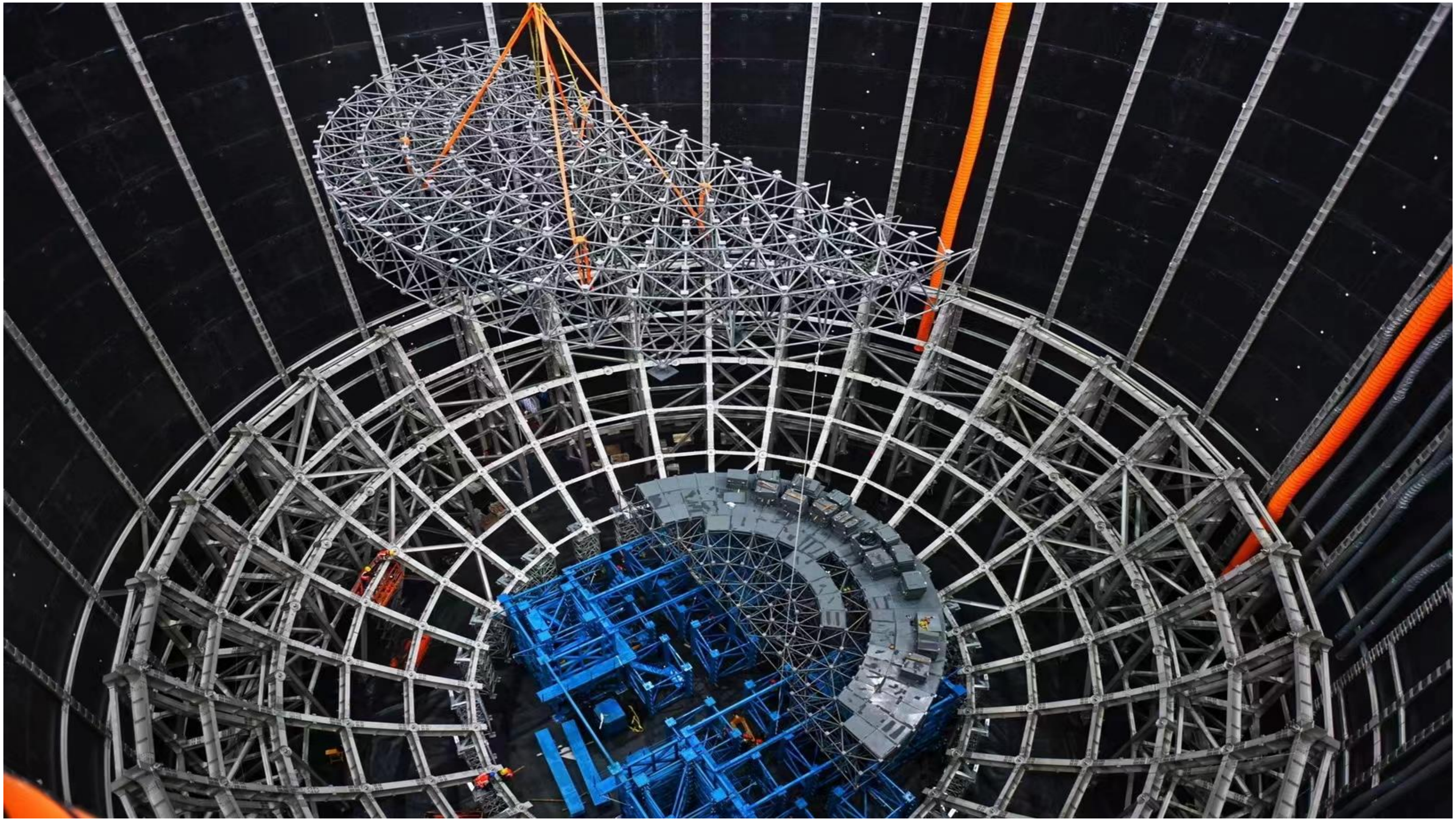
国内中微子实验相关结果



凌家杰（中山大学）

第三届粒子物理前沿研讨会

2022/07/23

The 3-neutrino Mixing

B. Pontecorvo, Z. Maki, M. Nakagawa, S. Sakata, E. Majorana

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U_{\alpha i}^{*} |\nu_i\rangle$$

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{i\eta_1} & 0 & 0 \\ 0 & e^{i\eta_2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

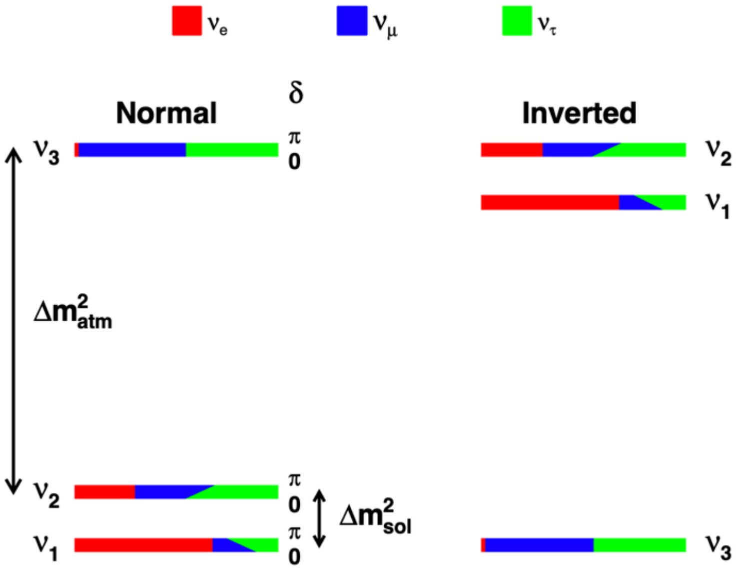
$c_{ij} = \cos\theta_{ij}$ $\quad s_{ij} = \sin\theta_{ij}$

Three mixing angles: $\theta_{23}, \theta_{13}, \theta_{12}$

$c_{12}^2 \equiv \cos^2\theta_{12} = \frac{|U_{e1}|^2}{1-|U_{e3}|^2}$ $\quad s_{12}^2 \equiv \sin^2\theta_{12} = \frac{|U_{e2}|^2}{1-|U_{e3}|^2}$

$s_{13}^2 \equiv \sin^2\theta_{13} = |U_{e3}|^2$

$s_{23}^2 \equiv \sin^2\theta_{23} = \frac{|U_{\tau 3}|^2}{1-|U_{e3}|^2}$ $\quad c_{23}^2 \equiv \cos^2\theta_{23} = \frac{|U_{\tau 3}|^2}{1-|U_{e3}|^2}$



Current Status of PMNS Parameters

NuFIT 4.0	θ_{12} (°)	θ_{23} (°)	θ_{13} (°)	δ_{CP} (°)	Δm^2_{21} ($\times 10^{-5}\mathrm{eV}^2$)	Δm^2_{32} ($\times 10^{-3}\mathrm{eV}^2$)
Normal	$33.44^{+0.77}_{-0.74}$	$49.2^{+0.9}_{-1.2}$	$8.57^{+0.12}_{-0.12}$	197^{+27}_{-24}	$7.42^{+0.21}_{-0.20}$	$2.443^{+0.026}_{-0.028}$
Inverted	$33.45^{+0.78}_{-0.75}$	$49.3^{+0.9}_{-1.1}$	$8.60^{+0.12}_{-0.12}$	282^{+26}_{-30}	$7.42^{+0.21}_{-0.20}$	$-2.498^{+0.028}_{-0.028}$
Relative 1σ precision	2.3%	2.0%	1.4%	13.2%	2.7%	1.1%

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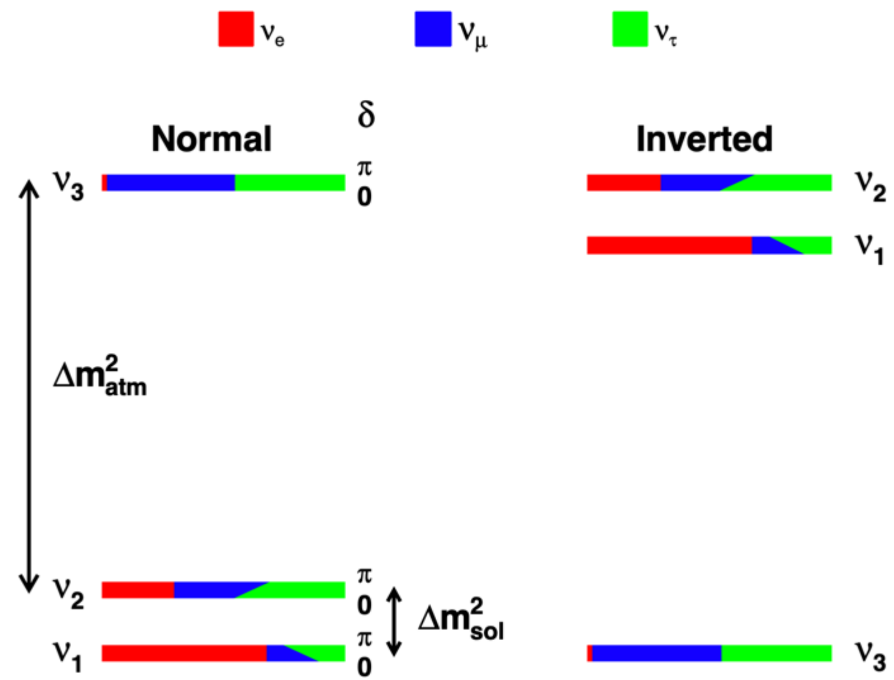
Well measured: θ_{12}, θ_{13}, Δm^2_{21}, $|\Delta m^2_{32}|$
Not-so-well measured: θ_{23} **Octant,** δ_{CP}, **neutrino mass ordering (sign of** Δm^2_{32}**)**

- $\theta_{23} > \pi/4$ is mildly preferred with $\Delta\chi^2 = 0.53$ (2.2 with SK − atm)
- Normal mass ordering is slightly preferred with $\Delta\chi^2 = 2.7$ (7.1 with SK − atm)

Open Questions of Massive Neutrinos

- What's the neutrino mass ordering?
- Are neutrinos responsible for the matter anti-matter asymmetry?
- Are neutrinos Dirac or Majorana particles?
- What is the neutrino mass?
- Do sterile neutrinos exist?
- Why neutrino mass is so tiny?
- ……



NO : $|\Delta m^2_{31}| = |\Delta m^2_{32}| + \Delta m^2_{21}$

IO: $|\Delta m^2_{31}| = |\Delta m^2_{32}| - \Delta m^2_{21}$

Reactor Antineutrino Oscillation

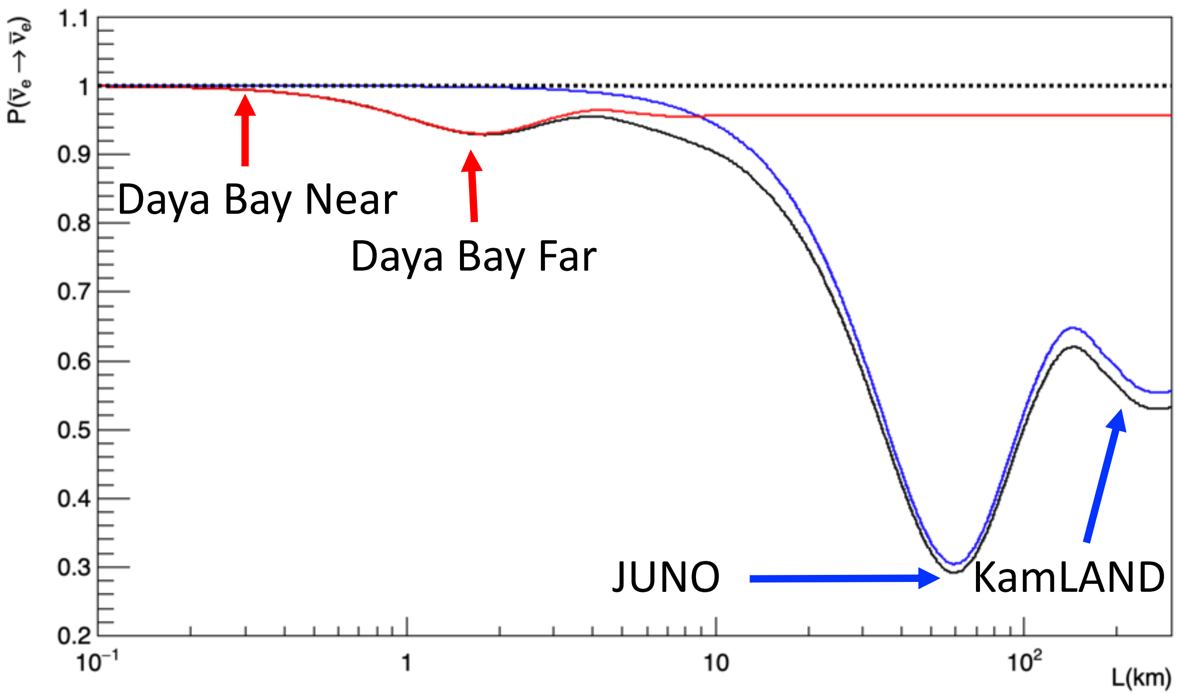
$$P_{\alpha\beta} = \left|\langle \nu_\beta | \nu_\alpha(t)\rangle\right|^2 = \delta_{\alpha\beta} - 4\sum_{i<j}^{3} Re\left[U_{\alpha i}U_{\beta i}^{*}U_{\alpha j}^{*}U_{\beta j}\right]\sin^2\Delta_{ij} + 2\sum_{i<j}^{3} Im\left[U_{\alpha i}U_{\beta i}^{*}U_{\alpha j}^{*}U_{\beta j}\right]\sin 2\Delta_{ij}$$

