

## 2 In situ calibration of the single photoelectron charge 3 response of the IceCube photomultipliers

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ABSTRACT: This article outlines the in situ calibration of the single photoelectron charge distributions for each of the Hamamatsu Photonics R7081-02 photomultipliers in the IceCube Neutrino Observatory. We discuss the single photoelectron identification procedure, how we extract the single photoelectron charge distribution using a deconvolution the multiphotoelectron charge distribution, and examine various correlations between the shape of the single photoelectron charge distribution and various hardware components. The time dependence of the charge distributions is also investigated.

Definitions (this will be removed in the final draft):

1. Charge: WaveDeform fits the waveform with an SPE pulses template. The integral of the fitted pulse, divided by the load resistance, divided by the gain, is the reported measured *charge* of the pulse. It is reported in units of a single electron.
2. PE: The unit of charge. This represents the charge relative to one electron.
3. 1PE: The HV on each DOM is set such that the gain on the PMT is  $10^7$ . It is determined to be at the proper gain ( $10^7$ ), when the Gaussian mean of the fitted charge distribution is at 1PE.
4. Photoelectron: The physical electron emitted from the photocathode.
5. SPE: (Single Photoelectron) A single physical electron emitted from the photocathode.
6. MPE: (Multiple Photoelectron): multiple electrons emitted from the photocathode, charges may have been combined.
7. Charge distribution: The distribution of the measured charges. This will include both SPE and MPE events.
8. Single Photoelectron Charge distribution: The hypothetical charge distribution generated by observing a pure sample of single photoelectron.
9. SPE Template: The functional form that is used to fit the charge distribution.

5 **KEYWORDS:** IceCube, single photoelectron, charge distribution, PMT.

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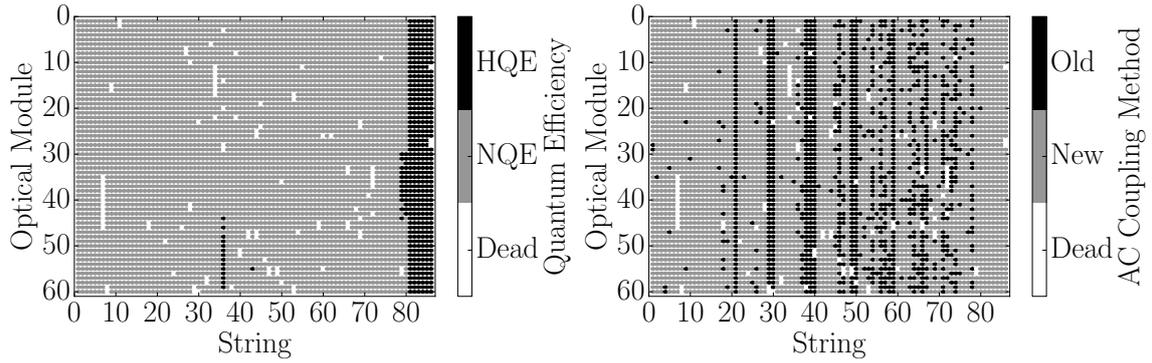
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## 24 1. Introduction

25 The IceCube Neutrino Observatory [1, 2] is a cubic kilometer sized array of 5,160 photomultiplier tubes (PMTs) buried in the Antarctic ice sheet designed to observe high energy neutrinos  
 26 interacting with the ice [3]. In 2011, the IceCube collaboration completed the installation of 86  
 27 vertical *strings* of PMT modules; 8 of which were arranged in a more densely arranged array for  
 28 the DeepCore detector [4] and the remaining for the main IceCube detector. Each string in the  
 29 detector contains 60 digital optical modules (DOMs), that contain a single PMT each, as well as  
 30 all required electronics [5]. The DOMs extend from 1450 m to 2450 m below the surface of the ice  
 31 sheet and are spaced 17 m apart in the IceCube detector, and 7 m apart in the DeepCore detector.  
 32

33 Each DOM consists of a 0.5" thick spherical glass pressure vessel that houses a single down  
 34 facing 10" R7081-02 PMT from Hamamatsu Photonics [6]. The PMT is specified for wavelengths  
 35 ranging from 300 nm to 650 nm, with peak quantum efficiency of 25% near 390 nm. Each PMT is  
 36 coupled to the glass housing with optical gel and is surrounded by a wire mesh of  $\mu$  metal to reduce  
 37 the effect of the ambient Earth's magnetic field. Then glass housing is transparent to wavelengths  
 38 350 nm and above [7].

