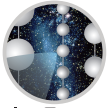


## 2 In-situ calibration of the single-photoelectron charge 3 response of the IceCube photomultiplier tubes

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4 ICECUBE

### 5 IceCube collaboration

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131 **ABSTRACT:** We describe an improved in-situ calibration of the single-photoelectron charge distri-  
132 **butions** for each of the in-ice Hamamatsu Photonics R7081-02[MOD] photomultiplier tubes in  
133 **the IceCube Neutrino Observatory.** The accurate characterization of the individual PMT charge  
134 **distributions** is important for PMT calibration, data and Monte Carlo simulation agreement, and  
135 **understanding** the effect of hardware differences within the detector. We discuss the single photo-  
136 **electron identification** procedure and how we extract the single-photoelectron charge distribution  
137 **using a deconvolution** of the multiple-photoelectron charge distribution.

138 **KEYWORDS:** IceCube, single-photoelectron charge distribution, photomultiplier tubes, calibration

139 **ARXIV EPRINT:** [tbd](#)

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140 **Contents**

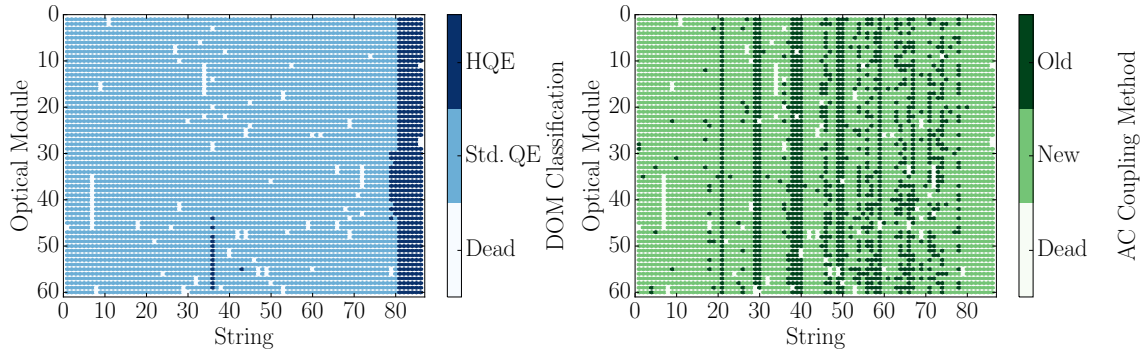
141	<b>1 Introduction</b>	<b>1</b>
142	1.1 Single-photoelectron charge distributions	3
143	1.2 IceCube datasets and software definitions	5
144	<b>2 Extracting the SPE charge templates</b>	<b>7</b>
145	2.1 Single photoelectron pulse selection	7
146	2.2 Characterizing the low-charge region	8
147	2.3 Fitting procedure	9
148	2.4 SPE charge template fit results	10
149	<b>3 Discussion</b>	<b>11</b>
150	3.1 Correlations between fit parameters and DOM hardware differences	11
151	3.2 Fitting parameters variation over time	13
152	3.3 Quantifying observable changes when modifying the PMT charge distributions	13
153	3.3.1 Model comparison	15
154	3.4 SPE charge templates for calibration	15
155	3.5 SPE charge templates in simulation	15
156	<b>4 Conclusion</b>	<b>16</b>

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157 **1 Introduction**

158 The IceCube Neutrino Observatory [1, 2] is a cubic-kilometer-sized array of 5,160 photomultiplier  
159 tubes (PMTs) buried in the Antarctic ice sheet, designed to observe high-energy neutrinos interacting  
160 with the ice [3]. In 2011, the IceCube Collaboration completed the installation of 86 vertical *strings*  
161 of PMT modules, eight of which were arranged in a denser configuration known as the DeepCore  
162 sub-array [4]. Each string in IceCube contains 60 digital optical modules (DOMs), which contain  
163 a single PMT each, as well as all required electronics [5]. The primary 78 strings (excluding  
164 DeepCore) are spaced 125 m apart in a hexagonal grid, with the DOMs extending from 1450 m to  
165 2450 m below the surface of the ice sheet. The additional DeepCore strings (79-86) are positioned  
166 between the centermost strings in the detector, reducing the horizontal DOM-to-DOM distance in  
167 this region to 42 m and 72 m. The lower 50 DOMs on these strings are located in the deepest 350 m  
168 of the detector near the clearest ice, while the upper ten provide a cosmic ray veto extending down  
169 from 1900 m to 2000 m below the surface.

170 Each DOM consists of a 0.5"-thick spherical glass pressure vessel that houses a single down-  
171 facing 10" PMT from Hamamatsu Photonics. The PMT is coupled to the glass housing with optical  
172 gel and is surrounded by a wire mesh of mu metal to reduce the effect of the Earth's ambient  
173 magnetic field. The glass housing is transparent to wavelengths 350 nm and above [6].



**Figure 1.** Left: A mapping of the HQE (dark blue) and Standard QE DOMs (light blue). Right: The version of AC coupling, old toroids (dark green) and new toroids (light green). DOMs that have been removed from service are shown in white.

174 Of the 5,160 DOMs, 4,762 house a R7081-02 Hamamatsu Photonics PMT, sensitive to wave-  
 175 lengths ranging from 300 nm to 650 nm, with peak quantum efficiency of 25% near 390 nm. These  
 176 are classified as Standard Quantum Efficiency (Standard QE) DOMs. The remaining 398 DOMs  
 177 are equipped with the Hamamatsu R7081-02MOD PMTs, which, having a peak quantum efficiency  
 178 of 34% near 390 nm (36% higher efficiency than the Standard QE DOMs), are classified as High  
 179 Quantum Efficiency (HQE) DOMs [4]. These DOMs are primarily located in DeepCore and on  
 180 strings 36 and 43, as shown in the left side of Fig. 1.

181 The R7081-02 and R7081-02MOD PMTs have 10 dynode stages and are operated with a  
 182 nominal gain of  $10^7$  and high voltage ranging from approximately  $1215 \pm 83$  V and  $1309 \pm 72$  V,  
 183 respectively. A typical amplified single photoelectron generates a  $5.2 \pm 0.3$  mV peak voltage after  
 184 digitization with a full width half maximum of  $13 \pm 1$  ns. The PMTs operate with the anodes at  
 185 high voltage, so the signal is AC-coupled to the front-end amplifiers. There are two versions of AC  
 186 coupling in the detectors, referred to as the *new* and *old toroids*, both of which use custom-designed  
 187 wideband bifilar wound 1:1 toroidal transformers<sup>1</sup>. The locations of DOMs with the different  
 188 versions of AC-coupling are shown on the right side of Fig. 1. The DOMs with the old toroids  
 189 were designed with an impedance of  $43 \Omega$ , while the new toroids are  $50 \Omega$  [7]. All HQE DOMs are  
 190 instrumented with the new toroids.

191 IceCube relies on two observables per DOM to reconstruct events: the total number of detected  
 192 photons and their timing distribution. Both the timing and the number of photons are extracted from  
 193 the digitized waveforms. This is accomplished by deconvolving the waveforms [8] into a series of  
 194 scaled single photoelectron pulses (so-called pulse series), and the integral of the individual pulses  
 195 (divided by the load resistance) defines the observed charge. It will often be expressed in units of  
 196 PE, or photoelectrons, which further divides the measured charge by the charge of a single electron  
 197 times the nominal gain.

