France
Bugey, France
Rovno, Russia
Goesgen, Switzerland
Krasnoyark, Russia
Palo Verde
Chooz, France
KamLAND, Japan
Double Chooz, France
Reno, Korea
Daya Bay, China

What now?

- Opportunities
- Challenges
- Efforts&Expectations

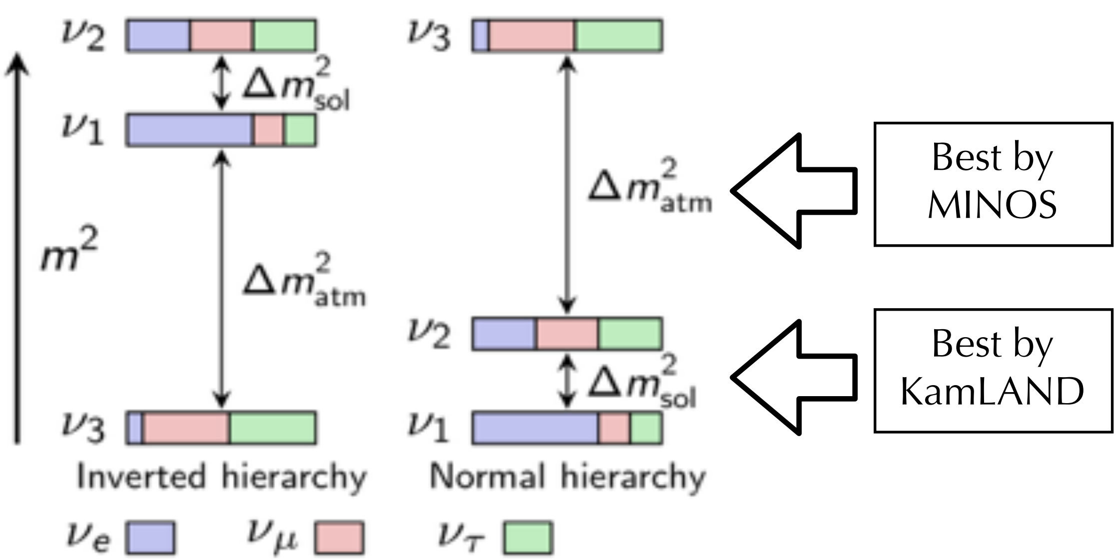
Knowns and Unknowns in Neutrino Physics

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric Sector:
SK, K2K, T2K, MINOS, etc

The Lastly Known:
Short-baseline **Reactor**

Solar Sector:
SNO, SK, **KamLAND** etc



Inverted ⇦ ? ⇨ Normal

States m_1 and m_2 are differentiated by solar neutrino data (MSW effect)

- **Mass hierarchy?**
- CP phase?
- Theta23 octant?
- Sterile neutrinos?
- Dirac vs Majorana?
- Absolute mass?
- Mass generation mechanism?
- ……

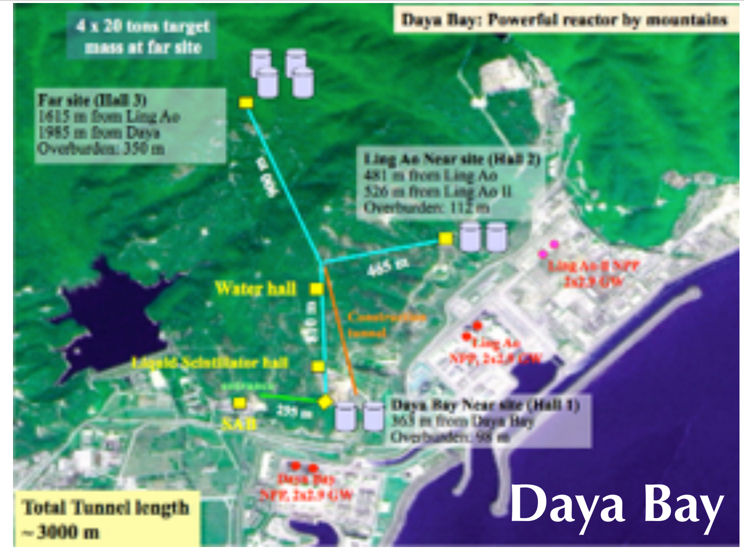
The Hunt of θ_{13} by Reactor Based Experiments

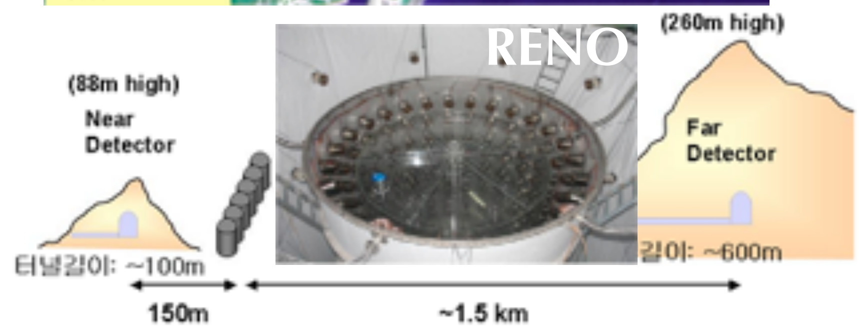
- Two ways to measure θ_{13}

$$P_{\nu_\alpha \to \nu_\beta} = 1 - 4 \sum_{i<j} |V_{\alpha j}|^2 |V_{\beta i}|^2 \sin^2 \frac{\Delta m^2_{ji} L}{4E}$$

  - **Appearance experiments $\nu_\mu \to \nu_e$** depends on 3 unknown parameters θ_{13}, δ_{CP} and mass hierarchy:
    - Summer 2011, T2K results had hints of $\sin^2 2\theta_{13} > 0$. MINOS had consistent results
  - **Short-baseline reactor experiments** depend only on 2 unknown parameters θ_{13} and mass hierarchy, with mass hierarchy has little effect:
    - Dec 2011, Double Chooz showed an indication $\sin^2 2\theta_{13} > 0$

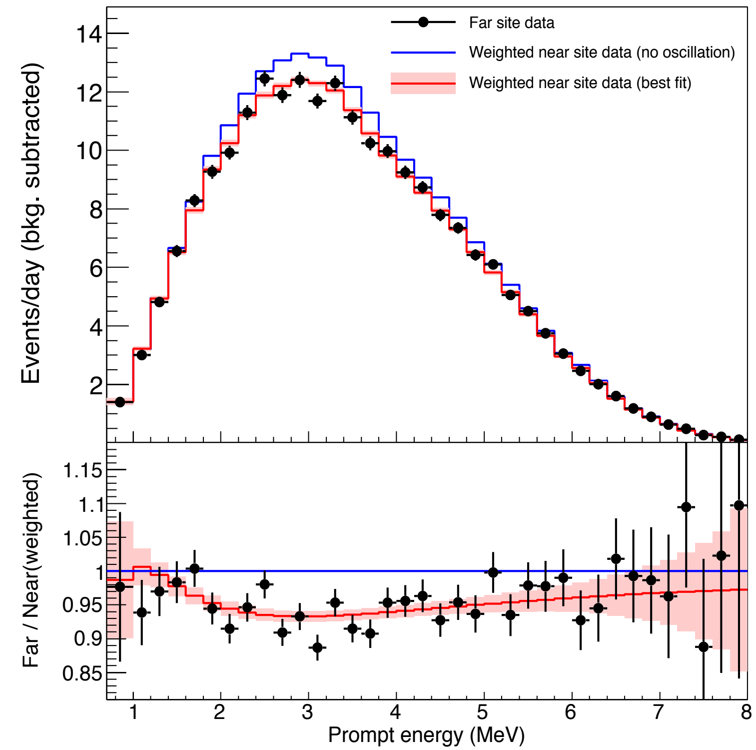
- **On March 8, 2012, Daya Bay announced $\sin^2 2\theta_{13} > 0$ with, $>5\sigma$ significance.**
(RENO showed consistent results after 1 month)

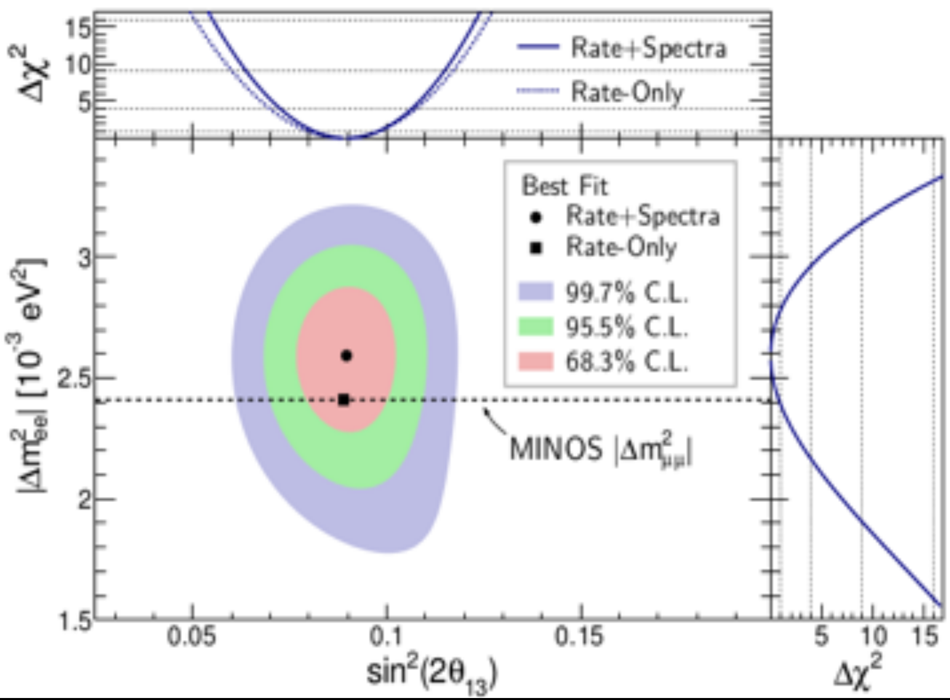




The First Δm^2_{atm} Measurement in Electron Flavor

- Daya Bay has the most precise theta13 measurement
- Daya Bay measured Δm^2_{atm} for the first time in electron flavor sector
    - So what?





$$\sin^2 2\theta_{13} = 0.090^{+0.008}_{-0.009}$$

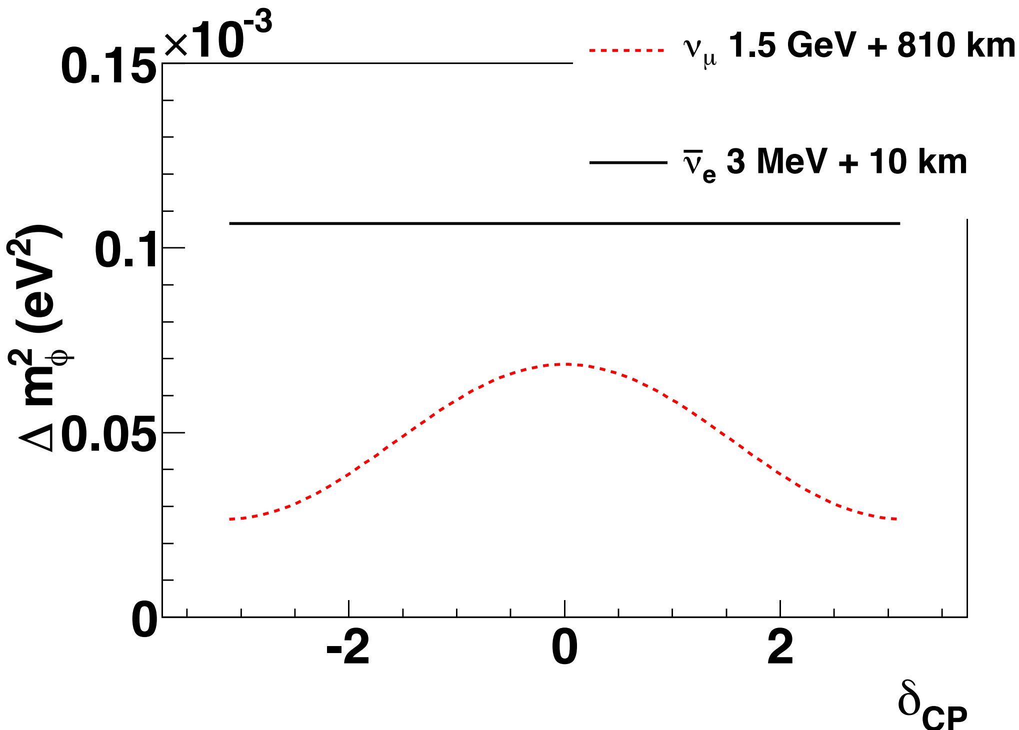
$$|\Delta m^2_{ee}| = 2.59^{+0.19}_{-0.20} \cdot 10^{-3}\text{eV}^2$$

$$\chi^2/N_{\text{DoF}} = 162.7/153$$

One Way to Reach Neutrino Mass Hierarchy

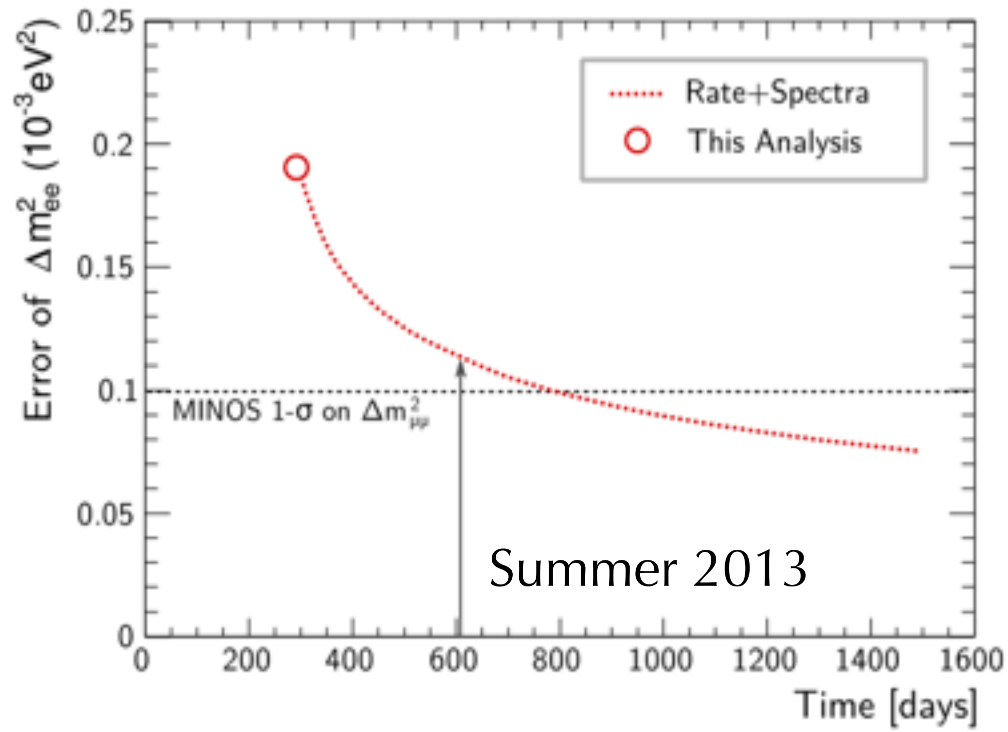
$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - 2s_{13}^2 c_{13}^2 - 4c_{13}^4 s_{12}^2 c_{12}^2 \sin^2 \Delta_{21} + 2s_{13}^2 c_{13}^2 \sqrt{1 - 4s_{12}^2 c_{12}^2 \sin^2 \Delta_{21}} \cos(2\Delta_{32} \pm \phi)$$

$$P_{\nu_\mu \to \nu_\mu} = 1 - P_{21}^{\mu} - \cos^2\theta_{13} \sin^2 2\theta_{23} \sin^2 \frac{(\Delta m_{32}^2 \pm \phi) L}{4E}$$



X. Qian et al, PRD87(2013)3, 033005

FIG. 6: The dependence of effective mass-squared difference $\Delta m^2_{ee\phi}$ (solid line) and $\Delta m^2_{\mu\mu\phi}$ (dotted line) w.r.t. the value of δ_{CP} for $\bar{\nu}_e$ and ν_μ disappearance measurements, respectively.



The Δm^2_{ee} precision projection of Daya Bay

Jiangmen Underground Neutrino Observatory

IOP Physics World News

China to build a huge underground neutrino experiment

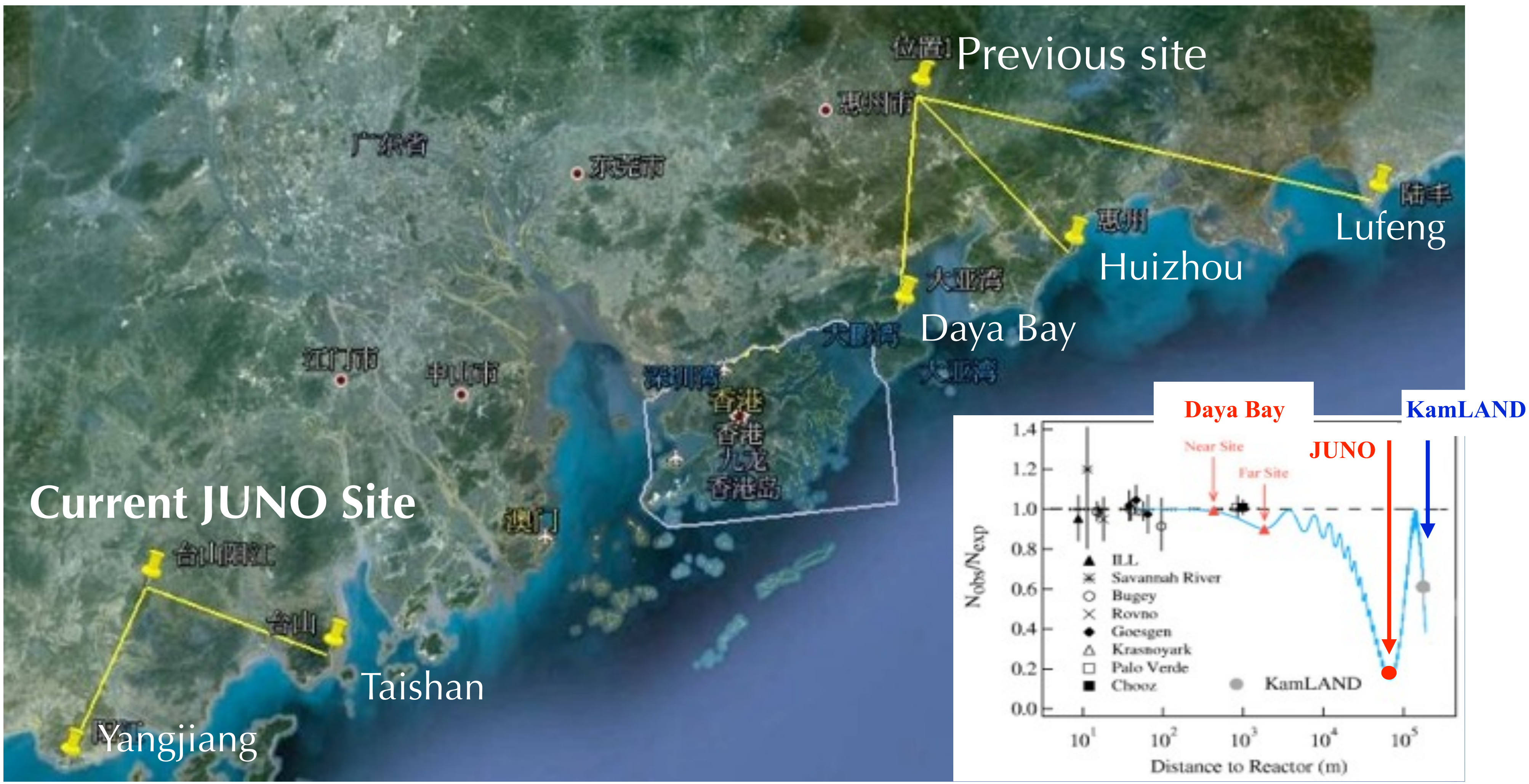
Mar 24, 2014 5 comments

Work has started on a huge underground neutrino lab in China. The $330m Jiangmen Underground Neutrino Observatory (JUNO) is being built in Kaping City, Guangdong Province, in the south of the country around 150 km west of Hong Kong. When complete in 2020, JUNO is expected to run for more than 20 years, studying the relationship between the three types of neutrino: electron, muon and tau.