39 IceCube has also deployed 399 DOMs with Hamamatsu R7081-02MOD PMTs, which, having  
 40 a peak quantum efficiency of 34% near 390 nm (36% higher efficiency than the standard DOMs),



**Figure 1.** Left: A mapping of the HQE DOMs (black) and standard normal quantum efficiency (NQE) DOMs (gray). Right: The version of AC coupling, old toroids (black) and new toroids (gray). DOMs that have been removed from service are shown in white.

41 are classified as high quantum efficiency (HQE) DOMs [4]. These DOMs are primarily located in  
 42 DeepCore and on strings 36 and 43, as shown in the left side of Fig. 1.

43 The R7081-02 and R7081-02MOD PMTs have 10 dynode stages and are operated with a gain  
 44 of  $10^7$  and high voltage around 1200 V (an typical amplified single photoelectron will generate a  
 45  $\approx 6$  mV peak voltage at the input to the front-end amplifiers). The PMTs operate with the anodes  
 46 at high voltage and the signal is AC coupled to the front-end amplifiers. There are two versions  
 47 of AC coupling in the detectors both of which use custom designed a wide-band bifilar wound 1:1  
 48 toroidal transformers<sup>1</sup> (the DOM specific AC coupling versions, new and old toroids, are shown in  
 49 the right side of Fig. 1). The DOMs with the old toroids were designed with an impedance of  $43\Omega$ ,  
 50 while the new toroids are  $50\Omega$  [8].

51 IceCube relies on two observables per DOM to reconstruct events: the total number of detected  
 52 photons and their timing distribution. Both the timing and the number of photons are extracted from  
 53 the on-board digitized waveforms in software. The waveforms are deconvolved into a series of  
 54 scaled single photoelectron pulses (so-called pulse series) and the integral of the individual scaled  
 55 pulses (divided by the load resistance) defines the observed charge. It will often be expressed in  
 56 units of PE, or photoelectrons, which further scales the measured charge by the charge of a single  
 57 electron times the nominal gain ( $10^7$ ). Accurately characterization of the individual PMT charge  
 58 distributions is crucial for calibration and event reconstructions relying on charge information.  
 59 The charge distribution can also be used to assess long term detector performance and identifying  
 60 discrepancies between data and Monte Carlo. It is therefore critically important to accurately  
 61 measure the single photoelectron charge distribution in order to understand the IceCube detector  
 62 behavior.

63 When one or more photons produce a voltage at the anode sufficient to trigger the on-board  
 64 discriminator (set via a DAC to approximately 1.3 mV, or equivalently 0.25PE), the signal acquisi-

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<sup>1</sup>Conventional AC coupling high voltage ceramic capacitors can produce noise from leakage currents and impractical requirements on the capacitors in order to meet the signal droop and undershoot requirements. The toroidal transformer effectively acts as a high-pass filter with good signal fidelity at high frequencies. It also provides higher reliability than capacitive coupling, and reduces the stored energy which might cause damage if there is HV discharge in the system [7]. However, the toroidal transformer AC coupling also introduces signal droop and undershoot.

65 tion process is triggered. The signal is feed into four parallel input channels. Three of the channels  
66 first pass through a 75 ns delay loop in order to capture the leading edge of the pulse, then into three  
67 high-speed (300 MSPS for 128 samples) 10-bit waveform digitizers (Analog Transient Waveform  
68 Digitizer, ATWD), each of which have a different level of amplification ( $15.7 \pm 0.6$ ,  $1.79 \pm 0.06$ ,  
69 and  $0.21 \pm 0.01$  [8]). There is also three extra ATWDs on-board each DOM: one used for cali-  
70 bration, and the other two operate in a ping-pong fashion to remove deadtime associated with the  
71 readout. The signal to the fourth channel is first shaped and amplified, then feed into a 10-bit  
72 fast analog-to-digital converter (fADC) operating at a sampling speed of 40 MSPS. Further detail  
73 regarding the description of the DOM electronics can be found in Refs. [5, 9].

