

JUNO & its potential on primary cosmic ray

Zhimin Wang

IHEP, CAS

Sep. 3, 2026, University of New South Wales (UNSW), Sydney, Australia



The XIX International Conference on Interconnections between Particle Physics and Cosmology (PPC2026)/4th Gordon Godfrey Workshop on Astroparticle Physics



- Introduction of the JUNO experiment
- Performance of the detector
- Neutrino results
- Primary cosmic ray with JUNO
- Summary

Location of JUNO

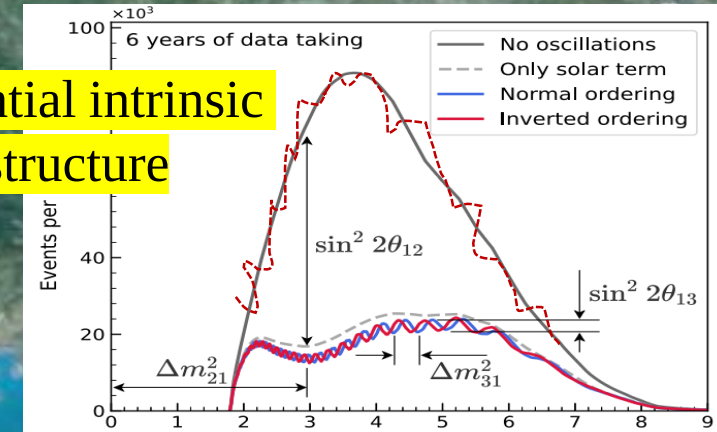


* Yangjiang and Taishan Reactor Group: one of the most powerful

* Taishan Nuclear Reactor: highest single-core power



Potential intrinsic fine structure



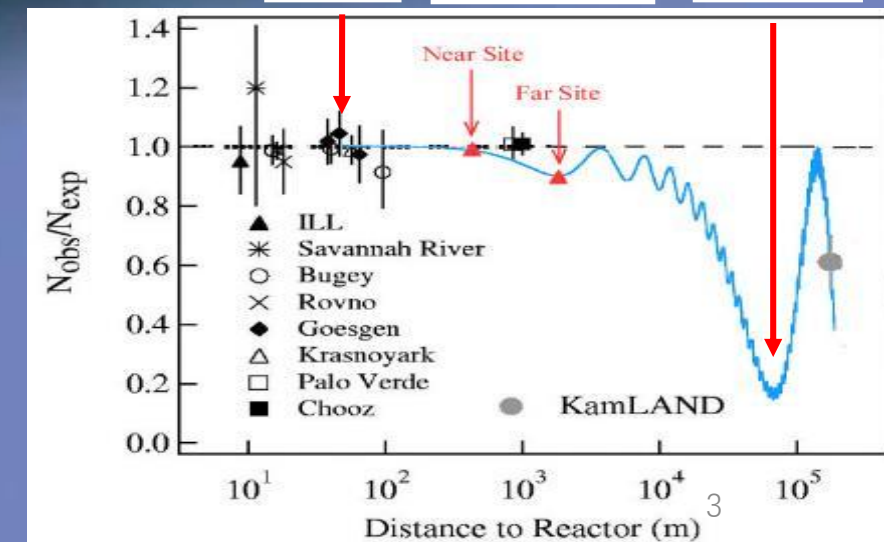
Huizhou NPP

Lureng NPP

TAO

Daya Bay

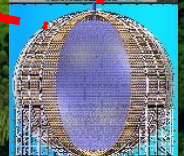
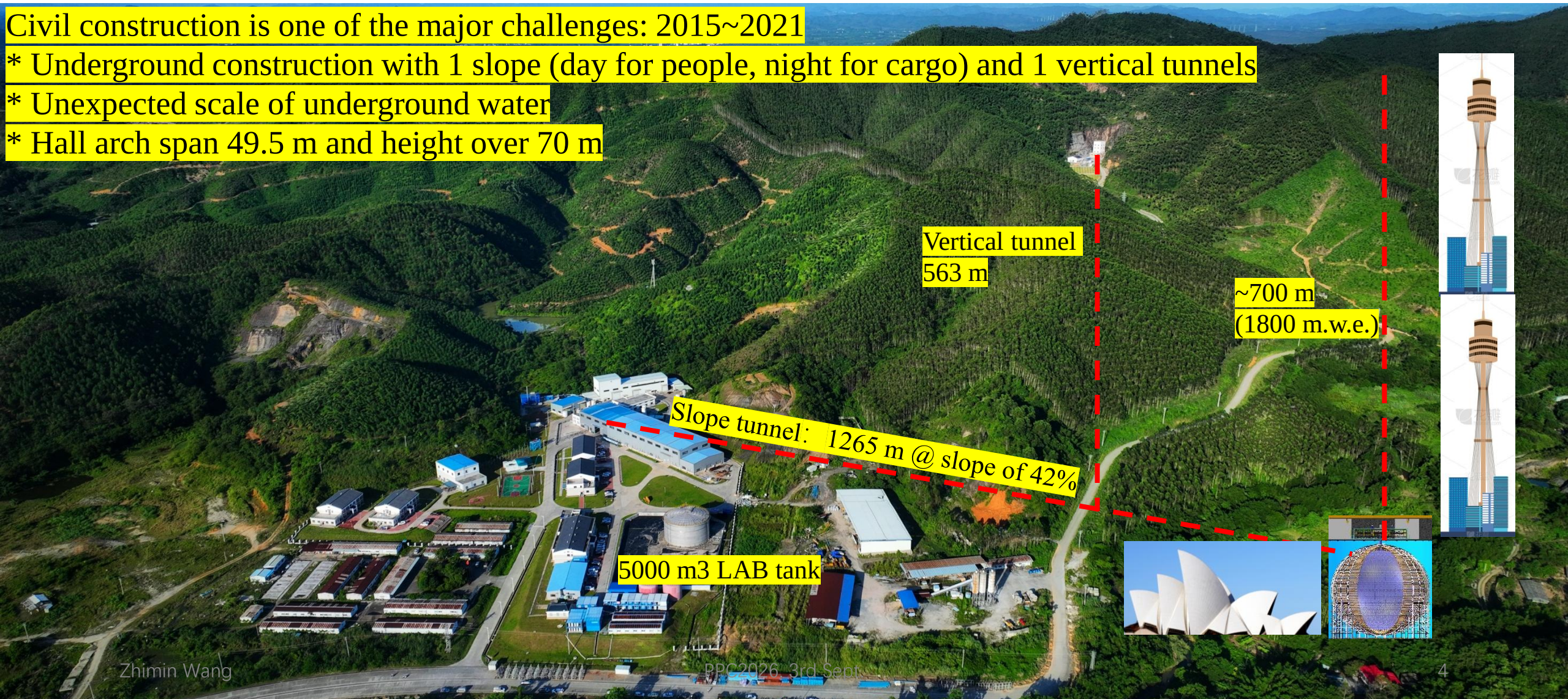
JUNO



JUNO Site: Jinji Village, Dashi Mountain

Civil construction is one of the major challenges: 2015~2021

- * Underground construction with 1 slope (day for people, night for cargo) and 1 vertical tunnels
- * Unexpected scale of underground water
- * Hall arch span 49.5 m and height over 70 m



Physics at JUNO



Solar Neutrinos

Examine the dynamics of stellar evolution



Supernova Neutrinos

Cosmic evolution, star formation, supernova explosion mechanism

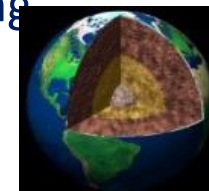
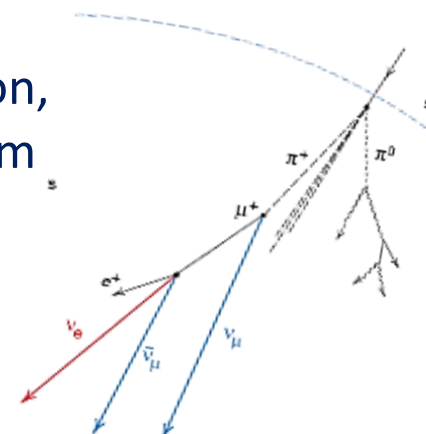
Diffuse Supernova Neutrinos:

Potential to discover

Cosmic ray

Atmospheric Neutrinos

Complementary to reactor neutrinos to improve the sensitivity to mass ordering



Geoneutrinos

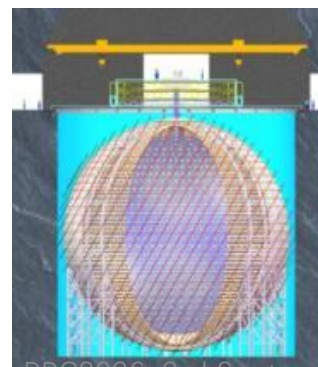
Examine the Earth's geophysical model

Reactor Neutrinos

Determine neutrino mass ordering

Measure oscillation parameters

	Current (PDG2020)	JUNO (100 days)	JUNO (6 years)
Δm^2_{31} (Δm^2_{32})	1.3%	0.8%	0.2%
Δm^2_{21}	2.4%	1.0%	0.3%
$\sin^2\theta_{12}$	4.2%	1.9%	0.5%
$\sin^2\theta_{13}$	3.2%	47.9%	12.1%



New physics searches

e.g., proton decay and sterile neutrinos

J. Phys. G 43 (2016) 030401

Prog. Part. Nucl. Phys. 123(2022), 103927

PPC2020, 3rd Sept.

5



JUNO Project and the collaboration

= 68 institutes
> 700 participants

- Project firstly approved in China in 2013 and later in other countries. Civil construction started in 2015
- Collaboration established in 2014, now >700 collaborators from 68 institutions in 16 countries/regions

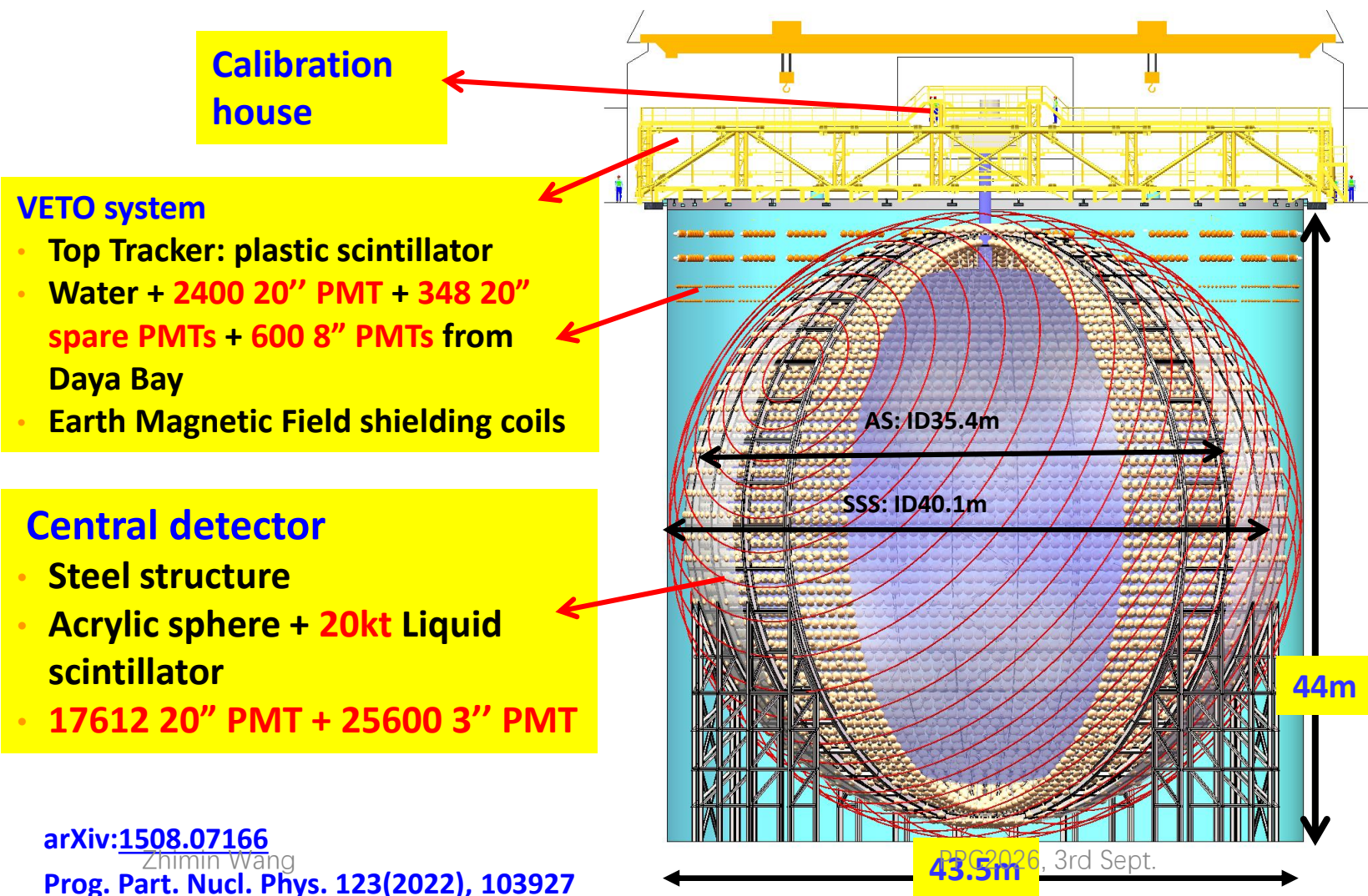
Country	Institute	Country	Institute	Country	Institute
Belgium	ULB	China	SUSTech-Geo	Italy	INFN-CT
China	BISEE	China	SUSTech-Phy	Italy	INFN-FE
China	CDUT	China	SYSU	Italy	INFN-LNF
China	CNPRI	China	THU	Italy	INFN-MI
China	CUGB	China	UCAS	Italy	INFN-MIB



JUNO Detector Design



- Target mass of 20 kt liquid scintillator → × 20 KamLAND, × 70 Borexino
- Energy resolution < 3%@ 1MeV → > 1200 PE/MeV



	KamLAND	JUNO	Ratio
Photon Statistics	250 p.e./MeV	1200 p.e./MeV	5
PMT coverage	34%	75%	2.2
LS transparency	~12 m	> 20 m	~0.9
Light yield (anthracene)	30%	45%	~1.5
Detection Eff.(QE×CE)	~15%	30%	~ 2

Main technical challenges

- Precise mechanical structure for small clearance between PMTs
- Very transparent LS
- High photon eff. PMTs

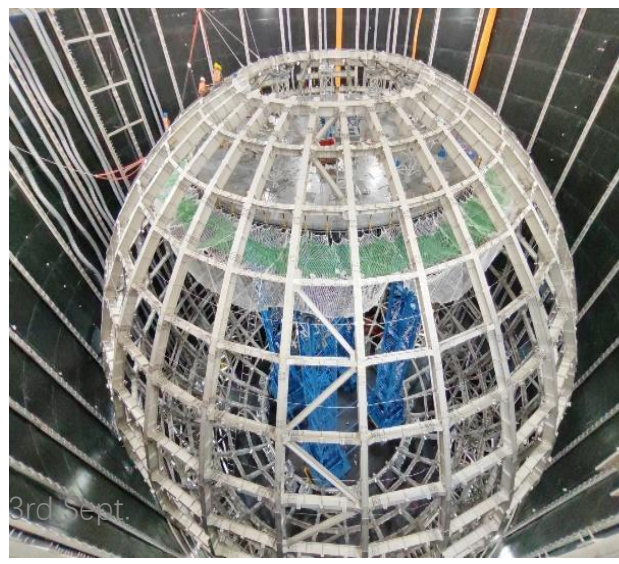
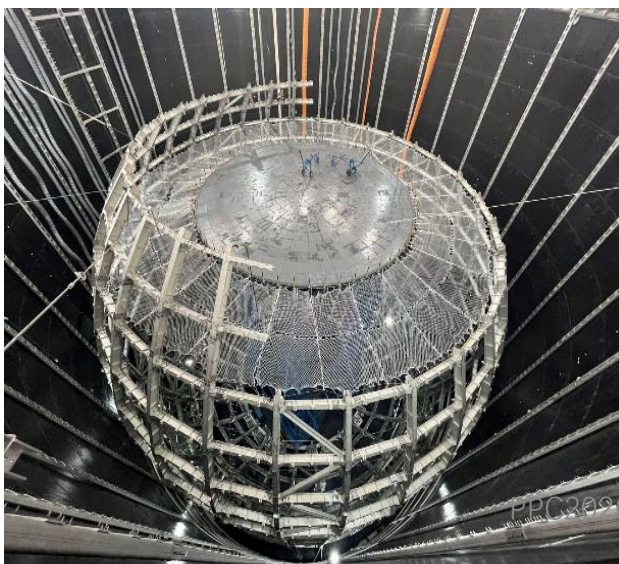
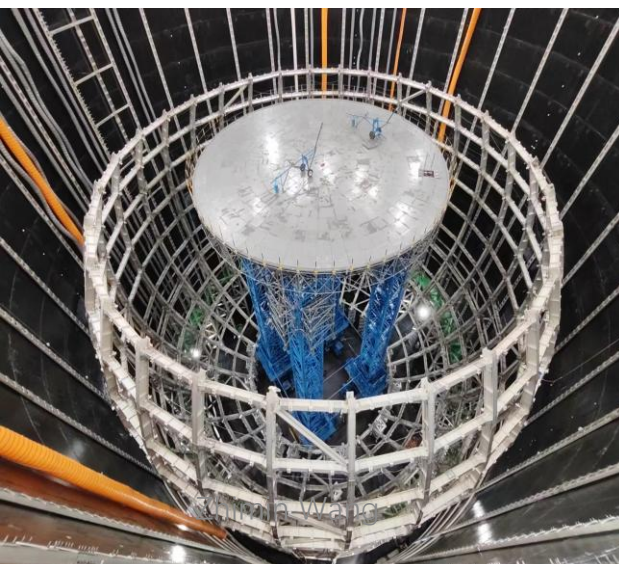
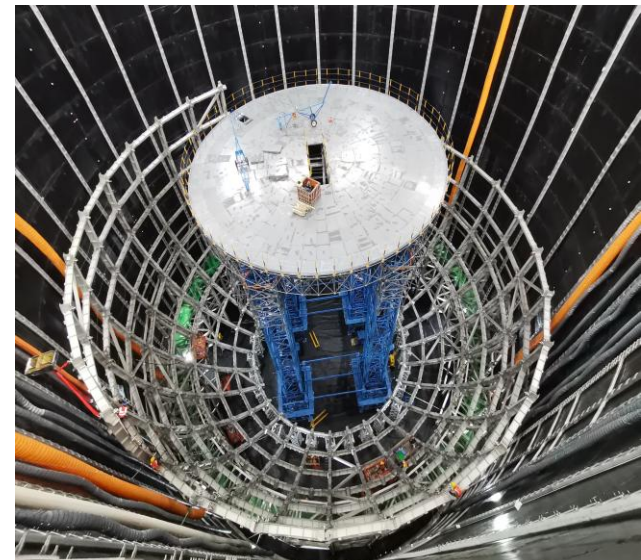
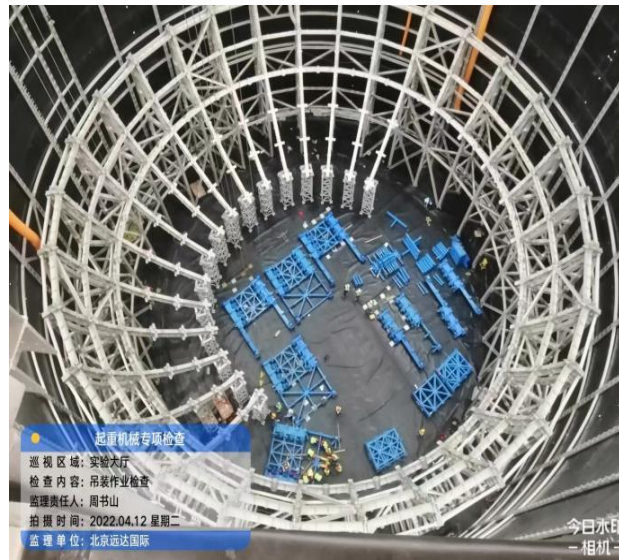
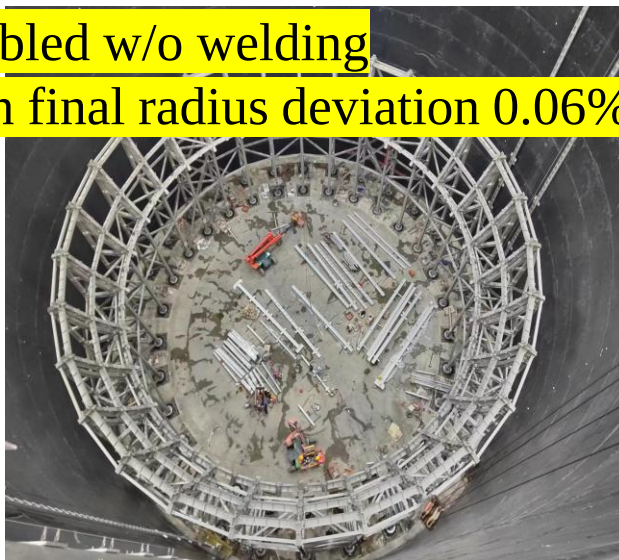
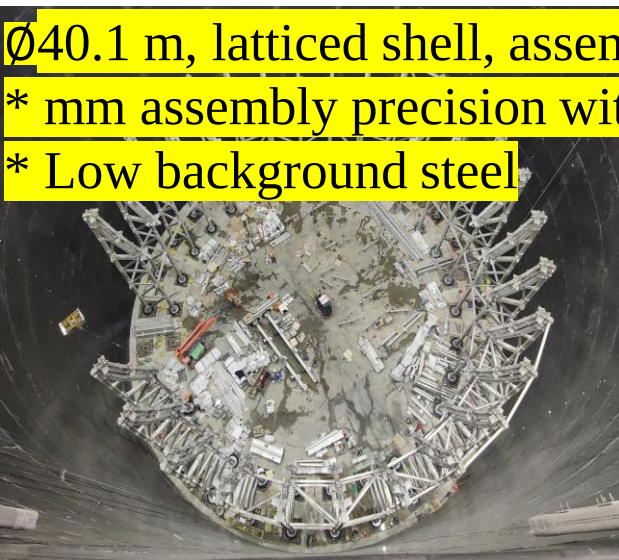
Stainless Steel Structure Assembly



