Muon Secondary Particles Study in JUNO Experiment

Haojing Lai (SJTU)
on behalf of JUNO Collaboration

PFSPA 2025

Shanghai, China, September 25, 2025

Outline

◆ JUNO Experiment

◆ Muon Secondary Particles Study in JUNO

- ➢ Muon-Induced Background
- ➢ Cosmogenic Neutron / Isotopes for Detector Calibration

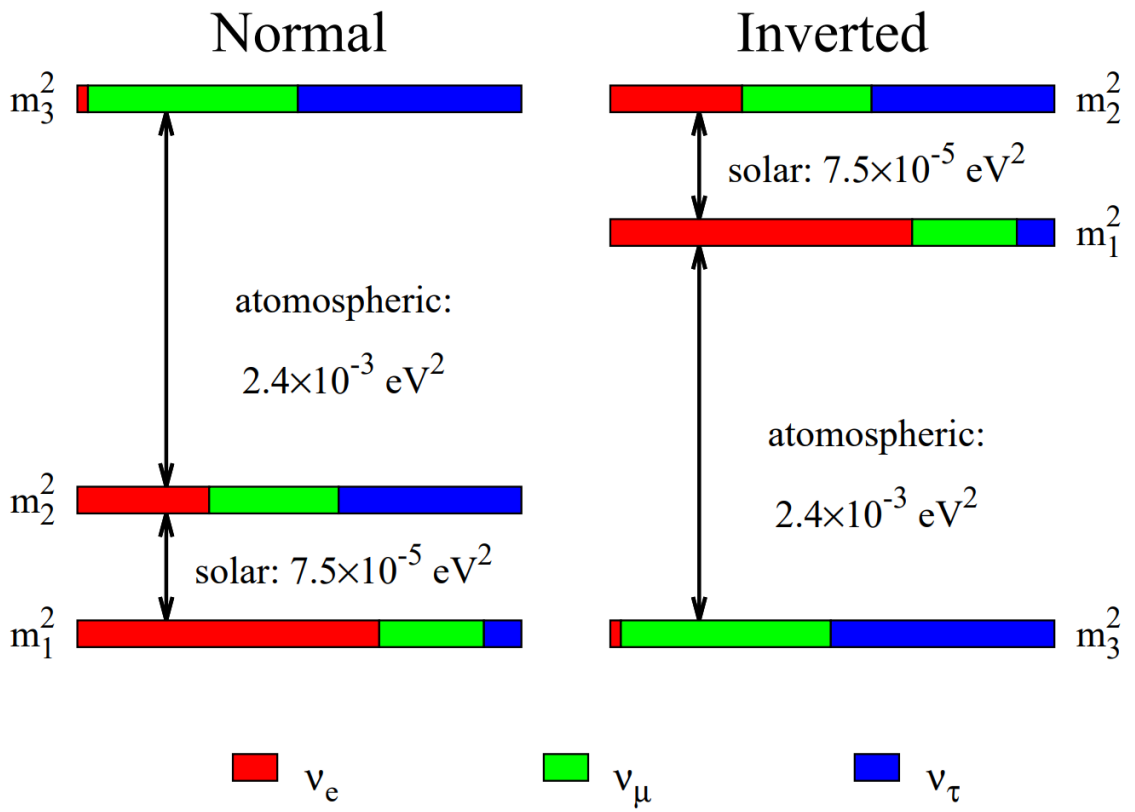
◆ Summary

JUNO Experiment

Neutrino mass ordering

- neutrino oscillation*: the flavor of neutrinos can be transformed into different flavors
- most parameters have been measured**, remaining unknowns:
  - mass ordering, δ_{CP}
  - Majorana or Dirac, absolute neutrino mass, *etc.*

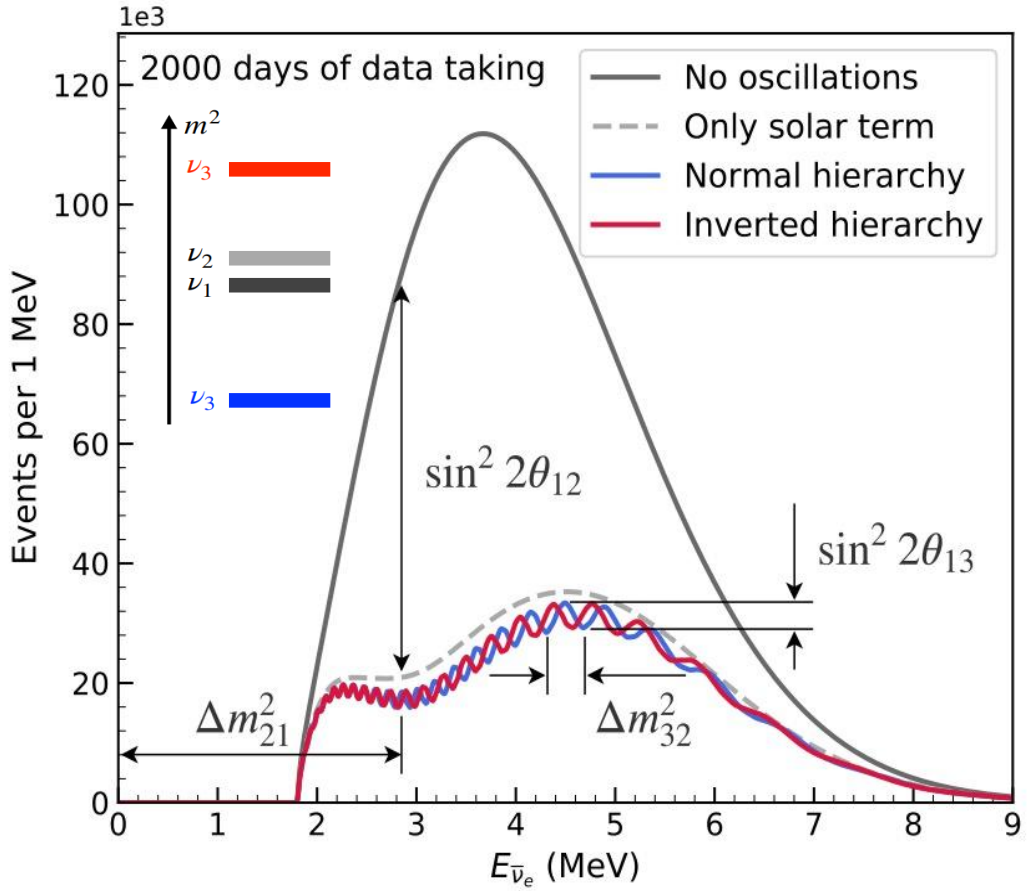
	PDG2020	Relative Uncertainty (1σ)
Δm^2_{32} (NMO)	$(2.453 \pm 0.034) \times 10^{-3}$ eV^2	1.4%
Δm^2_{32} (IMO)	$-(2.546 \pm 0.037) \times 10^{-3}$ eV^2	1.5%
Δm^2_{21}	$(7.53 \pm 0.18) \times 10^{-5}$ eV^2	2.4%
$\sin^2\theta_{12}$	0.307 ± 0.013	4.2%
$\sin^2\theta_{13}$	0.0218 ± 0.0007	3.2%



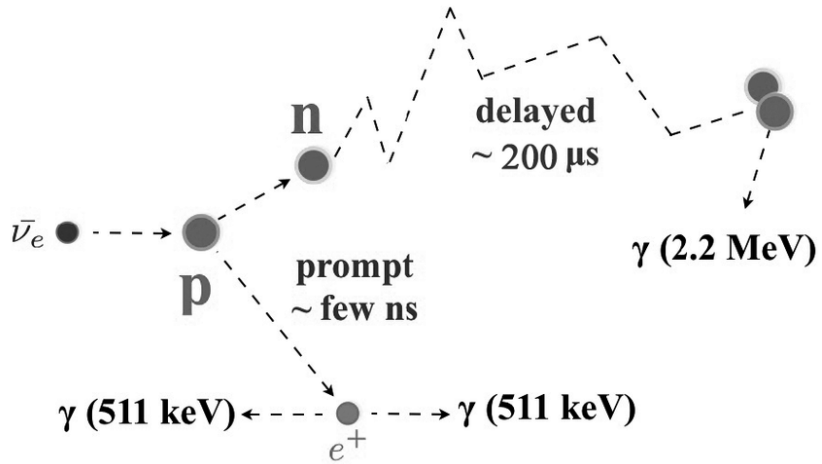
* An, F., & others (2016). Neutrino Physics with JUNO. J. Phys. G, 43(3), 030401.
** Abusleme, A., & others (2022). Sub-percent precision measurement of neutrino oscillation parameters with JUNO. Chin. Phys. C, 46(12),

Reactor Neutrino Disappearance

$$P(\overline{\nu}_e \to \overline{\nu}_e) = 1 - \sin^2 2\theta_{12} c_{13}^4 \sin^2 \frac{\Delta m_{21}^2 L}{4E} - \sin^2 2\theta_{13} \left[c_{12}^2 \sin^2 \frac{\Delta m_{31}^2 L}{4E} + s_{12}^2 \sin^2 \frac{\Delta m_{32}^2 L}{4E} \right]$$