Test site for the Jiangmen Underground Neutrino Observatory

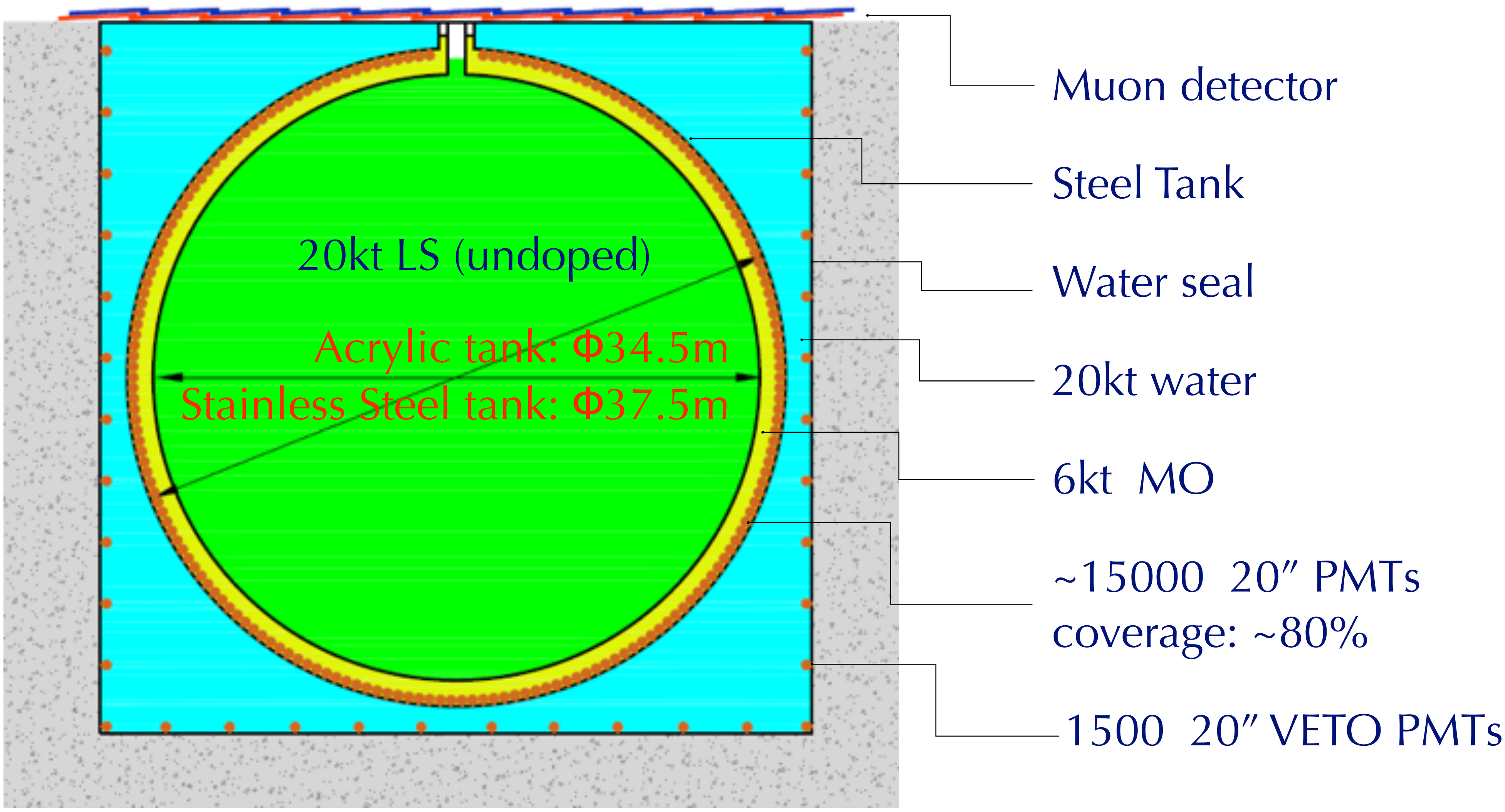
JUNO in Jiangmen City, Guangdong Province, China

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

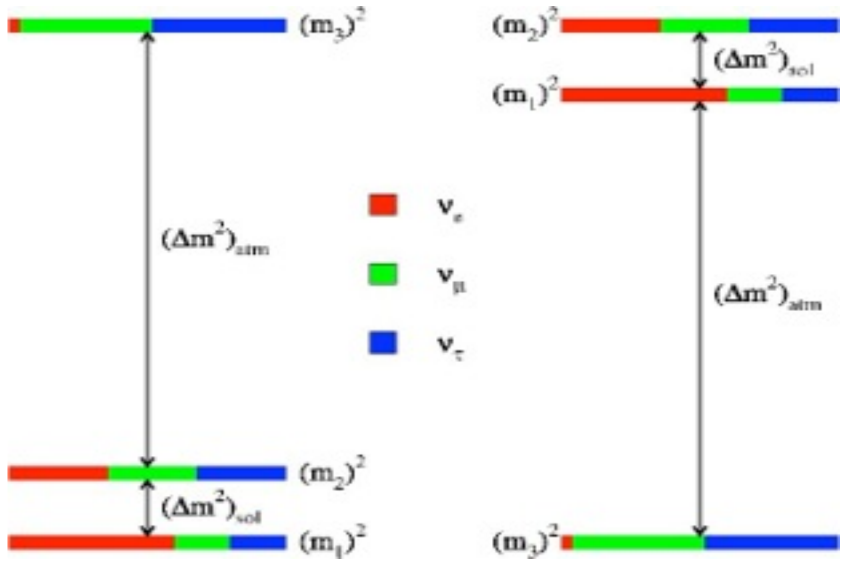


JUNO: A 20kt Liquid Scintillator Detector

- LS volume × 20 (KamLAND) ➔ for more statistics
- Light production × 5 ➔ for better resolution
- Multiple designs are being studied ➔ construction, background, coverage etc

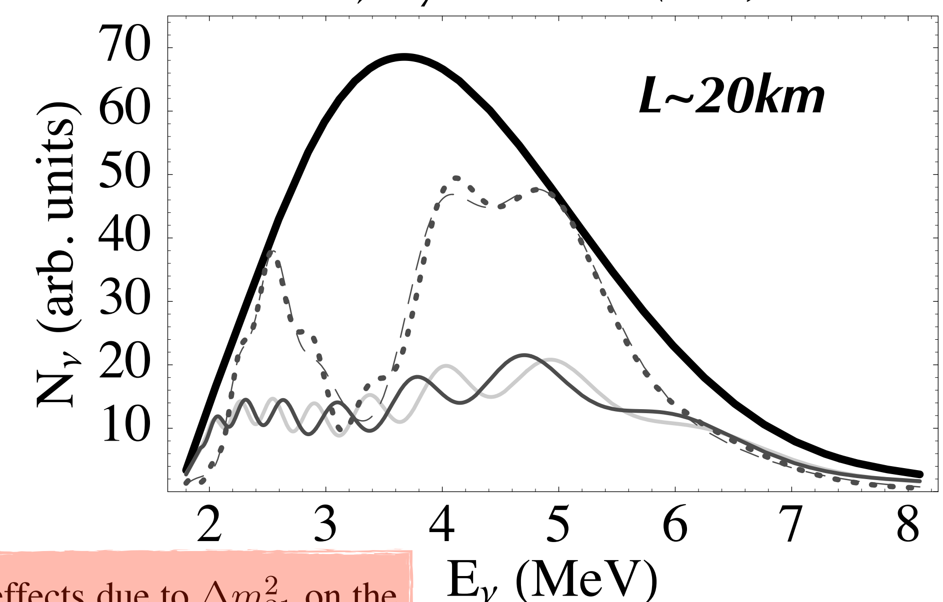


How Mass Hierarchy Manifests Itself



- How to resolve neutrino mass hierarchy using reactor neutrinos
  - KamLAND (long-baseline) measures the solar sector parameters
  - Short-baseline reactor neutrino experiments designed to utilize the oscillation of atmospheric scale
  - ✓ Both scales can be probed by observing the spectrum of reactor neutrino flux

Petcov&Piai, Phys. Lett. B533 (2002) 94-106



$$P_{\bar{\nu}_e\to\bar{\nu}_e} = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$

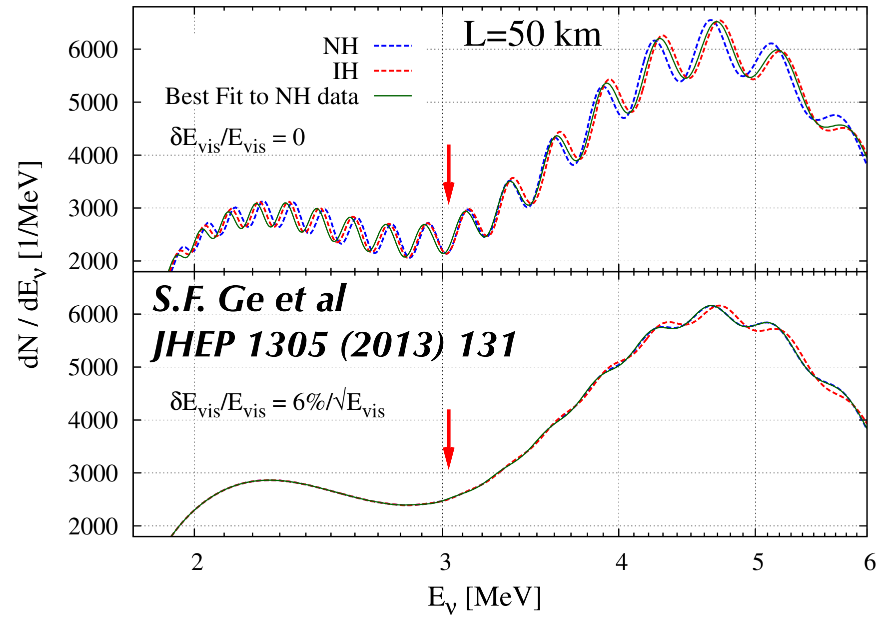
$$-\sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32})$$

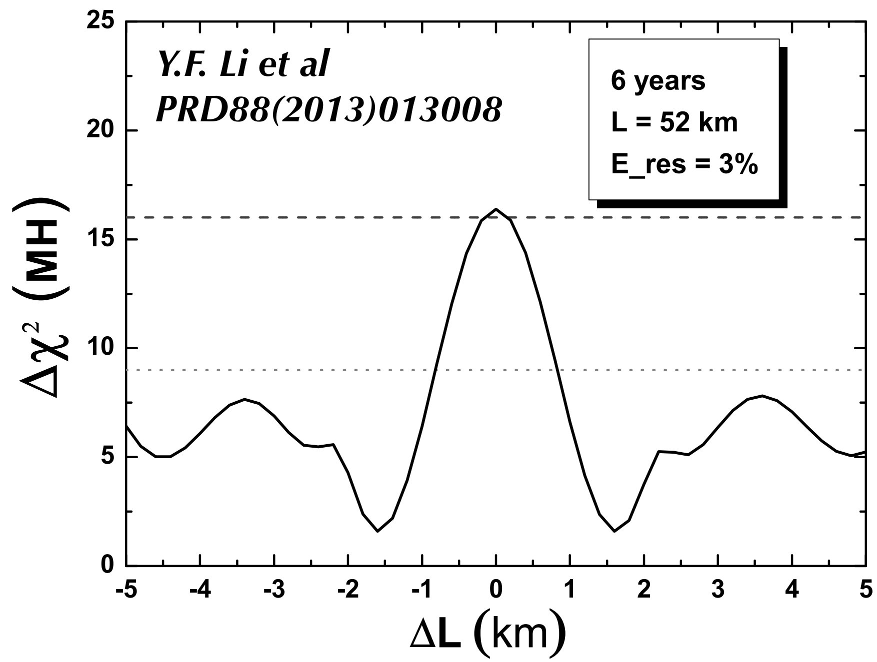
✓The mass hierarchy is contained in the spectrum
✓Independent of the unknown CP phase

- the value of $\sin^2\theta$, which controls the magnitude of the sub-leading effects due to Δm^2_{31} on the $\Delta m^2_{\odot}-$driven oscillations: the effect of interest vanishes in the decoupling limit of $\sin^2\theta \to 0$;

Challenges in Resolving MH using Reactors

- Energy resolution
- Energy non-linearity
- Statistics
- Reactor distribution
  - The mass hierarchy information is in the multiple atmospheric oscillation cycles in the survival spectrum. For the valuable part of the spectrum ~3.5MeV, the oscillation length is ~3.5km.
  - Thus, if two reactor cores with equal or close powers differ by half oscillation length, the mass hierarchy signal will get cancelled.

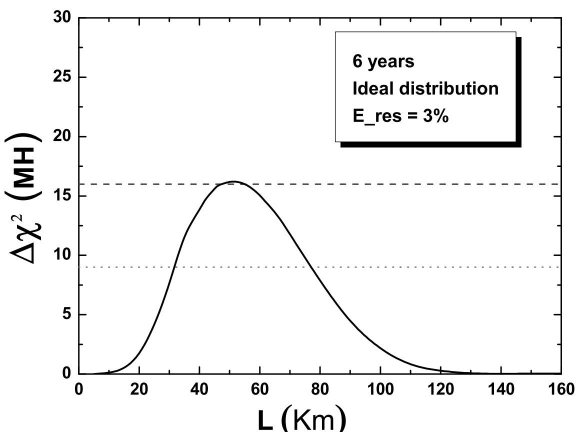


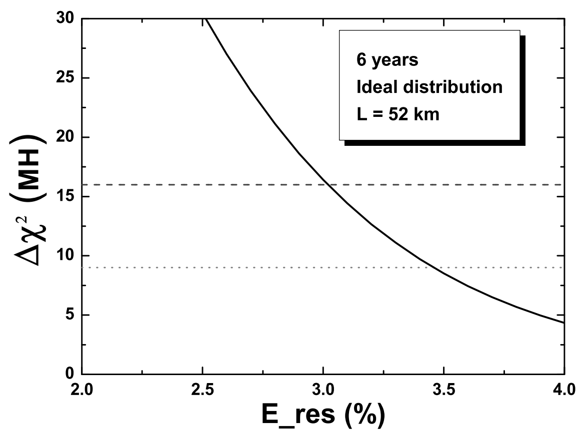


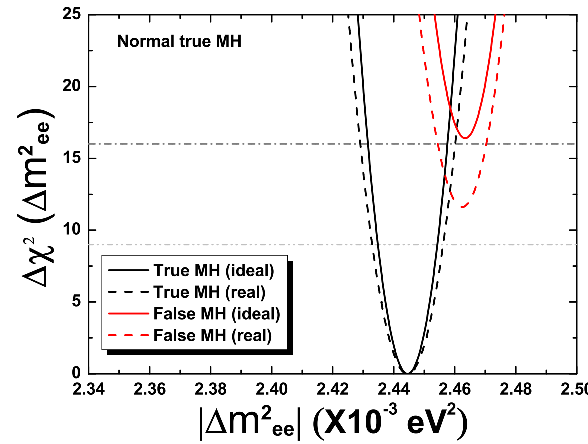
Sensitivity Prediction of JUNO

Chi-square analysis to fit the Asimov data generated assuming true MH

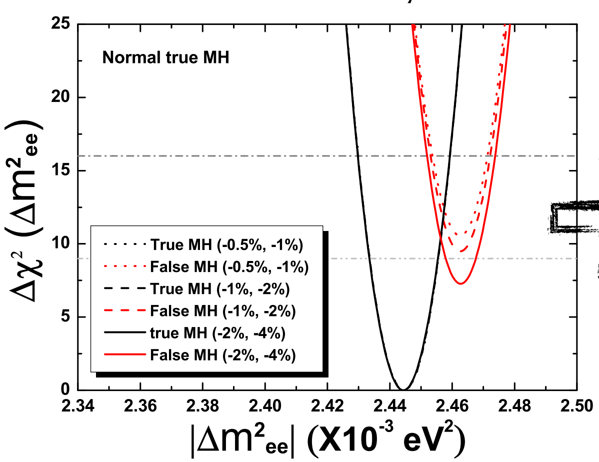
$$\chi^2_{\rm REA} = \sum_{i=1}^{N_{\rm bin}} \frac{[M_i - T_i(1+\sum_k \alpha_{ik}\epsilon_k)]^2}{M_i} + \sum_k \frac{\epsilon_k^2}{\sigma_k^2}, \quad \Rightarrow \quad \Delta\chi^2_{\rm MH} = |\chi^2_{\rm min}({\rm N}) - \chi^2_{\rm min}({\rm I})|$$



