ID: 279

Comprehensive SiPM mass testing for the JUNO-TAO experiment

G.F. Cao* and H.W. Wang† on behalf of the JUNO collaboration and TAO SiPM testing subgroup:
A. Rybnikov, N. Anfimov, M. Qu, A. Chetverikov et al.

* caogf@ihep.ac.cn, IHEP, CAS
† wanghanwen@ihep.ac.cn, IHEP, CAS

1. Introduction

The **Taishan Anti-neutrino Observatory**[1] (TAO, also known as JUNO-TAO) is a satellite experiment of the Jiangmen Underground Neutrino Observatory (JUNO)[2]. A conceptual design of TAO is shown in Fig. 1.

Based on a new low-temperature liquid scintillator technology and a large array of Silicon Photomultipliers (SiPMs) of nearly 10 m^2 photo-sensitive area, the TAO detector will measure the antineutrino energy spectrum of the reactor with an unprecedented energy resolution. TAO will adopt 4024 Hamamatsu S16088 visual-sensitive SiPM tiles, with each in a dimension of 50.7×50.7 mm^2. The structure details of this type of SiPM are discussed in Tab. 1.

Tab. 1 Structure Details of the HPK S16088 SiPM

Parameters	Value	Unit
Number of Channels	16 (4×4)	-
Effective Photonsensitive Area	12×12	mm^2 / ch.
Coverage of Photonsensitive Area	89.6	%
Pixel Pitch	75	μm
Number of pixels / channel	25,564	-
Window Material	Epoxy Resin	-
Window Refractive Index	1.54	-

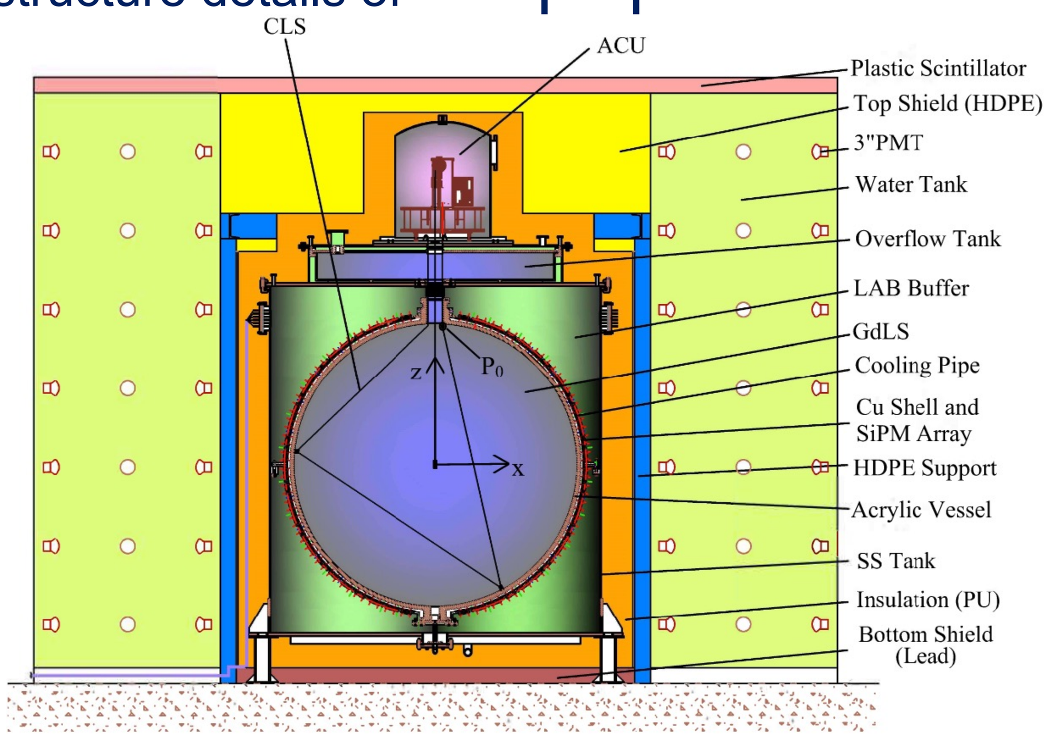
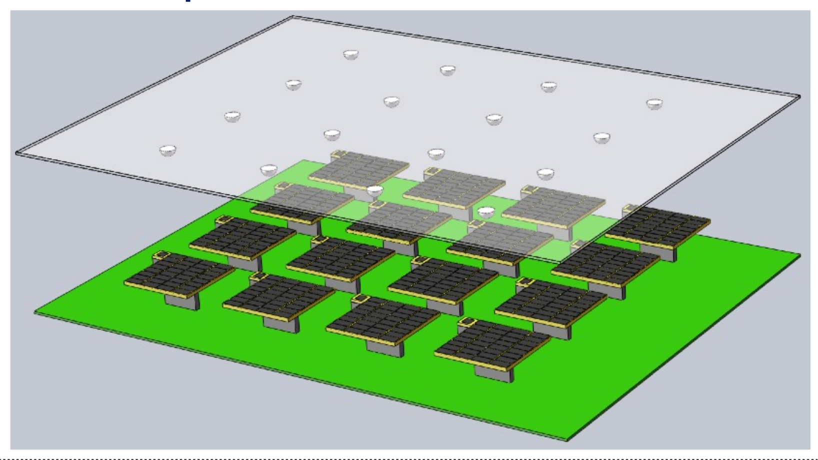


