Precision Measurement of Neutrino Oscillation Parameters in JUNO

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On behalf of the JUNO collaboration

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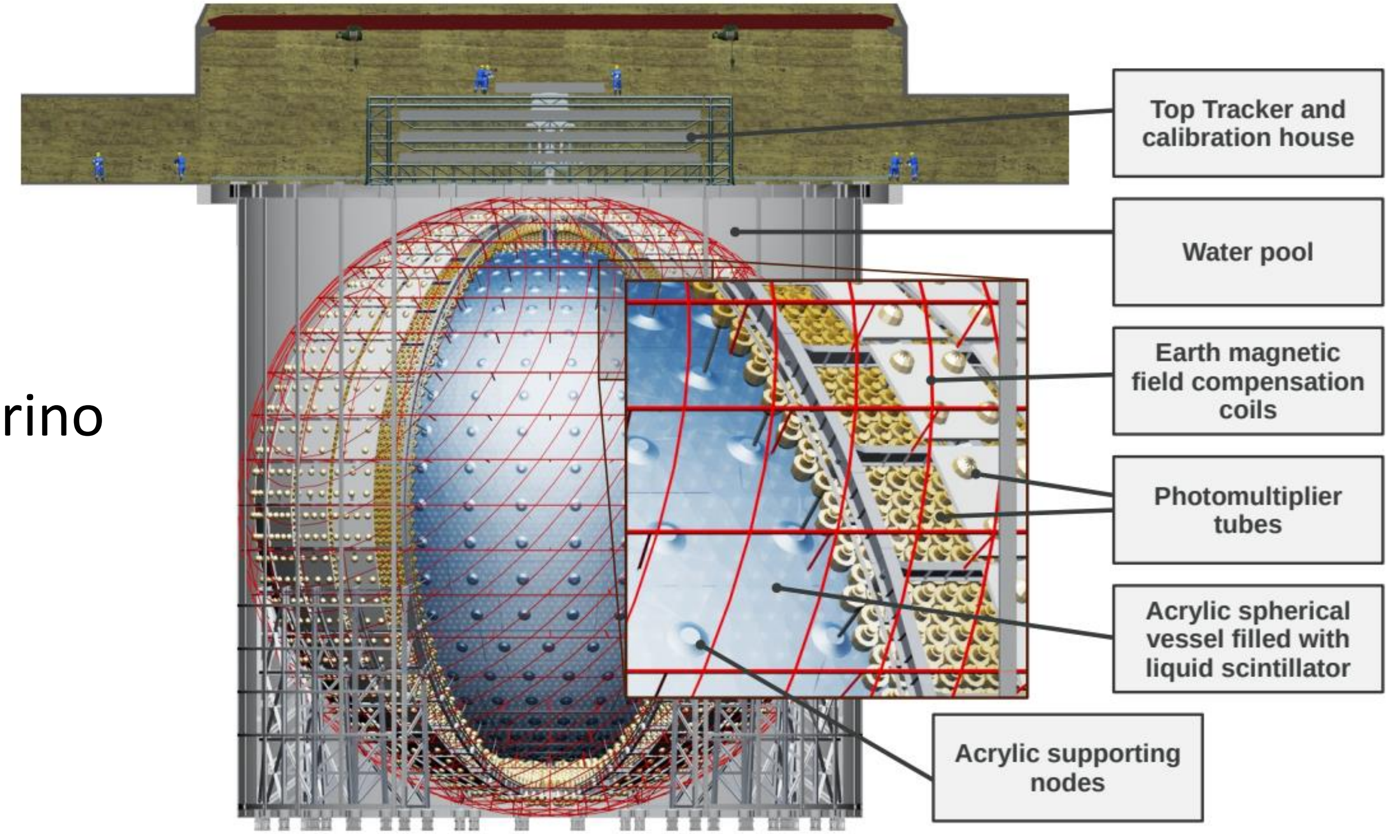
Outline

- JUNO introduction
- Neutrino oscillation parameters measurement with JUNO
- Reactor neutrino spectrum caculation
- Analysis and results
- Conclusion