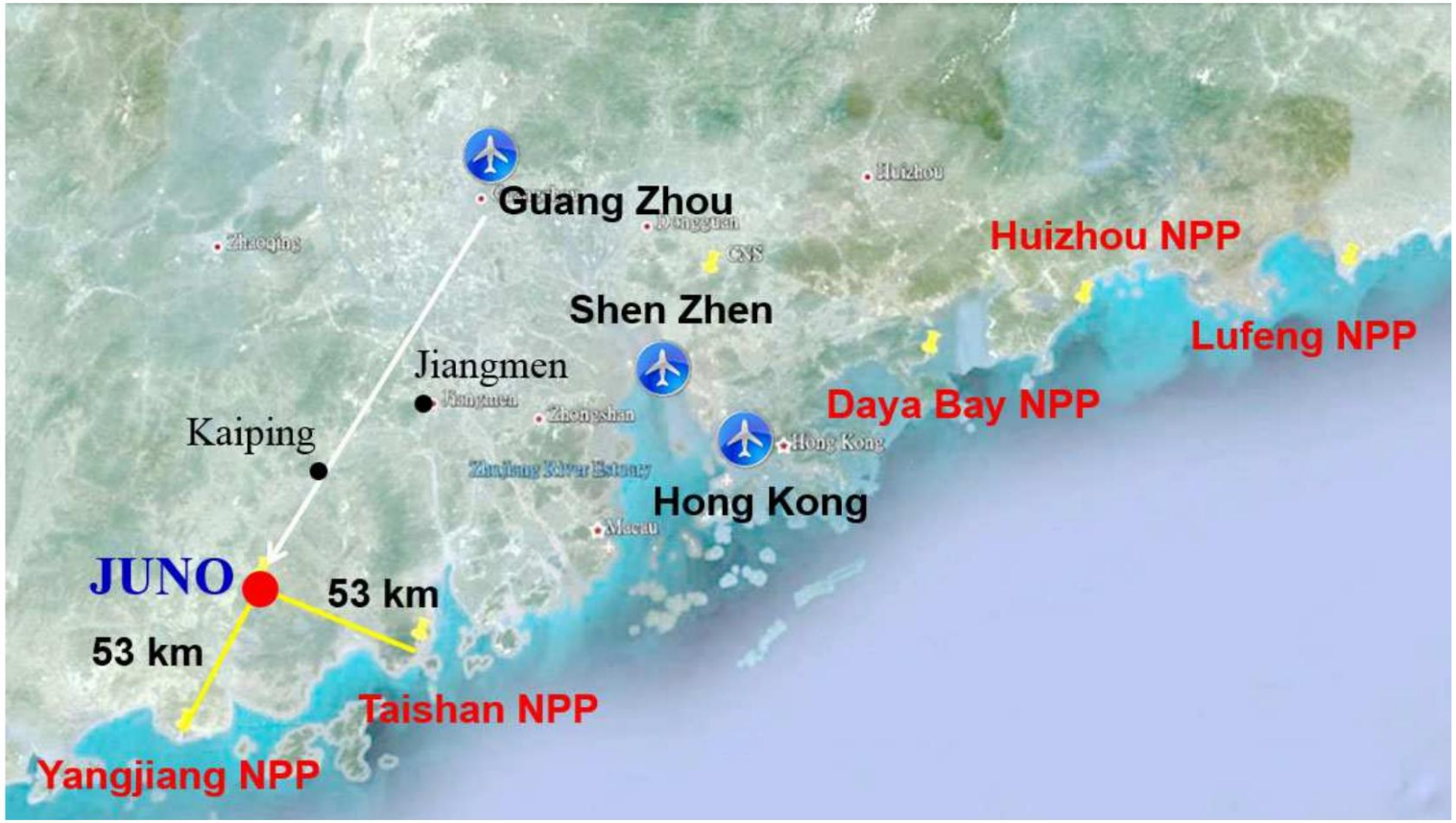


- neutrino spectrum: inverse beta decay (IBD)



- neutrino mass ordering
- precision measurement of θ_{12}, Δm^2_{21}, $|\Delta m^2_{31}|$

Experiment Location

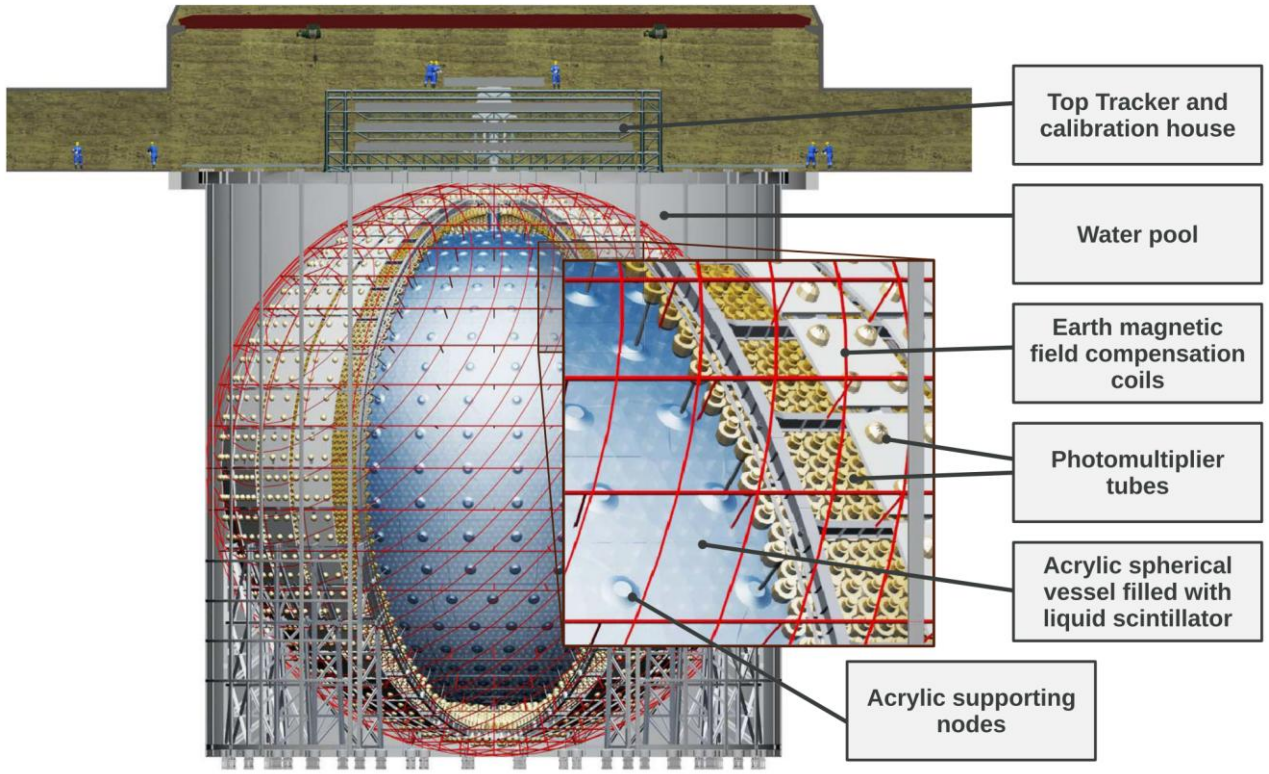


- JUNO (Jiangmen Underground Neutrino Observatory) is located in Jiangmen, Guangdong
- ~ 53 km from the Yangjiang nuclear power plant (NPP) and Taishan NPP
- physics data taking started on Aug. 26, 2025

Location

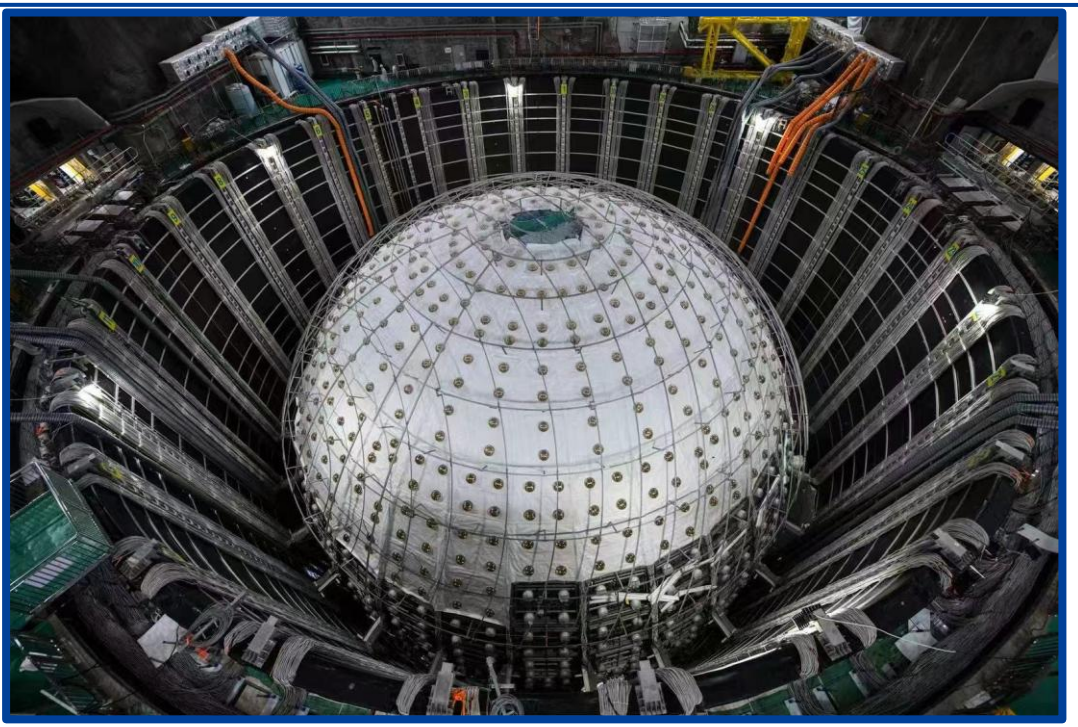
JUNO
~52.5 km
Taishan NPP
2×4.6 GW$_{th}$
TAO
Yangjiang NPP
6×2.9 GW$_{th}$
736.0 m
252.5 m
8 reactors
26.6 GW$_{th}$
~700 m
~52.5 km
JUNO
Vertical tunnel:
563 m
Overburden
~650 m
(1800 m.w.e.)
Slope tunnel: 1265 m
@ slope of 42 degrees
Civil construction finished in Dec, 2021

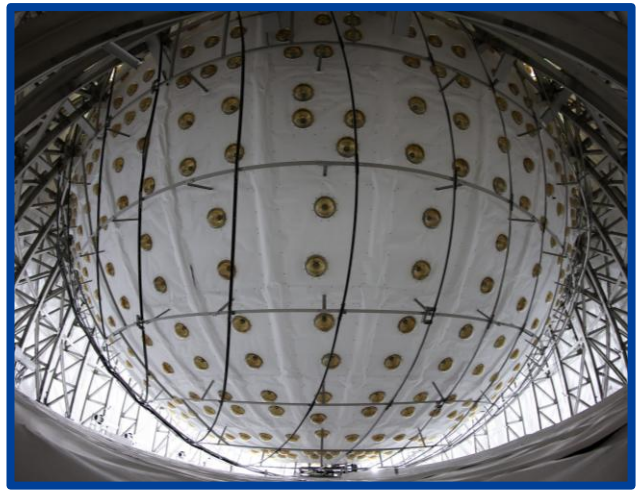
JUNO Detector



- energy resolution: 3% at 1 MeV
- 20 kton liquid scintillator (LS) contained in an acrylic sphere
- 78% photocathode coverage: 17612 large (20-inch) PMTs, 25600 small (3-inch) PMTs
- muon veto: top tracker, water pool