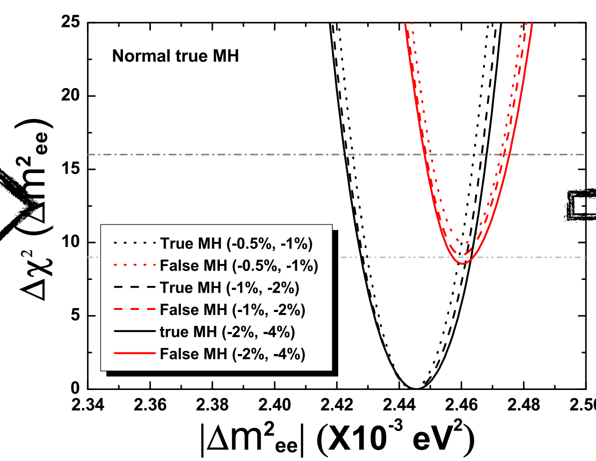




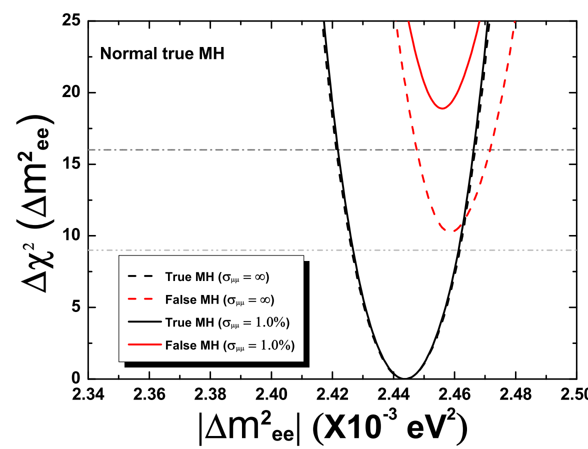
With non-linearity residual



With energy self-correction



With 1% $\Delta m^2_{\mu\mu}$ *prior*



Y.F. Li et al, PRD88(2013)013008

Addressing Challenge #1: Get More Photons

- Highly transparent LS:
  - ⇨ **Attenuation length/D: 15m/16m → 30m/34m ×0.9**
- High light yield LS:
  - ⇨ **KamLAND: 1.5g/l PPO → 5g/l PPO**

    Light Yield: 30%→ 45%; × 1.5
- Photocathode coverage :
  - ⇨ **KamLAND: 34% → ~ 80% × 2.3**
- High QE "PMT":
  - ⇨ **20" SBA PMT QE: 25% → 35% × 1.4**

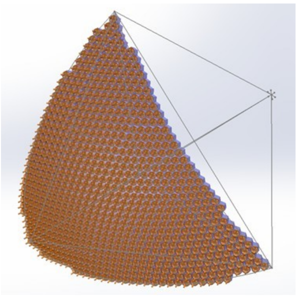
    or New PMT QE: 25% → 40% × 1.6

    Both: 25% → 50% × 2.0

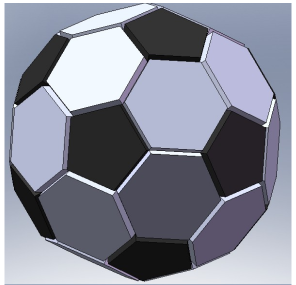
4.3 – 5.0 → (3.0 – 2.5)% $/\sqrt{E}$

Other contributions:

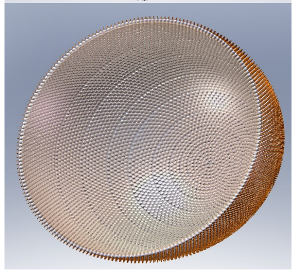
0.5% constant term & 0.5% neutron recoil uncertainty



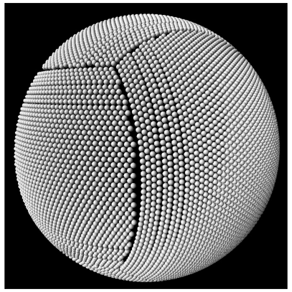
Triangle modules, ~14,300 PMTs ~72%



~14,000 PMTs, ~74%. Can be improved to ~83% if fill 2,600 PMTs at gaps



Latitude/longitude design, ~15,000 PMTs, ~77%



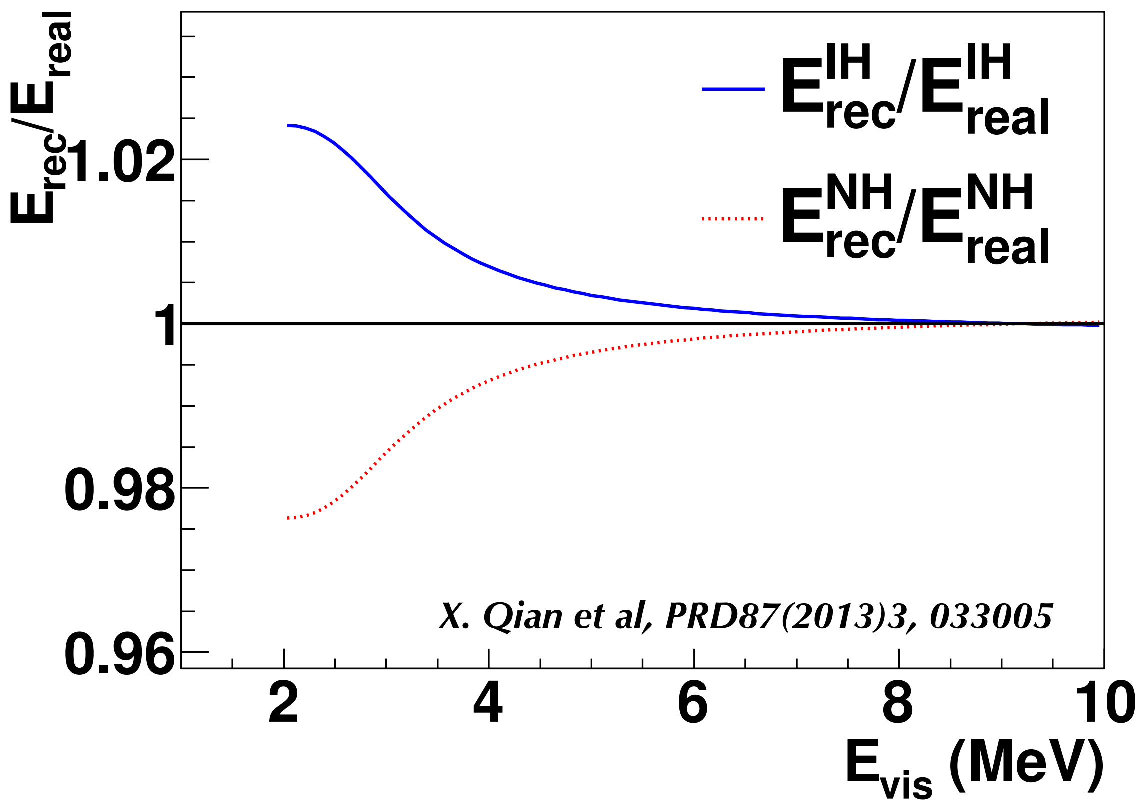
Volleyball, ~15,000 PMTs, ~78%

Addressing Challenge #2: Avoid Degenerated Spectra

- Recall the survival probability

$$P_{\bar{\nu}_e\to\bar{\nu}_e} = 1 - 2s_{13}^2c_{13}^2 - 4c_{13}^4s_{12}^2c_{12}^2\sin^2\Delta_{21}$$
$$+2s_{13}^2c_{13}^2\sqrt{1-4s_{12}^2c_{12}^2\sin^2\Delta_{21}}\cos(2\Delta_{32}\pm\phi)$$

$$\Rightarrow \quad E_{rec} = \frac{2|\Delta' m_{32}^2| + \Delta m_\phi^2(E_{\bar{\nu}_e}, L)}{2|\Delta m_{32}^2| - \Delta m_\phi^2(E_{\bar{\nu}_e}, L)} E_{real}$$



- The Δm^2_{atm} uncertainty and non-linear energy response could create the same survival spectrum.
  - ➡ Very difficult to resolve MH if the non-linearity uncertainty is large
- To enhance the sensitivity to MH, a comprehensive calibration R&D program is being developed, including a positron beam calibrating the whole spectrum

External Input: $\Delta m^2_{\mu\mu}$ Precision in Coming Years

- S.K. Agarwalla, S. Prakash, WW, http://arxiv.org/abs/1312.1477.

True $\sin^2\theta_{23}$	T2K (5ν)	NOνA ($3\nu + 3\bar{\nu}$)	T2K + NOνA
0.36	1.53%	2.33%	1.24% ($2.41^{+0.09}_{-0.09}$)
0.50	1.16%	1.45%	**0.87%** ($2.41^{+0.07}_{-0.06}$)
0.66	1.53%	2.26%	1.24% ($2.41^{+0.09}_{-0.09}$)

Table 2: Relative 1σ precision on $|\Delta m^2_{\mu\mu}|$ considering different true values of $\sin^2\theta_{23}$. Results are shown for T2K, NOνA, and their combined data. In the last column, inside the parentheses, we also give the 3σ allowed ranges of test $|\Delta m^2_{\mu\mu}|$ ($\times 10^{-3}$ eV^2) around its best-fit.

- Combining future MH experiments (INO? PINGU?)

Furthermore: Better Flux ☞ Better MH Sensitivity

- Reactor flux uncertainty improvements can also improve the sensitivity.

Uncertainty improvement	$\Delta\chi^2$ (Model I)	$\Delta\chi^2$ (Model II)	$\Delta\chi^2$ (Model III)
Current ~3%	9.5	17.3	13.9
Factor 2	11.5	21.7	18.4
Factor 3	12.1	23.2	19.9
Factor 4	12.4	23.8	20.5
Factor 5	12.6	24.1	20.9

A.B. Balantekin et al arXiv:1307.7419 Snowmass'13

- Who will provide better reactor flux measurements/predictions? (FRM-II has made the first round effort by remeasuring ^{238}U spectrum. Daya Bay? RENO? Double Chooz? Very short-baseline reactor experiments? Theorists?)

Daya Bay Projected Flux Precision (Snowmass'13)

3. **Absolute reactor flux measurement:** In addition to a shape analysis, an absolute flux measurement tests our understanding of reactor flux predictions and can, in principle, shed light on the issue whether there is an apparent deficit in the measured reactor neutrino flux at short baselines, also known as the "reactor anomaly". An analysis of past measurements and reactor flux predictions has revealed a discrepancy of about 5.7%. While Daya Bay has demonstrated superb relative detector uncertainties, an absolute measurement will be systematics limited. A statistical precision of 0.1% will be achievable. Improvements in the analysis may eventually reduce absolute detector uncertainties to <1%. An absolute flux measurement will be limited by our knowledge of the reactor flux normalization: this includes a theoretical uncertainty of 2.7% in the reactor flux predictions. One can compare Daya Bay data to previous reactor flux measurements by "anchoring" it to the absolute Bugey-4 measurement with an uncertainty of 1.4%. Daya Bay's measured flux and spectrum will provide important input to test the reactor anomaly.

Current Abs. Det. Uncertainty

Double Chooz	~1%
Daya Bay	~1.9%
RENO	~1.5%

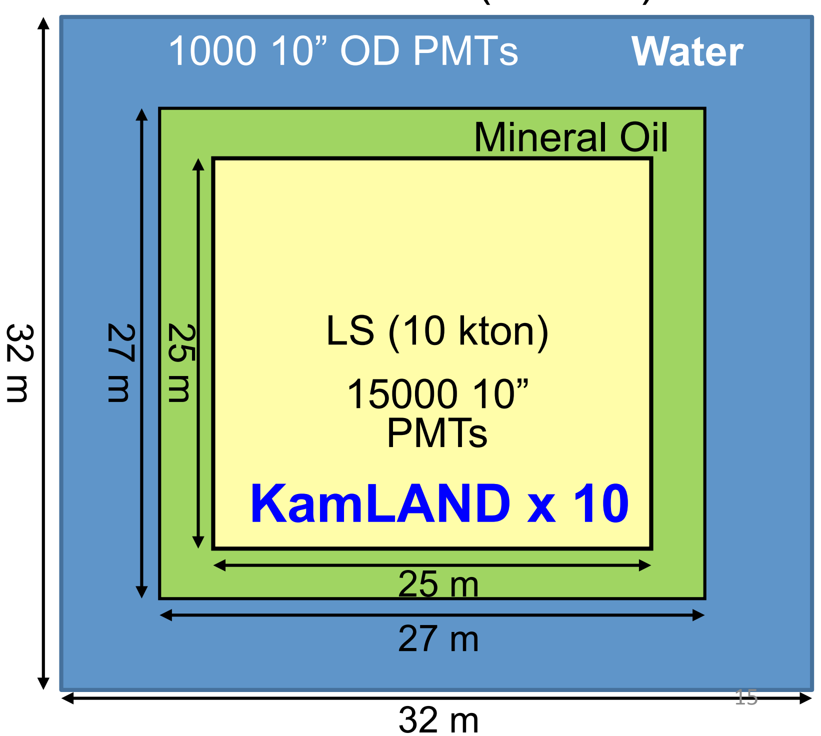
Another Medium-Baseline Experiment: RENO-50

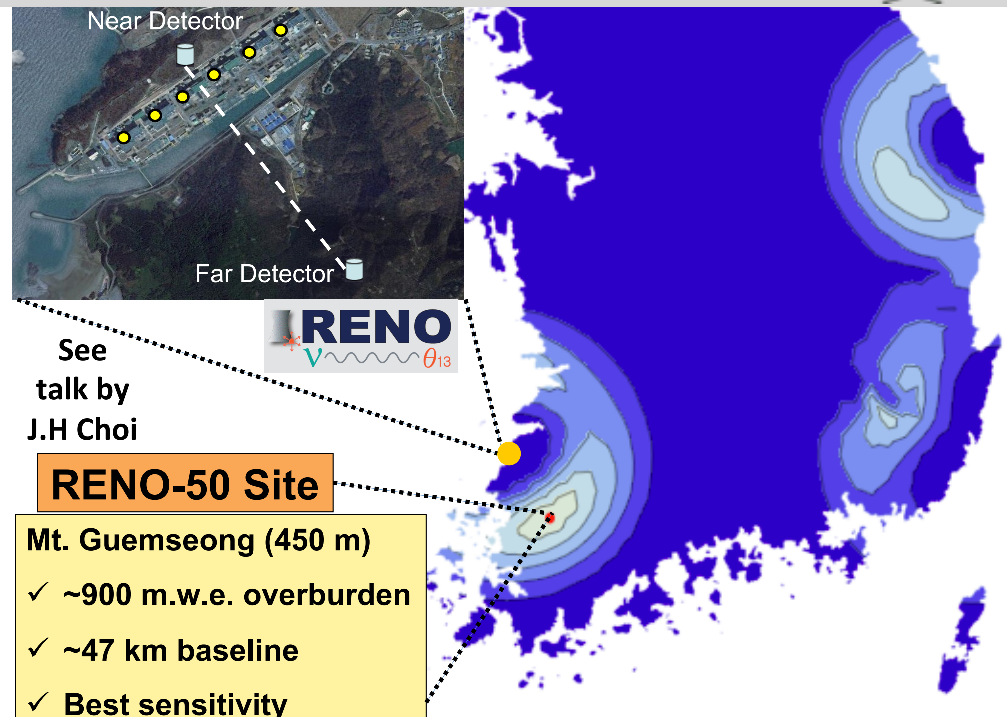
- Utilizing the current 6 RENO reactors
- Baseline ~47km
- Target mass 10kt
- Cylinder-shaped detector

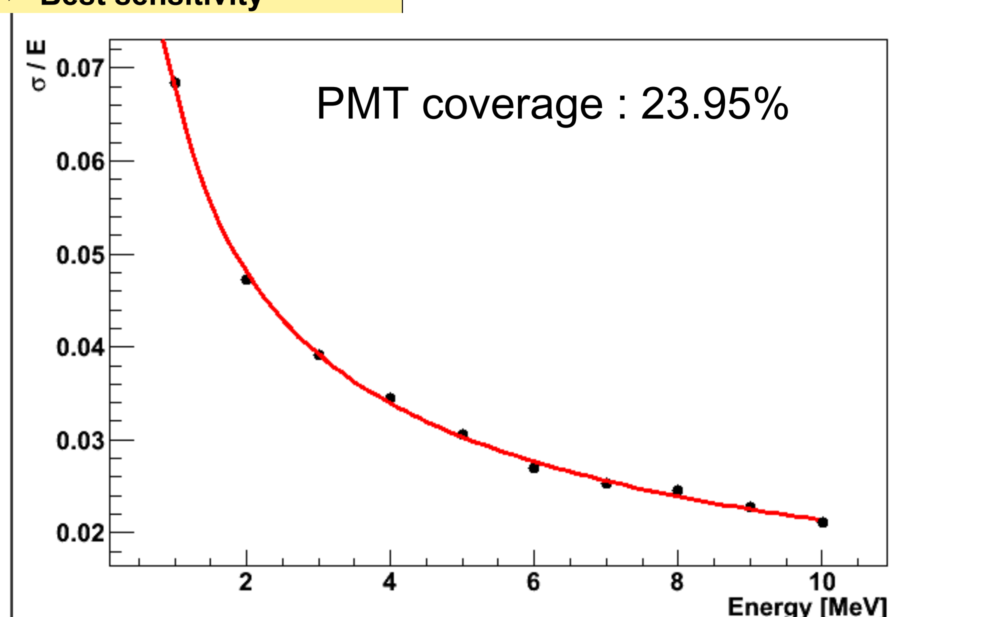
➡ Simulation resolution is ~6% at 1MeV

➡ Need to improve photoelectrons

RENO-50 (default)



