Highlights of Neutrino Experiments

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Outline

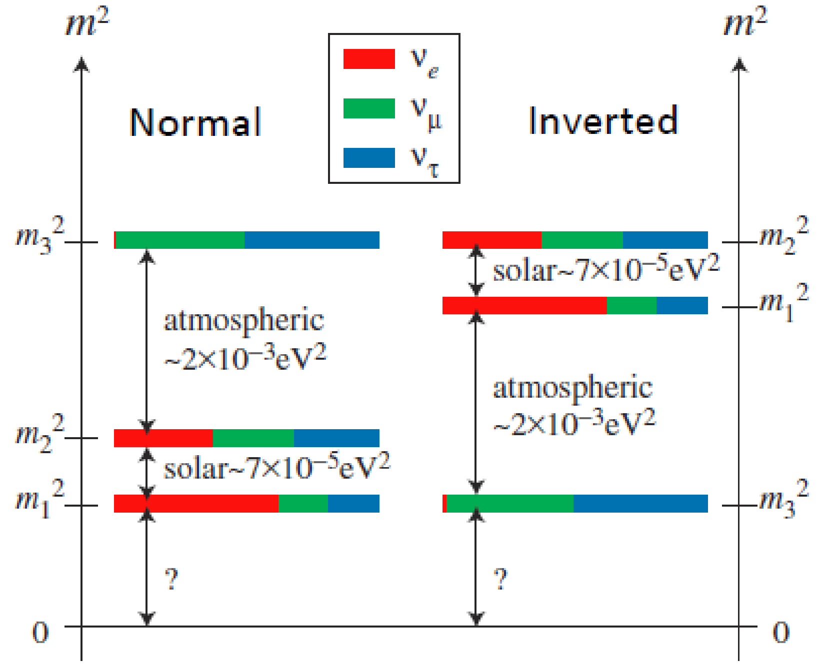
- Neutrino Oscillation Results
  - Reactors (Daya Bay, Double Chooz, RENO)
  - Accelerators (T2K, NOvA, MINOS)
  - Atmospheric (Super-K)
- Future reactor experiment
  - JUNO
- Non-oscillation experiment
  - $0\nu\beta\beta$

* Due to the limited time. Only a few selected experiments were discussed here

Neutrino Mixing

In a 3-ν framework

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



$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{-i\alpha_1/2} & 0 & 0 \\ 0 & e^{-i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

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

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

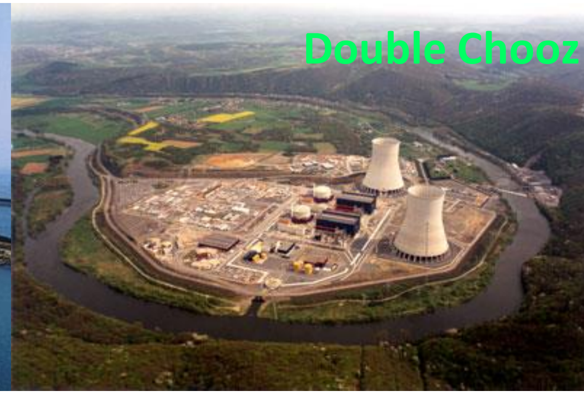
Atmospheric	"CP" sector	Solar	Majorana
$\theta_{23} \approx 45°$	$\theta_{13} = 9°$	$\theta_{12} \approx 34°$	

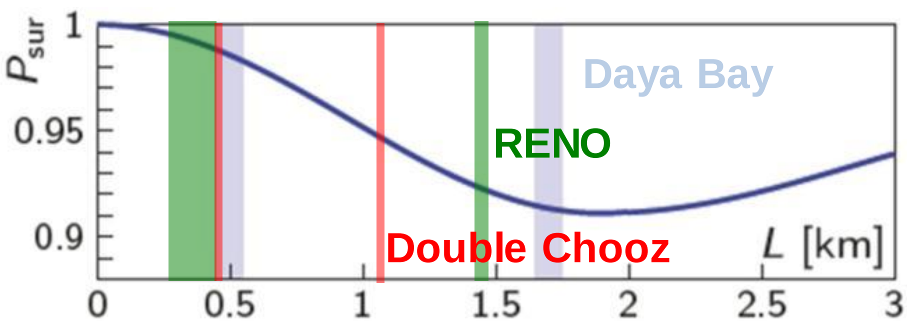
$|\Delta m^2_{32}| \approx |\Delta m^2_{31}| \approx 2.4 \times 10^{-3}$ eV^2

$\Delta m^2_{21} \approx 7.6 \times 10^{-5}$ eV^2

Reactor ν Results

Reactor Experiments





$$\bar{\nu}_e + p \rightarrow e^+ + n$$

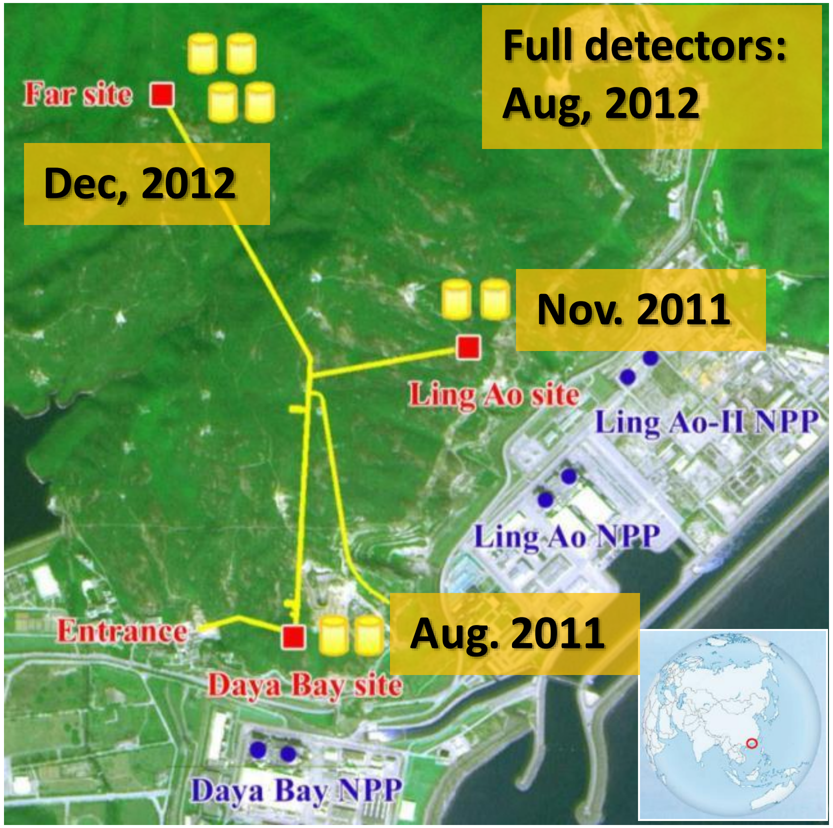
τ ≈ 28 μs (0.1% Gd)

n + p → d + γ (2.2 MeV)

n + Gd → Gd* + γ (8 MeV)

Designs	**Luminosity (ton·GW)**	**Detector Systematics**	**Overburden (near/far, mwe)**	**Sensitivity (3y, 90% CL)**
Daya Bay (China)	1400	0.38%/√N	250 / 860	~ 0.008
Double Chooz (France)	70	0.6%	120 / 300	~ 0.03
RENO (Korea)	260	0.5%	120 / 450	~ 0.02

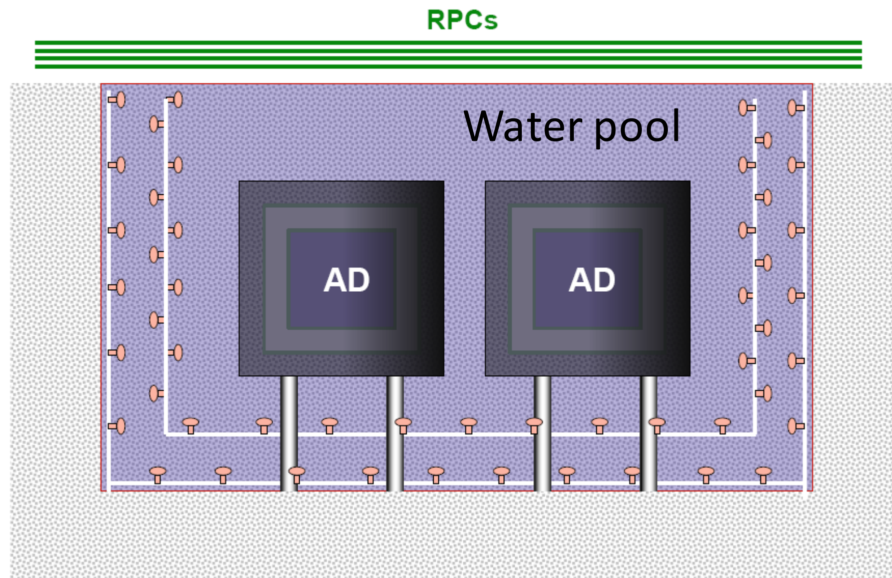
Daya Bay Experiment



Design sens. : $\sin^2 2\theta_{13}$~0.01 (90% CL)

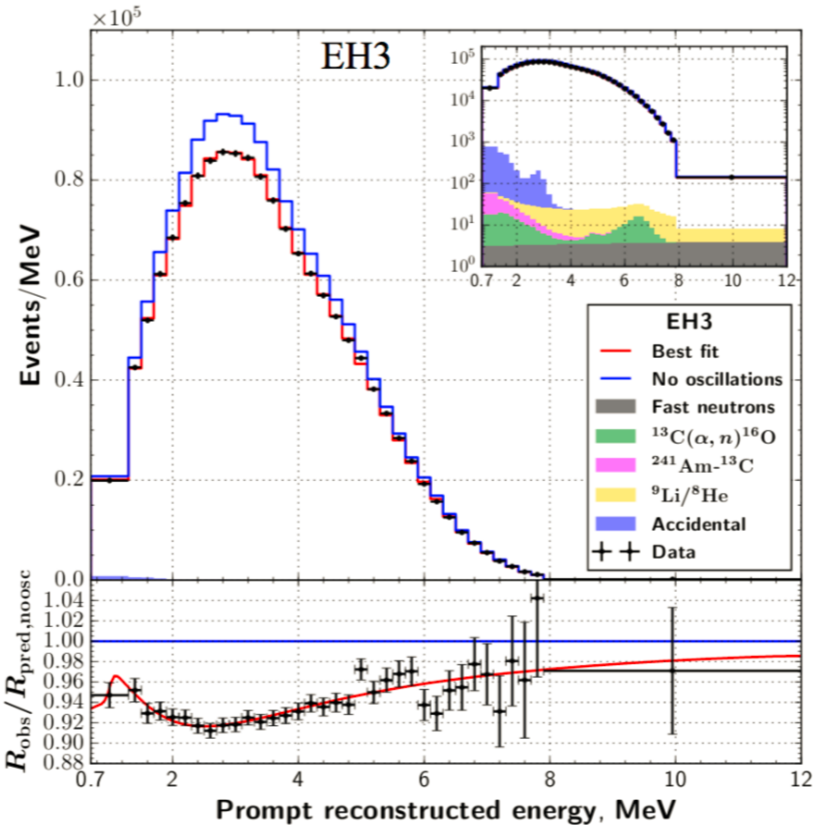
→ rapid obs. of $\bar{\nu}_e$ disappearance

→ precision measurements of θ_{13}



- Luminosity : 1400 ton·GW (5-20 times of DC and RENO)
- Close to mountains → enough shielding
- Featured design → side-by-side calibration (2-4 ADs at each site) → actual relative detector error: **$0.2\%/\sqrt{N}$** (design value: **0.38%**)

Precision measurement at Daya Bay

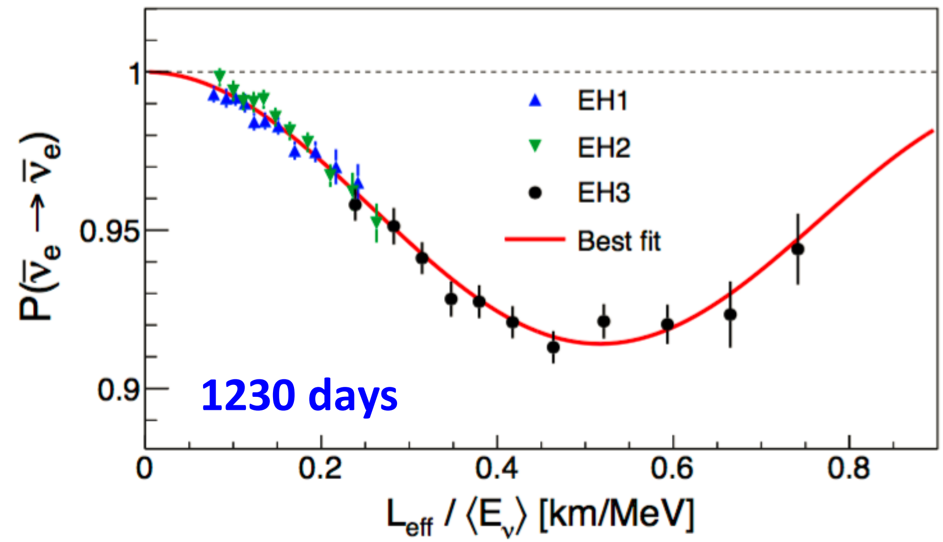


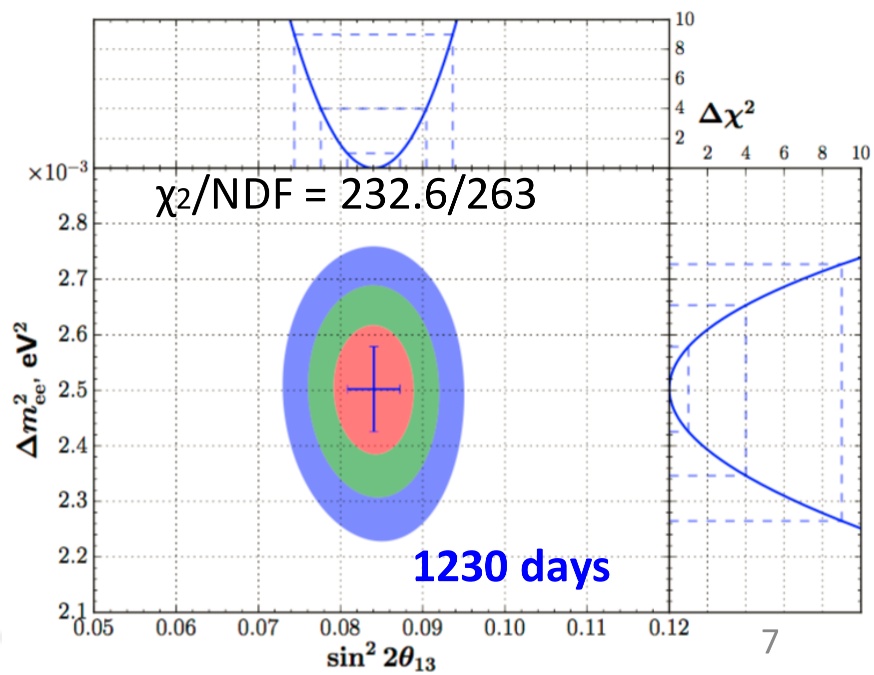
$Sin^2 2\theta_{13}$ = [8.41 ± 0.33] × 10^{-2}