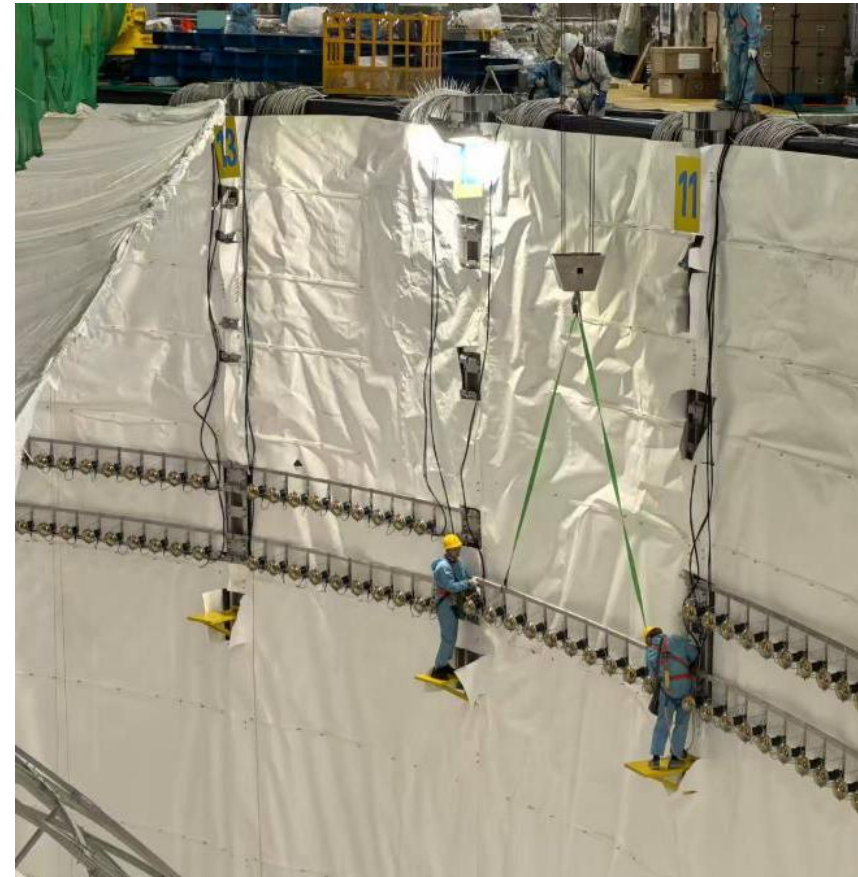
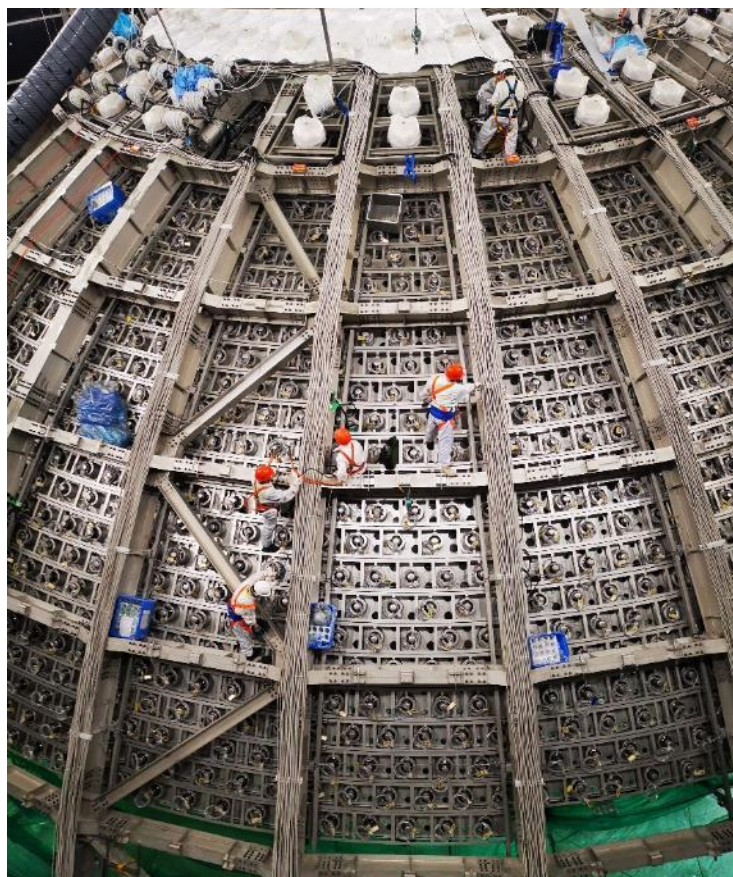
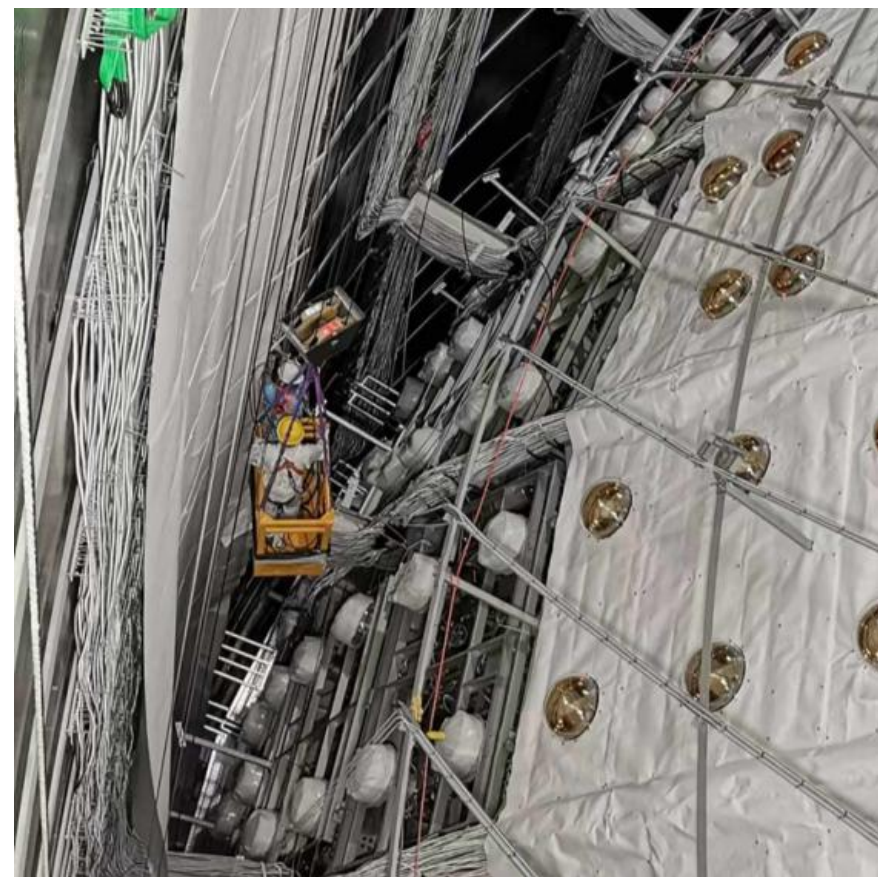
Ø40.1 m, latticed shell, assembled w/o welding

* mm assembly precision with final radius deviation 0.06%

* Low background steel



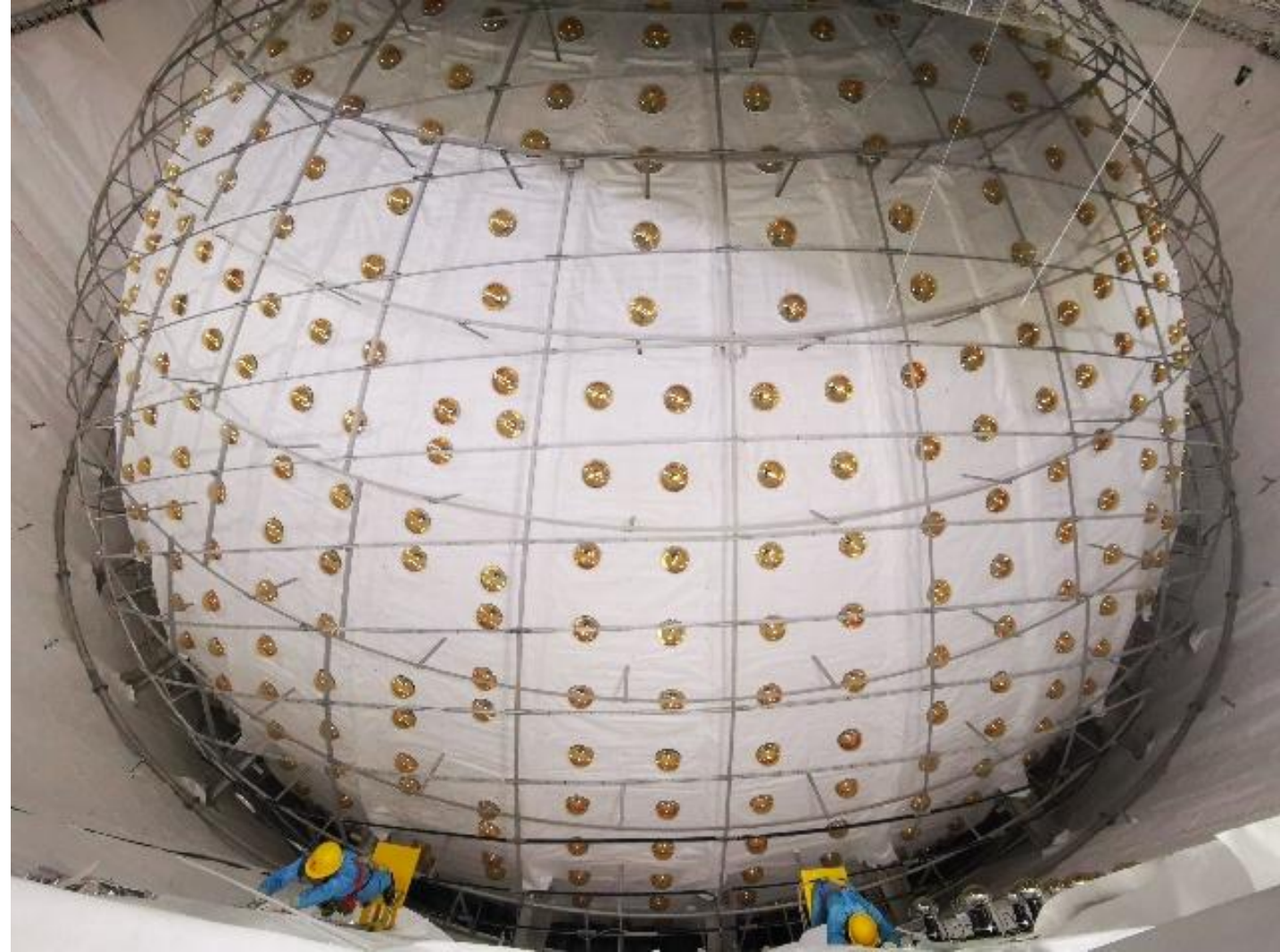
PMT Installation



Installation Completed



Zhimin Wang



PPC2026, 3rd Sept.

Liquid Scintillator Production and Performance

- LAB + 2.5 g/L PPO + 3 mg/L bis-MSB + 50mg/kg BHT
 - High light yield long attenuation length (>20m required, **20.6m @430nm**),
 - Low background (U/Th < 1 ppq required, **~0.1 ppq measured**)



5000 m³ LAB storage tank



1) Al₂O₃ for optical transparency



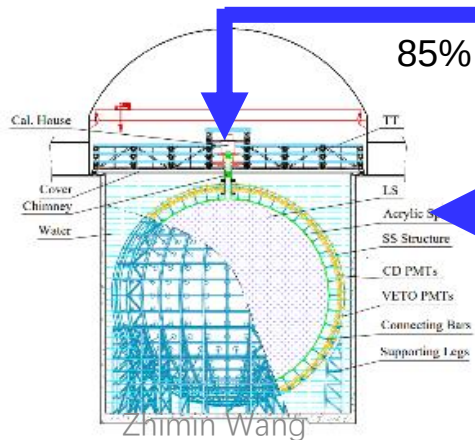
2) Distillation for radiopurity



Mixing LAB with PPO and bis-MSB



1800 m SS pipes to underground



Monitoring pre-detector (OSIRIS)

15%



4) Gas stripping to remove Rn and O₂



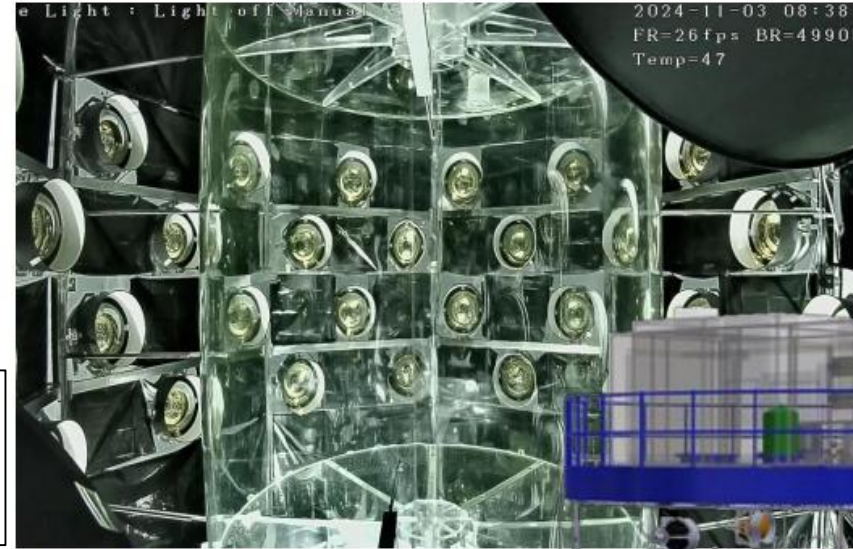
3) Water extraction to remove radioactive impurities

JUNO Scintillator Filling: OSIRIS pre-detector



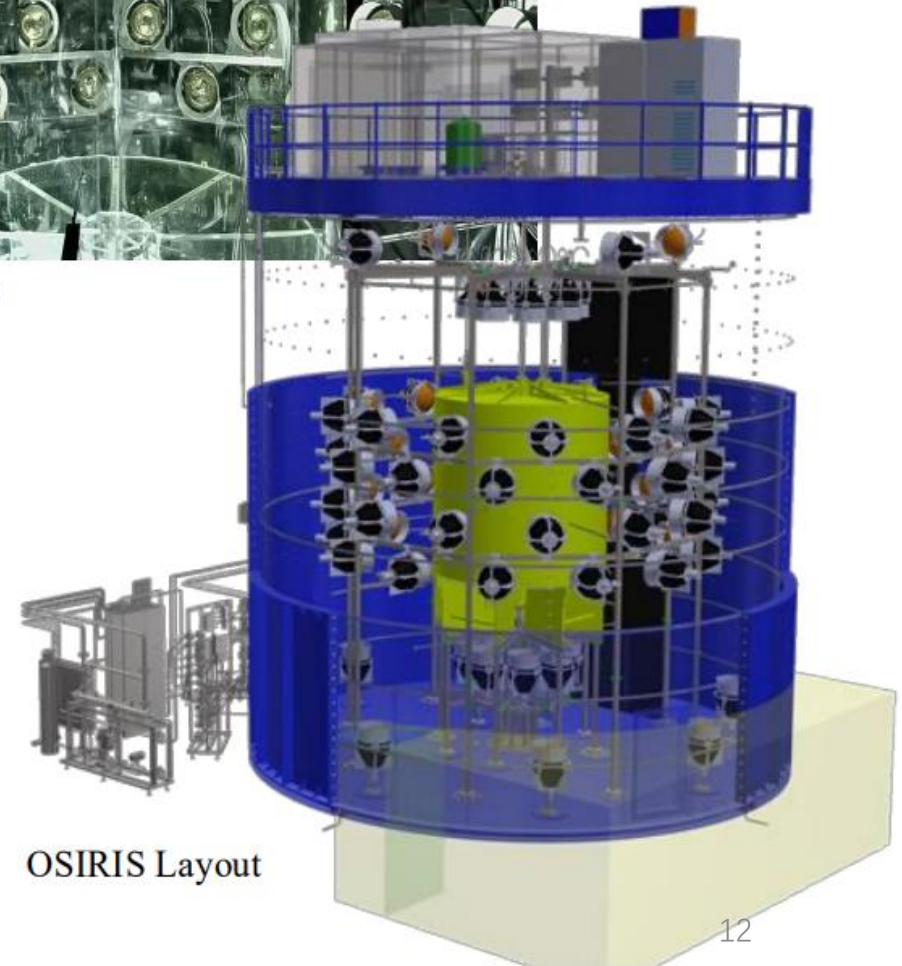
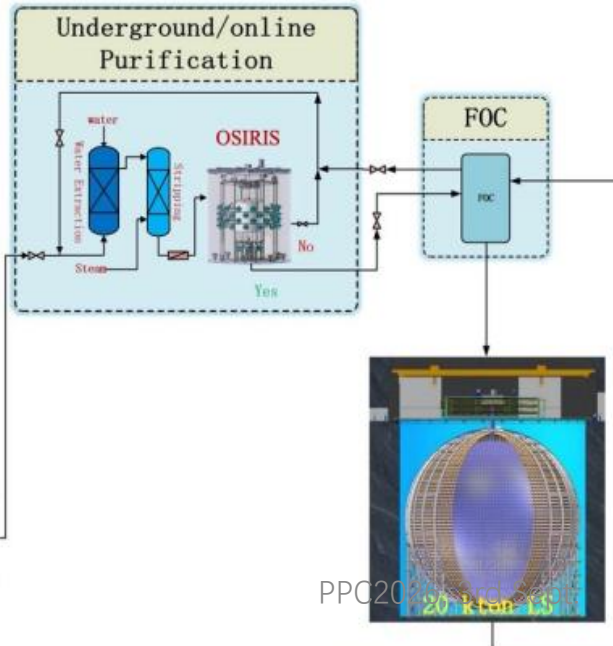
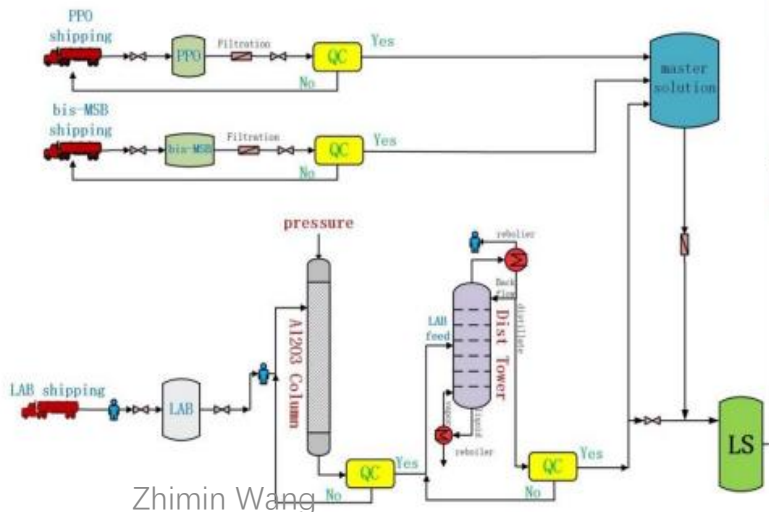
- Ultra-low background levels in scintillator are essential for neutrino detection
- OSIRIS as the last station in the scintillator production and purification chain
- *in-situ* radiopurity monitoring during JUNO filling
 - Radon: $< 0.1 \text{ mBq/m}^3$
 - Uranium: $< 10^{-15} \text{ g/g of U}$
 - Thorium: $< 5 \times 10^{-16} \text{ g/g Th}$