198 When one or more photons produce a voltage at the anode sufficient to trigger the onboard

<sup>1</sup>The toroidal transformer effectively acts as a high-pass filter with good signal fidelity at high frequencies and offers a higher level of reliability than capacitive coupling. Conventional AC-coupling high-voltage ceramic capacitors can also produce undesirable noise from leakage currents and are impractical given the signal droop and undershoot requirements [6].

199 discriminator (set via a DAC to approximately 1.2 mV, or equivalently to  $\sim 0.23$  PE), the signal  
200 acquisition process is triggered. The signal is fed into four parallel channels for digitization. Three  
201 channels pass through a 75 ns delay loop in order to capture the leading edge of the triggering pulse,  
202 and are then subject to different levels of amplification prior to being digitized by a high-speed  
203 (300 MSPS for 128 samples) 10-bit Analog Transient Waveform Digitizer (ATWD). The high-gain  
204 channel has a nominal amplification of 16 and is most suitable for single photon detection. Two  
205 ATWD chips are present on the DOM Mainboard (MB) and operate in a ping-pong fashion to  
206 remove dead time associated with the readout. The signal to the fourth parallel channel is first  
207 shaped and amplified, then fed into a 10-bit fast analog-to-digital converter (fADC) operating at a  
208 sampling rate of 40 MSPS. Further detail regarding the description of the DOM electronics can be  
209 found in Refs. [5, 9].

210 This article discusses an accurate method for determining the in-situ individual PMT single-  
211 photoelectron charge distributions, which can be used to improve calibration and the overall detector  
212 description in Monte Carlo (MC) simulation. The SPE charge distribution refers to the charge  
213 probability density function of an individual PMT generated by the amplification of a pure sample  
214 of single photoelectrons. The measured shape of the SPE charge distributions is shown to be useful  
215 for examining hardware differences and long term stability of the detector. This was recently made  
216 possible with the development of two pieces of software:

- 217 1. A specially-designed unbiased pulse selection developed to reduce the multiple photoelec-  
218 tron (MPE) contamination while accounting for other physical phenomena (e.g. late pulses,  
219 afterpulses, pre-pulses, and baseline shifts) and software-related effects (e.g. pulse splitting).  
220 This is further described in Sec. 2.1.
- 221 2. A fitting procedure developed to separate the remaining MPE contamination from the SPE  
222 charge distribution by deconvolving the measured charged distribution. This is further de-  
223 scribed in Sec. 2.3.

224 By using in-situ data to determine the SPE charge distributions, we accurately represent the  
225 individual PMT response as a function of time, environmental conditions, software version and  
226 hardware differences, and realistic photocathode illumination conditions. This is beneficial since  
227 it also allows us to inspect the stability and long-term behavior of the individual DOMs, verify  
228 previous calibration, and correlate features with specific DOM hardware.

## 229 1.1 Single-photoelectron charge distributions

230 Ideally, a single photon produces a single photoelectron, which is then amplified by a known  
231 amount, and the measured charge corresponds to 1 PE. However, there are many physical processes  
232 that create structure in the measured charge distributions. For example:

- 233 • **Statistical fluctuation due to cascade multiplication** [10]. At every stage of dynode  
234 amplification, there is a stochastic spread in the number of emitted electrons that make it to  
235 the next dynode. This in turn causes a spread in the measured charge after the gain stage of  
236 the PMT.

- 237 • **Photoelectron trajectory.** Some electrons may deviate from the favorable trajectory, re-  
 238 ducing the number of secondaries produced at a dynode or the efficiency to collect them  
 239 on the following dynode. This can occur at any stage, but it has the largest effect on the  
 240 multiplication at the first dynode [11]. The trajectory of a photoelectron striking the first  
 241 dynode will depend on many things, including where on the photocathode it was emitted,  
 242 the uniformity of the electric field, the size and shape of the dynodes [10], and the ambient  
 243 magnetic field [12, 13].
  
- 244 • **Late or delayed pulses.** A photoelectron can elastically or inelastically scatter off the first  
 245 dynode. The scattered electron can then be re-accelerated to the dynode, creating a second  
 246 pulse. The difference in time between the initial pulse and the re-accelerated pulse in the  
 247 R7081-02 PMT was previously measured to be up to 70 ns [6, 14]. The two sub-pulses have  
 248 lower charges, but the sum of the two tends to add up to the original charge. Collecting either  
 249 the initial pulse or the late pulse will result in the charge being reconstructed in the low-PE  
 250 region [15].
  
- 251 • **Afterpulses.** When photoelectrons or the secondary electrons produced during the electron  
 252 cascade gain sufficient energy to ionize residual gas in the PMT, the positively charged ionized  
 253 gas will be accelerated in the electric field towards the photocathode. Upon impact with the  
 254 photocathode, electrons can be released from the photocathode, creating what is called an  
 255 afterpulse. For the R7081-02 PMTs, the timescale for afterpulses was measured to occur  
 256 from 0.3 to 11  $\mu$ s after the initial pulse, with the first prominent afterpulse peak occurring  
 257 at approximately 600 ns [6]. The spread in the afterpulse time depends on the position  
 258 of photocathode, the charge-to-mass ratio of the ion produced, and the electric potential  
 259 distribution [16], whereas the size of the afterpulse is related to the momentum and species  
 260 of the ionized gas and composition of the photocathode [17].
  
- 261 • **Pre-pulses.** If an incident photon passes through the photocathode without interaction and  
 262 strikes one of the dynodes, it can eject an electron that is only amplified by the subsequent  
 263 stages, resulting in a lower measured charge (lower by a factor of approximately 10). For the  
 264 IceCube PMTs, the prepulses have been found to arrive approximately 30 ns before the signal  
 265 from other photoelectrons from the photocathode [6].
  
- 266 • **MPE contamination.** When multiple photoelectrons arrive at the first dynodes within several  
 267 nanoseconds of each other, they can be reconstructed by the software as a single MPE pulse.
  
- 268 • **Dark noise.** Photoelectron emission, not initiated from a light source, can be attributed to  
 269 thermionic emission from the low work function photocathode and the dynodes, Cherenkov  
 270 radiations initiated from radioactive decay within the borosilicate glass housing, and field  
 271 emission from the electrodes. It is shown in Fig. 28 of Ref. [18] that the dark noise preferen-  
 272 tially populates the low-charge region.
  
- 273 • **Electronic noise.** This refers to the fluctuations in the analog-to-digital converters (ATWDs  
 274 and FADC) and ringing that arises from the electronics.



275 Beyond the physical phenomena above that modify the measured charge distribution, there is  
 276 also a lower limit on the smallest charge that can be extracted. For IceCube, the discriminator only  
 277 triggers for peak voltages above the threshold and subsequent pulses in the readout time window  
 278 are subject to a software-defined threshold. The software threshold was set conservatively to avoid  
 279 extracting pulses that originated from electronic noise. This threshold can be modified to gain  
 280 access to lower charge pulses and will be discussed in Sec. 2.2.