Fig. 1 Conceptual Design of the TAO Detector

A comprehensive characterization of SiPM parameters is essential for ensuring optimal detector performance and uniformity. The SiPM testing process consists of three parts: **a Room Temperature Burn-in Test**, **Optical Inspection of the SiPM Surface**, and **Mass Characterization of the SiPM**.

2. Mass Testing Setup

The testing setup[3] for characterizing the SiPMs consists of a PCB motherboard designed to accommodate 16 SiPM tiles. To ensure uniform light illumination across the tiles, 16 fibers equipped with PTFE diffusers at their ends are used. These fibers guide the light generated by a 420nm LED light source, which is then split using a fiber splitter[4]. To monitor the light intensity across the SiPMs, 16 individual reference SiPMs are placed adjacent to each tile, as shown in Fig.3 (bottom), serving as monitors. The entire motherboard is mounted on a translation stage equipped with step motors, enabling precise movement in two directions for the scan of the light field. For the SiPM testing, a 16-channel ADC TQDC16VS is used to record waveforms for further analysis.



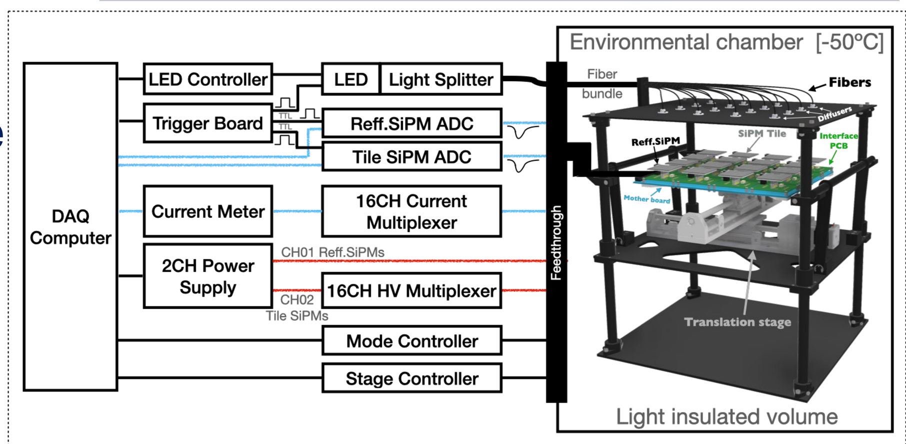


Fig. 2 Actual picture of the platform inside the cyrogenic chamber (top), Simplified illustration of the platform design (middle), Scheme of the mass-testing setup (bottom)

3. Data Analysis

Each ADC channel has a sampling rate of **125 MHz**, recording amplitude every **8 ns**. Consequently, each waveform comprises 2010 data points, corresponding to a time duration of approximately 16 μs. Approximately 26,000 waveforms, representing around 0.4 seconds of data, are recorded per channel for each preset overvoltage. The **LED signal range** (1256 to 1300) is choosen for the charge integral. For the charge spectra fit, we adopt **Generalized Poisson**[5] to describe initial discharges and prompt crosstalk, while a geometric distribution models the after-pulses (Fig. 4). Significant efforts have been dedicated to achieving precise, unsupervised fits of the charge spectra. The model has proven successful, as evidenced by the nice χ^2 results shown in Fig. 5.