NH: Δm^2_{32} = [2.45 ± 0.08] × 10^{-3} eV^2

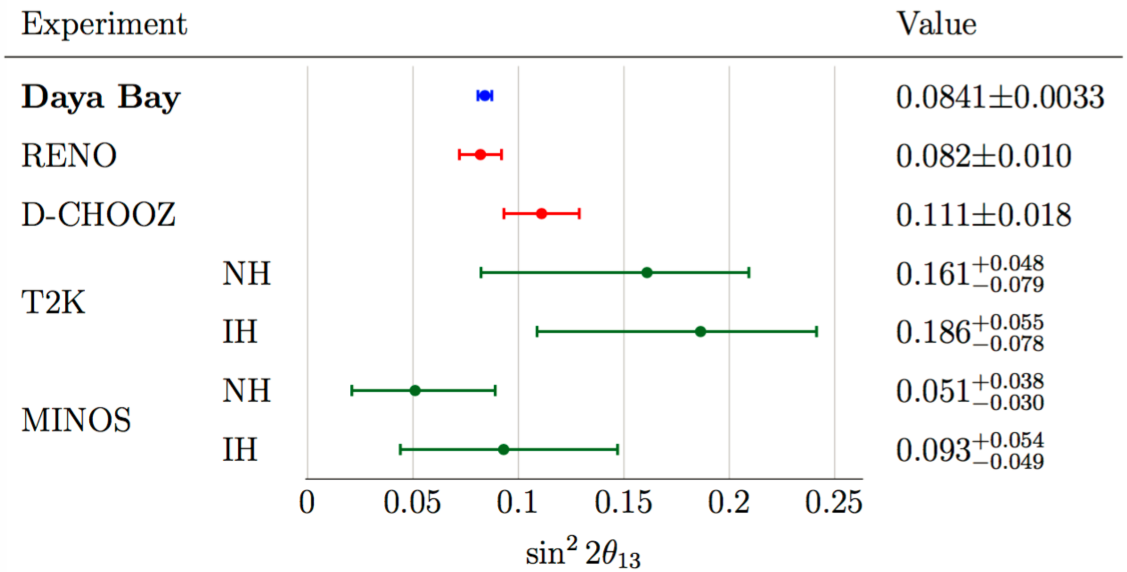
IH: Δm^2_{32} = [-2.55 ± 0.08] × 10^{-3} eV^2

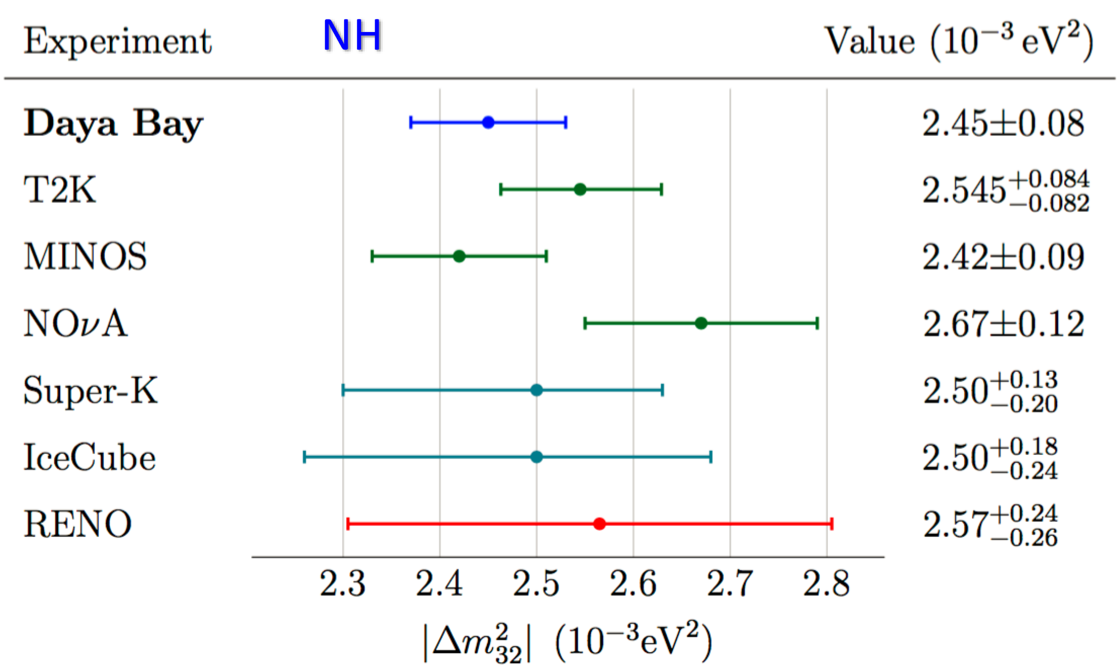
- Independent $\sin^2 2\theta_{13}$ meas. from nH
- run until 2020, achieve uncertainty ≤3%





Global comparison





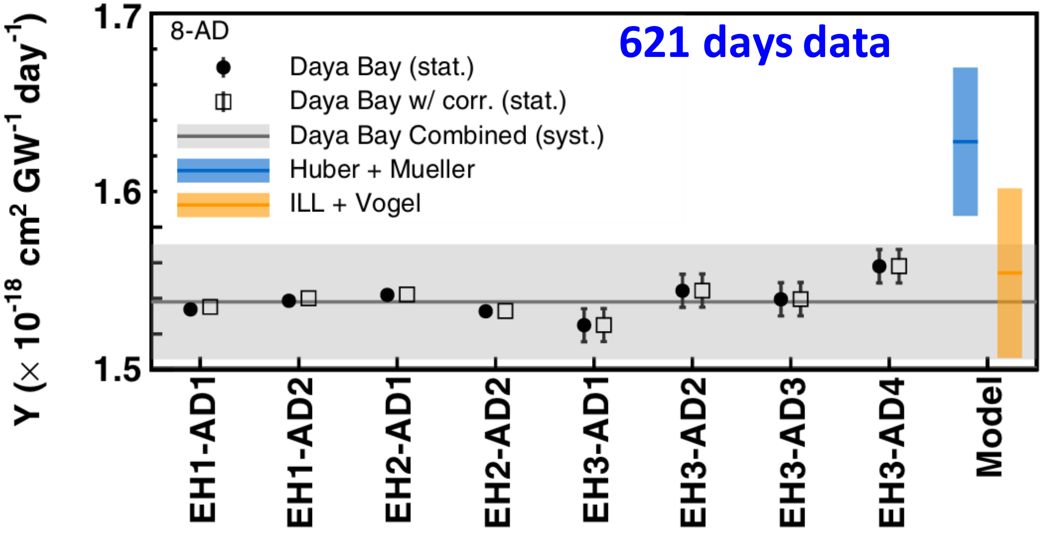
Most precise measurement

- $\sin^2 2\theta_{13}$ uncertainty: 3.9%
- $|\Delta m^2_{32}|$ uncertainty: 3.4%

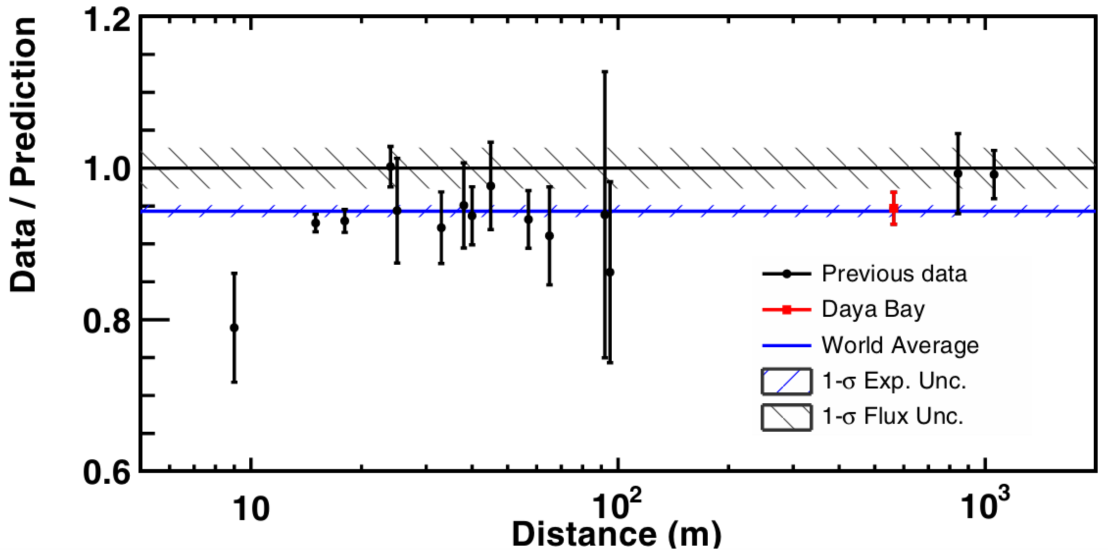
Consistent results with reactor and accelerator experiments.

Absolute Reactor $\bar{\nu}_e$ flux

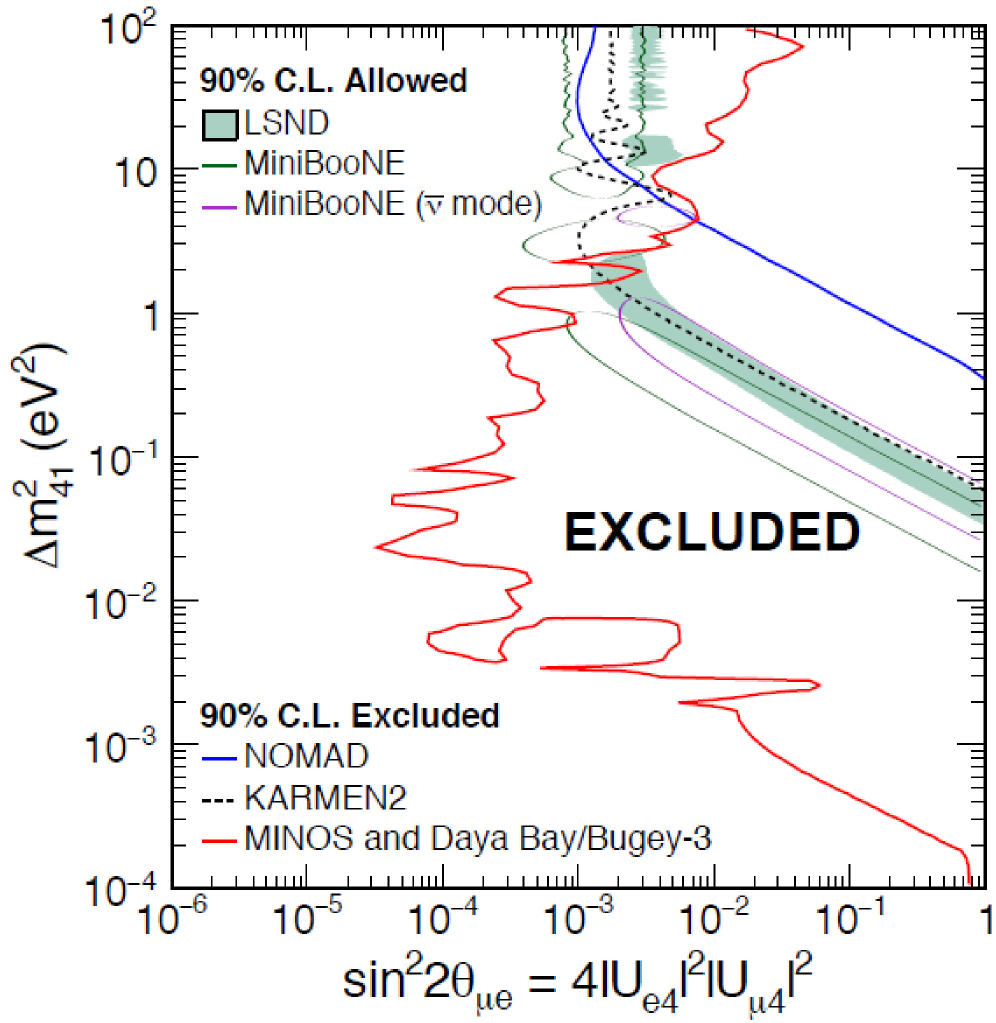
Discrepancies to the Huber+Mueller model indicate:
Over estimated flux and/or underestimated flux uncertainty
Or the existence of a sterile neutrino



