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Calibration of 20-inch Photomultiplier Tubes in JUNO

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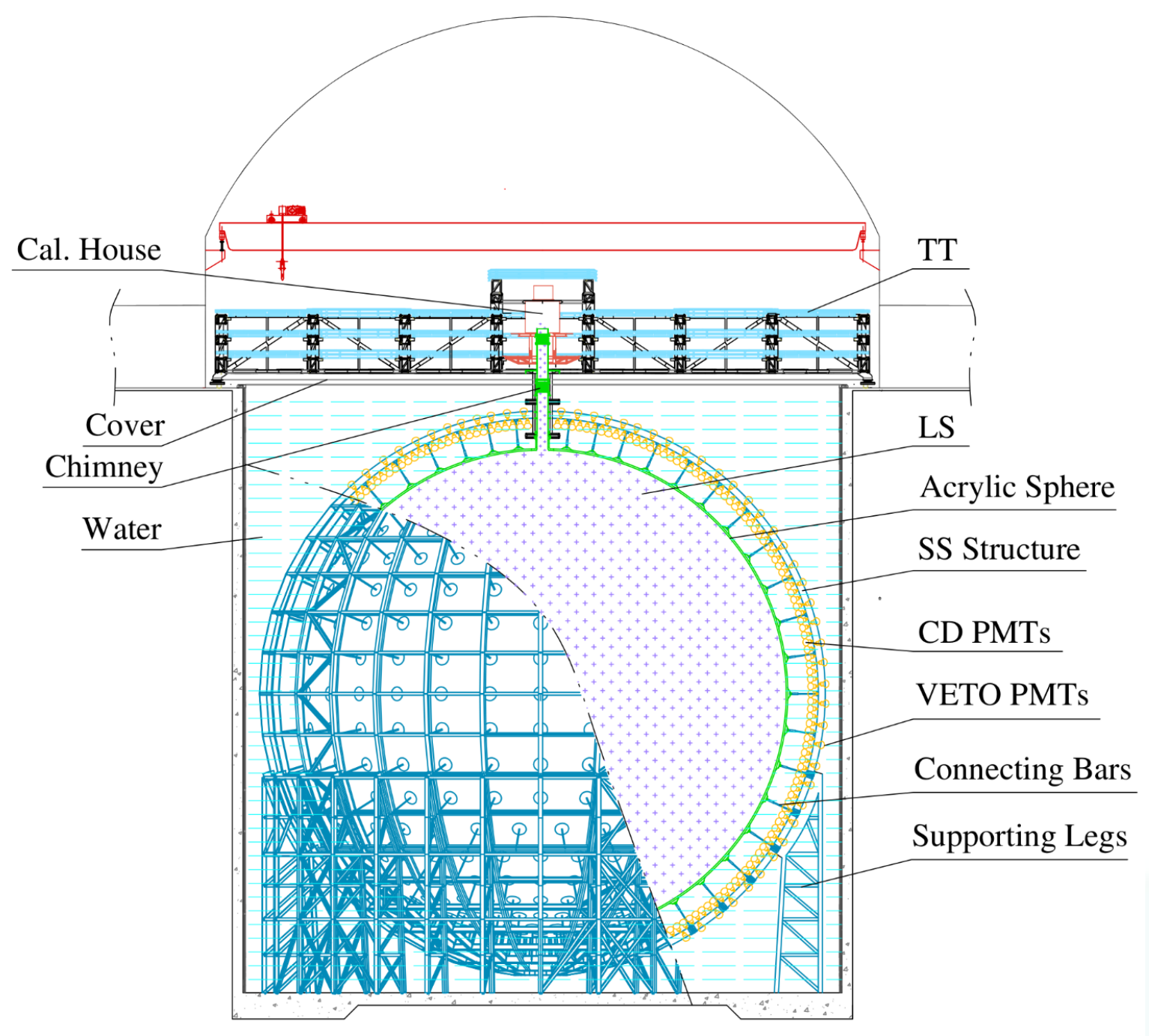
Introduction