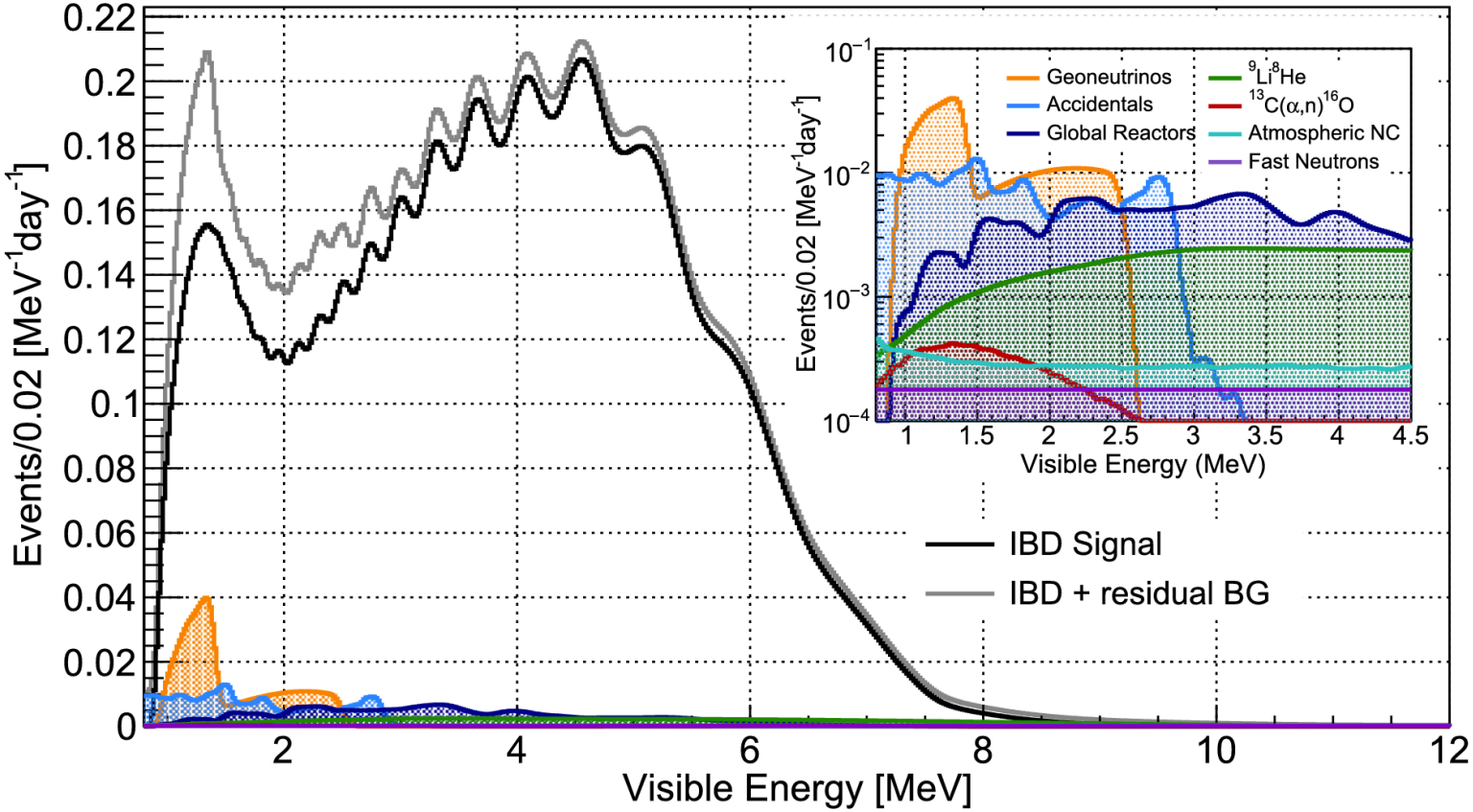
JUNO Detector





Expected Energy Spectra

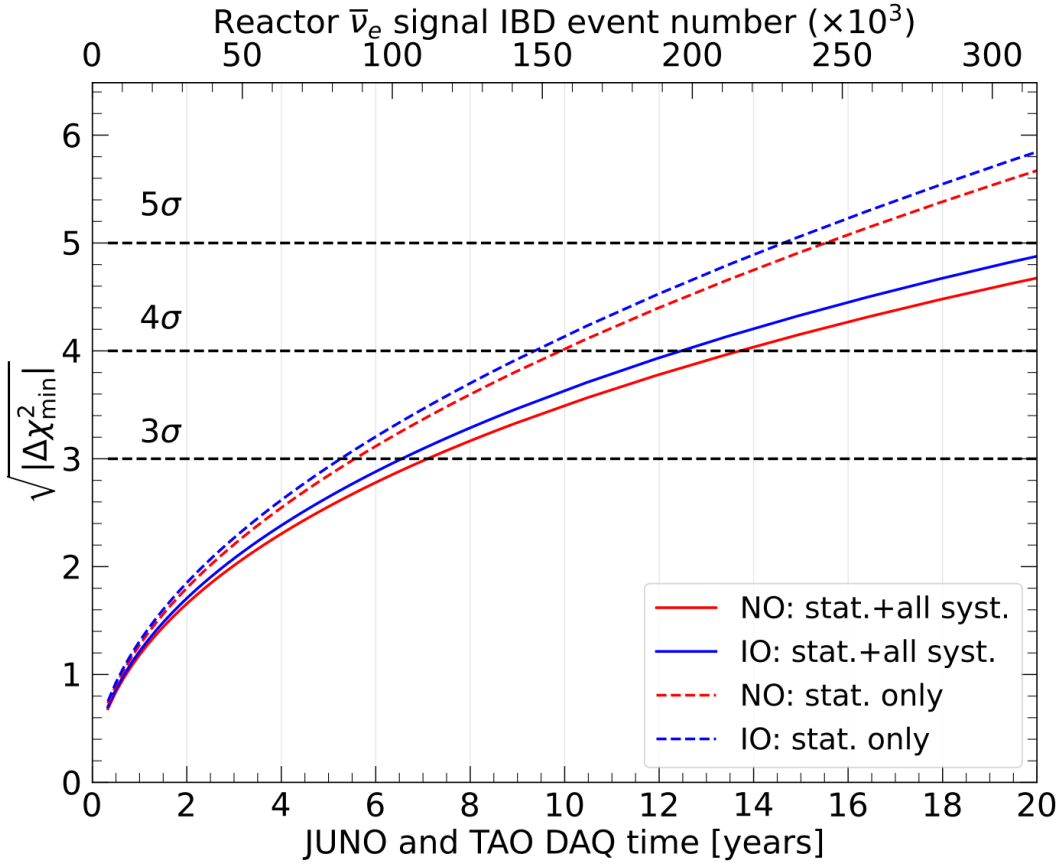
- IBD events from reactor anti-neutrinos: ~47 events per day*
- major backgrounds: accidentals, geoneutrinos, ^{9}Li/^{8}He, fast neutron, global reactors, with about 1 events per day for each

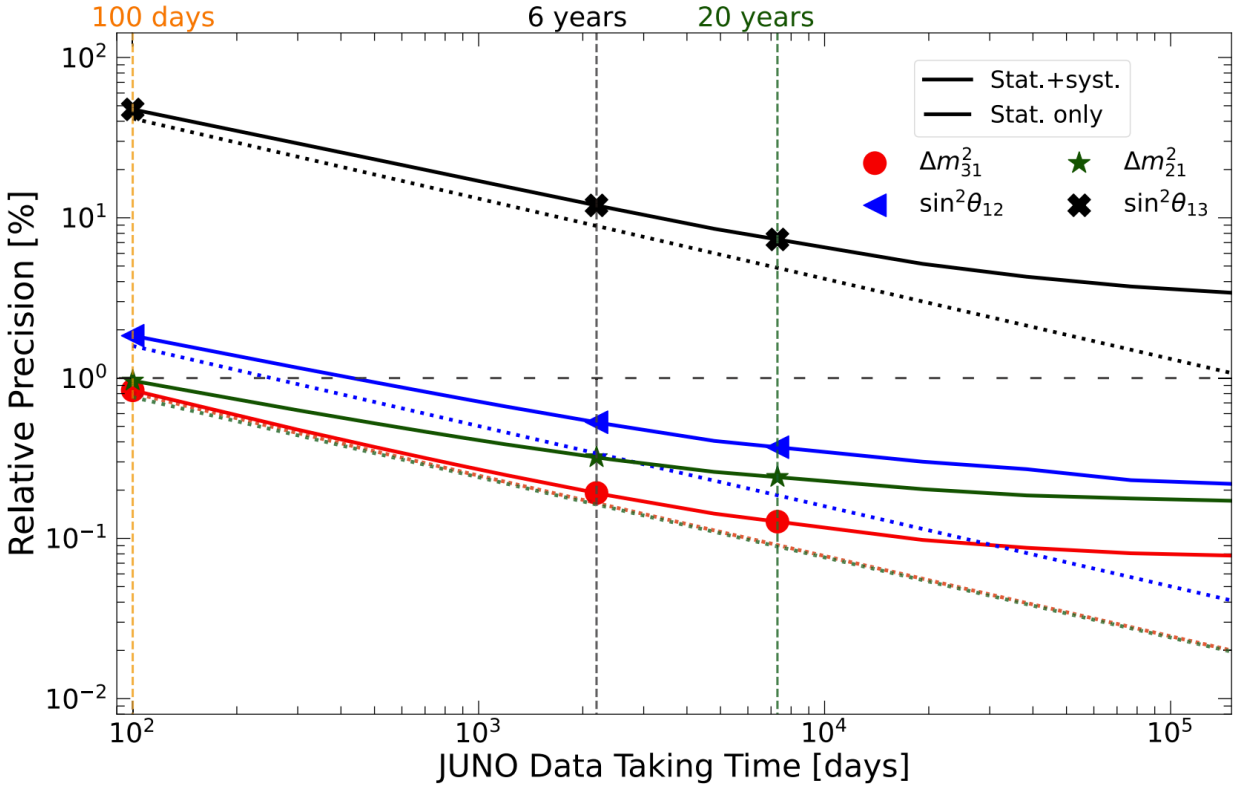


* Abusleme, A., & others (2022). Sub-percent precision measurement of neutrino oscillation parameters with JUNO. Chin. Phys. C, 46(12),

Physics Sensitivity

- 3σ with about 6 years' data*
- precision of $sin^2\theta_{12}$, Δm^2_{21}, $|\Delta m^2_{31}|$ < 0.5% in 6 years**