20m³ LS (3m AV)
~550ton water (9m ST)
Data from 2024



OSIRIS Inner View

JUNO LS Production & Purification & Filling

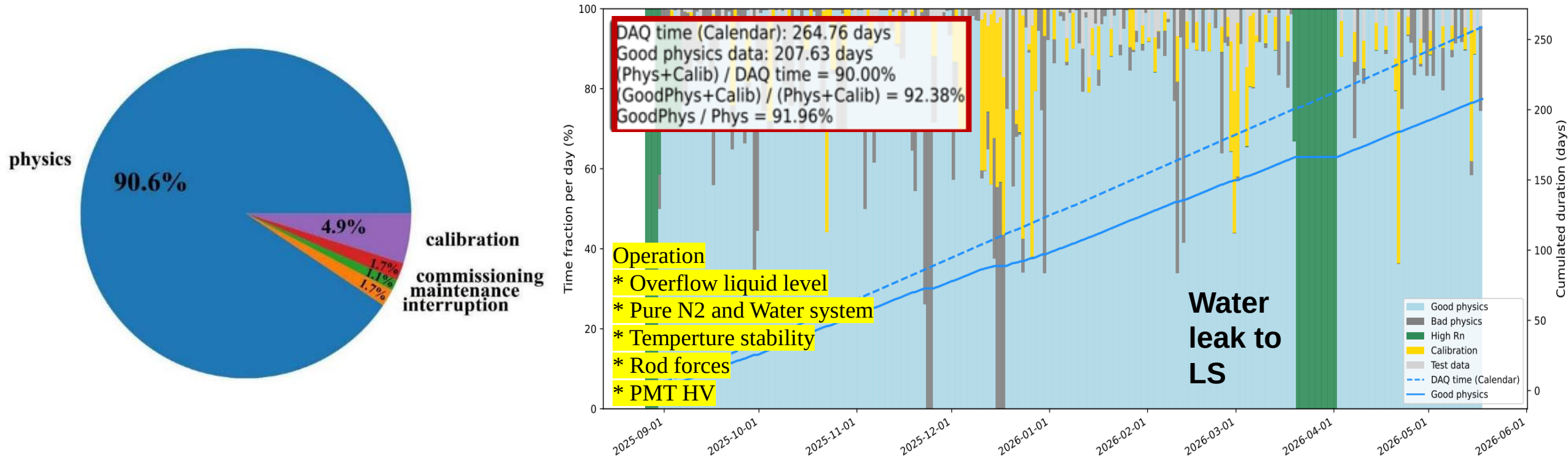


OSIRIS Layout

JUNO Detector in Stable Data-taking



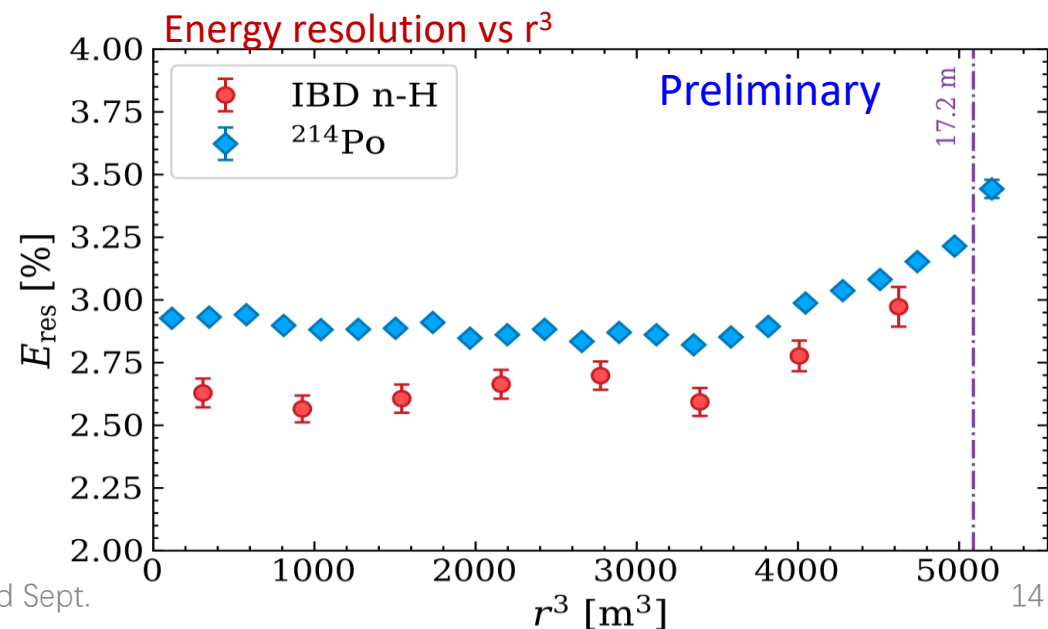
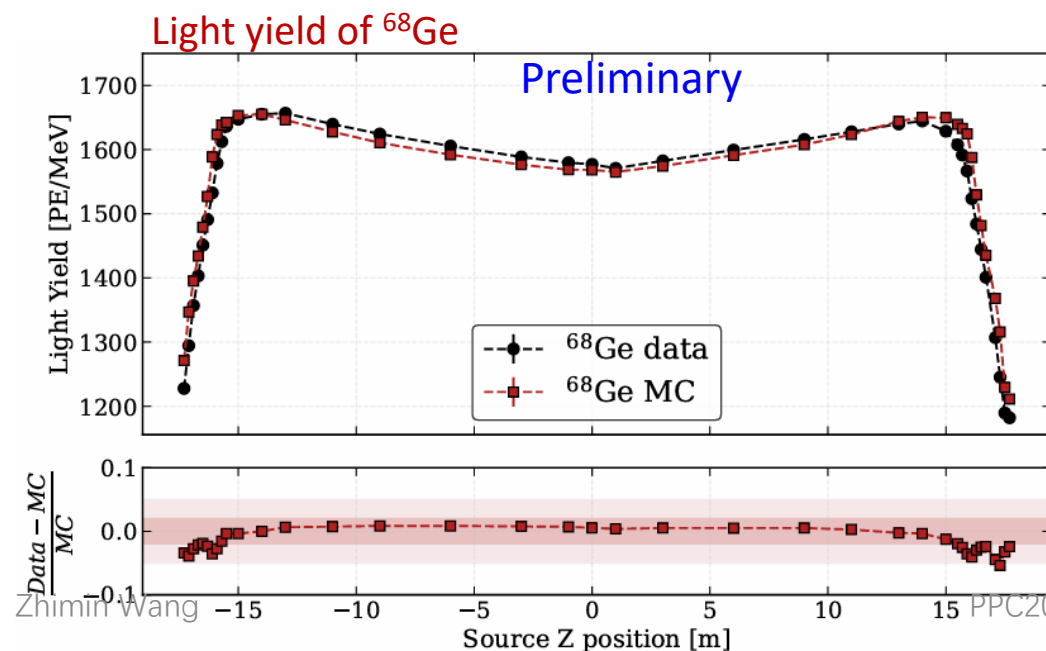
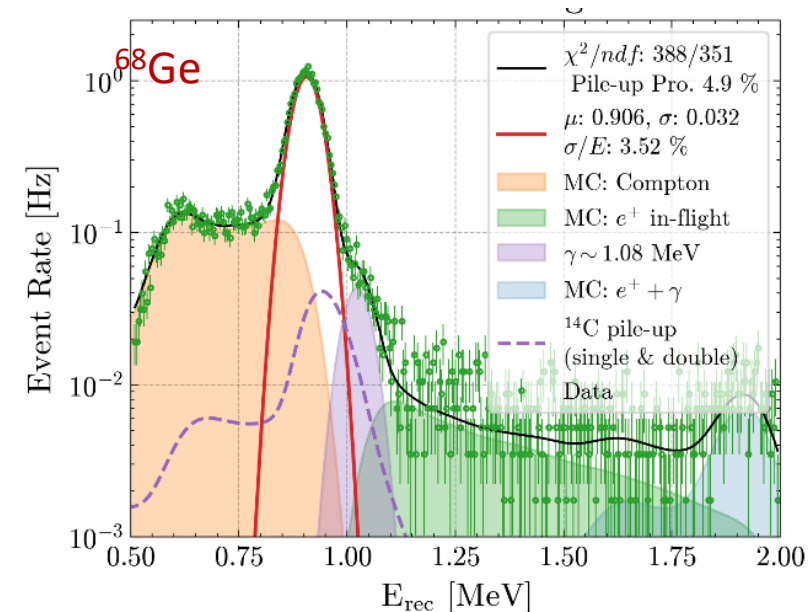
- Data taking period for this analysis: 2025.08.30-2026.05.18
- Golden data are selected for physics analysis



➤ Power outage due to weather is one of the main causes of interruptions

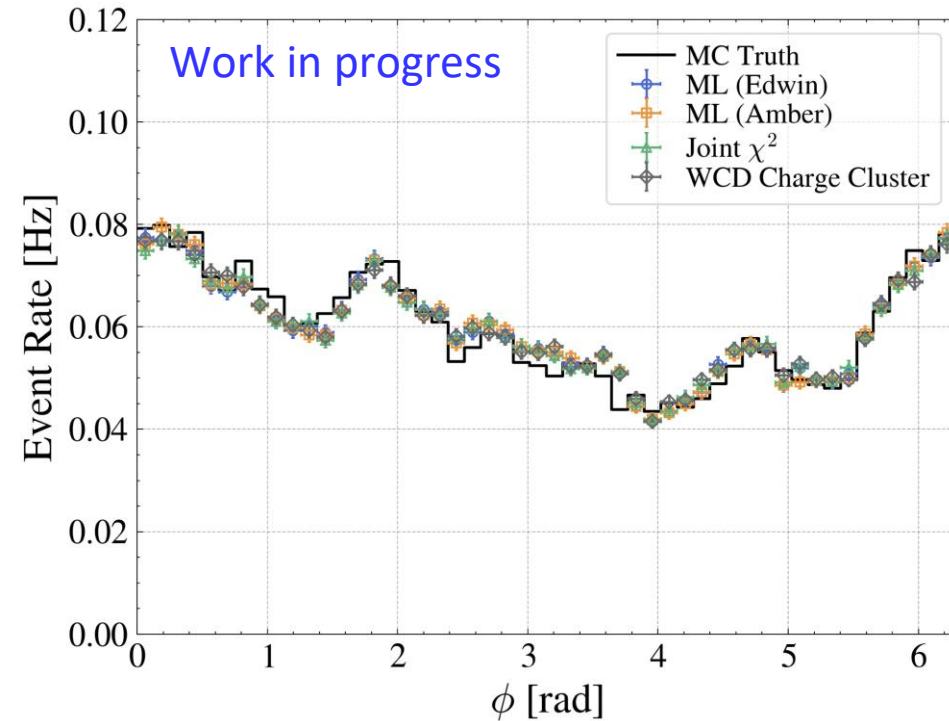
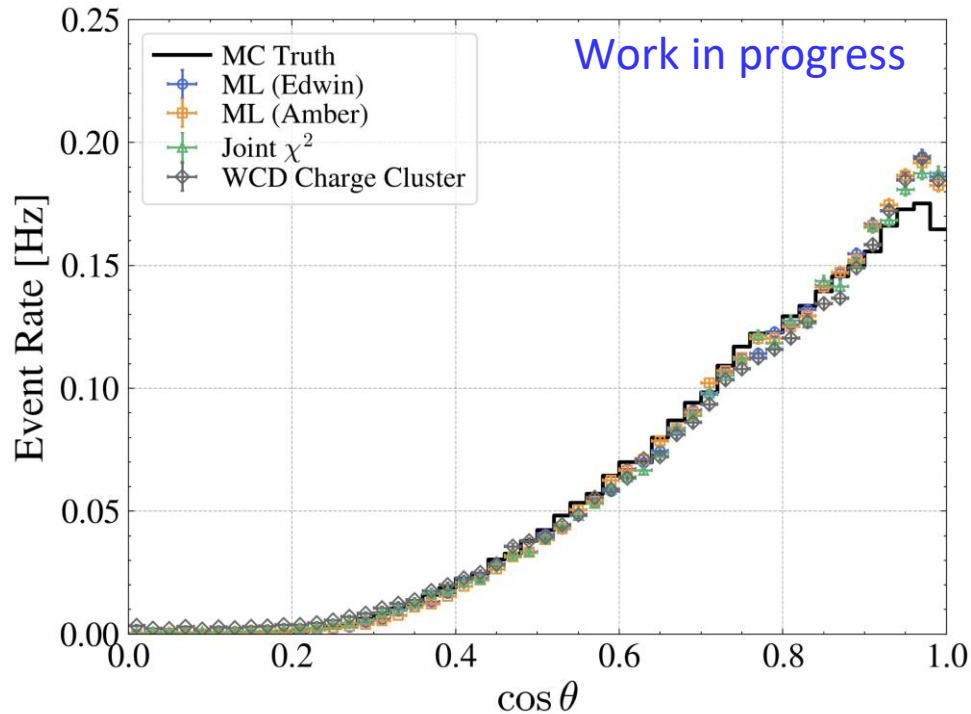
Light Yield and Energy Resolution

- Light yield at the detector center is ~ 1600 PE/MeV for ^{68}Ge and ~ 1785 PE/MeV for neutrons, in good agreement with MC
- Energy resolution for ^{68}Ge is $\sim 3.5\%$ @ 2×0.511 MeV at the center, slightly worse than the expected 3.1%
 - ⇒ Better MC for Č process, optical boundaries, δ electrons, ...
 - ⇒ Possible improvements: ML to remove ^{14}C , more calibration, better reconstruction and fitting methods, ...
- Energy resolution for alpha from ^{214}Po is $\sim 2.9\%$ @ 0.93MeV



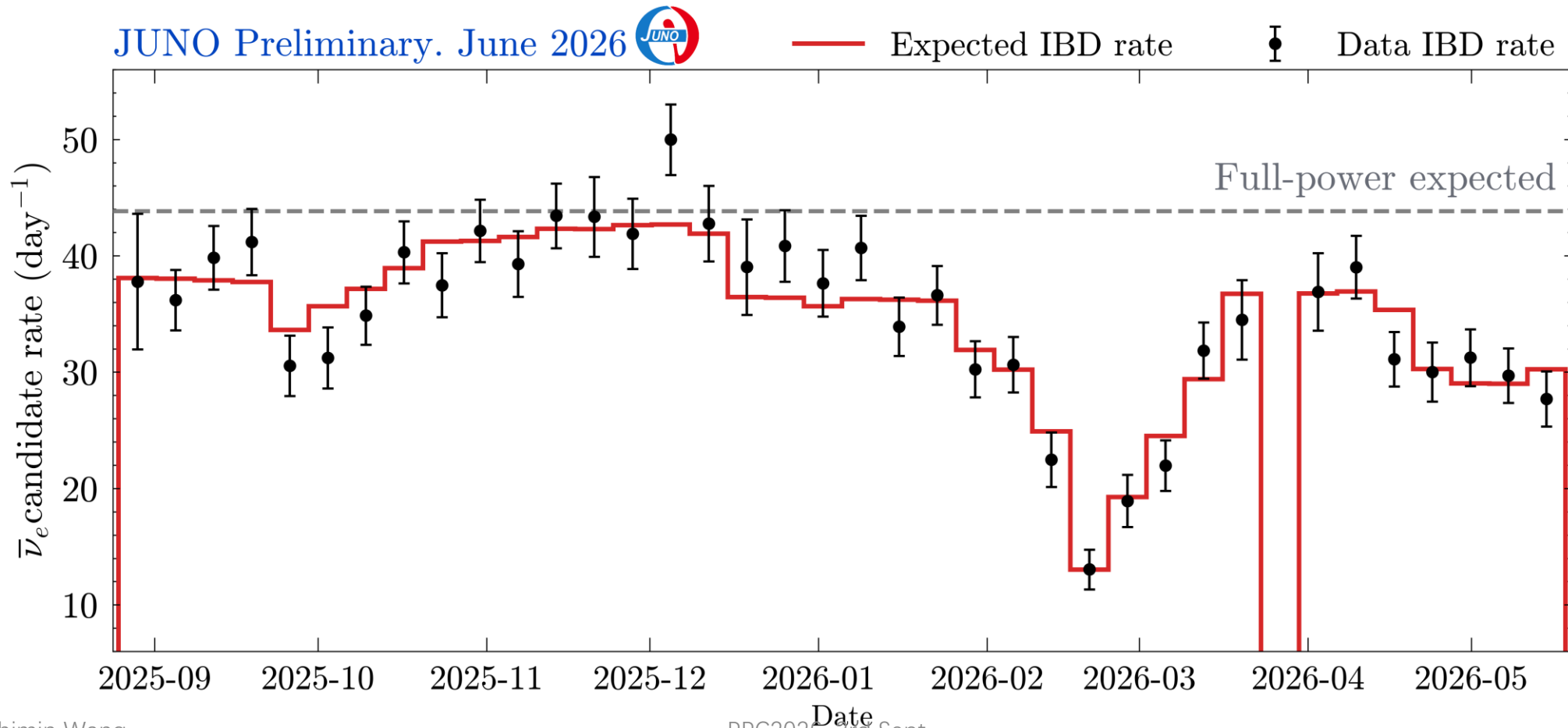
Events and Track Reconstruction

- Muon trigger rate in CD ~ 5 Hz, in Water Pool ~ 4 Hz
- Muon detection efficiency of CD through-going muons $> 99.5\%$
- Two types of track reconstruction methods: traditional and data-driven ML
- Reconstructed angular distributions in good agreement with Monte Carlo simulation:
 $\Rightarrow$ Extremely important to veto muon tracks to reject cosmogenic $^8\text{He}/^9\text{Li}$ background

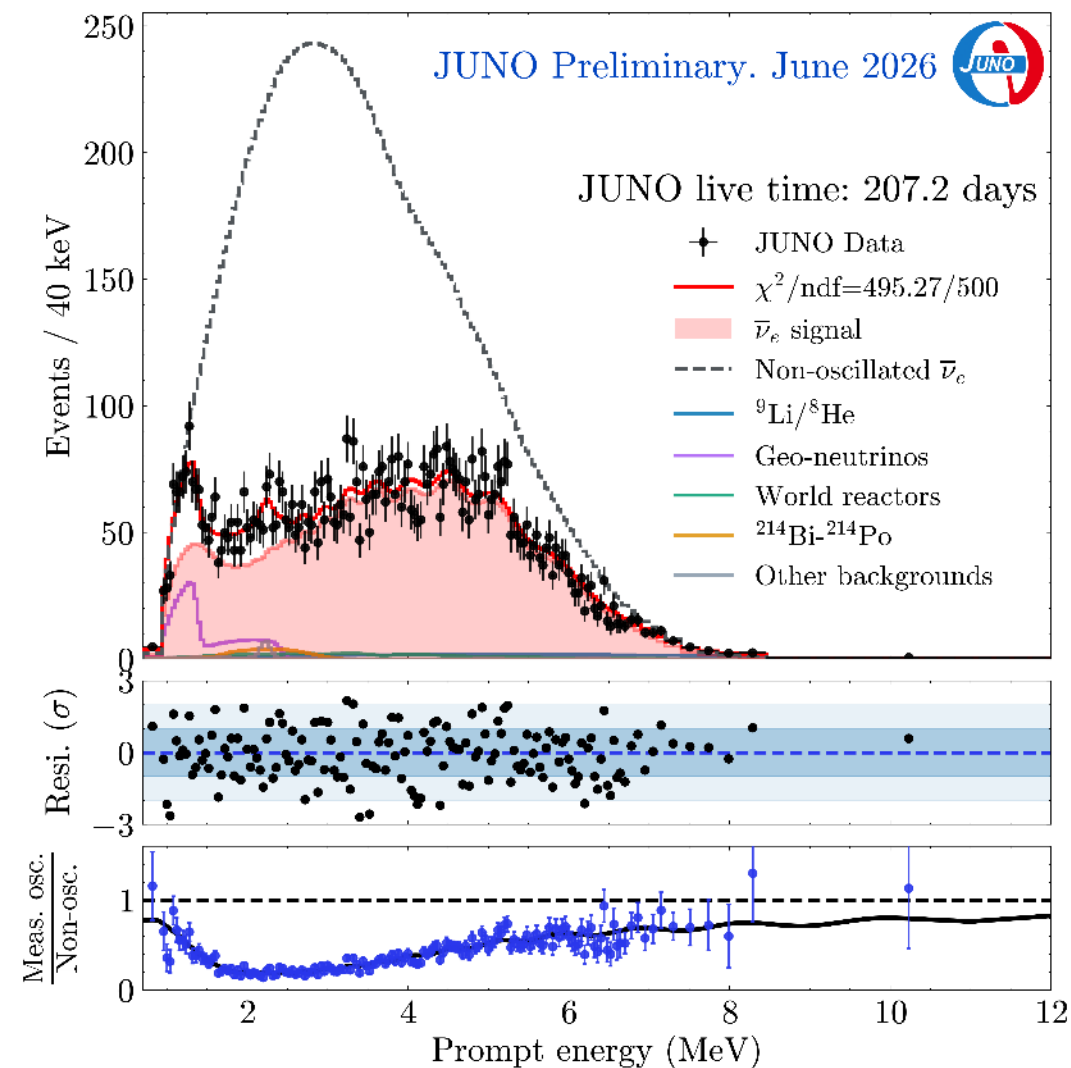


Reactor Neutrino Event Rate versus Time

- Measured reactor neutrino event rate consistent with expectation
- Total live time is 207.2 days