- **Jiangmen Underground Neutrino Observatory (JUNO) -- world's largest liquid scintillator detector[1]**
  - 20 kton liquid scintillator
  - 17,612 20-inch photomultiplier tubes (PMTs)
    - 12,612 MCP-PMT manufactured by Northern Night Vision Technology Co. (NNVT)
    - 5,000 dynode-PMT manufactured by Hamamatsu Photonics K.K. (HPK)
  - 25,600 3-inch PMTs manufactured by Hainan Zhanchuang Photonics Technology Co. (HZC)
- **Multiple-purpose neutrino detector**
  - Reactor/earth/atmospheric/solar/supernova neutrinos/new physics/…
  - Neutrino mass ordering/precision measurement of oscillation parameters/B8 solar neutrino/core-collapse supernova/diffuse supernova neutrino background/0nbb/…
- **High requirements on detector performance**
  - Energy scale uncertainty <1%
  - Energy resolution better than 3%@1 MeV
- **Precise calibration of PMT charge response is a prerequisite for understanding the JUNO detector**
  - PMT gain: determination of detector light yield
  - Single photoelectron (SPE) charge PDF: critical input for energy reconstruction

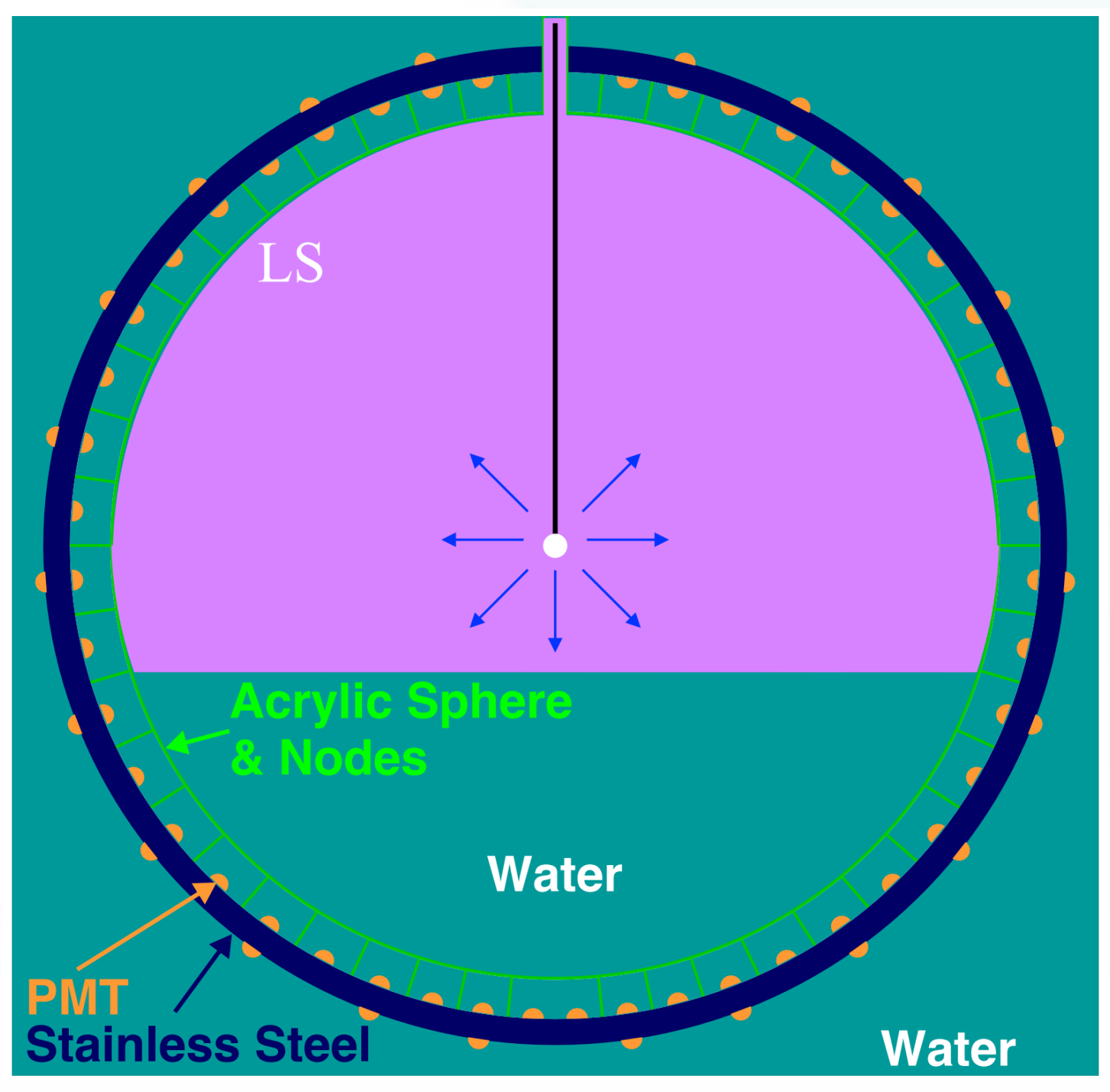


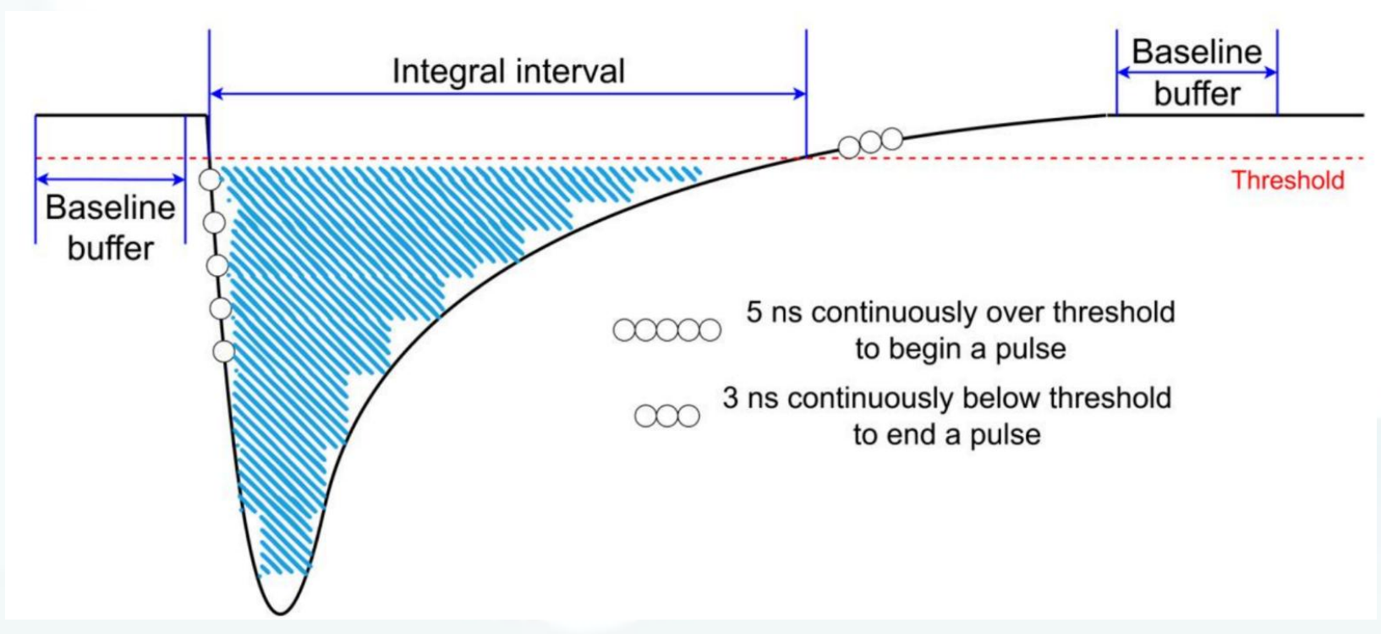
HPK dynode-PMT

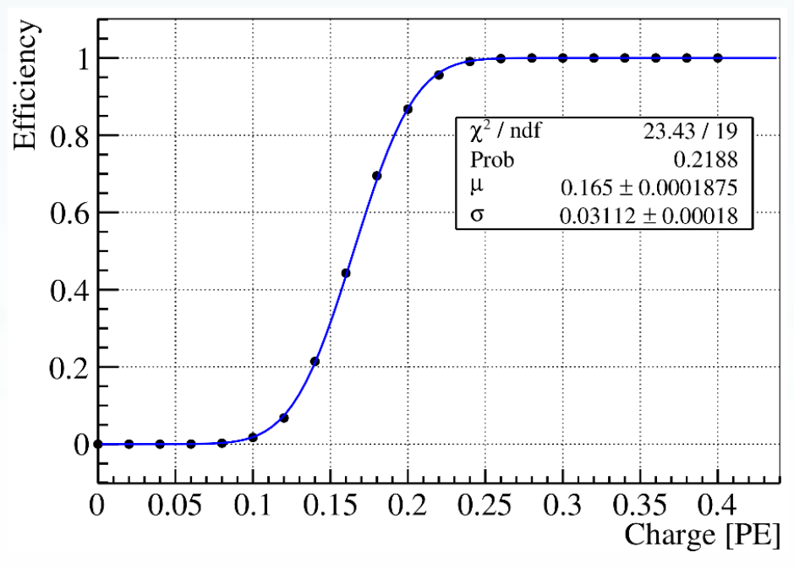
NNVT MCP-PMT

Data-taking & WF Processing

- **Laser/radioactive sources deployed into central detector with the Automatic Calibration Unit (ACU) system[2]**
  - 1D scan along z-axis, various light intensities
- **Raw waveform processed with COTI (Consecutive 5 points Over Threshold Integral) algorithm to extract charge & time information**
  - Waveforms with extremely low charge may be undetected → COTI inefficiency
    - Modeled with an error function
- **The charge of each waveform obtained by summing over all the reconstructed charges within the laser-on time window**







MC study on COTI efficiency

COTI efficiency modeled with an error function:

$$f(x;\mu,\sigma)=\frac{1}{2}\left[1+\mathrm{Erf}\left(\frac{x-\mu}{\sqrt{2}\sigma}\right)\right]$$

Models & Results

- **The charge spectra of both HPK dynode-PMT & NNVT MCP-PMT do not follow simple Gaussian distribution**
  - HPK dynode-PMT: "small component" at low charge region
  - NNVT MCP-PMT: "long tail" at high charge region
- **Two gain definitions introduced:**
  - Peak gain (Gp): peak position of the SPE charge spectrum
  - Mean gain (Gm): expectation value of the SPE charge spectrum
- **Two different SPE charge response models constructed for different PMTs**
  - HPK dynode-PMT: double Gaussian model
    - One for normally amplified PE, the other for insufficiently amplified PE
  - NNVT MCP-PMT: recursive model
    - PEs may directly enter the micro-channel, being amplified
    - It may also hit on MCP surface, producing multiple secondary electrons
    - Secondary electron can knock out more secondary electrons recursively
- **FFT-based numerical method used for convolution calculation[3]**
  - Flexible to deal with an arbitrarily complex SPE charge response model