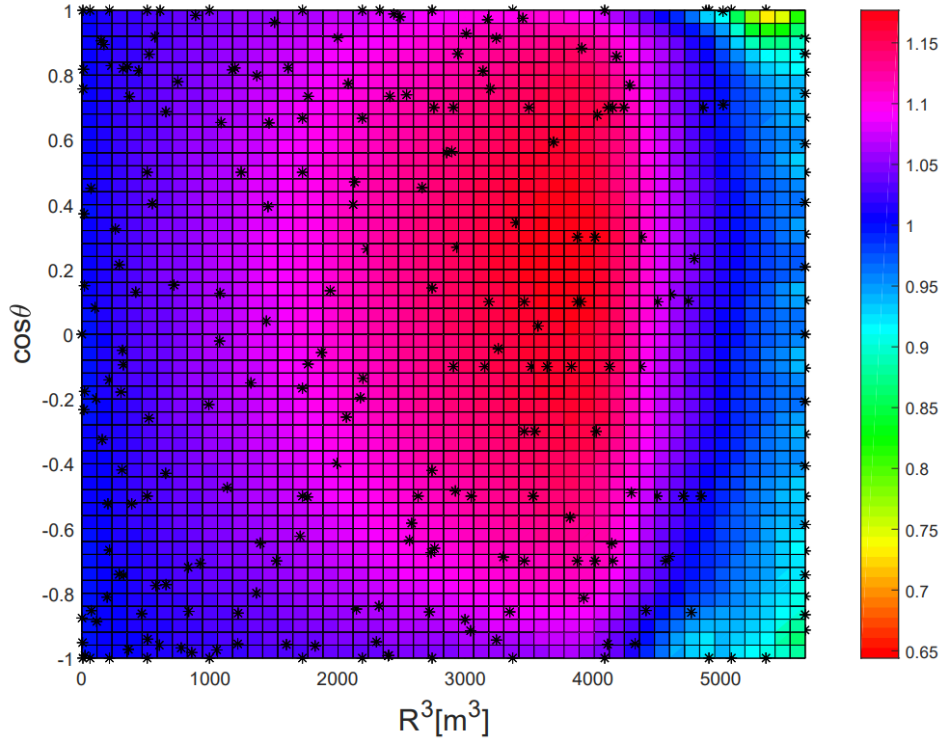


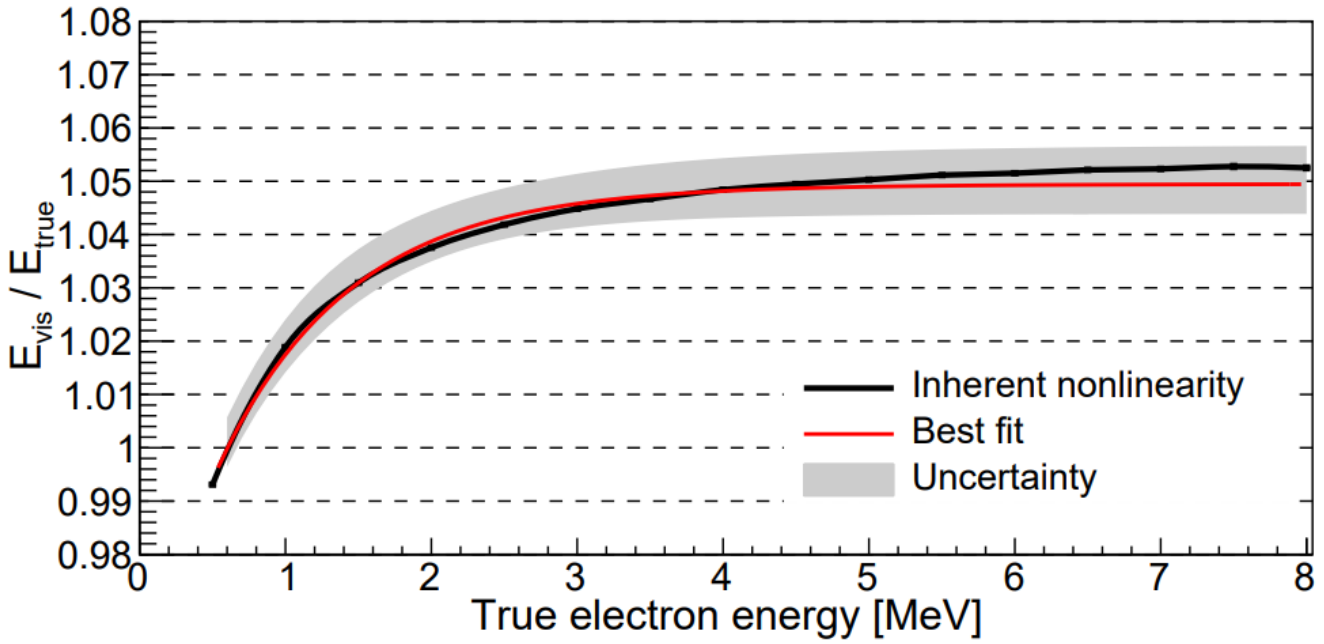
* Abusleme, A., & others (2025). Potential to identify neutrino mass ordering with reactor antineutrinos at JUNO. Chin. Phys. C, 49(3), 033104.
** Abusleme, A., & others (2022). Sub-percent precision measurement of neutrino oscillation parameters with JUNO. Chin. Phys. C, 46(12),

Muon Secondary Particles Study in JUNO

Motivation

- cosmogenic background: $^{9}Li/^{8}He$, fast neutrons
- detector calibration: cosmogenic neutrons, ^{12}B, ^{11}C*





* Abusleme, A., & others (2021). Calibration Strategy of the JUNO Experiment. JHEP, 03, 004.

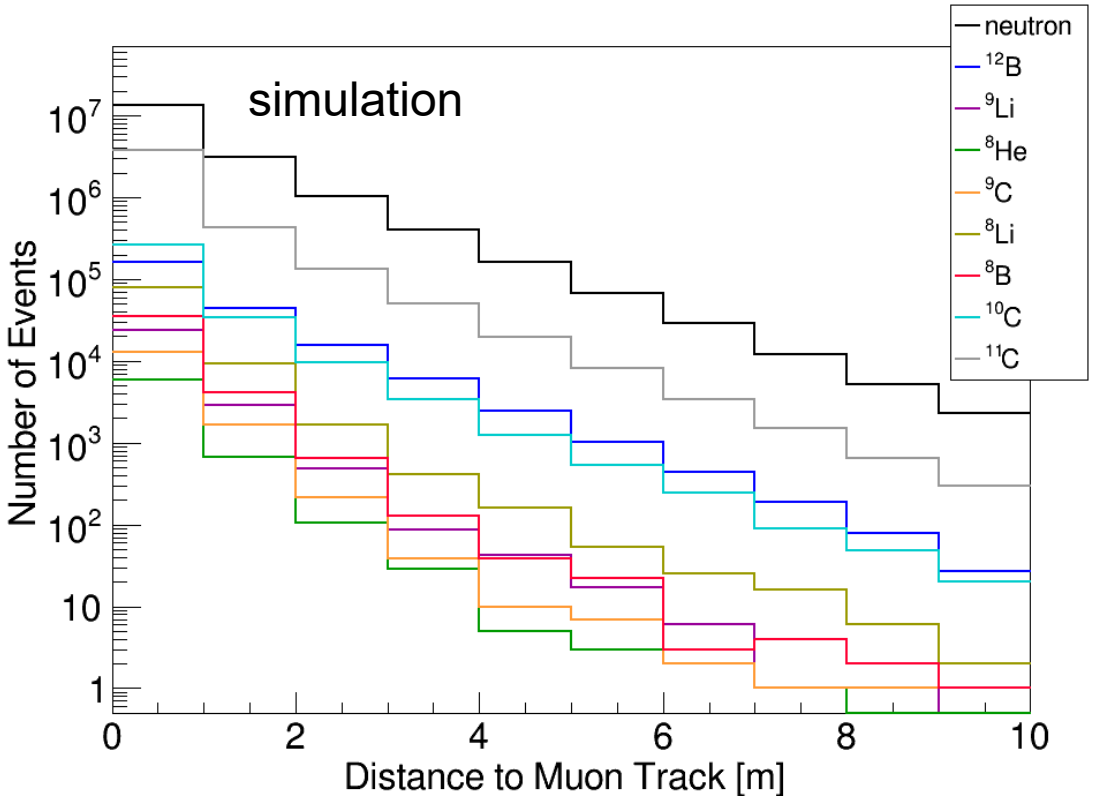
Muon-induced Isotope Yield in Liquid Scintillator

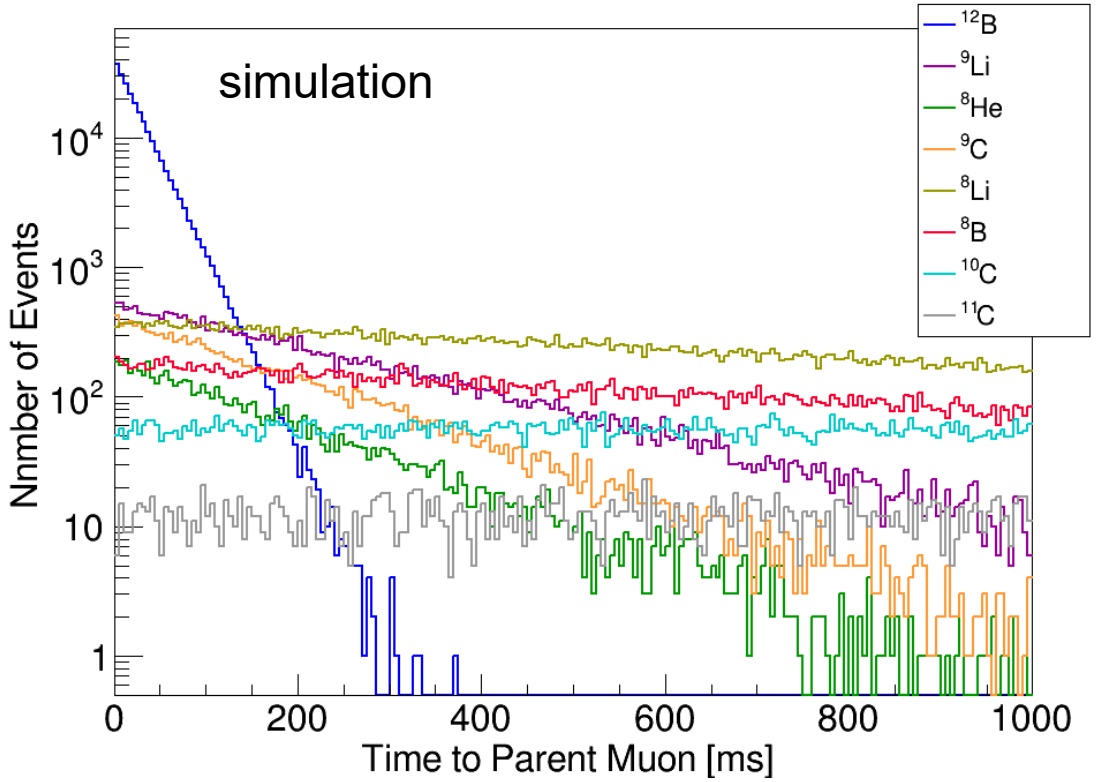
	Lifetime in KamLAND LS*	Radiation energy(MeV)	Yield scaled from KamLand (per day)
neutron	207.5 μs	2.225 (capture γ)	196932
^{12}N	15.9 ms	17.3 (β+)	127.19
^{12}B	29.1 ms	13.4 (β−)	3031.36
^{9}C	182.5 ms	16.5 (β+)	211.983
^{9}Li	257.2 ms	13.6 (β−γn)	155.454
^{8}He	171.7 ms	10.7 (β−γn)	49.4627
^{8}Li	1.21 s	16.0 (β−α)	862.064
^{8}B	1.11 s	18.0 (β+α)	593.552
^{10}C	27.8 s	3.65 (β+γ)	1165.91
^{11}C	29.4 min	1.98 (β+)	61192.4

* Abe, S., & others (2010). Production of Radioactive Isotopes through Cosmic Muon Spallation in KamLAND. Phys. Rev. C, 81, 025807.