Measured Reactor Neutrino Spectrum



Fitting constrained
by the near detector
spectra from TAO
and Daya Bay (PRL
130 16, 161802)

Antineutrinos ($\bar{\nu}_e$) Candidates Summary		
DAQ live time (days)	207.2	
$\bar{\nu}_e$ candidates	8294	
Selection Efficiencies (%)	ϵ	σ_{rel}
Fiducial volume	87.12%	0.96%
PMT flasher rejection	> 99.9%	Negligible
μ veto	93.67%	0.02%
Multiplicity cut	95.94%	negligible
Prompt-delayed coinc.	95.50%	0.32%
Correlated discriminator	98.99%	0.15%
Total efficiency (ϵ_{tot})	74.01%	1.02%
Event rates (cpd)	Pre-fit	Post-fit
Reactor $\bar{\nu}_e$ signal	36.02 ± 0.81	34.62 ± 0.64
Backgrounds		
$^9\text{Li}/^8\text{He}$	1.05 ± 0.27	1.41 ± 0.26
Geoneutrinos	1.30 ± 0.52 ^a	2.12 ± 0.32
World reactors	0.92 ± 0.09	0.92 ± 0.09
^{214}Bi - ^{214}Po	0.42 ± 0.31	0.57 ± 0.34
$^{13}\text{C}(\alpha, \text{n})^{16}\text{O}$	0.05 ± 0.02	0.05 ± 0.02
Fast neutrons	0.02 ± 0.02	0.02 ± 0.02
Double neutrons	0.10 ± 0.10	0.13 ± 0.10
Atmospheric neutrinos	0.09 ± 0.04	0.11 ± 0.05
Accidentals	0.07 ± 0.01	0.07 ± 0.01
Total backgrounds	4.01 ± 0.68	$5.40^{17} \pm 0.47$

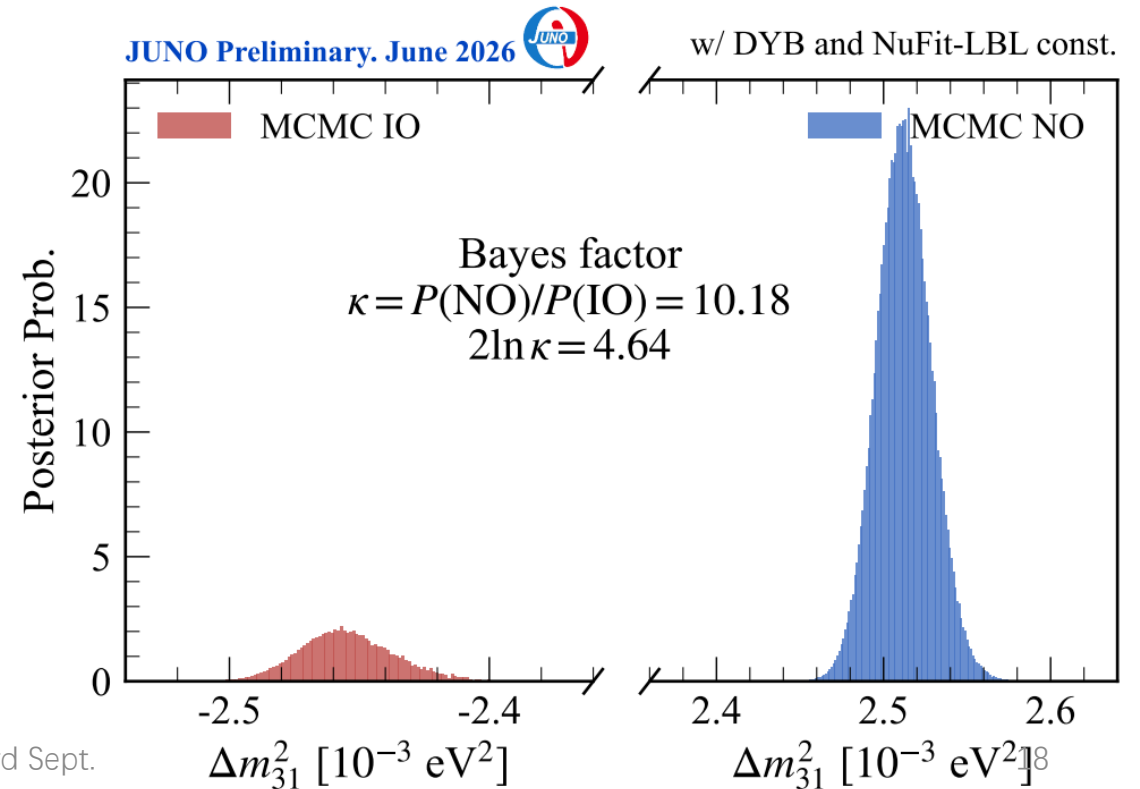
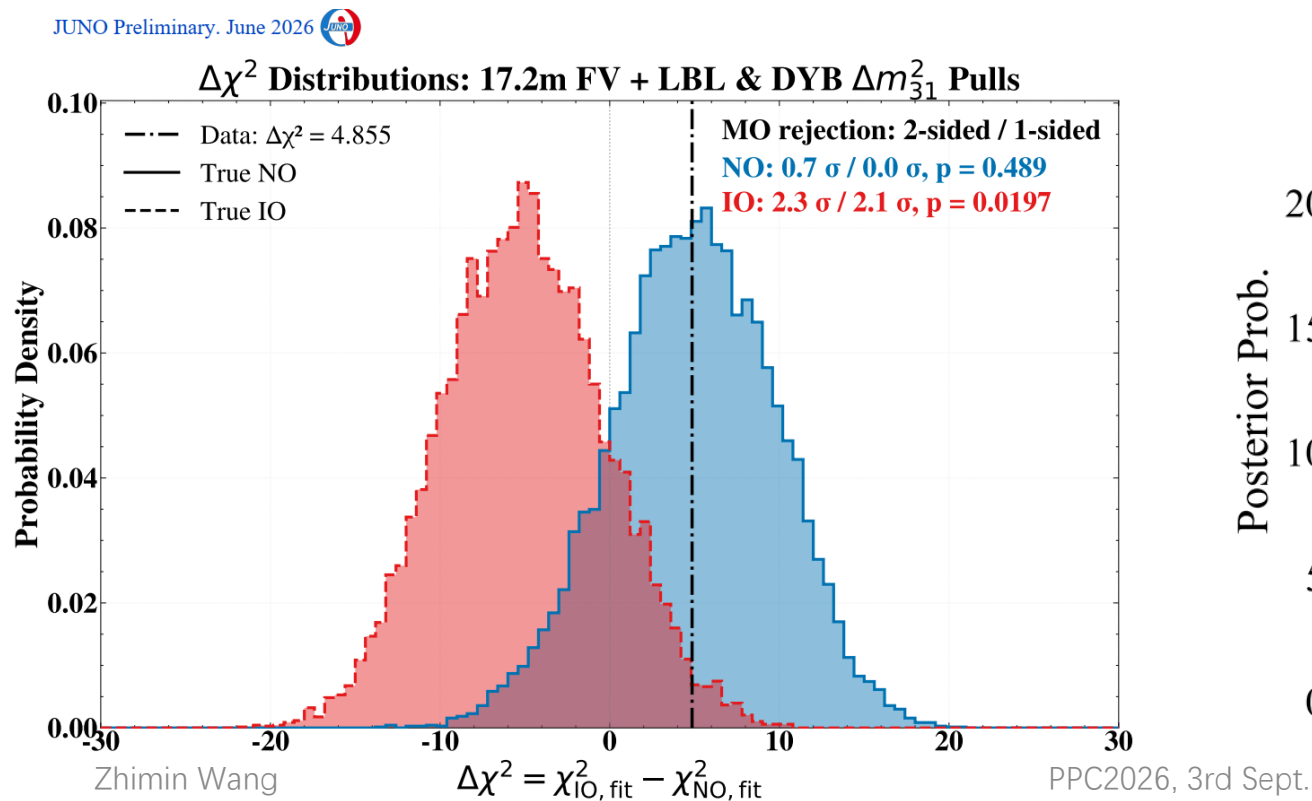
Consistent results from three independent analyses

Zhimin Wang

PRL2026, 30 Sept.

Neutrino Mass Ordering Significance

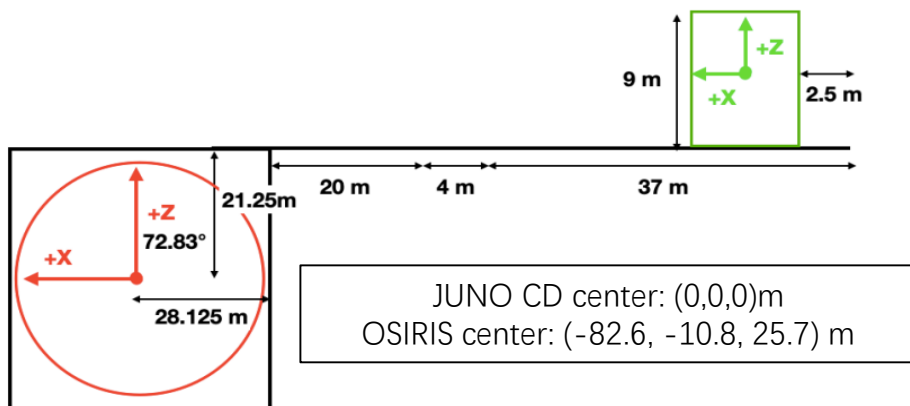
- Frequentist approach using pseudo exp. to convert $\Delta\chi^2$ to significance
- Influence of δ_{CP} considered (scanned)
- Normal Ordering is favored at **2.3 σ**
- Bayesian approach using Markov Chain Monte Carlo(MCMC) method
- Normal Ordering is favored with a Bayes factor of **10.18** $\rightarrow 2\ln \kappa = 4.64$
- $\Rightarrow$ Consistent with the frequentist $\Delta\chi^2$



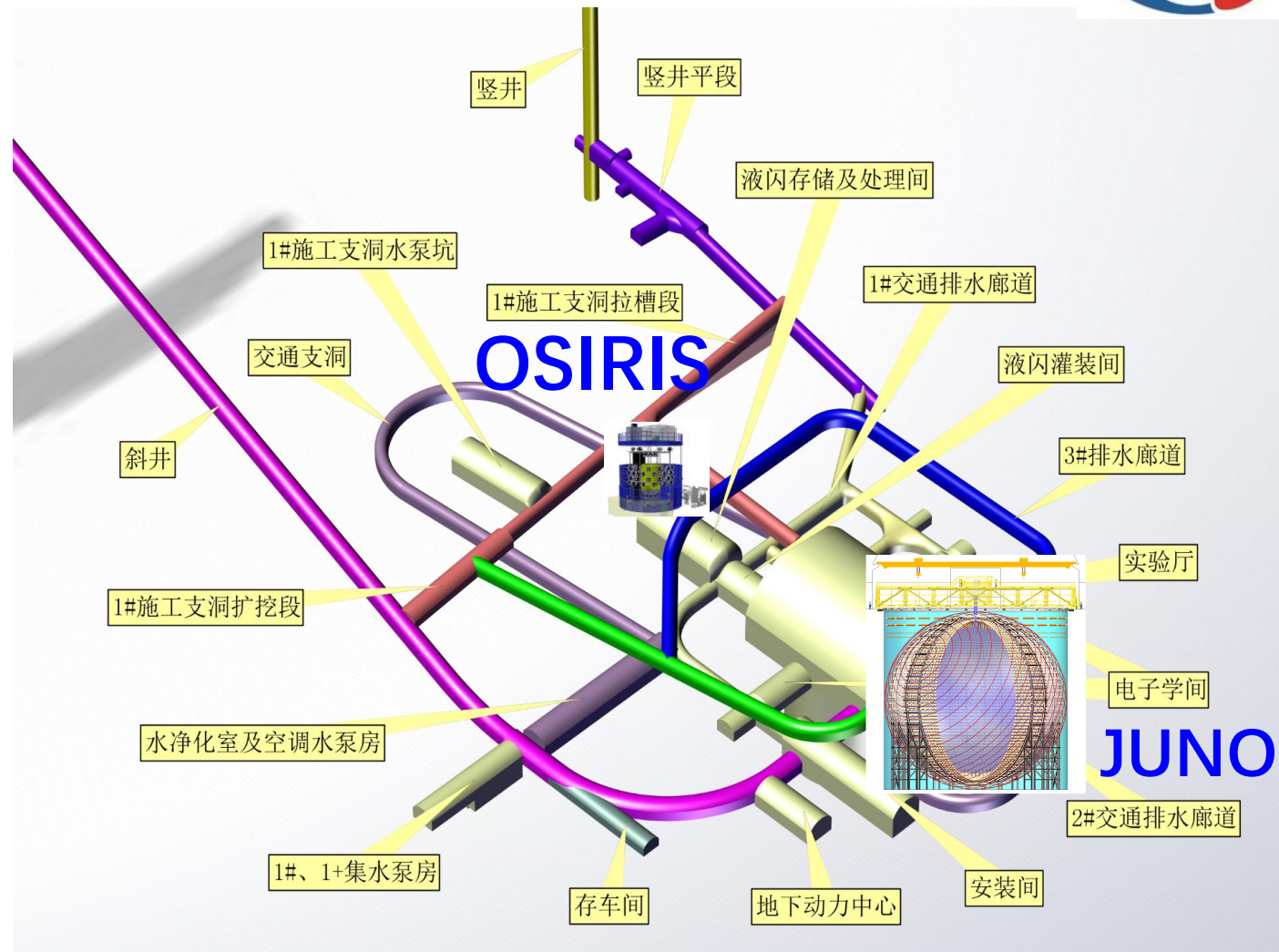
Cosmic ray with JUNO



- Muon Flux Measurements and Rock Shadowing
- Primary Cosmic-Ray Flux
 - Synergies between JUNO & OSIRIS
- Probing Lunar and Solar Shadows
- Large-Scale Anisotropy of Cosmic Rays
- Characterization of Neutrino-Related Events
- High-Energy Gamma-Ray Searches
 - Observation of the Crab Nebula



Zhimin Wang

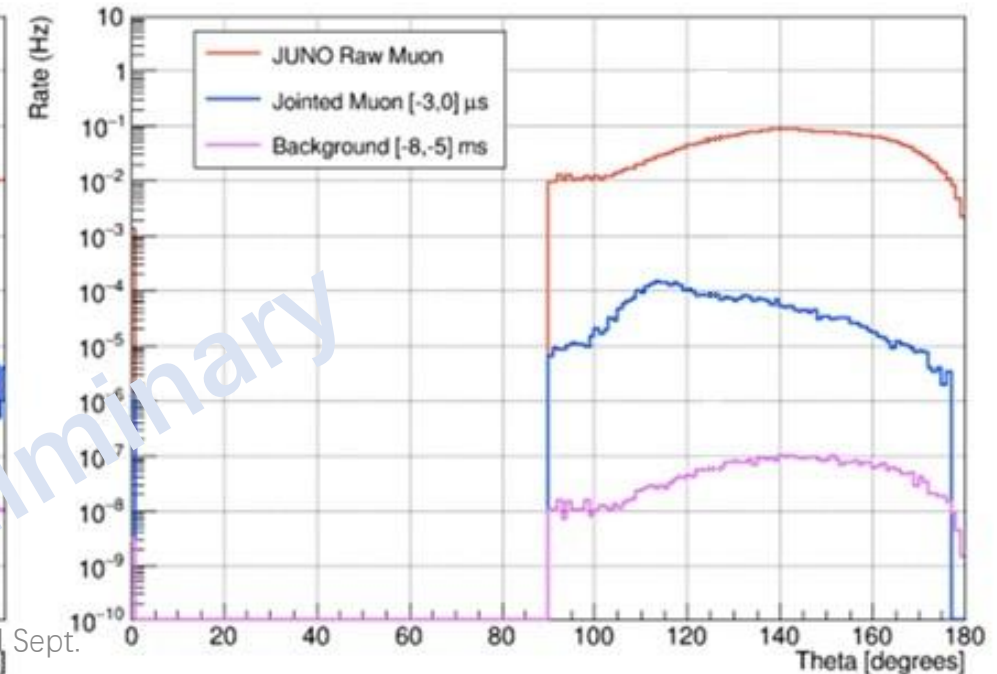
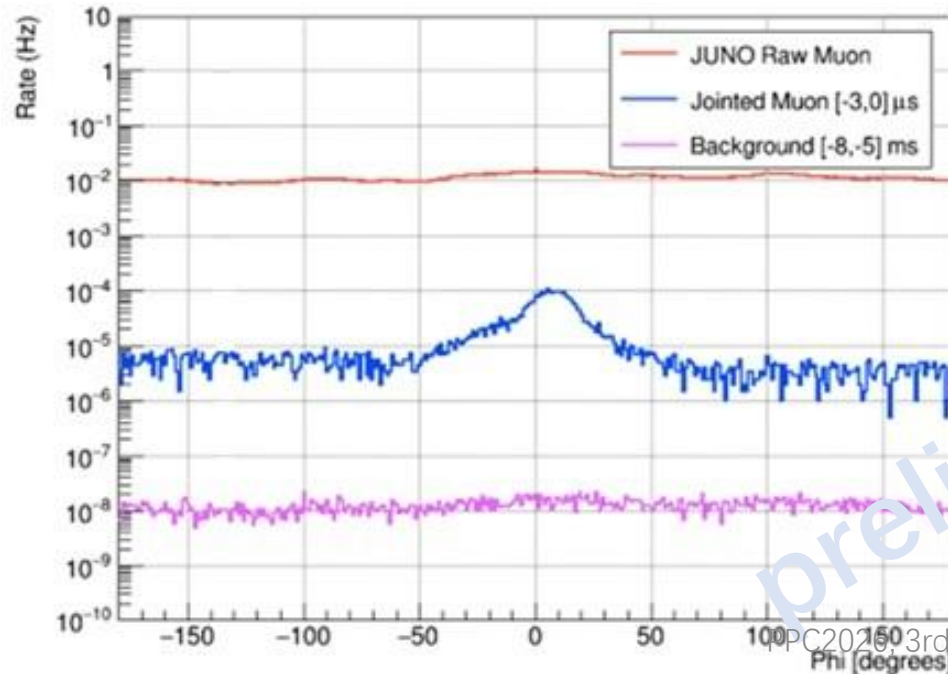
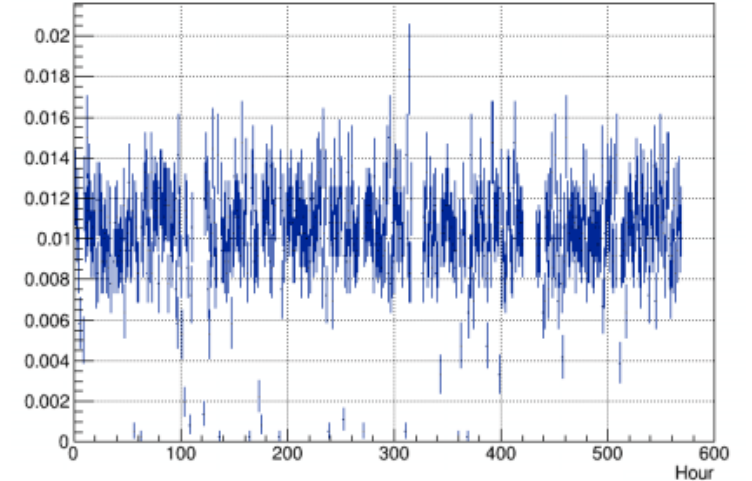
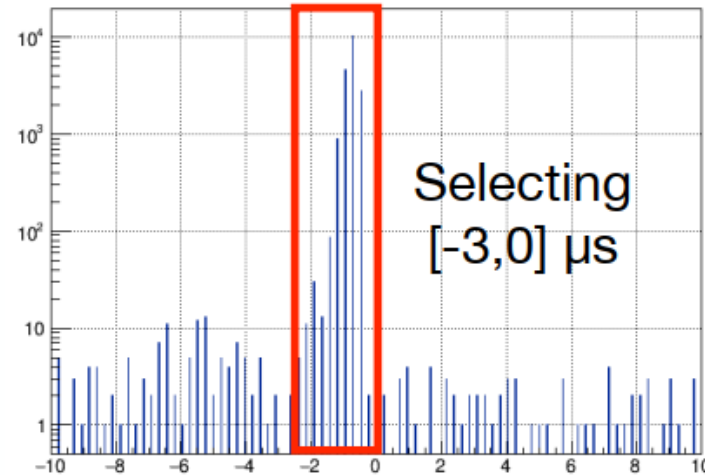


PPC2026, 3rd Sept.