JUNO experiment

- **J**iangmen **U**nderground **N**eutrino **O**bservatory
- 20k ton liquid scintillator
- ~18k 20' PMT, 26k 3' PMT
- Energy resolution <3%@1MeV



Scientific Goals:

- Neutrino mass ordering
- Precision measurement of neutrino oscillation parameters
- Supernova neutrino
- Atmospheric neutrino
- Solar neutrino
- Proton decay

……

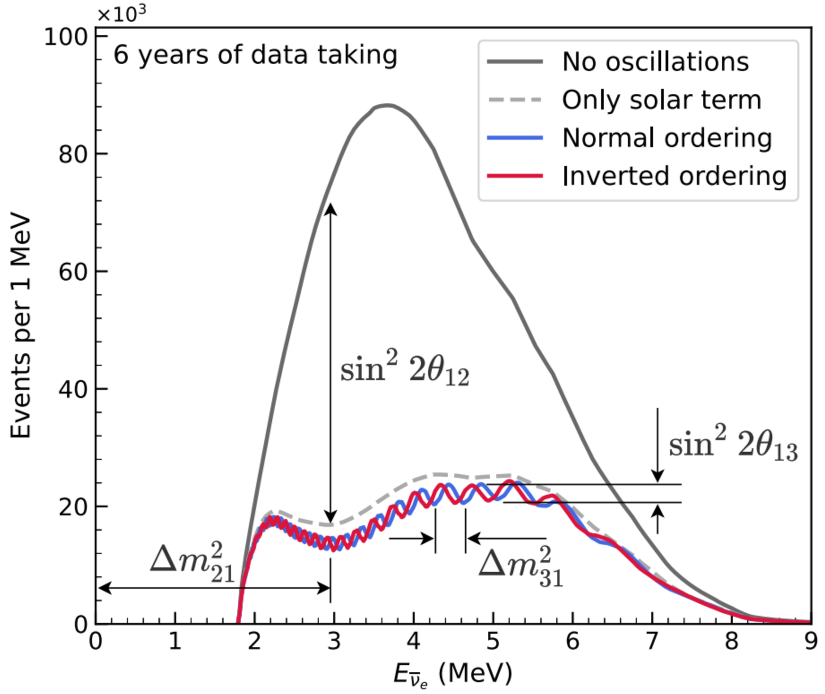
Reactor Neutrino Oscillation

Reactor anti-neutrino survival probabilities:

$$\Delta_{ij} \equiv \Delta m^2_{ij} L/(4E)$$

$$\mathcal{P}(\overline{\nu}_e \to \overline{\nu}_e) = 1 - \sin^2 2\theta_{12}\, c^4_{13} \sin^2 \Delta_{21} - \sin^2 2\theta_{13} (c^2_{12} \sin^2 \Delta_{31} + s^2_{12} \sin^2 \Delta_{32})$$

Slow component (solar oscillation mode) Fast component (atmospheric oscillation mode)