Consistent flux measurement with previous short baseline reactor experiments



MINOS, Daya Bay and Bugey-3



Parameter space allowed by LSND and MiniBooNE is excluded
For $\Delta m^2_{41} < 0.8$ eV^2 at 95% C.L.

arXiv:1607.01177

Accelerator ν Results

ν_μ ($\bar{\nu}_\mu$) Oscillations

$$P(\nu_\mu \to \nu_\mu) \sim 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right)$$

$$P(\nu_\mu \to \nu_e) \sim \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2[(1-x)\hat{\Delta}]}{(1-x)^2}$$

$$-\alpha \sin\delta \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\,\theta_{23} \sin\hat{\Delta} \frac{\sin[\hat{\Delta}x]}{x} \frac{\sin[(1-x)\hat{\Delta}]}{(1-x)}$$

$$+\alpha \cos\delta \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\,\theta_{23} \cos\hat{\Delta} \frac{\sin[\hat{\Delta}x]}{x} \frac{\sin[(1-x)\hat{\Delta}]}{(1-x)}$$

$$+ O(\alpha^2)$$

$$\Delta m_{ij}^2 = m_i^2 - m_j^2 \qquad \alpha = \left|\frac{\Delta m_{21}^2}{\Delta m_{31}^2}\right| \sim \frac{1}{30} \qquad \hat{\Delta} = \frac{\Delta m_{31}^2 L}{4E} \qquad x = \frac{2\sqrt{2}G_F N_e E}{\Delta m_{31}^2}$$

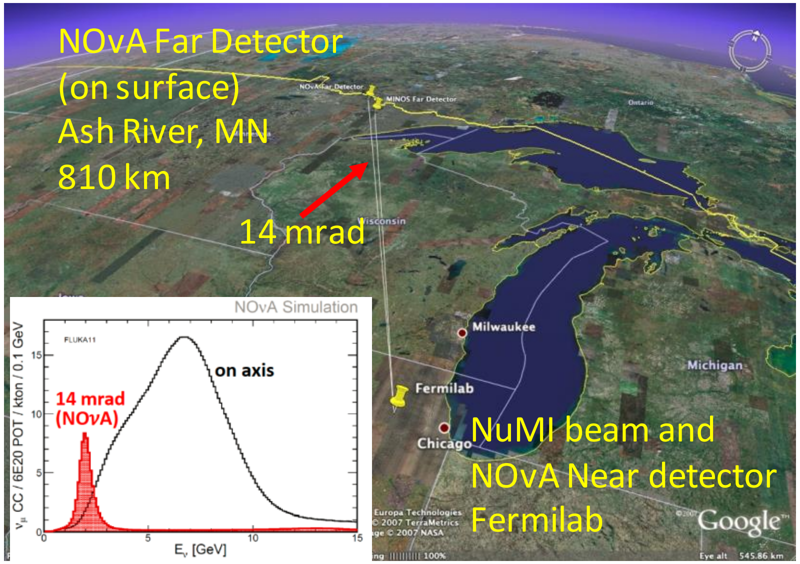
M. Freund, Phys.Rev. D64 (2001) 053003

- CPT test with P($\bar{\nu}_\mu \to \bar{\nu}_\mu$)
- CP odd phase δ changes sign for $\bar{\nu}$-mode P($\bar{\nu}_\mu \to \bar{\nu}_e$)

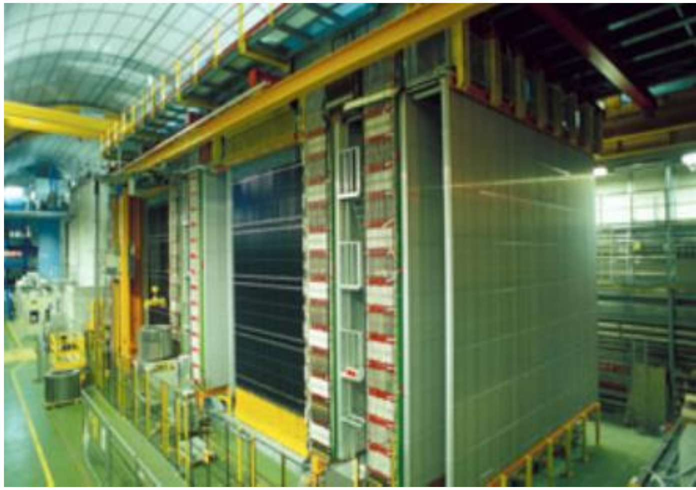
Accelerator Experiments

MINOS (USA)

NOνA

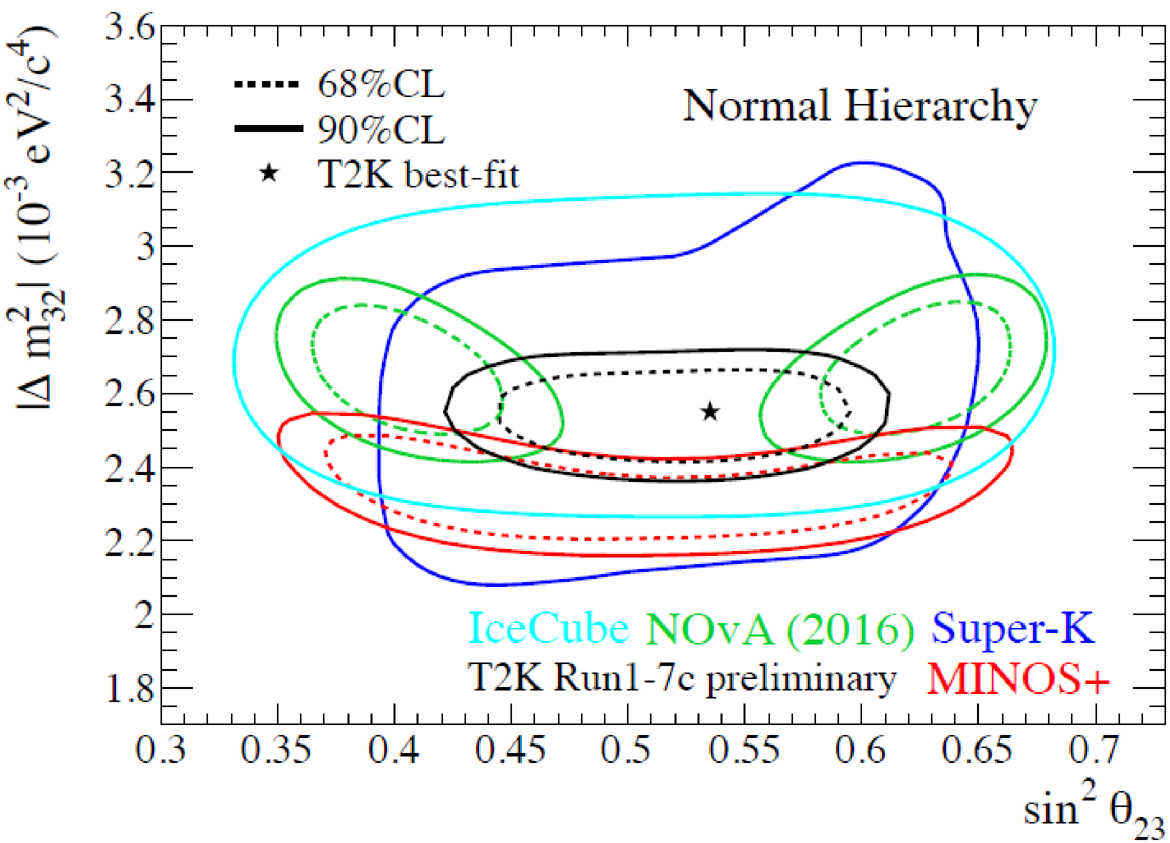


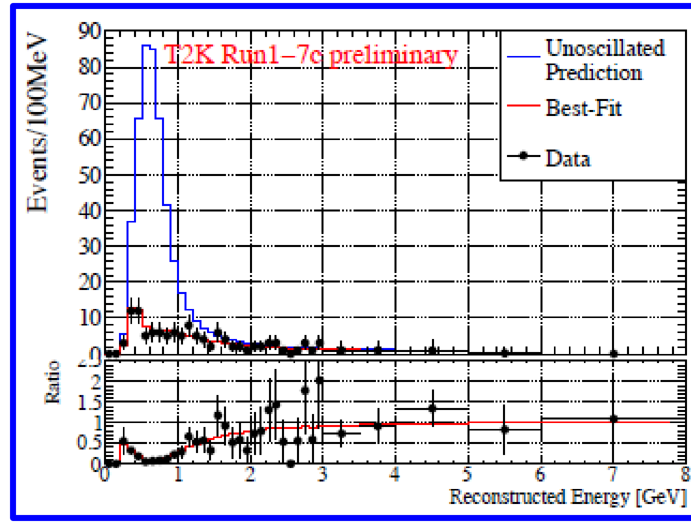
T2K (Japan)



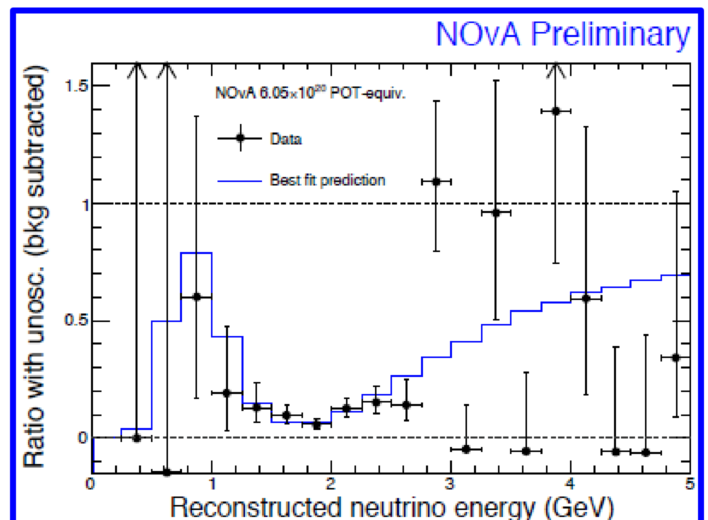
OPERA (Europe)

$Sin^2\theta_{23}$ & Δm^2_{32}





Daya Bay:
$|\Delta m^2_{ee}| = (2.45 \pm 0.08) \times 10^{-3} eV^2$
90% CL (NH)



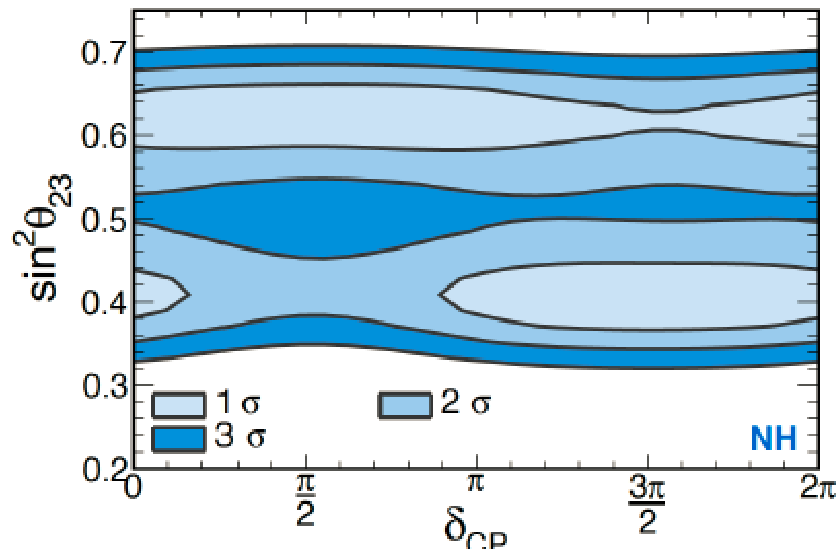
K. Iwamoto @ ICHEP

NOvA ν_e contours

J.M.Bian@ ICHEP

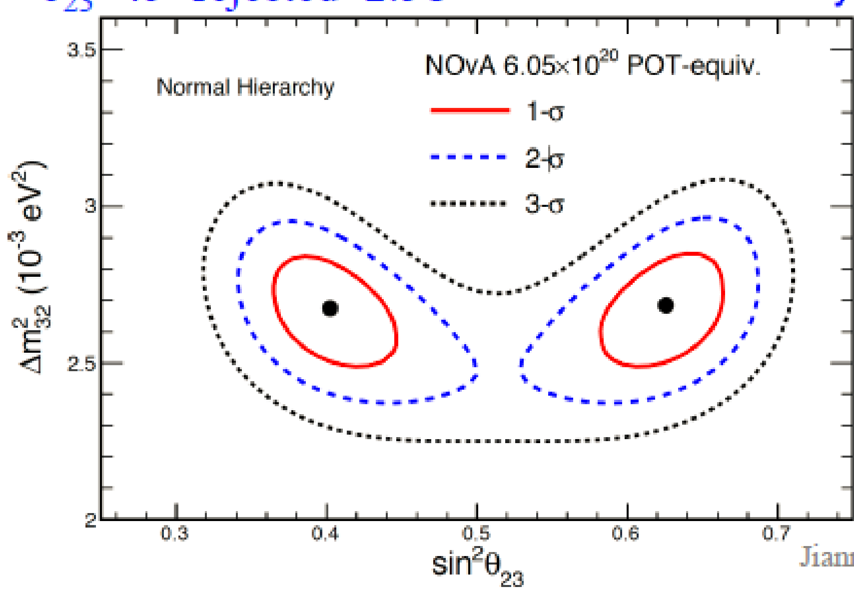
- Constrain Δm^2 and $\sin^2\theta_{23}$ with NOvA ν_μ disappearance results
- Global best fit: Normal Hierarchy, $\delta_{CP} = 1.49\pi$, $\sin^2\theta_{23} = 0.4$
- IH, $\delta_{CP}\sim\pi/2$ is rejected (3σ) for lower octant
- Both octants and MHs are allowed at 1σ, best fit IH-NH: $\Delta\chi^2=0.47$

