Calibration method for the non-linearity in the response of 20-inch PMTs in the JUNO experiment

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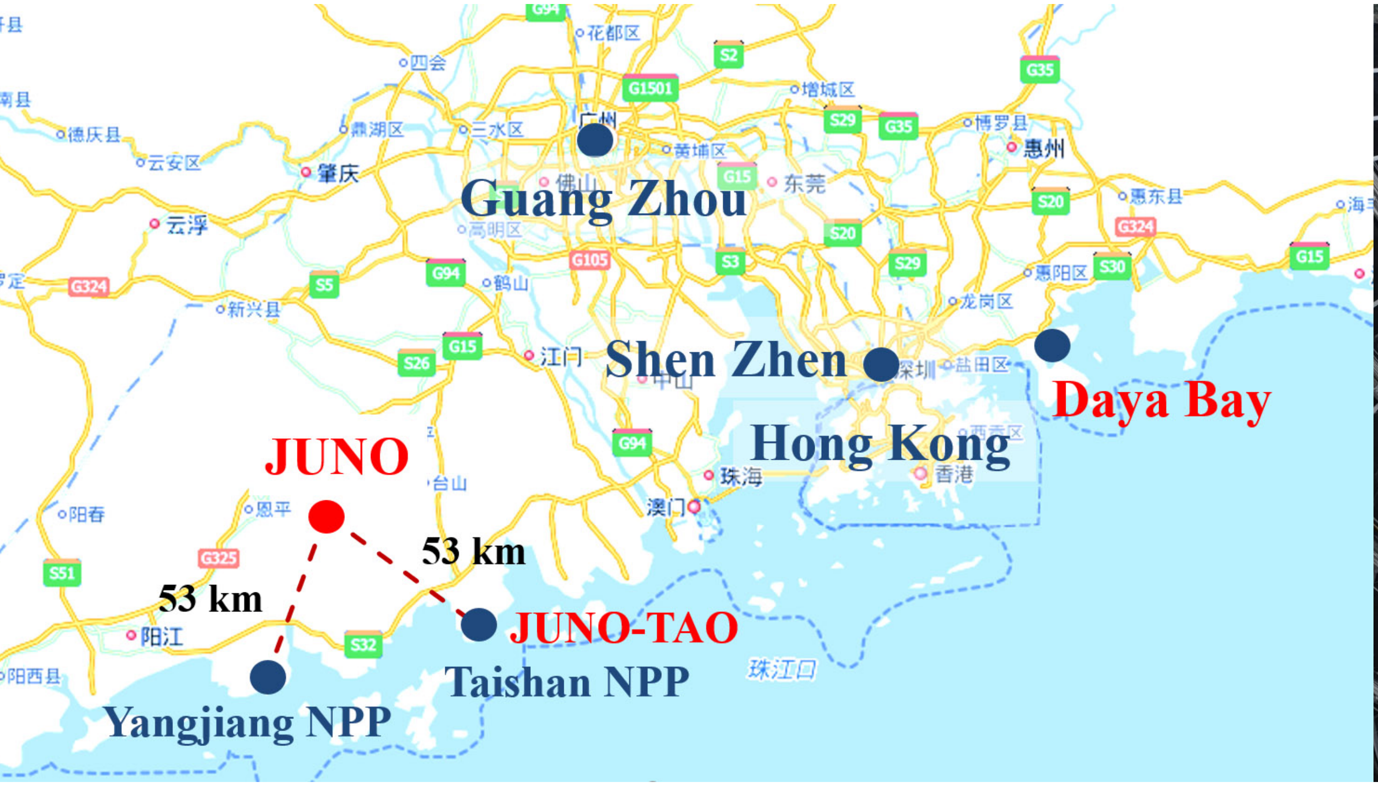
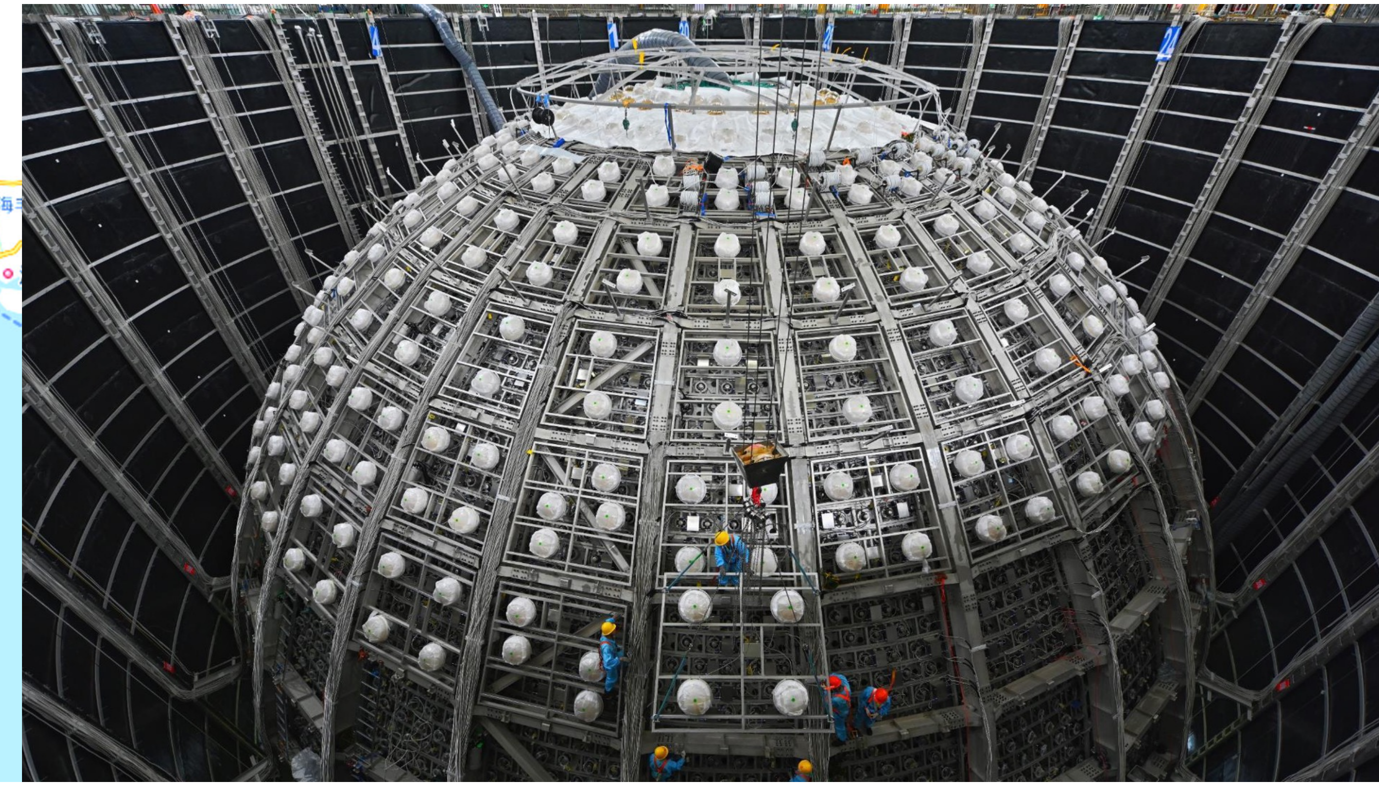
6th International Workshop on New Photon-Detectors, 19th/Nov./2024

JUNO Experiment

PPNP 123, 103927 (2022)

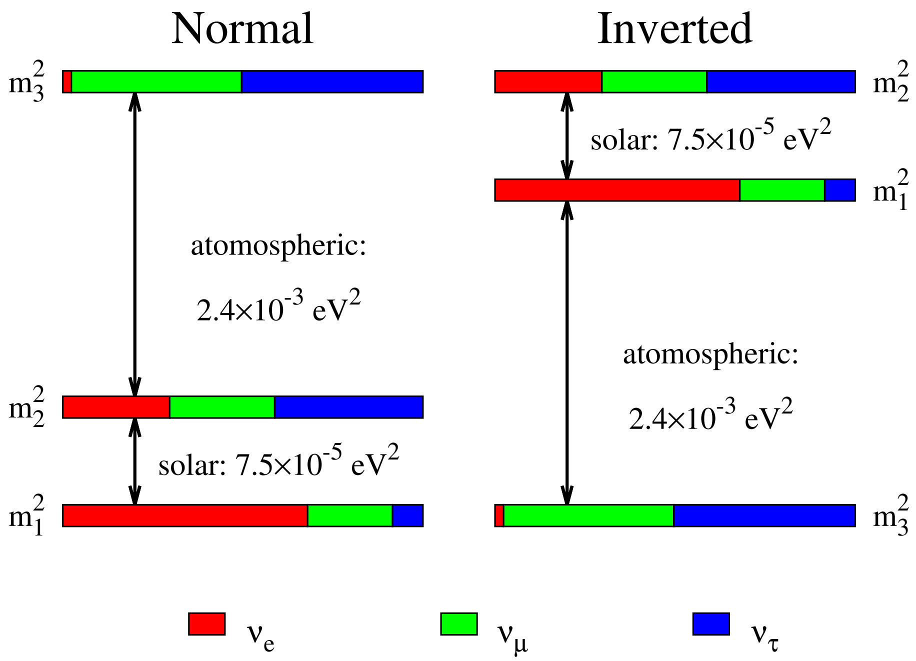




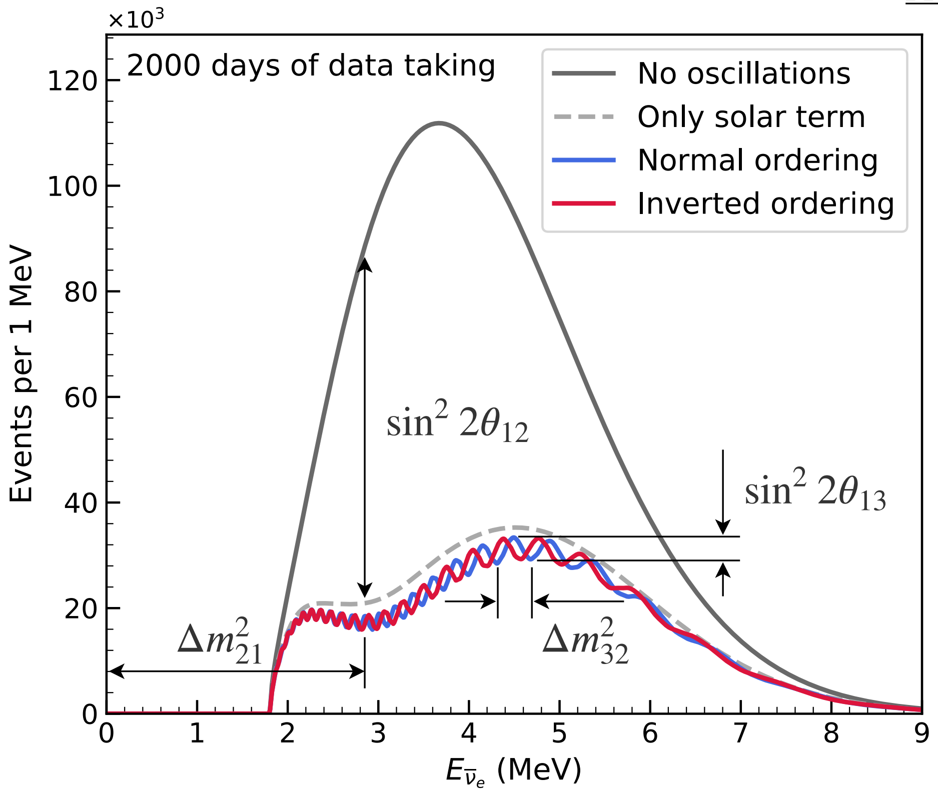
- JUNO is the world's largest underground (~650 m overburden) liquid scintillator experiment, located in Jiangmen, China.
- The detector construction is at the final stage, and it is scheduled to begin operations next year.
- The collaboration consists of 74 institutions and over 700 members.

Physics in JUNO

PPNP 123, 103927 (2022)



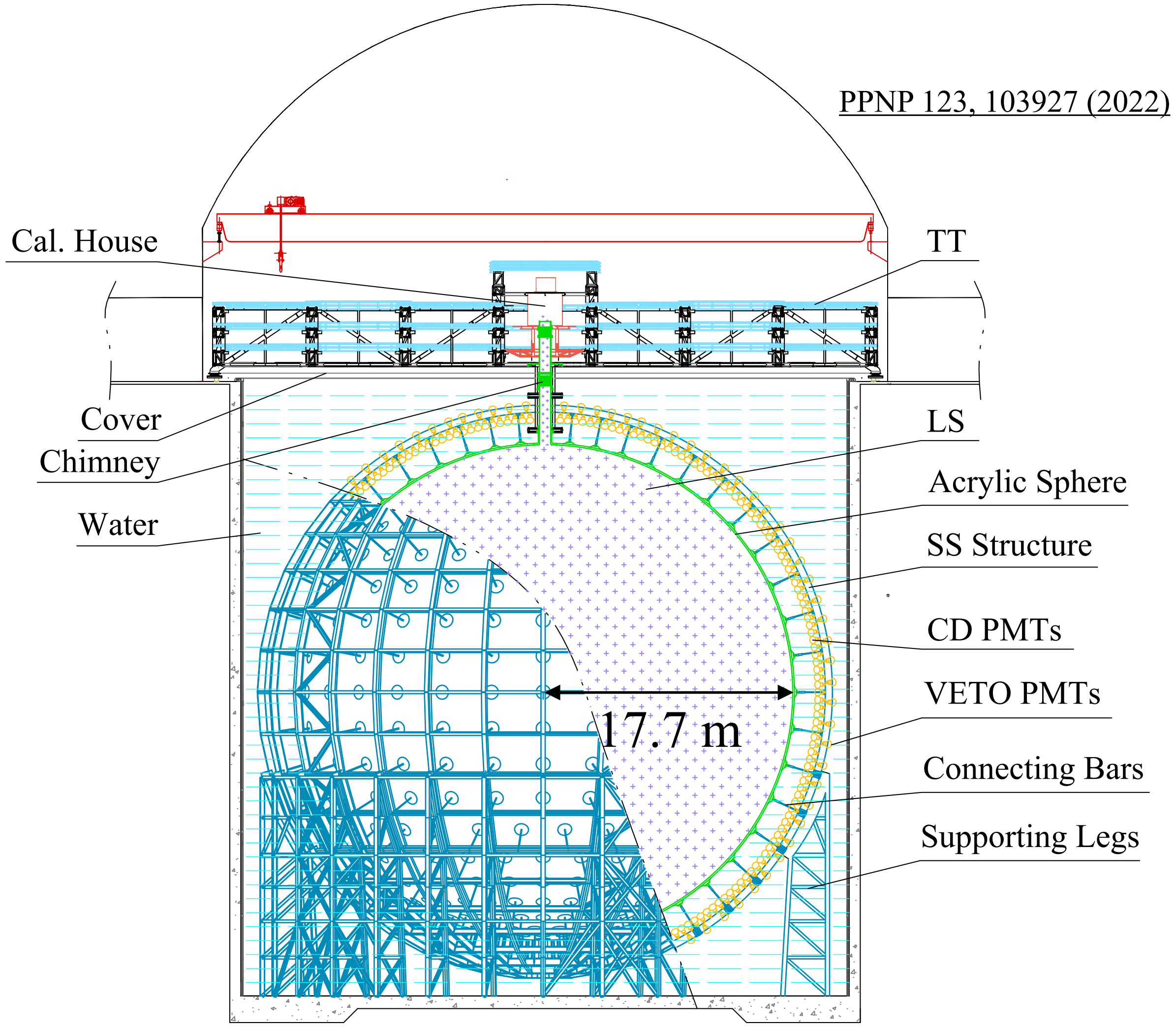
Neutrino mass ordering

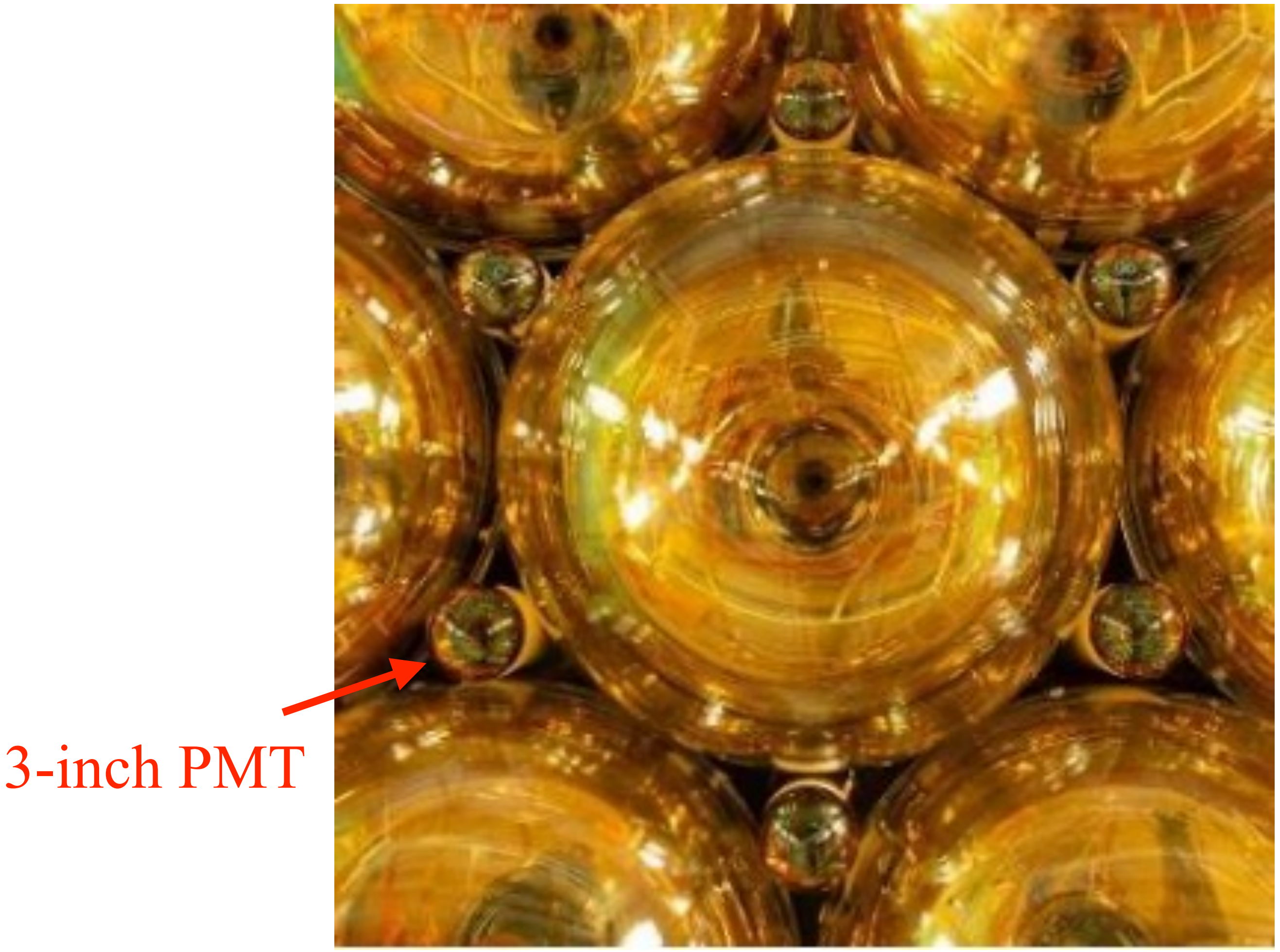


Reactor neutrino energy spectra

- JUNO will address a variety of physics topics:
  - Reactor, atmospheric, solar, geo, and supernova neutrino observations, nucleon decay searches, etc.
- Determination of the neutrino mass ordering through reactor neutrino measurement requires accurate/precise energy calibration:
  - an optimized energy resolution of 3% at 1 MeV.
  - energy scale uncertainty remains below 1%.