281 The standard SPE charge distribution used for all DOMs in IceCube, known as the TA0003  
 282 distribution [6], models the above effects as the sum of an exponential plus a Gaussian. The TA0003  
 283 distribution represents the average SPE charge distribution extracted from a lab measurement of  
 284 118 Hamamatsu R7081-02 PMTs. This was performed in a  $-32^\circ\text{C}$  freezer using a pulsed UV LED  
 285 centered along the axis of the PMT, directly in front of the photocathode.

286 Recently, IceCube has made several lab measurements using the R7081-02 PMTs with in-time  
 287 laser pulses, confirming that the in-time charge distribution includes a steeply falling low-charge  
 288 component below the discriminator threshold. To account for this, a new functional form including  
 289 a second exponential was introduced. This form of the charge distribution  $f(q)_{\text{SPE}} = \text{Exp}_1 + \text{Exp}_2$   
 290 + Gaussian, is referred to as the *SPE charge template* in this article. Explicitly, it is:

$$f(q)_{\text{SPE}} = E_1 e^{-q/w_1} + E_2 e^{-1/w_2} + N e^{-\frac{(q-\mu)^2}{2\sigma^2}}, \quad (1.1)$$

291 where  $q$  represents the measured charge;  $E_1$ ,  $E_2$ , and  $N$  represent normalization factors of each  
 292 component;  $w_1$  and  $w_2$  are the exponential decay widths; and  $\mu$ ,  $\sigma$  are the Gaussian mean and  
 293 width, respectively. This is the assumed functional shape of the SPE charge distributions, and the  
 294 components of Eq. 1.1 are determined in this article for all in-ice DOMs. IceCube defines 1 PE as  
 295 the location of the Gaussian mean ( $\mu$ ) and calibrates the gain of the individual PMTs prior to the  
 296 start of each season to meet this definition. The choice of where we define 1 PE is arbitrary, since  
 297 linearity between the total charge collected and the number of incident photons is satisfied up to  
 298  $\sim V$  [7], or approximately 375 PE. This is because the average of the distribution is a set fraction of  
 299 the Gaussian mean and the mean of a  $N$ -fold convolution is the sum of means. Any bias in the total  
 300 observed charge can be absorbed into an efficiency term, such as the quantum efficiency.

## 301 1.2 IceCube datasets and software definitions

302 The amount of observed light depends on the local properties of the ice [19]. Short term climate  
 303 variations from volcanoes and longer-term variations from atmospheric dust affect the optical  
 304 properties of the ice, producing nearly horizontal layers. This layered structure affects how much  
 305 light the DOMs see, and, with it, the trigger rate. The largest contribution to the IceCube trigger  
 306 rate comes from downward-going muons produced in cosmic ray-induced showers [20]. Cosmic  
 307 ray muons stopping in the detector cause the individual trigger rate to decrease at lower depths.

308 At in-ice temperatures ( $-8^\circ$  to  $-32^\circ$ ), the dark noise induced by thermionic photoelectron  
 309 emission is suppressed, and the average dark noise is measured to be 560 Hz for DOMs with  
 310 Standard QE PMTs and 780 Hz for the HQE PMTs. The majority of which was found to originate  
 311 from the decay of Potassium-40 within the glass housing [7]. Dark noise is seen in data as accidental  
 312 coincident charge deposits in the observed event.

313 An induced signal in the PMT that passes through the AC coupling toroid located on the  
314 base of the PMT is compared to a discriminator threshold. If a DOM and its nearest or next-to-  
315 nearest neighbor observe a discriminator threshold crossing within a set time window, a *Hard Local*  
316 *Coincidence* (HLC) is initiated, and the corresponding waveforms are sampled 128 times and read  
317 out on the three ATWD channels.

318 After waveform digitization, there is a correction applied to remove the measured DC baseline  
319 offset. The signal droop and undershoot introduced by the toroidal transformer AC coupling is  
320 compensated for in software during waveform calibration by adding the expected temperature-  
321 dependent reaction voltage of the undershoot to the calibrated waveform. If the undershoot voltage  
322 drops below 0 ADC counts, the ADC values are zeroed and then compensated for once the waveform  
323 is above the minimum ADC input. For each version of the AC coupling, scaled single photoelectron  
324 pulse shapes are then fit to the waveforms using software referred to as "WaveDeform" (waveform  
325 unfolding process), which determines the individual pulse time stamps and charges and populates  
326 a pulse series.

327 The pulse series used in this analysis come from two datasets provided by IceCube:

328 1. The **MinBias dataset**. This dataset records the full waveform readout of randomly-triggered  
329 HLC events at a rate that corresponds on average to 1/1000 events. The largest contribution to  
330 the IceCube trigger rate comes from downward-going muons produced in cosmic-ray-induced  
331 showers [20] and therefore is the largest signal component in this dataset. These muons tend  
332 to have small energies when they reach the detector, thus they produce minimal MPE con-  
333 tamination. The full waveform of these events allows us to extract the raw information about  
334 the individual pulses. This will be used to measure the individual PMT charge distributions.

335 2. The **BeaconLaunch dataset**. This is a forced triggered filter that is typically used to mon-  
336 itor the individual DOM baseline. It includes the full ATWD-window waveform readout.  
337 Since this dataset is forced-triggered, the majority of these waveforms represent DC baseline  
338 fluctuations with minimal contamination from the occasional coincidental pulse that makes  
339 it into the readout window. This dataset will be used to examine the noise contribution to the  
340 charge distributions.

341 When using this dataset, the weight of every pulse is multiplied by a factor of 28.4 to account  
342 for the livetime difference between the MinBias dataset and the BeaconLaunch dataset.  
343 Weight, in this context, refers to the number of photons in the MinBias dataset proportional  
344 to one photon in the BeaconLaunch dataset for which both datasets have the same equivalent  
345 livetime.

346 This analysis uses the full MinBias and BeaconLaunch datasets from IceCube seasons 2011 to  
347 2016 [21] (subsequently referred to as IC86.2011 to IC86.2016). Seasons in IceCube typically start  
348 in May of the labeled year and end approximately one year later. Calibration is performed before  
349 the start of each season.

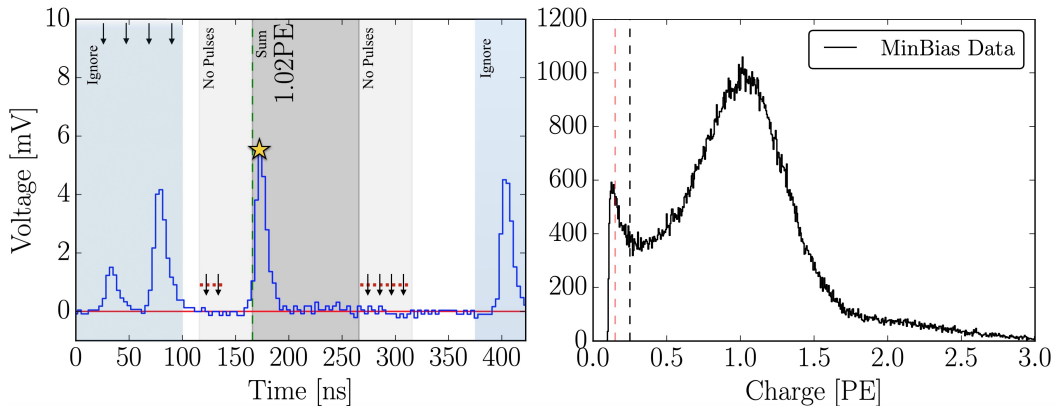
## 350 2 Extracting the SPE charge templates

### 351 2.1 Single photoelectron pulse selection

352 The pulse selection is the method used to extract candidate, unbiased, single photoelectron pulses  
 353 from high-gain ATWD channel while minimizing the MPE contamination. It avoids collecting  
 354 afterpulses, rejects late pulses from the trigger, reassembles late pulses, accounts for the discrimi-  
 355 nator threshold, reduces the effect of droop and baseline undershoot, and gives sufficient statistics  
 356 to perform a season-to-season measurement. An illustrative diagram of the pulse selection is shown  
 357 in the left side of Fig. 2, while a description of the procedure is detailed below.