Applying global reactor constraint of $\sin^2 2\theta_{13}=0.086\pm0.05$ NOvA Preliminary

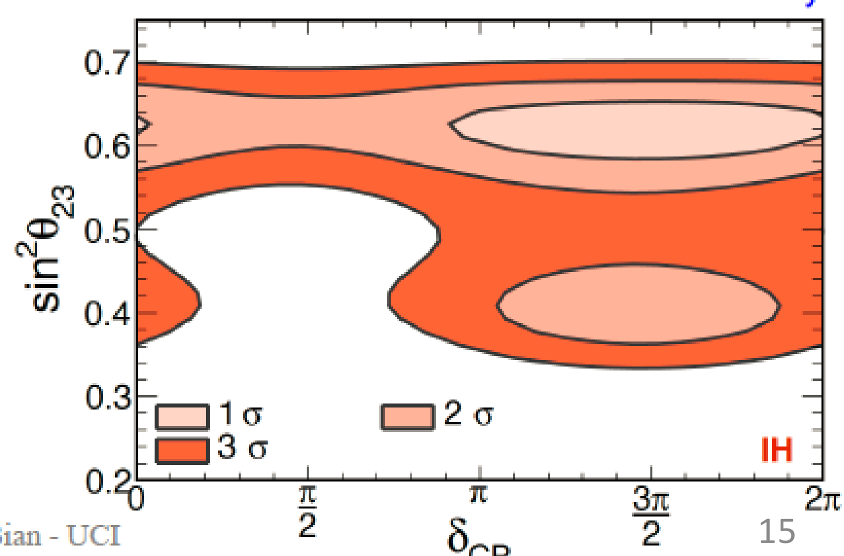


NOvA ν_μ results:

$\theta_{23}=45°$ rejected>2.5σ NOvA Preliminary

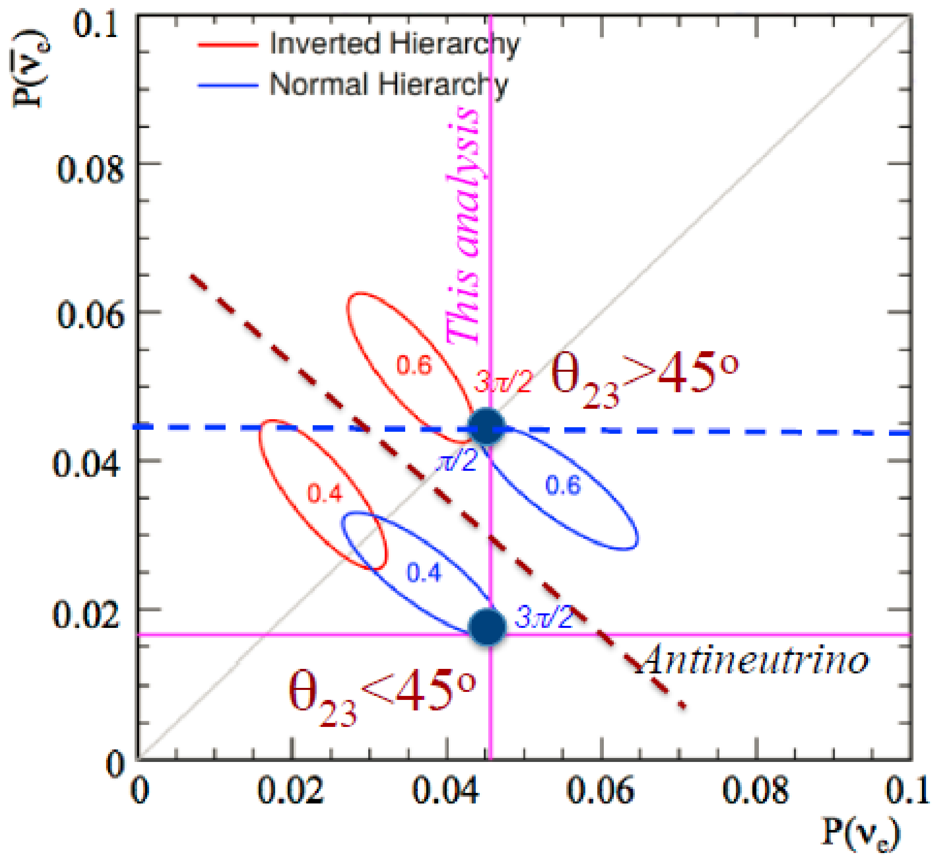


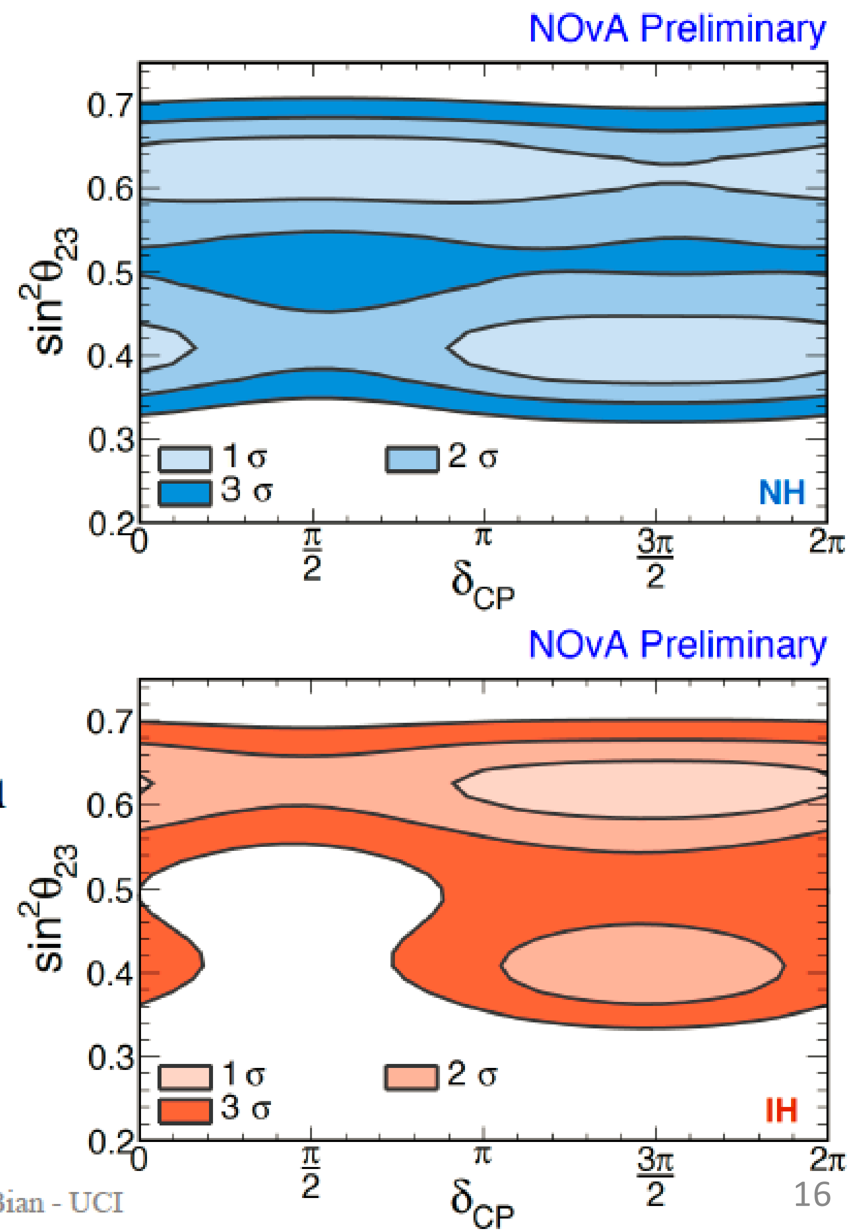
NOvA Preliminary



NOvA ν_e contours

J.M.Bian@ ICHEP



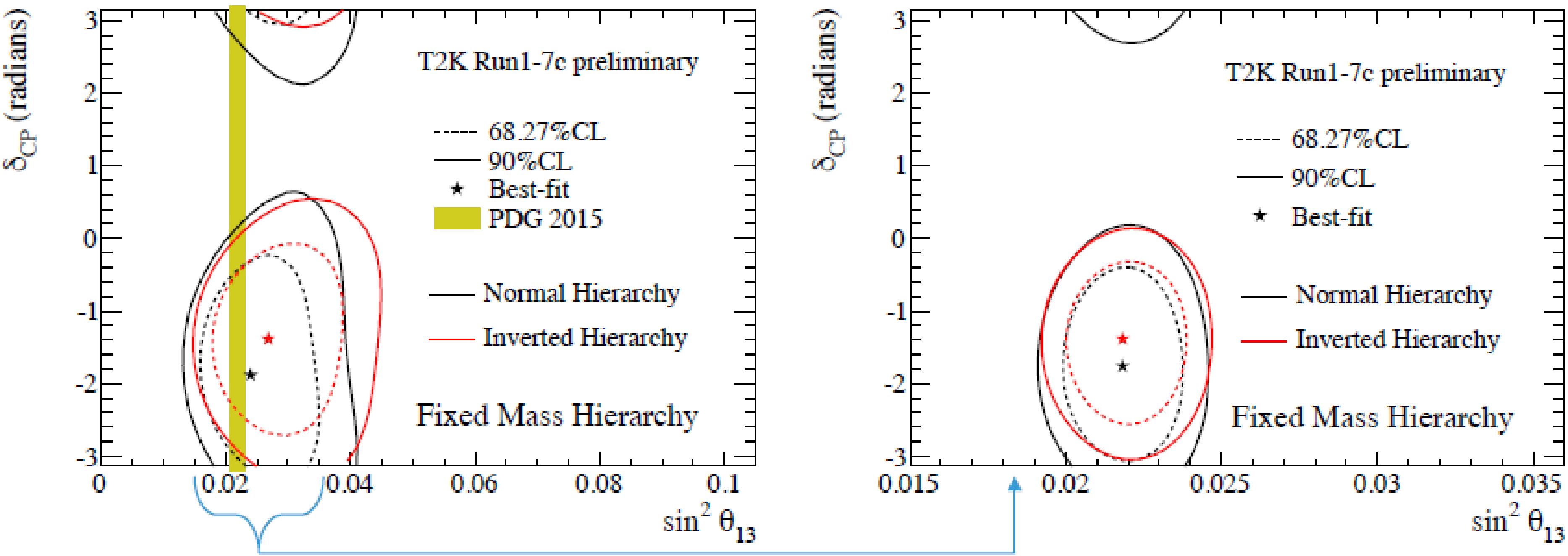


- Ambiguity caused by the octant of θ_{23}, antineutrino is crucial to solve MH
- Anti-ν_e rates for higher octant > 2x lower octant

θ_{13} & δ_{CP} @ T2K

T2K-Only

T2K Result with Reactor Constraint
$(sin^2 2\theta_{13} = 0.085 \pm 0.005)$

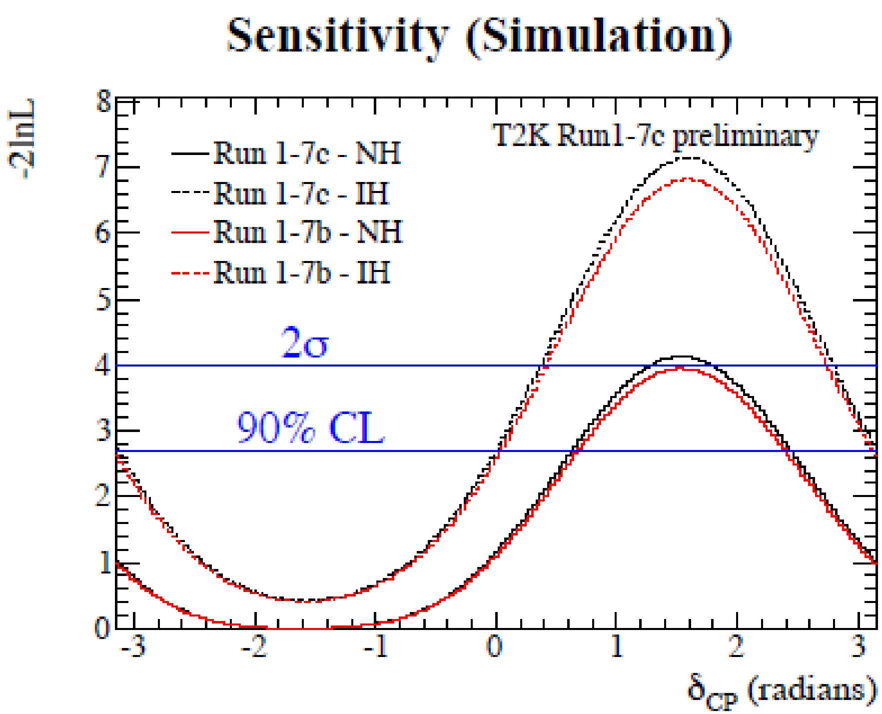


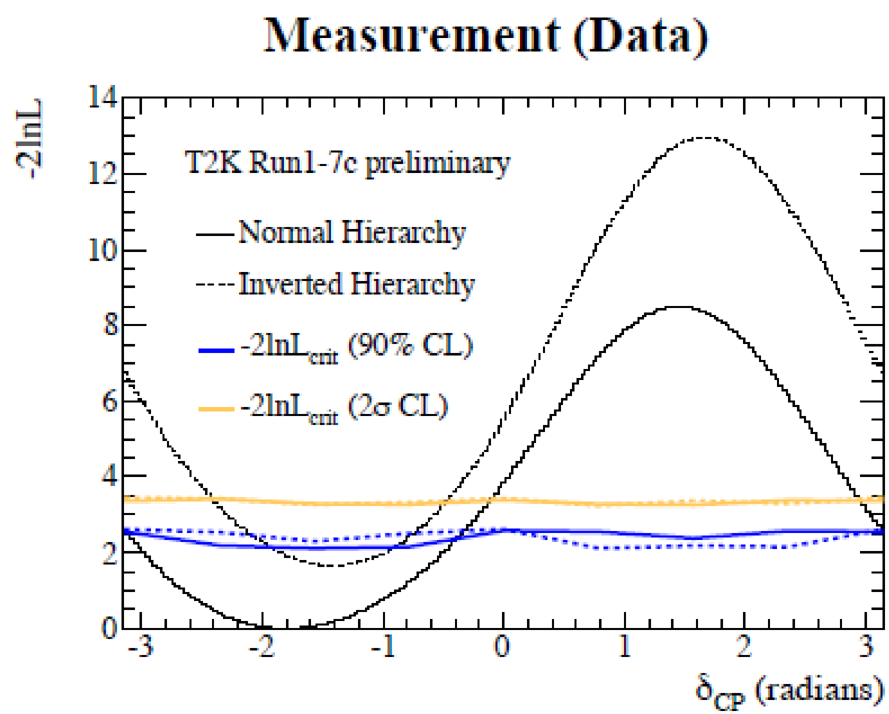
- T2K-only result consistent with the reactor measurement
- Favors the $\delta_{cp} \sim -\frac{\pi}{2}$ region