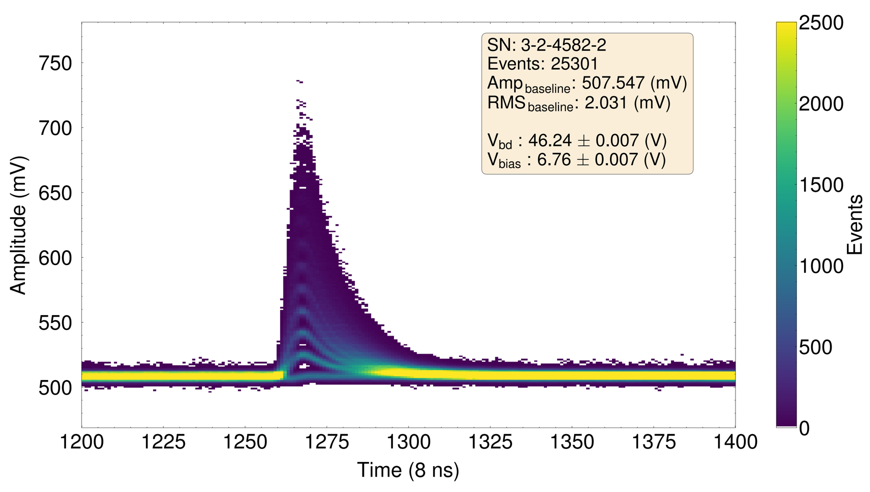


Fig. 3 Waveforms around the LED signal range of a selected SiPM

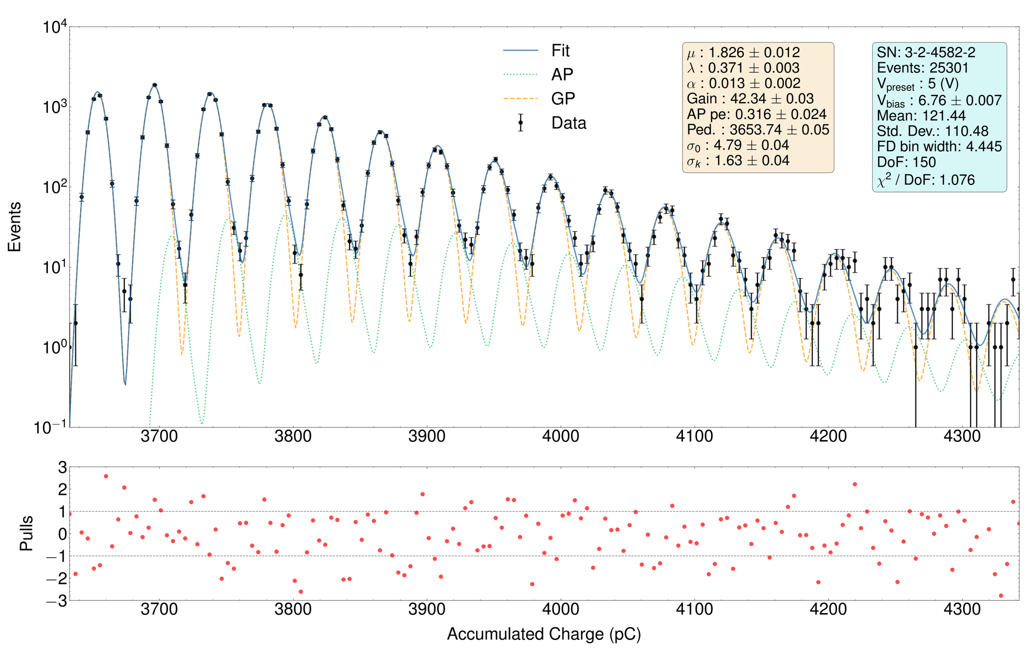


Fig. 4 Charge spectrum fit

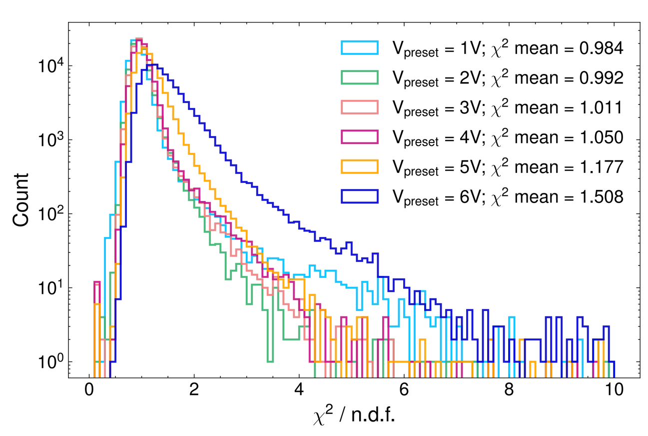


Fig. 5 Normalized χ^2 results

Major SiPM parameters like crosstalk parameter λ, initial p.e. μ, relative gain and afterpulse parameters are derived from the fit.

