Calibration Strategy of JUNO

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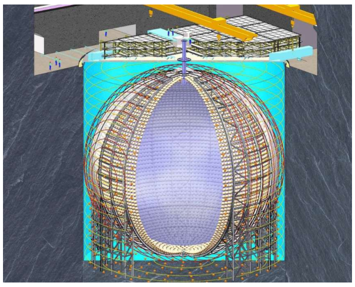
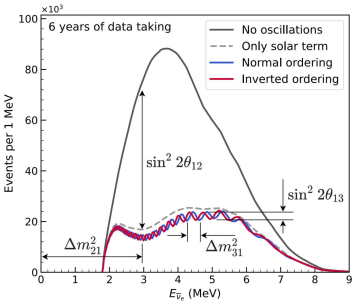
JUNO Experiment

- Jiangmen Underground Neutrino Experiment (JUNO)
  - ✓ neutrino mass ordering measurement
  - ✓ precision measurement of $|\Delta m^2_{31}|, \Delta m^2_{21}$ and θ_{12}
- calibration goal: for uniformly distributed e+ events
  - ✓ better than 1% energy calibration precision
  - ✓ better than 3% energy resolution at 1 MeV
- 17612 20-inch PMTs, 25600 3-inch PMTs, 78 % photocathode coverage



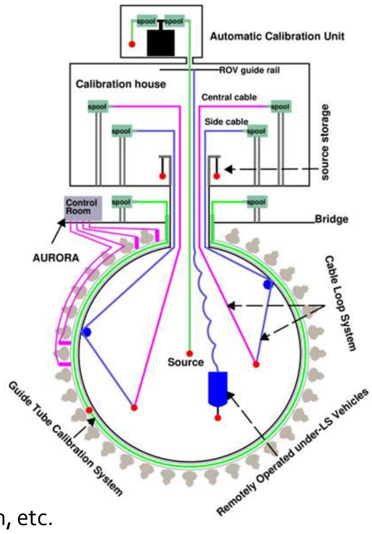


Calibration System

- Automatic Calibration Unit
- Cable Loop System
- Guide Tube Calibration System
- Remotely Operated Vehicle

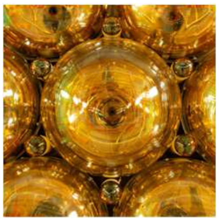
source	type	energy
^{137}Cs	γ	0.662 MeV
^{54}Mn	γ	0.835 MeV
^{60}Co	γ	1.173 + 1.333 MeV
^{40}K	γ	1.461 MeV
^{68}Ge	γ	0.511 + 0.511 MeV
^{241}Am-Be	n, γ	n + 4.43 MeV (^{12}C*)
^{241}Am-^{13}C	n, γ	n + 6.13 MeV (^{16}O*)
$(n,\gamma)p$	γ	2.22 MeV
$(n,\gamma)^{12}$C	γ	4.94 MeV or 3.68 + 1.26 MeV

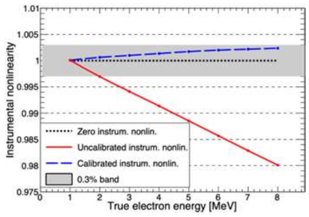
+ low energy sources: ^{226}Rn, ^{241}Am, etc.



20-inch PMT Calibration

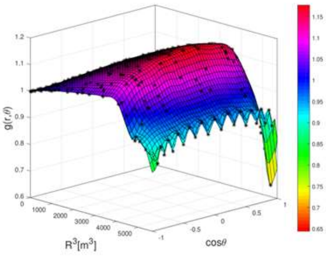
- dark noise, time alignment, gain calibration
- first hit time vs. charge
- relative photon detection efficiency
- 20-inch PMT non-linearity: electronics, waveform reconstruction
  - ✓ use 266 nm laser to inject light on a Teflon ball at detector center
  - ✓ 3-inch PMTs working in digital mode: fired or non-fired
  - ✓ Poisson-zero method: use the number of non-fired 3-inch PMTs to calibrate laser intensity

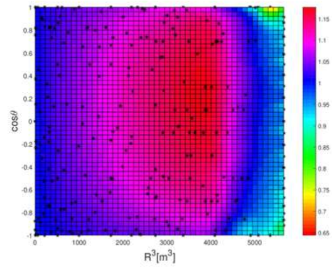




Non-Uniformity Calibration

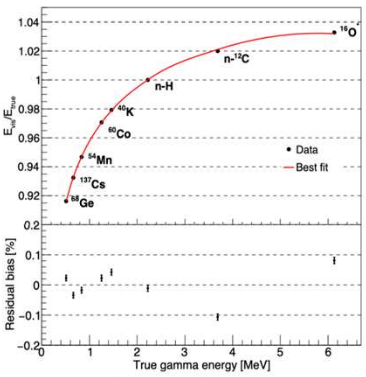
- detector non-uniformity: PMT acceptance, light attenuation, total internal reflection at the acrylic-water interface
- calibration sources deployed by the calibration system at different positions in the detector
- cosmogenic neutrons, about 1 M / week
- develop reconstruction algorithms that use these calibration data as input to largely remove the detector non-uniformity



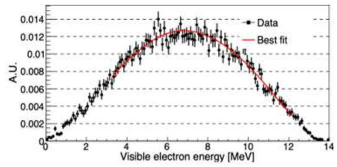


Liquid Scintillator Non-Linearity Calibration

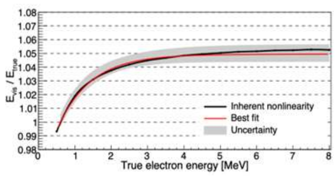
- liquid scintillator non-linearity: Birks' law, Cherenkov light
- gamma calibration sources at different energies
  - ✓ treat a gamma event as a collection of e- and e+ using Geant4
  - ✓ build a non-linearity model for e-/e+, fit to calibration data
  - ✓ predict the non-linearity for e+
- constraint from continuous spectra from cosmogenic B12 and C11



(a) Gamma non-linearity



(b) Boron Spectrum



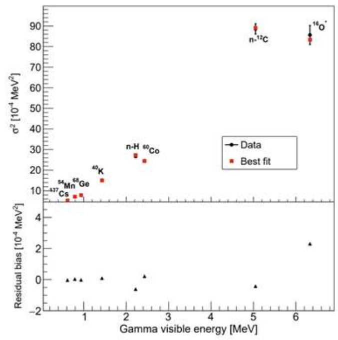
(c) Electron non-linearity

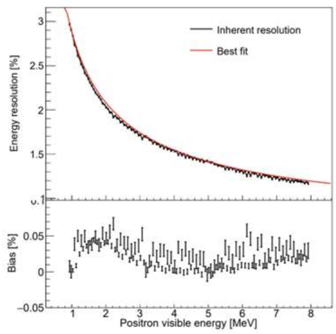
Positron Energy Resolution Calibration

- use the e+/e- nonlinearity model to predict resolution curve for e+
- further parametrize the resolution curve with

$$\sigma/E = \sqrt{a^2/E + b^2 + c^2/E^2}$$

- contributing factors: a: Poisson, b: non-uniformity and Cherenkov, c: mainly dark current and e+ annihilation





References: *JHEP* 03 (2021) 004, F. Zhang PhD thesis (2021), *Chin.Phys.C* 46 (2022) 12, 123001, arXiv:2405.18008