K. Iwamoto @ ICHEP

θ_{13} & δ_{CP} @ T2K

- T2K result with reactor constraint ($\sin^2 2\theta_{13} = 0.085 \pm 0.005$)

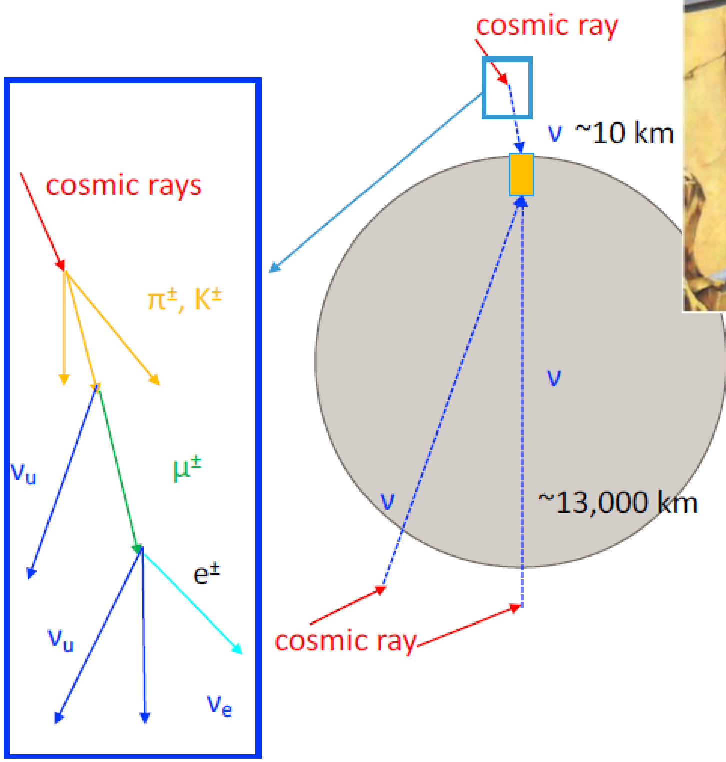


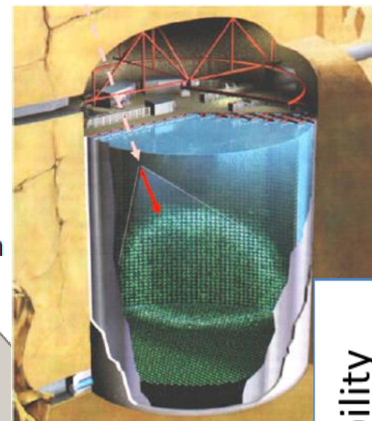


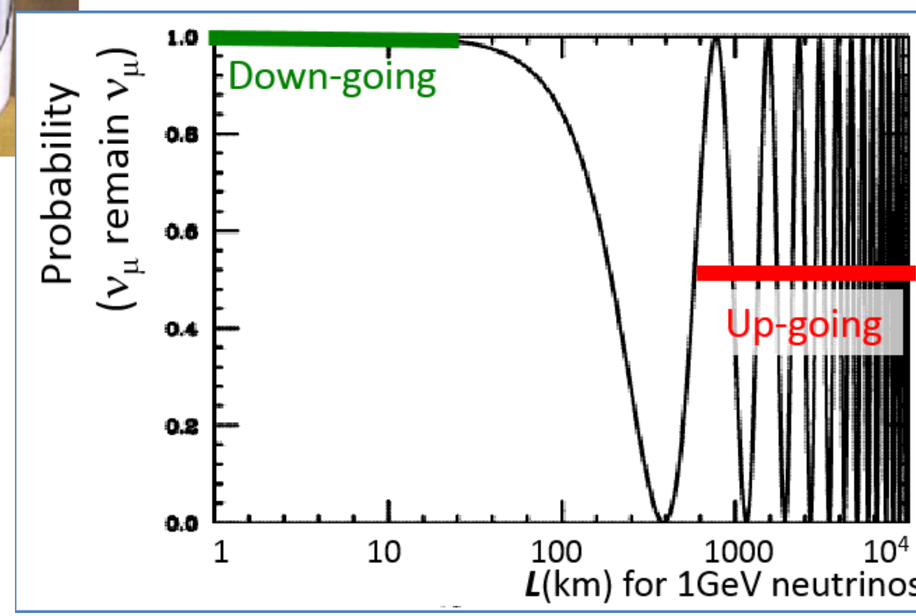
$$\delta_{cp} = [-3.13, -0.39](NH), [-2.09, -0.74]\ (IH) \text{ at } 90\% \text{ CL}$$

K. Iwamoto @ ICHEP

Atmospheric ν Results

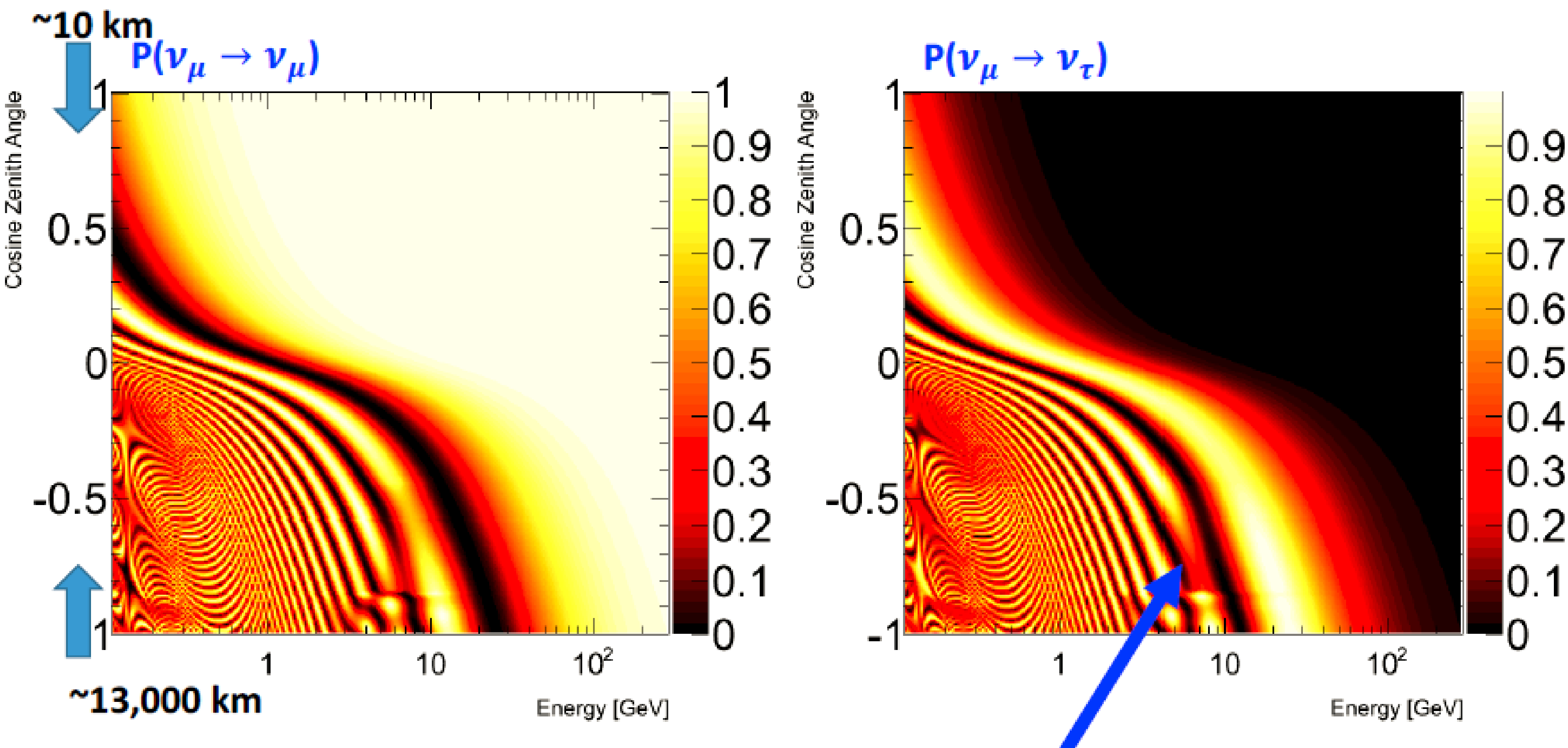






Ref. Zepeng Li @ICHEP2016

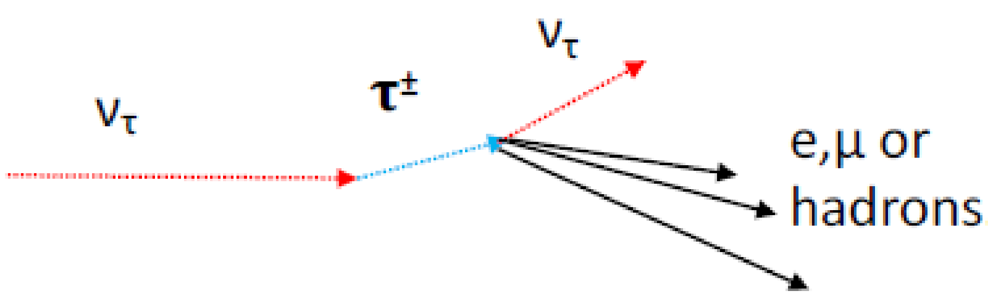
ν_τ appearance at SK

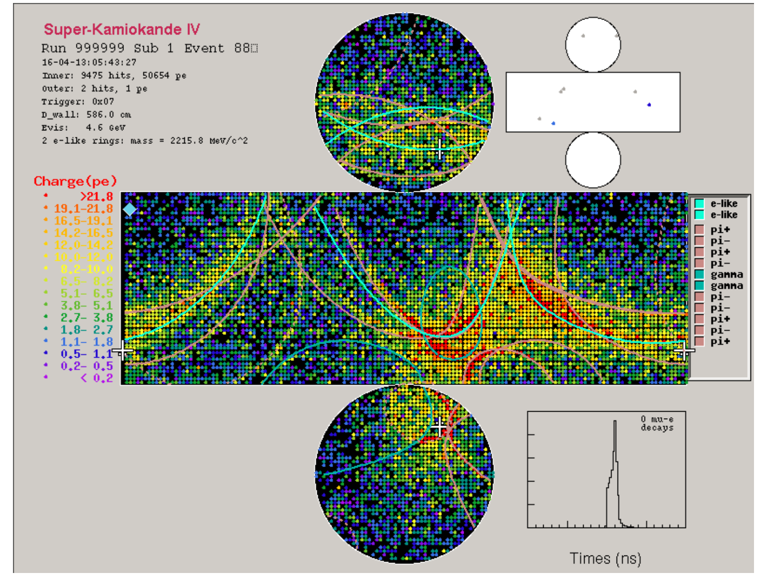


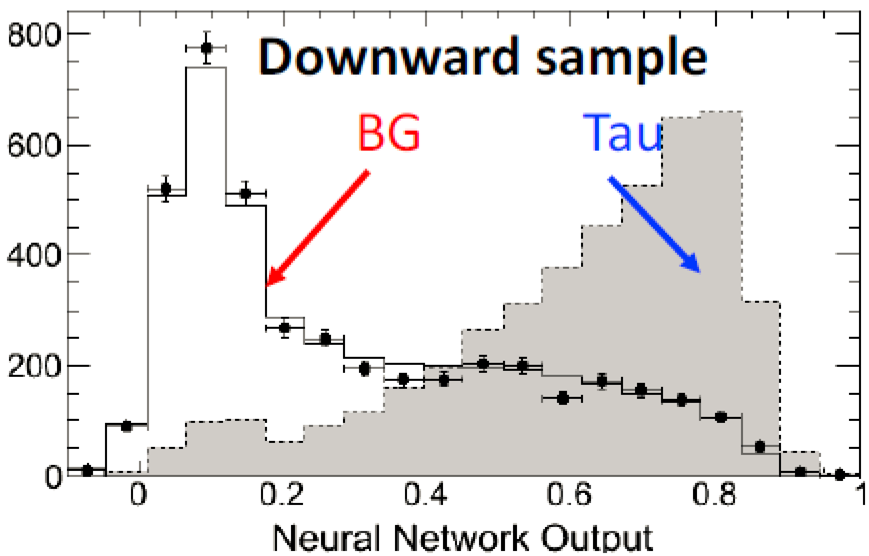
Leading effect is ν_μ disappearance($\nu_\mu \rightarrow \nu_\tau$).