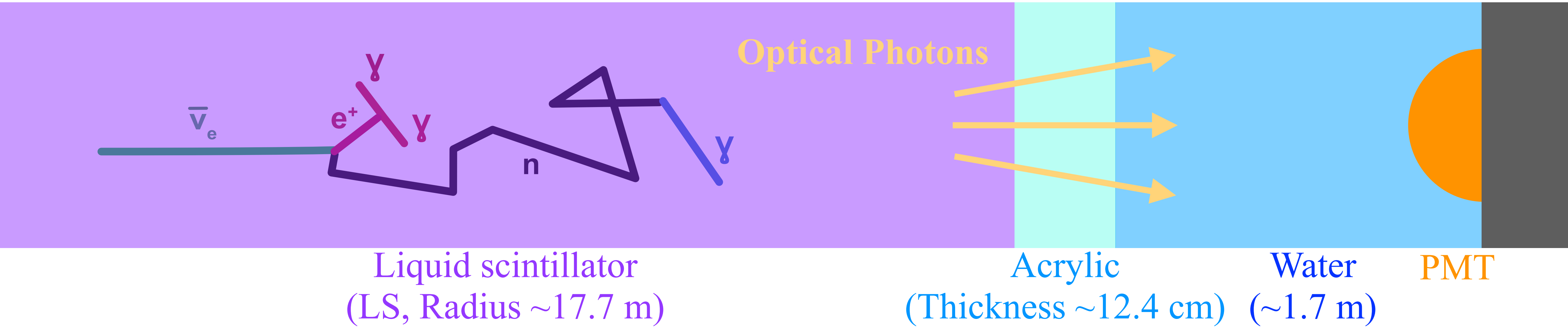
JUNO Detector





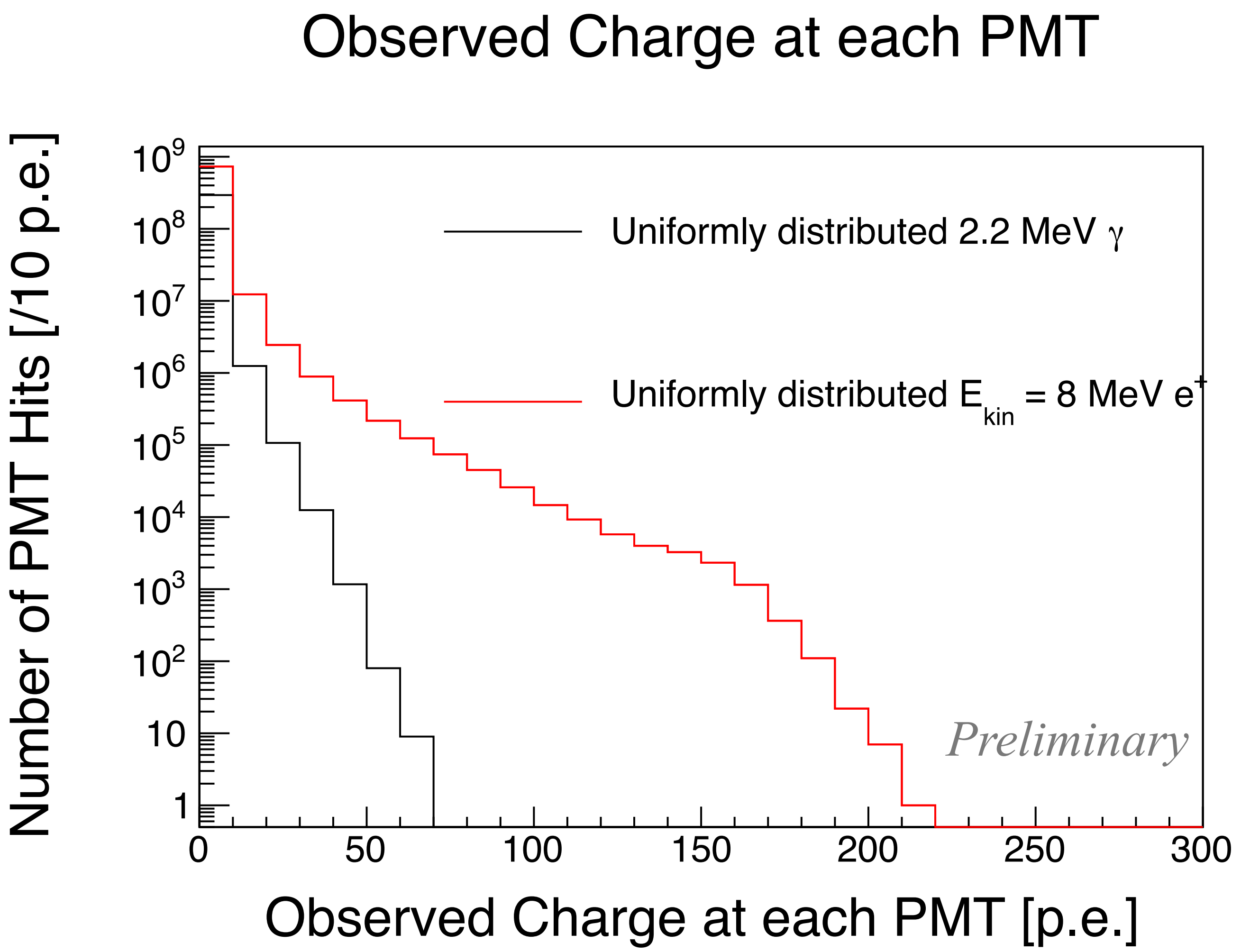
- The 20-kton liquid scintillator (LS) is housed in an acrylic sphere, sustained by a stainless steel structure, submerged in pure water.
- A large number of photomultiplier tubes (PMTs) are being installed in the stainless steel structure:
  - 17,612 20-inch PMTs (**LPMTs**, 75% photo coverage) and 25,600 3-inch PMTs (**SPMTs**, 3% photo coverage).

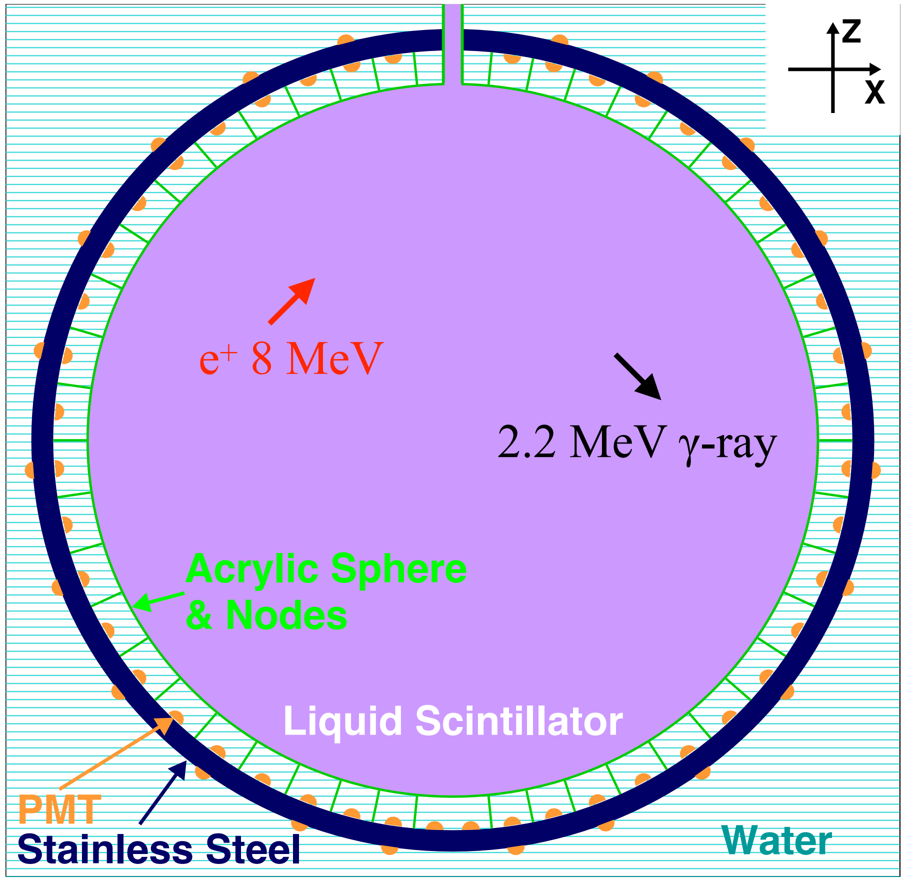
Photon Detection Principle



- Energetic charged particles (such as those from neutrino interactions) in LS produce scintillation and Cherenkov light.
  - The amount of produced photons is non-linear to the particle energy and will be calibrated with various radioactive sources. JHEP 2021(3), 4 (2021)
- Photons travel in LS, acrylic, and water before reaching PMTs.
- The number of photons detected at each PMT depends on the spatial relationship between the charged particle and PMT positions.
  - Due to geometrical acceptance and optical processes (absorption, scattering, reflection, etc) in their travel.

Expected Charge Range in LPMTs in JUNO

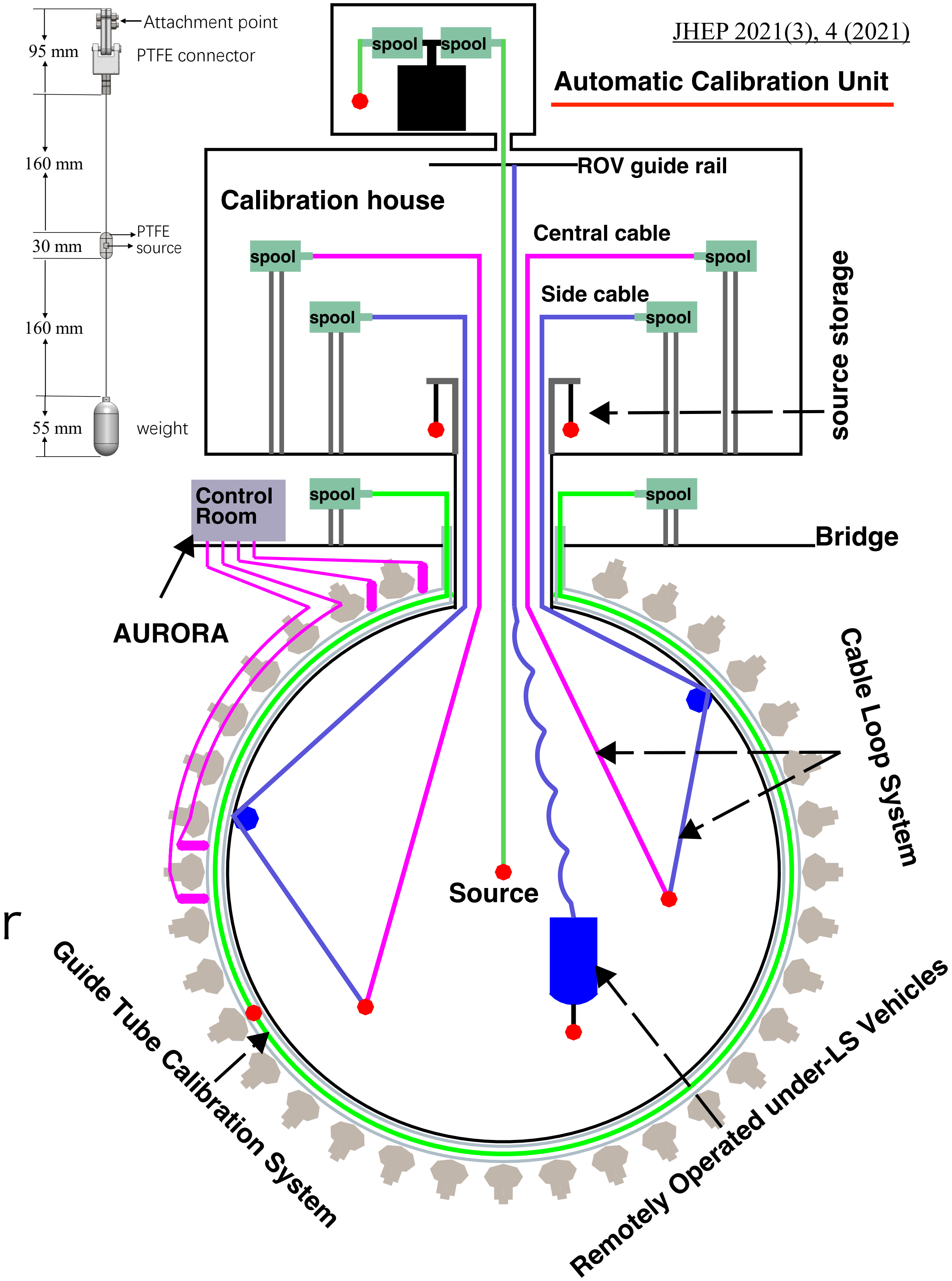




- Waveform signals from each LPMT are processed by electronics, and their observed charge (number of photoelectrons) is reconstructed.
- At each LPMT level, it ranges from a single photoelectron to ~200 p.e. level in events in the reactor neutrino energy range.
  - LPMT charge non-linearity in this range should be calibrated.
  - It may cause non-negligible uncertainty (E-scale) unless corrected.

JUNO Calibration System

- Multiple calibration source deployment devices are being installed, placing a radioactive calibration source at different positions.
- They will calibrate the non-uniform energy response inside the detector to realize an optimal energy resolution.
- Automatic Calibration Unit enables us to deploy a laser source at the detector center to calibrate PMT responses.



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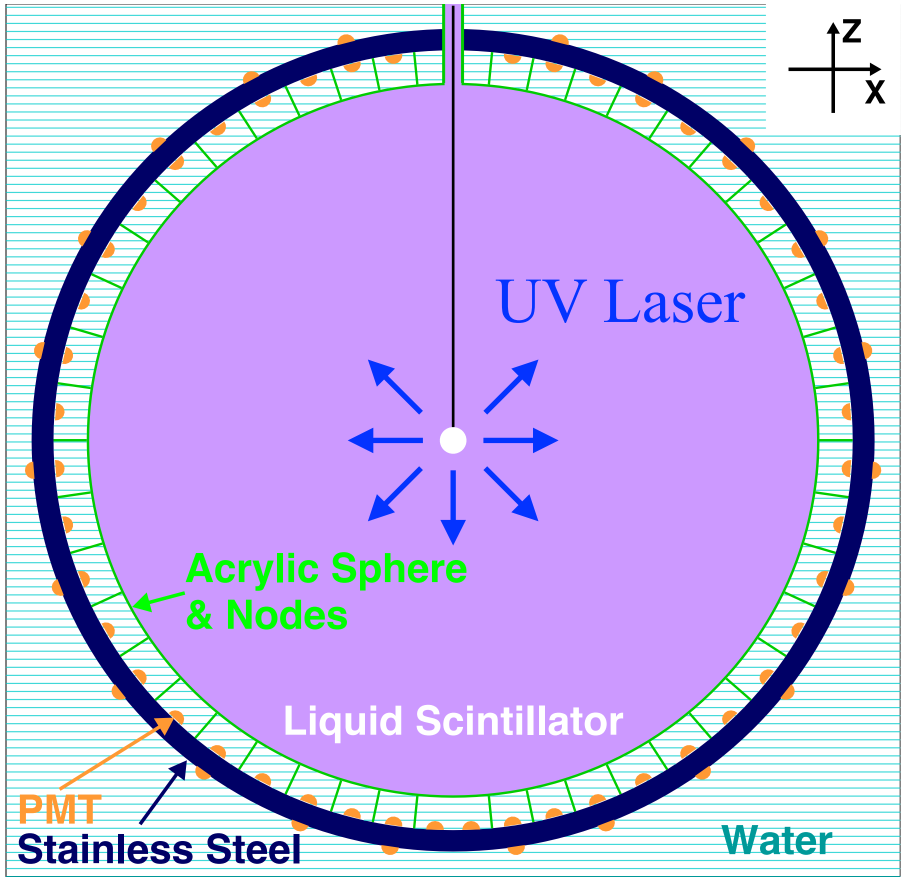
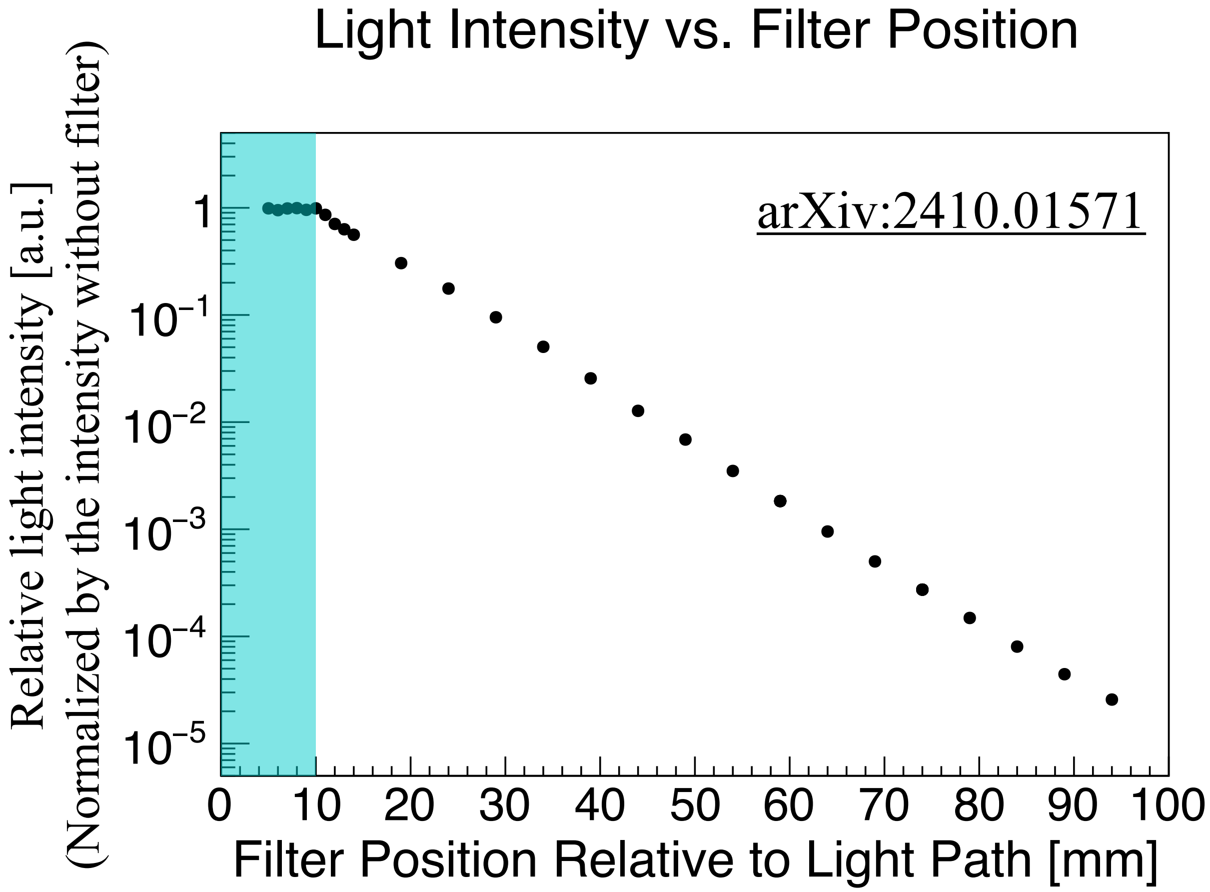
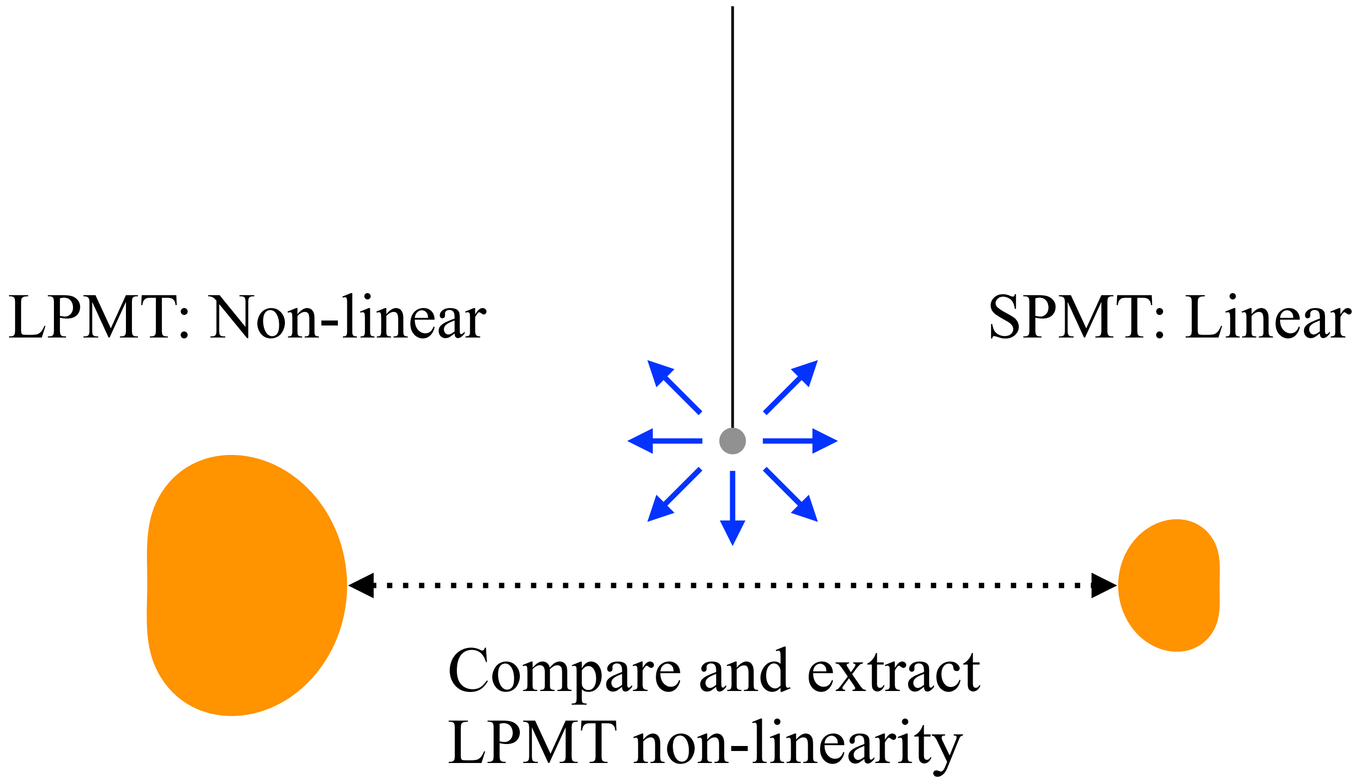
Laser Calibration System