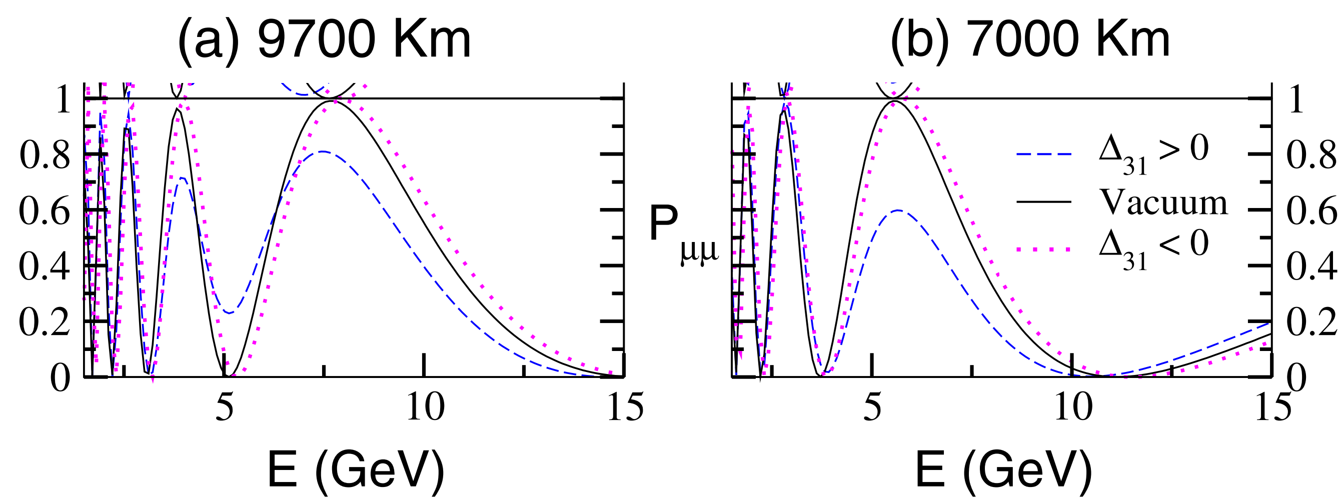




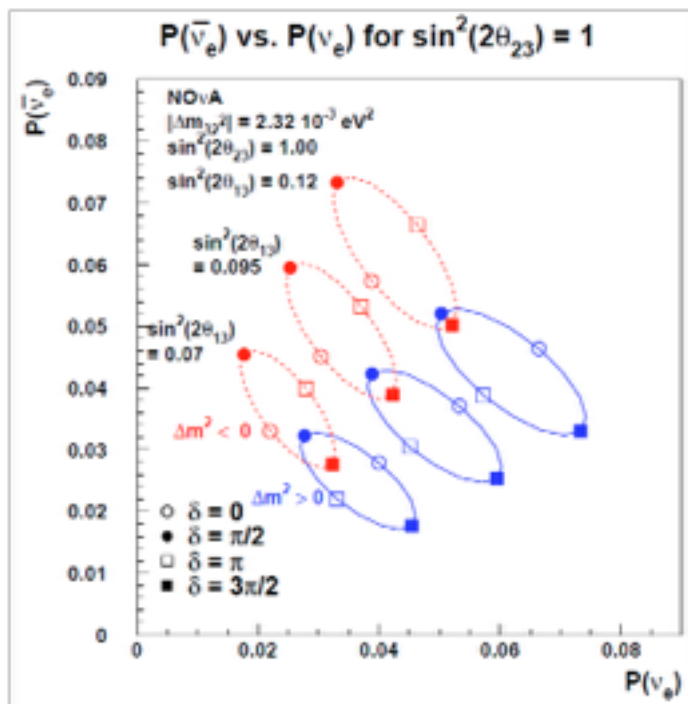
RENO-50 Workshop

Other Non-Reactor Approach Efforts

- Experiments having potential in neutrino mass hierarchy
  - INO, PINGU, Hyper-K/T2HK, LBNE



- Experiments attacking the CP problem in lepton sector
  - NOvA, T2K, Hyper-K/T2HK, LBNE



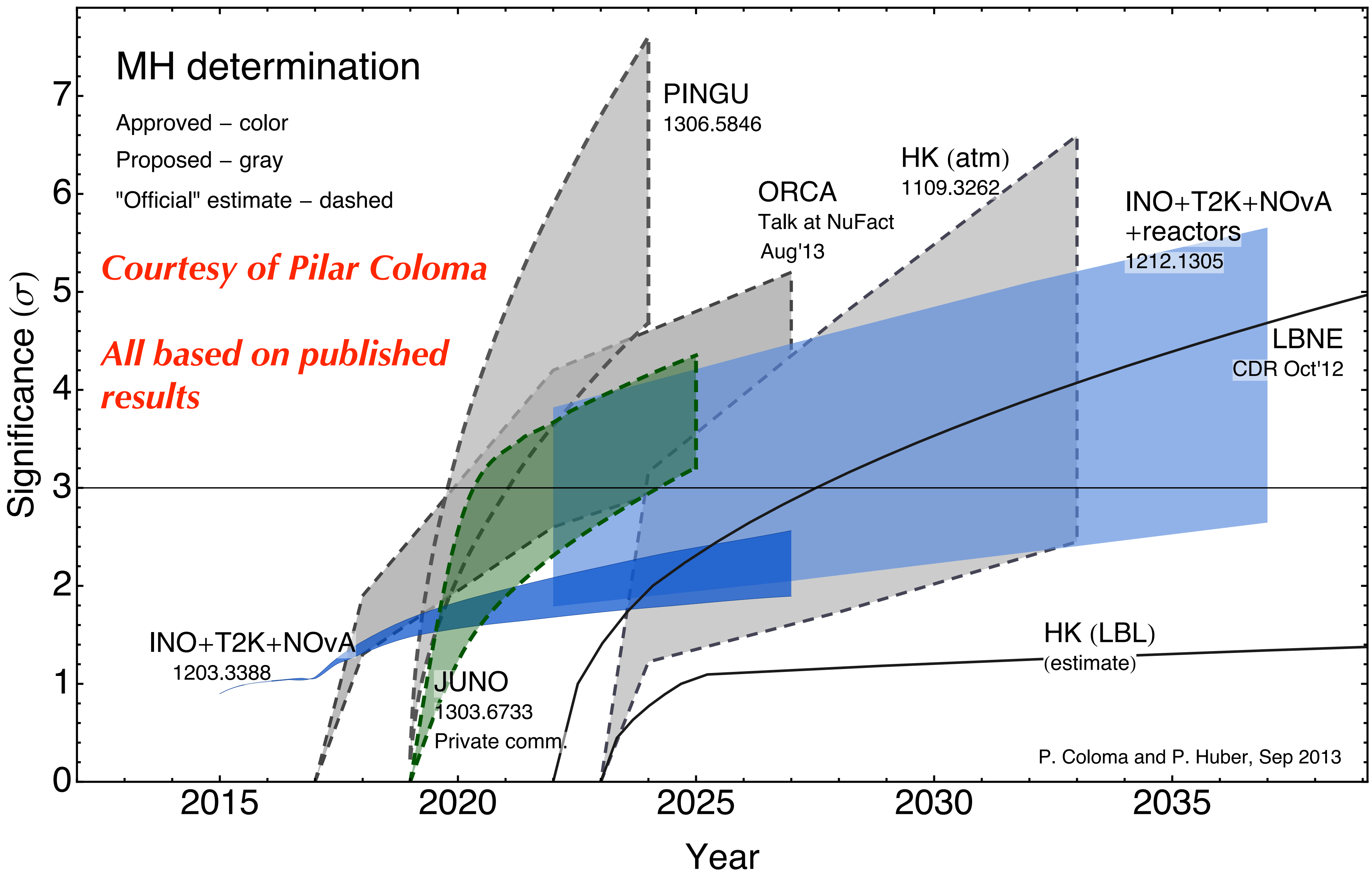
➡ MH and CP are entangled together

➡ Different energies

➡ A different flavor

➡ Complicated interactions

The Race to Mass Hierarchy Has Begun



JUNO Schedule

2013
Complete conceptual design, complete civil design, & bidding

2014
Start civil construction, complete prototyping (PMT & detector)

2015
PMT production line manufacturing

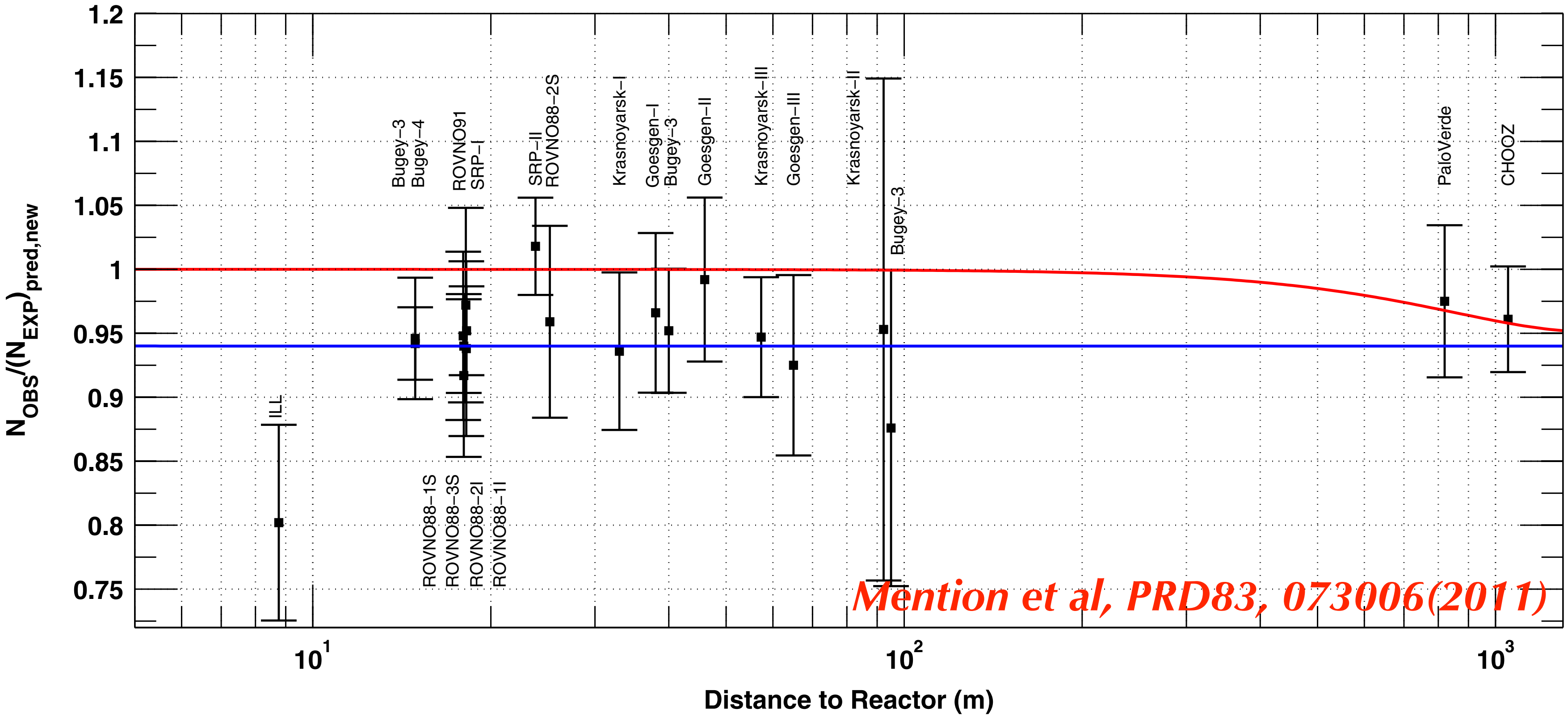
2016
Start PMT production, start detector production or bidding

2017
Complete civil construction, start detector construction & assembly

2018
Start LS production

2019
Complete detector assembly & installation, & LS filling

Aren't Reactors Perfect Antineutrino Sources?



- Reactor antineutrino anomaly
  - Mention et al re-evaluated the reactor flux in 2011 and found ~6% deficit compared with previous short-baseline reactor neutrino experiments, measured/predicted = 0.943+/-0.023

- What is causing the anomaly?
  - Common bias of ALL experiments?
  - Reactor flux calculation?
  - Or a new neutrino state?

Efforts Addressing the Reactor Anomaly Directly

Summary by Shaevitz
Project X, 2012

Experiment	Reactor	Baseline	Status	Latest Status	Detector Features
Nucifer (Saclay)	Osiris 70MW	7	Taking Data	Moving to ILL or a commercial reactor?	GdLS detector, one zone.
Stereo (Genoble)	ILL 50 MW	10	Proposal	Inviting collaborators?	GdLS, 5 segments
SCRAMM (CA)	San-Onofre 3 GW	24	Proposal	Designing detector?	Selecting the best design. Segmented?
NIST (US)	NCNR 20 MW	4-11	Proposal	**UW(Yale), Livemore, NIST. Forming design**	**GdLS, LiLS segmented, near-far detector**
NEUTRINO4	SM3 100 MW	6-12	Proposal	Prototype installation @ PNPI	LS, segmented
SCRAMM (Idaho)	ATR 150 MW	12	Proposal	**Same collaboration as the NIST one**	
DANSS (Russia)	KNPP 3 GW	14	Fabrication	Prototype taking data	Plastic scintillator bars (similar to SciBar of K2K)
CARR @ Chinese CIAE	**60MW**	**7-11**	**Funding secured? Design being formed?**	**LS, H_2O, D_2O targets being discussed. Near-far detector**	

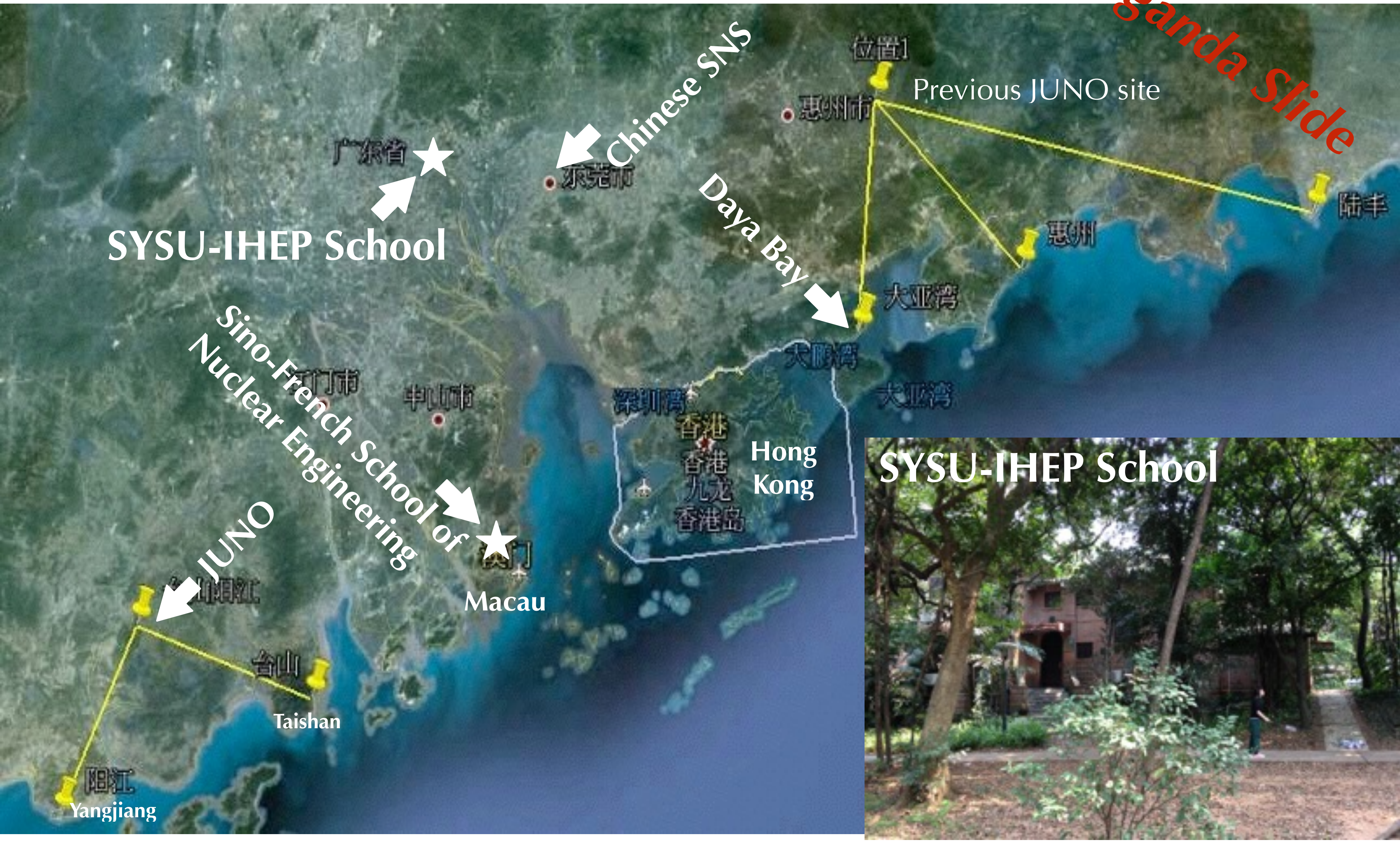
US Efforts merged to PROSPECT

Summary and Conclusion

- Daya Bay theta13 measurement has opened the gate to CP physics in lepton sector and has also enabled the MH resolution using reactor antineutrinos. *Fantastic!*
- JUNO has been funded in China, aiming at resolving MH, also has great potential in precision measurement. *Fantastic!*
- There are competitors for JUNO in MH resolution using the same approach and different approaches. *Fantastic!*
- Very short-baseline reactor-based experiments are targeting at resolving the so-called "reactor anomaly" and, potentially, can provide better reactor flux measurements. *Fantastic!*

➡ ***Beyond Daya Bay, neutrino physics, especially the reactor-based programs, has an even more promising future!***

Come to SYSU-IHEP School of HEP



Challenges of a 20kt LS Detector

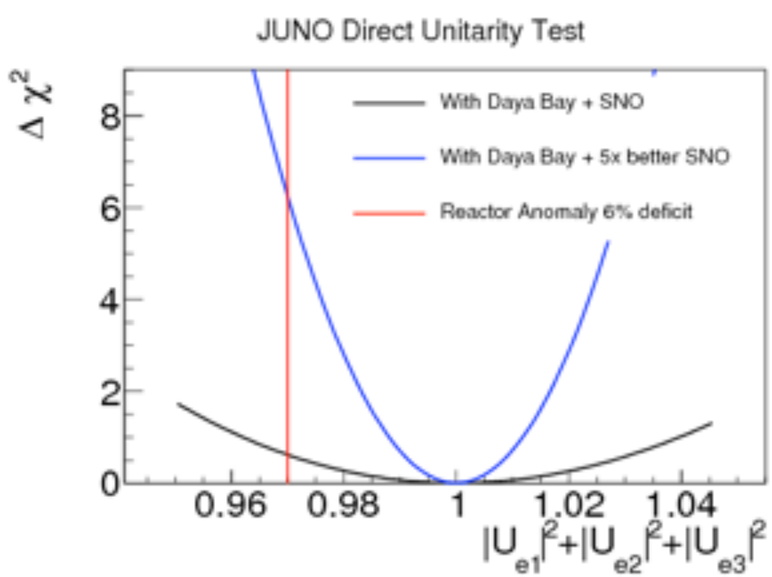
- **Large detector: >10 kt LS**
- **Energy resolution: < 3%/√E ➔ 1200 p.e./MeV**