358 We restrict the pulse selection to only extract information from waveforms in which the trigger  
 359 pulse does not exceed 10 mV ( $\sim 2$  PE) and no subsequent part of the waveform exceeds 20 mV  
 360 ( $\sim 4$  PE). This reduces the effect of the baseline undershoot due to the AC coupling or other artifacts  
 361 from large pulses.

362 In order to trigger a DOM, the input to the front-end amplifiers must exceed the discriminator  
 363 threshold. To avoid the selection bias of the discriminator trigger, we ignore the trigger pulse as well  
 364 as the entire first 100 ns of the time window. Ignoring the first 100 ns has the added benefit of also  
 365 removing late pulses that could be attributed to the triggering pulse. To ensure we are not accepting  
 366 afterpulses into the selection, we also enforce the constraint that the pulse of interest (POI) is within  
 367 the first 375 ns of the ATWD time window. This also allows us to examine the waveform up to  
 368 50 ns after the POI. In the vicinity of the POI, we ensure that WaveDeform did not reconstruct any  
 369 pulses up to 50 ns prior to the POI, or 100 to 150 ns after the POI (the light gray region of Fig. 2



**Figure 2.** Left: An illustrative diagram of the pulse selection criteria for selecting a high-purity and unbiased sample of single photoelectrons. The digitized ATWD waveform is shown in blue. The pulse of interest is identified with a yellow star. This example waveform was triggered by a small pulse at 25 ns (recall that the delay board allows us to examine the waveform just prior to the trigger pulse), followed by a potential late pulse at 70 ns. At 400 ns, we see a pulse in the region susceptible to afterpulses. Waveform voltage checks are illustrated with arrows, and various time windows described in the text are drawn with semi-opaque regions. The POI is reported to have a charge of 1.02 PE, given by WaveDeform, and would pass the pulse selection criteria. Right: The collected charges from string 1, optical module 1 (DOM 1,1), from the MinBias dataset collected from IC86.2011 to IC86.2016 that pass the pulse selection. The discriminator threshold at 0.25 PE is represented as a dotted black vertical line. For visual purposes, a vertical dashed red line is also included at 0.15 PE.

370 (left)). This latter constraint is to reduce the probability of accidentally splitting a late pulse in the  
371 summation window.

372 If a pulse is reconstructed between 100 and 375 ns after the start of the waveform and the voltage  
373 criteria are met, it is accepted as a candidate photoelectron and several checks are performed on  
374 the waveform prior to and after the pulse. The first check is to ensure that the waveform is near the  
375 baseline just before the rising edge of the POI. This is accomplished by ensuring that the waveform  
376 does not exceed 1 mV, 50 to 20 ns prior to the POI, and eliminates cases where the POI is a late  
377 pulse. We also ensure the waveform returns to the baseline by checking that no ADC measurement  
378 exceeds 1 mV, 100 to 150 ns after the POI. These constraints are illustrated as the horizontal red  
379 dotted lines and black arrows in the left side of Fig. 2.

380 If all the above criteria are met, we sum the reconstructed charges from the POI time, given by  
381 WaveDeform, to +100 ns (the dark gray area in Fig. 2 (left)). This ensures that any nearby pulses  
382 are either fully separated or fully added. WaveDeform may occasionally split an SPE pulse into  
383 multiple smaller pulses, therefore it is always critical to perform a summation of the charge within  
384 a window. The 100 ns summation also means that the pulse selection will occasionally accept MPE  
385 events.

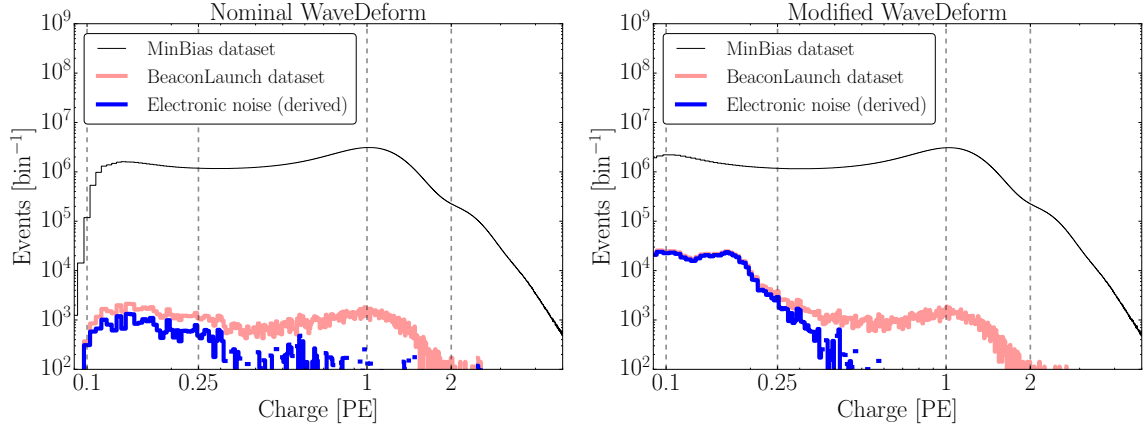
## 386 2.2 Characterizing the low-charge region

387 Fig. 2 (right) shows the charge distributions of the selected pulses that pass the single photoelectron  
388 pulse selection for string 1, optical module 1, DOM(1,1). In the low-charge region (below 0.25 PE),  
389 we see a second threshold at approximately 0.13 PE. This is a software-defined threshold that comes  
390 from a gradient-related termination condition in WaveDeform. The threshold was set to avoid  
391 electronic noise being interpreted as PMT pulses and contaminating the low-charge region.

392 The steeply falling component of the region from 0.13 PE to 0.25 PE is in agreement with the  
393 in-time laser tests mentioned in Sec. 1.1 and emphasizes the importance of collecting data below the  
394 discriminator threshold. This section will assess the noise contribution to this region and examine  
395 the effect on the charge distribution and noise contribution by lowering the WaveDeform threshold.

396 Fig. 3 (left) shows the charge distributions for the MinBias (black) and the BeaconLaunch  
397 (red) datasets using the default settings of WaveDeform. As mentioned in Sec. 1.2, occasionally  
398 a photoelectron will be coincident with the forced BeaconLaunch time window. These charges  
399 populate a SPE charge distribution. Subtracting the shape of the MinBias charge distribution from  
400 the BeaconLaunch dataset yields an estimate of the amount of electronic noise contamination (blue).  
401 The bin with the lowest signal-to-noise ratio (SNR) above 0.1 PE was found to have a SNR of 744.7.  
402 The SNR for the full distribution was found to be  $1.98 \times 10^5$ . Fig. 3 (right) shows the same data after  
403 lowering the WaveDeform threshold. Correspondingly, the bin with the lower SNR was found to  
404 have a SNR of 57.9, whereas the total SNR was found to be  $0.69 \times 10^5$ .