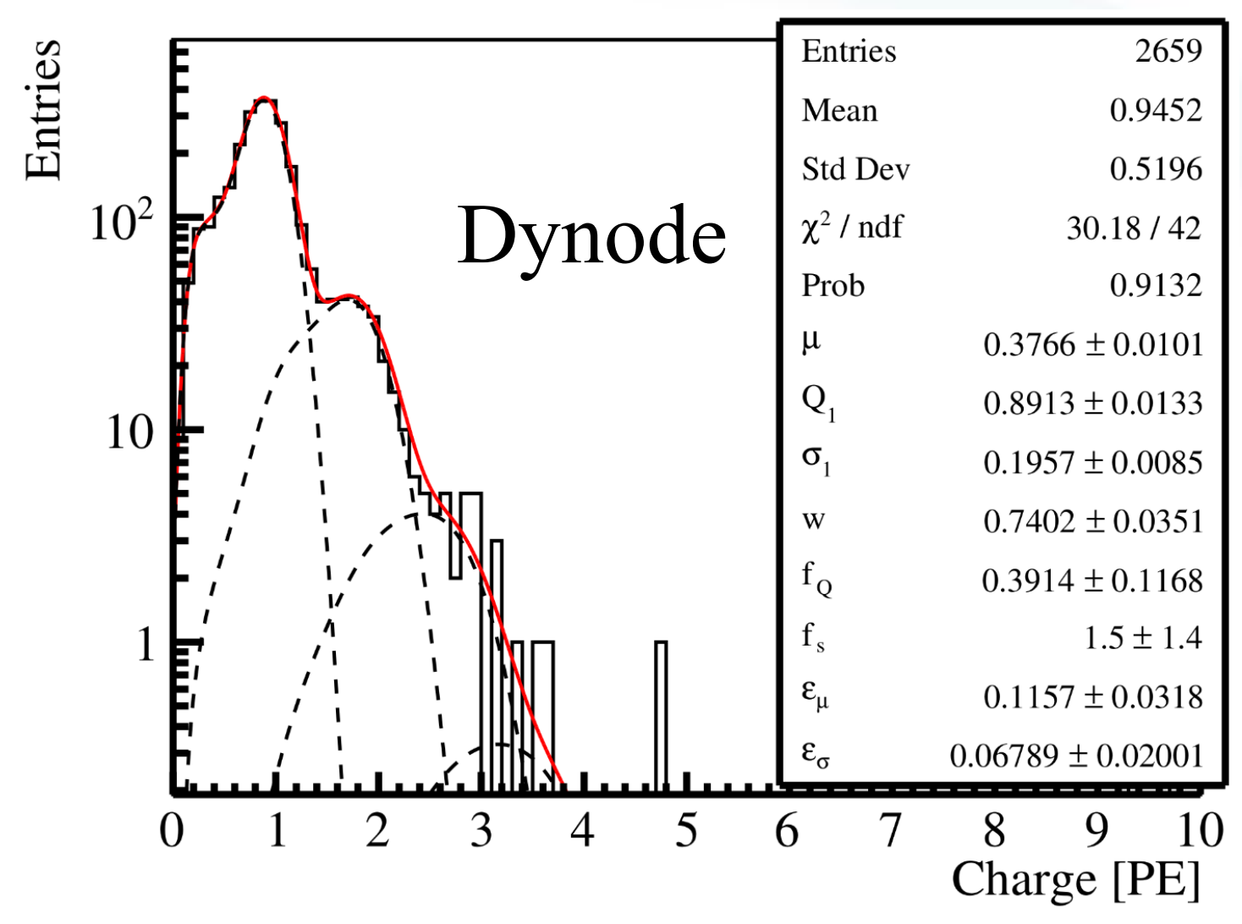
HPK dynode-PMT: SPE model in "charge" domain