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13}\left(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}\right) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$

$$\approx 1 - \boxed{\sin^2 2\theta_{13}\sin^2\Delta_{ee}} - \boxed{\cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}}$$

$$\Delta_{ij} = \Delta m_{ij}^2 \frac{L}{4E}$$

Immune to CP violation and matter effects



Key for a precise measurement:

- ✓ **Baseline Optimization**

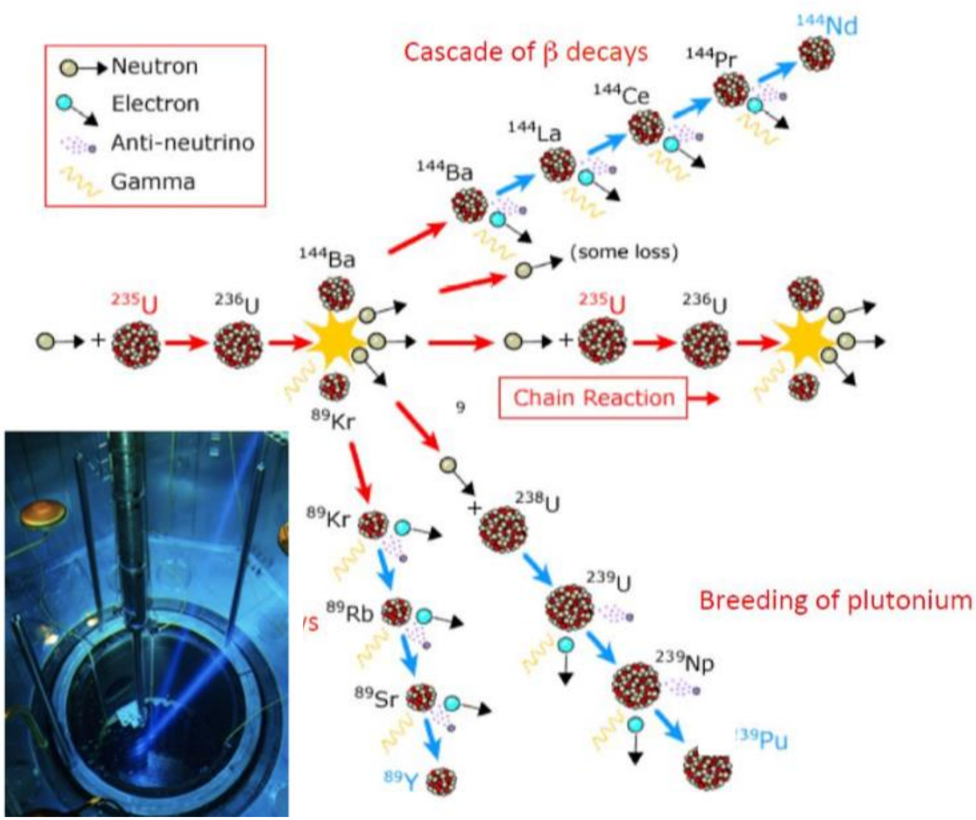
$$L(\mathrm{m}) \sim \frac{\pi \cdot E\ (\mathrm{MeV})}{2.54 \cdot \Delta m^2 (\mathrm{eV}^2)}$$

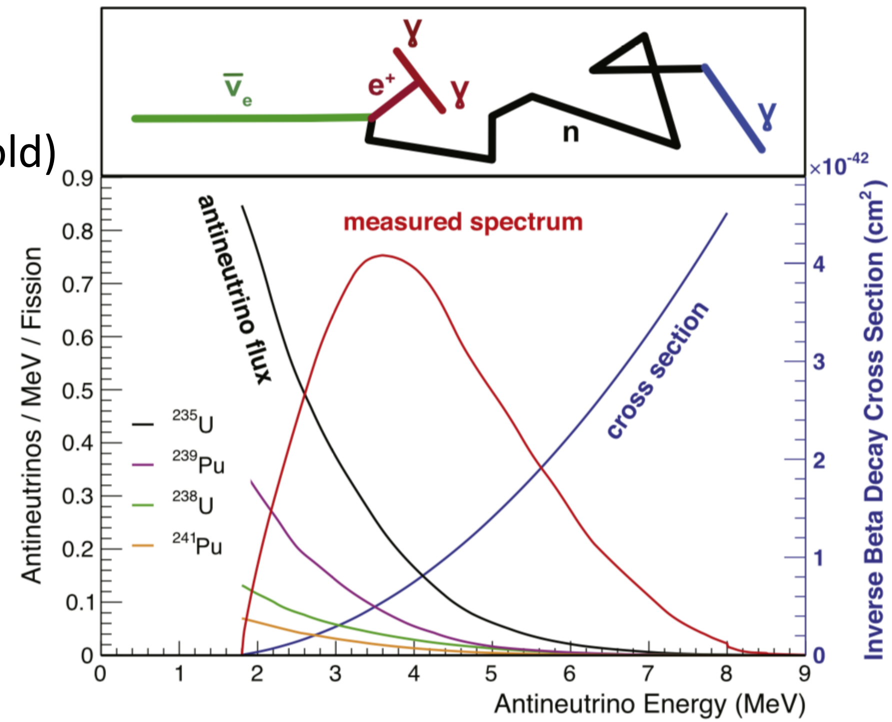
- ✓ **Large statistics**
  - Large $\bar{\nu}_e$ flux
  - Massive target mass
- ✓ **Background control**
  - Large overburden
  - Detector shielding
- ✓ **Systematics control**
  - Relative Far/Near measurement

Reactor $\bar{\nu}_e$ Production and Detection

Source: Pure $\bar{\nu}_e$ from cascade of beta decays

- ~ 200 MeV / fission
- ~ 2 x 10^{20} $\bar{\nu}_e$/GW_{th}/Sec (1/5 above IBD threshold)





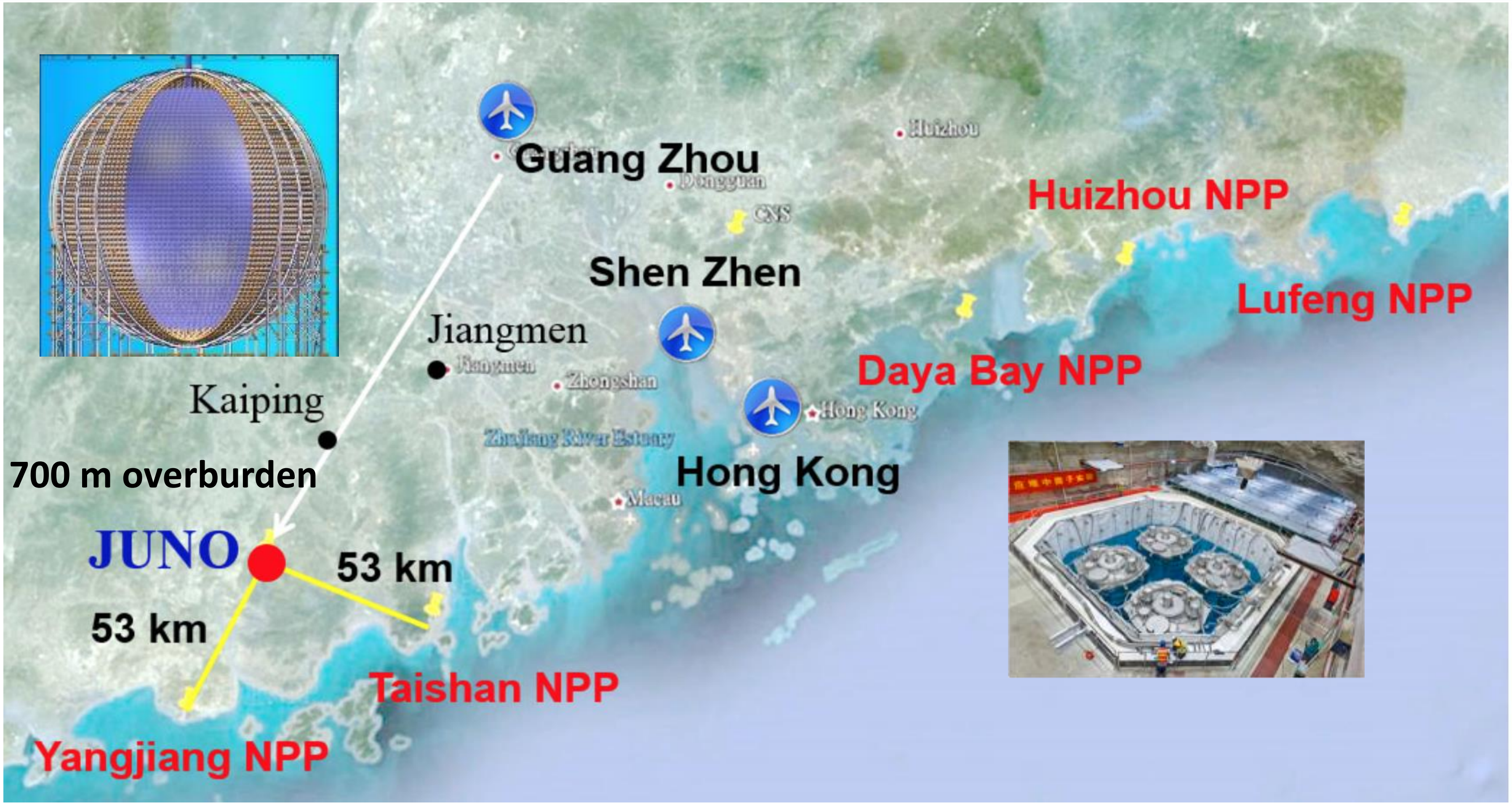
Inverse Beta decay (IBD) $\bar{\nu}_e + p \rightarrow n + e^+$