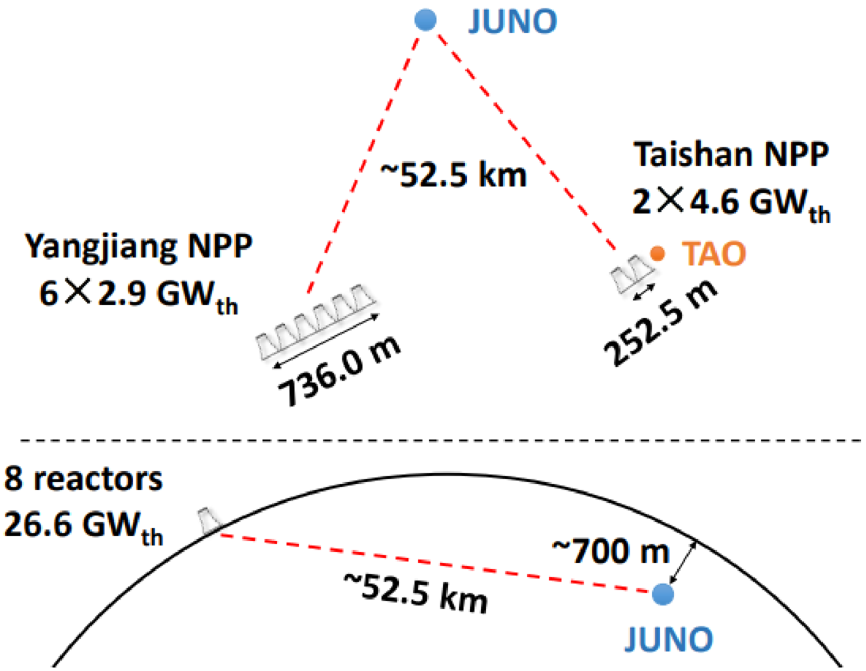


- Special location and high energy resolution give JUNO opportunity be the first experiment to observe two modes of neutrino oscillations simultaneously with reactor neutrino
- JUNO can measure $\sin^2\theta_{12}$, Δm^2_{21}, $\sin^2\theta_{13}$ and Δm^2_{31} at the same time!

Neutrino flux and oscillation

- Target neutrino signals mainly from 8 reactors ~52.5 km away from JUNO site, total 26.6 GW

Reactors	YJ-1	YJ-2	YJ-3	YJ-4	YJ-5	YJ-6	TS-1	TS-2	DYB	HZ
Power(GW)	2.9	2.9	2.9	2.9	2.9	2.9	4.6	4.6	17.4	17.4
Baseline(km)	52.74	52.82	52.41	52.49	52.11	52.19	52.77	52.64	215	265



- Neutrino flux calculation based on Huber-Mueller model and Daya Bay experimental observation correction on the spectral distortion in the ~[4, 6] MeV region:

$$\phi_r(E_r, t) = \frac{W_r(t)}{\sum_i f_{ir}(t) e_i} \sum_i f_{ir}(t) S_i(E_\nu)$$

$$S_0(E_\nu, t) = \sum_r \frac{P_{ee}(E_\nu, L_r)}{4\pi L_r^2} \phi_r(E_r, t) \cdot \mathrm{F}(E_\nu)$$

Considering the matter effects in neutrino oscillation $P_{ee}(E_\nu, L_r)$, The mixing parameters in the formula need to corrected to effective mixing parameters.

Detector response

Neutron recoil

⇩

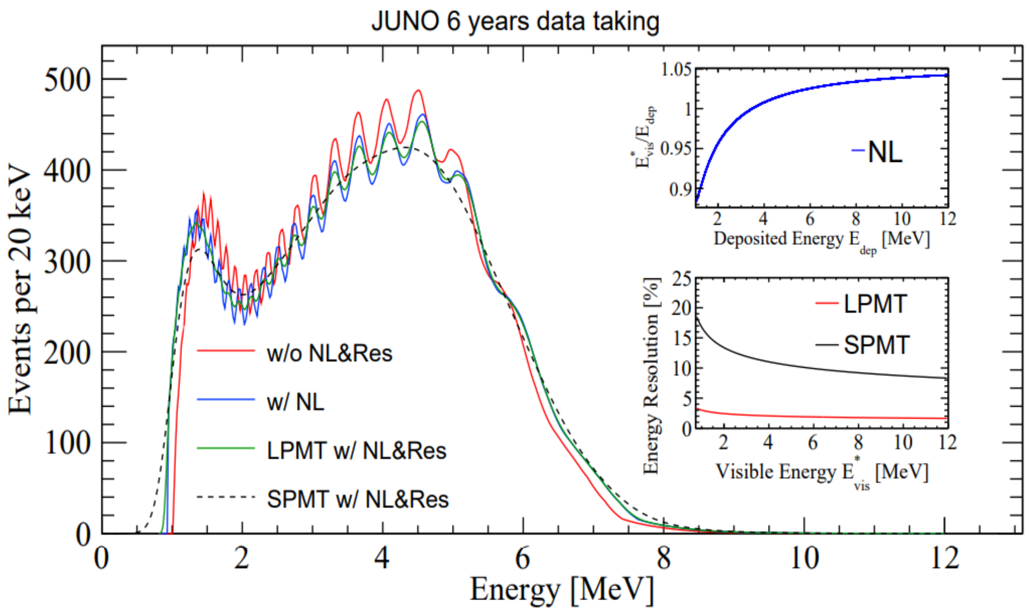
Energy non-linearity

⇩

Energy resolution

Energy model: $$\frac{\sigma_{E_{\mathrm{vis}}}}{E_{\mathrm{vis}}} = \sqrt{\left(\frac{a}{\sqrt{E_{\mathrm{vis}}}}\right)^2 + b^2 + \left(\frac{c}{E_{\mathrm{vis}}}\right)^2}$$