- Pulsed UV (λ~267 nm) laser photons are distributed inside the detector through a diffuser ball attached to an optical fiber end.
- UV photons will be immediately absorbed in the liquid scintillator, and scintillation photons are emitted and detected by the PMTs.
- The intensity of the laser light to the detector can be controlled.
  - Four orders of magnitude, covering a single photoelectron to O(100) p.e. level.

Calibration Method



LPMT: Non-linear

SPMT: Linear

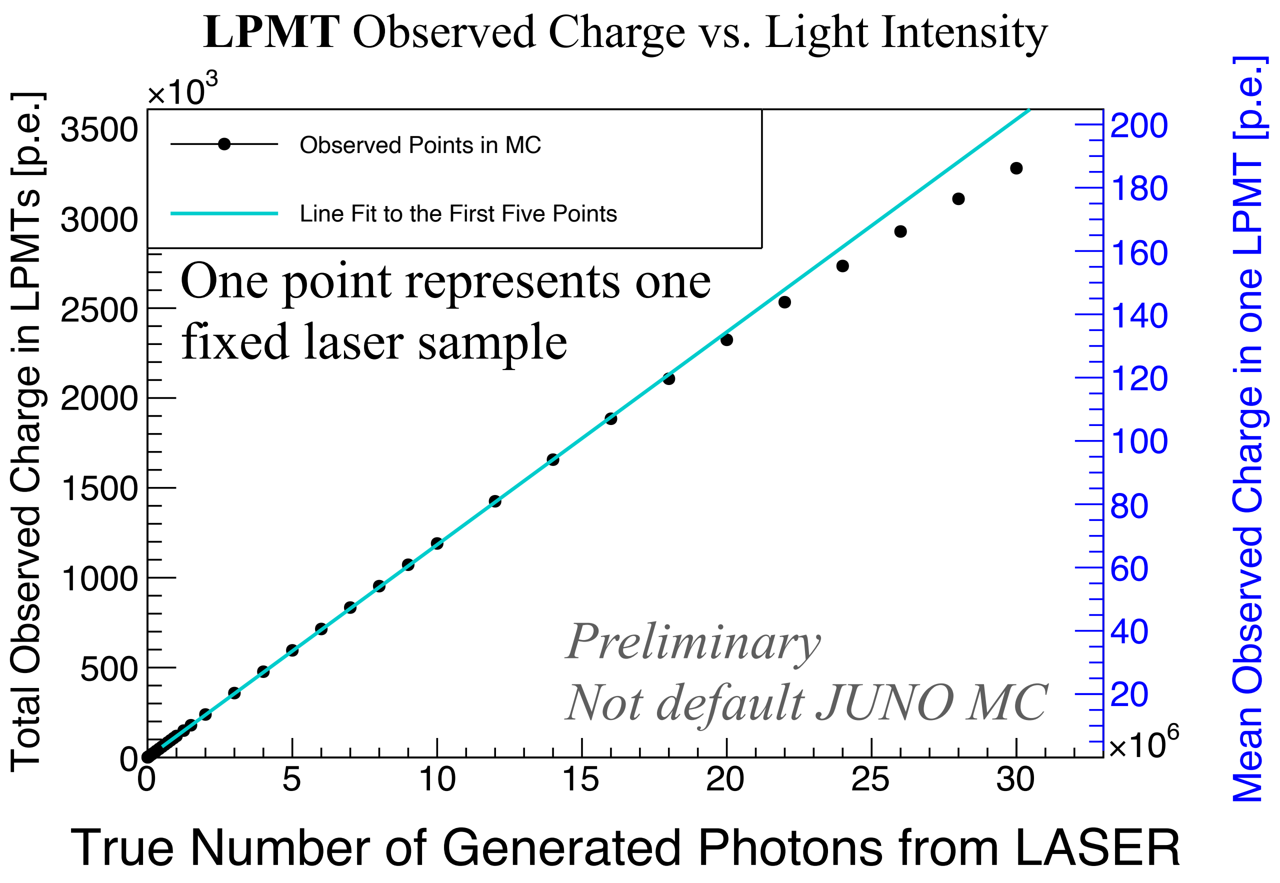
Compare and extract
LPMT non-linearity

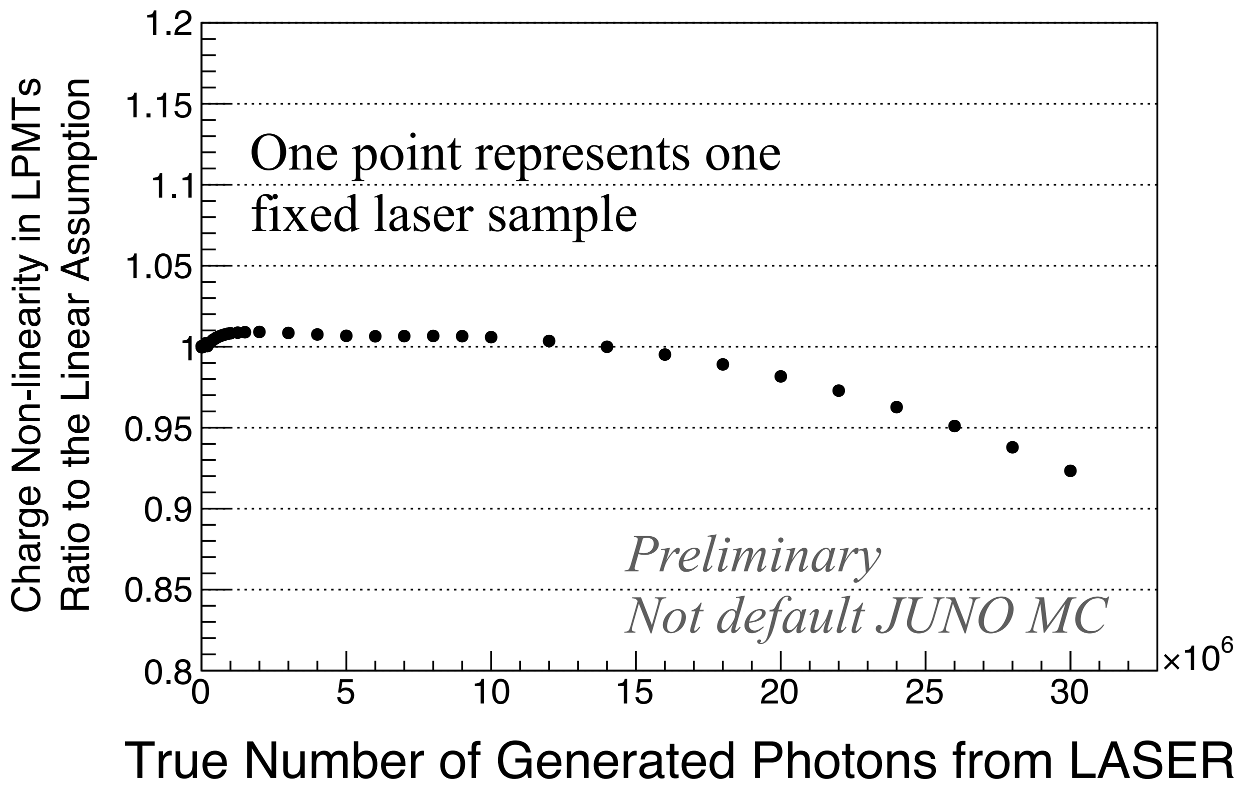
- With the laser device, the LPMT charge response is directly calibrated by illuminating them in different light intensities.
- Because of the smallness of the SPMT and digital counting treatment, described later, the SPMT response will keep its linearity.
  - Serving as a reference system to monitor the LPMT charge non-linearity, dual-calorimetry. Reference arXiv:2312.12991.
- Isolated from LS non-linearity and non-uniform detector responses.

Demonstration with Simulation

- The calibration method has been examined using the JUNO detector simulation.
  - To highlight the calibration performance, an artificial non-linear response of 10% at ~200 p.e. is implemented.
  - The actual non-linearity caused in each detector component (PMT saturation, electronics non-linearity, etc.) is estimated to be 1% level at 100 p.e.
    - These are from independent measurements from the test bench. Refs: RDTM 3, 11 (2019), NIMA 1053, 168322 (2023).
- Using low- to high-intensity UV laser simulation samples, calibration performances are evaluated in the following.

Non-linearity in Simulation

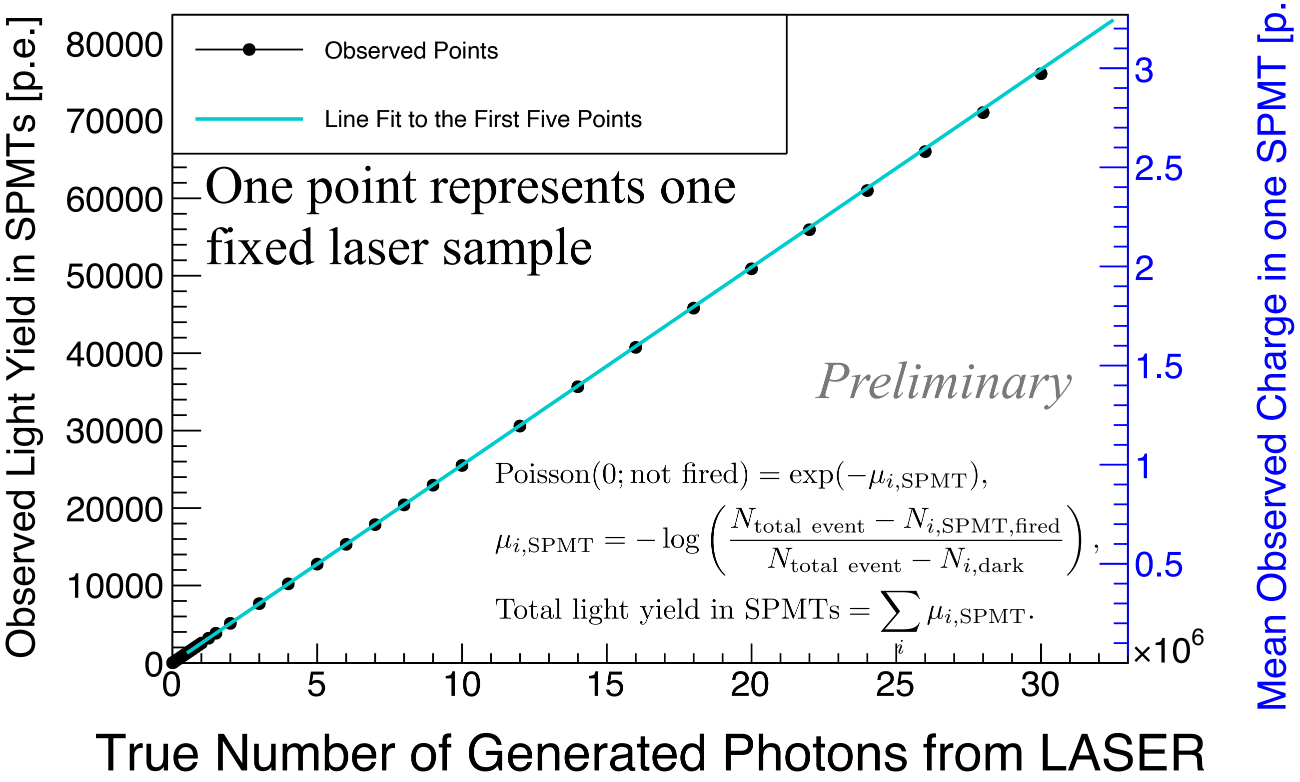




- The correlation between the true number of generated photons and the observed charge indicates the non-linearity of the instrumental responses.
- To demonstrate the effectiveness of the calibration, an artificial ~10% non-linearity at 200 p.e. is implemented in simulation.
- Deviation from linear extrapolation is regarded as the non-linear response.

SPMT System Outputs

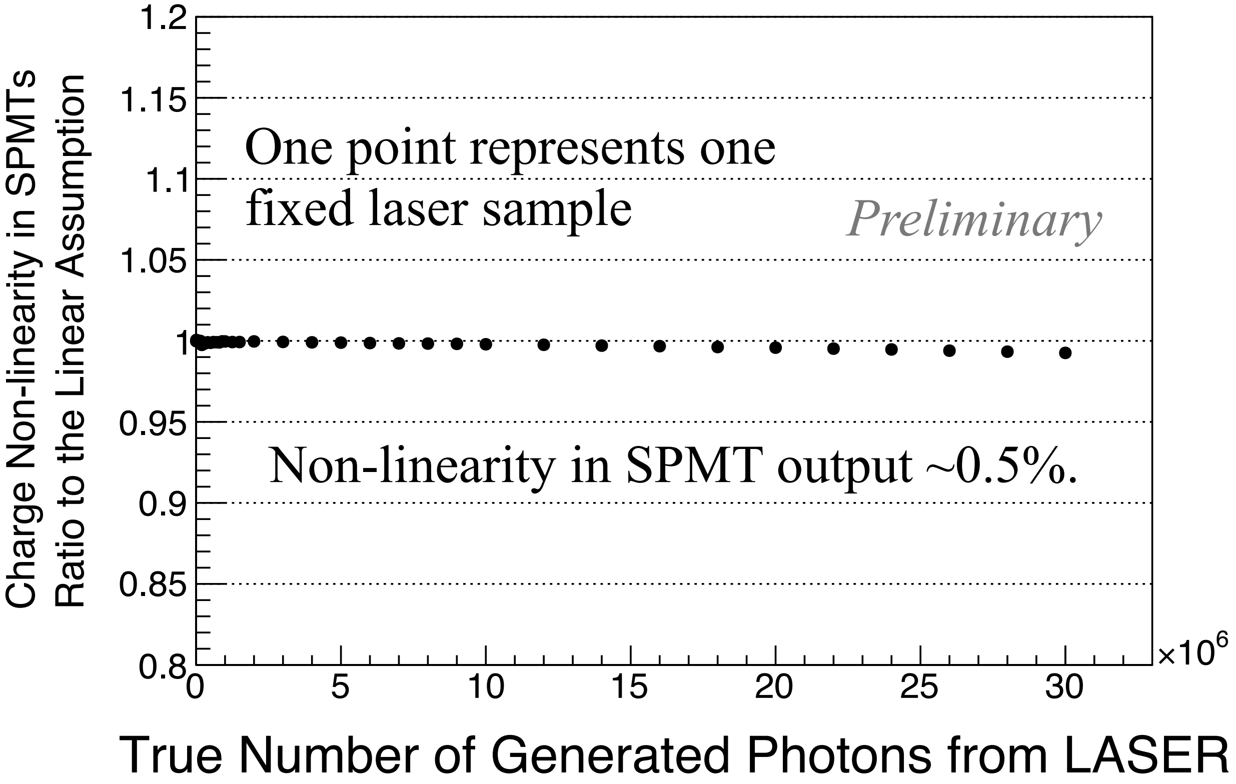
SPMT Observed Light Level vs. Light Intensity