Coincidence signals to suppress background

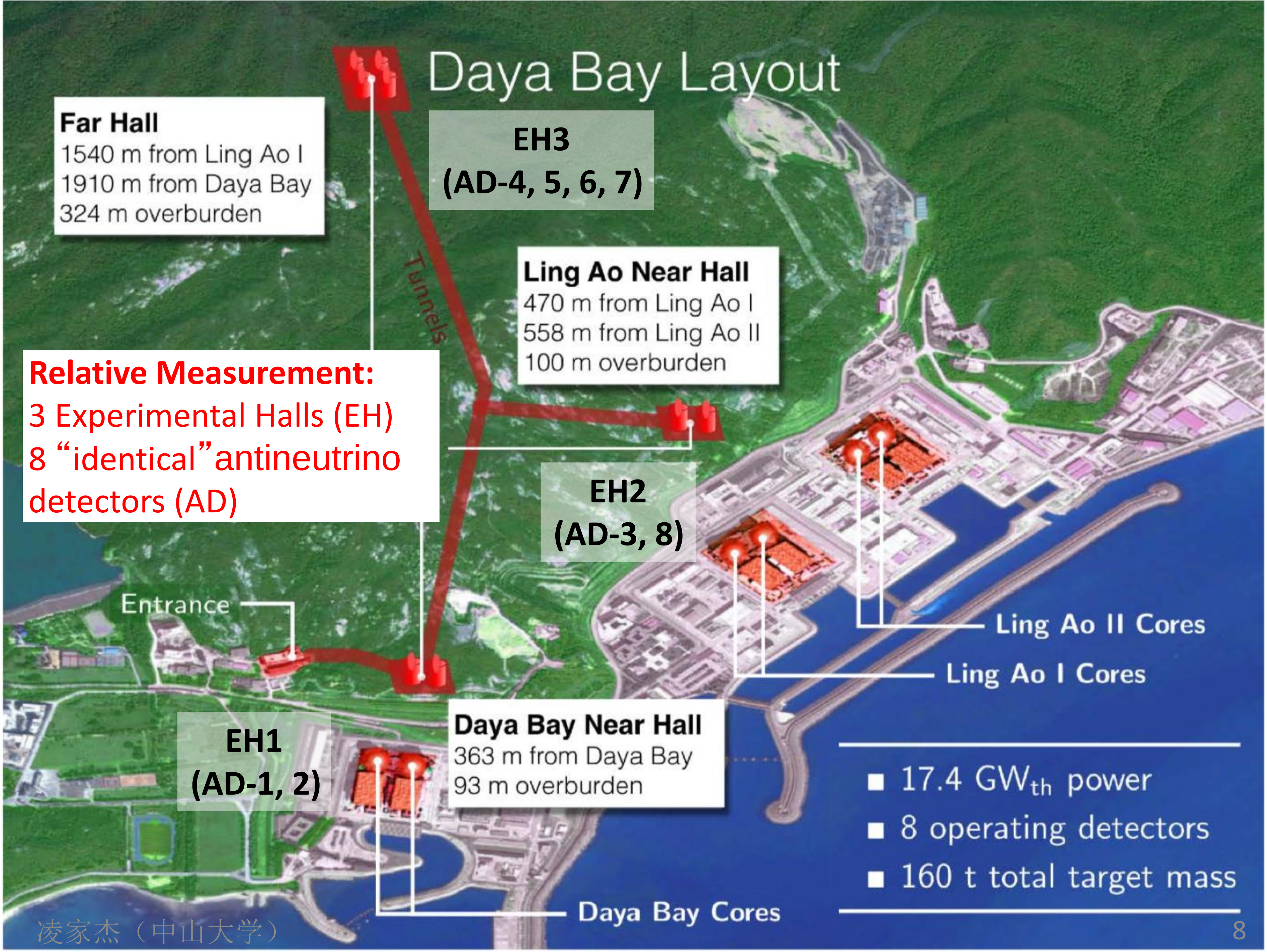
- Prompt: $E_{\text{prompt}} \approx E_\nu - 0.8\ MeV$
- Delayed: nH (2.2 MeV) or nGd (~8 MeV)

The Daya Bay and JUNO Site

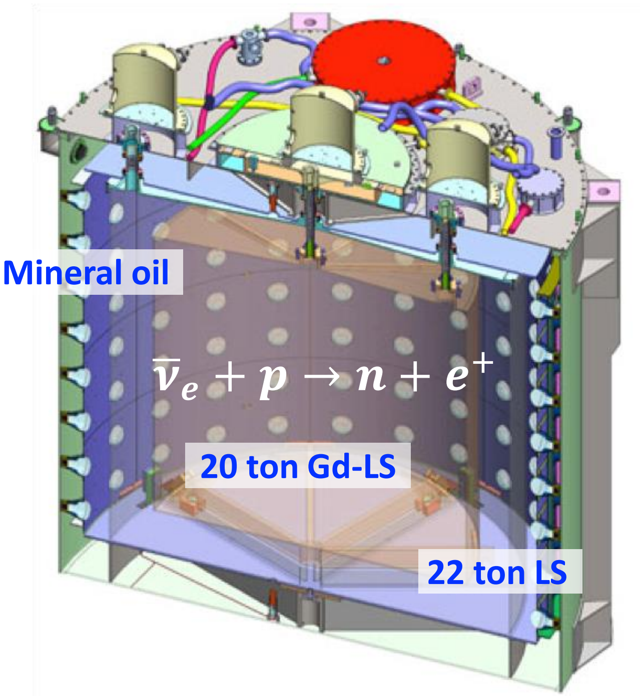
NPP	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	Operational	Planned	Planned	Operational	Operational
Power	17.4 GW	17.4 GW	17.4 GW	17.4 GW	9.2 GW



Daya Bay Layout



Antineutrino Detector (AD) System



6-AD (2-1-3)
24/12/2011 – 28/07/2012
217 days

8-AD (2-2-4)
19/10/2012 – 21/12/2016
1524 days

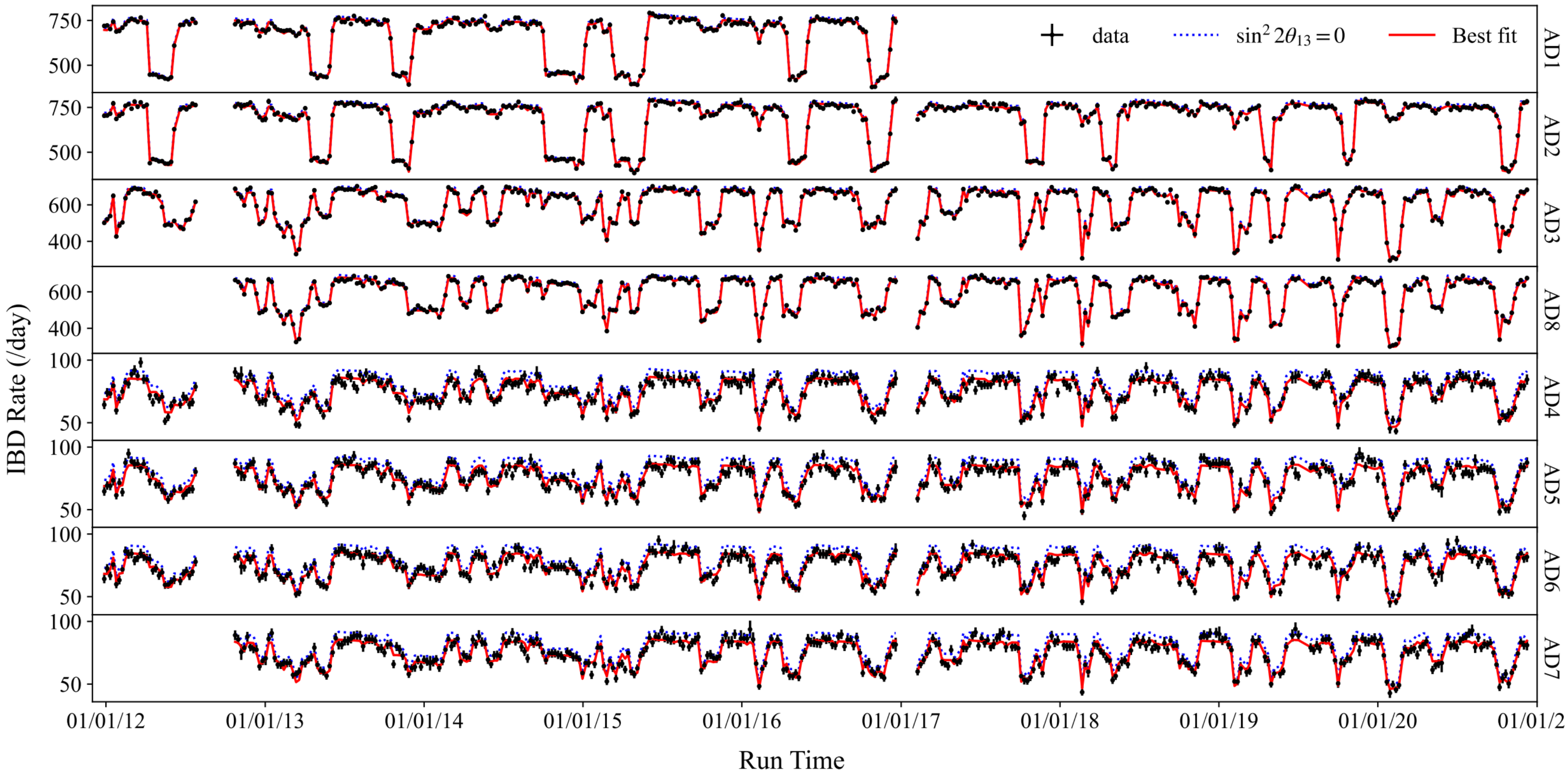
7-AD (1-2-4)
26/01/2017 – 12/12/2020
1417 days

- AD7-8 installation
- Special calibration
- AD1 FADC installation
- AD1 GdLS→ LS
- End of operation

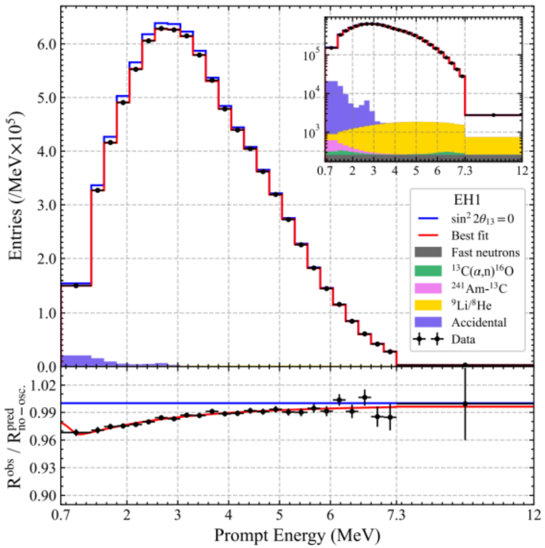
5.5 Million nGd IBD Candidates

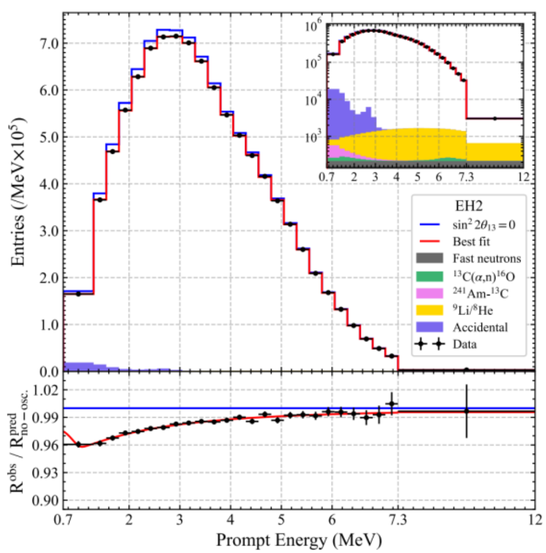
- 24/12/2011 – 12/12/2020 (3158 days)
  - ~2700 days of good data
- World largest IBD data sample
  - 5.5 M IBDs