19

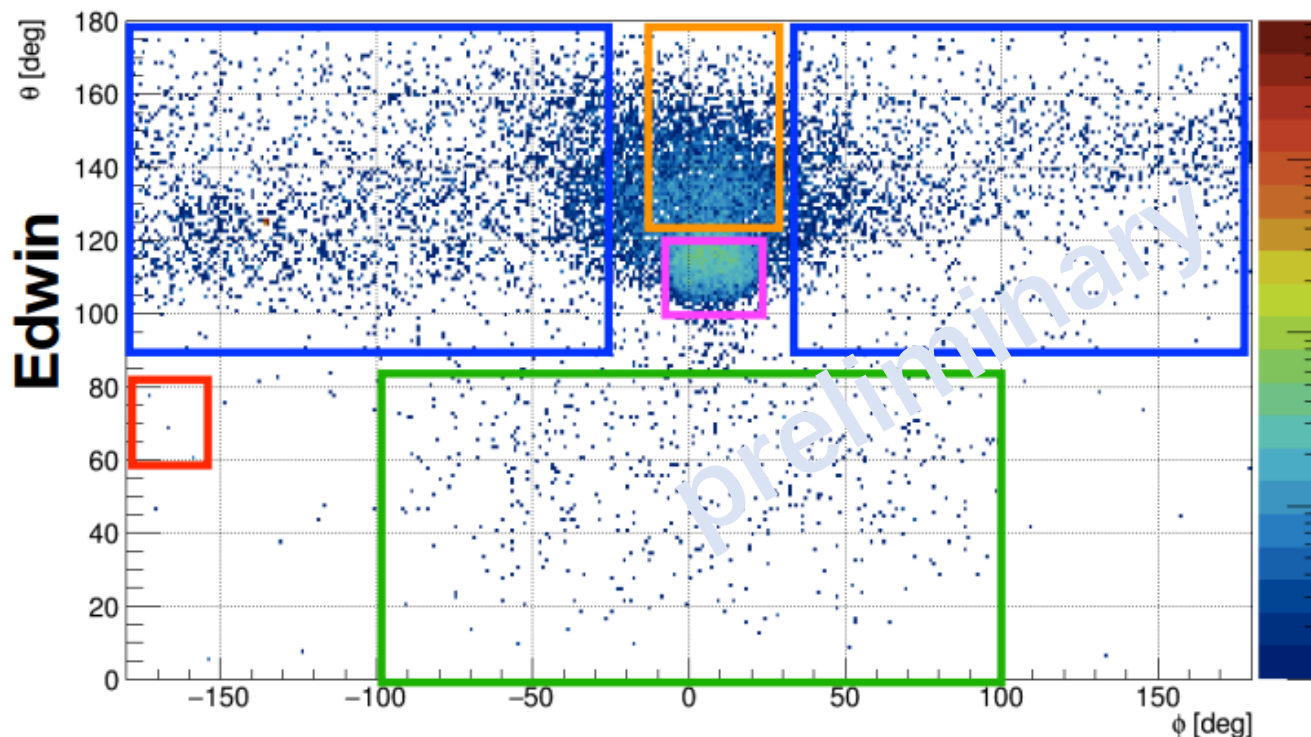
JUNO-OSIRIS Joint Muon Candidates

- Clear time correlation:
 - $\pm 1\mu\text{s}$
- Rate: $\sim 0.01\text{Hz}$
- Obviously identified from
 - JUNO only
 - Random coincidence



JUNO-OSIRIS Angular Distribution

JUNO Angular Distribution (Time Filtered)

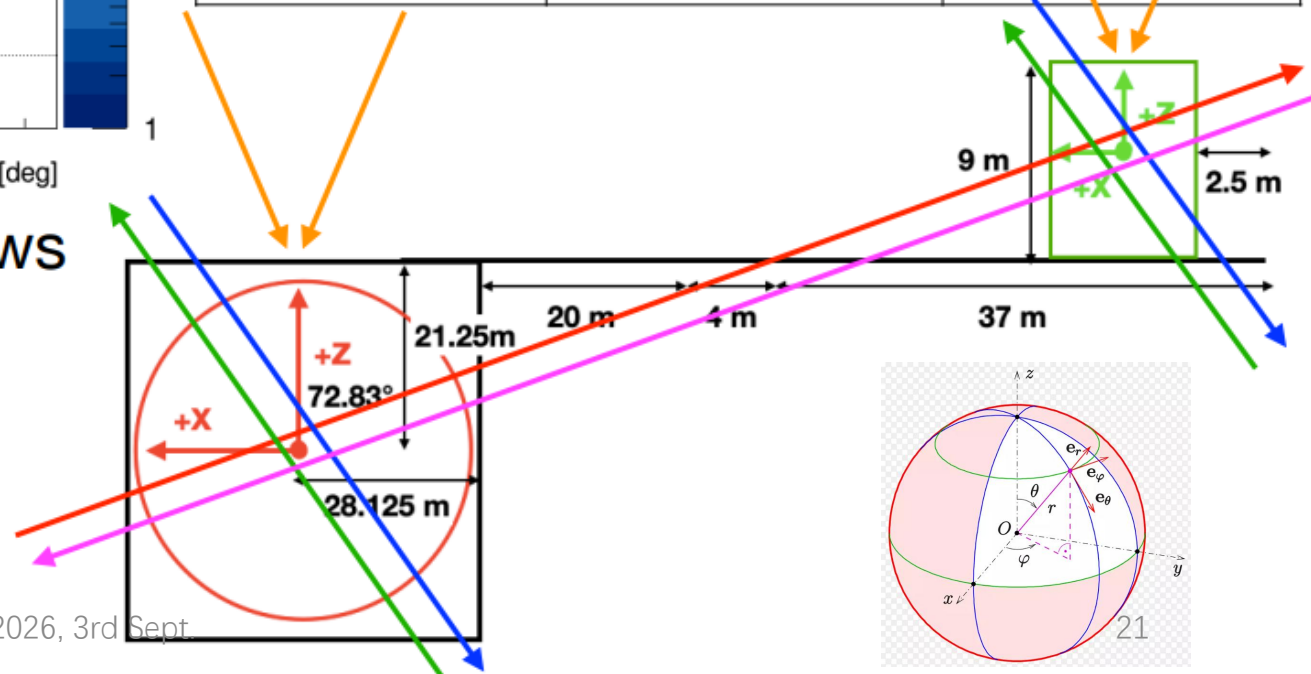


	JUNO $\rightarrow$ OSIRIS	OSIRIS $\rightarrow$ JUNO
center-to-center θ	72.82°	107.18°
θ Range	$60.1^\circ - 87.6^\circ$	$98.6^\circ - 115.1^\circ$
center-to-center ϕ	-172.55°	7.45°
ϕ Range	$[-175.6^\circ, -169.5^\circ]$	$4.4^\circ - 10.5^\circ$

- JUNO muon angular distribution shows different possibilities of muon track
- Going-through muons with OSIRIS
- Muon bundles

Zhimin Wang

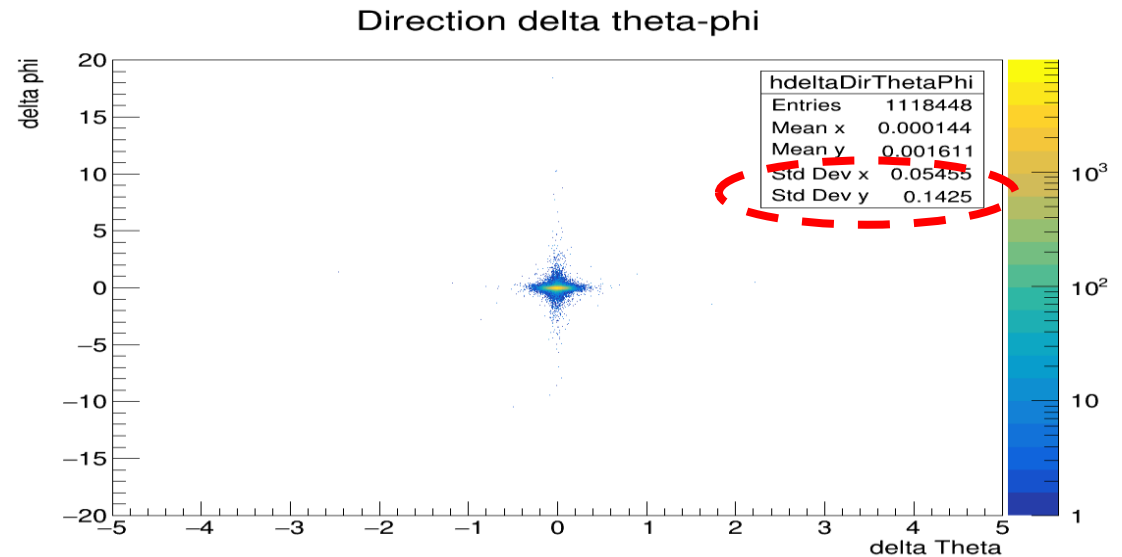
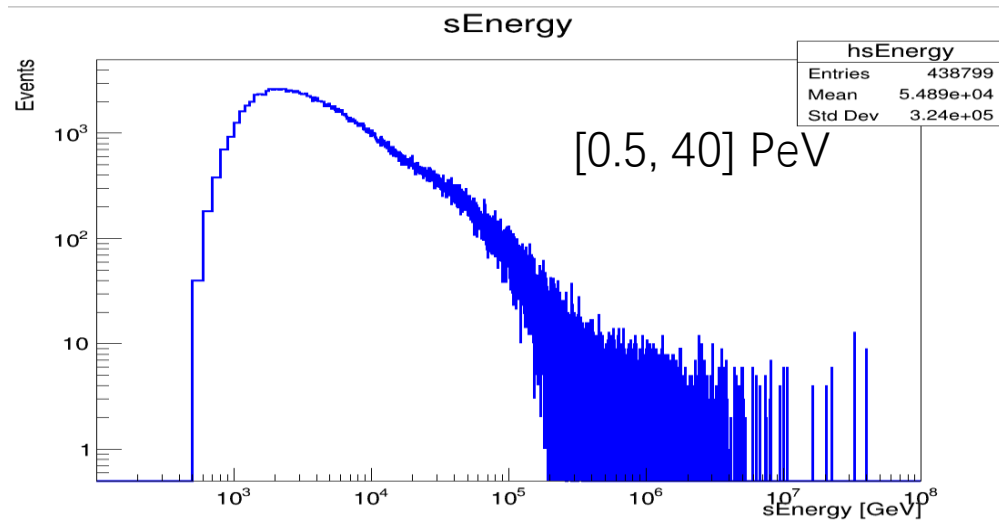
PPC2026, 3rd Sept



Primary cosmic ray MC Samples (CORSIKA)

JUNO ground

- Simulated primary cosmic ray in atmosphere
 - Proton, He, CNO, Al, Fe
- Checked sub-muons
 - On ground $\sim 0\text{m}$
 - Sub-TeV muons are good tracers of their parent cosmic-ray direction.
 - Better than 0.1 degree when $E > 400\text{GeV}$ of sub muons
- Preliminarily checked underground muon variation to ground

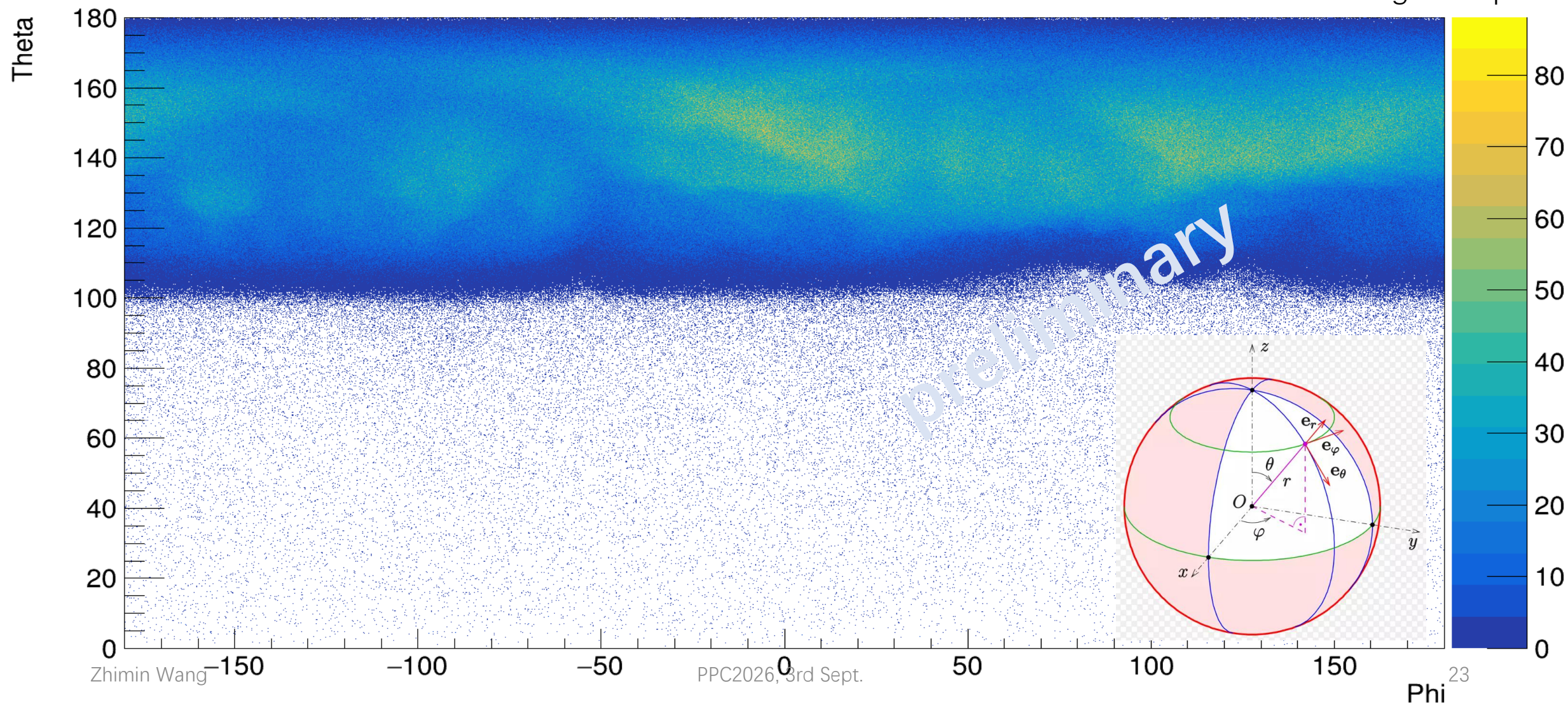


JUNO only Muon

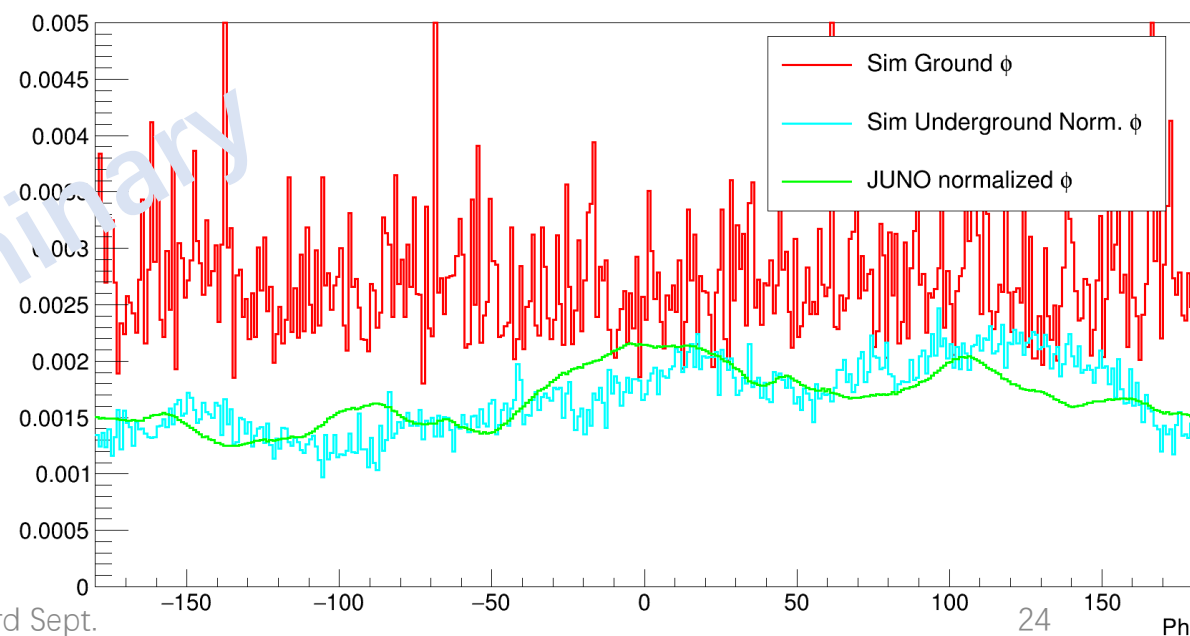
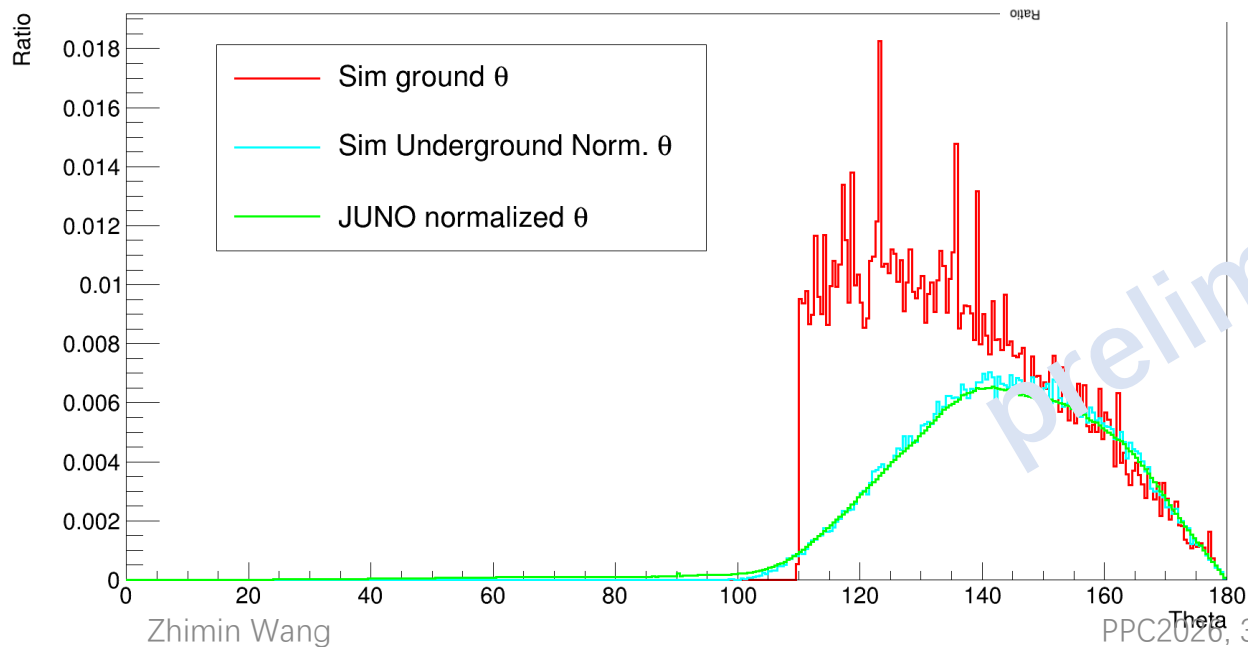
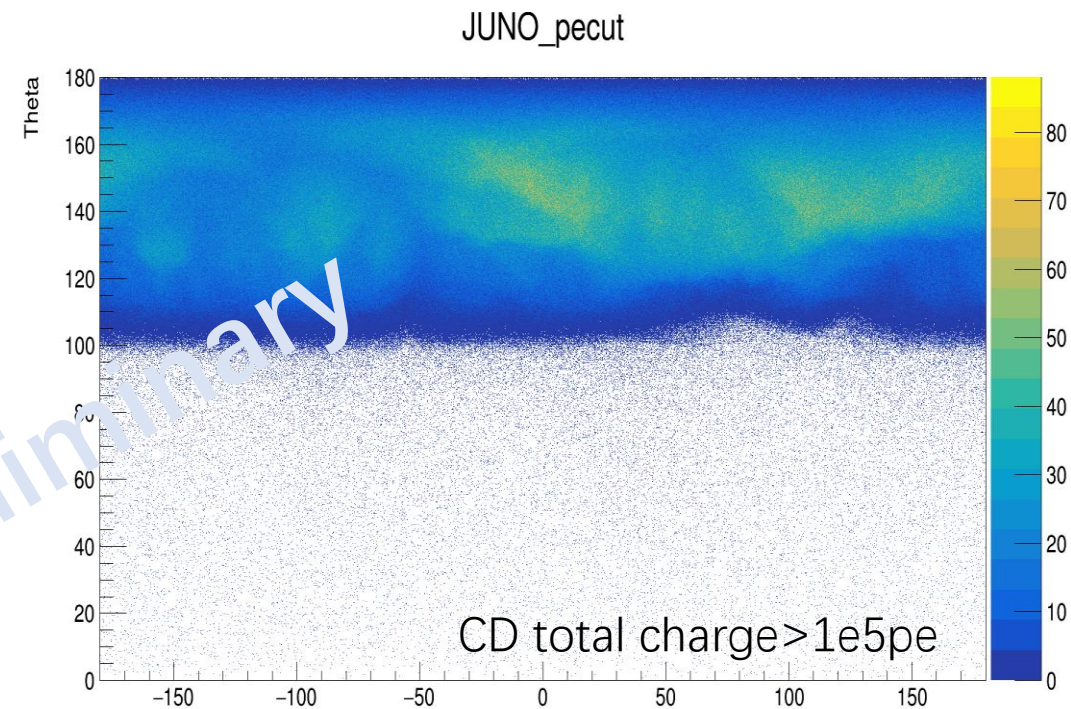
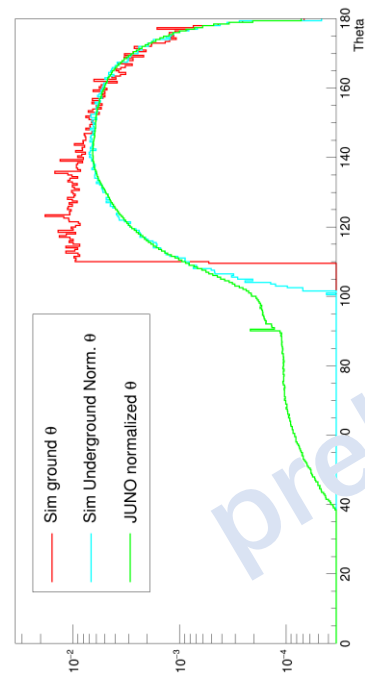
(preliminary reconstruction)