$$\mathrm{Poisson}(0;\text{not fired}) = \exp(-\mu_{i,\mathrm{SPMT}}),$$

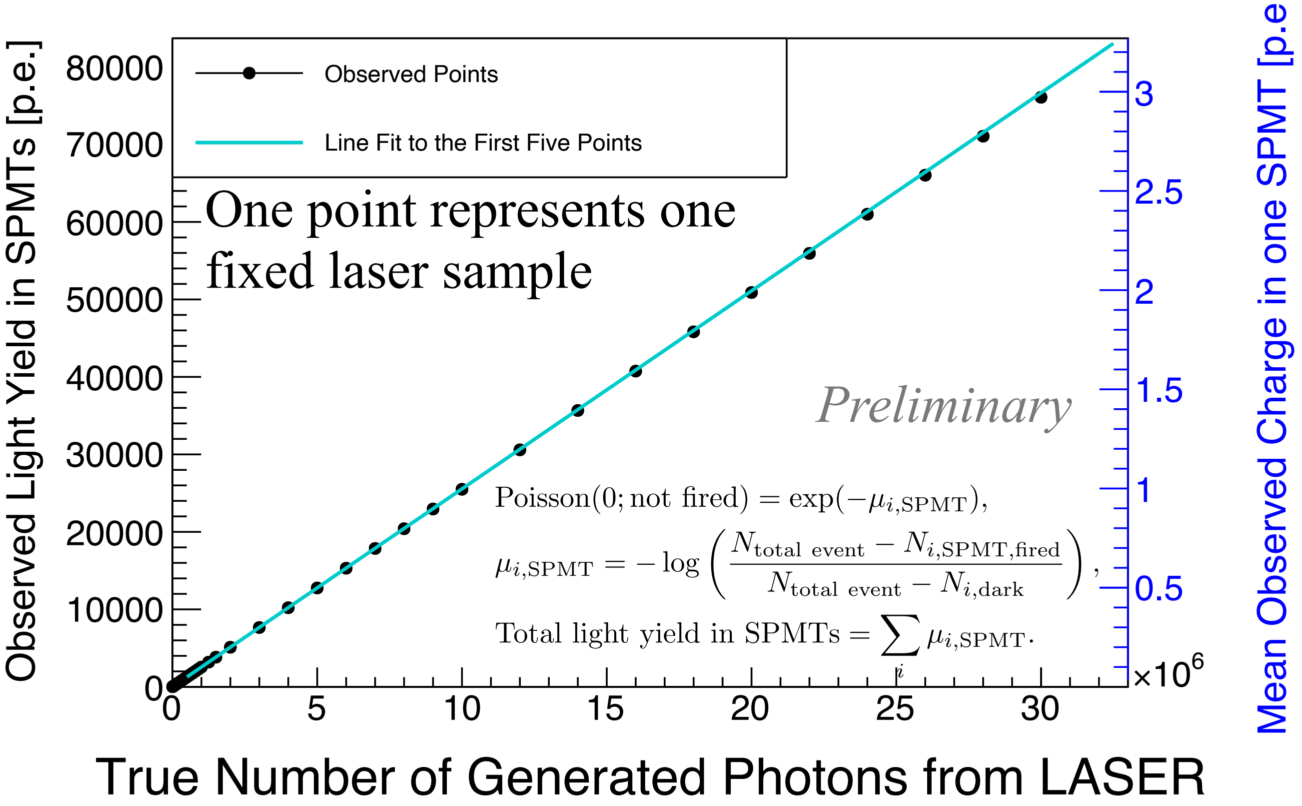
$$\mu_{i,\mathrm{SPMT}} = -\log\left(\frac{N_{\text{total event}} - N_{i,\mathrm{SPMT,fired}}}{N_{\text{total event}} - N_{i,\mathrm{dark}}}\right),$$

$$\text{Total light yield in SPMTs} = \sum_i \mu_{i,\mathrm{SPMT}}.$$

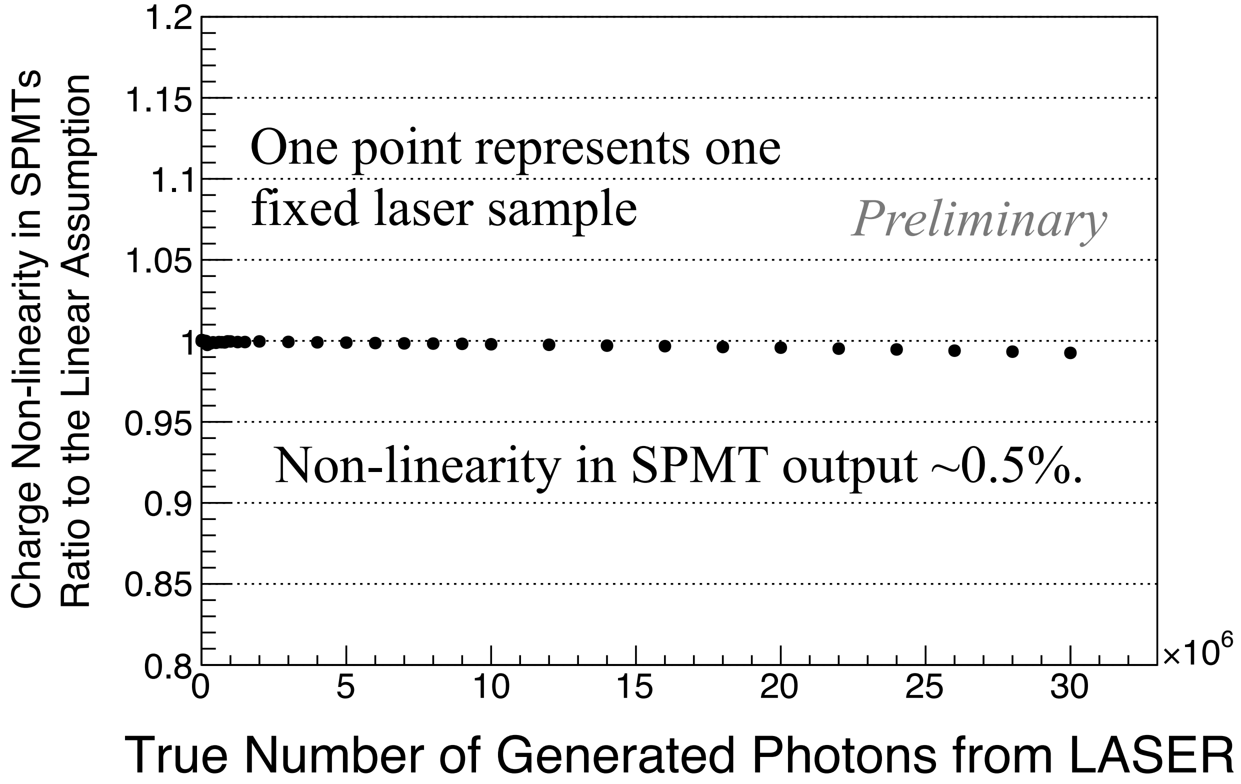


- In the calibration, the SPMT system serves as a reference system and has to keep its output linearity.
- However, when quite high-intensity light is injected into the detector, SPMTs may also receive multiple photons.
- The non-linearity in the SPMT system output needs to be considered or mitigated first.

Treatment of SPMT Outputs



SPMT Observed Light Level vs. Light Intensity

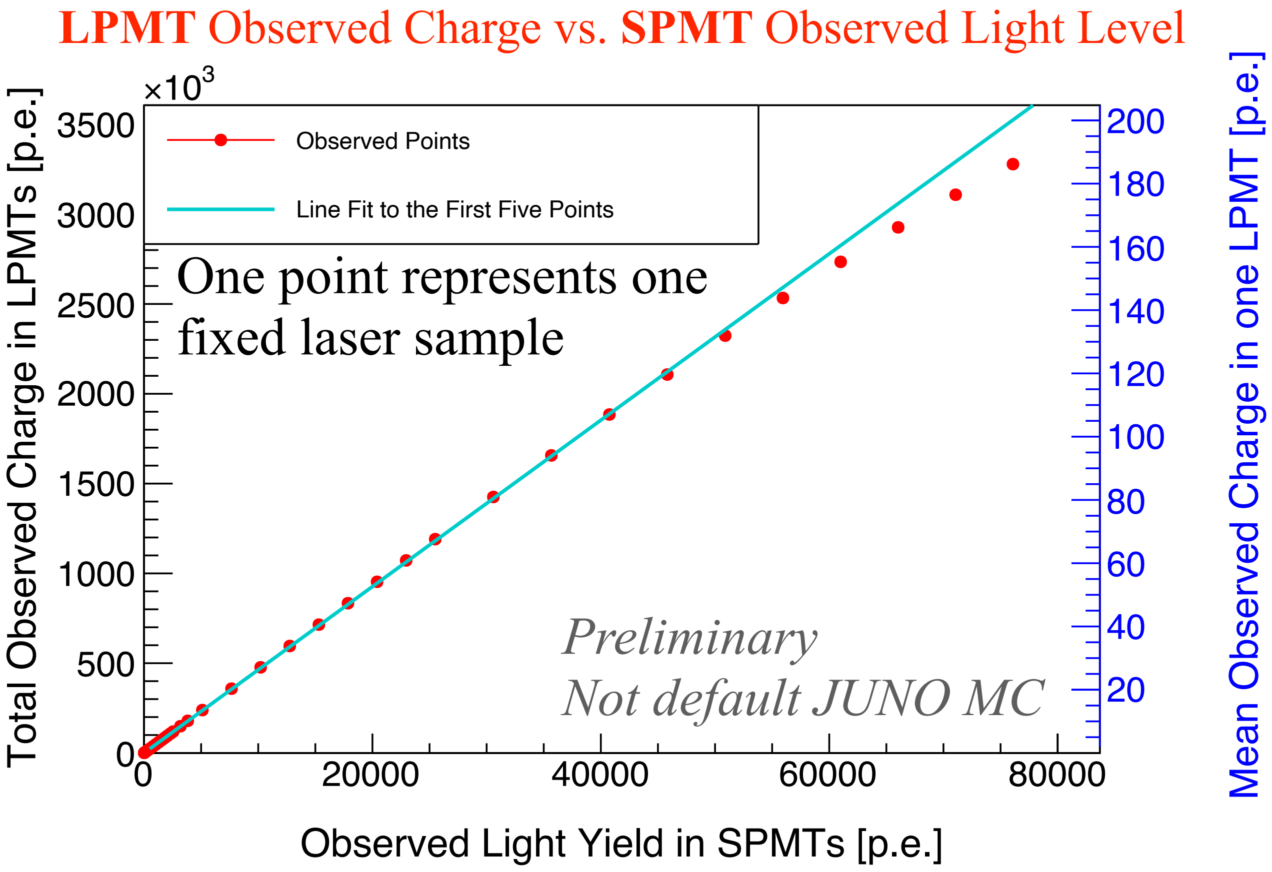


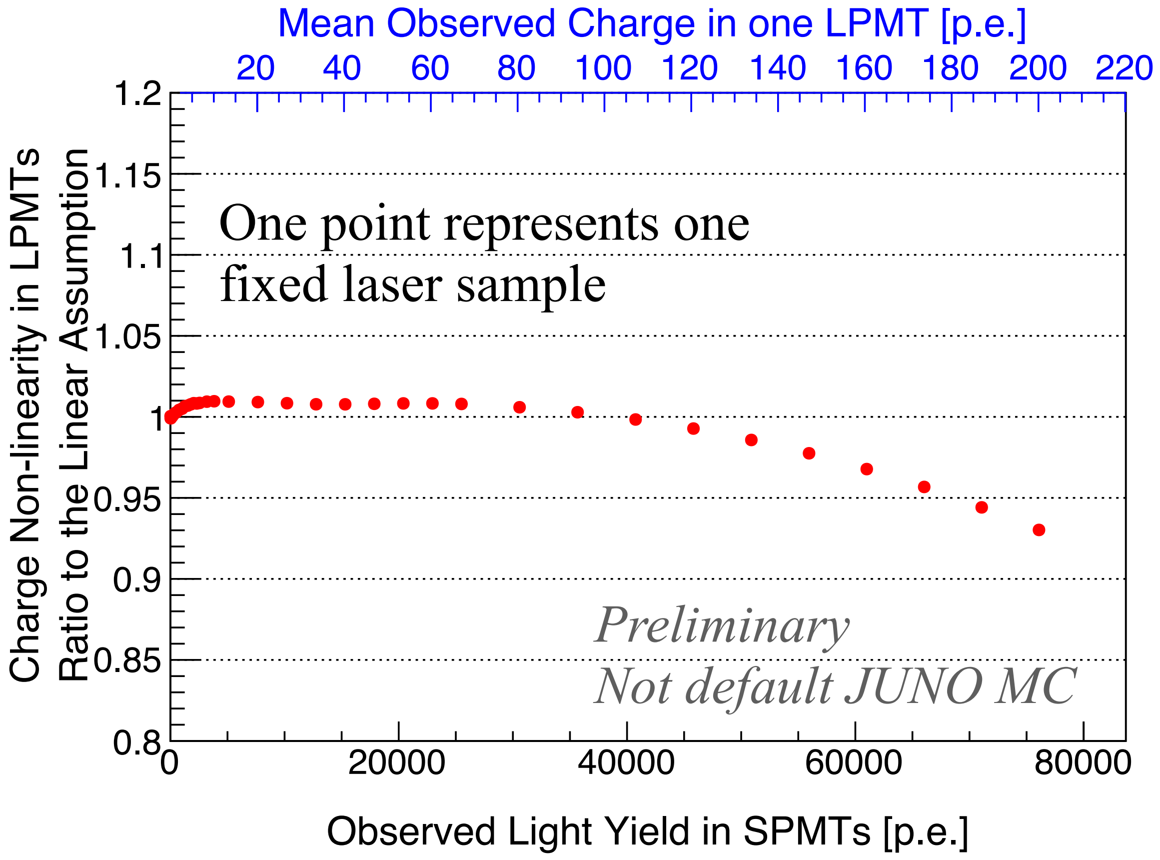
- To avoid the effect of the non-linearity in the SPMT system, the mean light yield at each SPMT is estimated using a digital counting method.

$$\begin{aligned}\mathrm{Poisson}(0;\text{non fired probability}) &= \frac{N_{\text{total event}} - N_{\text{fired}}}{N_{\text{total event}}}\\ &= \exp\left(-\mu\right) \qquad \mu : \text{Mean light intensity}\end{aligned}$$

- The light intensity is estimated by counting how many times the SPMT does not detect photoelectrons.
- The non-linearity in the SPMT system is at a 0.5% level.

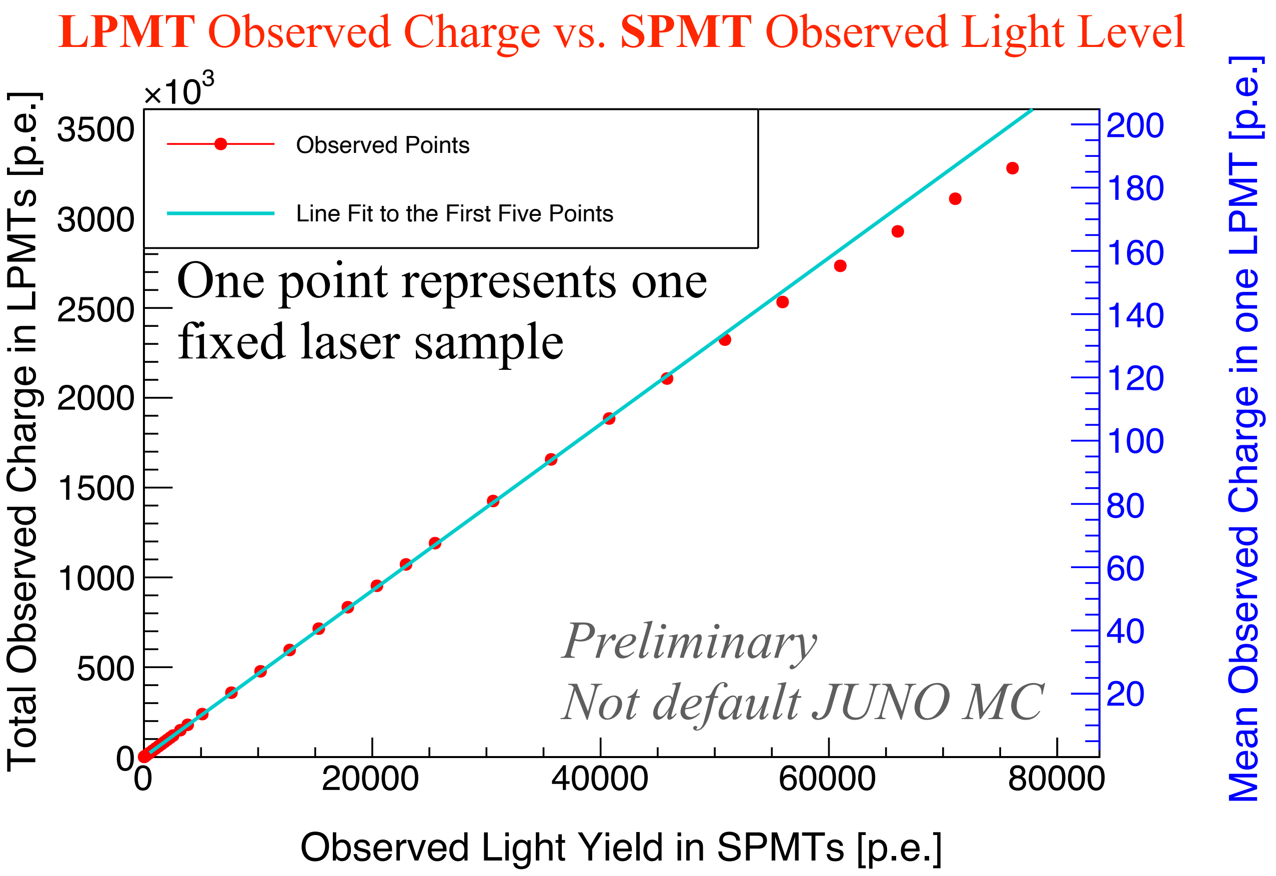
Non-linearity Calibration

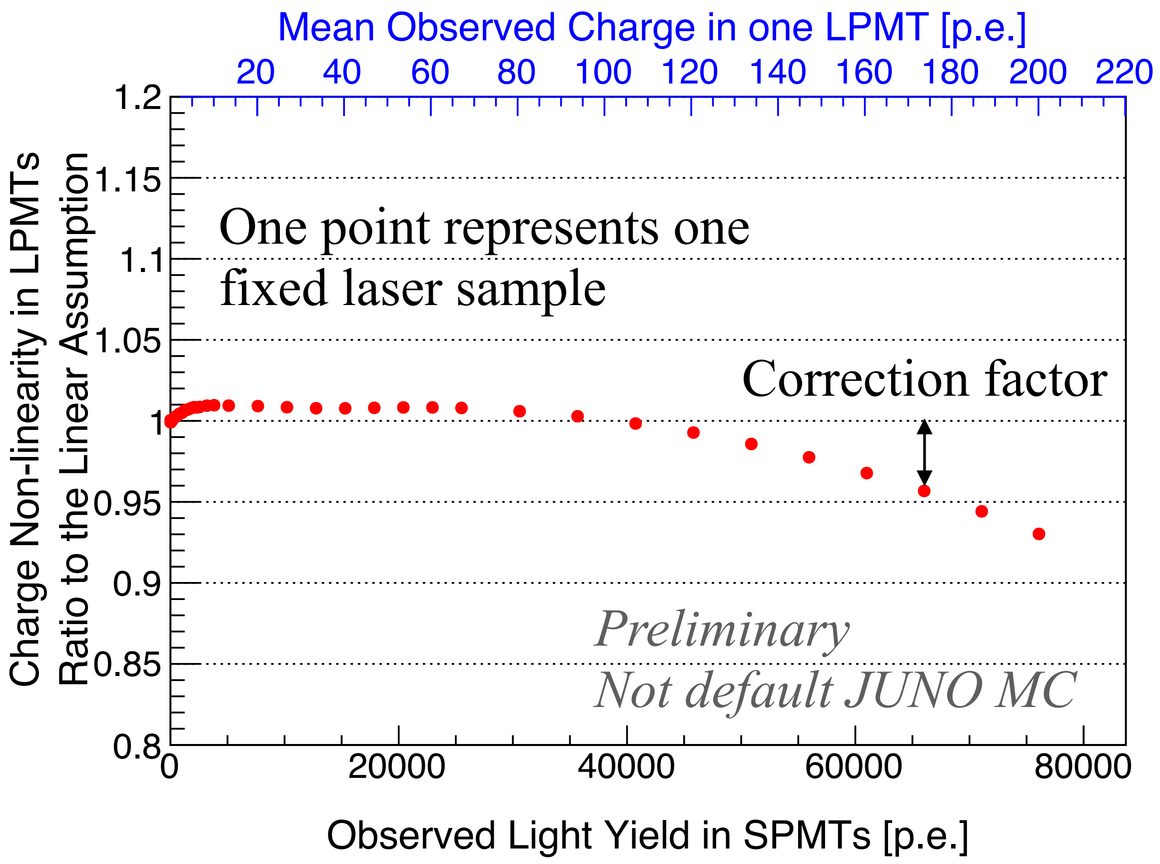




- Outputs from the LPMT and SPMT systems are directly compared.
- Non-linearity in the LPMT system output manifests as a deviation from the linear SPMT system output.
- The size of the deviation is calibrated and tabulated at each LPMT as a function of the observed charge.