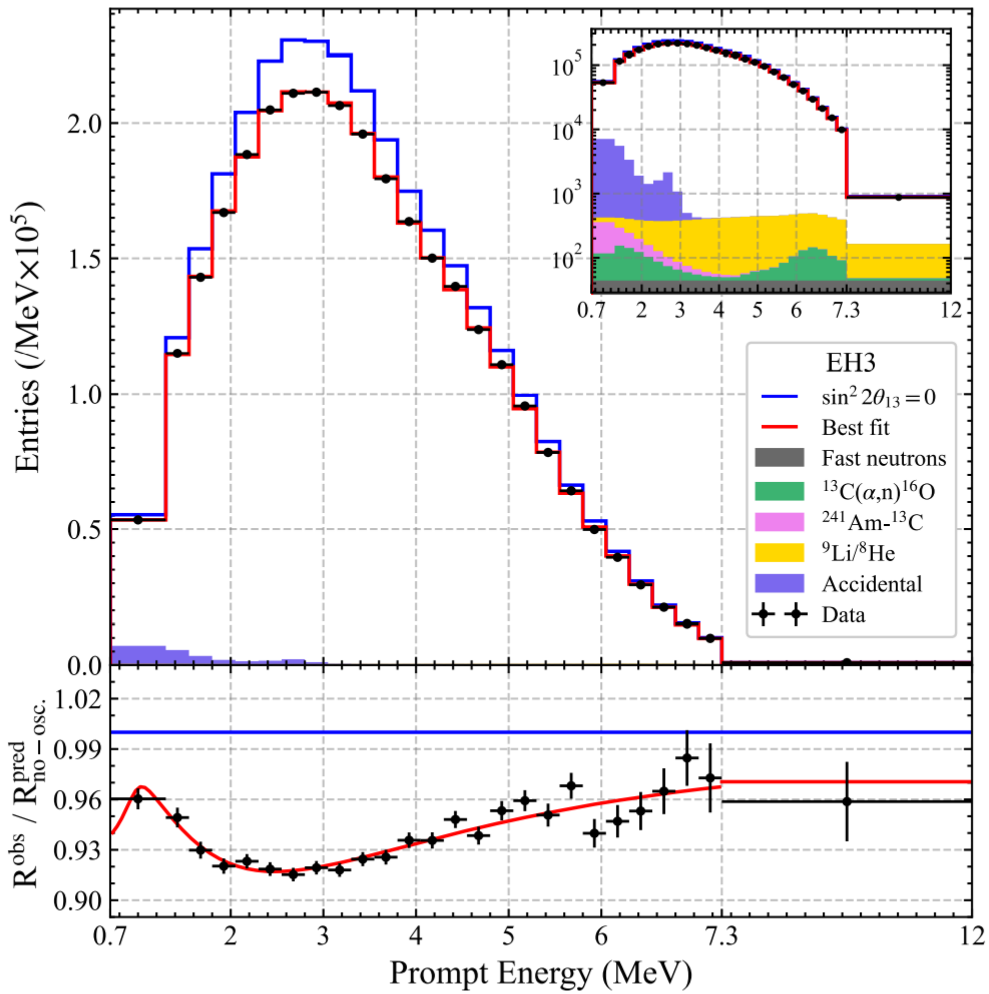
Site	EH1 (Near)	EH2 (Near)	EH3 (Far)
IBD candidates	2,236,810	2,544,894	764,414



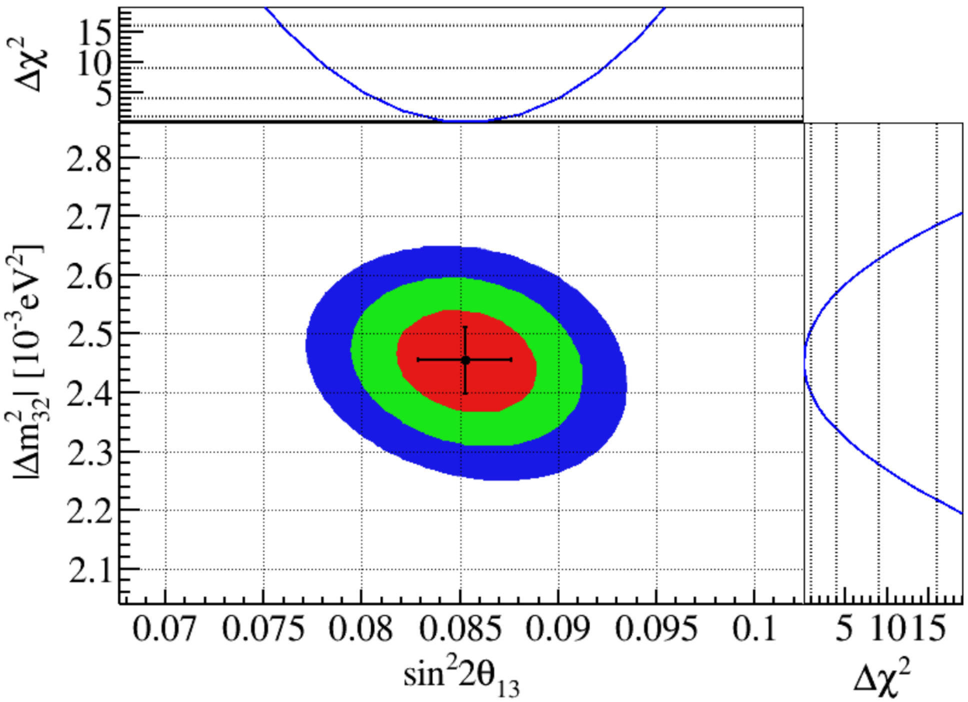
Prompt Energy Spectra

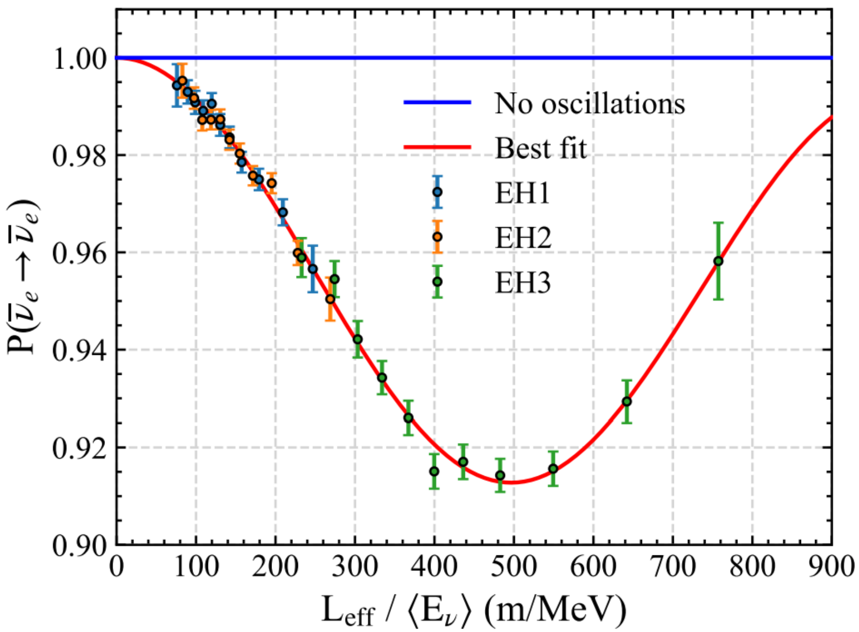






Rate+Spectra Oscillation Results





Best-fit results: χ^2/ndf = 559/518

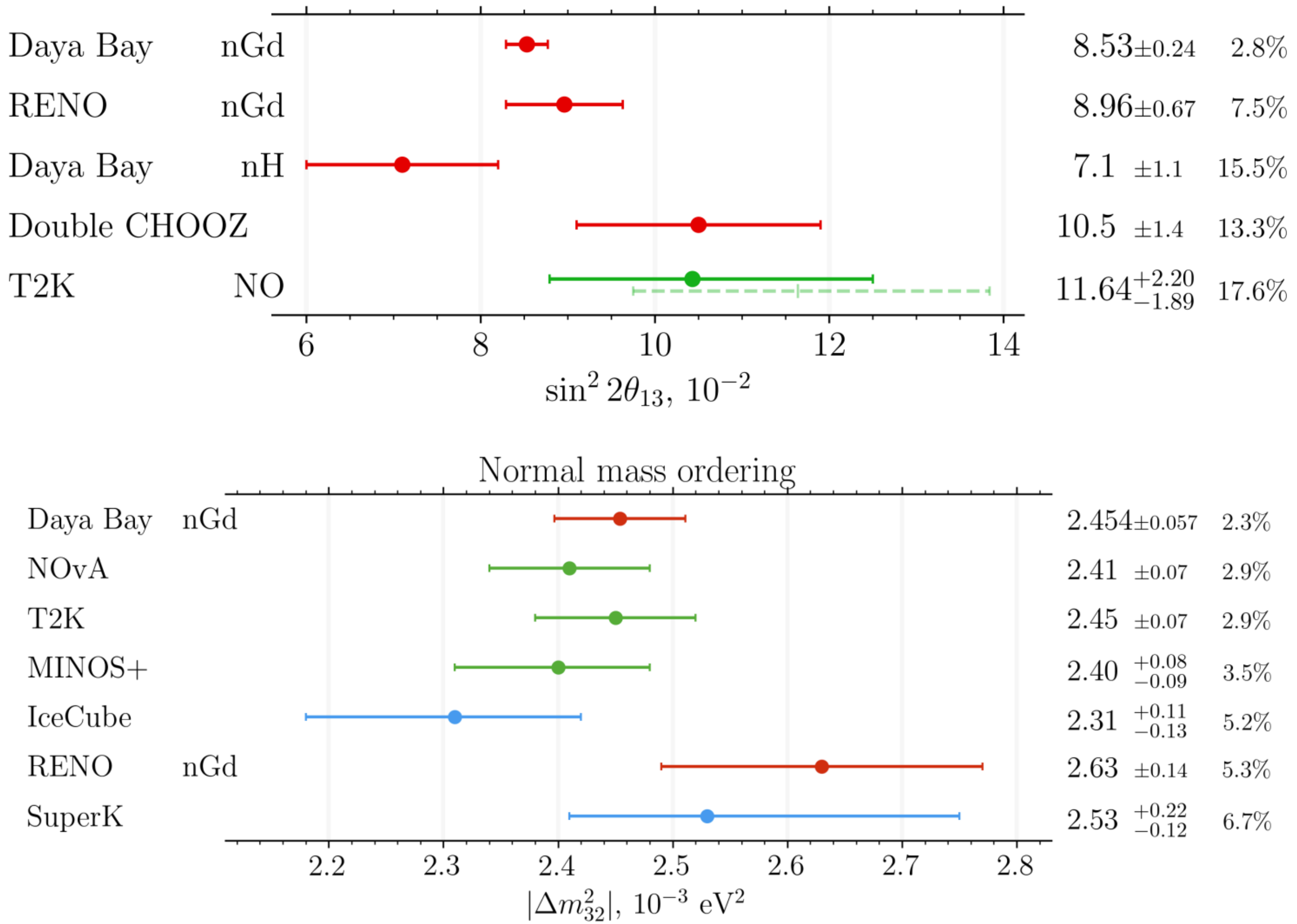
$\sin^2 2\theta_{13} = 0.0853^{+0.0024}_{-0.0024}$ (2.8% precision)

Normal hierarchy: $\Delta m^2_{32} = +\left(2.454^{+0.057}_{-0.057}\right) \times 10^{-3}\ \mathrm{eV}^2$

Inverted hierarchy: $\Delta m^2_{32} = -\left(2.559^{+0.057}_{-0.057}\right) \times 10^{-3}\ \mathrm{eV}^2$

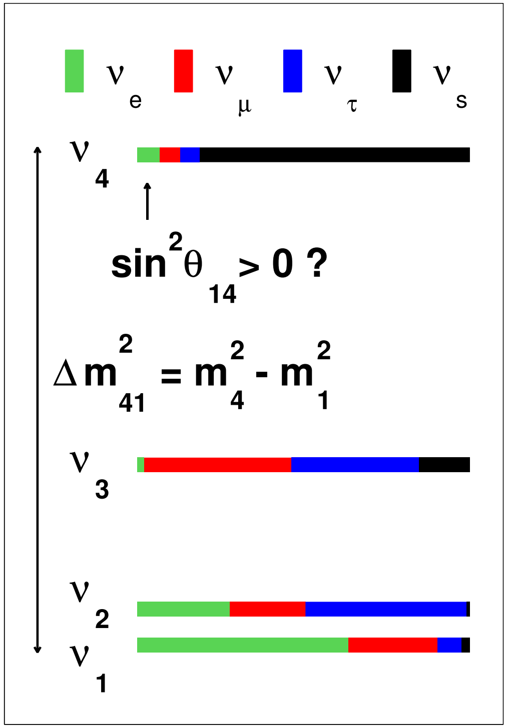
(2.3% precision)