- Neutron recoil
  - Using average transfer energy of neutron recoil is used
- Energy non-linearity
  - Liquid flash nonlinearities based on Daya Bay experiment: 1 expected line +4 PULL nonlinearities that can contain all possibilities
- Energy resolution
  - The LPMT system uses the values of the JUNO calibration paper: A =2.61%, B =0.82%, C =1.23%



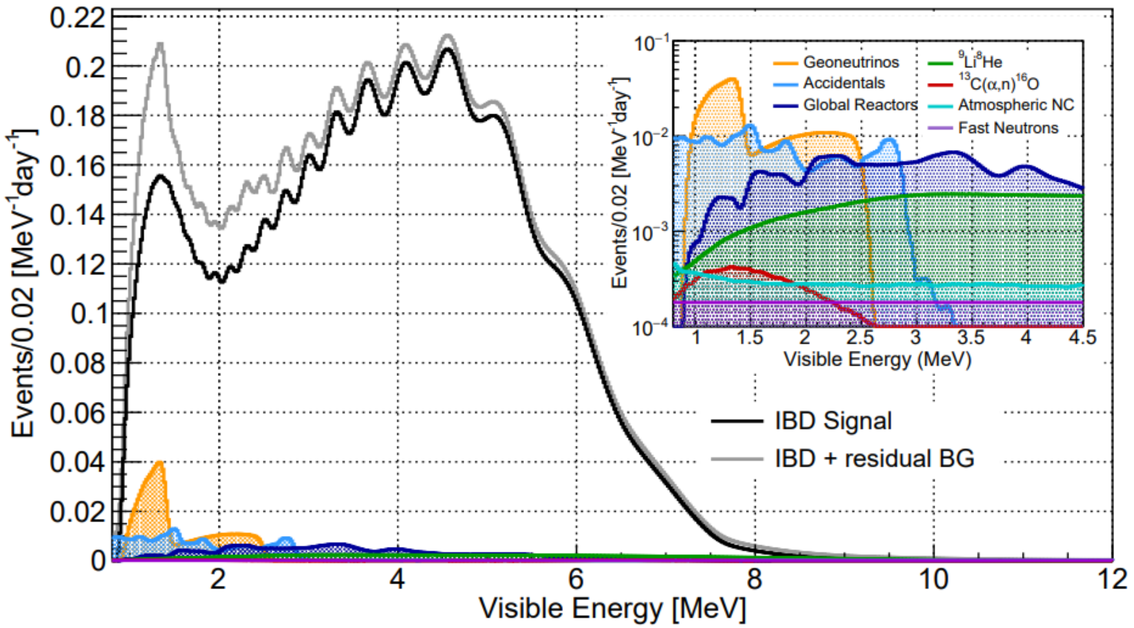
Signals and backgrounds

- IBD signals

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

Prompt: e^+ Delayed: n captured by p

- Background signal sources:
  - Accidental background
  - $^{9}Li/^{8}He$
  - Fast neutron
  - $^{13}C\ (\alpha,\ n)\ ^{16}O$
  - Geo-neutrino
- Various selection criteria are designed to suppress the
  - Fiducial Volume cut
  - IBD selection(Energy range, Time correlation, spatia correlation)
  - Muon Veto