Non-linearity Calibration


LPMT Observed Charge vs. **SPMT** Observed Light Level



- Outputs from the LPMT and SPMT systems are directly compared.
- Non-linearity in the LPMT system output manifests as a deviation from the linear SPMT system output.
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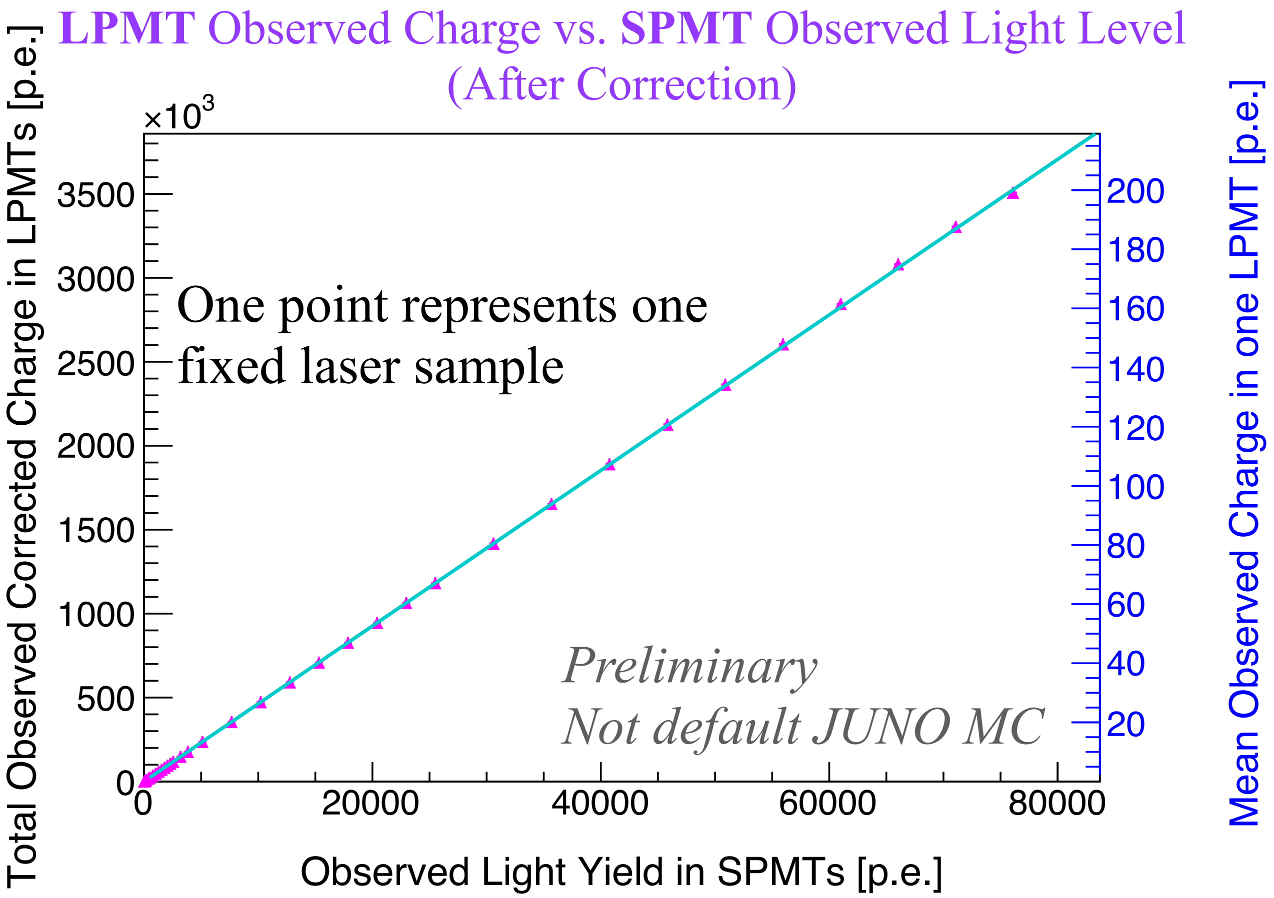
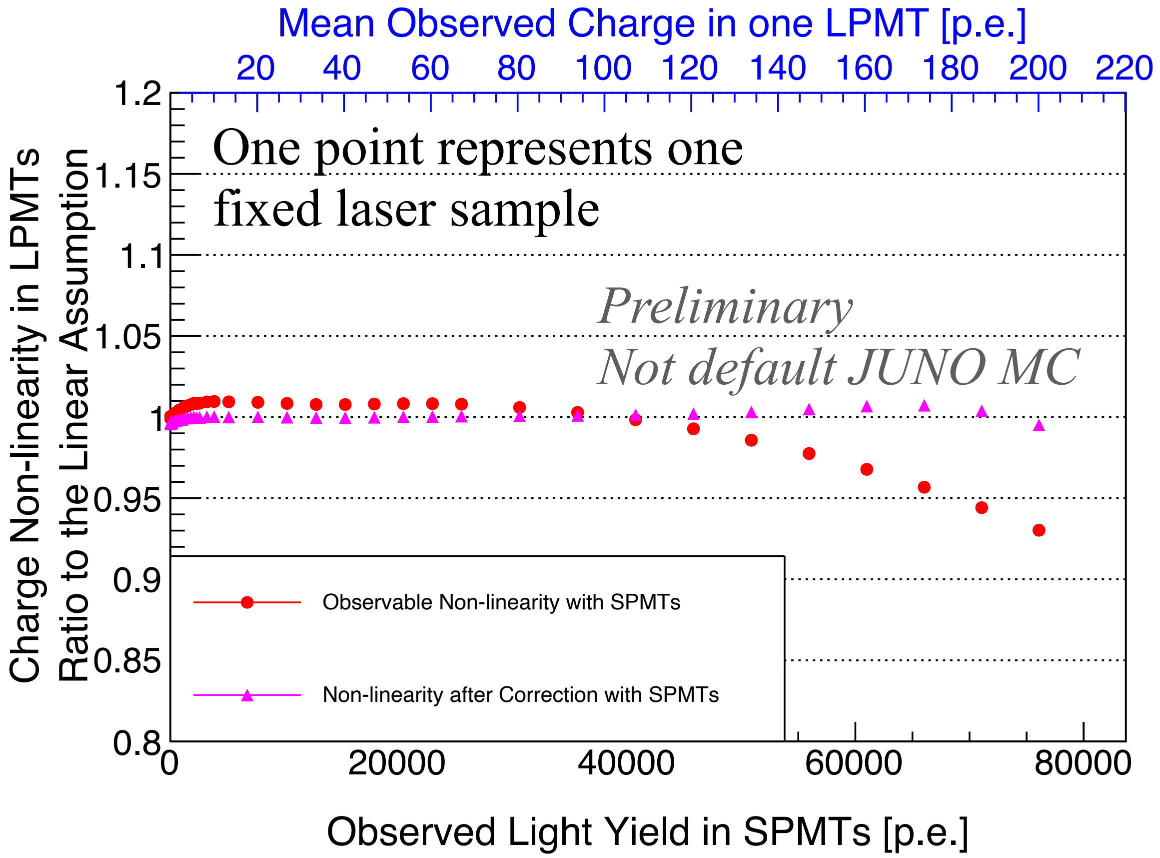
Non-linearity Correction





- Adopting the correction table to each LPMT observed charge restores the linearity of the LPMT charge response.
- After the correction, the non-linearity in the LPMT output is suppressed to a ~0.5% level.
- These corrections are applied to other physics events, ex. ν events.
- Calibration with radioactive sources and cosmogenic products with various energies is also considered for additional validation.

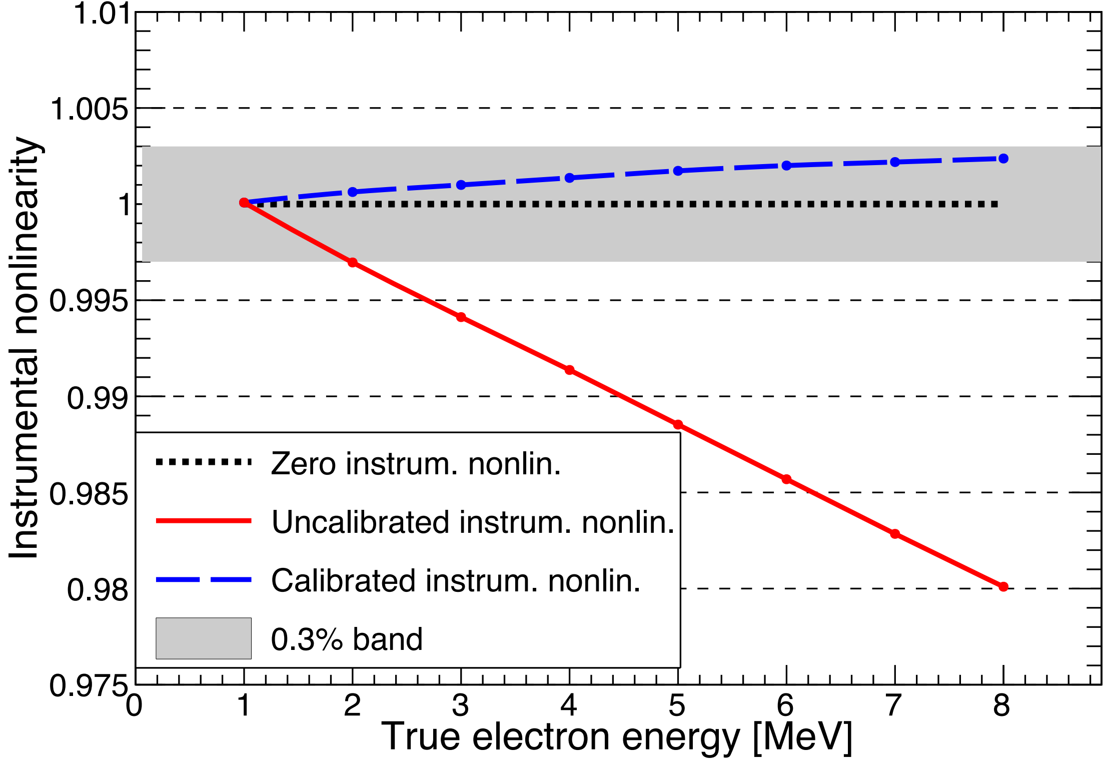
Summary

- JUNO aims to determine the neutrino mass ordering through reactor neutrino measurement by achieving:
  - an optimal energy resolution of 3% at 1 MeV and
  - better than 1% systematic uncertainty on the energy scale.
    - Based on an accurate PMT response calibration with a variable-intensity laser system.
- Charge non-linearity in LPMTs in JUNO will be calibrated by referencing SPMTs as a linear response system.
  - The output of the SPMTs is handled in a digital counting method to make it serve as a linear indicator of the laser light intensity.
- A simulation study demonstrates that this method can suppress potential charge non-linearity in the LPMT system to a level of 0.5%.
  - This meets the experimental requirements.
- The method can be applied to other experiments.

backup

Influence on Energy Measurement in JUNO

Assuming extreme non-linearity 50% at 100 p.e.



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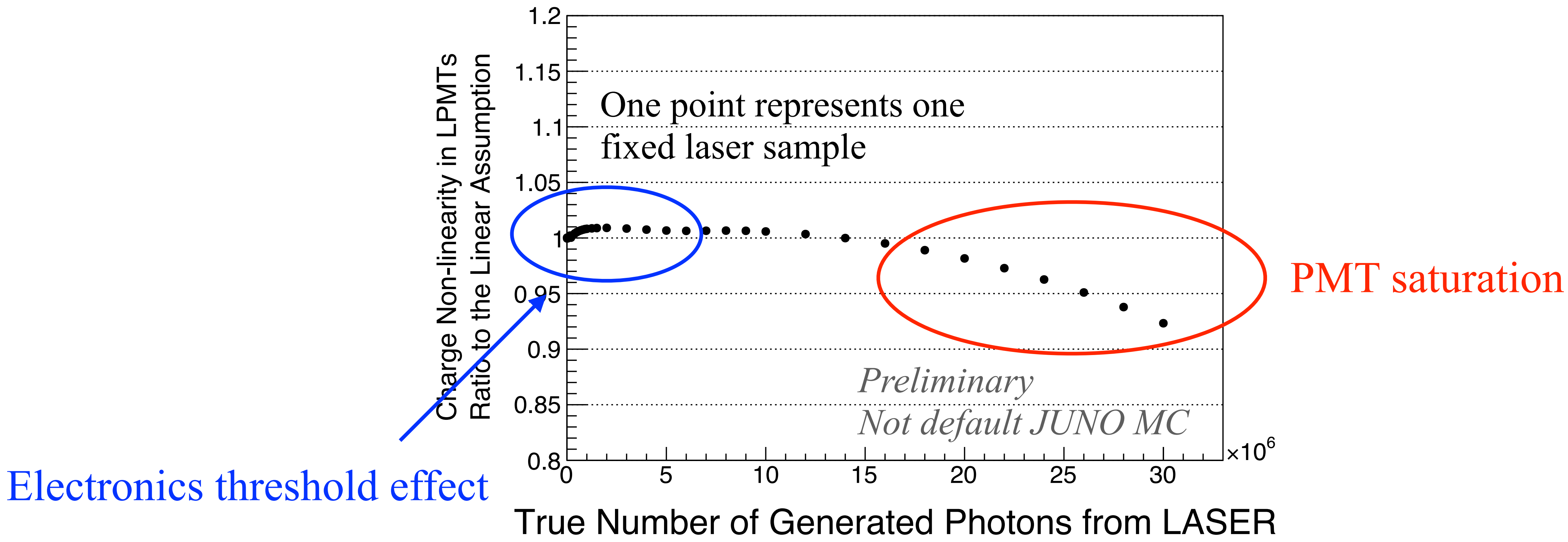
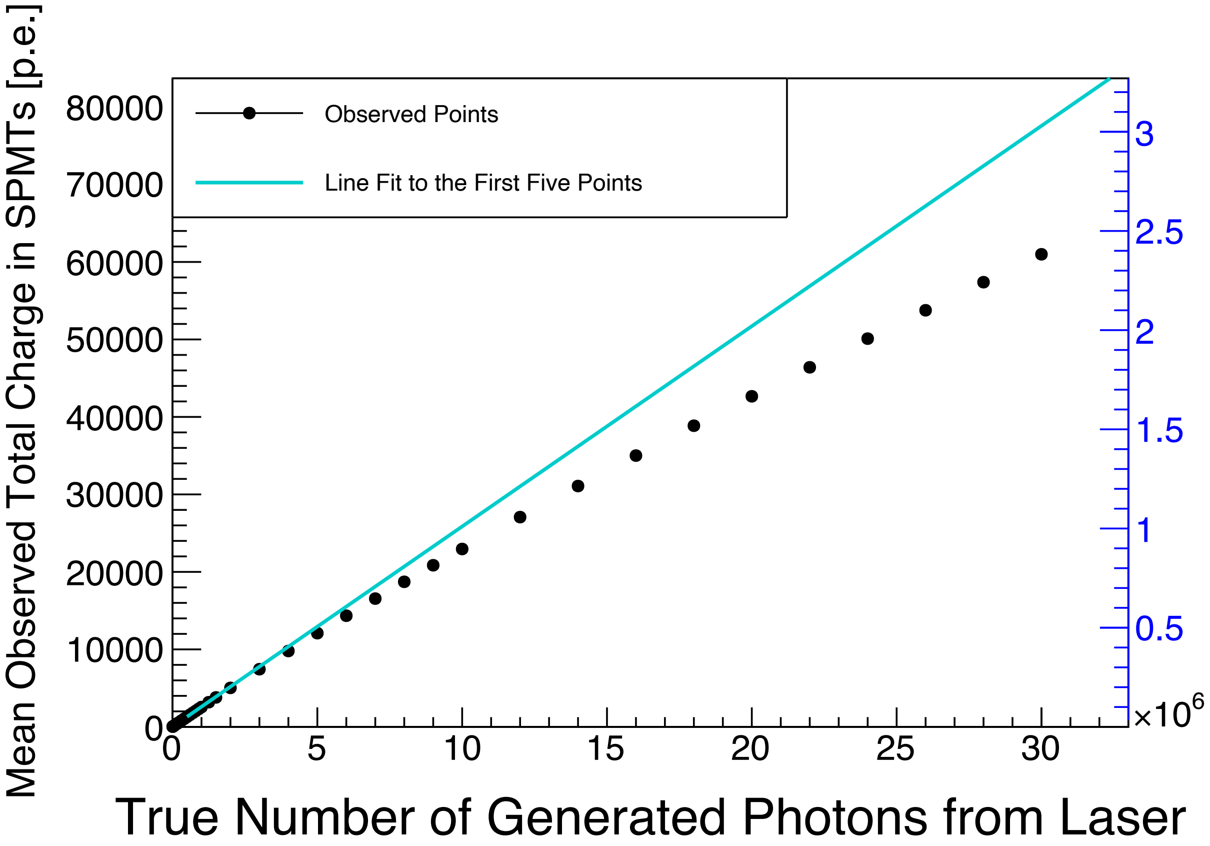
- The amount of detected photoelectrons at each PMT depends on the particle energy and spatial relationship with the particle position.
  - Non-linear charge response at each LPMT would degrade the accuracy of the calibration of the LS non-linear response.
  - It would also degrade the calibration/reconstruction performances of the particle energy in different positions inside the detector.
- In an extreme scenario, it would yield non-negligible uncertainty in the energy measurement unless this charge non-linearity is corrected.