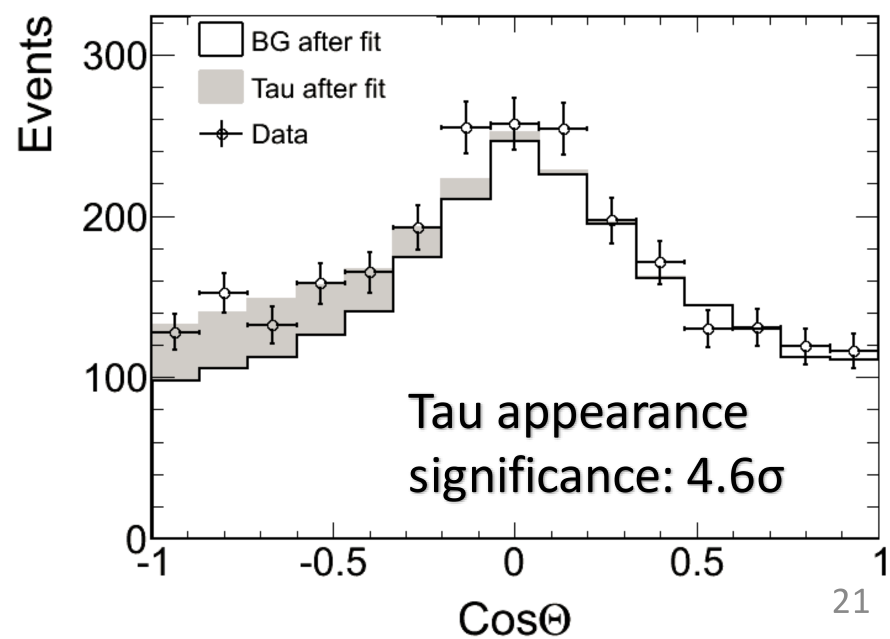
ν_τ appearance from neutrino oscillations could be detected by charged current ν_τ interaction in SK.

ν_τ appearance at SK

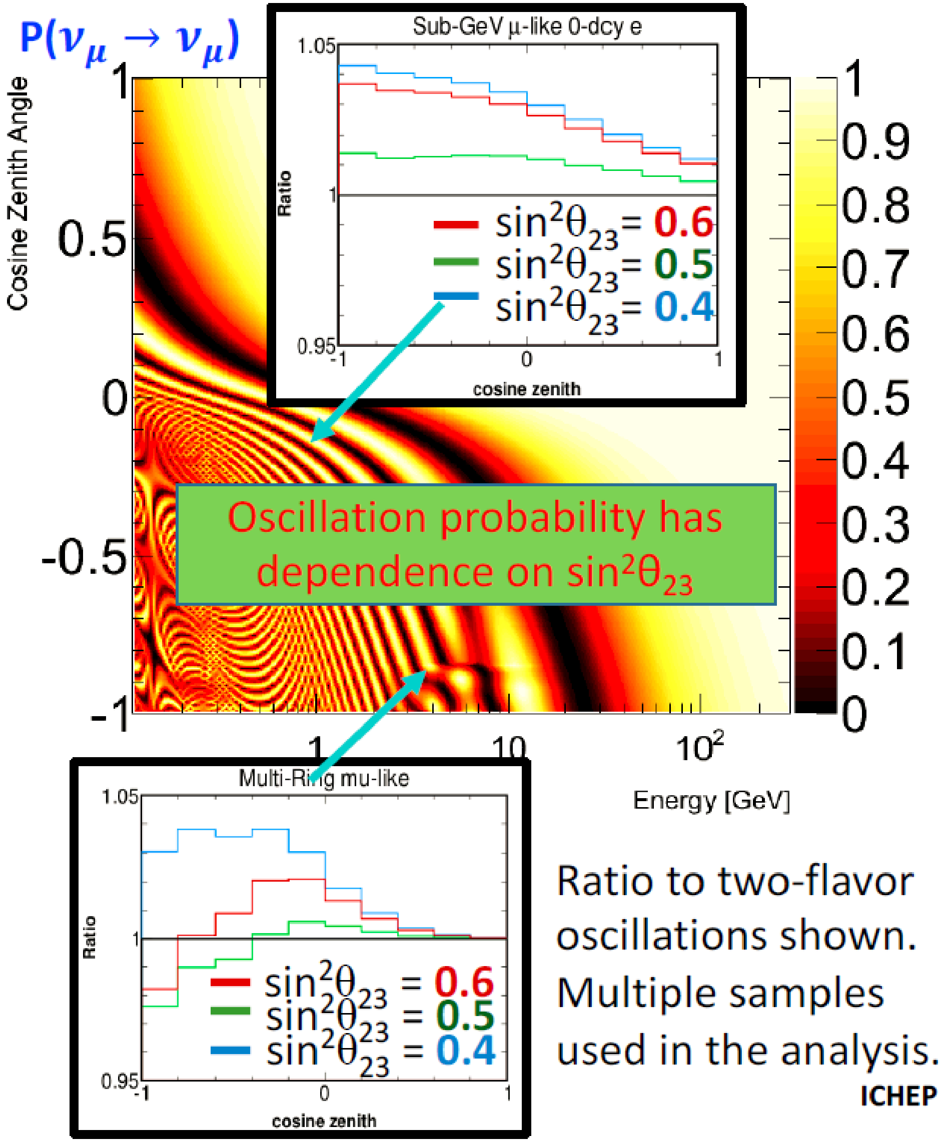


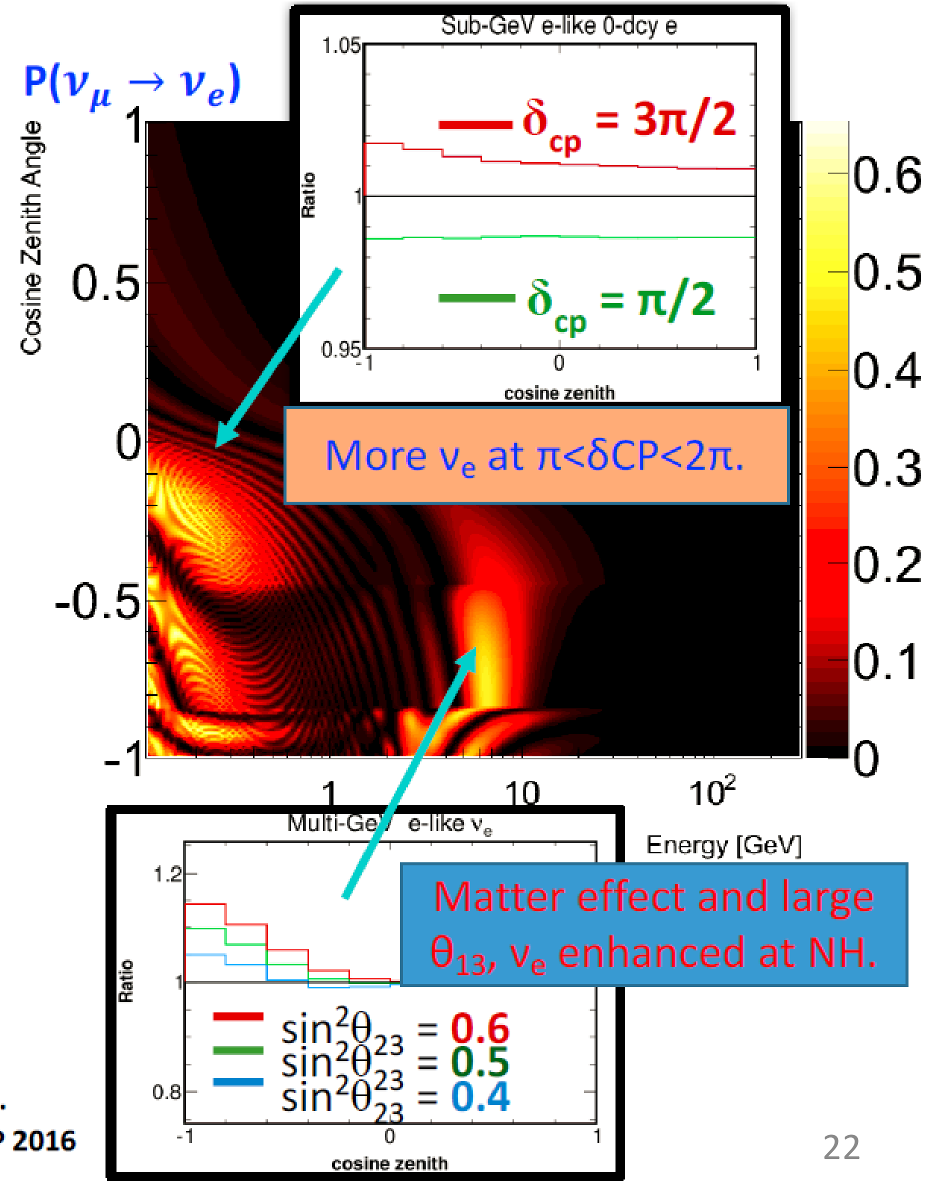






ν Oscillation at SK

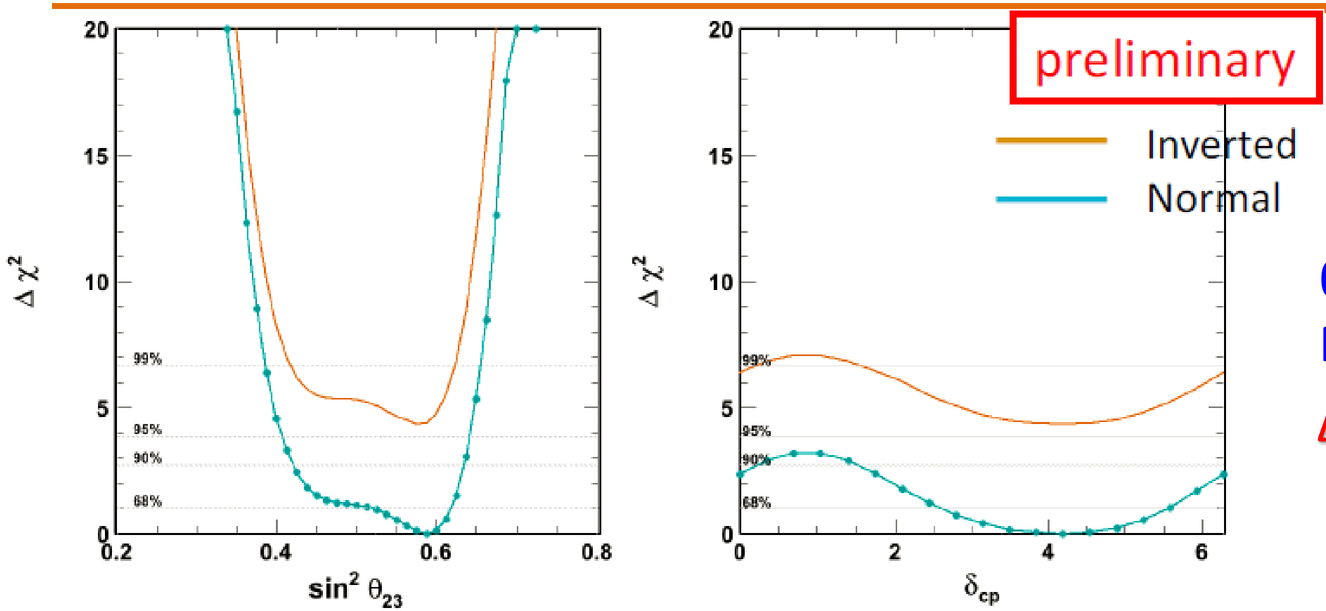




Ratio to two-flavor oscillations shown. Multiple samples used in the analysis.