Aug. 2025 ~ May. 2026

CD total charge $> 1e5pe$



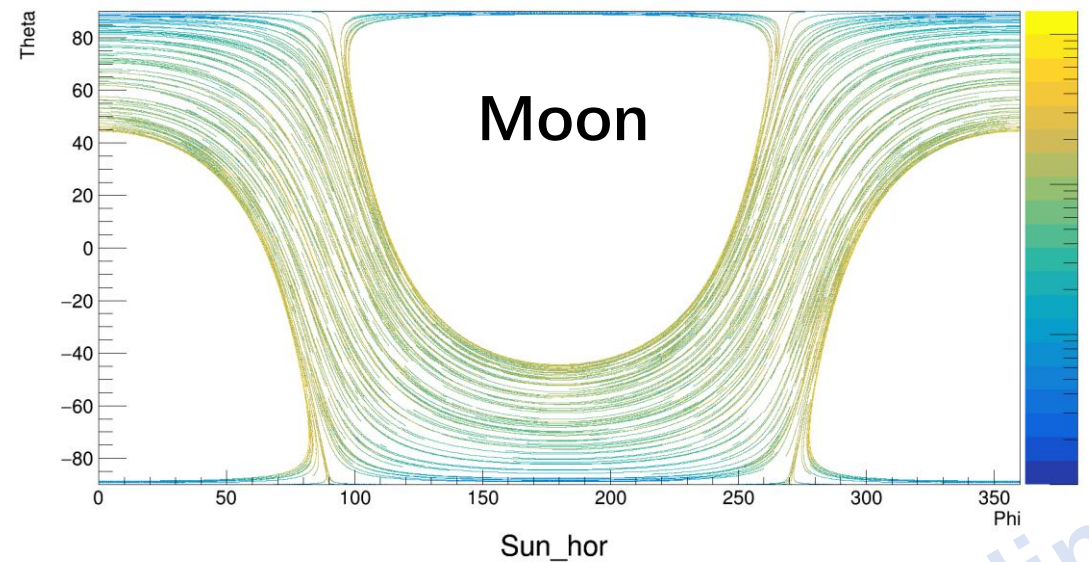
Underground muon direction



Check correlation to Moon/Sun

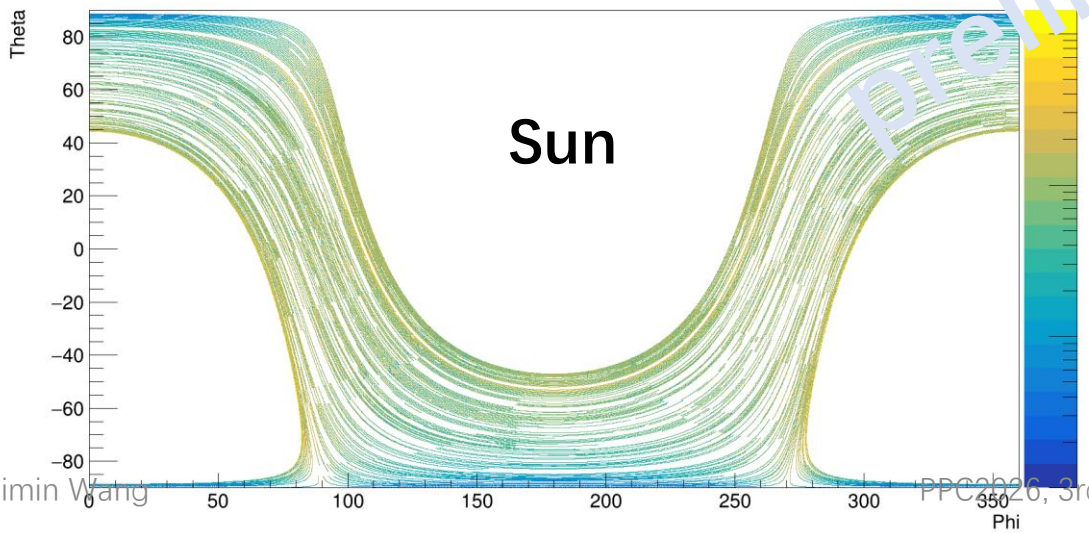
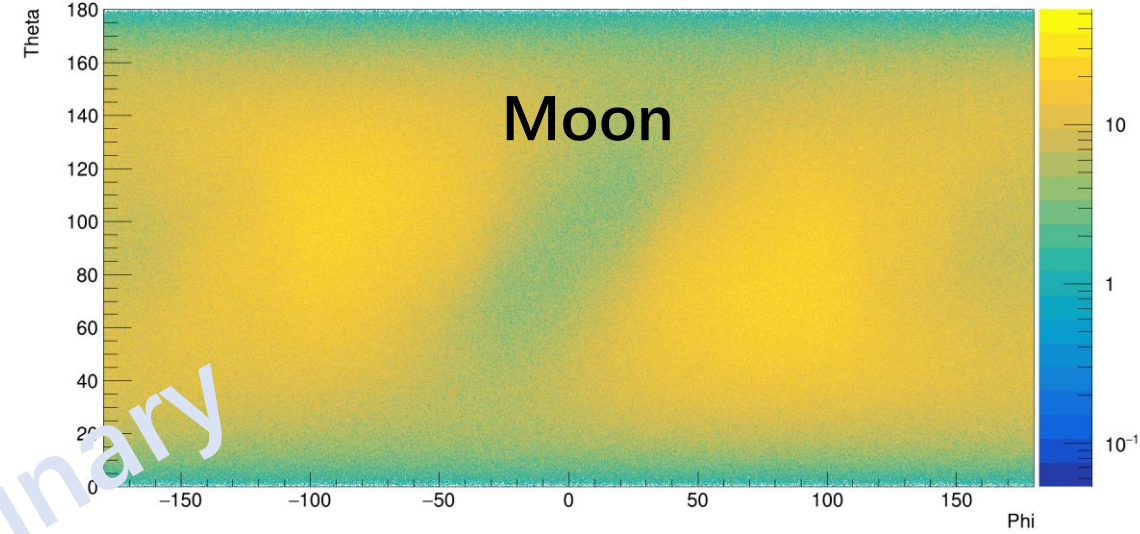
Horizontal coordination

Moon_hor

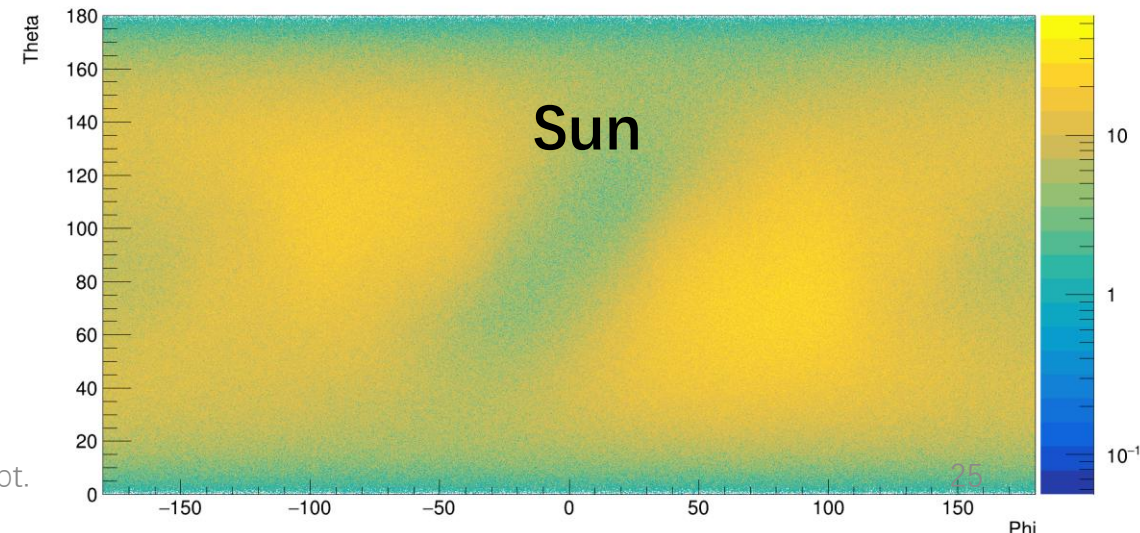


JUNO → Moon/Sun

Moon



Sun

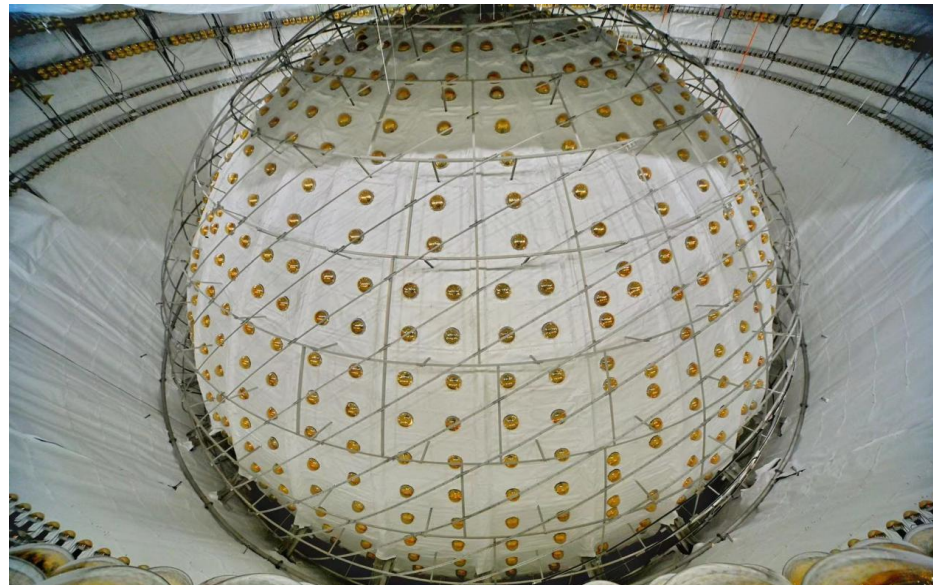


JUNO Muon on Equatorial coordinate system



Summary

- The JUNO detector and TAO are successfully built and operating smoothly
- Initial performance shows that the detector works well as designed
- With external constraint, **Normal Mass Ordering** is favored at $\sim 2.3\sigma$
- JUNO (&OSIRIS) will provide a good chance to measure the primary cosmic ray with good direction reconstruction



Thanks



backup

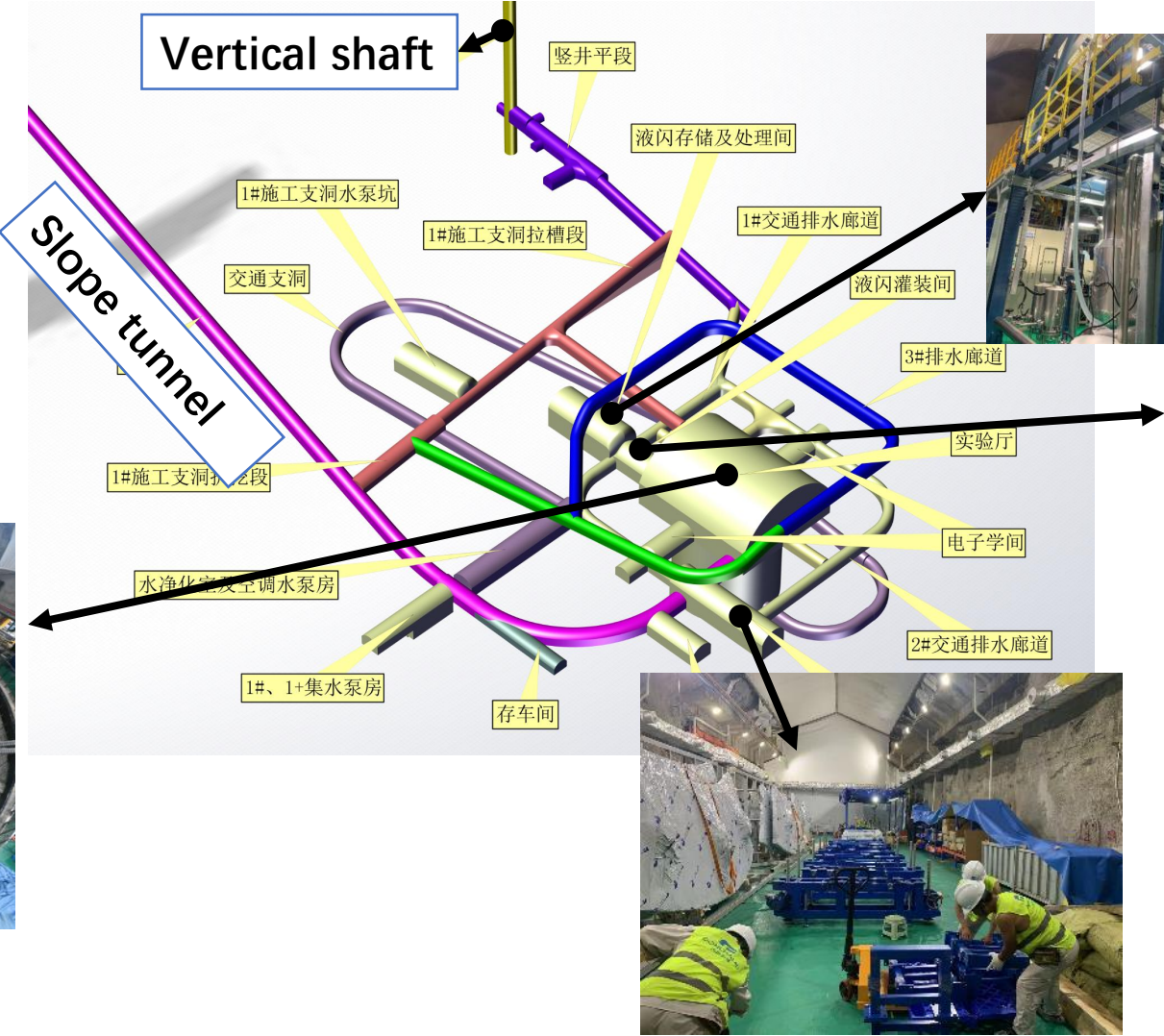
JUNO Underground Lab



Electronics rooms



Experimental Hall



OSIRIS



Liquid Scintillator hall



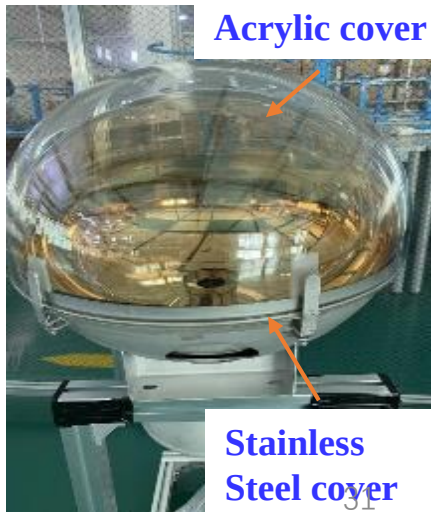
Filling Overflow Circulating room



Underground installation room

PMTs and Electronics

	LPMT (20-inch)		SPMT (3-inch)
	Hamamatsu	NNVT	HZC
Quantity	5000	15012	25600
Charge Collection	Dynode	MCP	Dynode
Photon Efficiency	28.5%	30.1%	25%
Dynamic range	[0, 100] PEs		[0, 2] PEs
Coverage	75%		3%
Reference	Eur.Phys.J.C 82 (2022) 12, 1168		NIM.A 1005 (2021) 165347