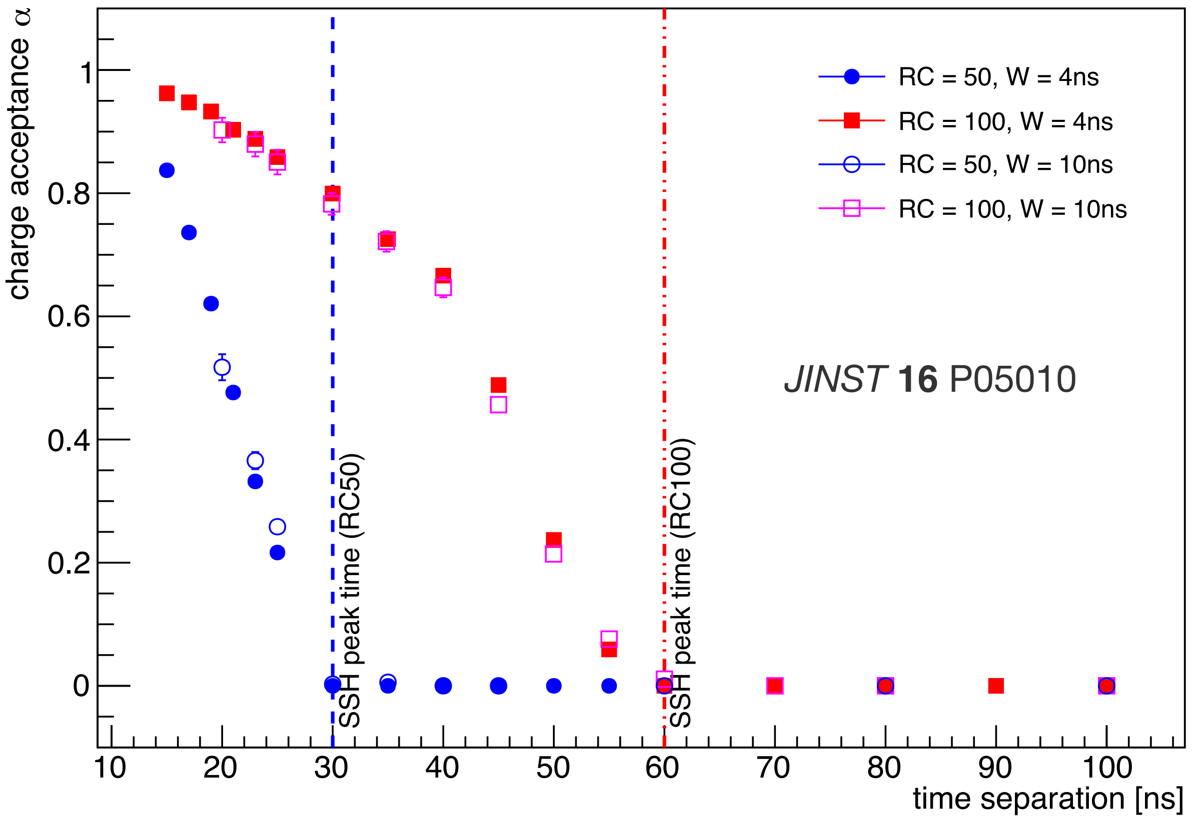
Cause of Non-linearity



- In low-intensity light level, some of the single photoelectron pulses may not exceed the threshold.
  - Observed charge for such a pulse becomes 0. The mean observed light level is biased to be lower.
    - Ex: μ_{true} = 0.5 p.e. → μ_{obs} = 0.4 p.e.
- In high-light intensity samples, multiple pulses are piled up and the threshold effects will be negligible. μ_{true} = 50 p.e. → μ_{obs} = 50 p.e.

SPMT Charge Non-linearity

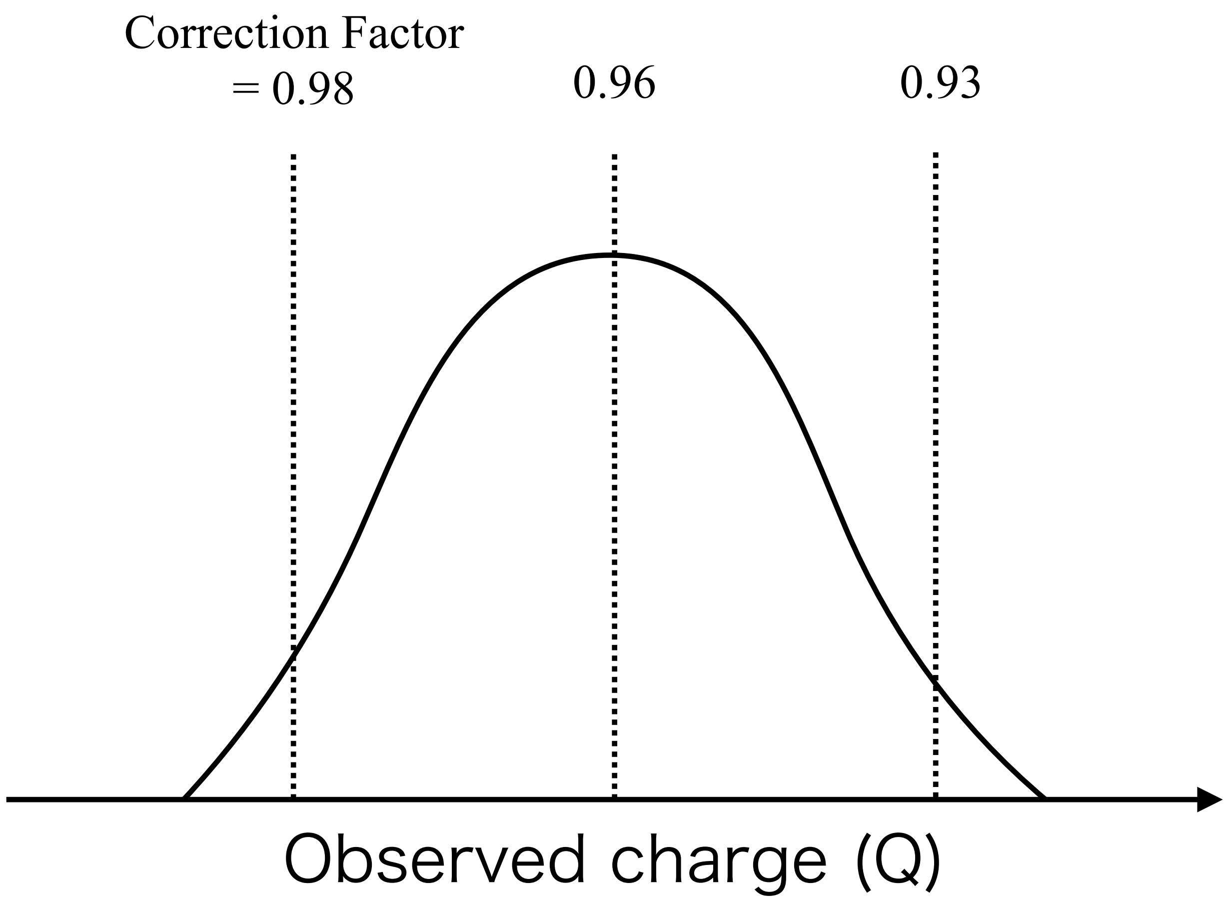


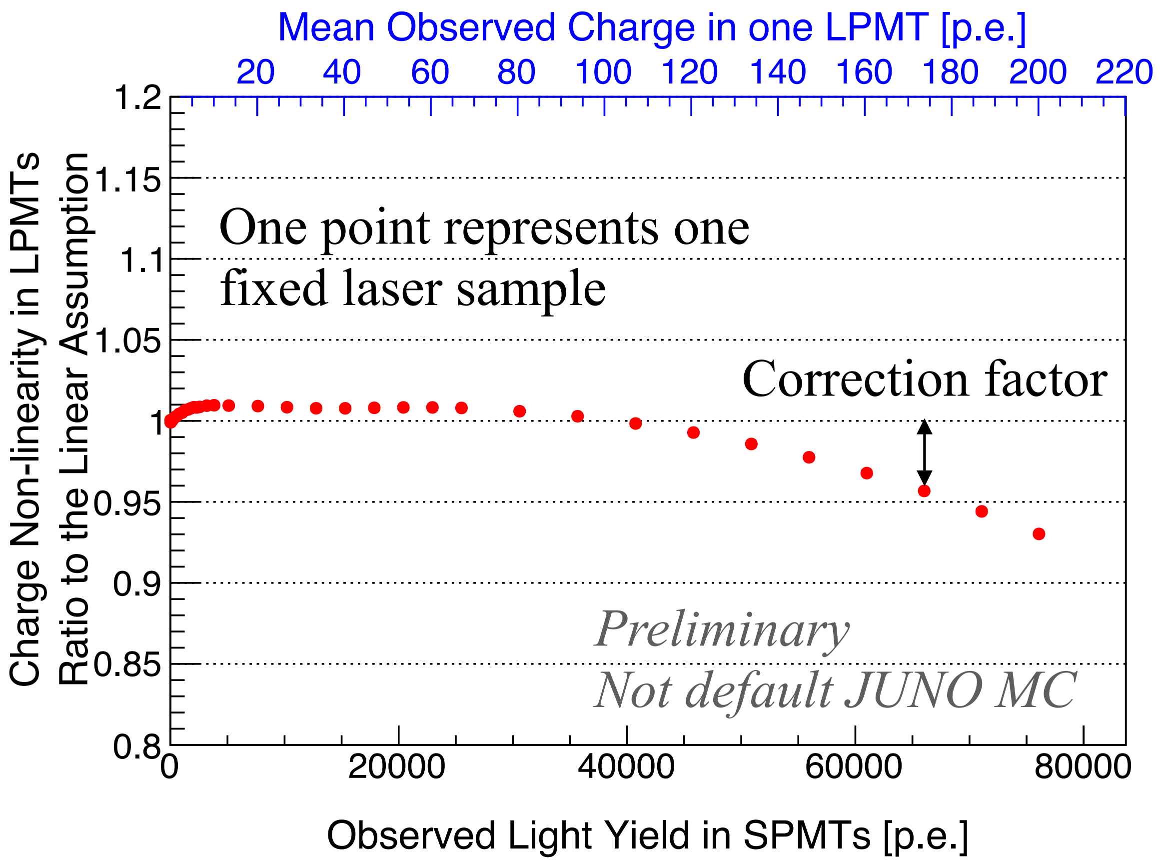


JINST **16** P05010

- The observed charge in the SPMT system is anticipated to be subject to a significant non-linearity caused by the associated electronics.
- Channel-level dead time makes it difficult to collect all charges in sequential pulses.
  - Preventing us from using the observed charge.

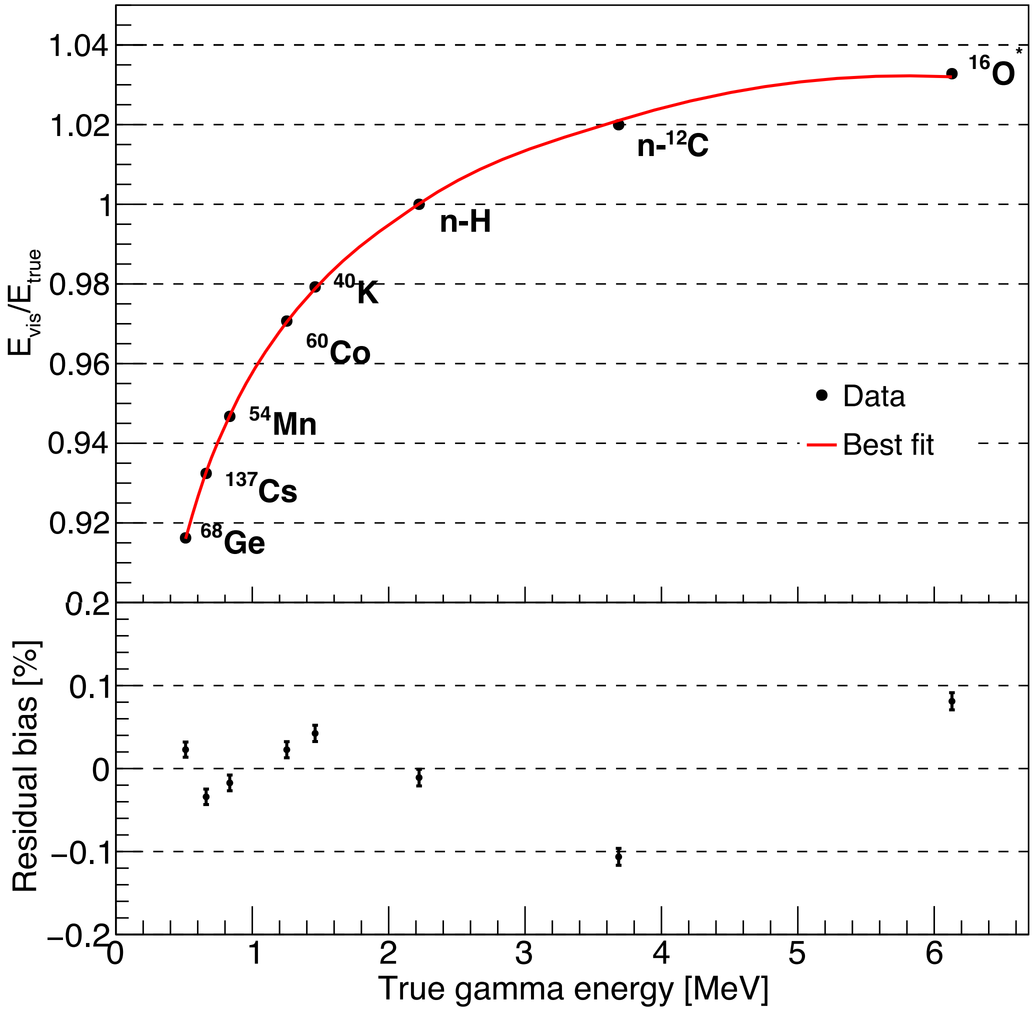
Residual Bias





- The correction factor is derived by comparing the mean observed charge at each LPMT and mean observed light yield in the SPMTs.
  - While the correction is applied to hit by hit charge value.
- This inconsistency can lead to residual biases in case the correction factor is not the same over the focused charge region.
- The mean of hit by hit correction does not necessarily match the mean bias.

JUNO Calibration Strategy (1)



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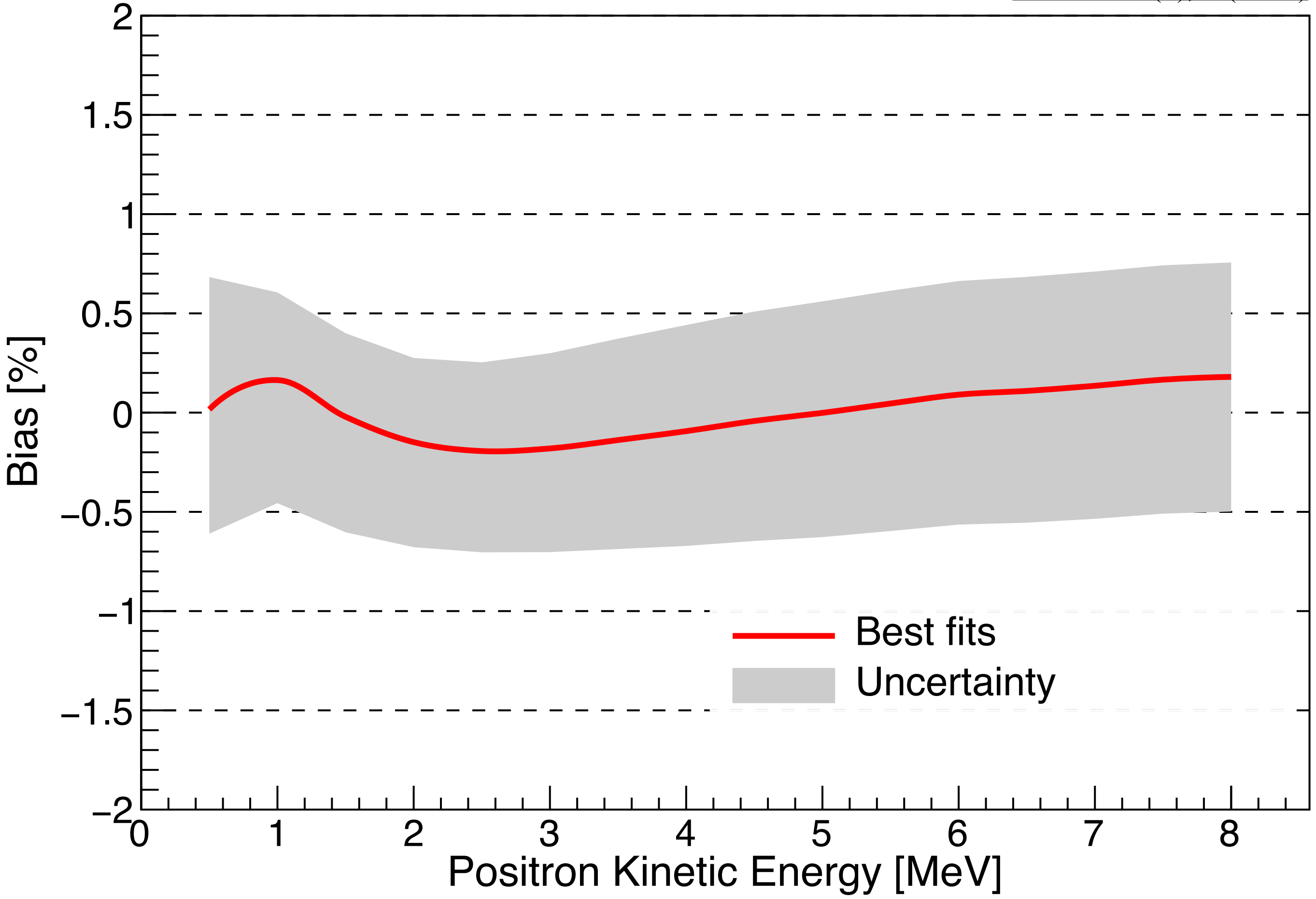
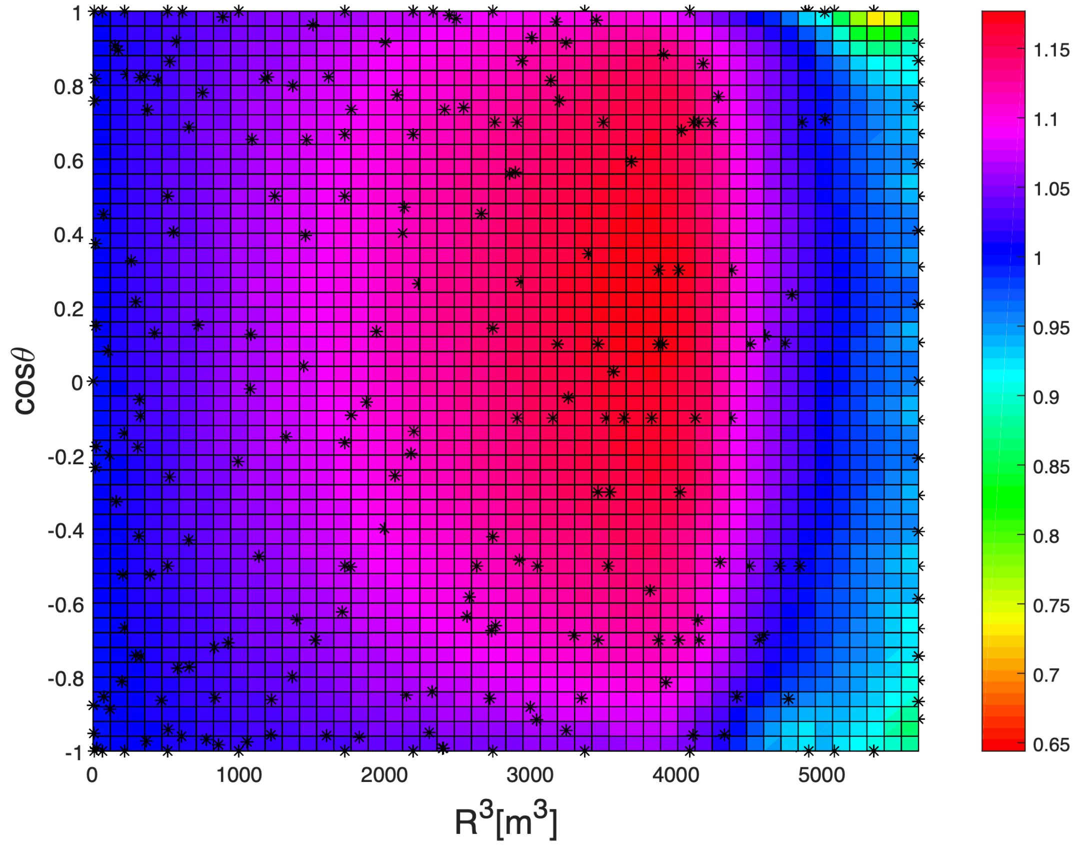


- The light yield of the LS is non-linear to the deposited energy of the particle due to the LS quenching and Cherenkov light contribution.
- Several γ-ray calibration sources will be deployed in the detector to understand this non-linearity and establish a positron energy model.
- In addition, cosmogenic products, such as ^{12}B (Q-value 13.4 MeV), will cover the higher energy region.