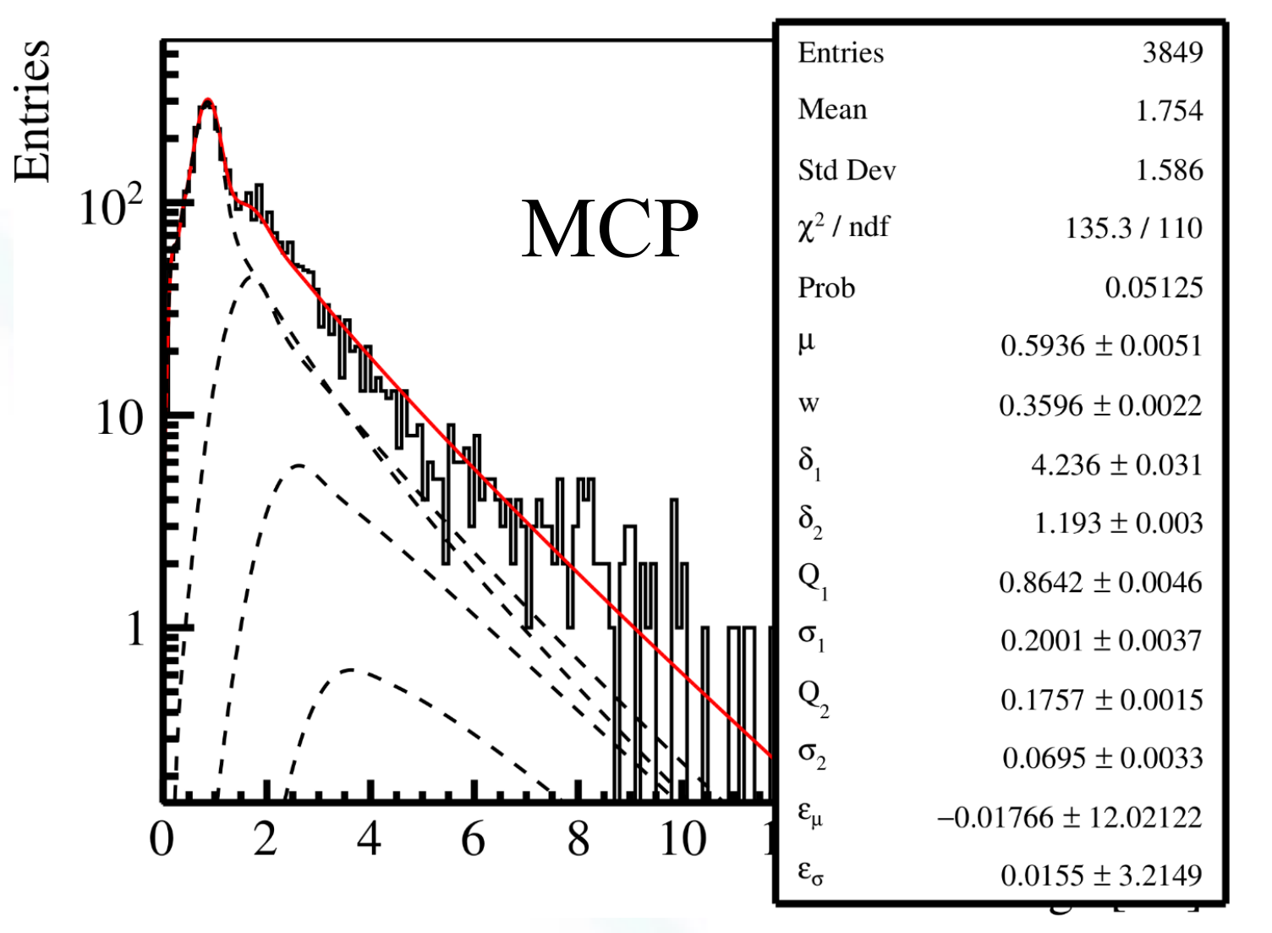
$$S(q)=w\cdot G(Q_1,\sigma_1)+(1-w)\cdot G(f_Q\cdot Q_1,f_s\cdot\sigma_1)$$

NNVT MCP-PMT: SPE model in "frequency" domain

$$\tilde{S}(\omega)=w\cdot\tilde{G}(\omega;\ Q_1,\sigma_1)+(1-\omega)e^{\delta_1[\tilde{s}(\omega)-1]}$$

$$\tilde{s}(\omega)=w\cdot\tilde{G}(\omega;Q_2,\sigma_2)-\frac{\mathrm{LambertW}\left(\delta_2\cdot(w-1)\cdot\exp\left(\delta_2\cdot\left(\tilde{G}(\omega)\cdot w-1\right)\right)\right)}{\delta_2}$$





Conclusions

The JUNO experiment will enter the stable data-taking phase immediately, aiming to address fundamental questions in neutrino physics. The physics goal of JUNO necessitates an energy resolution better than 3% @1 MeV and energy uncertainty <1%, both of which impose rigorous calibration requirements on PMT charge response. This poster outlines the calibration procedure for the 20-inch PMTs in JUNO, including calibration strategy, waveform processing, and fitting methods. Preliminary results demonstrate good agreement between data and model.

Bibliography

1. **"JUNO physics and detector", JUNO collaboration, Prog.Part.Nucl.Phys. 123 (2022) 103927, arXiv:2104.02565**
2. **"Calibration strategy of the JUNO experiment", JUNO collaboration, JHEP 03 (2021) 004, arXiv:2011.06405**
3. **"A fast numerical method for photomultiplier calibration", L. N. Kalousis, J. P. A. M. de André, E. Baussan, and M. Dracos, JINST 15 P03023 (2020), arXiv:1911.06220**