Distance and Time to Muon

- muon secondary particles are close to muons in space and time
- selection of isotopes are based on their decay times and distance to muons



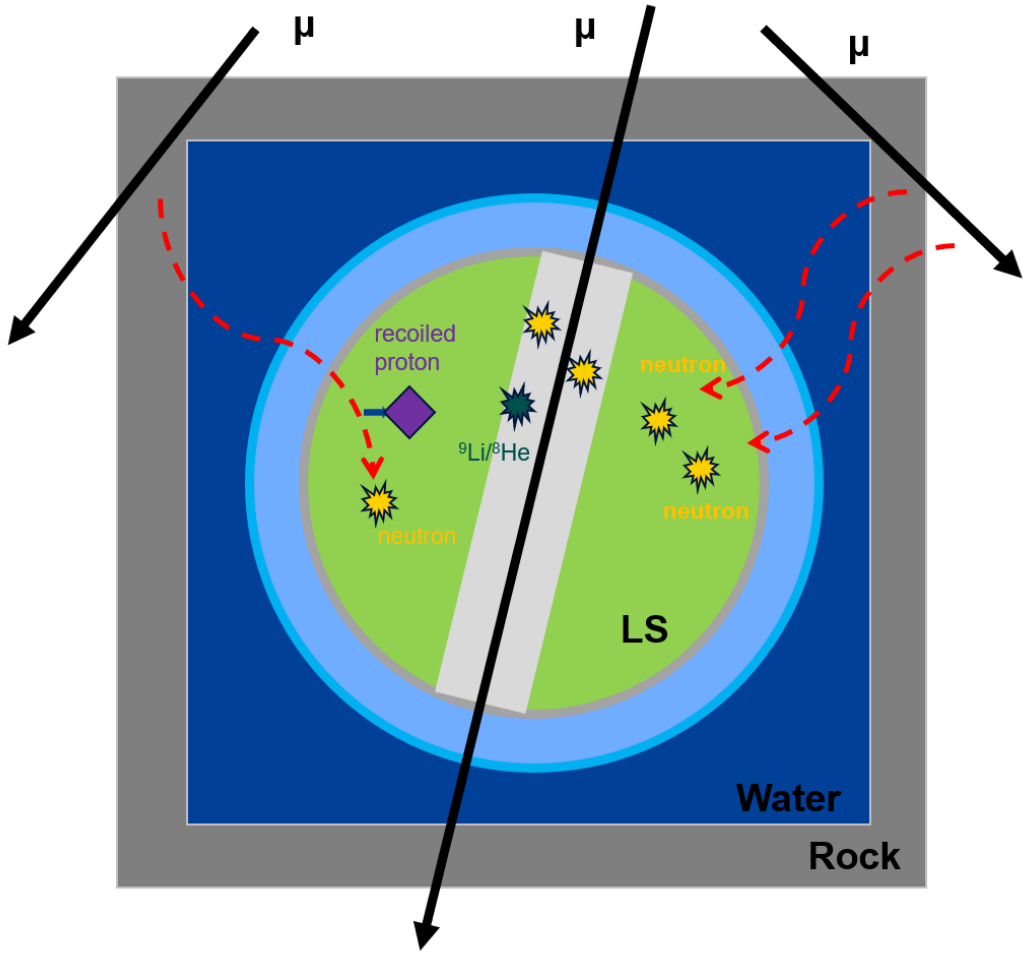


Muon induced background: ^{9}Li/^{8}He

$$^{9}Li \xrightarrow{\beta-} e^{-} + {}^{9}Be^{*} \rightarrow e^{-} + \alpha + \alpha + n$$

$$^{8}He \xrightarrow{\beta-} e^{-} + {}^{8}Li^{*} \rightarrow {}^{7}Li + e^{-} + n$$

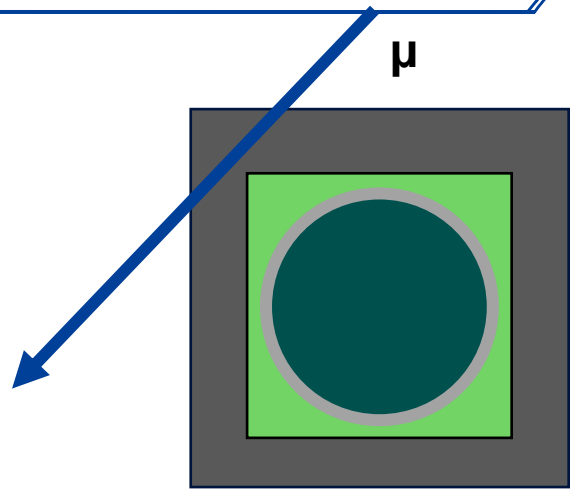
- about 51% ^{9}Li and 16% ^{8}He undergo β-n decay
- veto a sufficient detector volume along the muon track for *O*(1s) (based on ^{9}Li/^{8}He's lifetime)
- after veto, the rate of ^{9}Li/^{8}He is reduced to ~1/day, with ~8% IBD efficiency loss*



* Abusleme, A., & others (2022). Sub-percent precision measurement of neutrino oscillation parameters with JUNO. Chin. Phys. C, 46(12),

Muon induced background: Fast neutron

- muon go through the rock (or just clip the water pool), produce some fast neutrons which can go into the LS
- those muons can not be directly detected, muon veto do not work



types of Fast-neutron background:

recoiled proton-neutron pair

recoiled with proton

inelastic scattering

neutron

neutron

inelastic scattering

neutron

gamma

deutron

gamma

double neutron

neutron capture

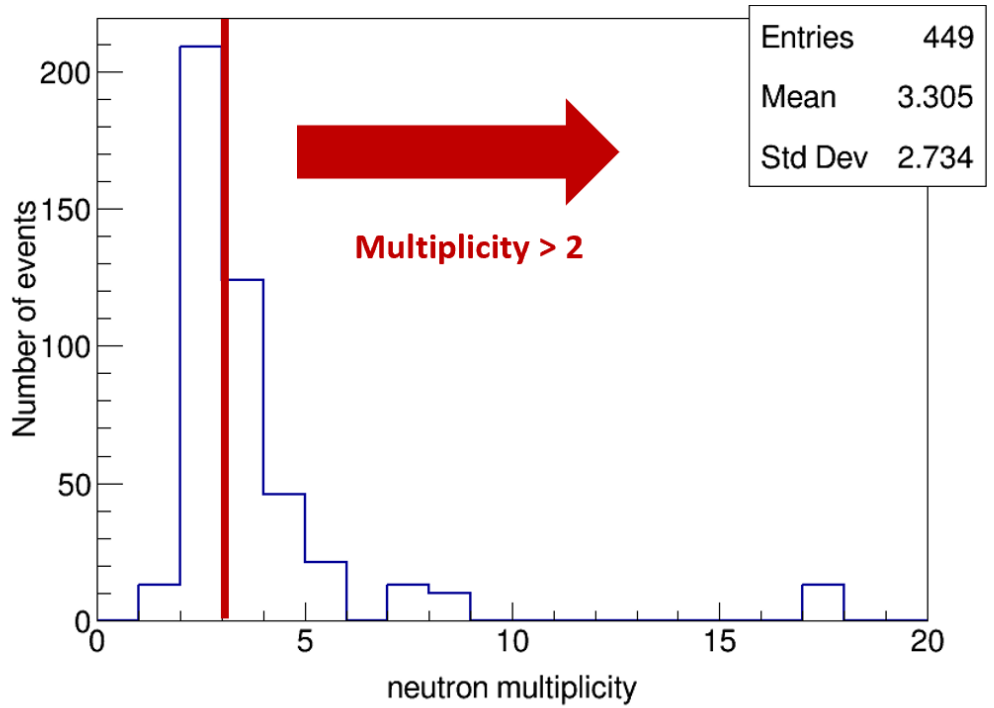
neutron

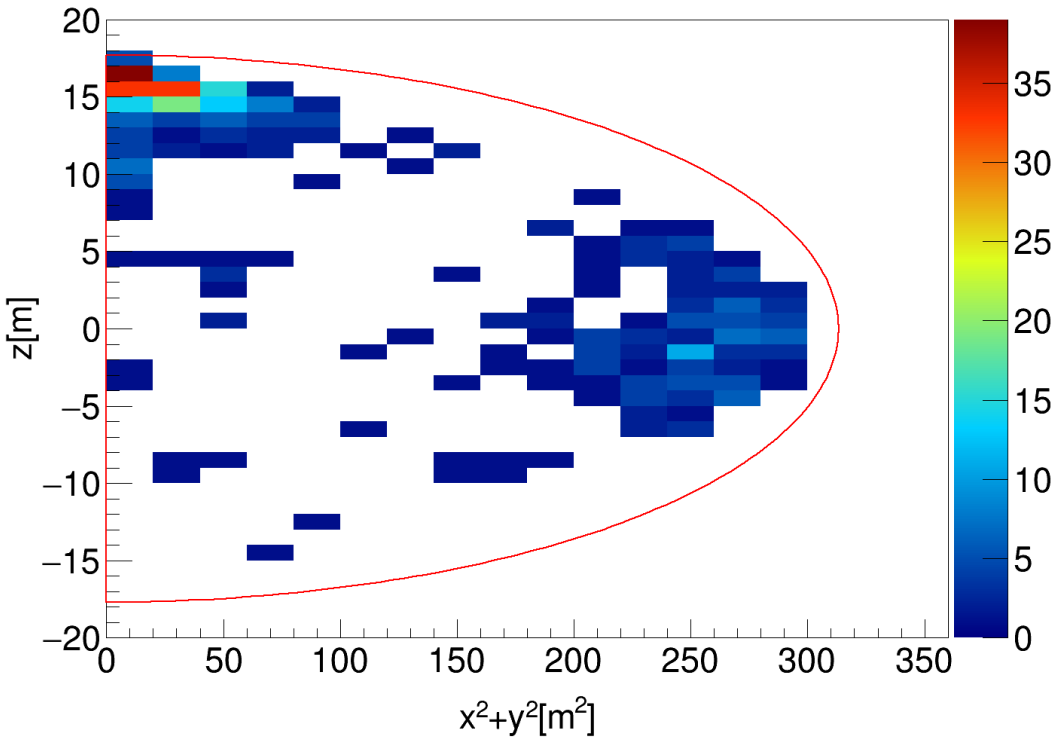
deutron

double-neutron pair

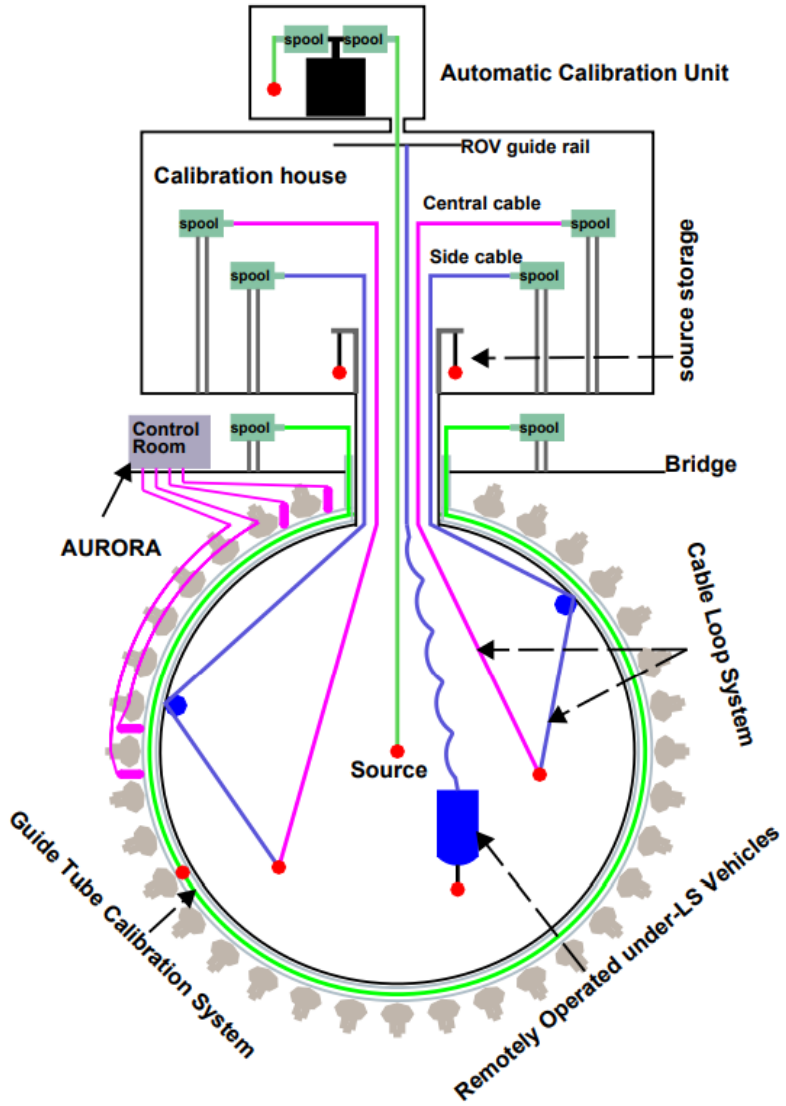
Muon induced background: Fast neutron

- remove fast neutron background: multiplicity cut
- estimation: based on space distribution





JUNO Detector Calibration



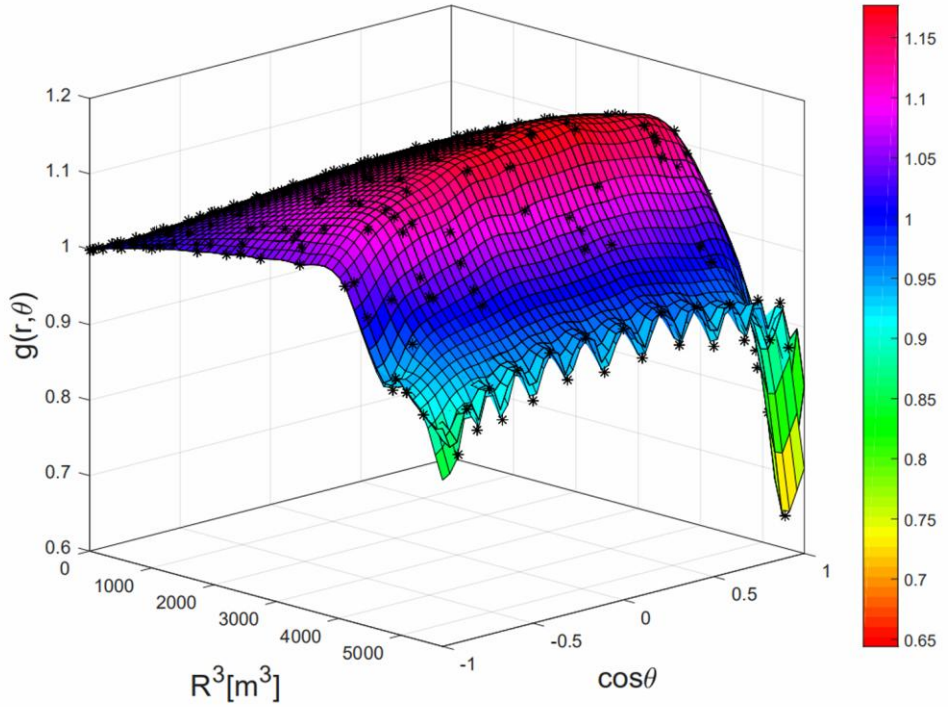
Sources/Processes	Type	Radiation
$^{137}\mathrm{Cs}$	γ	0.662 MeV
$^{54}\mathrm{Mn}$	γ	0.835 MeV
$^{60}\mathrm{Co}$	γ	1.173+1.333 MeV
$^{40}\mathrm{K}$	γ	1.461 MeV
$^{68}\mathrm{Ge}$	e^{+}	0.511 + 0.511 MeV
$^{241}\mathrm{Am} - {}^{13}\mathrm{C}$	n,γ	n + 6.13 MeV
$(\mathrm{n},\gamma)\mathrm{P}$	n,γ	2.22 MeV
$(\mathrm{n},\gamma)^{12}\mathrm{C}$	n,γ	4.94 or 3.68 + 1.26 MeV

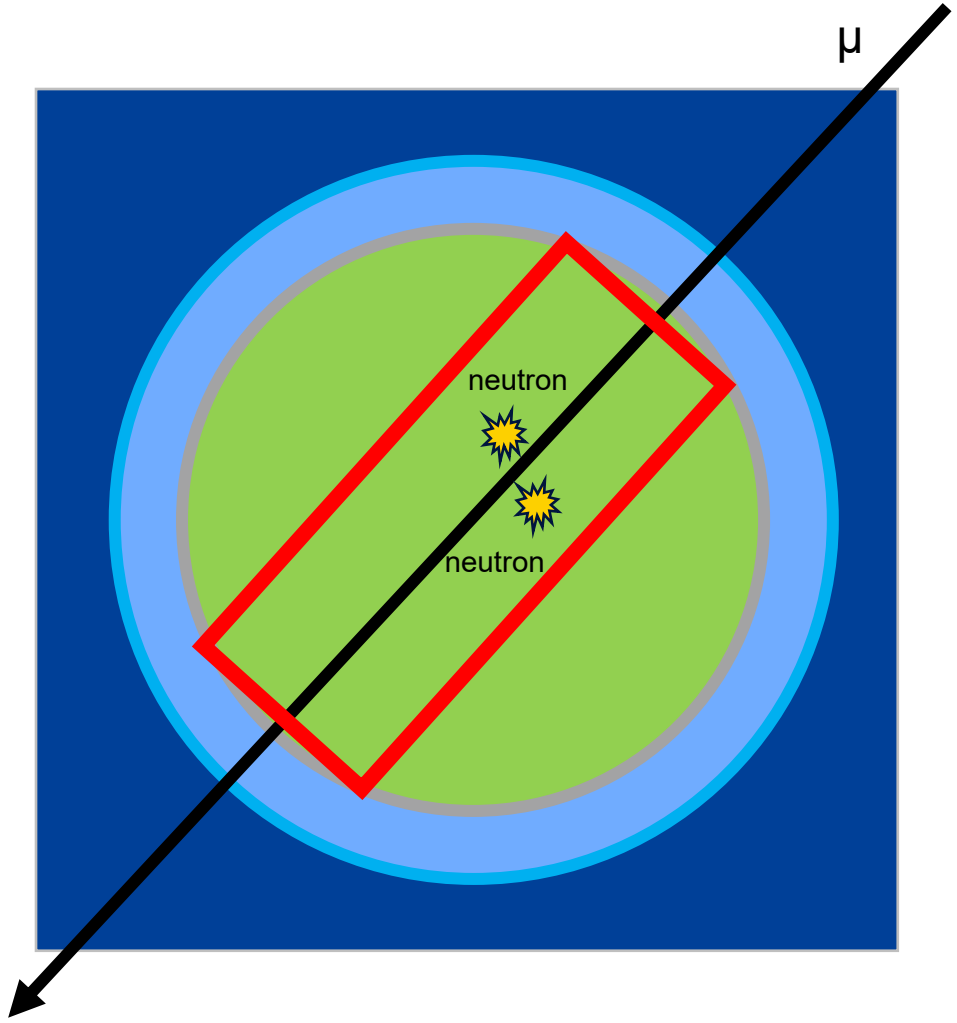
- gamma source only, limited energy range* → ^{12}B, ^{11}C with e-/e+ in a wider energy range
- limited positions → cosmogenic neutrons for non-uniformity calibration

* Abusleme, A., & others (2021). Calibration Strategy of the JUNO Experiment. JHEP, 03, 004.