	Daya Bay	BOREXINO	KamLAND	RENO-50	JUNO
LS Mass	20t	~300t	**~1kt**	18kt	20kt
Light Yield	~160 PE/MeV	**~500 PE/MeV**	~250 PE/MeV	>1000 PE/MeV	~1200 PE/MeV
Photocathode Coverage	~12%	**~34%**	**~34%**	~67%	~80%
Energy Resolution	~7.5%/√E	**~5%/√E**	~6%/√E	3%/√E	3%/√E
Energy Scale	~1.5%	**~1%(?)**	~2%	?	<1%

JUNO Impact of Precision Measurements

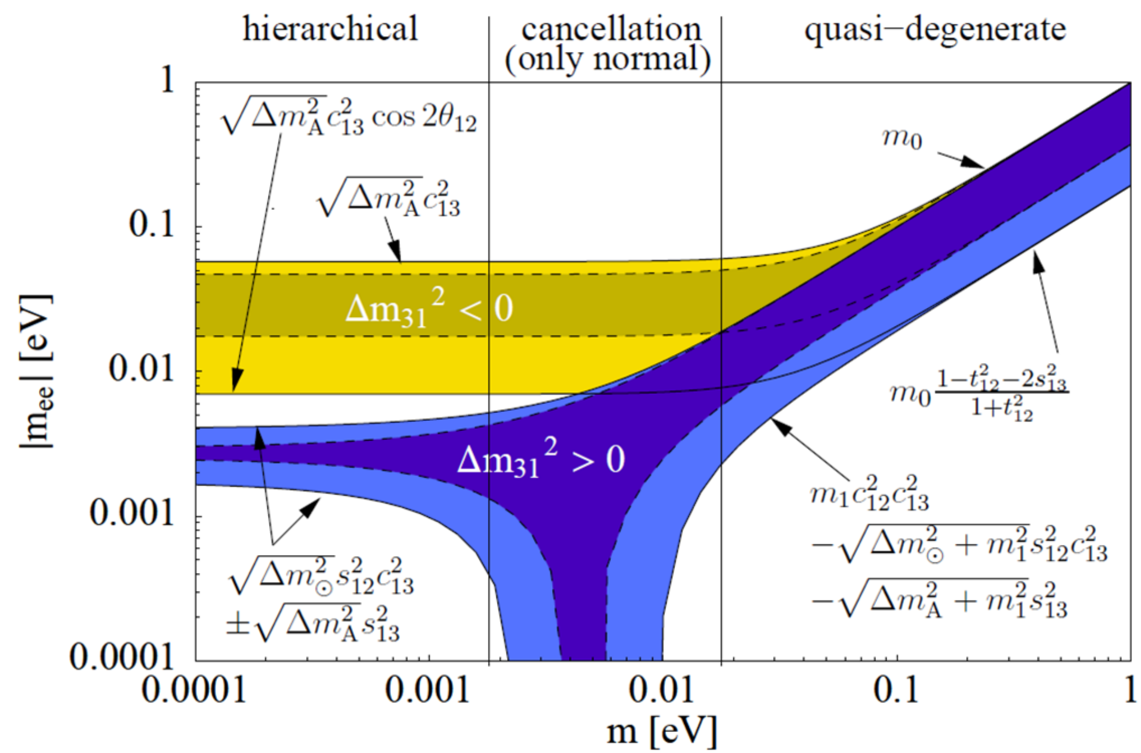
- Three-neutrino paradigm test
- Valuable input to the neutrinoless double beta decay experiments.

$c_{12}c_{13}$ $s_{12}c_{13}$ $s_{13}e^{-i\delta}$



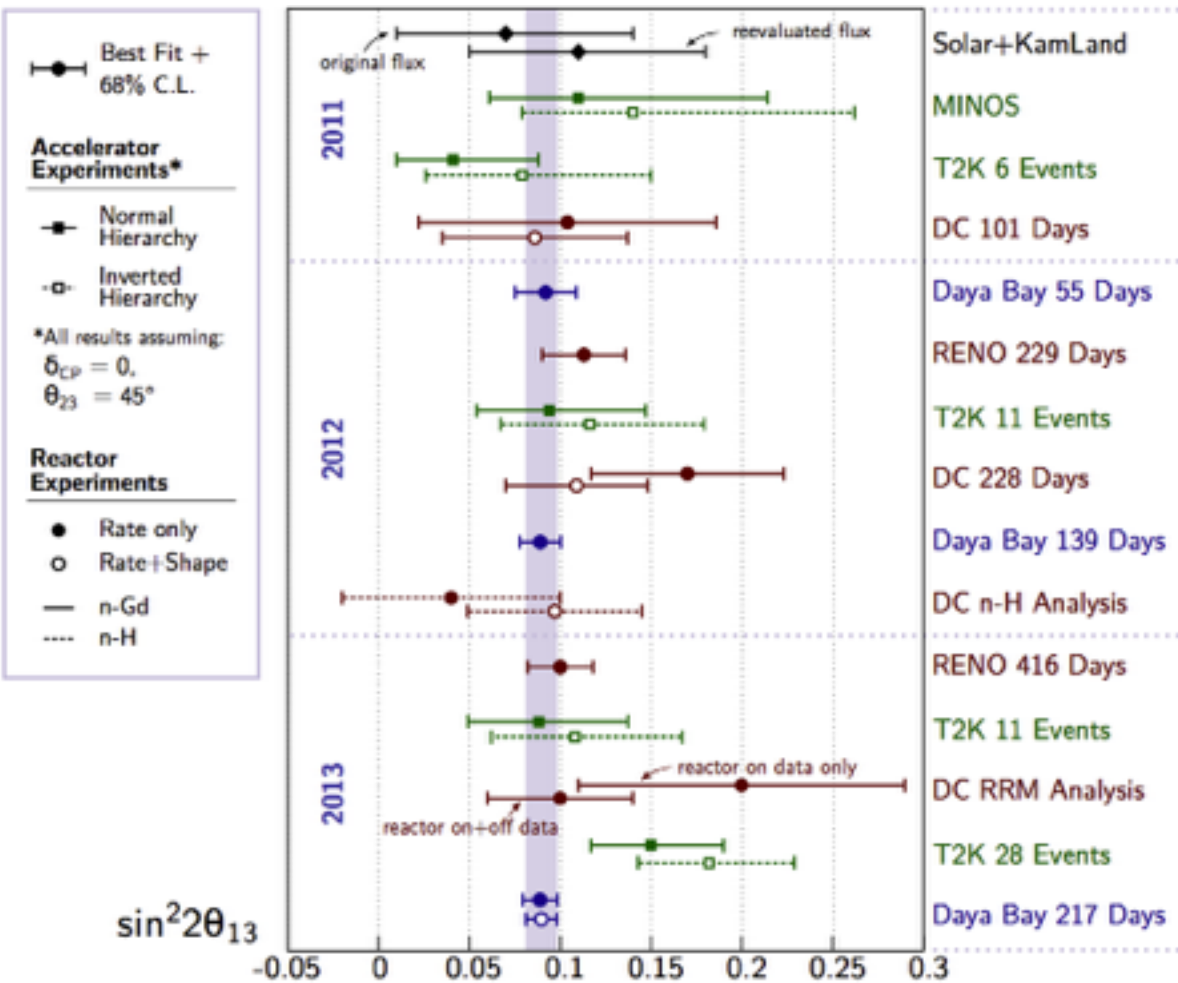
Qian, X. et al. arXiv:1308.5700

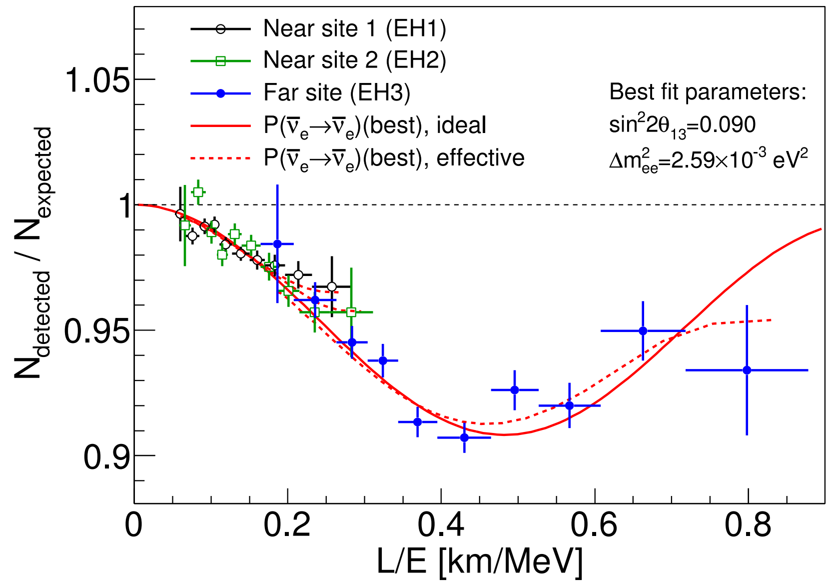
W. Rodejohann, J. Phys. G **39**, 124008 (2012)



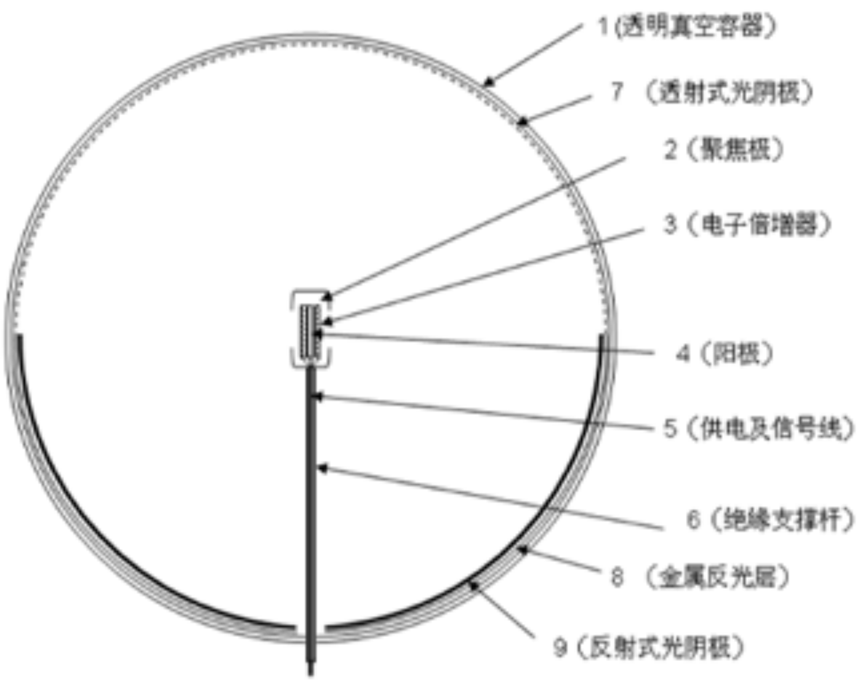
Direct unitarity test of $|U_{e1}|^2+|U_{e2}|^2+|U_{e3}|^2=1$ by combining JUNO, Daya Bay, and solar results. We considered two scenarios i) current SNO constraint and ii) a five times better constraint than SNO.

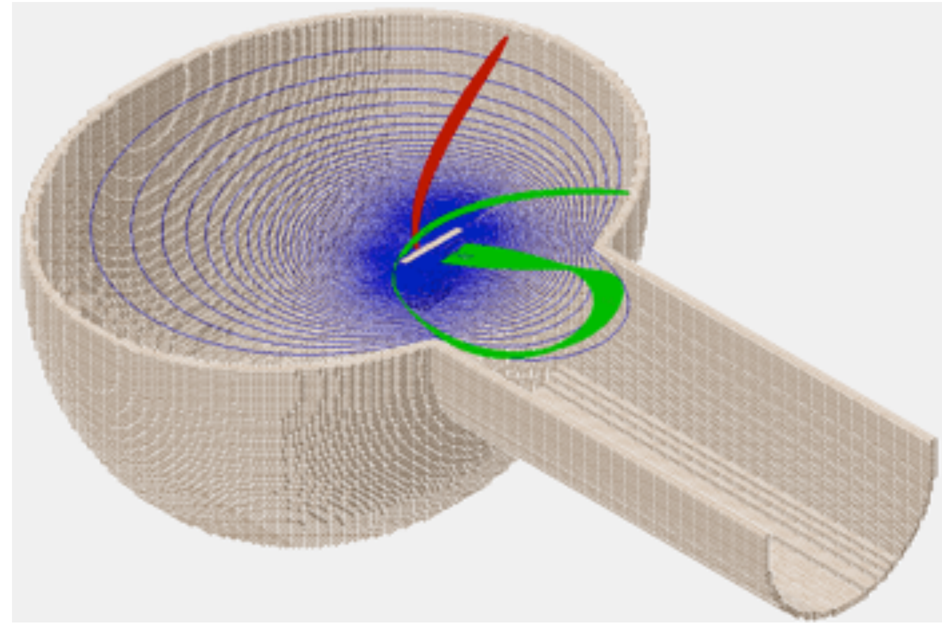
The Current Theta13 Measurements





A new type of PMT: higher photon detection eff.





- **Top: transmitted photocathode**
- **Bottom: reflective photocathode**

  additional QE: ~80%*40%
- **MCP to replace Dynodes → no blocking of photons**

~ ×2 improvement

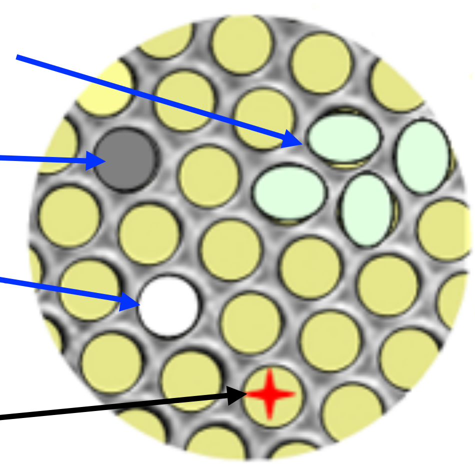
Low cost MCP by accepting the following:

1. asymmetric surface;

2. Blind channels;

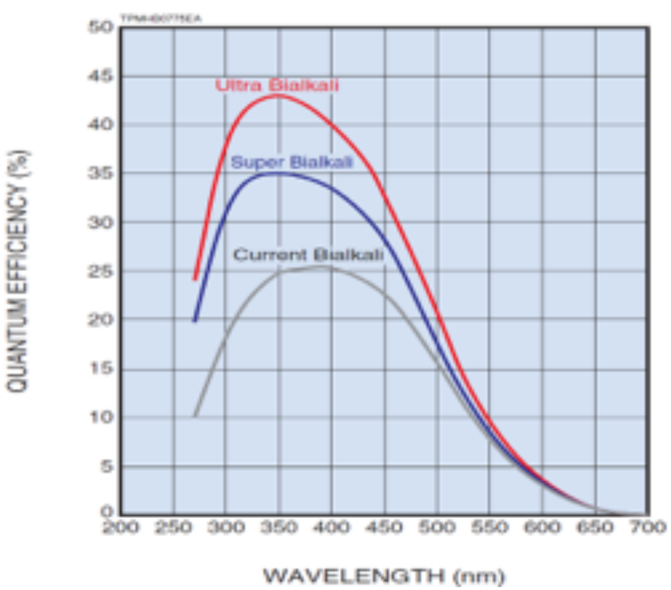
3. Non-uniform gains

4. Flashing channels

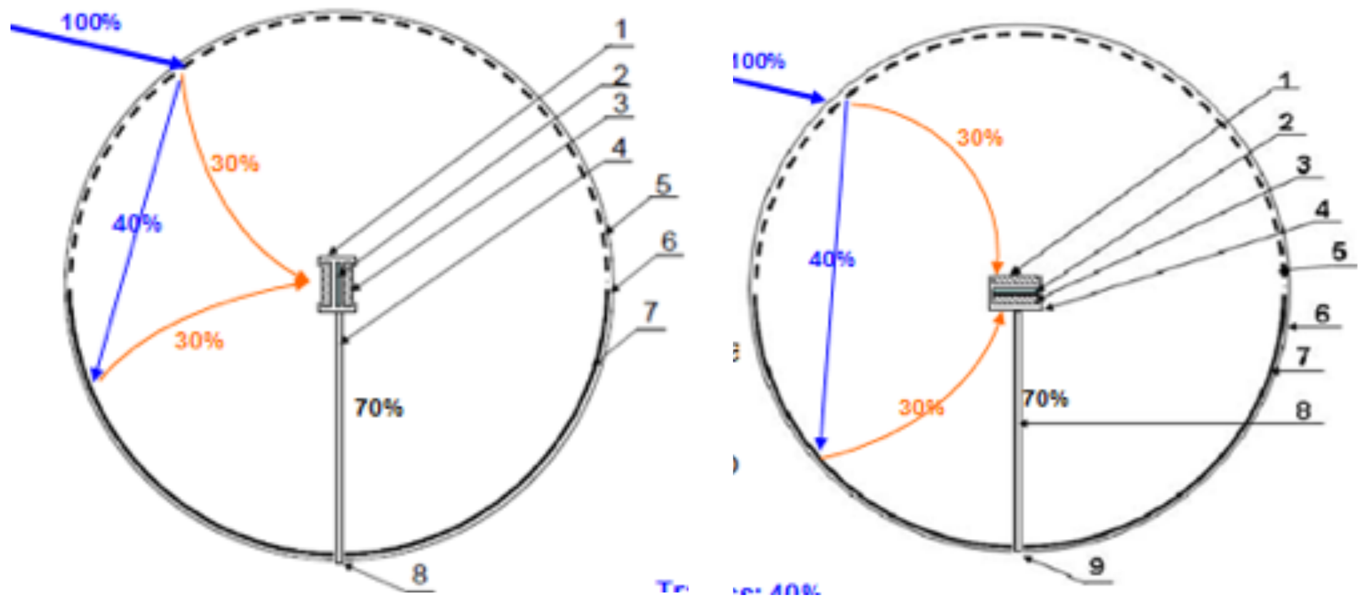


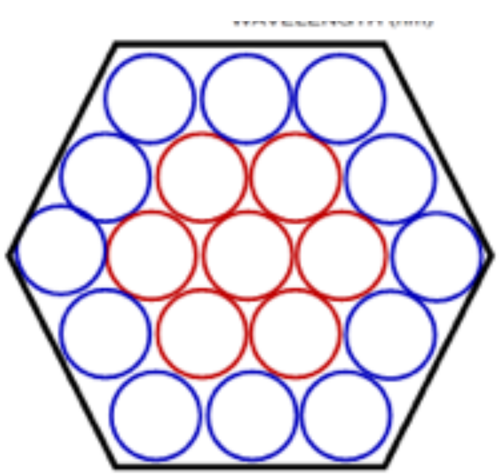
More Photoelectrons — New PMTs

SBA photocathode



New type of PMT: MCP-PMT



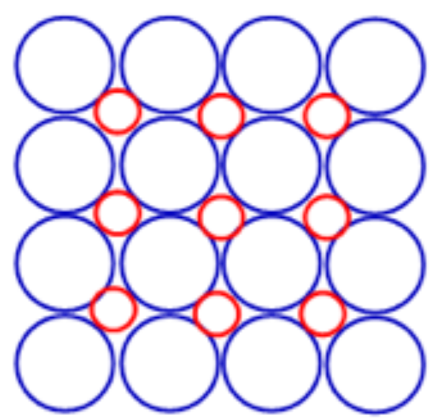


No clearance:

coverage 86.5%

1cm clearance:

coverage: 83%

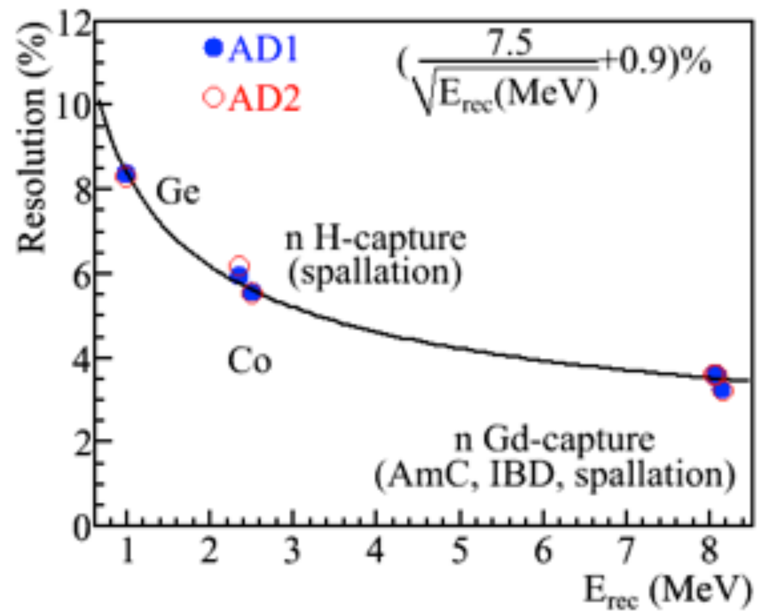


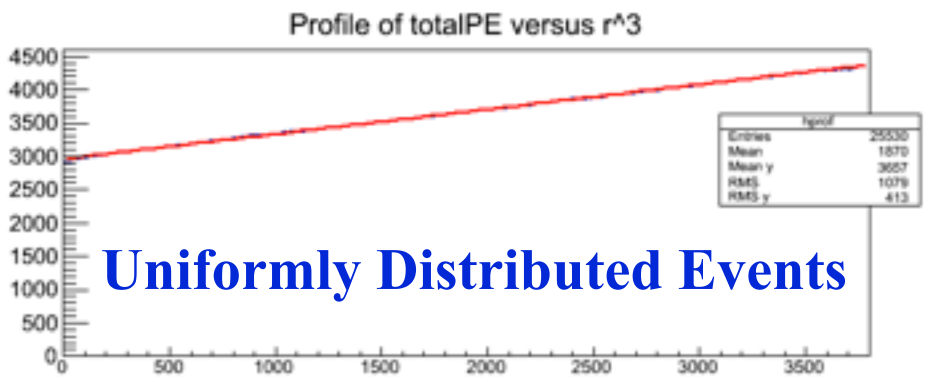
20" + 8" PMT

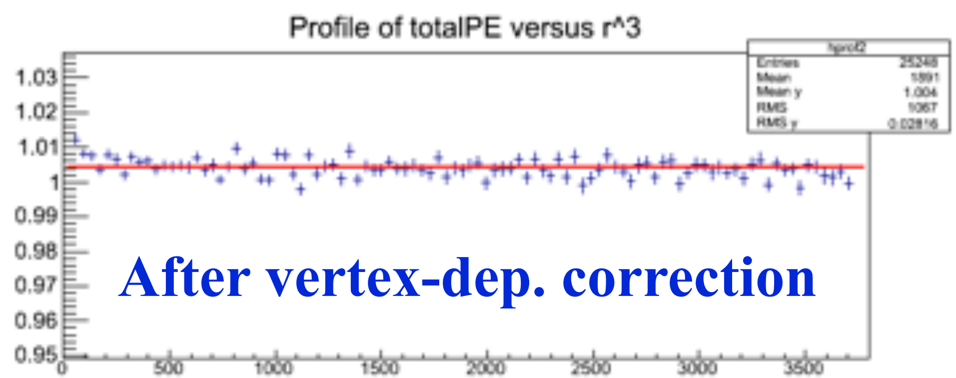
8" PMT for better timing(vertex)

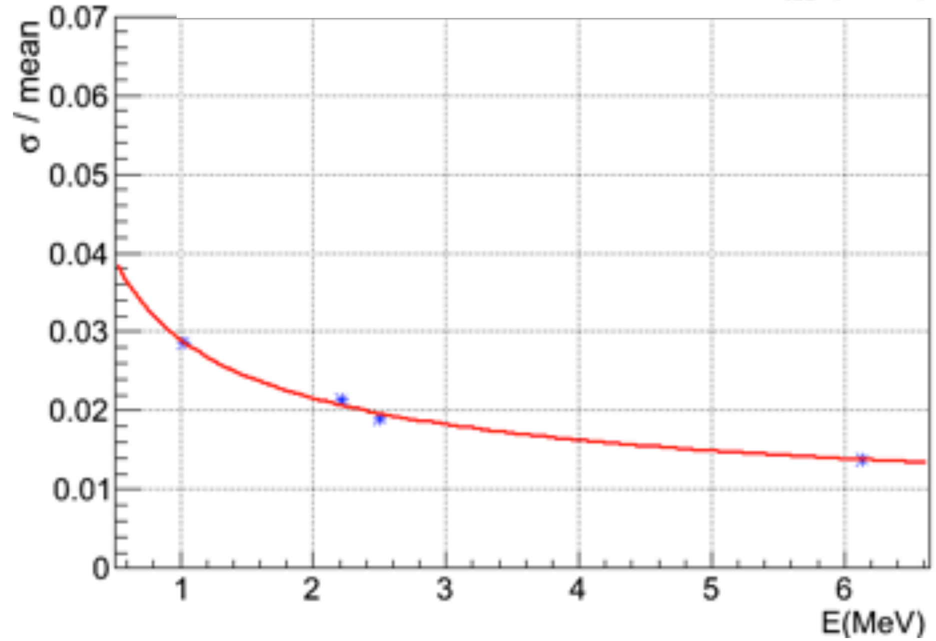
MC Study of the Energy Resolution

- JUNO MC, based on DYB MC (tuned to data), except
  - ⇨ JUNO Geometry and 80% photocathode coverage
  - ⇨ SBA PMT: maxQE from 25% -> 35%
  - ⇨ Lower detector temperature to 4 degree (+13% light)
  - ⇨ LS attenuation length (1m-tube measurement@430nm)
    - ✓ from 15m = absorption 24m + Raleigh scattering 40 m
    - ✓ to 20 m = absorption 40 m + Raleigh scattering 40m









$3.0\%/\sqrt{E}$, or $(2.6/\sqrt{E}+0.3)\%$

How to Conquer the Energy Scale Challenge?

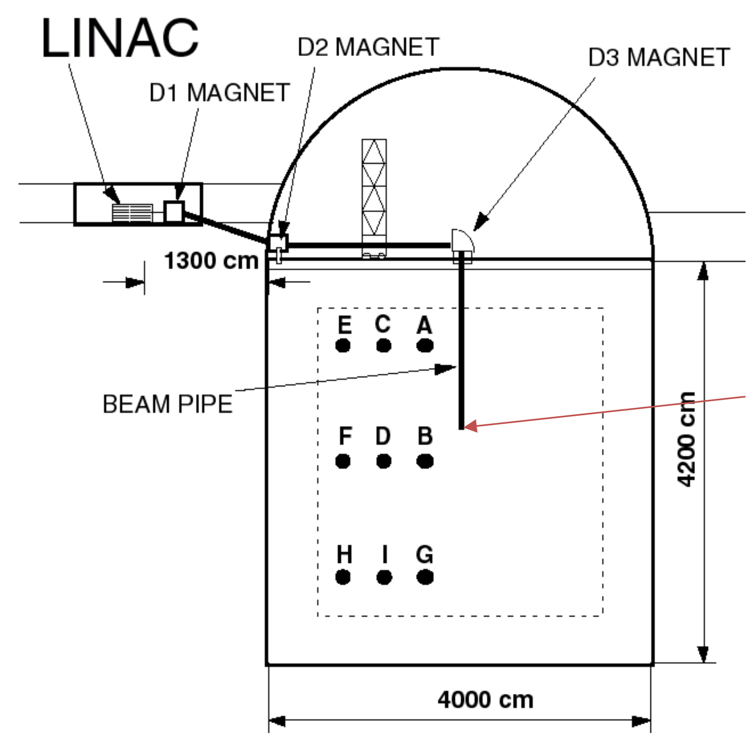
- Improve the energy calibration accuracy.
- Dual detector to mitigate the energy scale challenge?
  - See E. Ciuffouli et al, arXiv:1211.6818
- Which approach is more effective?

S. Kettell et al arXiv:1307.7419

2nd Detector	$\Delta\chi^2$	$\Delta\chi^2$ ($\sigma_{scale}/4$)
20kt at 53km	4.2	14.3
0.1kt at 2km	4.9	11.5
5kt at 30km	10.3	13.6

- To reach the same level of improvements, energy scale uncertainty needs to be greatly improved.
  - Remark: Super-K solar does reach the level of 0.6% in absolute energy scale using an electron LINAC
  - Could we realize this accuracy in a JUNO-like detector?
    Proposed R&D: a positron and electron gun to cover the whole inverse beta decay spectrum. Preliminary MC shows plausibility.

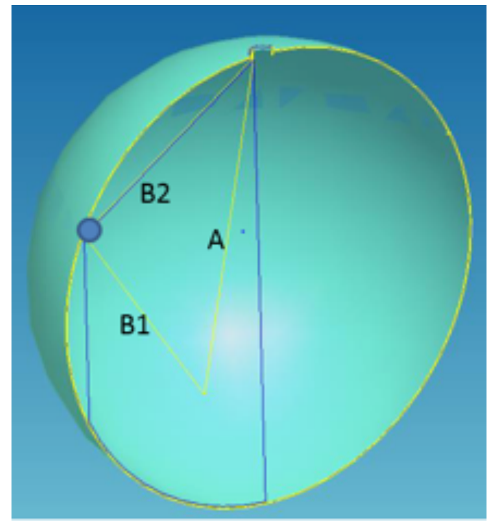
Super-K LINAC calibration

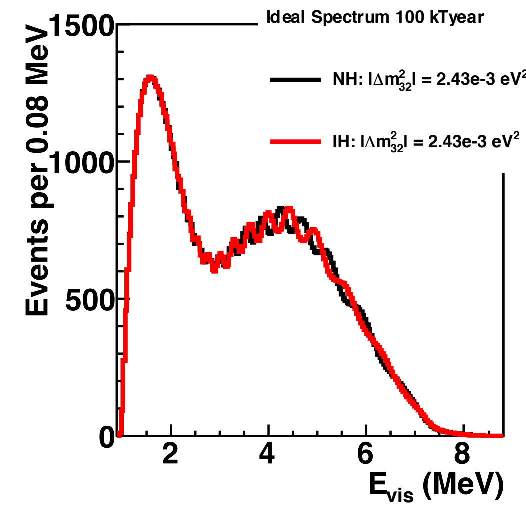


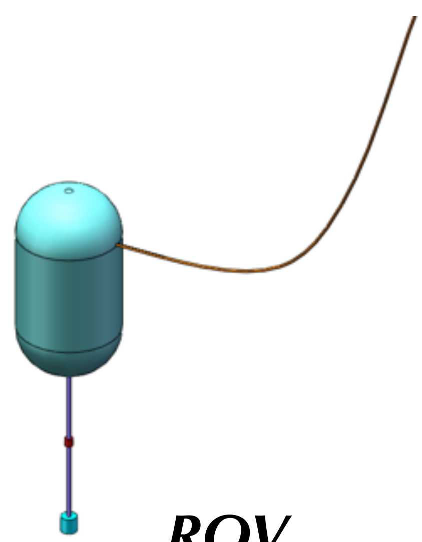
- Beam energy: 5 ~ 16 MeV/c

Various Energy Calibration Endeavors

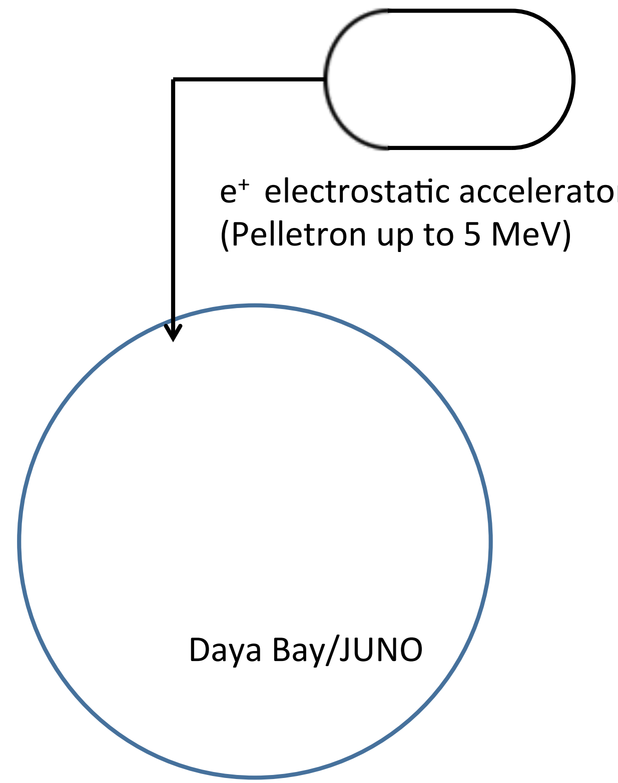
- Rope system like SNO
  - Mechanically mature
  - Hard to find positron sources
- ROV like SNO
  - Plausibility?
  - Challenging to position
  - Shadowing effect
- Add guide tubes like Double Chooz
  - To calibrate boundary effect
- Positron accelerator
  - **Real positron source with continuous energy coverage**
  - Shadowing effect?







ROV

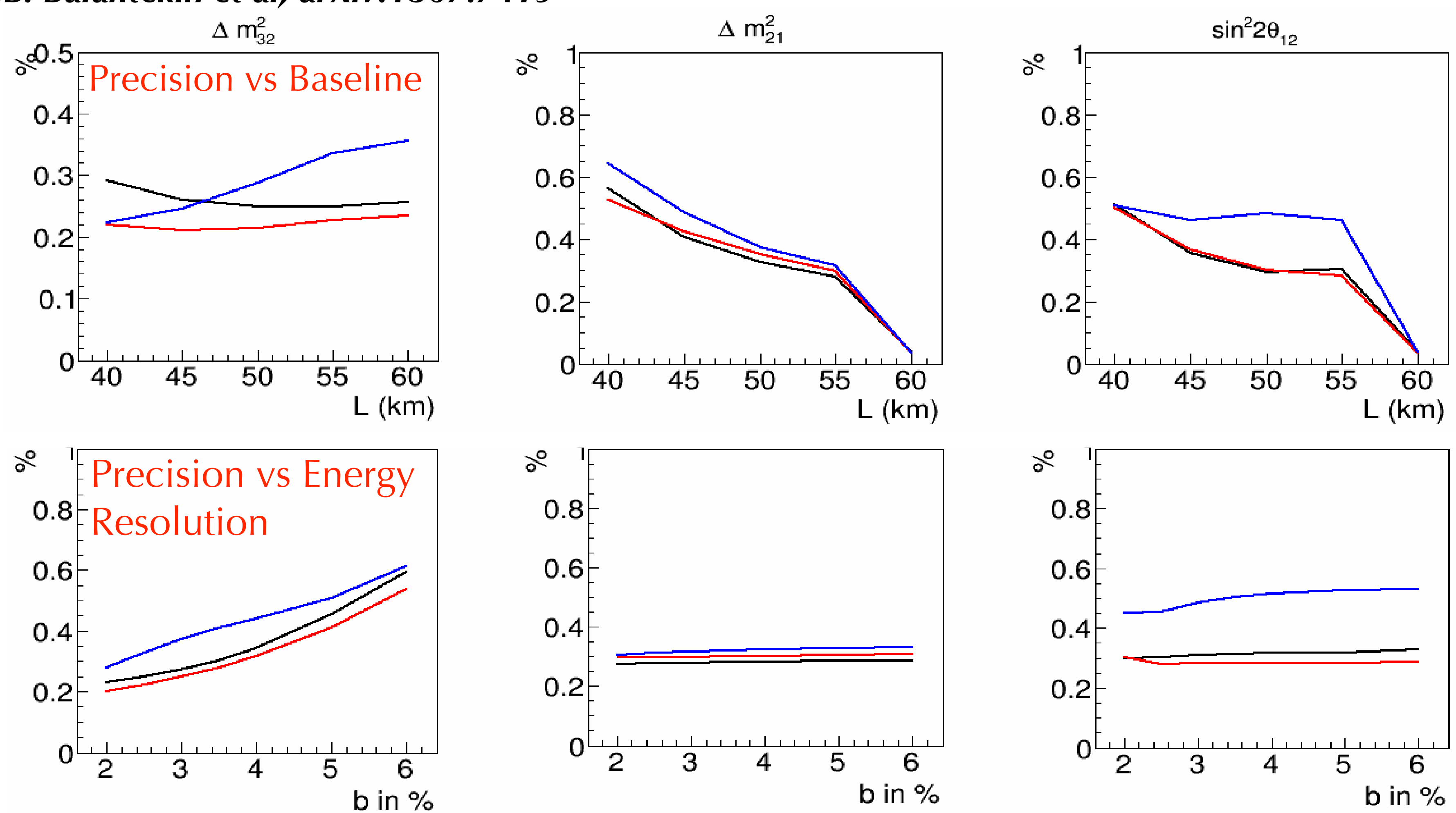


JUNO Precision Measurements (almost) Warranted

- Precision <1% measurements are warranted in JUNO-like experiments
  - Enable a future ~1% level PMNS unitarity test
  - Neutrinoless double beta decay needs precise θ_{12}