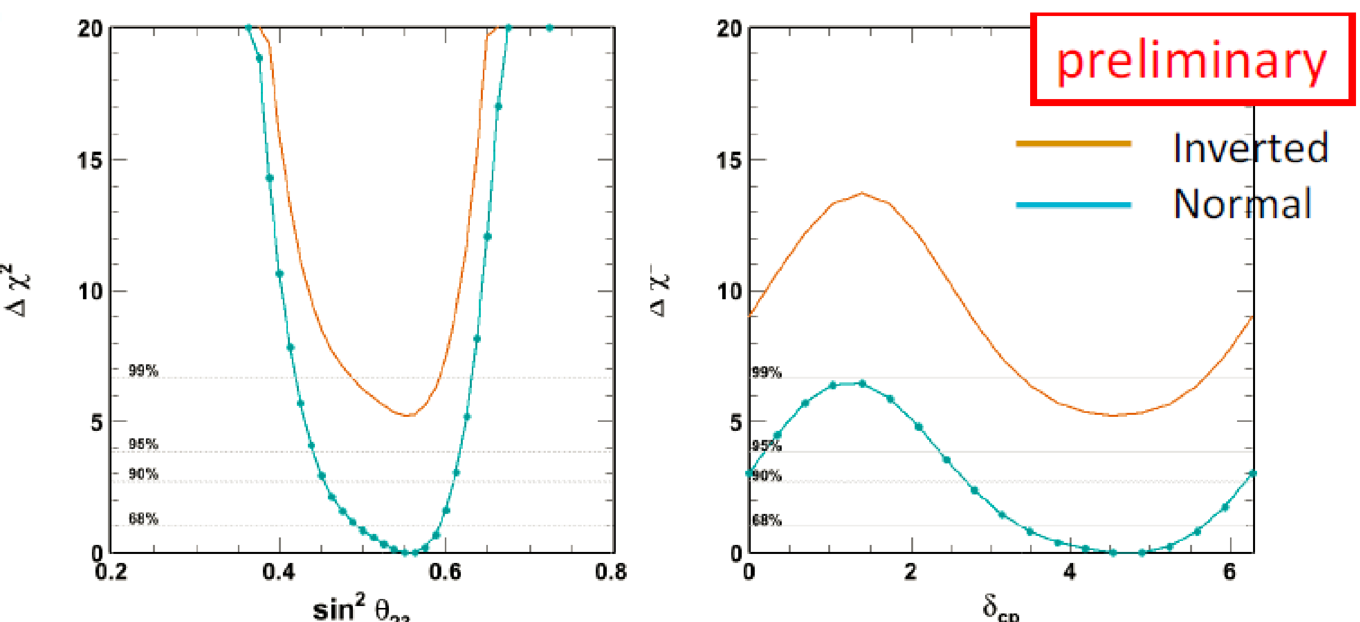
ICHEP 2016

SK Oscillation Analysis



θ_{13} is constrained at PDG average

$\Delta\chi 2 = \Delta\chi^2_{NH} - \Delta\chi^2_{IH} = -4.3$



With constraint from published T2K data

$\Delta\chi 2 = -5.2$

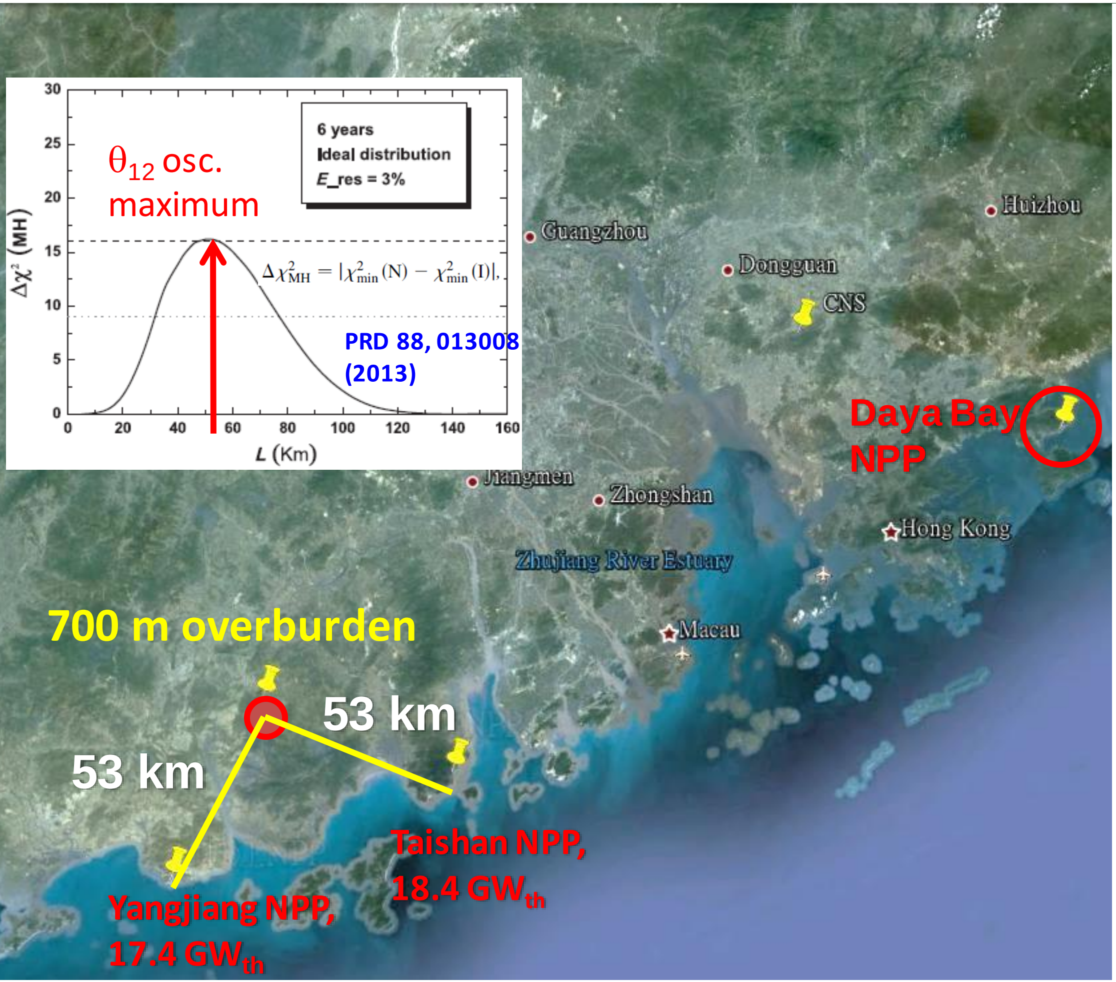
Weak preference of second octant and δ_{CP} near $3/2\pi$.

Jiangmen Underground Neutrino Observatory

JUNO Experiment

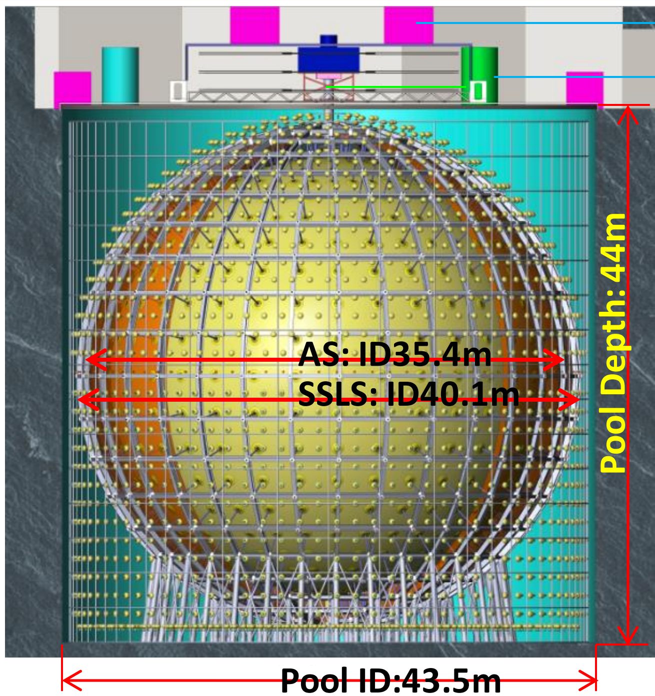
- Jiangmen Underground Neutrino Observatory
  - 20 kton LS detector, 3%/$\sqrt{E}$ energy resolution
- A multiple-purpose neutrino experiment

J. Phys. G 43: 030401 (2016)
(arXiv:1507.05613)

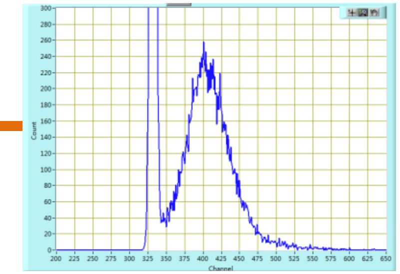


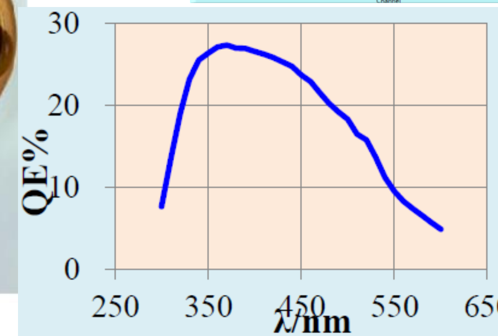
- Rich Physics
  - Reactor neutrinos: Mass hierarchy & Precision measurement of mixing parameters
  - Supernova neutrinos
  - Geo-neutrinos
  - Solar neutrinos
  - Sterile neutrinos
  - Atmospheric neutrinos
  - Exotic searches

JUNO Experiment

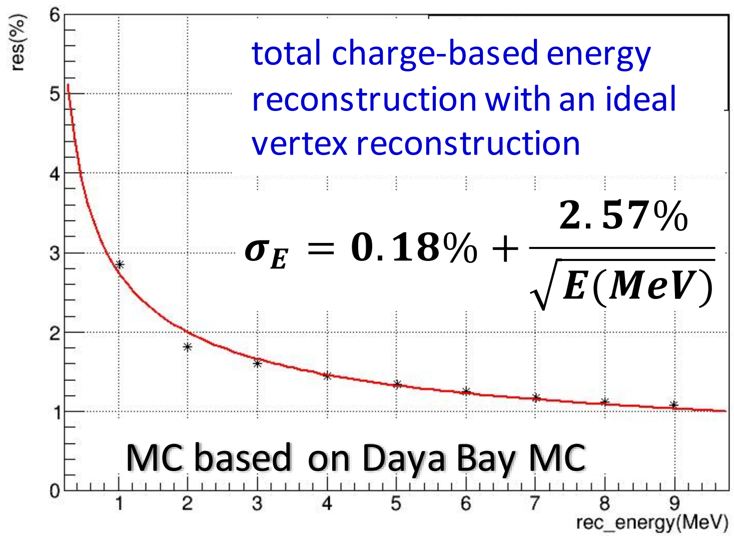


MCP 20” (NNVT)

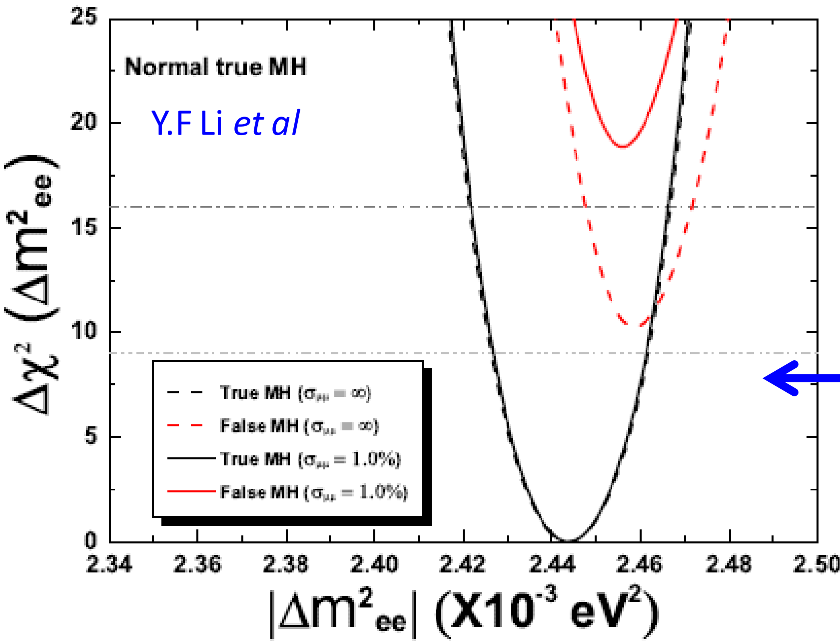




Type	8″	20″
	Typ.	Typ.
Photocathode characteristics		
Spectral Range(nm)	300-650	300-650
Maximum sensitivity at (nm)	380	380
Sensitivity		
Luminous(μA/lm)	70	60
QE at 420nm(%)	26	26
Supply Voltage(V)	-1700	-1600
Gain	1×10^7	1×10^7
Anode Dark Current(nA)	100	150
Background Noise(cps)	5 K	30 K
Single Electron Spectrum		
Energy Resolution(%)	60	40
Peak to Valley Ratio	2.5	3.5
Anode Pulse		
Rise Time(ns)	1.7	1.7
Duration at half height(ns)	8.8	8.8

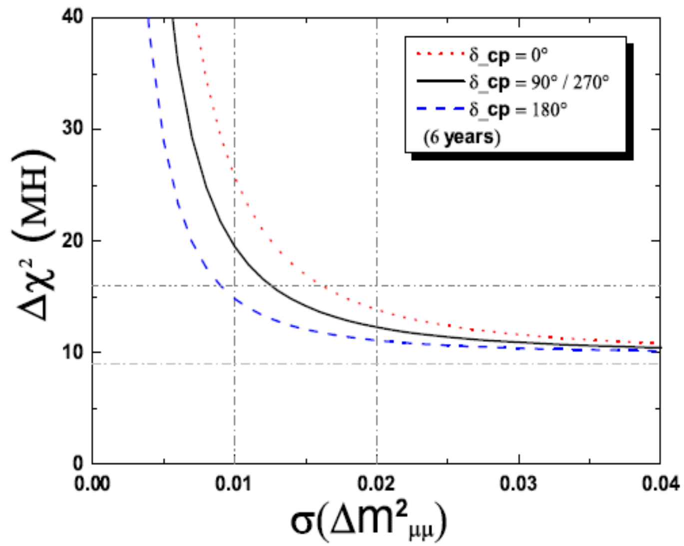


Sensitivity on MH



JUNO MH sensitivity with 6 years' data:

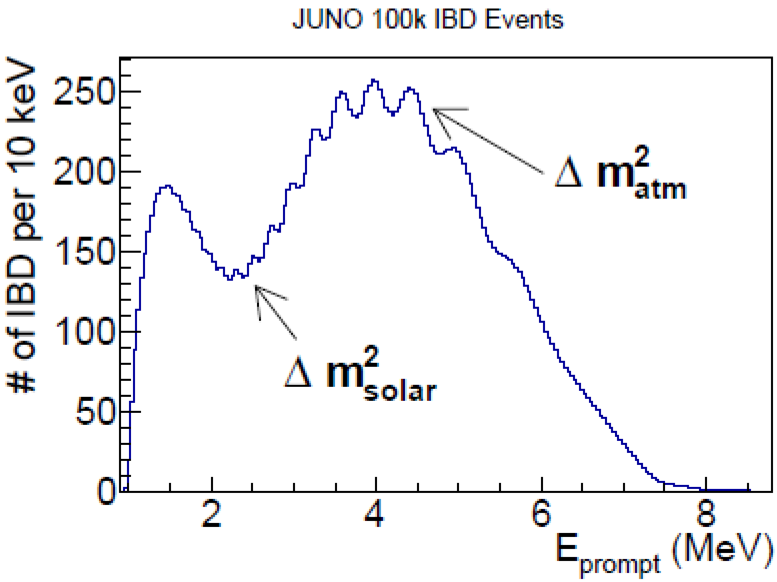
Ref: Y.F Li et al, PRD 88, 013008 (2013)	Relative Meas.	[(a)]Use absolute Δm^2
Ideal case	4σ	5σ
[(b)]Realistic case	3σ	4σ