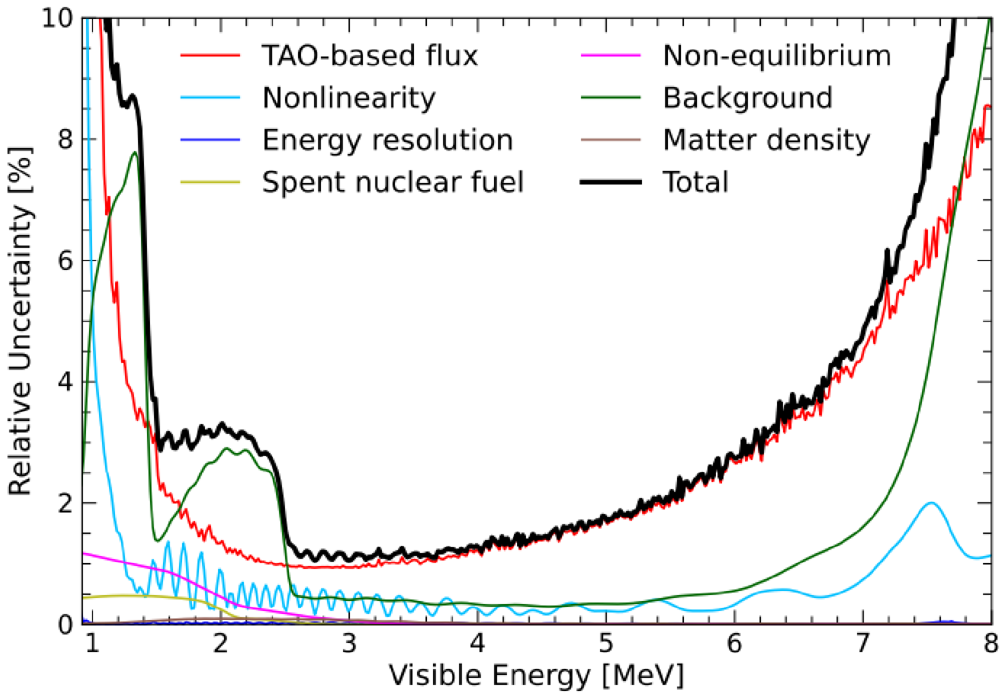
Selection	IBD efficiency (%)	IBD	Geo-vs	Accidental	$^{9}Li\ ^{8}He$	Fast n	(α, n)
-	-	57.4	1.5	$\sim 2.2 \times 10^4$	71	-	-
Fiducia volumel	91.5						
Energy cut	99.83	51.5	1.3	0.66			
Time cut	99.02					0.1	0.05
Vertex cut	99.16						
Muon veto	91.6	47.1	**1.2**	**0.8**	**1.4**		
Combined	82.2	**47.1**	**3.55**				

Systematic uncertainty sources

Summarize of rate systematic effects and their corresponding uncertainties

Component	Input Uncertainty (%)
Flux	2.2
Baseline (L)	-
Energy per Fission	0.2
Thermal Power (P)	0.5
Fission Fraction	0.6
Mean Cross-Section per Fission	2.0
Detection	1.0
Fiducial volume (2 cm vertex bias)	0.4
IBD Selection cuts	0.2
Muon Veto	-
Proton Number	0.9
Backgrounds	1.0
Geoneutrinos	0.8
^{9}Li/^{8}He	0.4
Atmospheric neutrinos	0.2
Fast neutrons	0.2
^{13}C(α,n)^{16}O	0.1
Accidentals	$<$0.1
World reactors	$<$0.1

Relative shape uncertainties, obtained by generating toy MC samples.



The main contributions are reactor antineutrino spectrum and background systematics uncertainties

Neutrino Oscillation Analysis

- Comparison of nominal spectrum against model based on the standard parametrization

$$\chi^2 \equiv (\boldsymbol{M} - \boldsymbol{T}(\boldsymbol{\theta}, \boldsymbol{\alpha}))^T \cdot \boldsymbol{V}^{-1} \cdot (\boldsymbol{M} - \boldsymbol{T}(\boldsymbol{\theta}, \boldsymbol{\alpha})) + \sum_i \left(\frac{\alpha_i}{\sigma_i}\right)^2$$