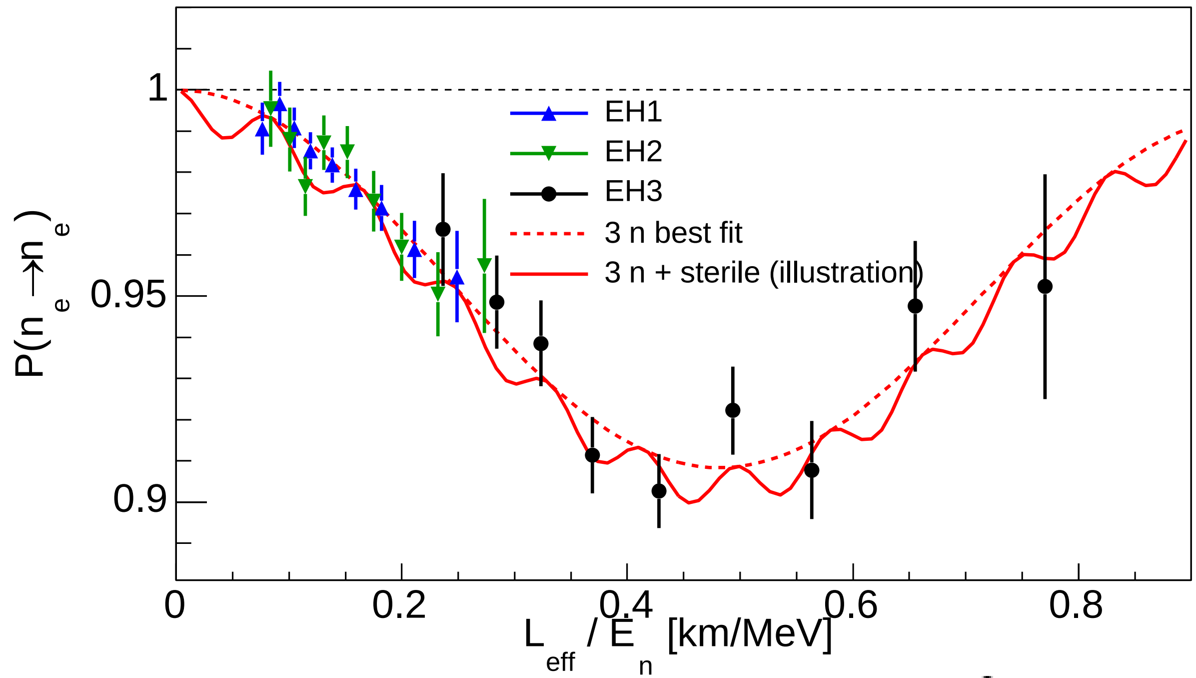
Precision Measurements



World most precise measurement of $\sin^2 2\theta_{13}$ and $|\Delta m^2_{32}|$

light sterile neutrino oscillation



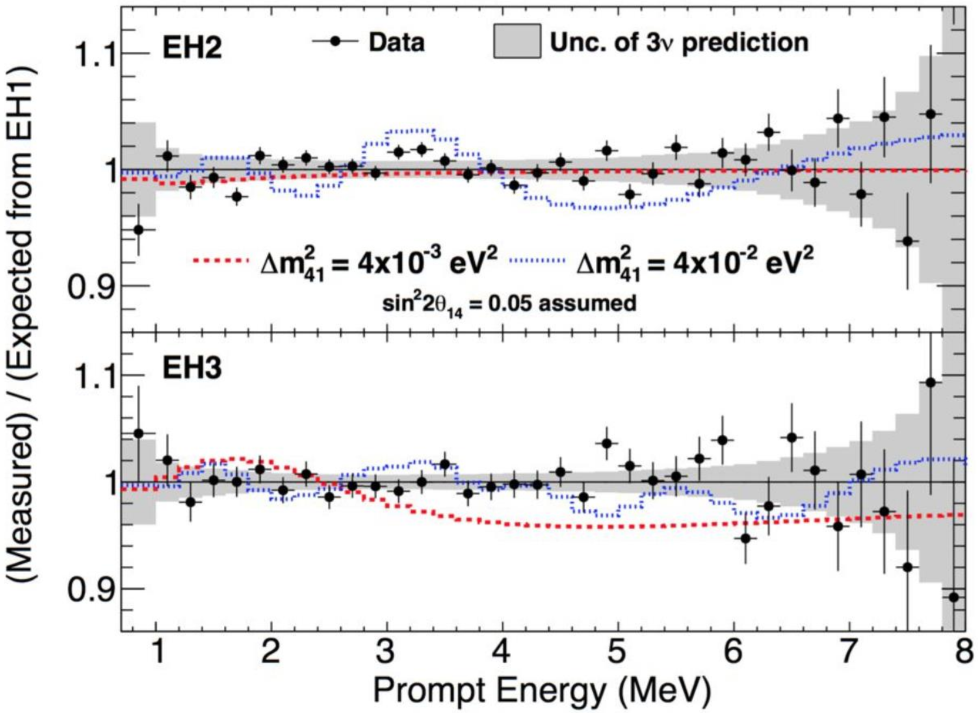


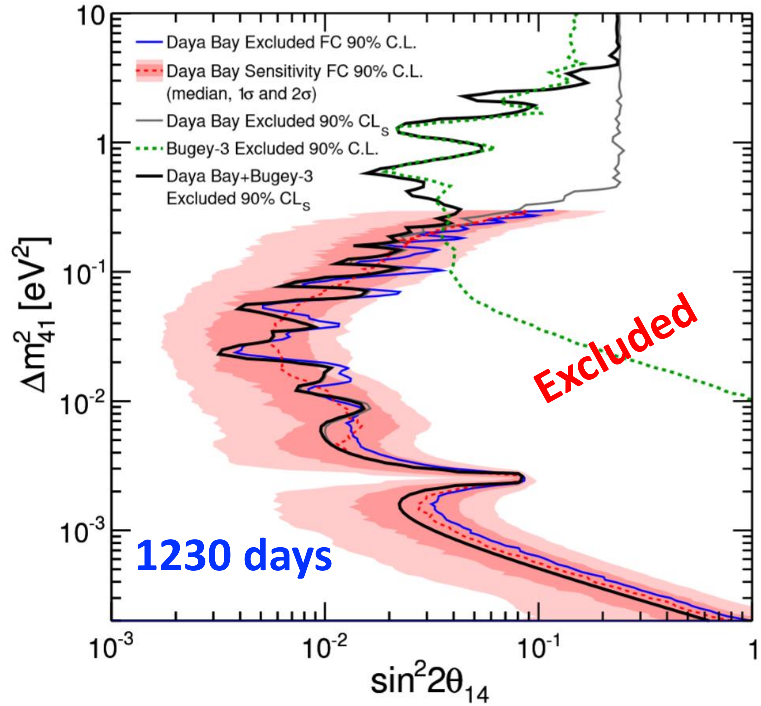
$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \cos^4\theta_{14}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{ee}L}{4E_\nu}\right) - \sin^2 2\theta_{14}\sin^2\left(\frac{\Delta m^2_{41}E}{4E_\nu}\right)$$

- A minimum extension of the 3-ν model: 3(active) + 1(sterile)-ν model
- Search for a higher frequency oscillation pattern besides $|\Delta m^2_{ee}|$

Sterile Neutrino Search

PRL 125, 071801 (2020)





- Data is consistent with 3-ν model; No light sterile neutrino signal observed
- Consistent results from Feldman-Cousins and CLs methods

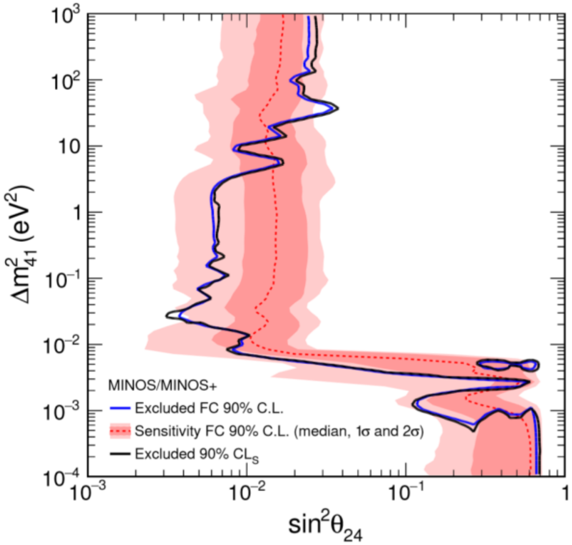
The most stringent upper limit for light sterile neutrinos ($\Delta m^2 < 0.2$ eV²)

Joint Sterile Neutrino Searches

*PRL **122** 091803 (2019)*

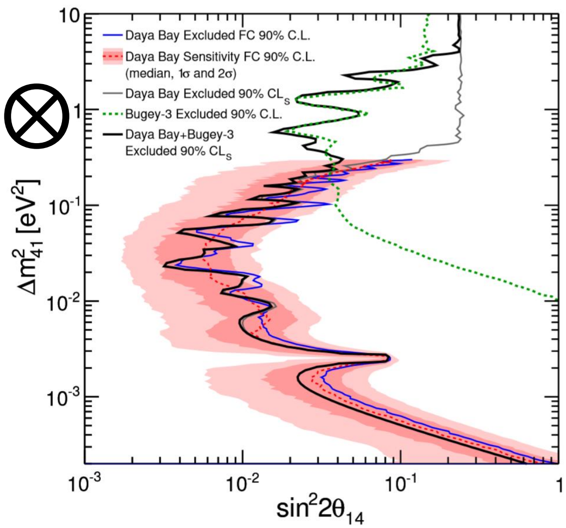
PRL 125, 071801 (2020)