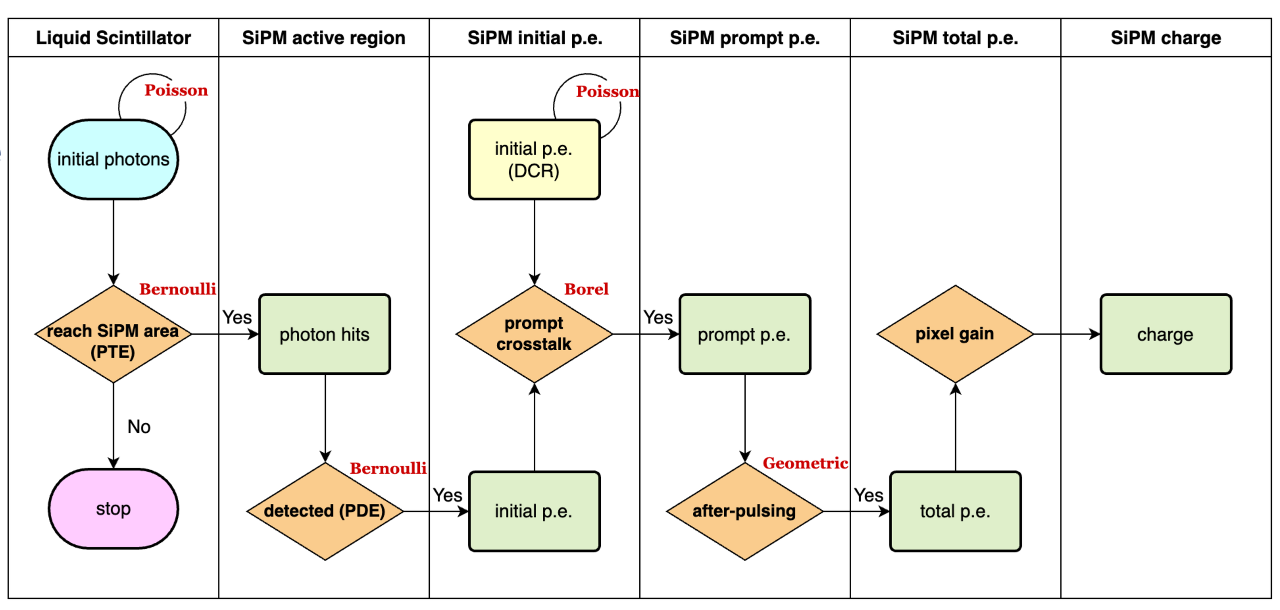
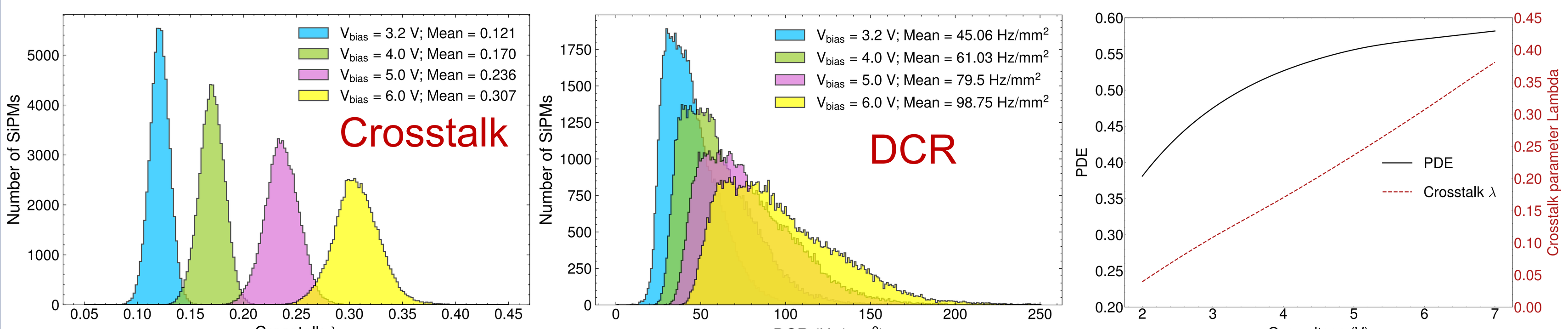