JUNO Calibration Strategy (2)

Observed photoelectrons per unit energy w.r.t. the center



Source deployment positions

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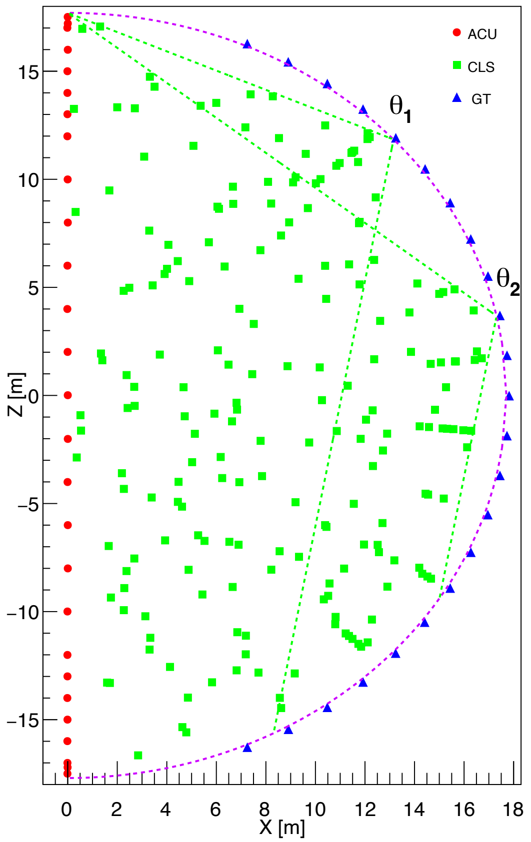
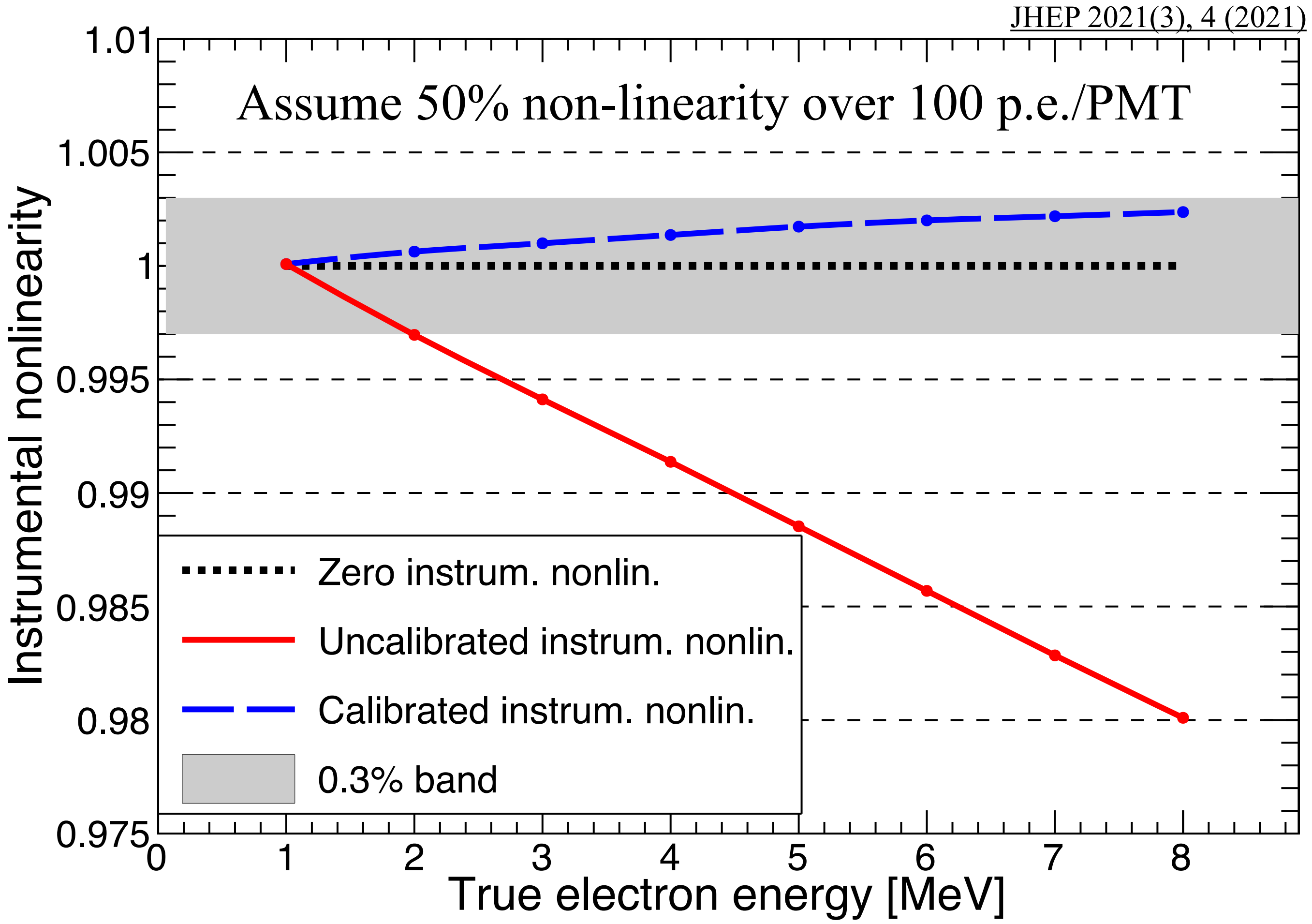


- The observed number of photoelectrons per unit energy varies by more than ±10%.
  - Due to complex light propagation processes inside the detector.
- This non-uniform energy scale will be calibrated by deploying a calibration source at multiple positions.
- 2.2 MeV γ-ray from spallation neutrons can be an option as well.

JUNO Calibration Strategy (3)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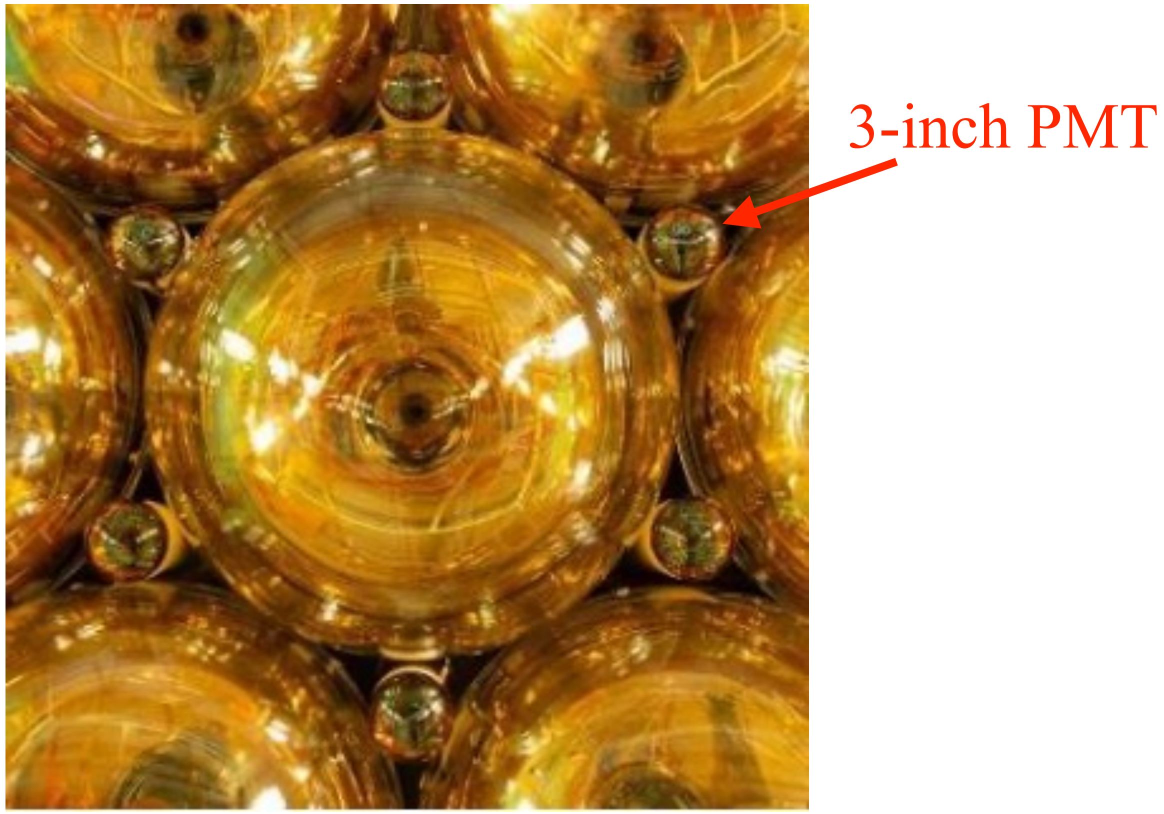
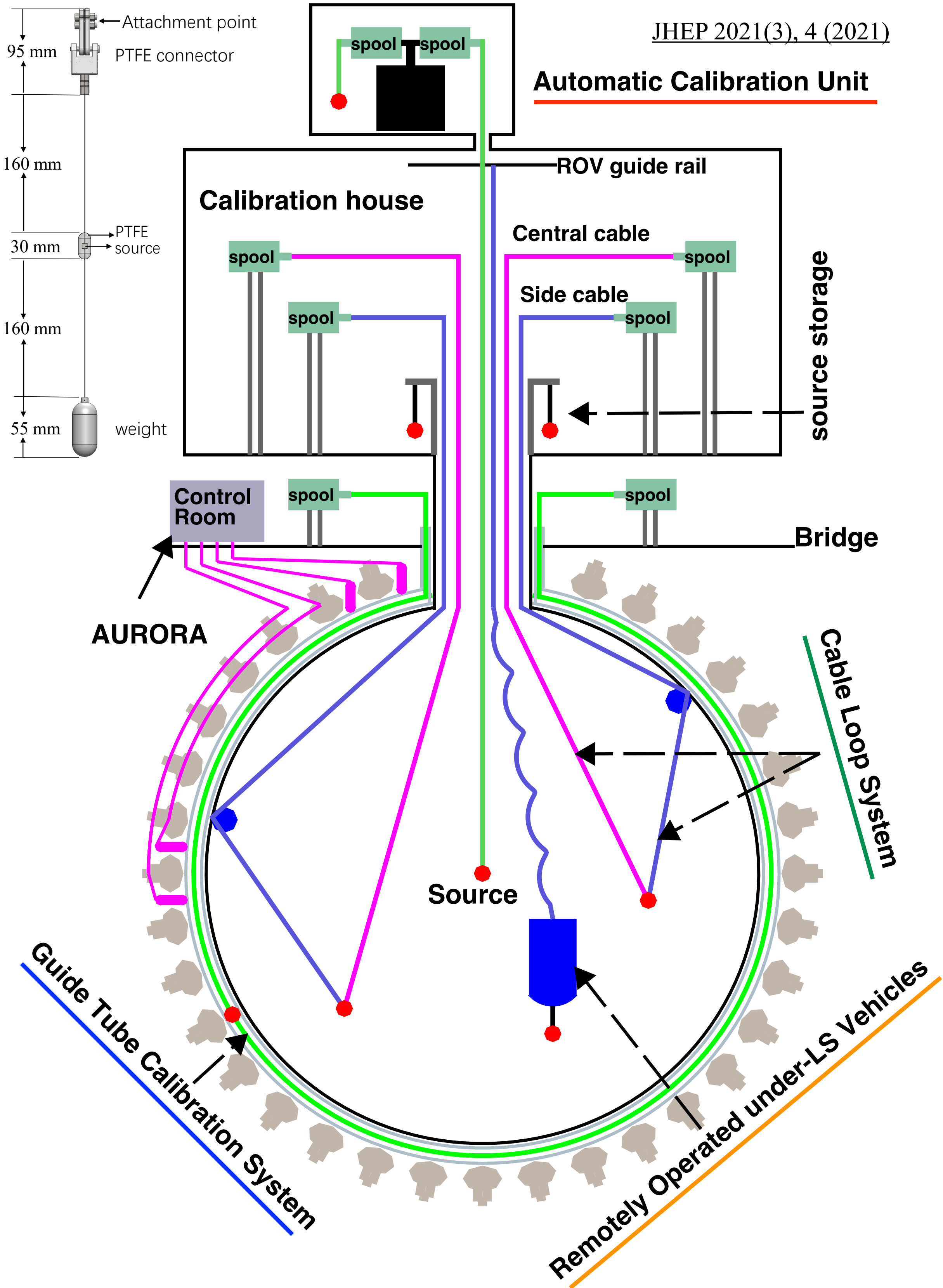


- An inaccurate understanding of the 20-inch PMT non-linearity may degrade the LS non-linearity and non-uniformity calibration qualities.
- A laser calibration source will illuminate the 20-inch PMTs (charge mode) from a single photoelectron (p.e.) to more than 100 p.e.
- By comparing their response to the 3-inch PMTs (mostly single p.e. counting), the instrumental non-linearity will be calibrated.

JUNO Calibration System

- Multiple calibration source deployment devices will be installed, placing a calibration source at different positions:
  - Automatic Calibration Unit (ACU) will cover the central axis.
  - Cable Loop System (CLS) can cover the off-axis region in a two-dimensional plane.
  - Guide Tube Calibration System (GTCS) will deploy the source on the outer surface of the acrylic sphere.
  - Remotely Operated Vehicle (ROV) can access any position inside the LS volume.



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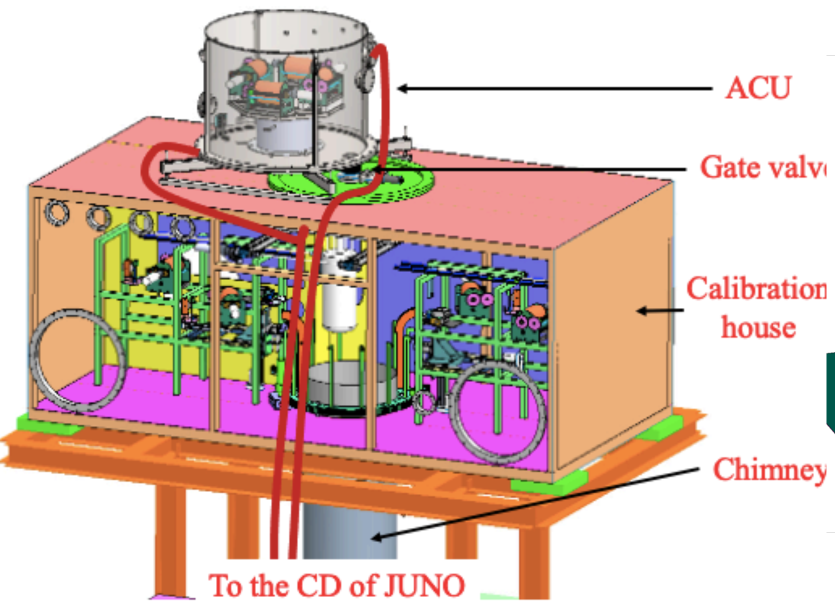
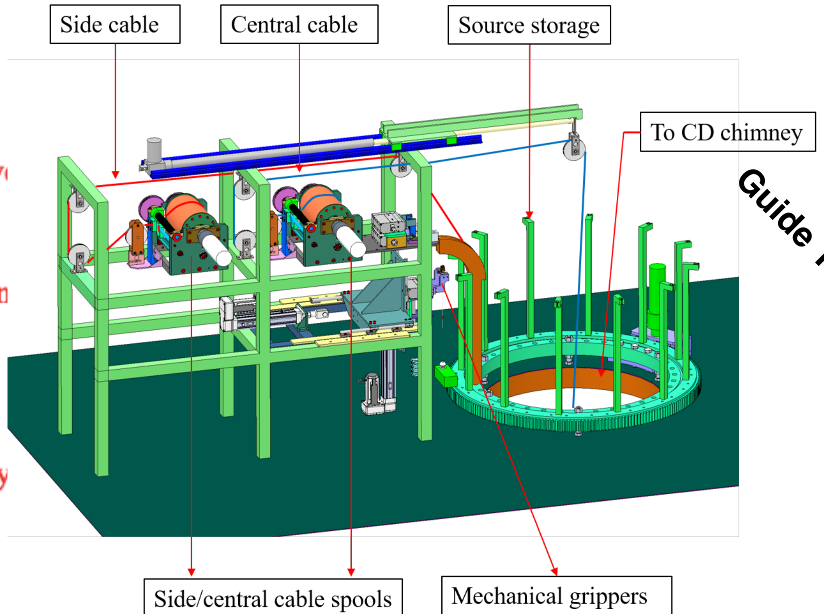
ACU & CLS

- ACU can deploy radioactive and laser sources along the central axis by tuning the wire length with a spool system.
- Position accuracy is estimated to be ~1 cm.
- CLS will move a radioactive source within a two-dimensional plane by adjusting the length of the two wires.
- The source position will be monitored by an ultrasonic system with ~3 cm accuracy.