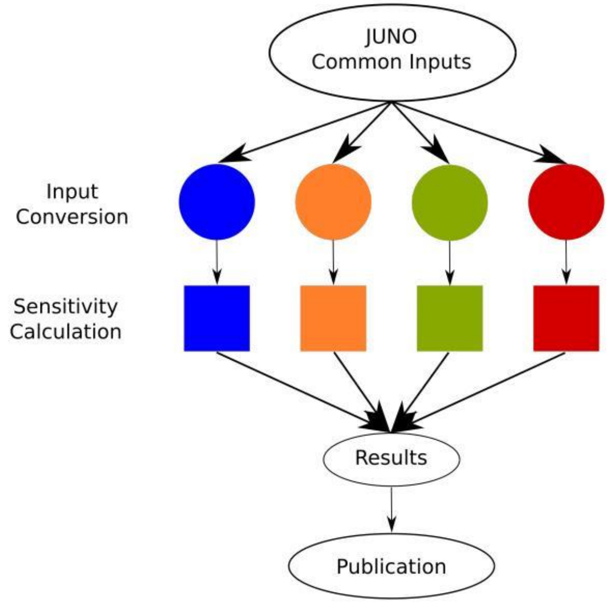
Covariance matrix can substitute Pull terms (systematics) and vice-versa

4 analysis teams:

- Chuanya
- Jinnan
- Rebin / Thiago
- Diana / Yury

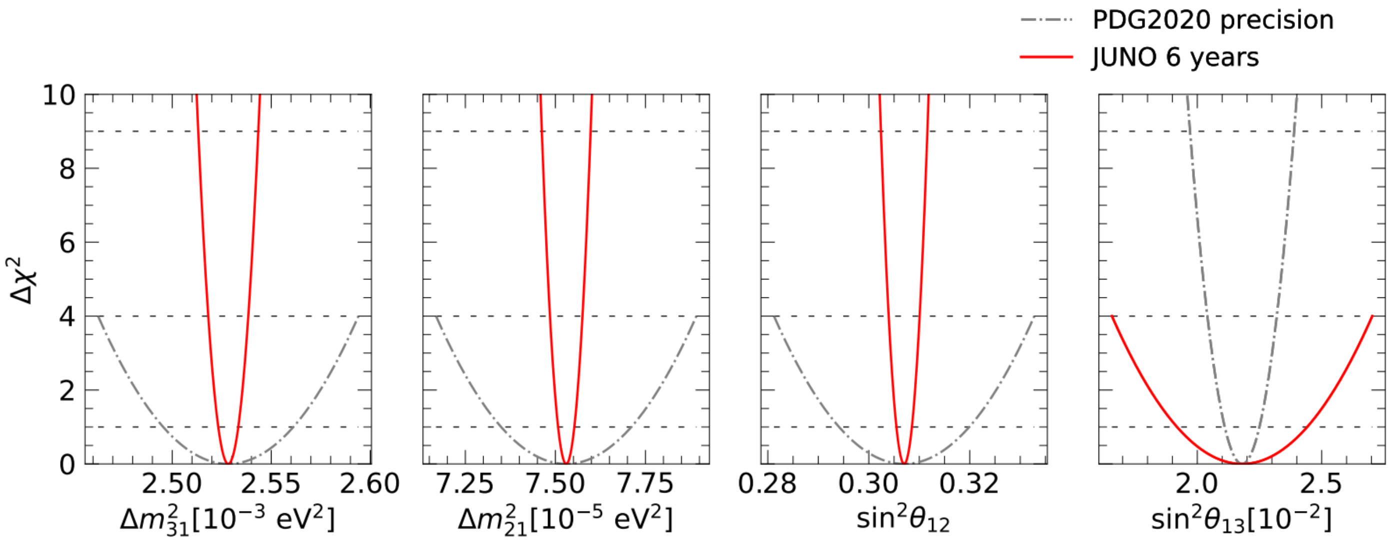
All analyses employ the least square method and follow a frequentist χ^2 approach

- with pull terms: Chuanya, Jinnan
- with covariance matrices: Rebin/Thiago, Diana/Yury



Four sub-groups working independently with excellent agreement achieved!