Fig. 7 Procedure of the toy MC for the energy resolution estimate

4. Results

Tab. 2 Requirements of the SiPM for JUNO-TAO

Parameters	Value	Measured	Unit
Photon Detection Efficiency	Min: 0.44, Typical: 0.47	0.488	-
Dark Count Rate	Max: 41.7, Typical: 13.9	45.06	Hz / mm^2
Crosstalk Probability	Max: 0.15, Typical: 0.12	0.121	-
After-pulsing Probability	Max: 0.08, Typical: 0.04	< 0.001	-
Pixel Gain	Min: 1×10^6, Typical: 4×10^6	> 1×10^6	-
Dark Current Deviance	Max: 95, Typical: 40	-	%
Operating Voltage Range	Min: 6, Typical: 6.5	> 6.5	Volt



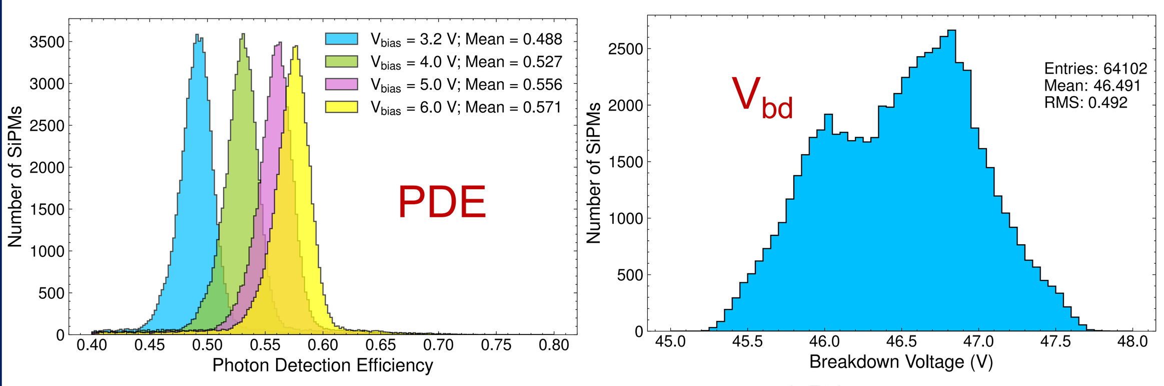
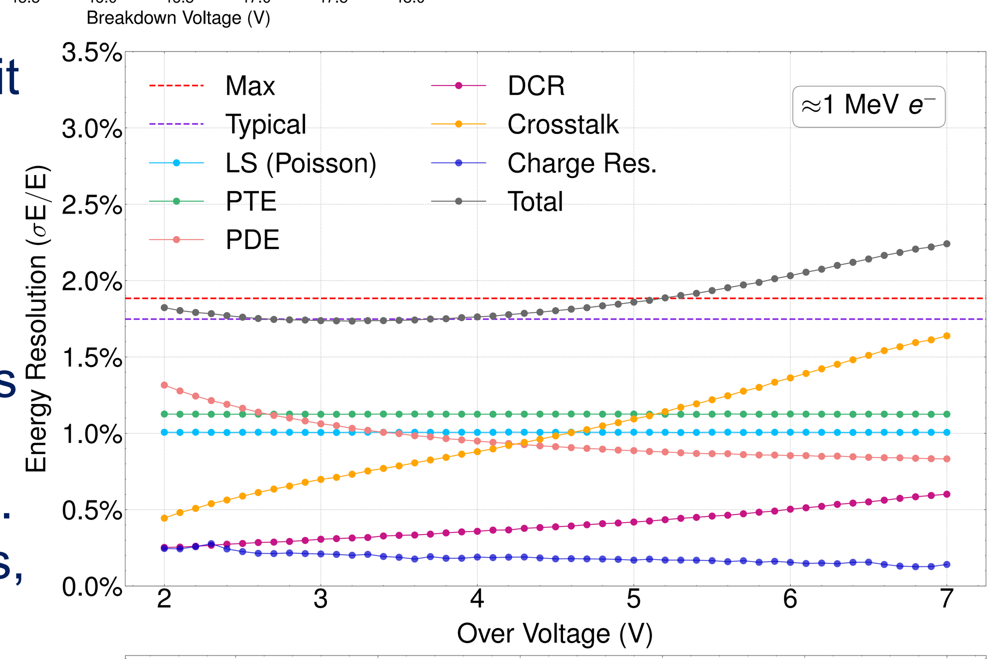