JINST 16(8), T08008 (2021)



NIMA 988, 164867 (2021)



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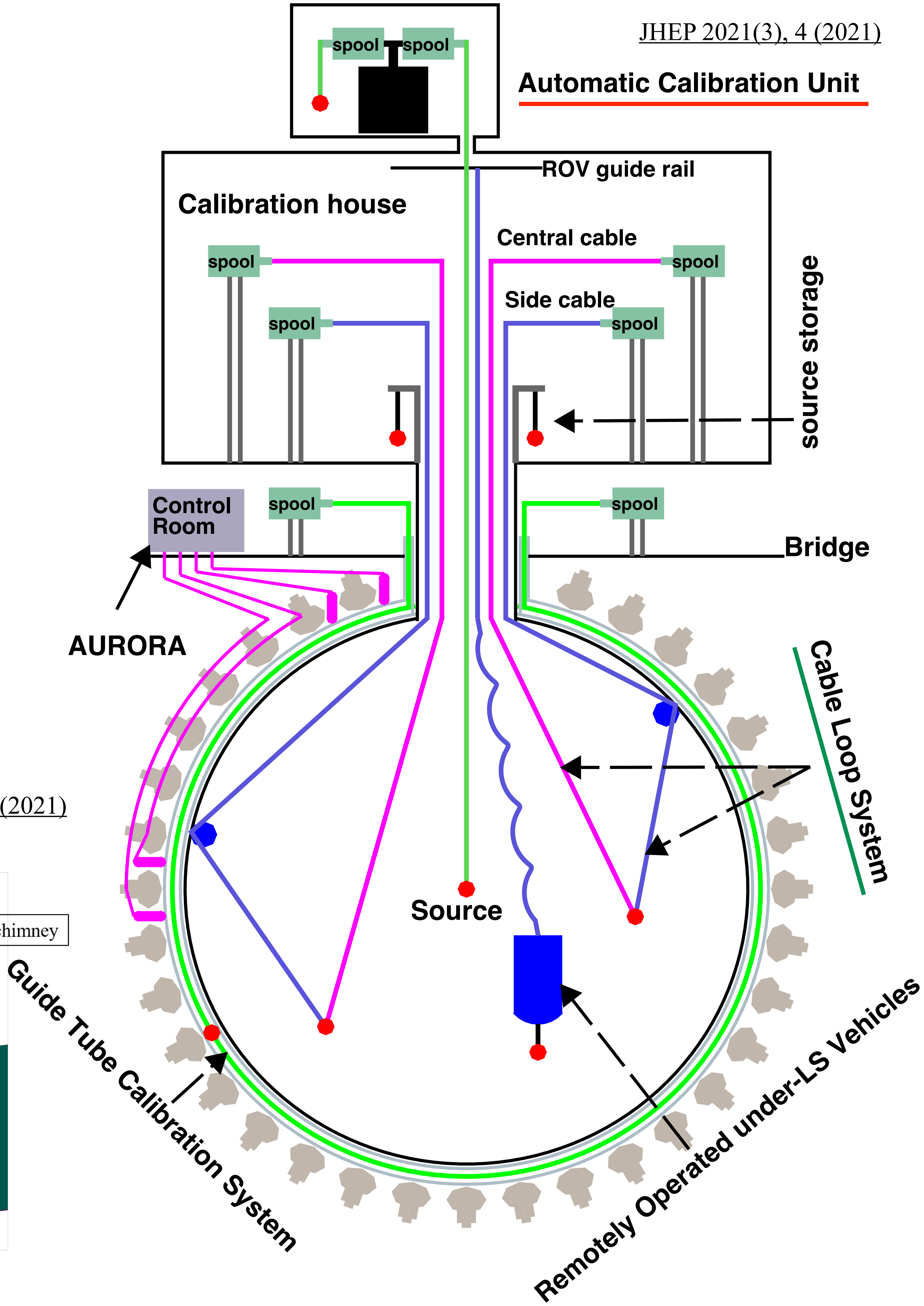
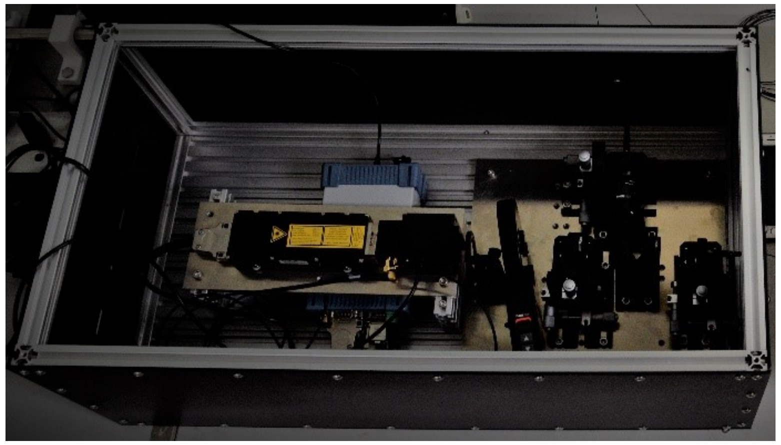


Laser Calibration System

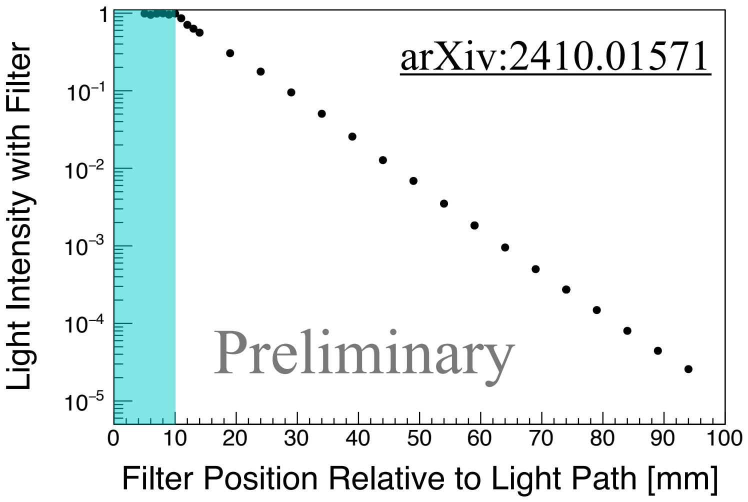
- A laser device placed outside the detector will deliver ultraviolet (UV, λ~267 nm) photons into the LS volume.
  - A light diffuser ball will be placed by ACU.
- UV photons will be immediately absorbed in the LS, and visible light will be emitted.
- Using an optical filter, the light intensity can be tuned.
  - More than four orders of magnitude.

JINST 14(1), P01009 (2019)

UV Laser Device



Light Intensity vs. Filter Position


arXiv:2410.01571

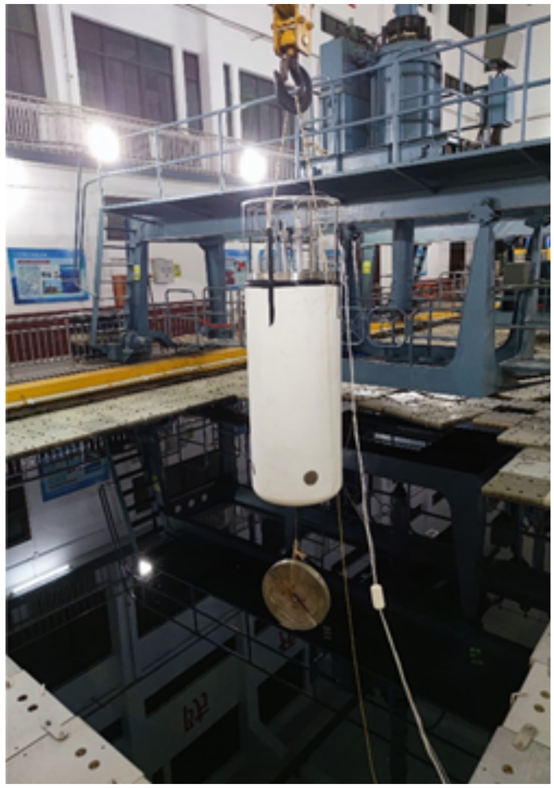
Natural density filter

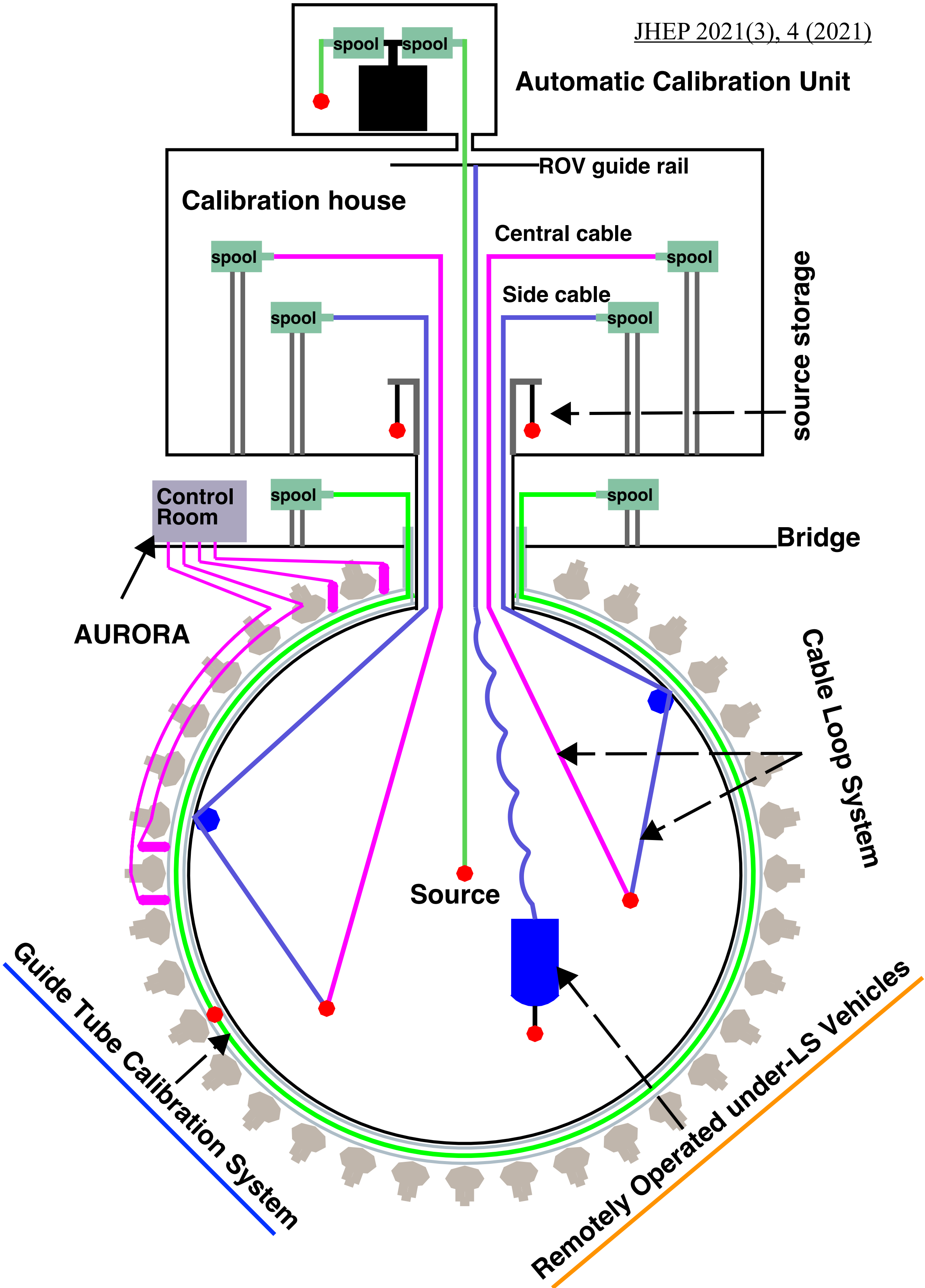
GTCS & ROV

- GTCS will help to calibrate the detector response at the detector edges.
- The source will be moved through the tube attached to the acrylic surface.
- ROV is a submarine deploying a radioactive source.
- Enables to carry out a 3D calibration.

Guide Tubes attached on the acrylic

ROV Testing





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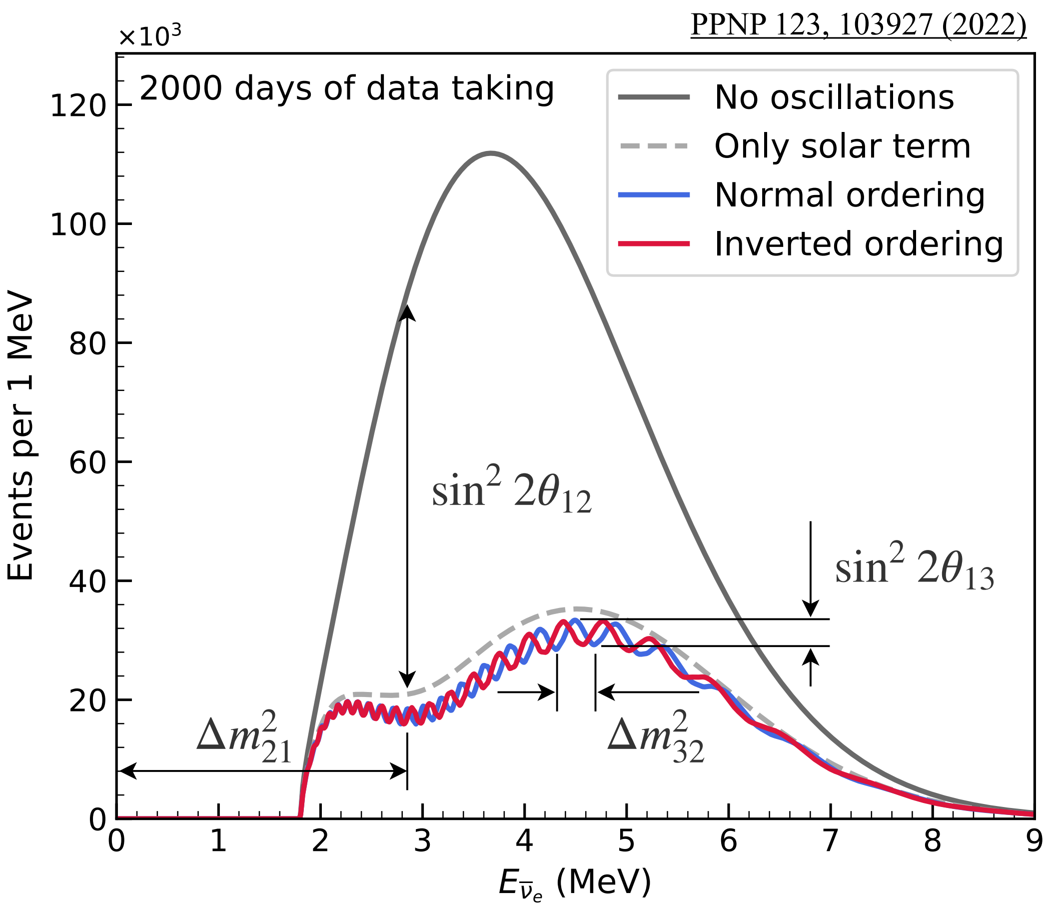
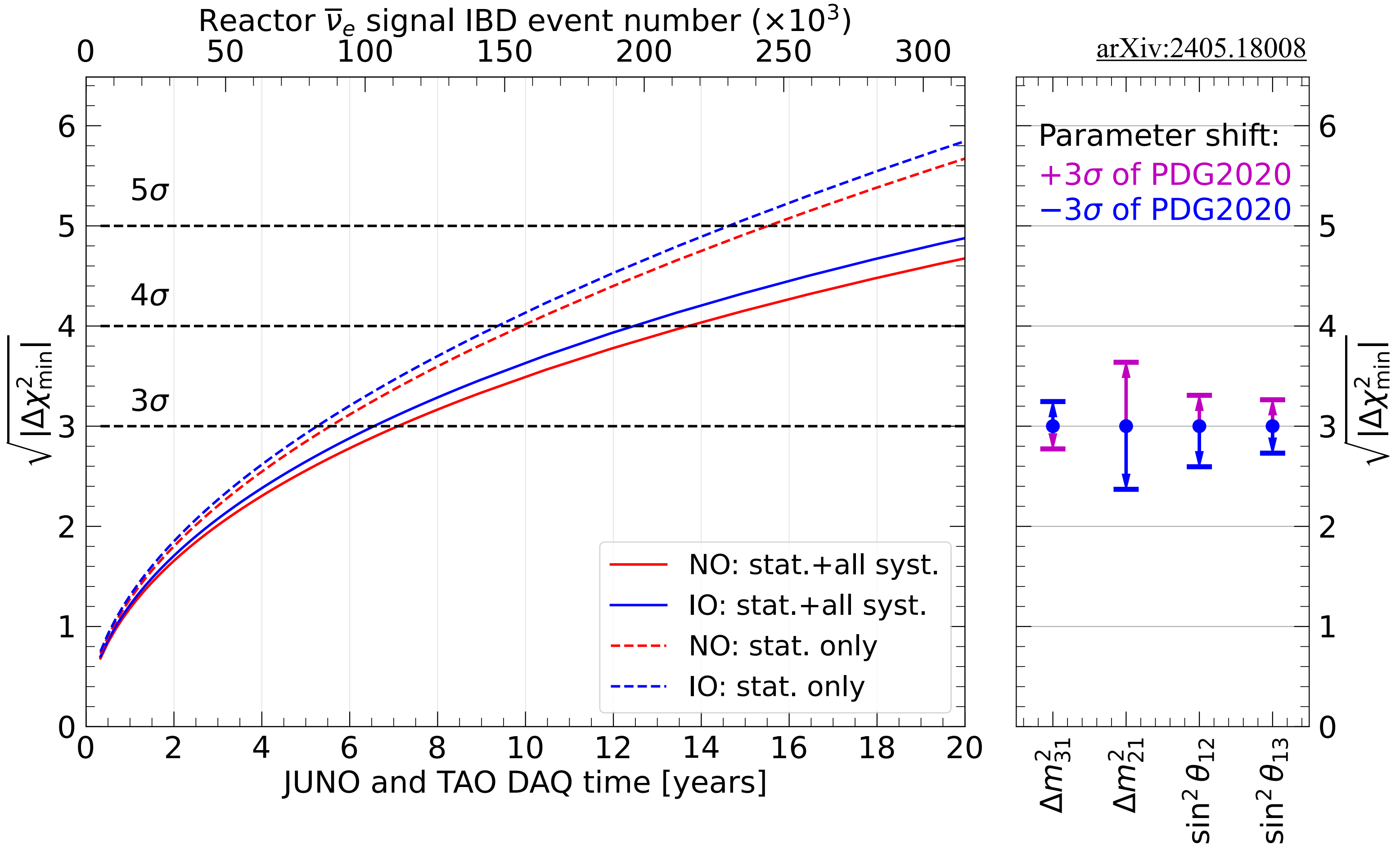
Neutrino Mass Ordering


PPNP 123, 103927 (2022)


arXiv:2405.18008

- The primary goal is to determine the neutrino mass ordering from the energy spectrum of reactor neutrinos.
  - The sign of the mass ordering manifests as a phase shift.
- The sensitivity will reach 3σ after ~6 to 7 years of operation with
  - an optimized energy resolution of 3% at 1 MeV.
  - energy scale uncertainty remains below 1%.