A.B. Balantekin et al, arXiv:1307.7419

Parameter	best-fit ($\pm 1\sigma$)
$\Delta m^2_\odot$ $[10^{-5}$ eV $^2]$	$7.58^{+0.22}_{-0.26}$ **3.2%**
$\lvert\Delta m^2_A\rvert$ $[10^{-3}$ eV $^2]$	$2.35^{+0.12}_{-0.09}$ **4.5%**
$\sin^2\theta_{12}$ **2.9%**	$0.306\ (0.312)^{+0.018}_{-0.015}$



Other Physics Potential

- Supernova neutrinos
  - Burst
  - Relic
- Geo-neutrinos
- Proton decay
  - neutrino + Kaon final state could be competitive
  - Need good time response
- Atmospheric neutrinos
  - Muon reconstruction is challenging but not impossible
- Sterile neutrino searches
- Indirect DM searches
- ……

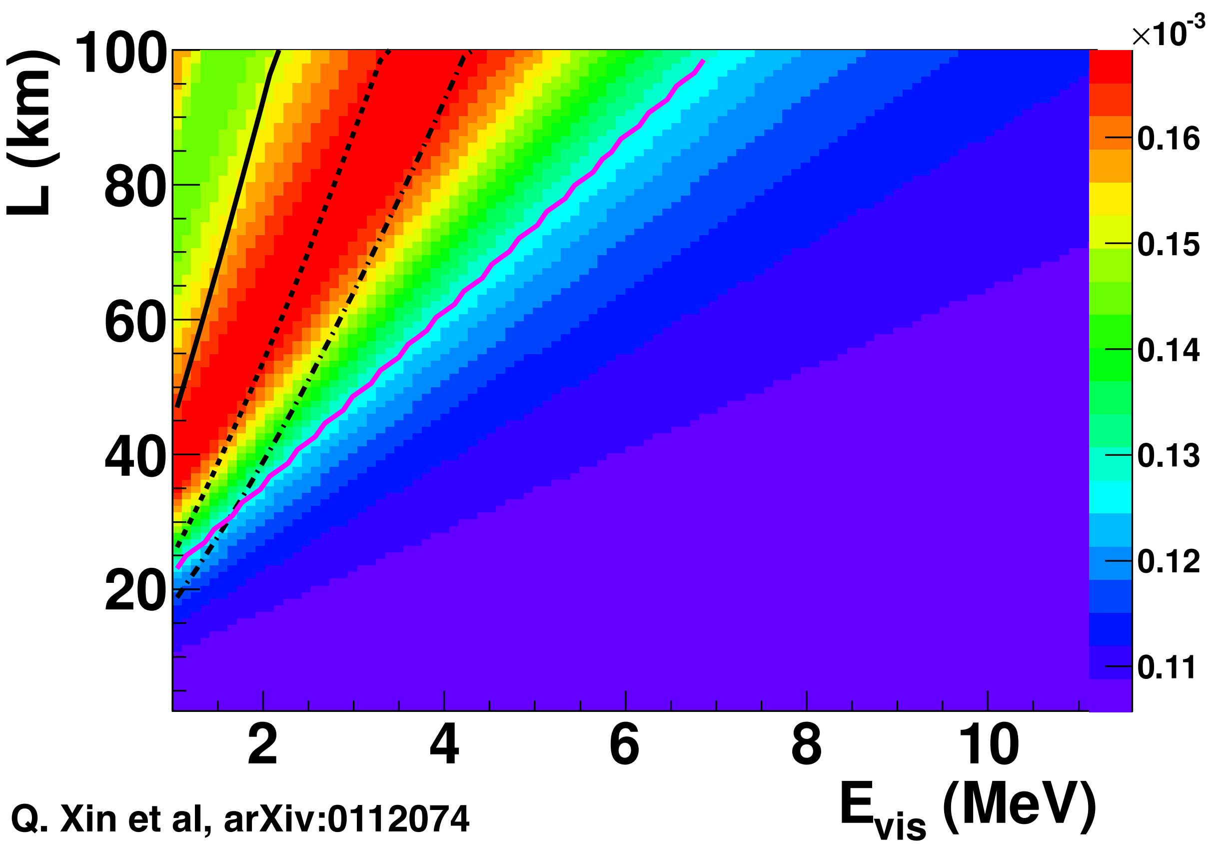
Channel	Number of Events
$\overline{\nu}_e + p \to e^+ + n$	5340
$\nu + p \to \nu + p$	2240
$\nu + e \to \nu + e$	360
$\nu + {}^{12}\mathrm{C} \to \nu + {}^{12}\mathrm{C}^*$	600
$\nu_e + {}^{12}\mathrm{C} \to e^- + {}^{12}\mathrm{N}$	50
$\overline{\nu}_e + {}^{12}\mathrm{C} \to e^+ + {}^{12}\mathrm{B}$	130

From S. Zhou

Reading the Signal in Another Way

$$P_{\bar{\nu}_e\to\bar{\nu}_e} = 1 - 2s_{13}^2c_{13}^2 - 4c_{13}^4s_{12}^2c_{12}^2\sin^2\Delta_{21}$$
$$+2s_{13}^2c_{13}^2\sqrt{1-4s_{12}^2c_{12}^2\sin^2\Delta_{21}}\cos(2\Delta_{32}\pm\phi)$$

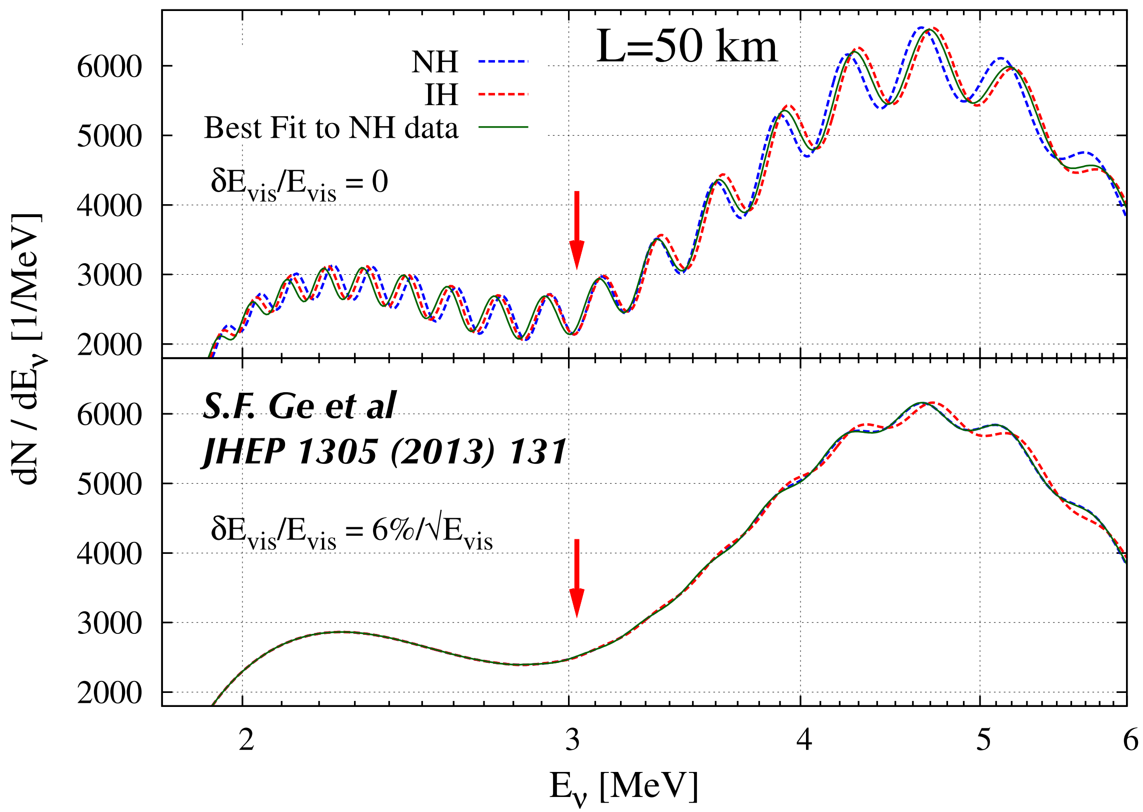
$$\tan\phi = \frac{c_{12}^2\sin 2\Delta_{21}}{c_{12}^2\cos 2\Delta_{21}+s_{12}^2} \Rightarrow \Delta m_\phi^2(L,E) = \frac{\phi}{1.27}\cdot\frac{E}{L}$$



Q. Xin et al, arXiv:0112074

- Reading it from a different perspective gives us, the experimentalists, a few obvious catches
  - Δm^2_{32} uncertainty is too big for the small differences caused by different mass hierarchies. The shift can be easily absorbed by the uncertainty
  - Energy resolution squeeze the "useful" part from the left

The Energy Resolution Requirement



- In order to see the atmospheric scale oscillations in the survival spectrum, to the first order, the energy resolution should be at least the ratio between solar mass-squared difference and the atmospheric one is ~3%

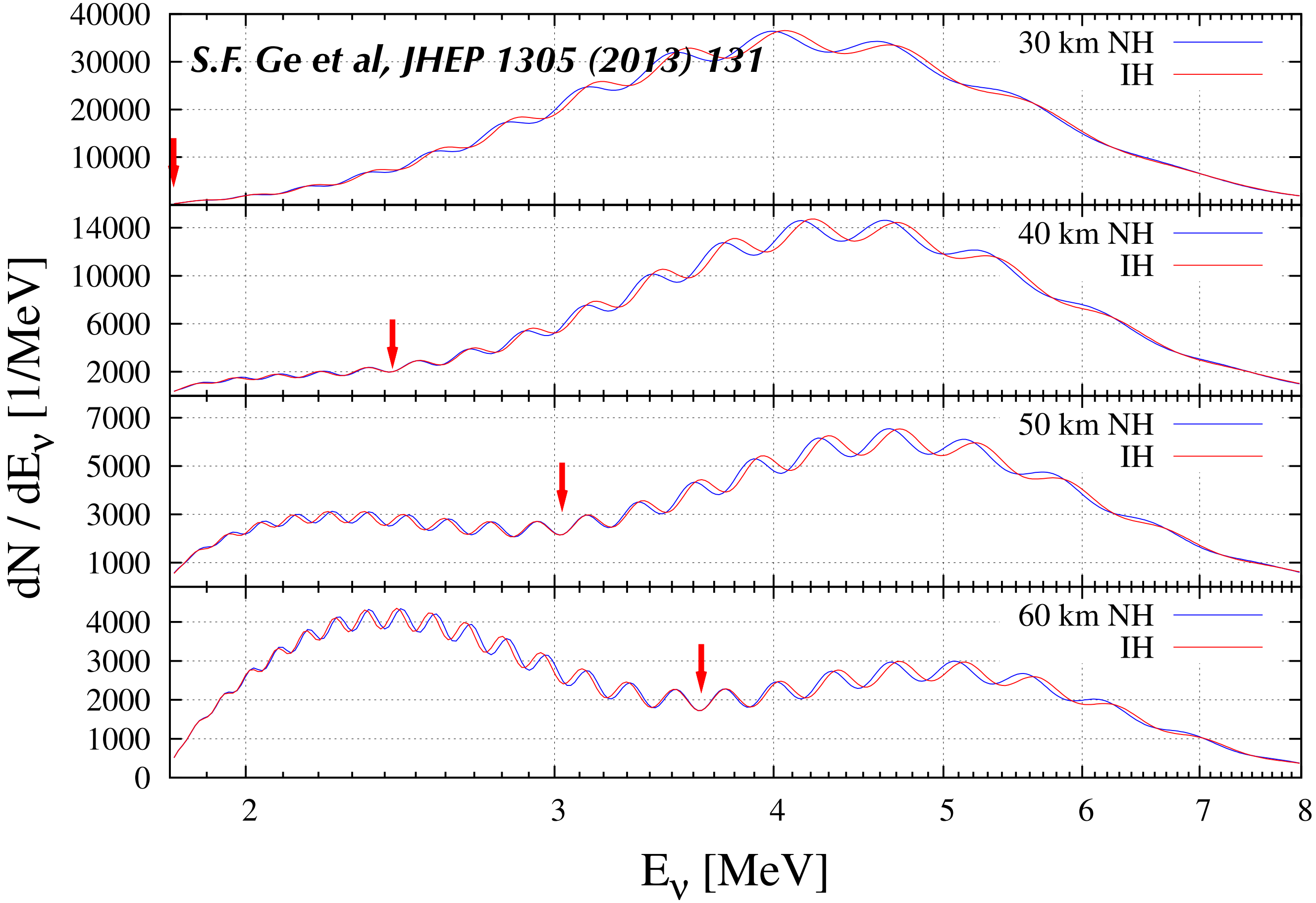
$$\frac{\Delta E}{E} = \sqrt{a^2 + \frac{b^2}{E} + \frac{c^2}{E^2}}$$

leakage & non-uniformity

Photon statistics (dominant). Needs <3%

Noise (related to bkg)

Give the MH Signal a Closer Look



- It is obvious that the baseline is better beyond 30km
- Practically speaking (for real experiments), the power lies in the contrast between the lower part and the higher part of the inverse beta decay spectrum

- At the energy where the effective mass-squared difference shift disappears, NH and IH spectra are identical. Below and above this energy, the phase difference between NH and IH shift in different direction.

Energy Scale Places A Challenge

S.J. Parke et al,
Nucl.Phys.Proc.Suppl. 188 (2009)

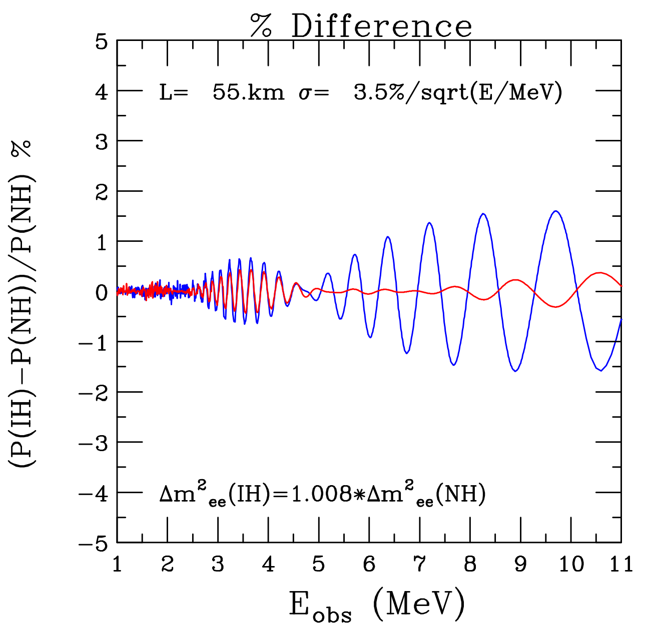
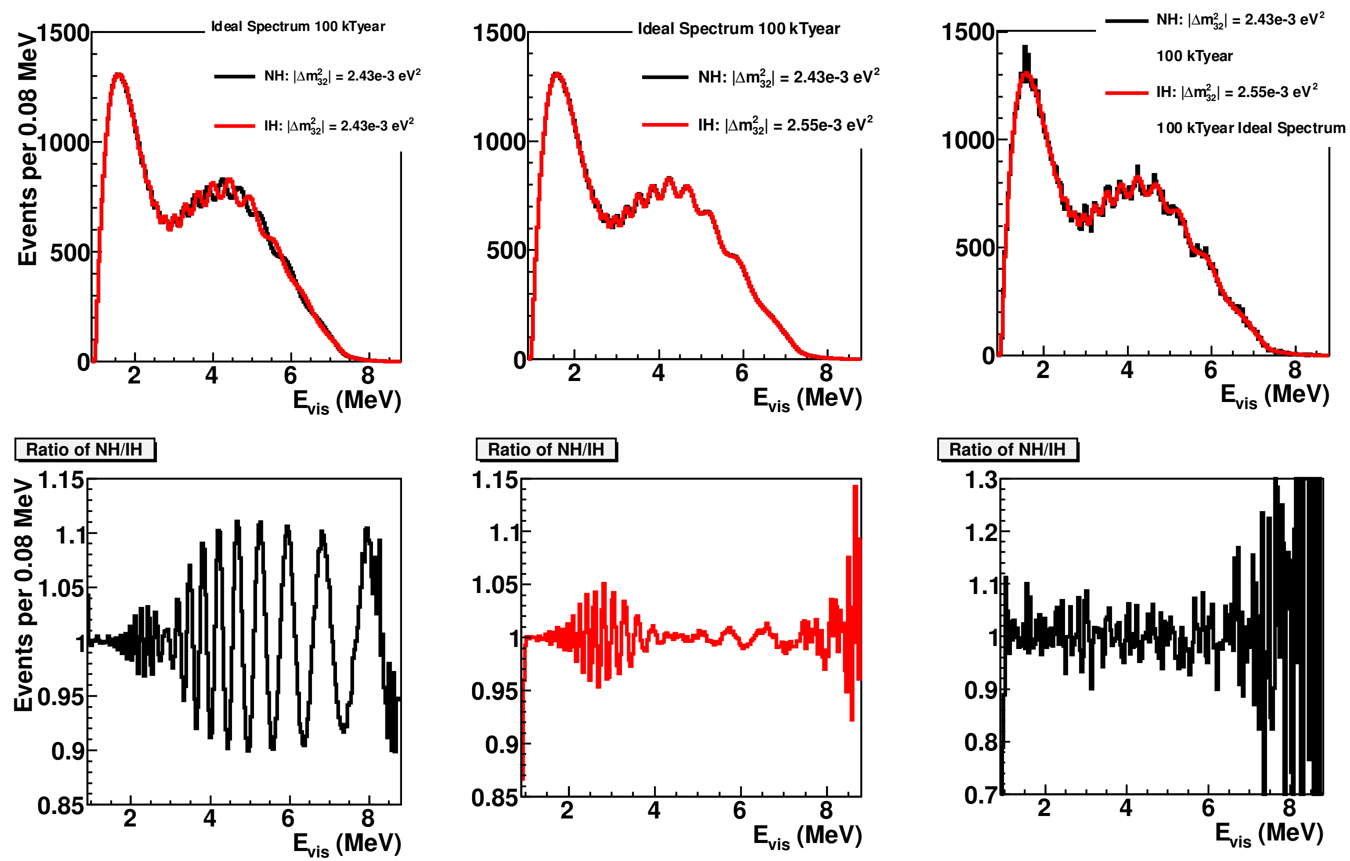


Figure 4. The percentage difference between the inverted hierarchy and the normal hierarchy. The blue curve is assuming $E_{obs} = E_{true}$ and maximum difference is less than 2%. Whereas for the red curve we have assumed that $E_{obs} = 1.015E_{true} - 0.07$ MeV for the IH, so as to represent a relative calibration uncertainty in the neutrino energy. Here the maximum percentage difference is less than 0.5%.