MINOS/MINOS+

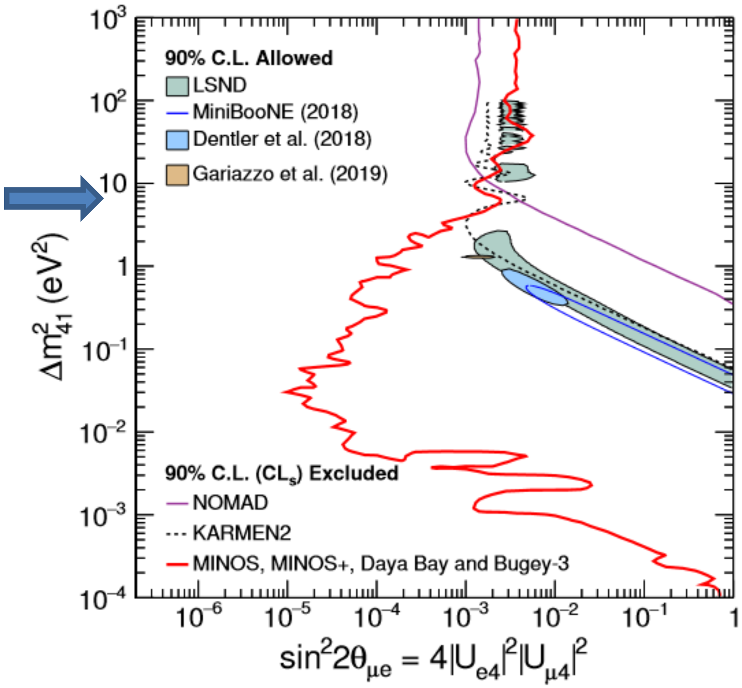


$|U_{\mu 4}|^2 = \sin^2\theta_{24}\cos^2\theta_{14}$

Daya Bay + Bugey-3

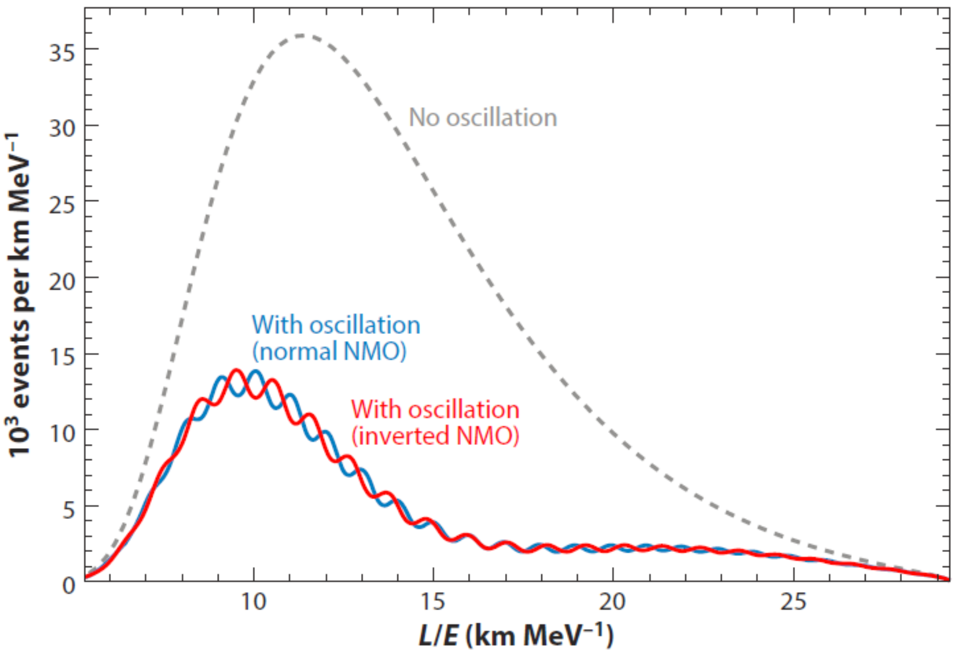


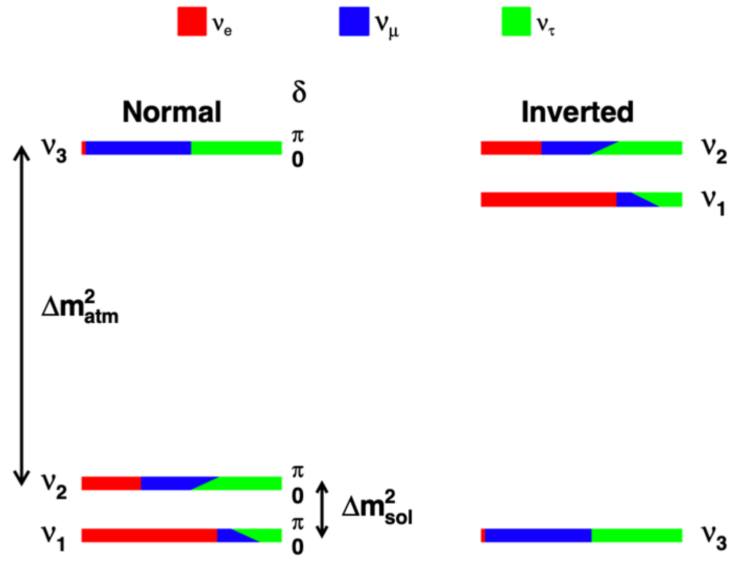
$|U_{e4}|^2 = \sin^2\theta_{14}$



- The combined results can exclude the LSND and MiniBooNE signal region at $\Delta m^2_{41} < 5$ eV² at 90% C.L.

Neutrino Oscillation at Jiangmen Underground Neutrino Observatory (JUNO)





$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - cos^4\theta_{13} sin^2 2\theta_{12} sin^2\Delta_{21}$$
$$-sin^2 2\theta_{13}\left(cos^2\theta_{12} sin^2\Delta_{31} + sin^2\theta_{12} sin^2\Delta_{32}\right)$$

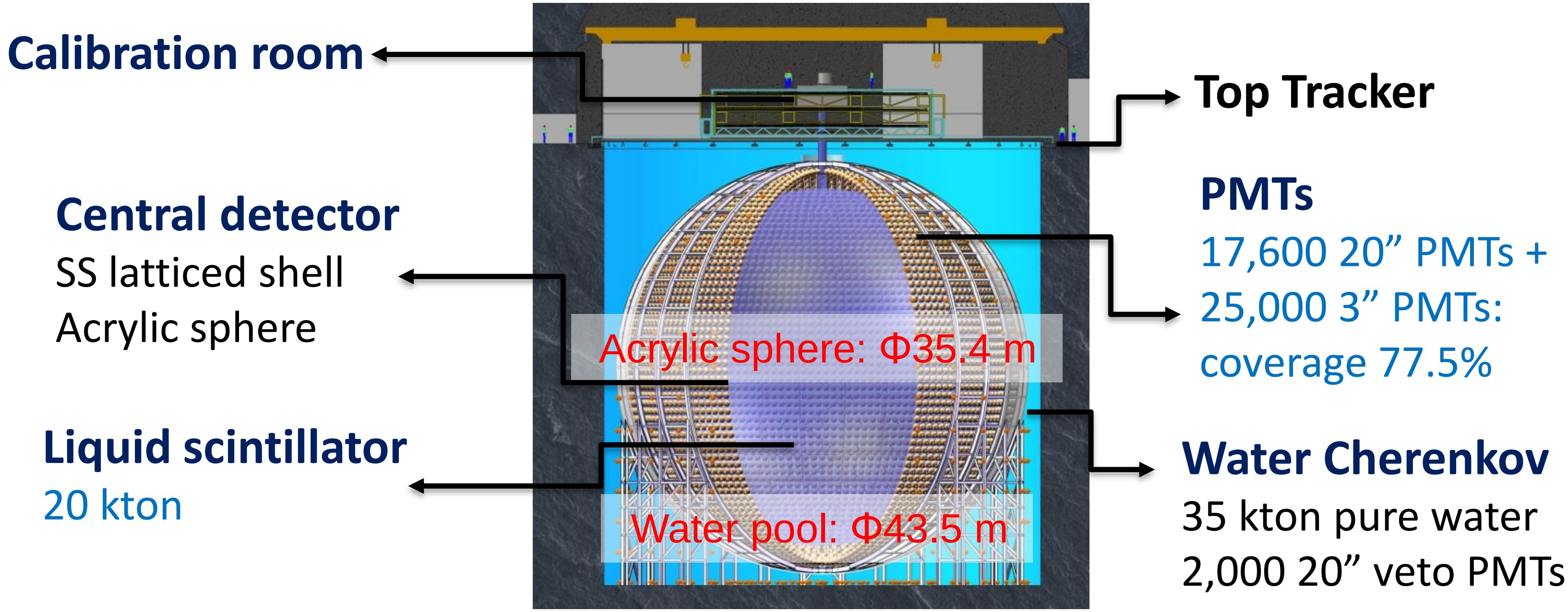
NO : $|\Delta m^2_{31}| = |\Delta m^2_{32}| + \Delta m^2_{21}$

IO: $|\Delta m^2_{31}| = |\Delta m^2_{32}| - \Delta m^2_{21}$

S.T. Petcov et al., PLB533(2002)94
S.Choubey et al., PRD68(2003)113006
J. Learned et al., PRD78, 071302 (2008)
L. Zhan, Y. Wang, J. Cao, L. Wen, PRD78:111103, 2008, PRD79:073007, 2009
J. Learned et al., arXiv:0810.2580
Y.F Li et al, PRD 88, 013008 (2013)
…

JUNO Detector Design

	KamLAND	Borexino	Daya Bay	JUNO
LS Mass [kton]	1	0.278	~0.04 x 8	20
E resolution@ 1 MeV	6%	5%	8%	3%
Photo-coverage	34%	30%	12%	77%
E calibration	1.4%	1%	0.5%	1%

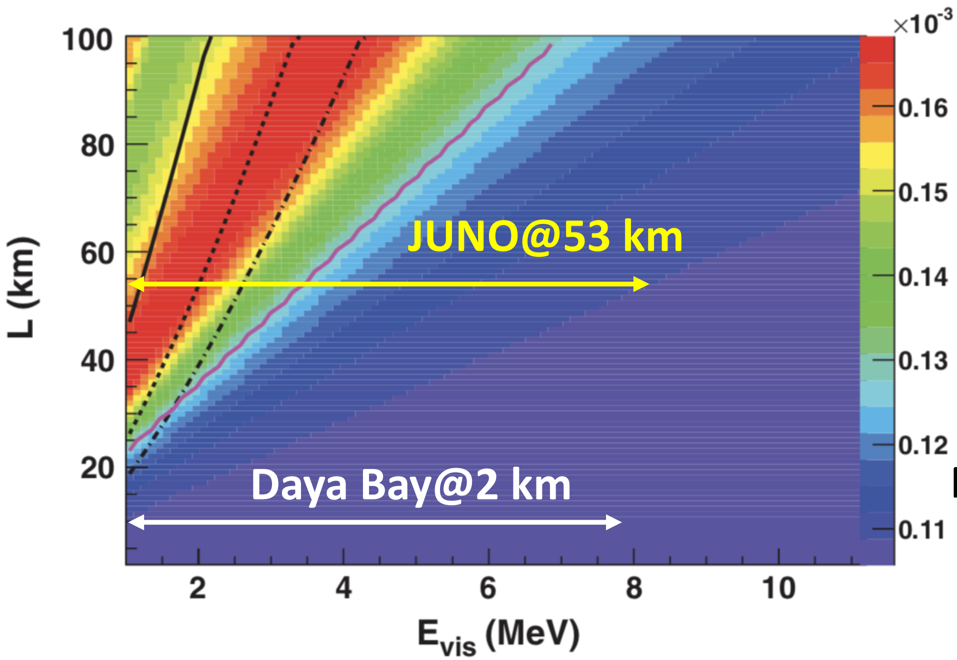


Neutrino Mass Ordering (NMO)

*X.Qian et al. Phys. Rev.D.**87**, 033005 (2013)*

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$$
$$= 1 - cos^4\theta_{13} sin^2 2\theta_{12} sin^2\Delta_{21} - sin^2 2\theta_{13}(cos^2\theta_{12} sin^2\Delta_{31} + sin^2\theta_{12} sin^2\Delta_{32})$$
$$= 1 - cos^4\theta_{13} sin^2 2\theta_{12} sin^2\Delta_{21} - 2sin^2\theta_{13} cos^2\theta_{13}$$
$$+2sin^2\theta_{13} cos^2\theta_{13}\sqrt{1 - 4sin^2\theta_{12} cos^2\theta_{12} sin^2\Delta_{21}}\cos(2\Delta_{32} \pm \phi_{ee})$$

+: Normal
−: Inverted



$$\Delta_{ij} = 1.27\frac{\Delta m^2_{ij}\, L(\mathrm{m})}{E\ (\mathrm{MeV})}$$

$$tan\phi = \frac{cos^2\theta_{12} sin 2\Delta_{21}}{cos^2\theta_{12} cos 2\Delta_{21} + sin^2\theta_{12}}$$

$$\Delta m^2_{\phi_{ee}}(\mathrm{eV}^2) = \frac{\phi}{1.27}\cdot\frac{E(\mathrm{m})}{L(\mathrm{MeV})}$$

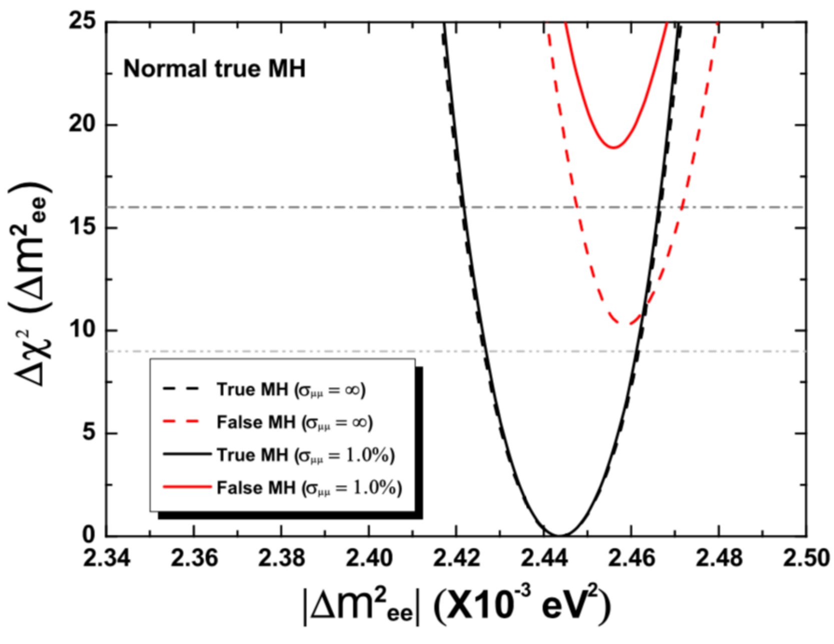
Mass ordering degeneracy at a certain L and E:

$$|\Delta m^2_{32}(\mathrm{IO})| = |\Delta m^2_{32}(\mathrm{NO})| + \Delta m^2_{\phi}(L, E)$$

The degeneracy of NMO can be broken with the reactor neutrino energy spectrum when the detector baseline > ~50 km.