405 The modified WaveDeform datasets show a minimal increase in the contribution of noise to  
406 the low-charge region. From this, we are able to extract charge information down to approximately  
407 0.10 PE and improve the overall description of the charge distribution below the discriminator. This  
408 will help constrain the values defining  $\text{Exp}_1$ .



**Figure 3.** The cumulative charge distributions of all DOMs for the MinBias (M) and BeaconLaunch (B) datasets. The blue histogram shows the derived contribution from electronic noise. This was found by subtracting the normalized MinBias dataset from the BeaconLaunch dataset ( $B - M \times (B|_{1PE}/M|_{1PE})$ ). Left: The charge distributions for the standard WaveDeform settings. Right: The charge distributions for the modified WaveDeform settings.

### 409 2.3 Fitting procedure

410 Fitting software called the "convolutional fitter" is used to determine the components of Eq. 1.1  
 411 from the measured charge distribution that includes the MPE contamination. The fit assumes that  
 412 there is a negligible three-PE contribution, which is justified by the lack of statistics in the 3 PE  
 413 region as well as the significant rate difference between the 1 PE and 2 PE region, as shown in Fig. 2  
 414 (right). The 2 PE charge distribution is assumed to be the SPE charge distribution convolved with  
 415 itself [22].

416 The exponential components of Eq. 1.1 represent poorly amplified photoelectrons, and we do  
 417 not allow it to extend beyond the high-charge region of the Gaussian component. In particular, we  
 418 include a constraint on the the parameter  $w_2$  to ensure that it falls off with the Gaussian component:

$$w_2 < \frac{\mu + 2\sigma}{4 - \ln(N/E_2)}. \quad (2.1)$$

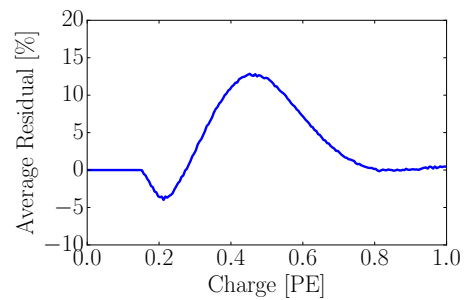
419 This equation was found by setting the  $\text{Exp}_2$  to be  $\exp^{-2}$  that of the Gaussian component at two  
 420 sigma (the  $\text{Exp}_1$  is neglected from this equation since it falls off in the low-charge region). Eq. 2.1  
 421 is used as a constraint during the fit to the charge distributions.

422 Pulses that fall below the WaveDeform threshold and are not reconstructed contribute to an  
 423 effective efficiency of the individual DOMs. This analysis assumes the same shape of the steeply  
 424 falling exponential component ( $\text{Exp}_1$ ) for all DOMs in the detector to avoid large fluctuations in  
 425 the individual DOM efficiencies. The modified WaveDeform data will strictly be used to determine  
 426 the  $\text{Exp}_1$  component. Specifically, using the modified WaveDeform, we background-subtract the  
 427 BeaconLaunch distribution from the MinBias data, fit the resulting distribution to determine the

428 components of Eq. 2.1, and use only the measured shape and normalization of  $\text{Exp}_1$  in all subsequent  
 429 unmodified WaveDeform fits.

430 As described in Sec. 1.1, the Gaussian mean ( $\mu$ ) is used to determine the gain setting for each  
 431 PMT. Therefore, it is particularly important that the fit quality in this region accurately describes the  
 432 data. While fitting to the full charge distribution improves the overall fit agreement, the mismatch  
 433 between the chosen functional form (Eq. 1.1) and a true SPE charge distribution can cause the  
 434 Gaussian component to pull away from its ideal location. To compensate for this, the convolutional  
 435 fitter prioritizes fitting to the data around the Gaussian mean. This is accomplished by first fitting  
 436 to the full distribution to get an estimate of the Gaussian mean location. Then, the statistical  
 437 uncertainty is reduced in the region  $\pm 0.15$  PE around the original estimated Gaussian mean, and  
 438 the distribution is re-fitted.

439 Upon fitting the MinBias data with the predetermined  
 440 values for  $\text{Exp}_1$ , the residual of each fit is calculated by  
 441 measuring the percentage difference between the fit and  
 442 the data. The average residual is then used as a global  
 443 scaling factor for all SPE charge templates to account for  
 444 the difference between the chosen model (Eq. 2.1) and  
 445 the actual data.



## 446 2.4 SPE charge template fit results

447 Using the background-subtracted modified WaveDeform  
 448 dataset, the  $\text{Exp}_1$  component was determined by fitting  
 449 the distribution from 0.1 PE to 3.5 PE. The result of the  
 450 fit yielded  $E_1 = 6.9 \pm 1.5$  and  $w_1 = 0.032 \pm 0.002$  PE. The  
 451 shape of  $\text{Exp}_1$  is then used to describe the low-PE charge  
 452 region for all subsequent fits.

**Figure 4.** The measured average residual of the SPE charge templates fit.

453 Using the MinBias dataset with the measured values of  $\text{Exp}_1$ , the SPE charge templates are  
 454 extracted for every DOM, separately for each IceCube season from IC86.2011 to IC86.2016. The  
 455 fit range for  $\text{Exp}_2$  and the Gaussian components is selected to be between 0.15 PE and 3.5 PE. An  
 456 average fit was also performed on the cumulative charge distribution, in which all the data for a  
 457 given DOM was summed together (labeled as "AVG").

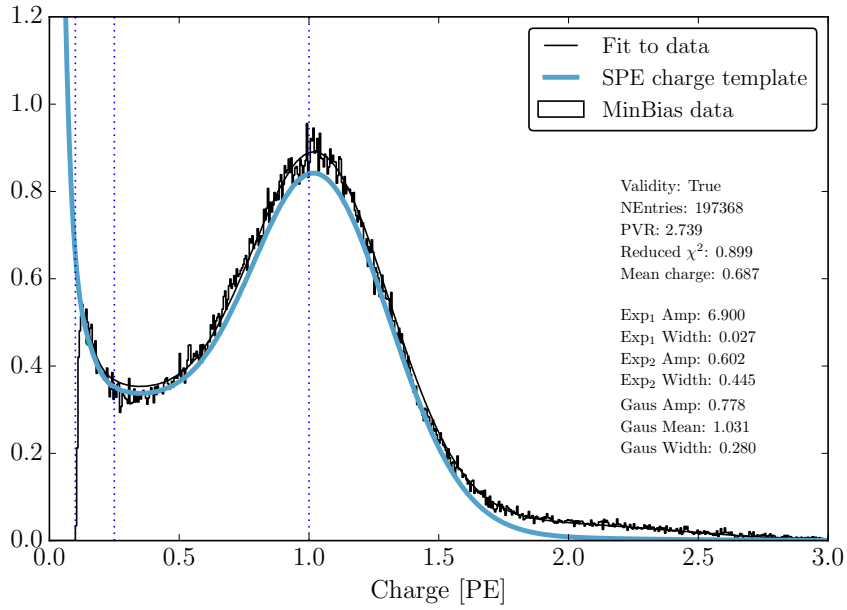
458 All the DOMs with "failed fits" are not included in this analysis. A DOM is classified as having  
 459 a failed fit if it does not pass one of the validity checks on the data requirements (e.g. the number of  
 460 valid pulses) or goodness of fit. The majority of these DOMs have been removed from service (107  
 461 to 111 DOMs over the seasons considered), and the remaining 6 DOMs that failed the AVG fits are  
 462 known to have various issues. In the IceCube MC simulation chain, these DOMs are assigned the  
 463 average SPE charge template.