Fig. 6 Parameter distributions from all tested SiPMs: Crosstalk λ (top, left) DCR (top, middle) PDE (bottom, left) $V_{breakdown}$ (bottom, right) Average PDE and λ (top, right)

We require the SiPMs to exhibit excellent performance to achieve sub-percent energy resolution for JUNO-TAO, as detailed in Tab. 2. The results from testing over **64,000** SiPMs are presented in Fig. 6 and also with the average in Tab. 2. Based on these measurements, we employed a toy Monte Carlo method to model the energy resolution, as illustrated in Fig. 7. The external effect[6] is also considered and used to correct the model. The final results indicate an optimal operating overvoltage of **3.2 V** for the SiPMs and an energy dependence of the energy resolution is also presented in Fig. 8. The performance of the SiPMs meets our requirements.



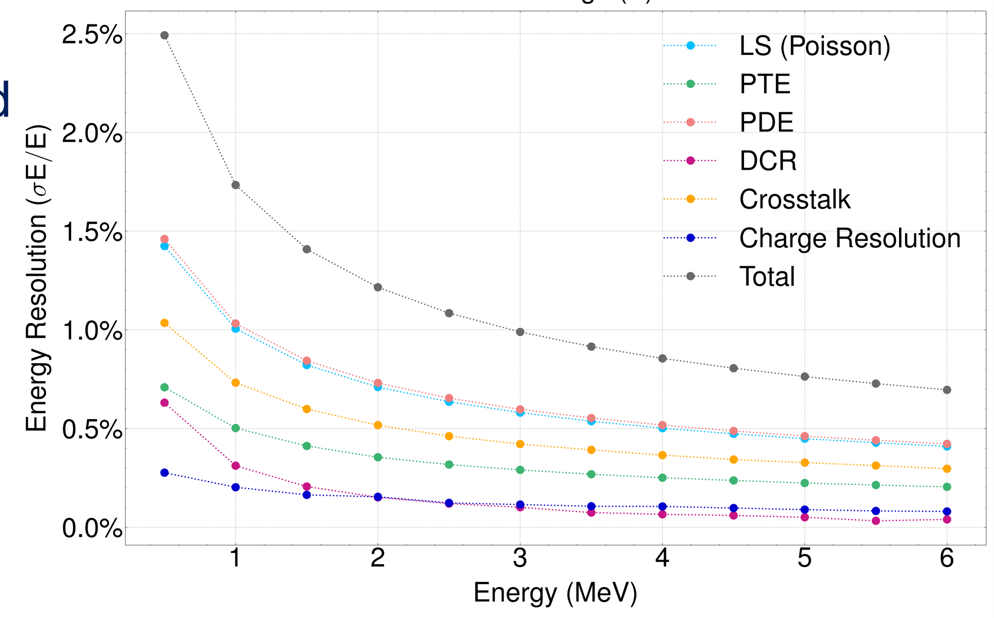


Fig. 8 Energy resolution versus overvoltage (top) and energy (bottom)

References:
[1] JUNO Collaboration, TAO conceptual design report, 2020, arXiv: 2005.08745.
[2] JUNO physics and detector." Progress in Particle and Nuclear Physics 123 (2022): 103927.
[3] A. Rybnikov, N. Anfimov, et al., Performance of the mass testing setup for arrays of silicon photomultipliers in the TAO experiment, arXiv:2402.05487.
[4] A.V. Rybnikov, N. Anfimov, D. Fedoseev, S. Sokolov and A. Sotnikov, Optical Fiber Splitter for Photodetector Testing, Phys. Part. Nucl. Lett. 19 (2022) 797.
[5] S. Vinogradov, Nuclear Instruments and Methods in Physics Research Section A, 695, 247 (2012).
[6] Y. Guan, N. Anfimov, G. Cao et al., Study of Silicon Photomultiplier External Cross-Talk, arXiv 2312.12901.