Sensitivity of NMO Determination

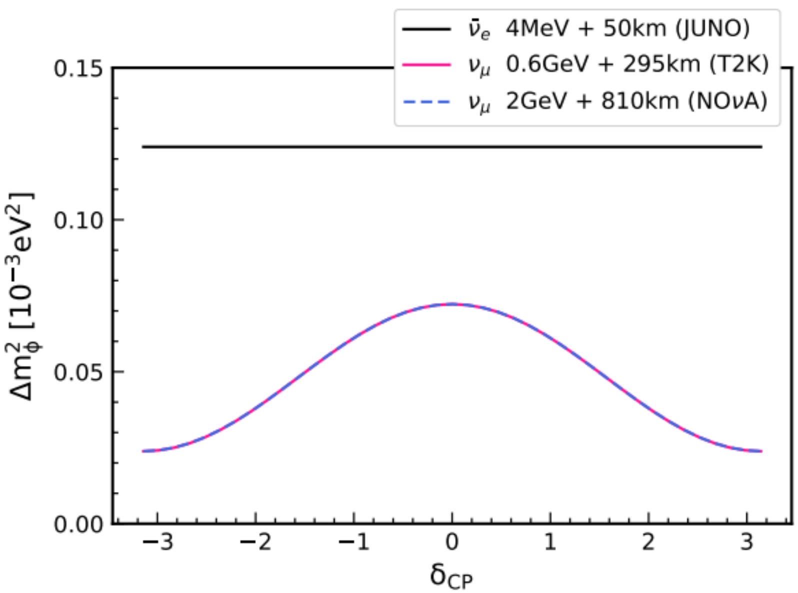
Event type	Rate (per day)	Rate uncertainty (relative)	Shape uncertainty
IBD candidates	60	—	—
Geo-νs	1.1	30%	5%
Accidental signals	0.9	1%	negligible
Fast-n	0.1	100%	20%
^{9}Li–^{8}He	1.6	20%	10%
^{13}C $(\alpha, n)^{16}$O	0.05	50%	50%

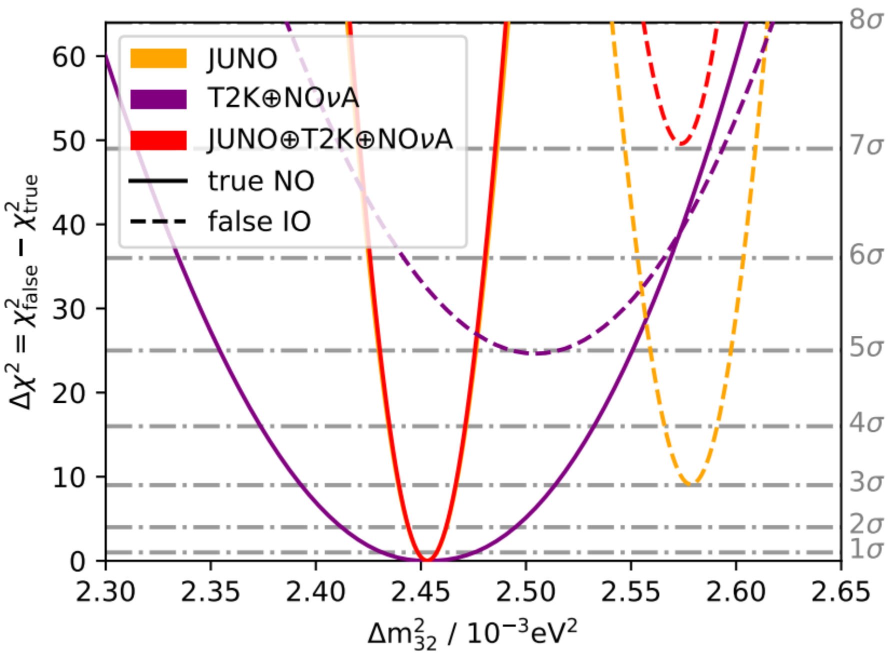


JUNO MO sensitivity with 6 years' data assuming full reactor power

	Size	$\Delta\chi^2_{MO}$
Ideal	52.5 km	+16
Core distr.	Real	-3
DYB & HZ	Real	-1.7
Spectral Shape	1%	-1
B/S (rate)	6.3%	-0.6
B/S (shape)	0.4%	-0.1

NMO Sensitivity with External ν_μ Constraints





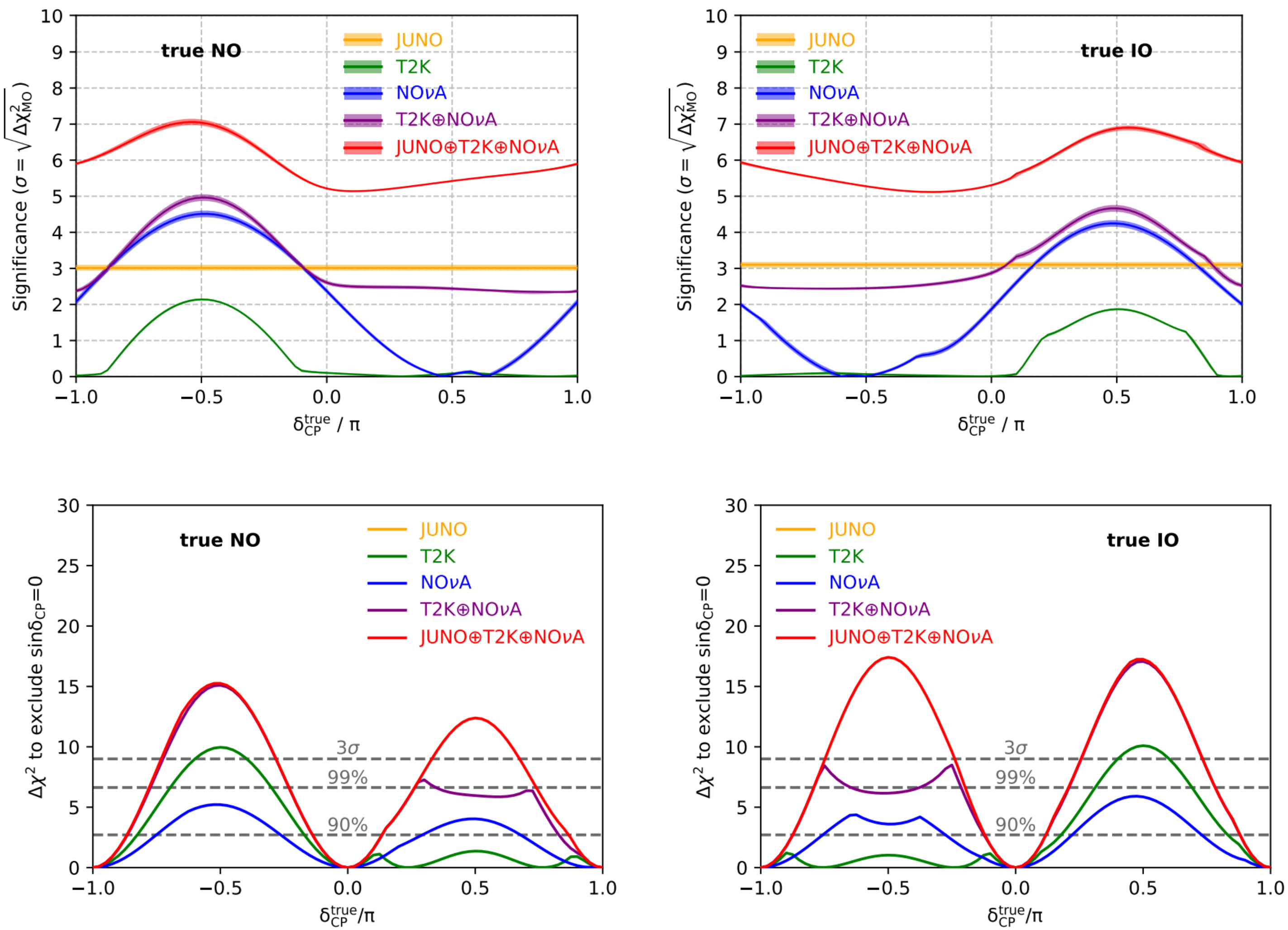
$$\Delta m^2_{ee} = cos^2\theta_{12}\Delta m^2_{31} + sin^2\theta_{12}\Delta m^2_{32}$$

$$\Delta m^2_{\mu\mu} = sin^2\theta_{12}\Delta m^2_{31} + cos^2\theta_{12}\Delta m^2_{32} + cos\delta_{CP} sin\theta_{13} sin2\theta_{12} tan\theta_{23}\Delta m^2_{21}$$

Sensitivity with 100k events (20k ton LS + 6 years with 26GW$_{th}$ reactor power)

- 3% energy resolution@1 MeV, <1% energy calibration
- $\overline{\Delta\chi^2} > 9$ ($\overline{\Delta\chi^2} > 16$ with external 1% $|\Delta m^2_{\mu\mu}|$ constraint)

Sensitivity to NMO and CPV

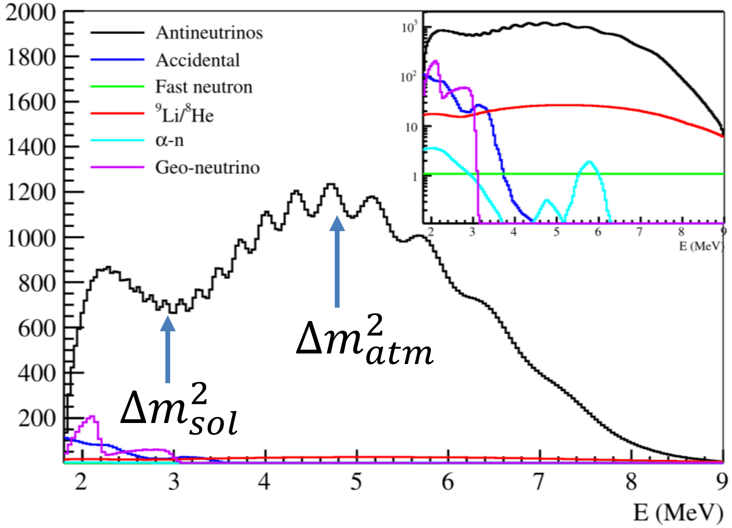


Precision Measurement at JUNO

Current precision

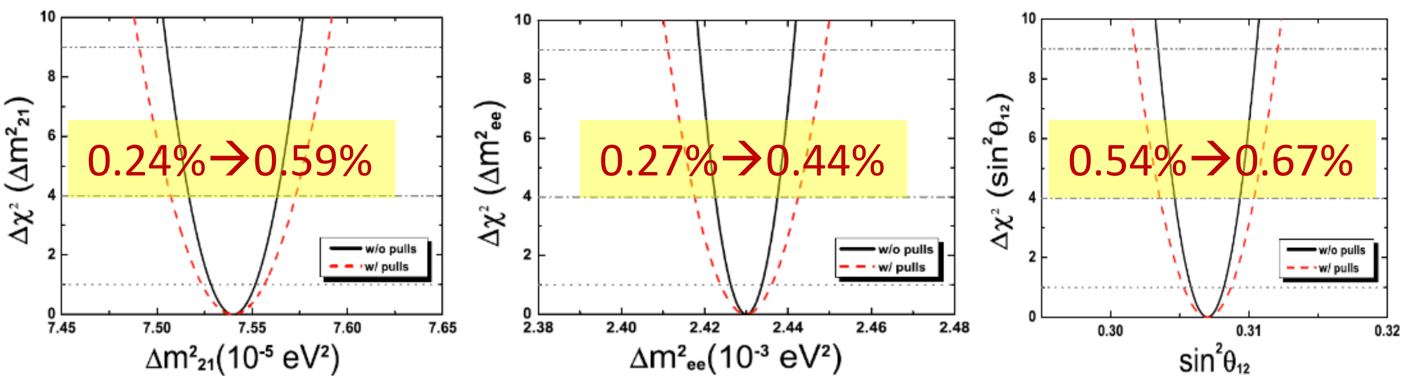
	Δm^2_{21}	$\lvert\Delta m^2_{31}\rvert$	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$	δ
Dominant Exps.	KamLAND	T2K	SNO+SK	Daya Bay	NOνA	T2K
Individual 1σ	2.4%	2.6%	4.5%	3.4%	5.2%	70%
Nu-FIT 4.0	2.4%	1.3%	4.0%	2.9%	3.8%	16%

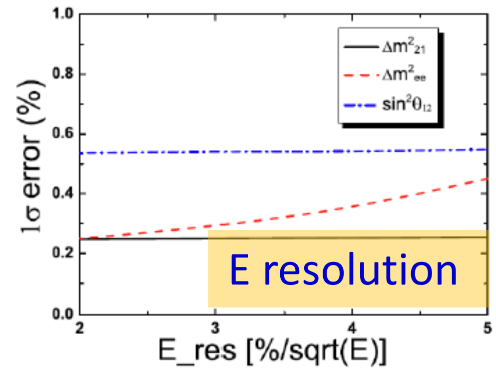
Probing the unitarity of U_{PMNS} to ~1%, more precise than CKM matrix elements!