464 We can divide the DOMs into subset of hardware differences: the HQE DOMs with the new  
 465 toroids, the Standard QE DOMs with the new toroids, and the Standard QE DOMs with the old  
 466 toroids. The mean value and standard error of the IC86.AVG fit parameters, excluding  $\text{Exp}_1$ , for  
 467 the subset of hardware differences are listed in Table 1. The average residual for all DOMs from 0  
 468 to 1 PE is shown in Fig. 4.

Hardware Configuration	Exp <sub>2</sub> Amp. (E <sub>2</sub> )	Exp <sub>2</sub> Width (w <sub>2</sub> )	Gaus. Amp. (N)	Gaus. Mean ( $\mu$ )	Gaus. Width ( $\sigma$ )
HQE / New Toroid	$0.644 \pm 0.003$	$0.405 \pm 0.003$	$0.715 \pm 0.002$	$1.0202 \pm 0.0010$	$0.311 \pm 0.001$
Std. QE / New Toroids	$0.566 \pm 0.001$	$0.403 \pm 0.001$	$0.751 \pm 0.001$	$1.0238 \pm 0.0004$	$0.316 \pm 0.001$
Std. QE / Old Toroids	$0.525 \pm 0.002$	$0.420 \pm 0.002$	$0.813 \pm 0.002$	$1.0074 \pm 0.0007$	$0.294 \pm 0.001$

**Table 1.** The average values and standard error of each fit parameter for the subset of hardware configurations listed in the first column.

469 An example fit is shown in Fig. 5 for the cumulative MinBias charge distribution for DOM  
470 (1,1). The collected charge distribution is shown in the black histogram, while the fit to the data is  
471 shown as the black line. The extracted SPE charge template from the fit is shown in blue. Both the  
472 fit and extracted SPE charge template have been scaled by the average residual shown in Fig. 4.



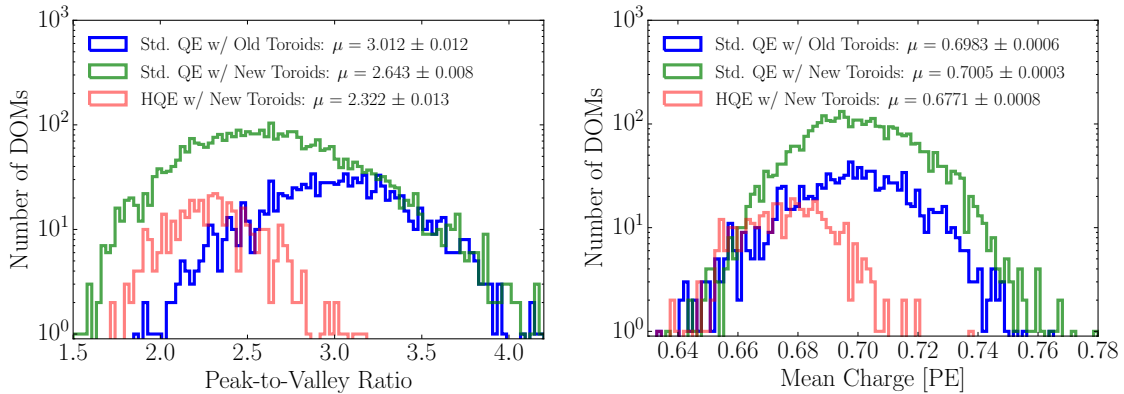
**Figure 5.** An example fit including the average residual from Fig. 4 for DOM(1,1) using the WaveDeform dataset for seasons IC86.2011 to IC86.2016. The result from the convolutional fitter is shown as a solid black line. The extracted SPE charge template is shown blue.

### 473 3 Discussion

#### 474 3.1 Correlations between fit parameters and DOM hardware differences

475 It is evident from the data in Table 1 that the average shape of the SPE charge templates is correlated  
476 with the DOM hardware. These differences can also be seen in the measured peak-to-valley ratios  
477 and mean charge of the SPE charge template (see Fig. 6). When we examine the subset of DOMs  
478 instrumented with the new toroids, the average HQE DOM were found to have a  $13.8 \pm 0.6\%$  larger  
479 E<sub>2</sub> component and  $4.77 \pm 0.03\%$  smaller Gaussian amplitude. Consequently, the average HQE  
480 peak-to-valley ratio is measured to be  $2.322 \pm 0.013$ , corresponding to  $12.12 \pm 0.06\%$  lower than

481 the average Standard QE DOMs. Also, interestingly, the mean charge of the average HQE DOM  
 482 was found to be  $3.34 \pm 0.01\%$  lower than that of the Standard QE DOMs. IceCube compensates for  
 483 the change in the mean measured charge in simulation, by increasing the HQE DOM efficiency by  
 484 the equivalent amount. This ensures that the total amount of charge collected by the HQE DOMs  
 485 remains the same prior to, and after, inserting the SPE charge templates into simulation.



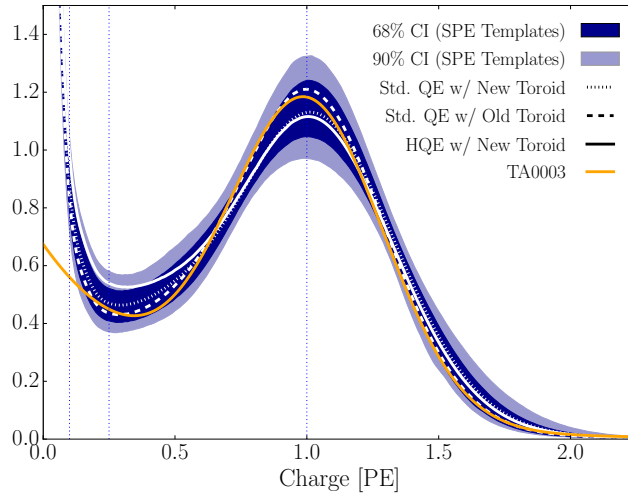
**Figure 6.** Comparison between the R7081-02MOD HQE DOMs and standard R7081-02 DOMs. Left: The peak-to-valley ratio for the two subsets of quantum efficiencies. Right: The mean charge of the individual DOM SPE charge templates.