X. Qian et al, PRD87(2013)3, 033005



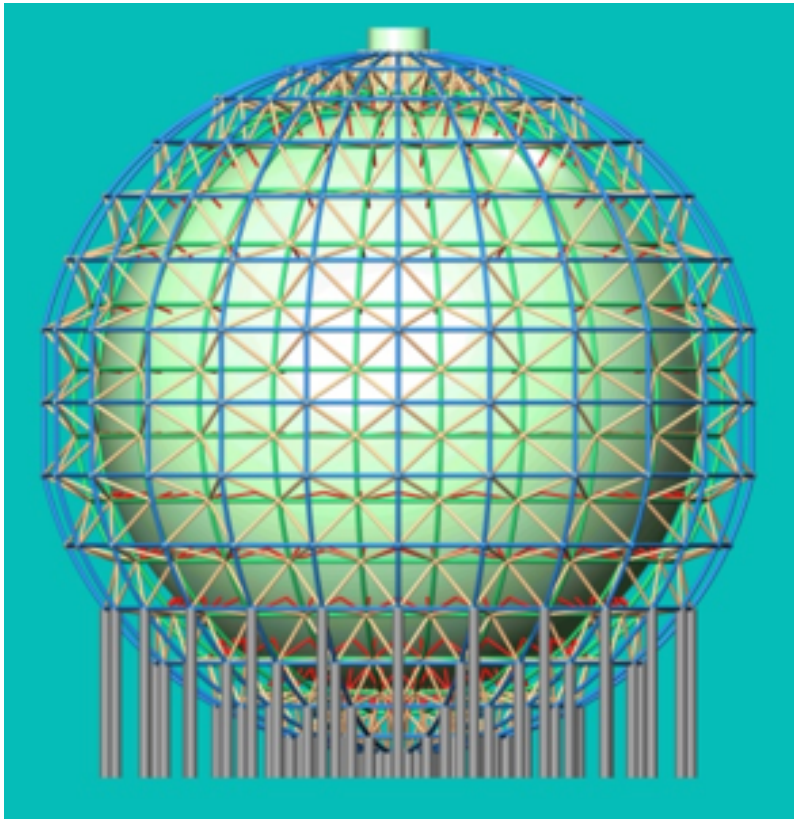
- Oscillation is governed by ~$\Delta m^2_{32}/E$, thus their uncertainties have very similar role in MH determination
- Uncertainty in Δm^2_{32} causes nearly degenerated spectra between NH and IH

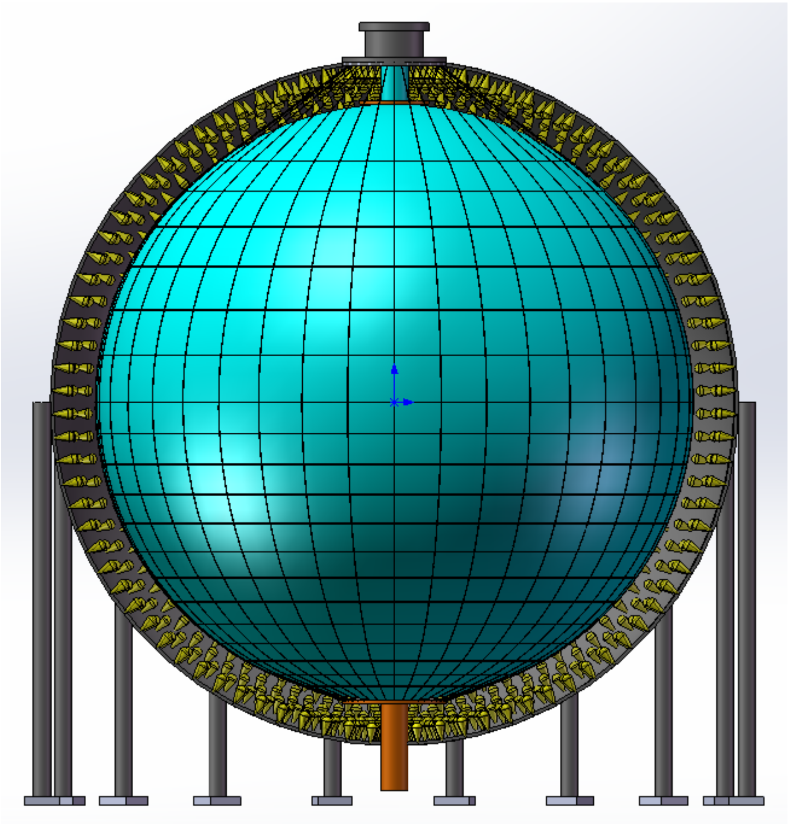
Site Selection

- Allowed region determined
  - ⇨ The site has been chosen so that the 6 baselines differ by ~<0.6km
  - ⇨ Surface buildings being designed
- Experimental hall selected:
  - ⇨ In granite
  - ⇨ Mountain height: 270 m
- Contacts with local government established, good support
  - ⇨ Civil bidding has completed

Cores	YJ-C1	YJ-C2	YJ-C3	YJ-C4	YJ-C5	YJ-C6
Power (GW)	2.9	2.9	2.9	2.9	2.9	2.9
Baseline(km)	52.75	52.84	52.42	52.51	52.12	52.21
Cores	TS-C1	TS-C2	TS-C3	TS-C4	DYB	HZ
Power (GW)	4.6	4.6	4.6	4.6	17.4	17.4
Baseline(km)	52.76	52.63	52.32	52.20	215	265

Different Options of the Central Detector



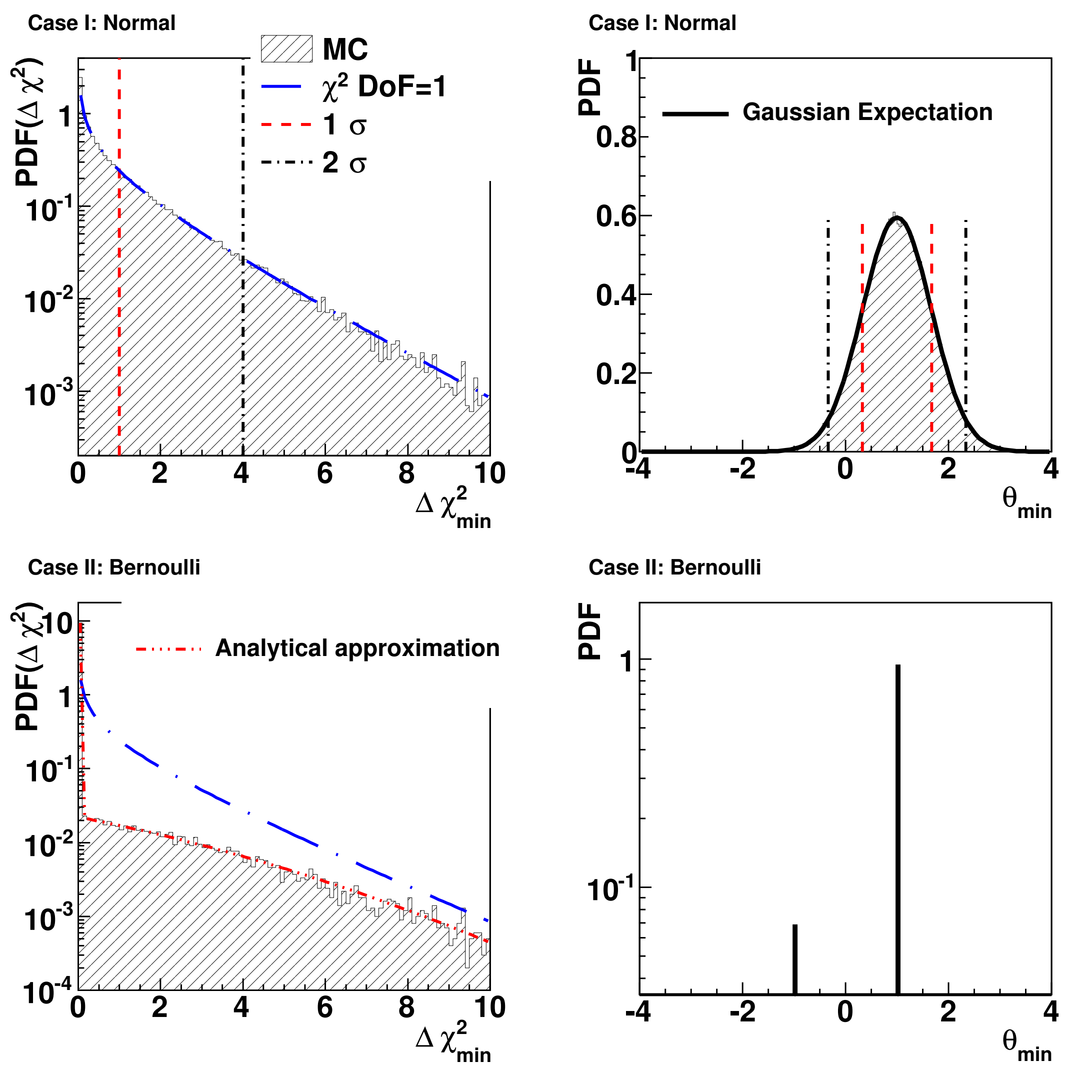


- **Truss + acrylic ball** like SNO
- Balloon + stainless steel design like KamLAND and BOREXINO
  - Fixing balloon with ropes?; Supporting balloon w/ connected but not sealed acrylic panels
- Online liquid scintillator circulation/purification system is being investigated (using a Daya Bay detector as a test bed)

The Special Statistical Case of MH Determination

- A common practice to show the quality of proposed/designed experiments is to use the delta chi-square method using the so-called Asimov data set.
  - It is meant to evaluate the performance of the most probable or the median experimental results without any statistical fluctuations.
  - We quote the squared root of the delta chi-square as the confidence interval or sensitivity in unit of sigma, which is based on Wilks Theorem.
  - Not proper for the mass hierarchy case due to its discrete nature.
- This is simply a special case that Feldman-Cousins pointed out long ago: when parameters are constrained, setting confidence intervals correctly needs MC

X. Qian et al, PRD86(2012)113011

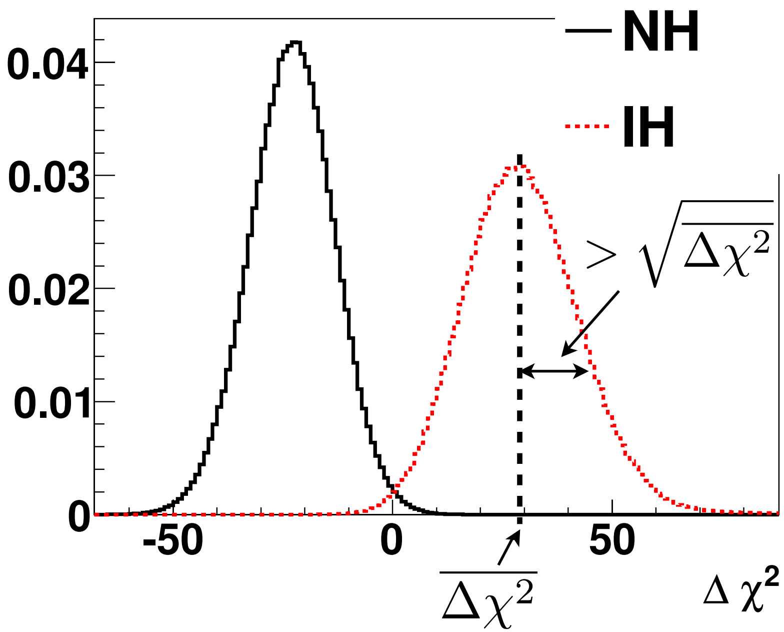


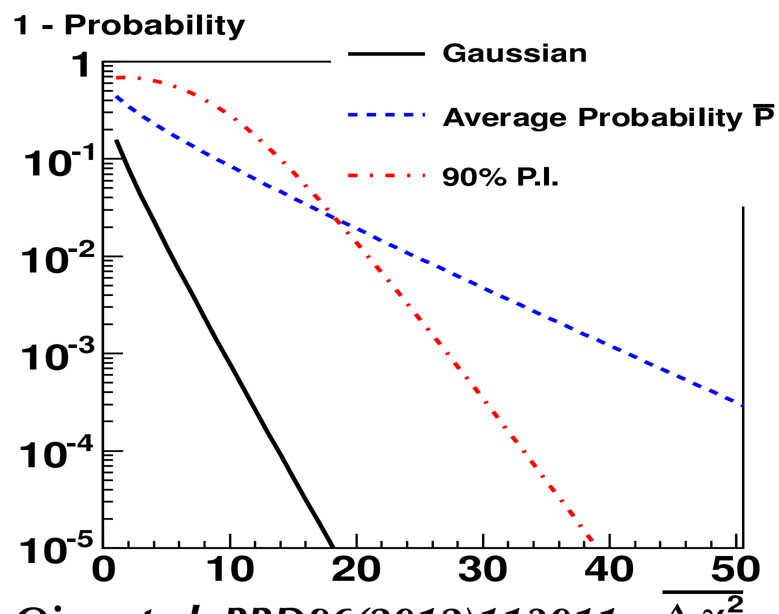
Cross-checks & Confirmations:
S.F. Ge et al JHEP 1305 (2013) 131; E. Eiuffoli et al arXiv:1305.5150

The MH Sensitivity

- The median sensitivity (Asimov dataset) is reduced by half if counted in unit of sigma's for the reactor MH sensitive. (A model w/o considering systematics. Other types of experiments, if signal has no large amount of statistics should check with MC)

$$N_i = \mu_i^{NH} + \sqrt{\mu_i^{NH}} \cdot g_i \quad \Rightarrow \quad \begin{cases} \overline{\Delta\chi^2} \equiv \sum_{i=1}^{n} \frac{\left(\mu_i^{NH} - \mu_i^{IH}\right)^2}{\mu_i^{IH}} \\ \sigma_{\Delta\chi^2} \equiv 2\sqrt{\sum_{i=1}^{n} \frac{\left(\mu_i^{NH} - \mu_i^{IH}\right)^2 \cdot \mu_i^{NH}}{(\mu_i^{IH})^2}} \\ \quad = 2\sqrt{\sum_{i=1}^{n} \left(\frac{\left(\mu_i^{NH} - \mu_i^{IH}\right)^2}{\mu_i^{IH}} + \frac{\left(\mu_i^{NH} - \mu_i^{IH}\right)^3}{(\mu_i^{IH})^2} \right)} \\ \quad \approx 2\sqrt{\overline{\Delta\chi^2}} \end{cases}$$



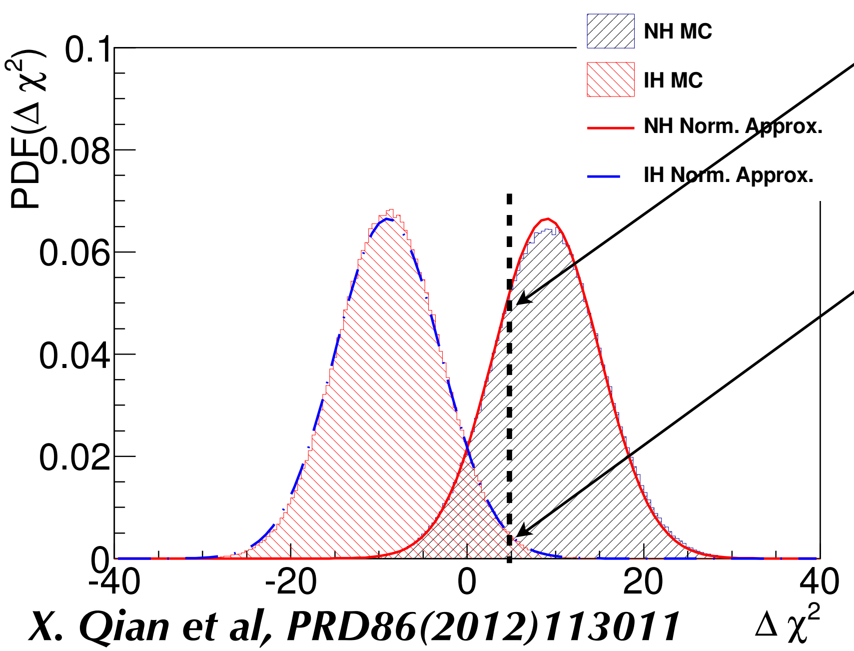


X. Qian et al, PRD86(2012)113011

Confidence Interval using Discriminator PDFs

- The neutrino mass hierarchy measurement is basically a model comparison case, or hypothesis test.
- Not complete if evaluating sensitivity only based on the sign of delta chi-square from Asimov dataset.
- We suggest a confidence interval setting method using discriminator PDFs. (This method has been effectively used in **L. Zhan et al., PRD79(2009)073007** based on Monte Carlo)

$$P(NH|\Delta\chi^2) = \frac{P(\Delta\chi^2|NH)\cdot P(NH)}{P(\Delta\chi^2)} = \frac{P(\Delta\chi^2|NH)}{P(\Delta\chi^2|NH)+P(\Delta\chi^2|IH)} = \frac{1}{1+e^{-\Delta\chi^2/2}}$$



X. Qian et al, PRD86(2012)113011

NOTE:

- The left example here is a 2-value binomial case, close to the reactor mass hierarchy resolution, sufficient to illustrate key points
  - Sensitivity value, now confidence level considering the PDFs, is between the values obtained from the square root value approach and the >0 probability approach.
- To be accurate, one should do complete MC to obtain PDFs like in **L. Zhan et al., PRD79(2009)073007.**

See also: G. Cowen et al Eur.Phys.J. C71 (2011) 1554