LPMT & sPMT

LPMT Underwater box

sPMT Underwater box

Potted PMT

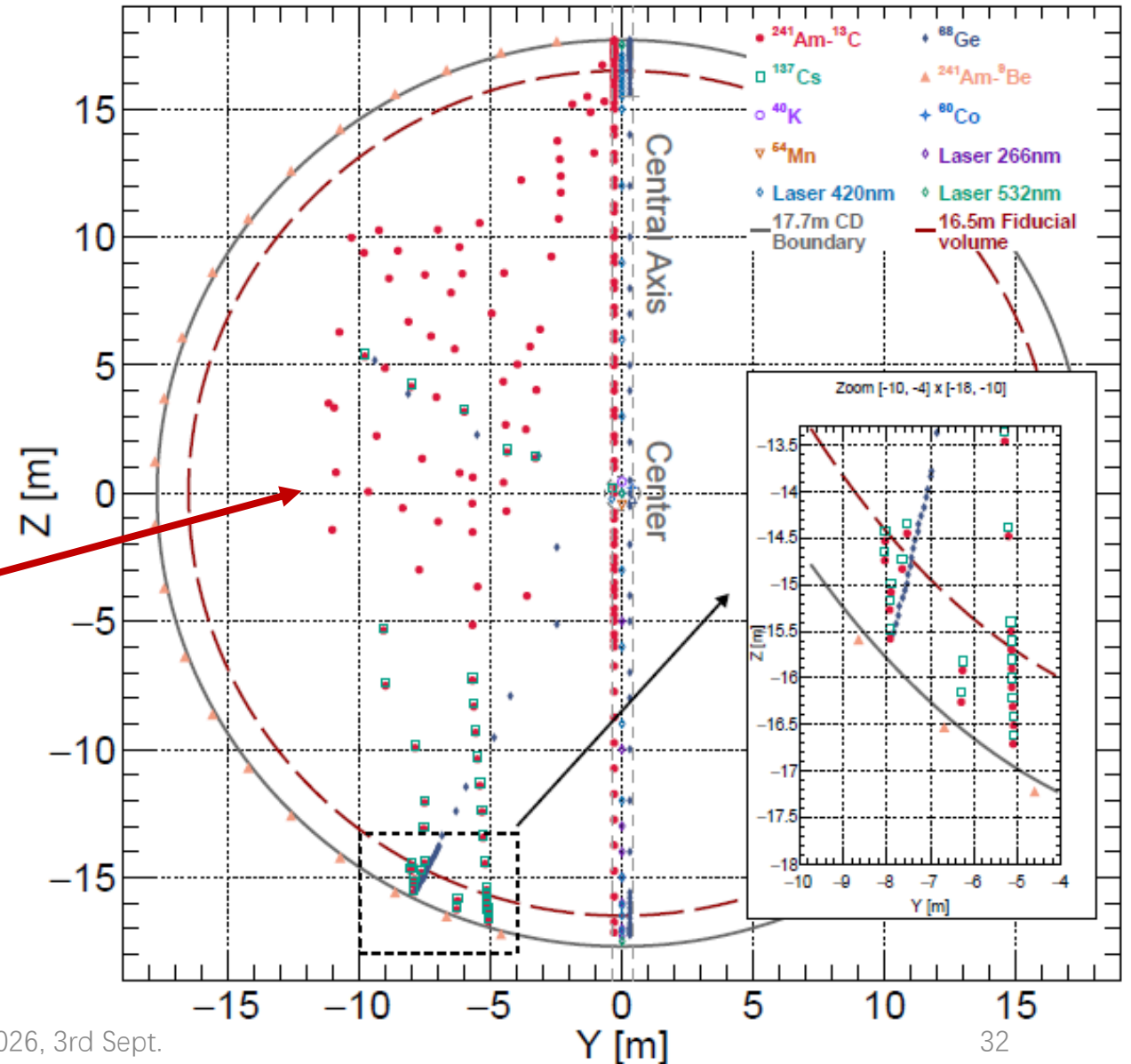
Acrylic cover

Stainless Steel cover

Calibration

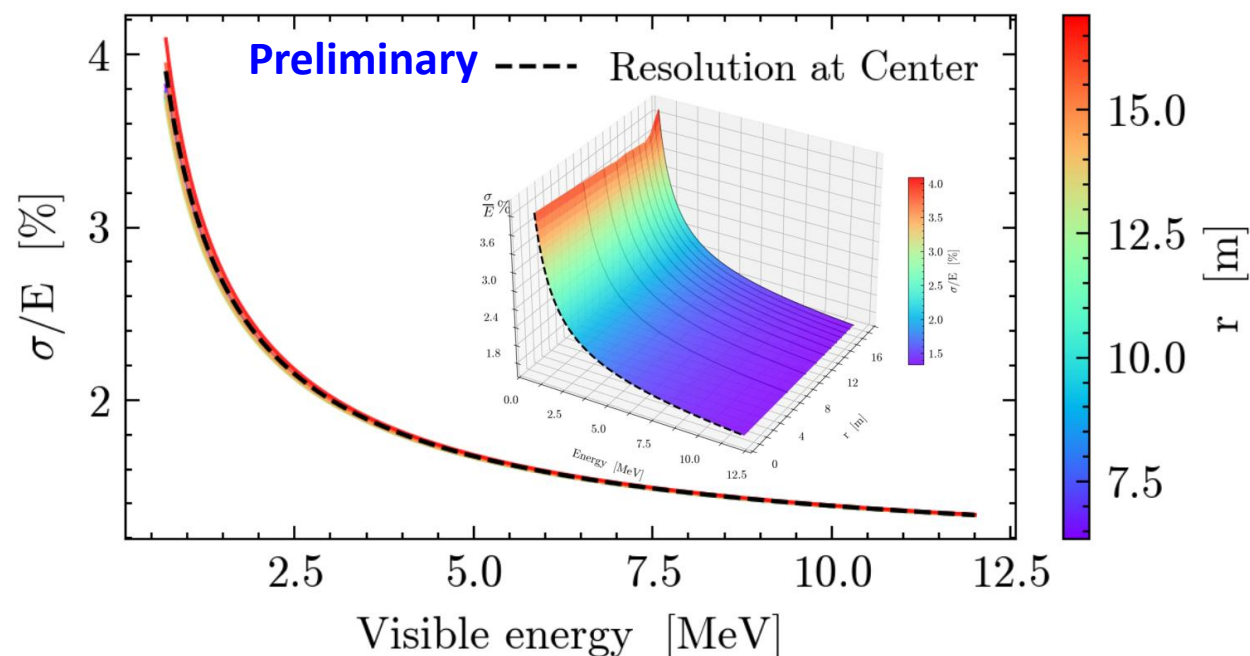
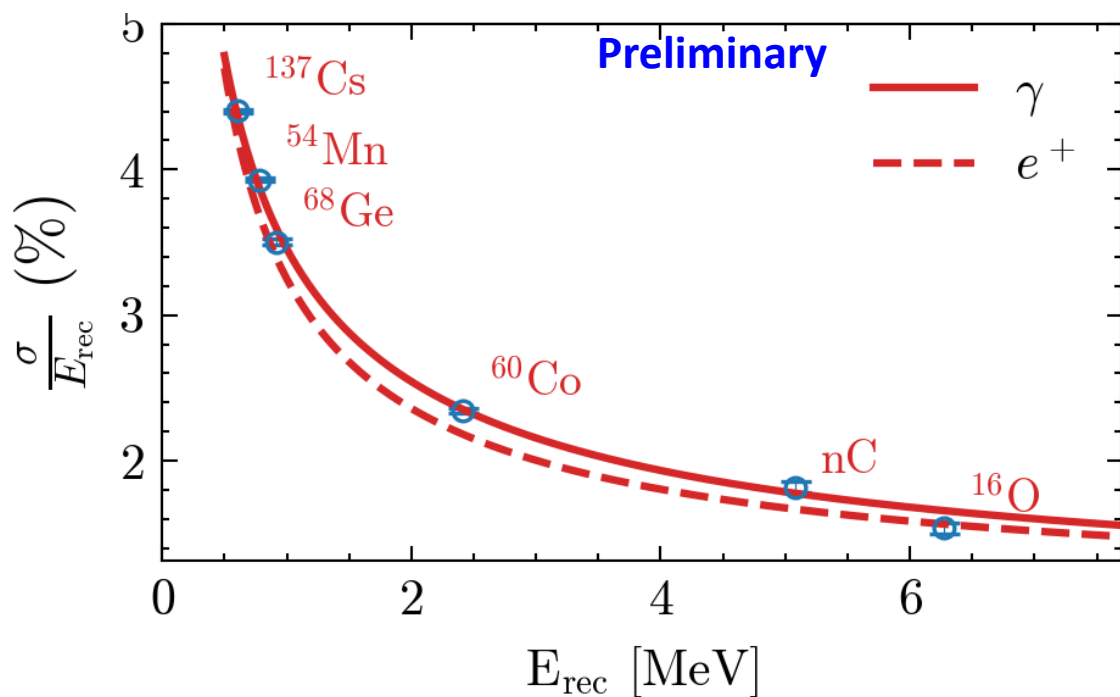
- 1D (central axis): ^{137}Cs , ^{54}Mn , ^{40}K , ^{68}Ge , ^{60}Co , Am-C, Am-Be, sensors, laser
- 2D (cable loop): Am-C, ^{68}Ge , ^{137}Cs
- 3D using cosmogenic backgrounds:
 ⇒ Bi-Po214 from Rn decays, spallation neutrons, other cosmogenic isotopes

- Positions at which source calibration performed
- No ^{222}Rn leakage or other contaminations introduced during calibration



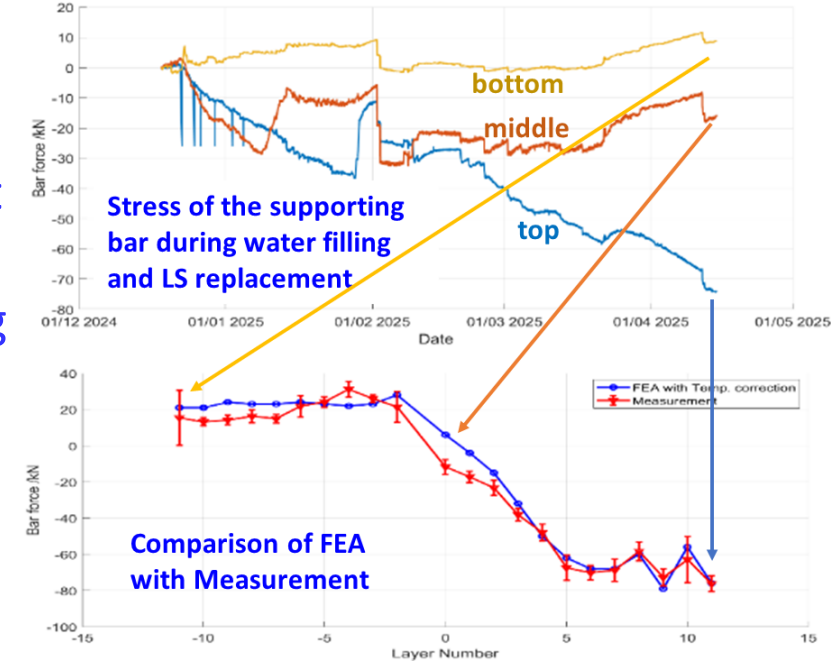
Energy Resolution Model

- Energy resolution is particle type, energy and space dependent
- An analytical R-dependent resolution model for e^+ was built using Geant4 simulation and data from calibration sources (α , γ)
- An energy response matrix was then used for e^+ spectrum fitting after adding ^{14}C pile-up to 5% events



Cracks on the Acrylic Tank

- Main structure is safe, stress within expectations
- However, a LS leak to water happened on March 21, 2025:
 - ⇒ Abnormal trigger rate observed and confirmed by under water robot
 - ⇒ Leak was stopped within 1 week using epoxy and tape by divers
 - ⇒ Further repair by epoxy and acrylic plate to reduce the stress (pulling open the crack) by 50%
- Another leak of water to LS happened on March 19, 2026:
 - ⇒ Experienced divers were called to stop the leak within 2 days
 - ⇒ Further repair in the following two days
 - ⇒ A total of $\sim 1\text{Bq } ^{222}\text{Rn}$ went into LS, 13 days of data excluded
 - ⇒ No other increase of radioactive backgrounds in LS



Zhimin Wang



PPC2026, 3rd Sept.



Reactor Neutrino Selection

Posters: 346, 328,
357, 273, 404

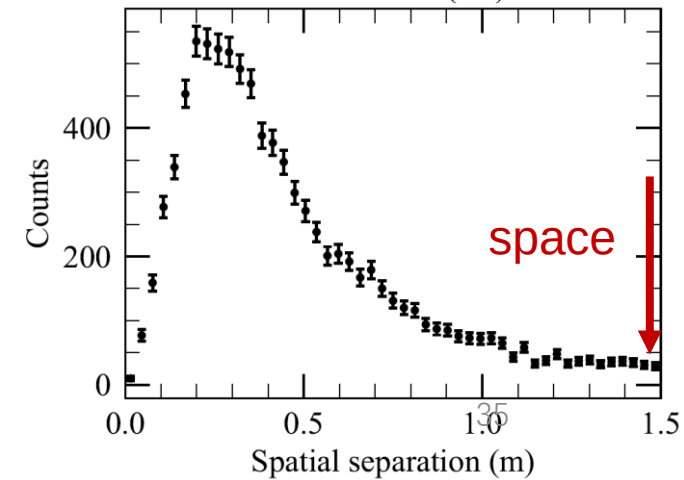
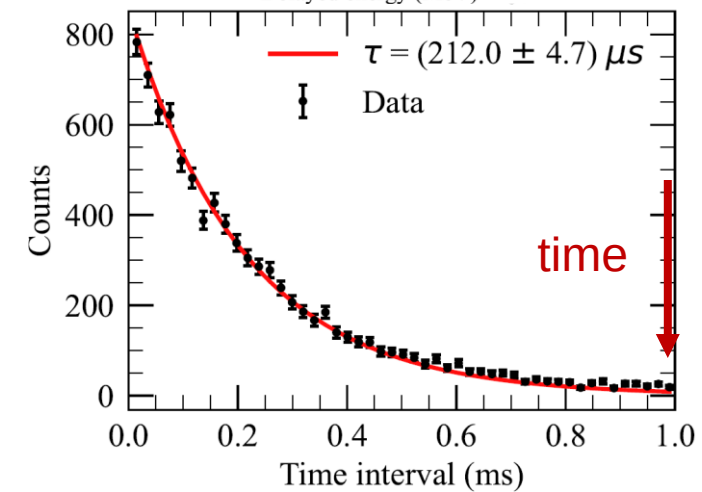
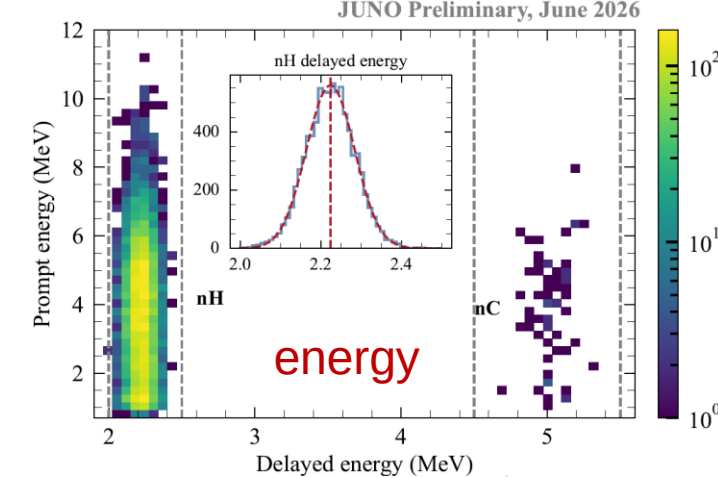
- Prompt and delayed coincidence in time, space with energy features

Criterion	Selection
PMT flasher	Applied
Fiducial volume	$r_p < 17.2$ m, $ z_p < 15.5$ m
Prompt energy	(0.7, 12) MeV
Delayed energy	(2.0, 2.5) $\cup$ (4.5, 5.5) MeV
Coincidence time	(5, 1000) μ s
Relative distance	< 1.5 m
Multiplicity cut	No other events > 0.7 MeV in the FV or (2.0, 6.0) MeV outside the FV within 2 ms before and 1 ms after the delayed event
Water pool muon veto	Veto if the delayed is within (0, 2) ms after NPE > 700 in WP
CD muon veto	Veto if the delayed is within (0, 5) ms after NPE $> 3 \times 10^4$ in CD
Spallation neutron veto	Veto if the delayed satisfies $\Delta r < 4$ m and $\Delta t < 1.2$ s after spallation neutrons with $NPE_{\text{spn}} \in (3000, 30000)$ and $T_{\text{spn}2\mu} \in (20, 2000) \mu$ s
Muon track veto	Veto if the delayed event: $\frac{\Delta r_{\mu d}}{2.5\text{m}} + \frac{\Delta t_{\mu d}}{0.5\text{s}} < 1$
Correlated discriminator	$\log(\text{L.R.}) > -1.26$

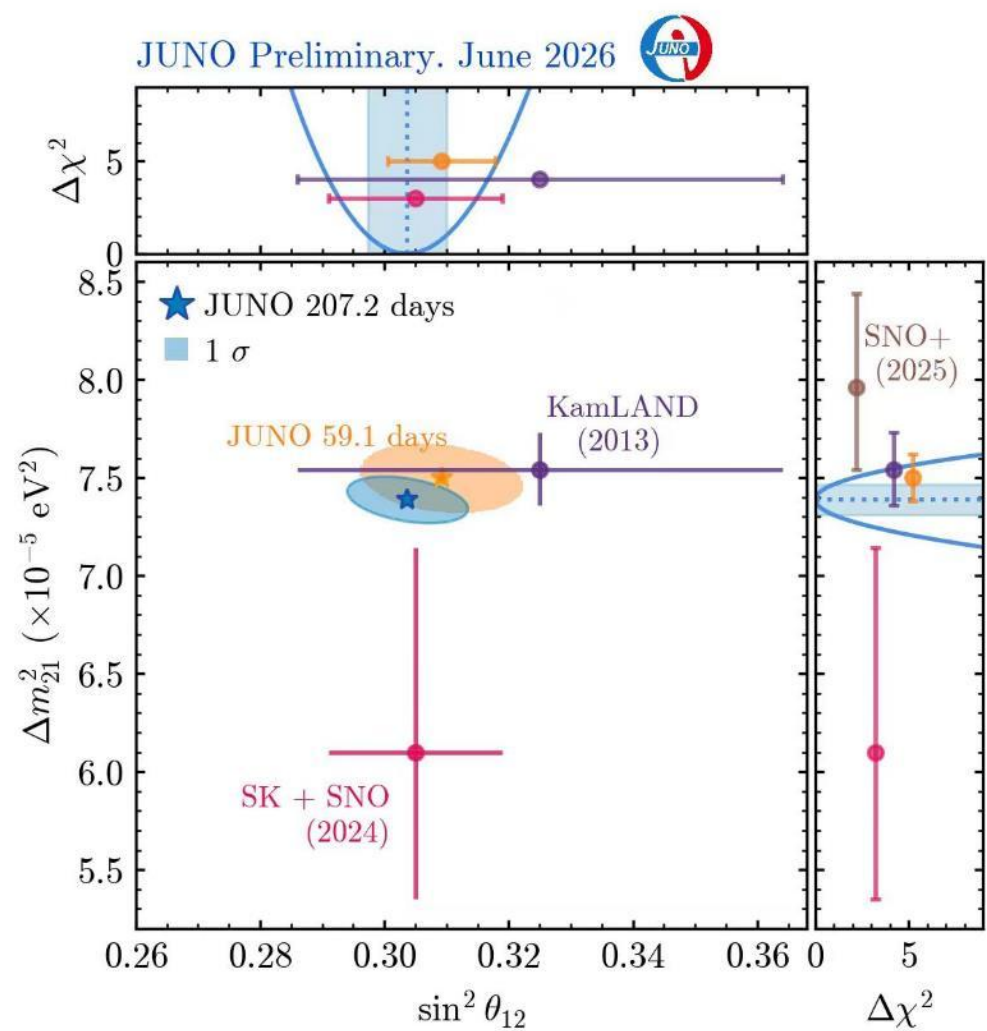
Similar to our
“Nature” paper

- What is new in this analysis:

- ~10% more fiducial volume (R=16.5m $\rightarrow$ 17.2m)
- ~60% reduction of ^9Li bkg.
- a factor of 50 reduction of accidental bkg. using likelihood cut
- model independent estimate of the ^{214}Bi bkg.