486 Similarly, using only the subset of Standard QE DOMs, the SPE charge templates compar-  
 487 ing the method of AC coupling were found to have measurably different shapes. The average  
 488 Gaussian amplitude and width for the DOMs instrumented with the old toroids were found to be  
 489  $8.31 \pm 0.01\%$  and  $-6.80 \pm 0.03\%$ , respectively. With these differences, we find a peak-to-valley  
 490 ratio of  $2.643 \pm 0.008$  for the new toroid DOMs and  $3.012 \pm 0.012$  for the old toroid DOMs. The  
 491 average Gaussian mean of the fit for the DOMs with the old toroids was also found to be  $1.6 \pm 0.1\%$   
 492 lower than those with the new toroids. This corresponds proportionally to a change in the expected  
 493 gain. The mean charge, however, between these two hardware configurations remains very similar  
 494 ( $-0.346 \pm 0.001\%$ ).

495 Although the DOMs instrumented with the old toroids were deployed into the ice earlier than  
 496 those with the new toroids, the differences above is still noted when examining individual deployment  
 497 years; therefore, the shape differences are not attributed to the change in the DOM behavior over time.  
 498 However, the DOMs with the old toroids were the first PMTs to be manufactured by Hamamatsu.  
 499 A gradual change over time of the fit parameters was observed when ordering the PMTs according  
 500 to their PMT serial number. This is compelling evidence that the observed differences between  
 501 the new and old toroids is due to a change in the production procedure rather than version of AC  
 502 coupling.

503 Fig. 7 illustrates the average shape differences in the extracted SPE charge templates between  
 504 the HQE DOM with the new toroids (solid white line), Standard QE with the new toroids (dotted  
 505 white line), Standard QE with the old toroids (dashed white line), compared to the spread in the  
 506 measured SPE charge templates for all DOMs in the detector (dark blue contours). The figure  
 507 also shows how the TA0003 distribution compares to this recent measurement. The observable  
 508 shape differences from the TA0003 are attributed to a better control of the low-charge region, the





**Figure 7.** The inner (outer) dark blue region shows the 68% (90%) confidence interval defined by the measured spread in the extracted SPE charge templates of all DOMs in the detector. Superimposed, is the average SPE charge template for the variety of hardware configurations shown in white. The TA0003 distribution is shown in orange. All curves have been normalized such that the area above 0.25 PE is the same.

509 difference in functional form (described in Section 1.1), and the fact that the SPE charge templates  
 510 were generated using a realistic photocathode illumination.

### 511 3.2 Fitting parameters variation over time

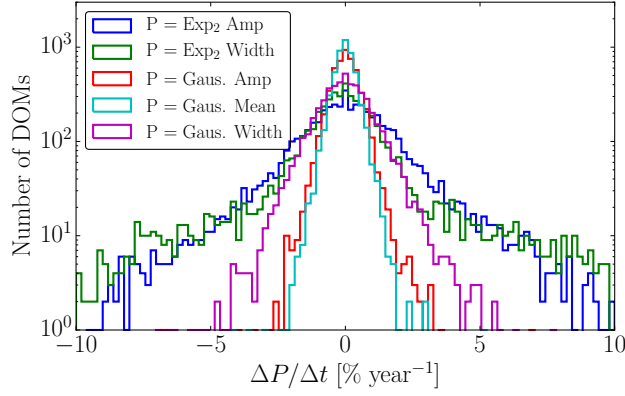
512 The SPE charge templates were extracted for each IceCube season independently to investigate the  
 513 time dependence of the fit parameters. For every DOM in the detector, the change over time of each  
 514 fit parameter (excluding  $\text{Exp}_1$ ) was calculated. Fig. 8 shows the change in a given fit parameter,  
 515 relative to the mean value, per year. The measured distribution was found to be consistent with  
 516 statistically scrambling the yearly measurements. The average of each fit parameters are found to  
 517 deviate less than 0.1%, which is in agreement with the stability checks performed in Ref. [7]. This  
 518 observation holds for the individual subset of DOMs with different hardware configurations as well.

### 519 3.3 Quantifying observable changes when modifying the PMT charge distributions

520 Changing the assumed gain response in simulation, as deduced from data, has different implications  
 521 depending on the typical illumination level present in different analyses. These differences are  
 522 outlined in the following discussion.

523 The PMT response is described by a combination of a "bare" efficiency,  $\eta_0$ , and a normalized  
 524 charge response function,  $f(q)$ . The bare efficiency represents the fraction of arriving photons that  
 525 result in any nonzero charge response, including those well below the discriminator threshold. The  
 526 normalization condition is:

$$\int_0^{\text{inf}} f(q) dq = 1. \quad (3.1)$$



**Figure 8.** The change in the individual DOM fitted parameters over time, represented as percentage deviation from the mean fit parameter value.

527 Generally,  $f(q)$  and  $\eta_0$  have to be adjusted together to maintain agreement with a quantity known  
 528 from lab or in-ice measurements, such as the predicted number of pulses above threshold for a dim  
 529 source.

530 **Dim source measurements** Where light levels are low enough, low occupancy ensures that  
 531 sub-discriminator pulses do not contribute any observed charge as they do not satisfy the trigger  
 532 threshold. Given some independent way of knowing the number of arriving photons, a lab or in-ice  
 533 measurement determines the trigger fraction above threshold  $\eta_{0.25}$  and/or the average charge over  
 534 threshold  $Q_{0.25}$ , either of which can be used to constrain the model as follows:

$$\eta_{0.25} = \eta_0 \int_{0.25q_{pk}}^{\infty} f(q) dq \quad (3.2)$$

$$Q_{0.25} = \eta_0 \int_{0.25q_{pk}}^{\infty} q f(q) dq \quad (3.3)$$

535 Here, the discriminator threshold is assumed to be 0.25 times the peak position  $q_{pk}$ . It is also  
 536 useful to multiply observed charges by  $q_{pk}$ , since we set each PMT gain by such a reference, and  
 537 then a measurement constraint would be stated in terms of  $Q_{0.25}/q_{pk}$ .

538 **Semi-bright source measurements** Once the ATWD window is open, subsequent pulses are not  
 539 limited by the discriminator threshold. WaveDeform introduces a software termination condition at  
 540 0.1 PE (described at the end of Section 2.1). The average charge of an individual pulse that arrives  
 541 within the time window is:

$$Q_{0.10} = \eta_0 \int_{0.10q_{pk}}^{\infty} q f(q) dq \quad (3.4)$$

542 **Bright source measurements** For light levels that are large, the trigger is satisfied regardless  
 543 of the response to individual photons, and the total charge per arriving photon therefore includes  
 544 contributions below both the discriminator and the WaveDeform thresholds:

$$Q_0 = \eta_0 \int_0^{\infty} q f(q) dq \quad (3.5)$$

545 As such, the total charge is directly proportional to the average charge of the SPE charge  
 546 template, having a strong dependence on  $\text{Exp}_1$ .

Model	Detector	$Q_0/Q_{0.25}$	$Q_0/Q_{0.10}$	$\eta_{0.25}/Q_{0.25}$
TA0003	All DOMs	1.017	1.0031	1.05
SPE charge templates	HQE + New Toroids	$1.021 \pm 0.002$	$1.0041 \pm 0.0004$	$1.05 \pm 0.02$
	Std. QE + New Toroids	$1.018 \pm 0.002$	$1.0035 \pm 0.0005$	$1.03 \pm 0.02$
	Std. QE + Old Toroids	$1.017 \pm 0.002$	$1.0033 \pm 0.0005$	$1.05 \pm 0.02$

**Table 2.** The distribution in bright-to-dim ratios for the previous charge distribution (TA0003) and the individual DOM SPE charge templates for the IceCube and DeepCore detectors.