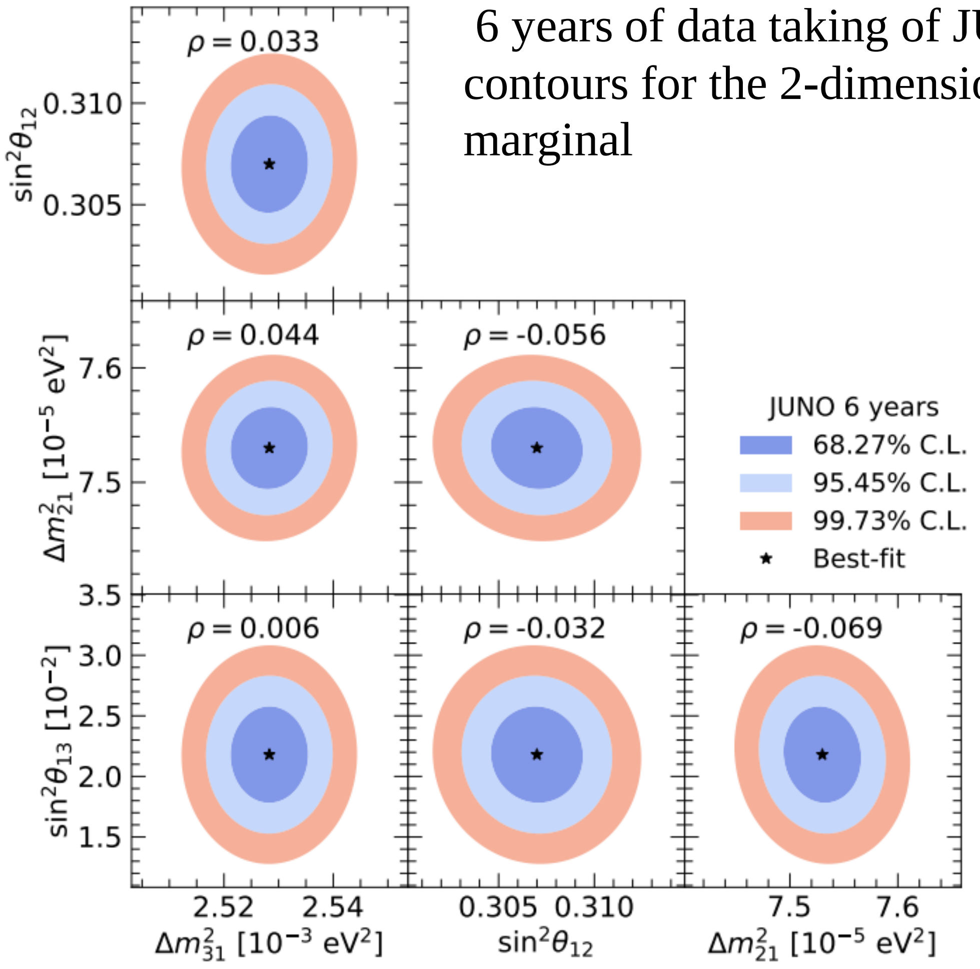
Analysis results



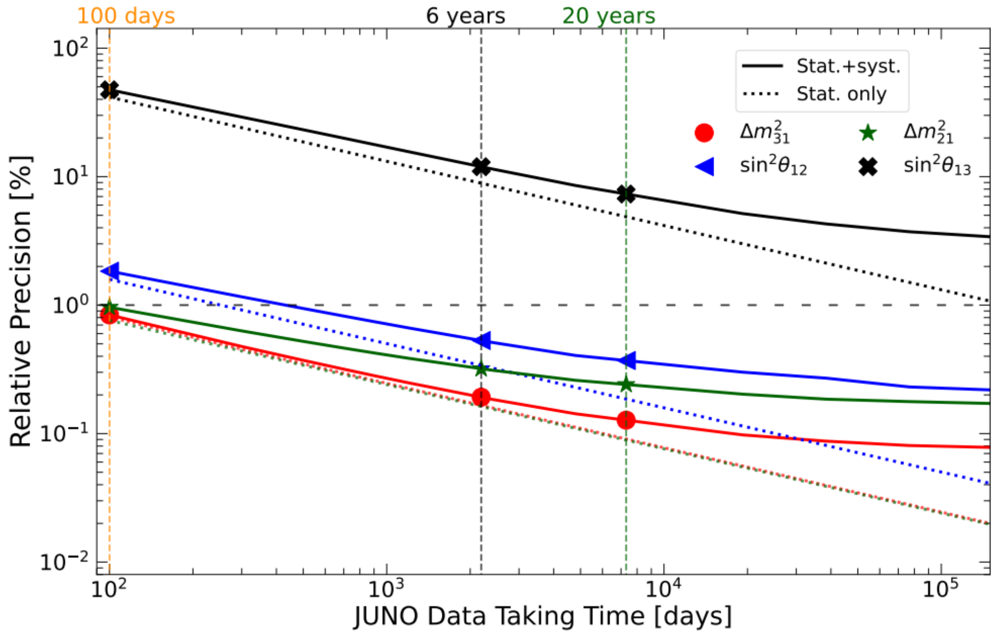
JUNO will improve the $\sin^2\theta_{12}$, Δm^2_{21} and Δm^2_{31} precision by a factor of 10 in it lifetime. With 100 days of data taking JUNO can get world-leading results for these three parameters