	Statistics	+BG, +1% b2b +1% EScale , +1% EnonL
$\sin^2\theta_{12}$	0.54%	**0.67%**
Δm^2_{21}	0.24%	**0.59%**
Δm^2_{32}	0.27%	**0.44%**

J. Phys. G43:030401 (2016)





Unitarity Conditions

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\begin{aligned} |U^{3\nu}_{\alpha 1}|^2 + |U^{3\nu}_{\alpha 2}|^2 + |U^{3\nu}_{\alpha 3}|^2 &= 1, \quad \alpha = e, \mu, \tau, \\ |U^{3\nu}_{ei}|^2 + |U^{3\nu}_{\mu i}|^2 + |U^{3\nu}_{\tau i}|^2 &= 1, \quad i = 1, 2, 3, \\ U^{3\nu}_{\alpha 1} U^{3\nu,*}_{\beta 1} + U^{3\nu}_{\alpha 2} U^{3\nu,*}_{\beta 2} + U^{3\nu}_{\alpha 3} U^{3\nu,*}_{\beta 3} &= 0, \quad \alpha, \beta = e, \mu, \tau, \quad \alpha \neq \beta, \\ U^{3\nu}_{ei} U^{3\nu,*}_{ej} + U^{3\nu}_{\mu i} U^{3\nu,*}_{\mu j} + U^{3\nu}_{\tau i} U^{3\nu,*}_{\tau j} &= 0, \quad i, j = 1, 2, 3, \quad i \neq j. \end{aligned}$$

Global Neutrino Data

Various neutrino experimental data can provide constraints on the different neutrino mixing elements

- Different energy scale
- Different baseline
- Different systematics

Types	Exps	Measurements
MBL Reactor	RENO, Daya Bay Double Chooz	$4\|U_{e3}\|^2(\|U_{e1}\|^2+\|U_{e2}\|^2)$
LBL Reactor	KamLAND	$4\|U_{e1}\|^2\|U_{e2}\|^2$
Solar	SNO	$\|U_{e2}\|^2$
LBL Accelerator $(\nu_\mu\to\nu_\mu)$	NOvA, T2K	$4\|U_{\mu3}\|^2(\|U_{\mu1}\|^2+\|U_{\mu2}\|^2)$
LBL Accelerator $(\nu_\mu\to\nu_e)$	NOvA, T2K	$4\Re[U_{e3}U^*_{\mu3}(U_{e1}U^*_{\mu1}+U_{e2}U^*_{\mu2})]$
LBL Accelerator $(\nu_\mu\to\nu_\tau)$	OPERA	$4\Re[U_{\tau3}U^*_{\mu3}(U_{\tau1}U^*_{\mu1}+U_{\tau2}U^*_{\mu2})]$

Unitarity Triangle

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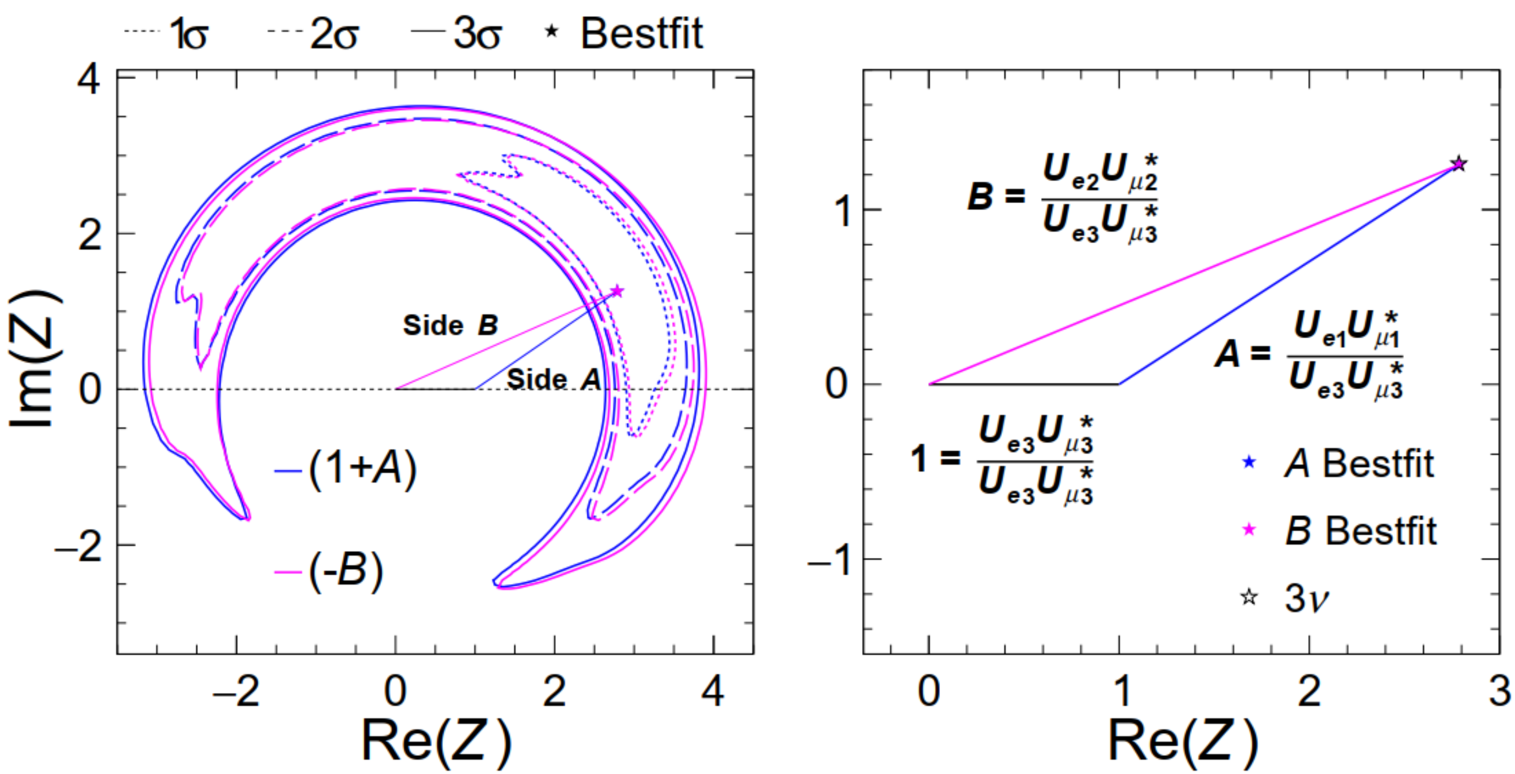
Matrix Orthogonal Test

$$U_{e1}U_{\mu1}^* + U_{e2}U_{\mu2}^* + U_{e3}U_{\mu3}^* = 0$$

$$\frac{U_{e1}U_{\mu1}^*}{U_{e3}U_{\mu3}^*} + \frac{U_{e2}U_{\mu2}^*}{U_{e3}U_{\mu3}^*} + 1 = 0$$



Unitarity Test

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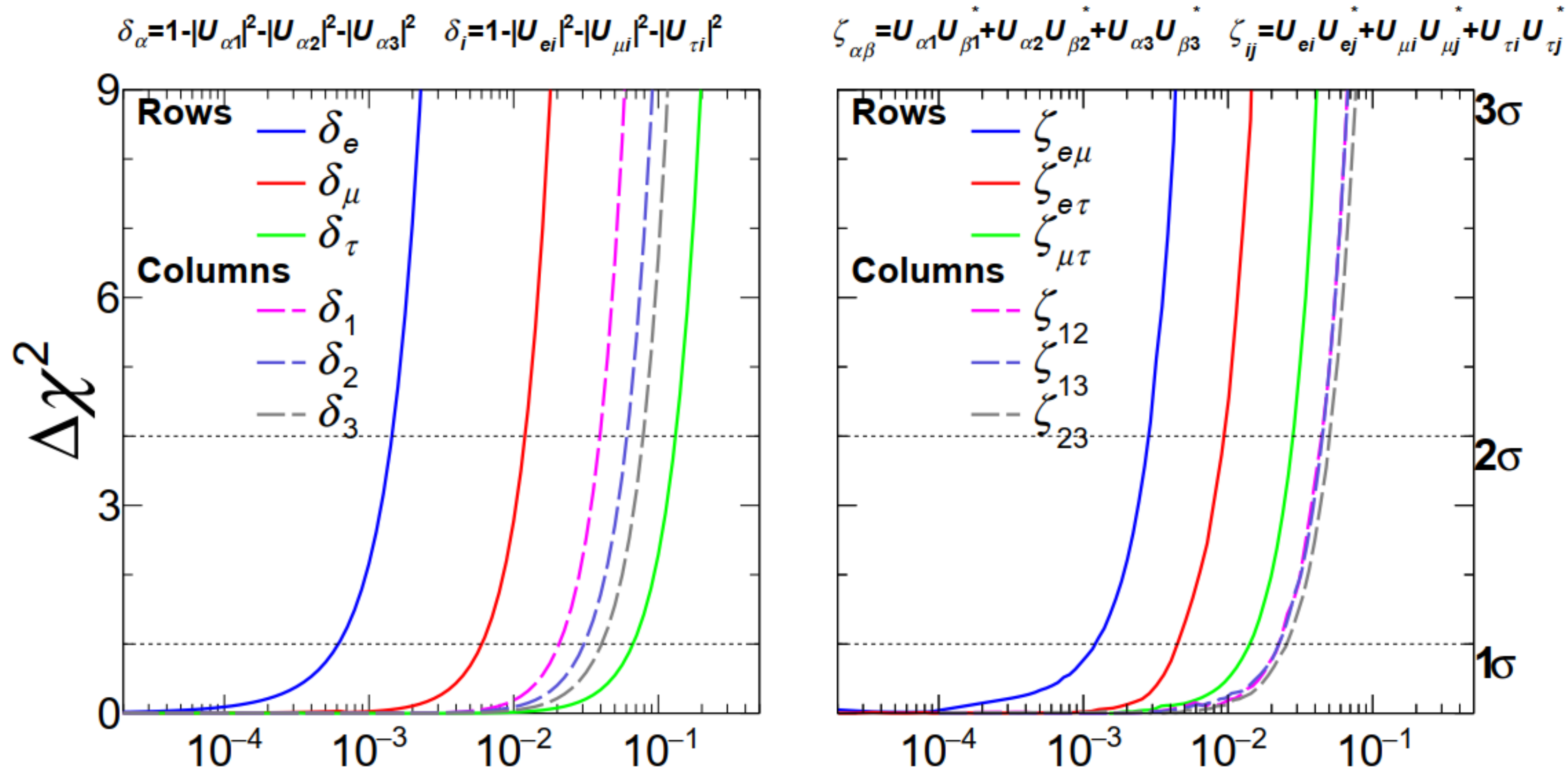

- Electron-type neutrinos have the best unitarity constraints due to large data sample
- Tau-type neutrinos are very limited by the experimental data

Summary

- Daya Bay has made the most precise measurements on $\sin^2 2\theta_{13}$ and $|\Delta m^2_{32}|$ with 2.8% and 2.3% precision
- Daya Bay set the most stringent upper limit for light sterile neutrino with $\Delta m^2_{41} < 0.2\ \mathrm{eV}^2$
  - A joint fit with MINOS/MINOS+ is able to exclude most of LSND/MiniBooNE signal region
- JUNO can measure NMO with 3σ sensitivity with 6 years
  - boost to $>5\sigma$ with accelerator experiments