### 547 3.3.1 Model comparison

548 When the charge distribution model is changed in a way that preserves agreement with the measured  
 549  $\eta_{0.25}$  or  $Q_{0.25}/q_{pk}$ , i.e.  $\eta_0$  is adjusted properly for changes in  $f(q)$ , the physical effect can be  
 550 summarized by the change in the bright-to-dim ratios  $Q_0/Q_{0.25}$ , and  $Q_0/Q_{0.10}$ . Conveniently, these  
 551 ratios depend only on the shape of  $f(q)$ . Table 2 compares these ratios in terms of the TA0003 charge  
 552 distribution and the SPE charge templates described here. It is shown that there are sub-percent  
 553 level differences in the physically-observable bright-to-dim ratios.

### 554 3.4 SPE charge templates for calibration

555 The gain setting on each PMT is calibrated prior to the beginning of each season such that the  
 556 Gaussian mean of the charge distribution corresponds to a gain of  $10^7$ , or equivalently 1 PE.  
 557 This gain calibration method, run directly on the DOMs, uses waveform integration for charge  
 558 determination instead of WaveDeform unfolding, resulting in a small systematic shift in gain. This  
 559 systematic shift was determined for every PMT, and was found to be on average  $2.00 \pm 0.03\%$  with  
 560 a standard deviation of  $3.54\%$ , corresponding to an overestimation of the measured charge in the  
 561 detector.

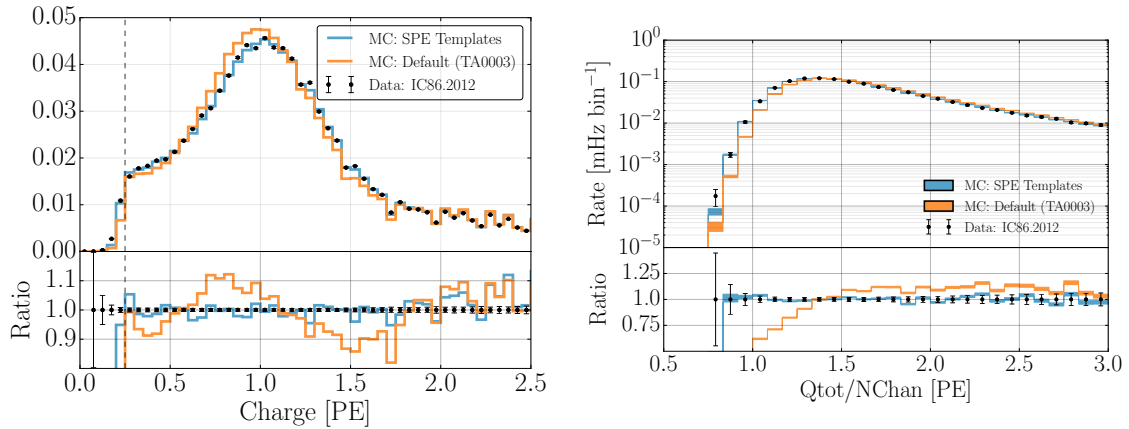
562 The correction to the systematic shift in the measured charge can be implemented retroactively  
 563 by dividing the reported charge from WaveDeform by the corresponding offset for a given DOM.  
 564 Alternatively, we can account for this by simply inserting SPE charge templates, measured in this  
 565 analysis, into simulation such that the corresponding systematic shift is also modelled in simulation.  
 566 This will be performed in the following subsection.

### 567 3.5 SPE charge templates in simulation

568 The IceCube MC simulation chain assigns a charge to every photoelectron generated at the surface  
 569 of the photocathode. The charge is determined by sampling from a normalized charge distribution  
 570 probability density function. A comparison between describing the charge distribution using the  
 571 SPE charge templates and the TA0003 distribution follows.

572 Two simulation sets consisting of the same events were processed through the IceCube Monte  
 573 Carlo simulation chain to the final analysis level of an update to the IC86.2011 sterile neutrino analy-  
 574 sis [23]. Here, the events that pass the cuts are  $>99.9\%$  upward-going (a trajectory oriented upwards

575 relative to the horizon) secondary muons produced by charged current muon neutrino/antineutrino  
 576 interactions. The muon energy range of this event selection is between approximately 500 GeV and  
 577 10 TeV.



**Figure 9.** A comparison between the SPE charge templates (blue) and the TA0003 (orange) model for describing the SPE charge distribution in Monte Carlo. The simulation is compared to the 2012 IceCube season. Left: The total measured charge per DOM, per event at analysis level. Right: The distribution of the total measured charge of an event divided by the number of DOMs that participated in the event.

578 Fig. 9 (left) shows the distribution of the total measured charge in a single DOM during an  
 579 event. The data is shown for the full IC86.2012 season but is statistically equivalent to any of the  
 580 other seasons. The simulation set using the TA0003 charge distribution is shown in orange, and  
 581 that using the SPE charge templates is shown in blue. Fig. 9 (right) shows the distribution of the  
 582 measured total charge of an event divided by the number of channels (NChan), or DOMs, that  
 583 participated in the event. Both plots in Fig. 9 have been normalized such that the area under the  
 584 histograms is the same.

585 The SPE charge templates clearly improve the overall MC description of these two low-level  
 586 variables. This update may be useful for analyses that rely on low-occupancy events (low-energy or  
 587 dim events) in which average charge per channels is below 1.5 PE, and will be investigated further  
 588 within IceCube.

## 589 4 Conclusion

590 This article outlines the procedure used to extract the SPE charge templates for all in-ice DOMs in the  
 591 IceCube detector using in-situ data from IC86.2011 to IC86.2016. The result of this measurement  
 592 was shown to be useful for improving the overall data/MC agreement as well as calibration of the  
 593 individual PMTs. It also prompted a comparison between the shape of the SPE charge templates  
 594 for a variety of hardware configurations and time dependent correlations.

595 The subset of HQE DOMs were found to have a smaller peak-to-valley ratio relative to the  
 596 Standard QE DOMs, as well as an overall  $3.34 \pm 0.01\%$  lower mean charge. It was also found that the  
 597 DOMs instrumented with the old toroids used for AC coupling (the first PMTs to be manufactured)  
 598 had narrower and larger Gaussian component corresponding resulting in an increased peak-to-valley

599 ratio of  $14.0 \pm 0.6\%$ . No significant time dependence in any of the fitted parameters associated with  
600 the SPE charge templates over the investigated seasons was observed. A reassessment of the PMT  
601 gain settings found a systematic bias of  $2.00 \pm 0.03\%$  with a standard deviation of  $3.54\%$ .

602 The SPE charge templates were inserted into the MC simulation and the results were compared  
603 to the default TA0003 distribution. A significant improvement in the description of the low-level  
604 variables, total charge per DOM and total charge over the number of channels, was shown. Analyses  
605 which rely on low-light occupancy measurements, may benefit from this update. As shown in the  
606 bright-to-dim ratios, the average mean charge for various light levels will not be affected by this  
607 update.

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