[(a)] If accelerator experiments, e.g NOvA, T2K, can measure $\Delta M^2_{\mu\mu}$ to ~1% level
[(b)] Take into account multiple reactor cores, uncertainties from energy non-linearity, etc

	Ideal	Core distr.	DYB & HZ	Shape	B/S (stat.)	B/S (shape)	$|\Delta m^2_{\mu\mu}|$
Size	52.5 km	Real	Real	1%	6.3%	0.4%	1%
$\Delta\chi^2_{MH}$	+16	- 3	-1	- 1	- 0.6	- 0.1	+ (4-12)

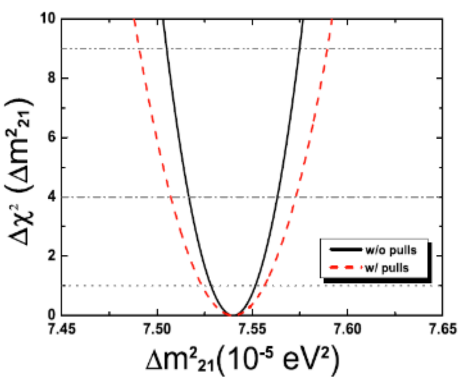
Precision Measurement



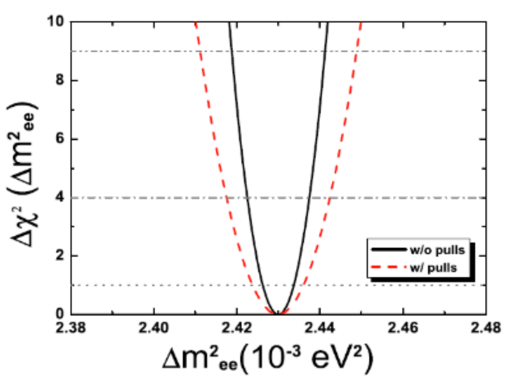
Probing the unitarity of U_{PMNS} to ~1%

more precise than CKM matrix elements !

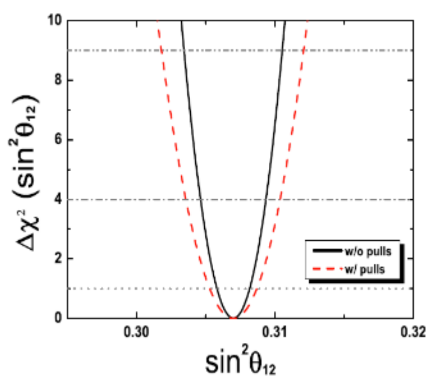
	Statistics	**+BG +1% b2b +1% EScale +1% EnonL**
$\sin^2\theta_{12}$	0.54%	0.67%
Δm^2_{21}	0.24%	0.59%
Δm^2_{ee}	0.27%	0.44%



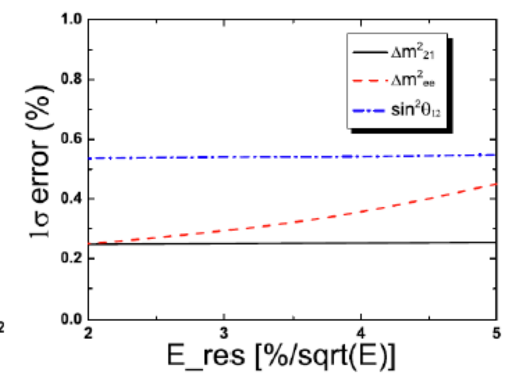
0.16%→0.24%



0.16%→0.27%



0.39%→0.54%

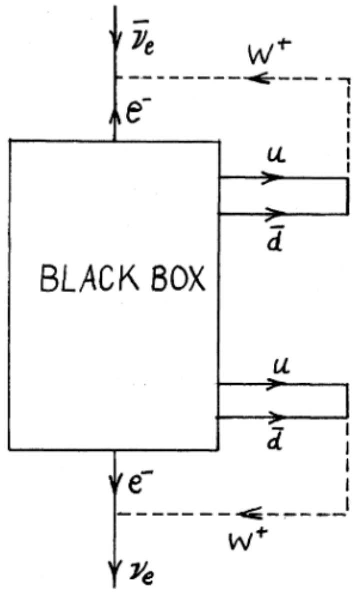


E resolution

Correlation among parameters

Probe the nature of ν's mass

0νββ Decay

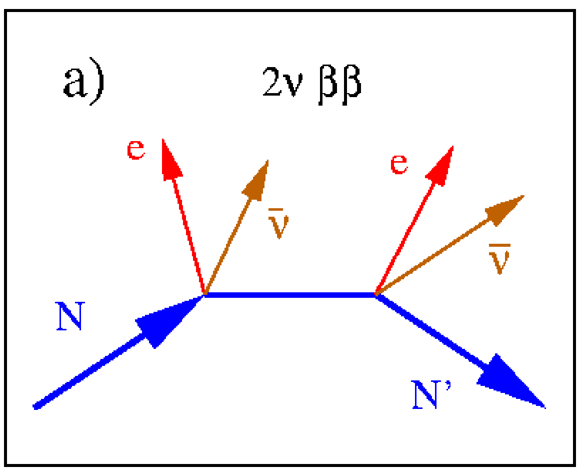


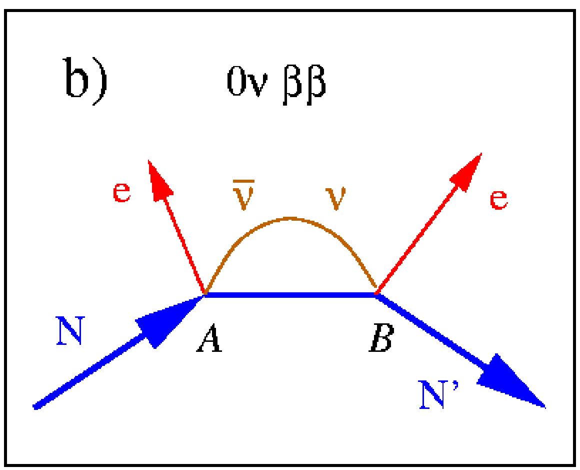
Schechter-Valle Theorem (1982) : if a 0νββ decay happens, there must be an effective Majorana mass term (ν is of Majorana nature)

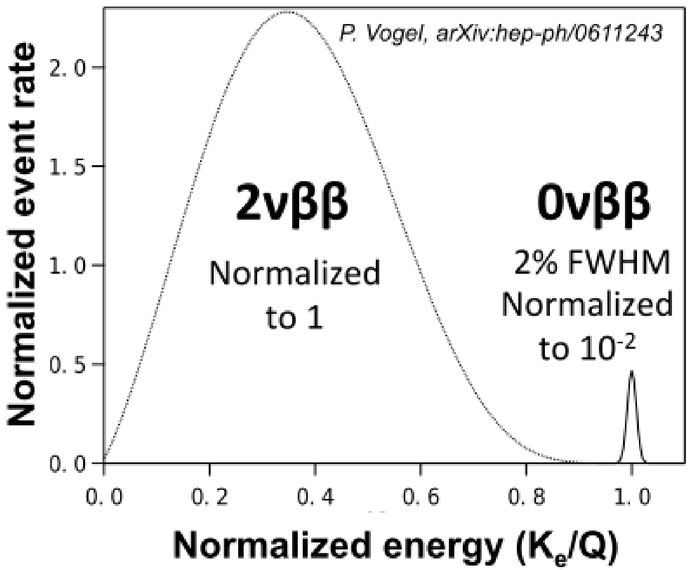
Keys:

Good energy resolution & ultra-low external background

Large detector volume







Recent results (>10^{25} yr half life)

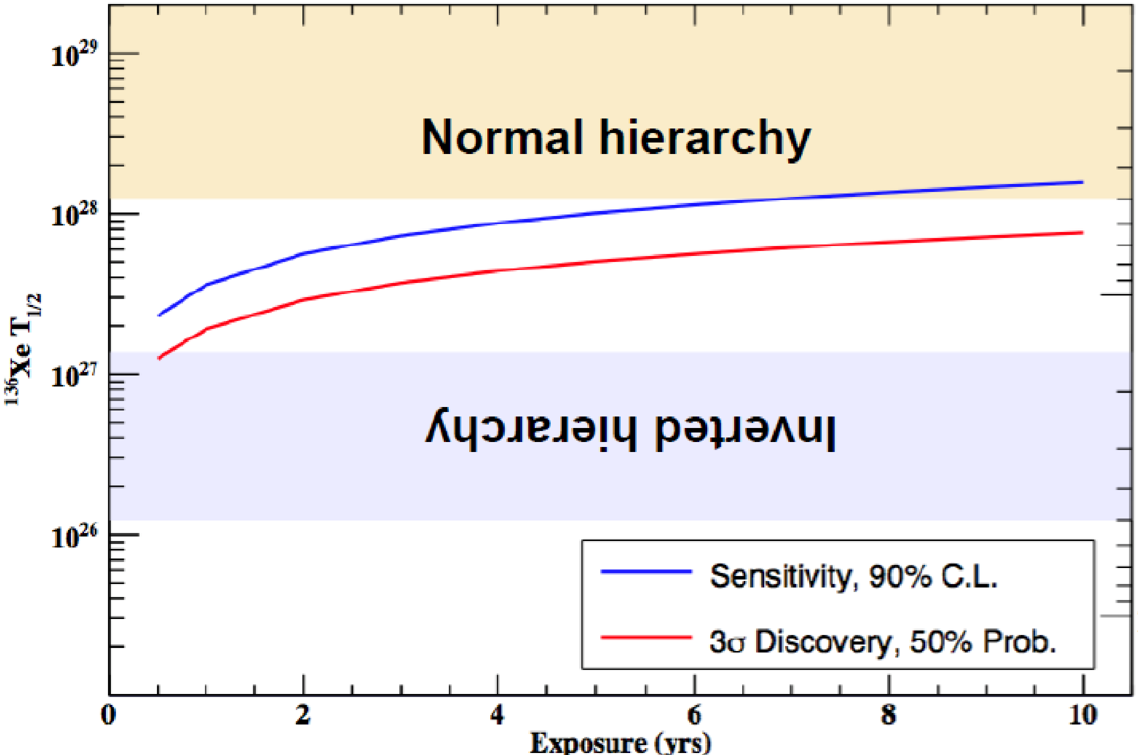
Isotope	Experiment	Exposure (kg yr)	$T_{1/2}^{0\nu\beta\beta}$ average sensitivity (10^{25}yr)	$T_{1/2}^{0\nu\beta\beta}$ (10^{25}yr) 90%CL	$T_{1/2}^{0\nu\beta\beta}$ (13.8Gyr) 90%CL	$< m_\nu >$ (meV) Range from NME*	Reference
^{76}Ge	Gerda	34.36	4.0	>5.2	>3.7×10^{15}	160-260	M.Agostini, Neutrino 2016
^{136}Xe	EXO-200	100	1.9	>1.1	>8.0×10^{14}	190-450	Albert et al. Nature 510 (2014) 229
	KamLAND-ZEN	504**	4.9	>11 (run 2)	>8.0×10^{15}	60-161	Gando et al., arXiv:1605.02889 (2016)

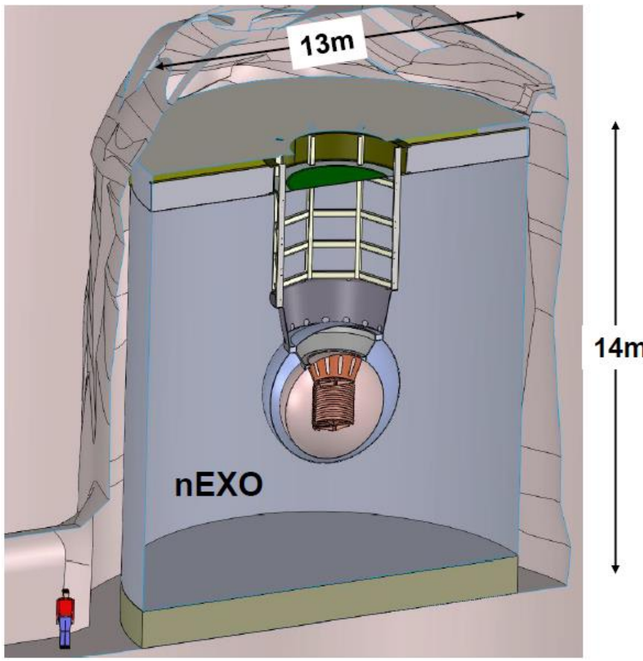
* Note that the range of "viable" NME is chosen by the experiments and uncertainties related to g_A are not included

** All Xe. Fiducial Xe is more like ~150 kg yr

G. Gratta @ ICHEP2016

nEXO





GCM: Rodriguez, Martinez-Pinedo,
Phys. Rev. Lett. 105 (2010) 252503

- ~ 5 tonne LXe TPC, 4.7 tonnes of active ^{enr}Xe (90% or higher)
- < 1.0% (σ/E) energy resolution

Thanks!