Detector Non-uniformity Calibration: cosmogenic neutrons

- 2.2 MeV gamma from cosmogenic neutron capture on hydrogens
- expected event rate: 1M / week

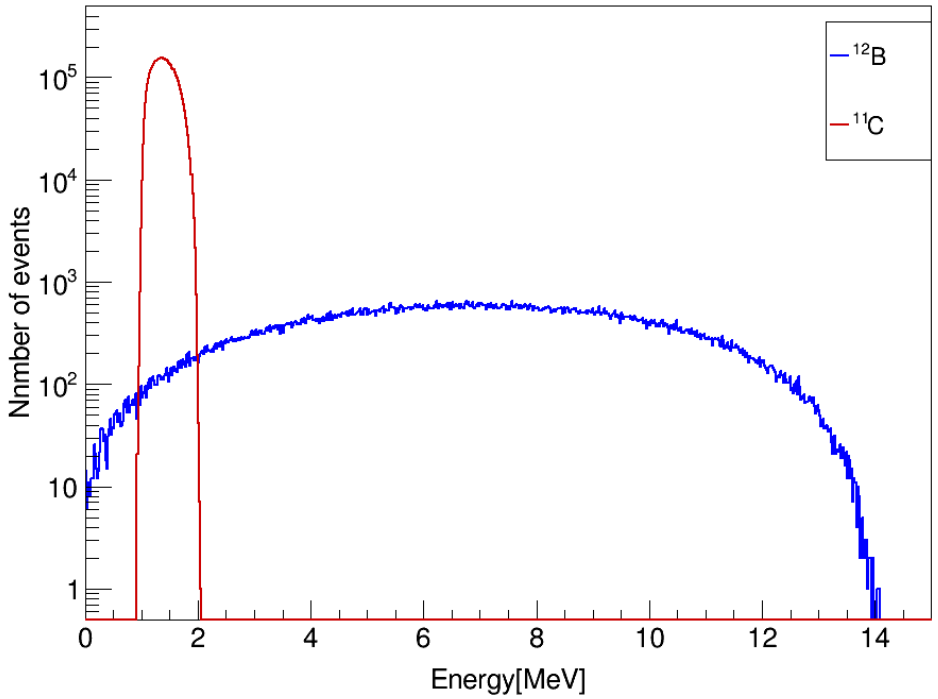


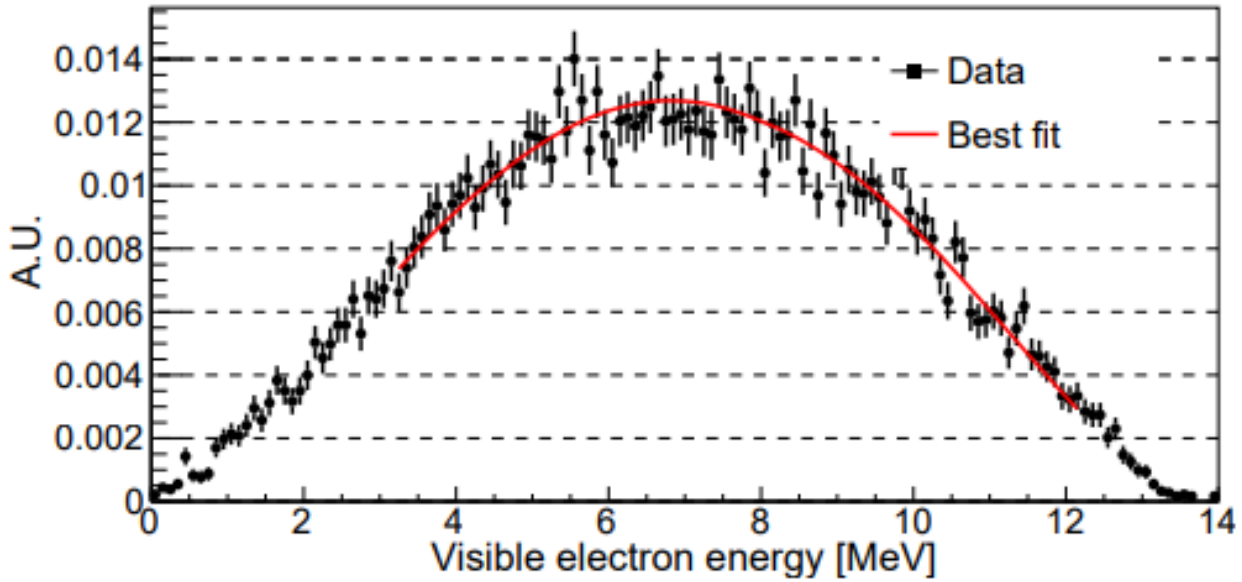


* Abusleme, A., & others (2021). Calibration Strategy of the JUNO Experiment. JHEP, 03, 004.

LS Non-Linearity Calibration: ^{12}B / ^{11}C

- LS non-linearity due to quenching (Birks' law) and Cherenkov light contribution*
- cosmogenic isotopes for LS non-linearity calibration
  - ^{12}B: 0-13.4MeV electron source
  - ^{11}C: 1.022-1.98MeV positron source





* Abusleme, A., & others (2021). Calibration Strategy of the JUNO Experiment. JHEP, 03, 004.

Summary

◆ **JUNO experiment**

- mass ordering measurement, 3σ with about 6 years' data
- precision measurement of $sin^2\theta_{12}$, Δm^2_{21}, $|\Delta m^2_{31}|$ <1% in 6 years

◆ **cosmogenic background**

- ^{9}Li/^{8}He background: ~1 / day.
- fast neutrons: ~0.1 / day

◆ **muon secondary particles as calibration sources**

- cosmogenic neutrons for detector non-uniformity
- ^{11}C/^{12}B for LS non-linearity

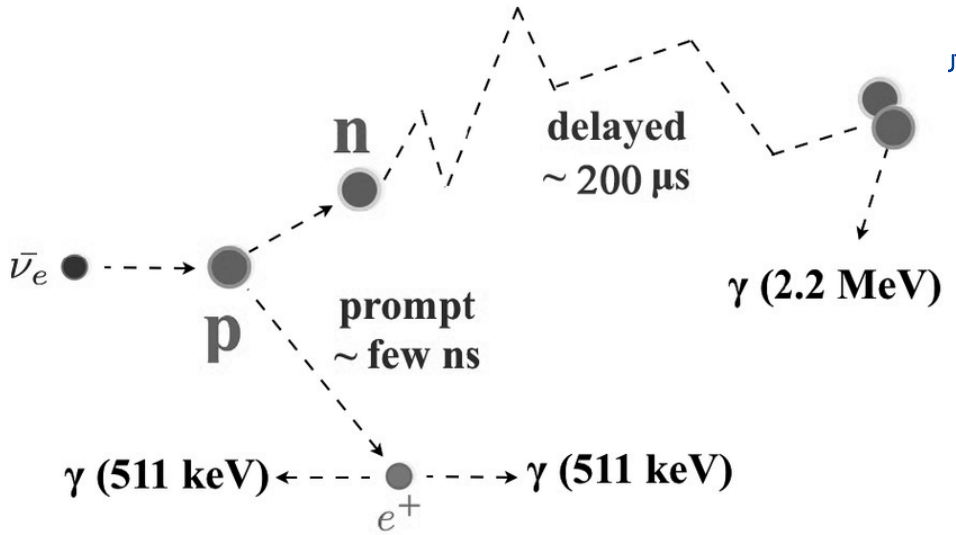
◆ **expect first oscillation measurement soon!**

Thank you for your attention!

Backup

$$P(\overline{\nu}_e \to \overline{\nu}_e) = 1 - \sin^2 2\theta_{12} c_{13}^4 \sin^2 \frac{\Delta m_{21}^2 L}{4E} - \sin^2 2\theta_{13} \left[c_{12}^2 \sin^2 \frac{\Delta m_{31}^2 L}{4E} + s_{12}^2 \sin^2 \frac{\Delta m_{32}^2 L}{4E} \right]$$

Event selection



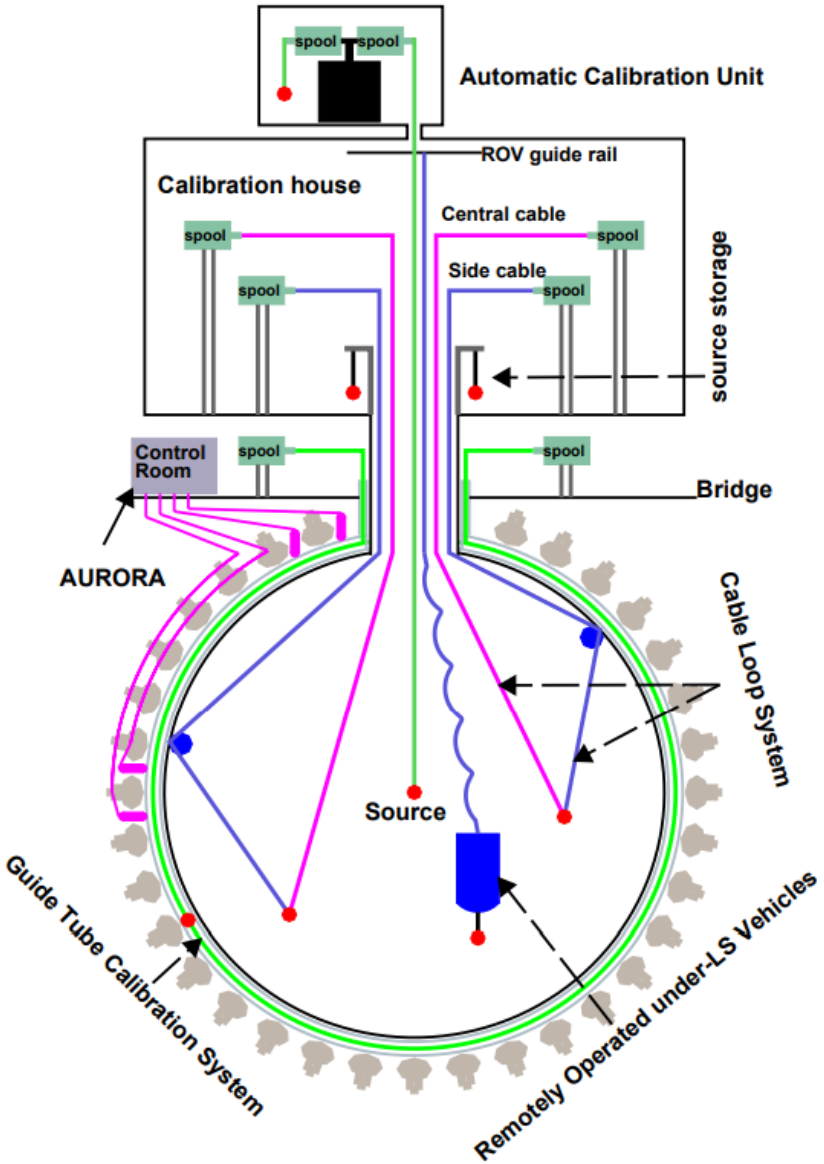
Event selection criteria:

- fiducial volume cut r < 17 m;
- the prompt energy cut 0.7 MeV < E_p < 12 MeV;
- the delayed energy cut 1.9 MeV < E_d < 2.5 MeV;
- time interval between the prompt and delayed signal ΔT <1.0 ms;
- the prompt-delayed distance cut R_{p-d} <1.5 m[1];
- Muon veto criteria:
  - – for muons tagged by Water Pool, veto the whole LS volume for 1.5 ms
  - – for good tracked muons in central detector and water Cerenkov detector, veto the detector volume within $R_{d2\mu}$ < 3 m and $T_{d2\mu}$ < 1.2 s
  - – for the tagged, non-trackable muons in central detector, veto the whole LS volume for 1.2 s

Inverse Beta Decay： $\bar{\nu_e} + p \rightarrow n + e^+$[3]

[1]. Fengpeng An et al. "Neutrino Physics with JUNO" J. Phys. G 43, no. 3, 030401(2016).

Select muon secondary particles as calibration source



JUNO has 4 calibration systems[5]:

- ACU (Automatic Calibration Unit, 1D)
- CLS (Cable Loop System, 2D)
- GTCS (Guide Tube Calibration System, 2D)
- ROV (Remotely Operated under-LS Vehicles, 3D)

Sources/Processes	Type	Radiation
^{137}Cs	γ	0.662 MeV
^{54}Mn	γ	0.835 MeV
^{60}Co	γ	1.173+1.333 MeV
^{40}K	γ	1.461 MeV
^{68}Ge	e^+	0.511 + 0.511 MeV
^{241}Am-^{13}C	n,γ	n + 6.13 MeV
(n,γ)p	n,γ	2.22 MeV
(n,γ)^{12}C	n,γ	4.94 or 3.68 + 1.26 MeV

Besides the above sources, we also use lasers for calibration[5].

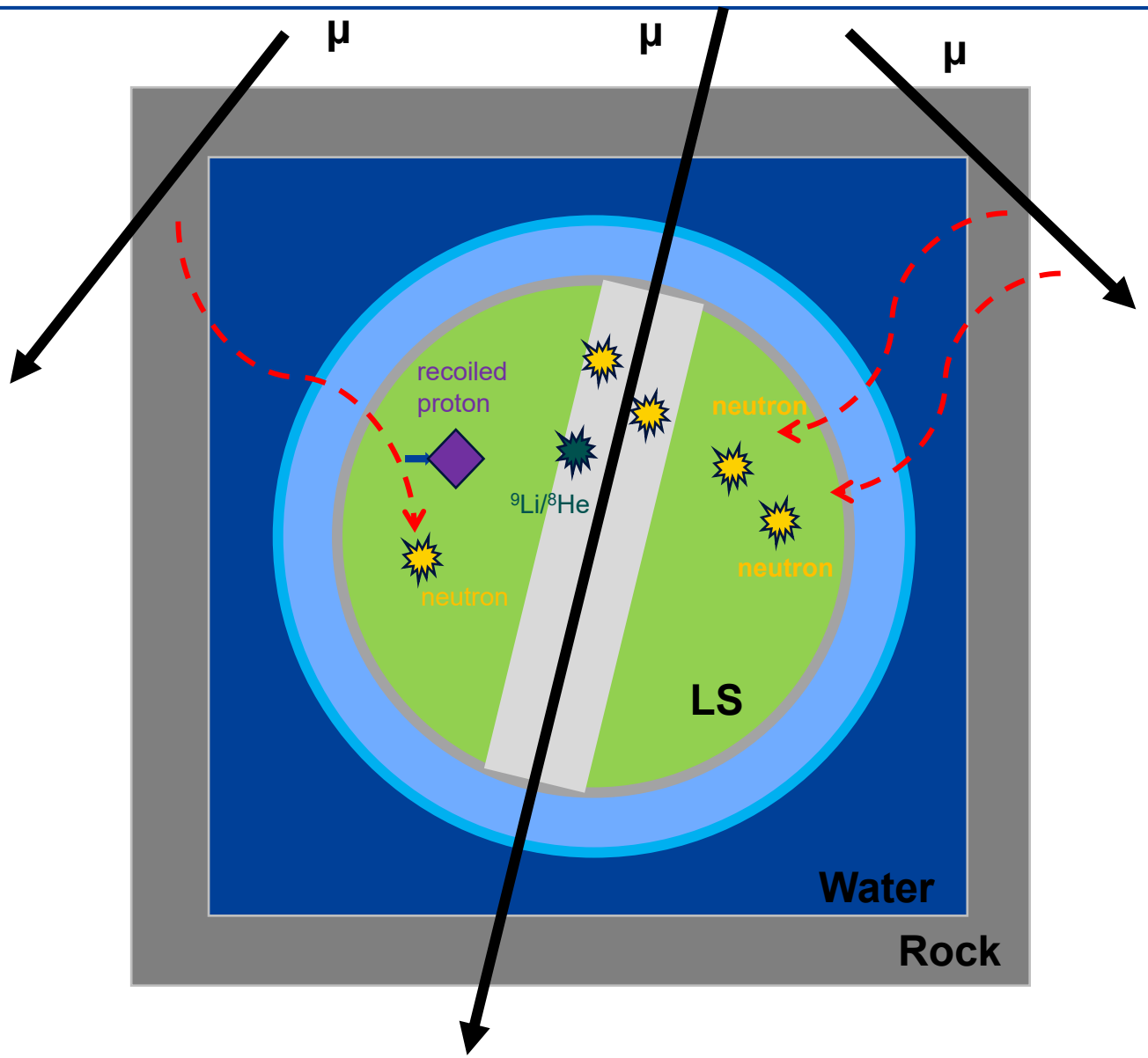
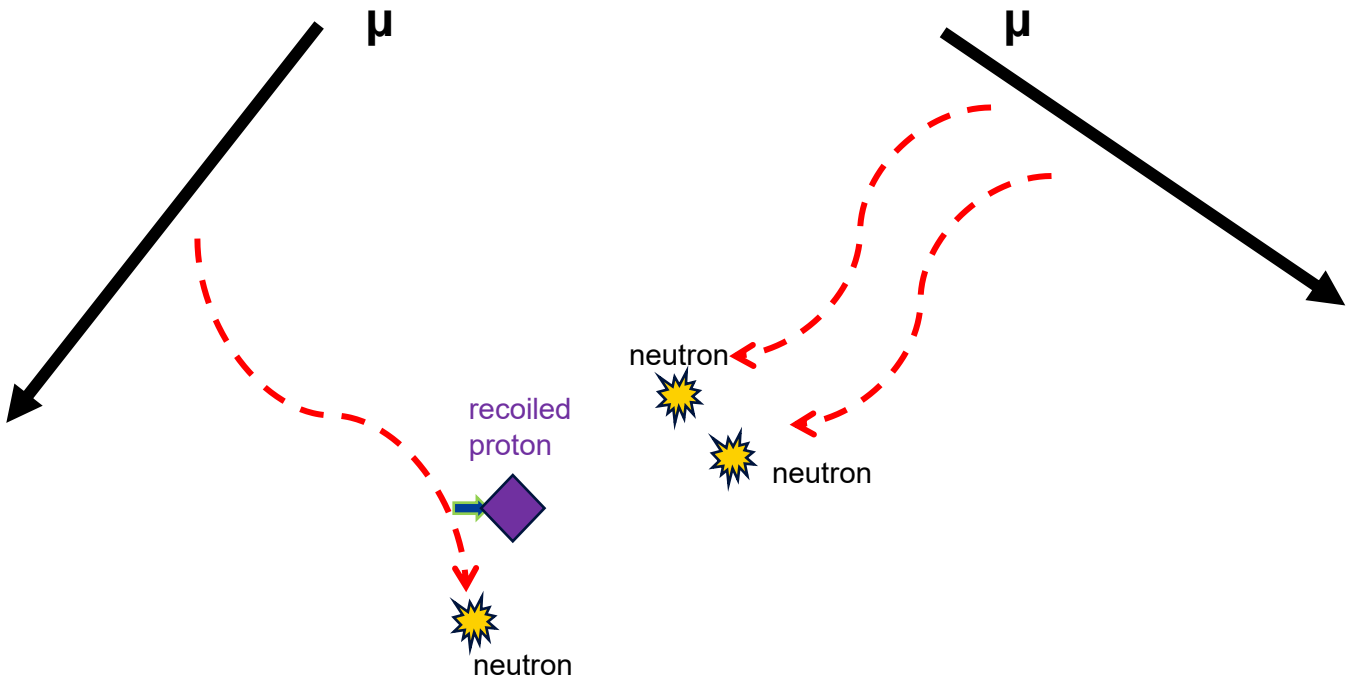
[5]. 张飞洋. “江门中微子实验刻度策略研究”.(2021).

Muon Isotope Yield in Liquid Scintillator

	Lifetime in KamLAND LS[5]	Radiation energy(MeV)	Yield scaled from KamLand(per day)
neutron	207.5 μs	2.225 (capt.γ)	196932
^{12}N	15.9 ms	17.3 (β+)	127.19
^{12}B	29.1 ms	13.4 (β−)	3031.36
^{9}C	182.5 ms	16.5 (β+)	211.983
^{9}Li	257.2 ms	13.6 (β−γn)	155.454
^{8}He	171.7 ms	10.7 (β−γn)	49.4627
^{8}Li	1.21 s	16.0 (β−α)	862.064
^{8}B	1.11 s	18.0 (β+α)	593.552
^{10}C	27.8 s	3.65 (β+γ)	1165.91
^{11}C	29.4 min	1.98 (β+)	61192.4

[5]. KamLAND Collaboration. S. Abe et al. "Production of radioactive isotopes through cosmic muon spallation in KamLAND", Phys.Rev.C 81 (2010).

Muon plot


μ
μ
μ
recoiled
proton
neutron
^{9}Li/^{8}He
neutron
neutron
LS
Water
Rock

Muon plot