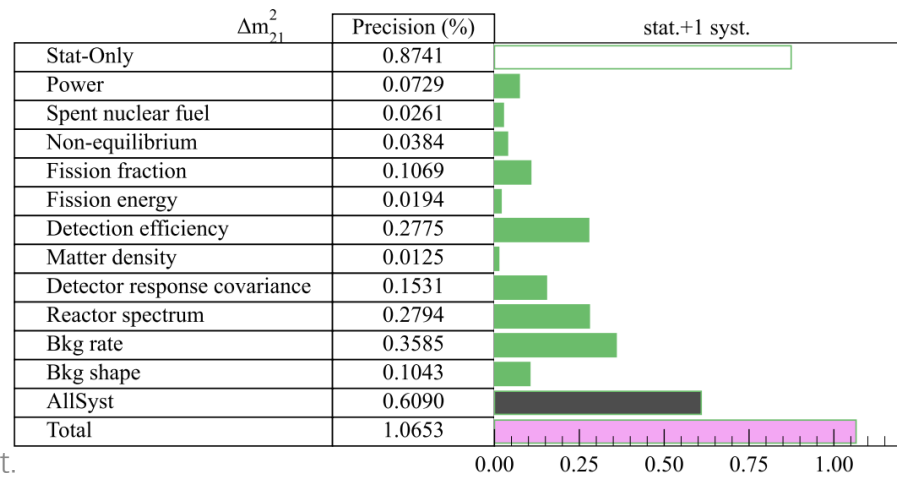
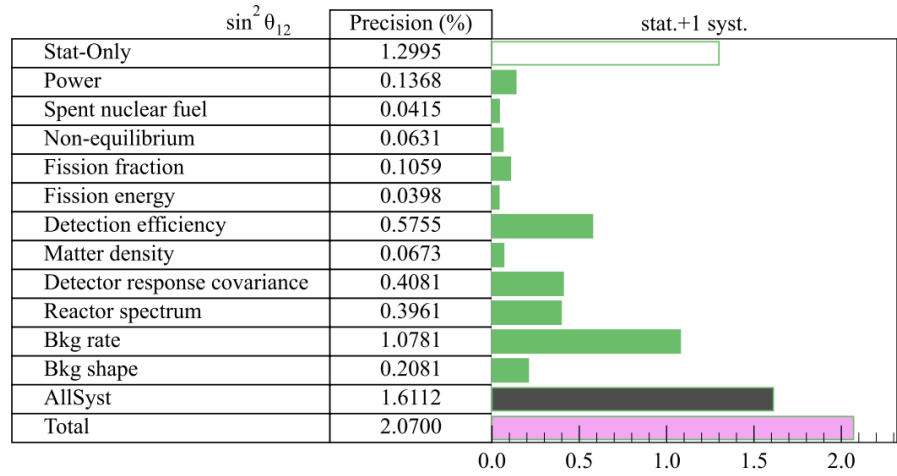
Solar Oscillation Parameters



Δm_{21}^2	7.388 ± 0.078 (1.60% → 1.06%)
$\sin^2 \theta_{12}$	0.3036 ± 0.0064 (2.8% → 2.1%)

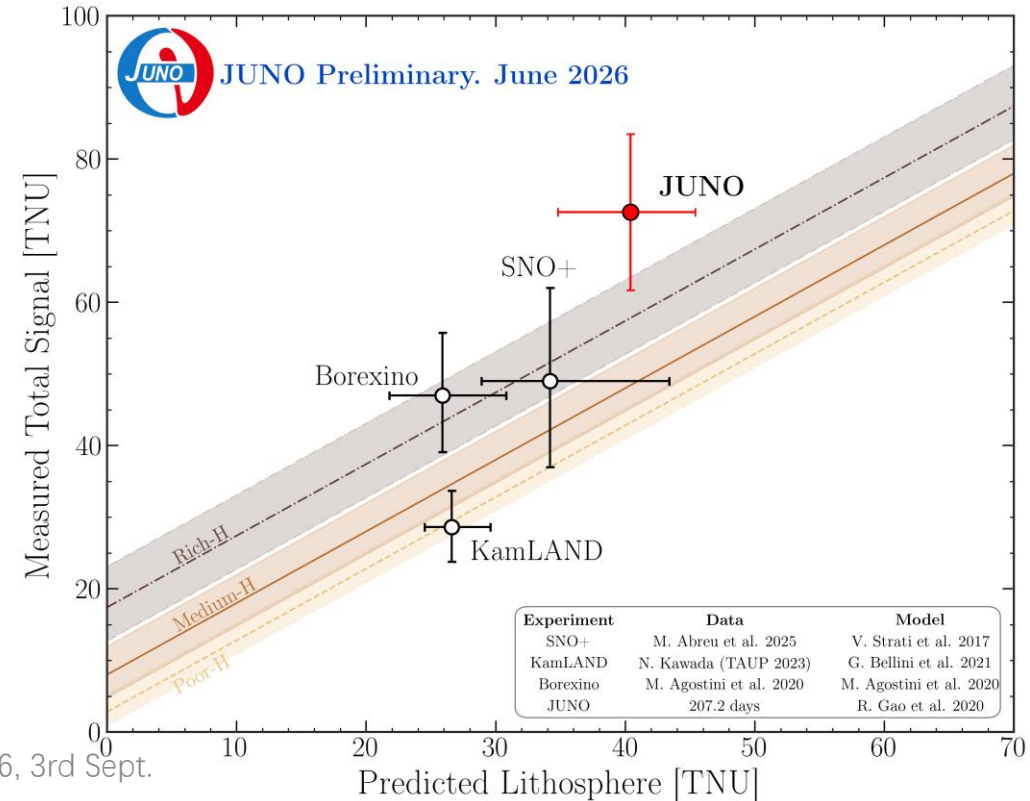
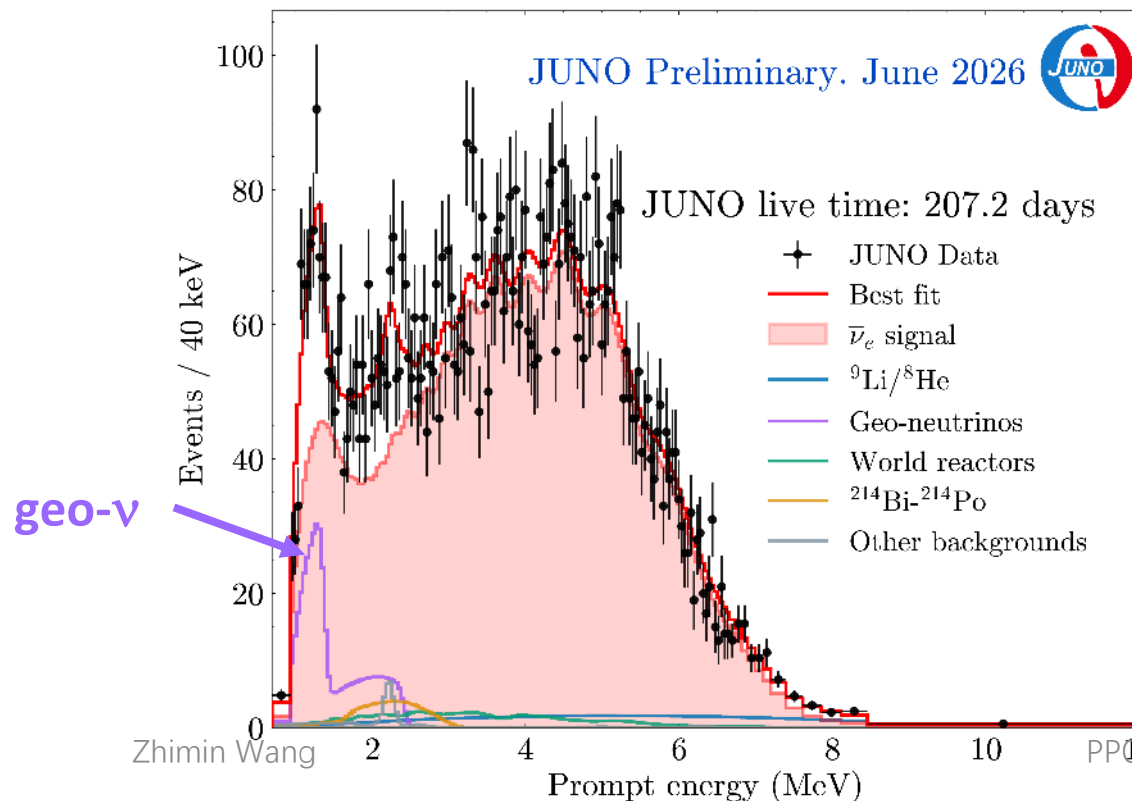
Zhimin Wang

- Even though the statistical uncertainty is dominant, systematic errors become important:
⇒ ^{214}Bi bkg. and detection eff. can be improved



Results on Geo-neutrinos

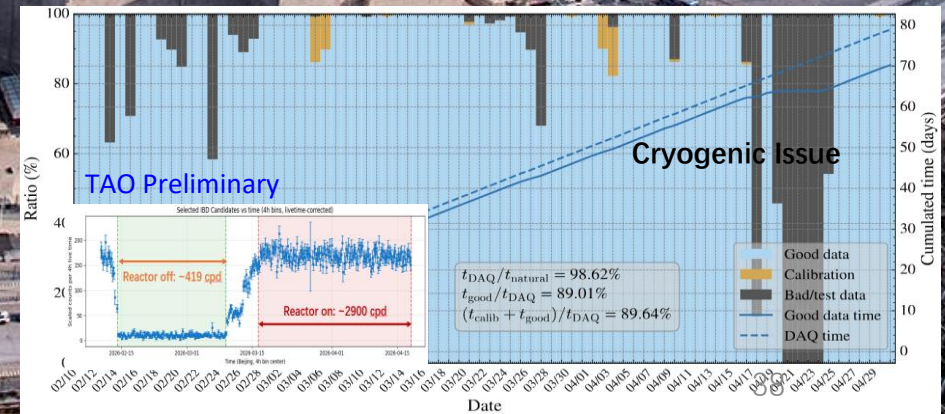
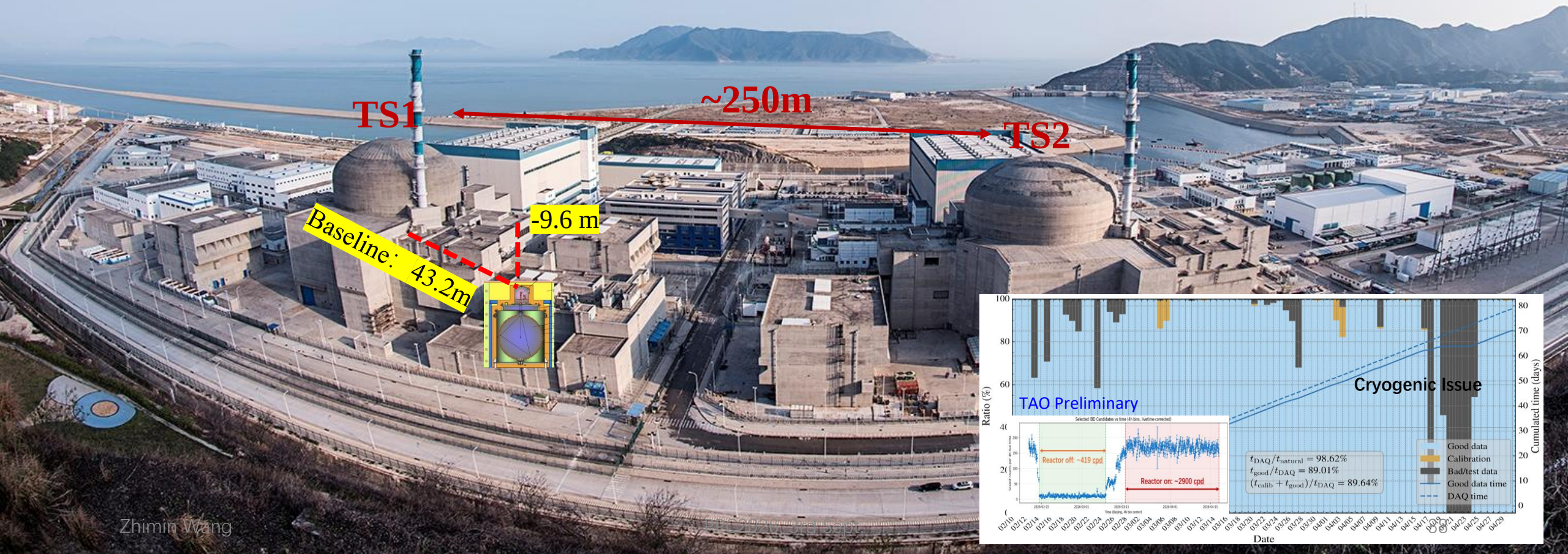
- Fits are performed without constraint on geo-neutrino flux, but with $3.4 \pm 10\%$ U/Th ratio
 - ⇒ Constraining the geo-nu flux doesn't change oscillation results
- Clear geo-nu signals at 1-3 MeV, giving a flux of 73 ± 11 TNU
 - ⇒ Largest geo-neutrino samples so far, and most precise measurement
- JUNO result is higher than expectation from existing models, but not statistically significant
- Need more JUNO data and more refined geological model predictions



TAO: Taishan NPP, Core #1

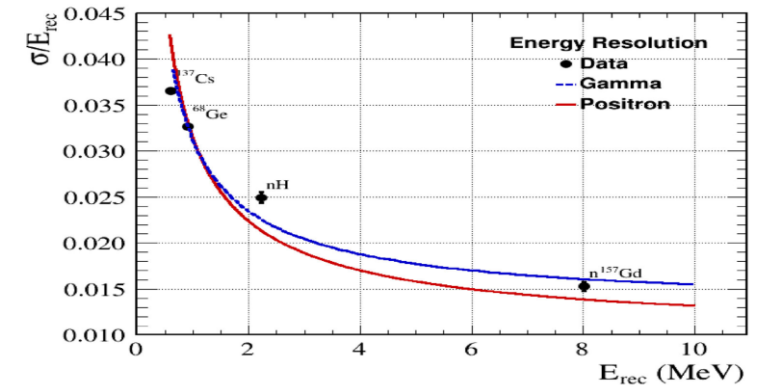
Ultra strict engineering management for civil work in Nuclear Island

TS1: world 1st EPR (3rd generation) in operation (China-French joint venture)

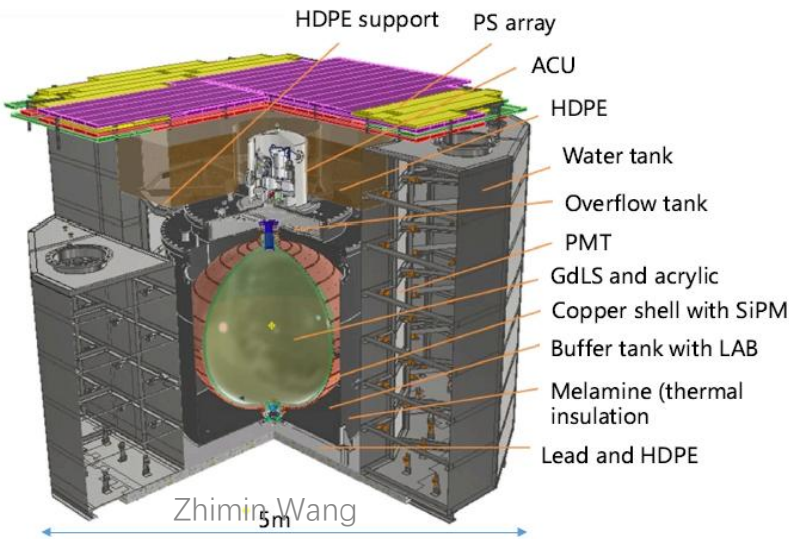
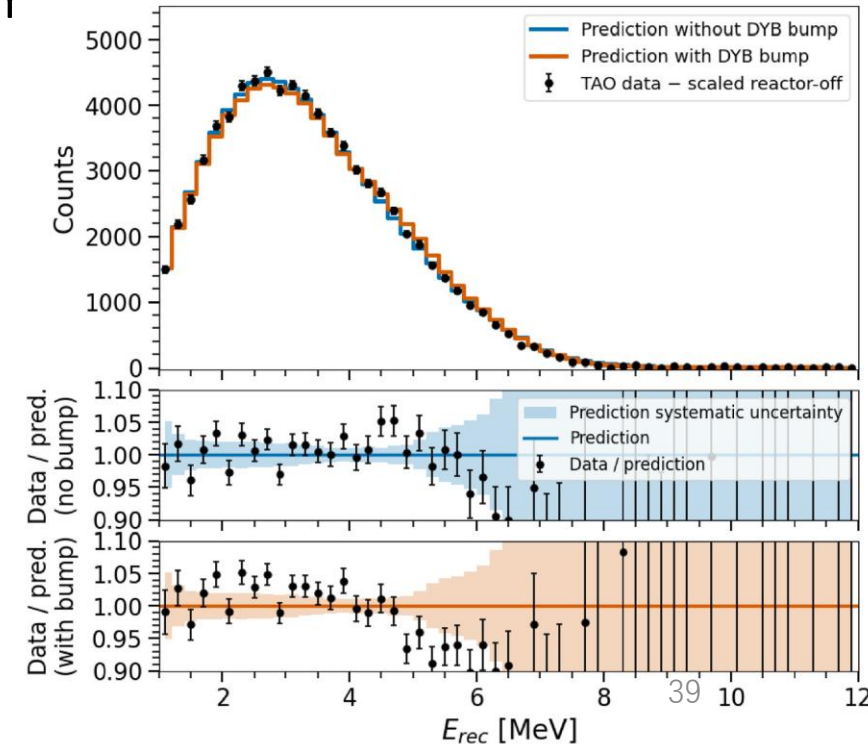


JUNO-TAO

- To measure the reactor neutrino spectrum as a reference
 - Mitigate possible fine structure and spectrum uncertainty issues
 - Improve nuclear database, search for sterile neutrinos
- Idea: Gd-loaded LS @-50°C + SiPM
 - 700k/year@44m from the core(4.6 GW), with ~10% bkg.
 - Energy resolution: 4500 p.e./MeV → ~2%@1 MeV
 - 10 m² SiPM (>94% coverage) w/ PDE > 50%
 - Operating at -50 °C to reduce the SiPM dark rate by 10³ to 50 Hz/mnr
 - 2.8 ton(1t fiducial volume) new type of Gd-LS for -50 °C

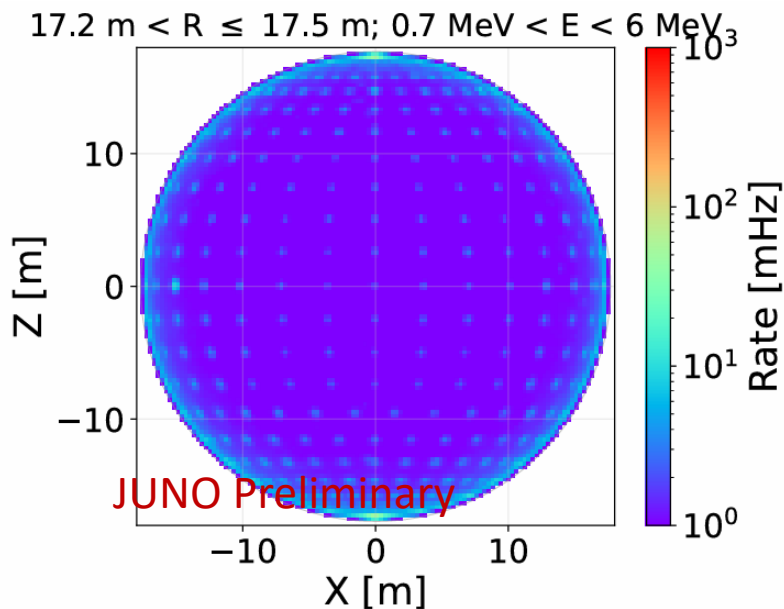


JUNO-TAO, 30 days

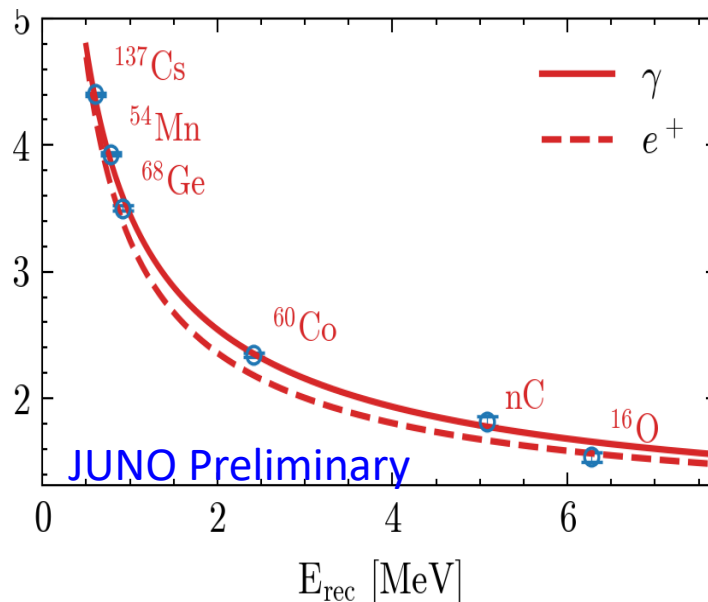


JUNO/TAO Key Performance

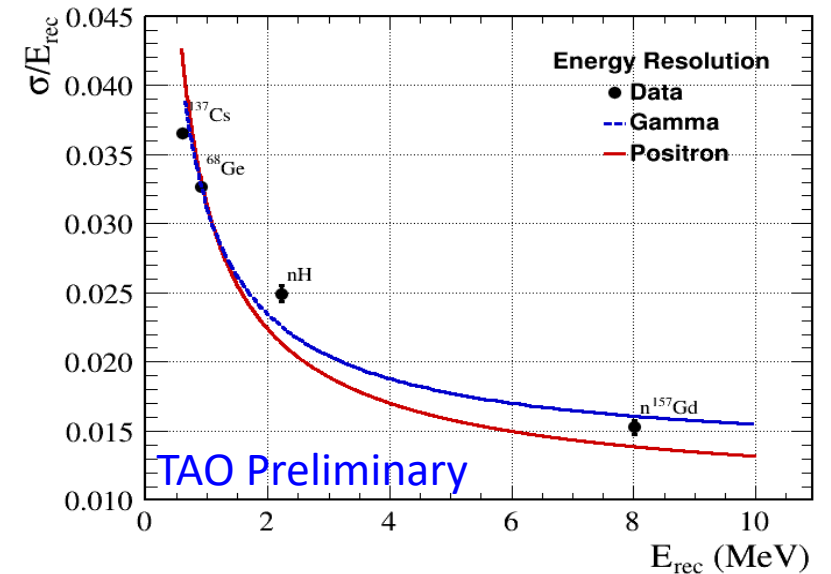
- JUNO / TAO energy resolution, 3.5% / 2.8% @ Ge-68 (~1MeV) (design 3% / 2%)
 - Further improvements ongoing
- JUNO low background: **detector is cleaner than design**
 - Dominating radioactivity is from PMT glass and SS node



Zhimin Wang



PPC2026, 3rd Sept.



40