	Central Value	PDG2020	100 days	6 years	20 years
Δm^2_{31} ($\times 10^{-3}$ eV^2)	2.5283	$\pm$0.034 (1.3%)	$\pm$0.021 (0.8%)	$\pm$0.0047 (0.2%)	$\pm$0.0029 (0.1%)
Δm^2_{21} ($\times 10^{-5}$ eV^2)	7.53	$\pm$0.18 (2.4%)	$\pm$0.074 (1.0%)	$\pm$0.024 (0.3%)	$\pm$0.017 (0.2%)
$\sin^2\theta_{12}$	0.307	$\pm$0.013 (4.2%)	$\pm$0.0058 (1.9%)	$\pm$0.0016 (0.5%)	$\pm$0.0010 (0.3%)
$\sin^2\theta_{13}$	0.0218	$\pm$0.0007 (3.2%)	$\pm$0.010 (47.9%)	$\pm$0.0026 (12.1%)	$\pm$0.0016 (7.3%)

Oscillation parameters correlation



6 years of data taking of JUNO contours for the 2-dimensional marginal



Relative precision of the oscillation parameters as a function of JUNO data taking time

Breakdown of systematic uncertainties

	Δm^2_{21} 1σ (%)	Δm^2_{31} 1σ (%)	$\sin^2\theta_{12}$ 1σ (%)	$\sin^2\theta_{13}$ 1σ (%)
Statistics	0.16	0.17	0.34	8.94
Reactor:				
- Uncorrelated	0.01	< 0.01	0.10	2.53
- Correlated	0.03	0.01	0.27	6.83
- Reference spectrum	0.07	0.05	0.09	3.48
- Spent Nuclear Fuel	0.07	< 0.01	0.05	1.55
- Non-equilibrium	0.14	< 0.01	0.10	2.65
Detection:				
- Efficiency	0.02	0.01	0.23	5.81
- Energy resolution	0.01	< 0.01	0.01	0.39
- Nonlinearity	0.05	0.04	0.09	2.09
- Backgrounds	0.18	0.04	0.20	4.89
Matter density	0.01	0.01	0.07	0.98
All systematics	0.27	0.08	0.40	8.16
Total	0.32	0.19	0.52	12.11

Relative impact of individual sources of uncertainty on the total precision of $\sin^2\theta_{12}$, Δm^2_{21}, $\sin^2\theta_{13}$ and Δm^2_{31} oscillation parameters.

All uncertainties correspond to six years of JUNO data and are reported as relative uncertainty contributions to the precision of the particular oscillation parameter.

The dominant systematics for precision measurement:

- Δm^2_{31} / Δm^2_{32} : reactor spectrum shape
- Δm^2_{21} : background, non-equilibrium effect
- $\sin^2\theta_{12}$, $\sin^2\theta_{13}$: normalization rate

(reactor and detection efficiency)

Conclusion

- JUNO will be the first experiment to observe two modes of neutrino oscillations simultaneously measurement of $\sin^2\theta_{12}$, Δm^2_{21}, $\sin^2\theta_{13}$ and Δm^2_{31} with reactor neutrino
- JUNO will improve the $\sin^2\theta_{12}$, $\Delta m^2_{21}$and Δm^2_{31} precision by a factor of 10. World-leading results can be achieved with just with 100 days of data taking!
- Paper already in arXiv: 2204.13249 submitted to Chinese Physics C