74 This article is concerned with accurately determining how the individual DOMs collect charge  
75 in order to improve calibration and the description of the detector in the IceCube Monte Carlo sim-  
76 ulation. It describes the procedure used to determine the PMTs gain characteristics as seen in the  
77 single photoelectron (SPE) charge distributions using in situ data from the IceCube and DeepCore  
78 detectors. The SPE charge distribution refers to the measured charge probability density function  
79 of the individual DOMs generated by the amplification of a pure sample of single photoelectrons.  
80 The extraction of the SPE charge distribution was recently made possible by developing two pieces  
81 of software:

- 82 1. A specially designed unbiased pulse selection was developed to reduce the MPE contami-  
83 nation while accounting for physical phenomena (e.g. late pulses, afterpulses, pre-pulses,  
84 and baseline shifts) and software related effects (e.g. pulse splitting). This will be further  
85 described in Sec. 2.1.
- 86 2. A fitting procedure that separates the remaining MPE contamination from the SPE charge  
87 distribution by deconvolving the measured charged distribution. This is elaborated on in  
88 Sec. 2.3.

89 In using in situ data to determine the SPE charge distributions, we accurately represent the in-  
90 dividual PMT response as a function of time, environmental conditions, software version, hardware  
91 differences, and sample photons uniformly over the surface of the photocathode. This is beneficial  
92 since it also allows us to inspect the stability and long term behavior of the individual DOMs, verify  
93 previous calibration, and correlate features and environment to DOM behavior.

## 94 1.1 Single photoelectron charge distributions

95 In an idealized scenario, a single photon produces a single photoelectron, which is then amplified  
96 by a known amount and the measured charge corresponds to 1PE. However, there are many physical  
97 processes which create structure in the measured charge distributions. For example:

- 98 • **Statistical fluctuation due to cascade multiplication** [10]. At every stage of dynode am-  
99 plification, there is a stochastic spread in the number of emitted electrons that make it to the  
100 next dynode. This in turn causes a spread in the measured charge after the gain stage of the  
101 PMT.
- 102 • **Photoelectron trajectory**. Some electrons may deviate from the favorable trajectory, reduc-  
103 ing the number of secondaries produced at a dynode or the efficiency to collect them on the

104 following dynode. This can occur at any stage but it has the largest effect on the multipli-  
105 cation at the first dynode [11]. The trajectory of a photoelectron striking the first dynode  
106 will depend on many things, include where on the photocathode it was emitted, the unifor-  
107 mity of the electric field, the size and shape of the dynodes [10], and the ambient magnetic  
108 field [12, 13].

109 • **Late or delayed pulses.** A photoelectron can elastically or inelastically scatter off the first  
110 dynode. The scattered electron can then be re-accelerated to the dynode, creating a second  
111 pulse. The difference in time between the initial pulse and the re-accelerated pulse in the  
112 R7081-02 PMT was previously measured to be up to 70 ns [7, 14]. The two sub pulses have  
113 lower chargers, but the sum of the two tends to add up to the original charge. Collecting either  
114 the initial pulse or the late pulse will result in the charge being reconstructed as lower [15].

115 • **Afterpulses.** When a photoelectron or the secondary electrons produced during the electron  
116 cascade gain sufficient energy to ionize residual gas in the PMT, the positively charged ion-  
117 ized gas will be accelerated in the electric field towards the photocathode. Upon impact with  
118 the photocathode, electrons can be again released from the photocathode, creating what is  
119 called an afterpulse. For the R7081-02 PMTs, the timescale for afterpulses was measured  
120 to occur from 0.3 to 11  $\mu$ s after the initial pulse, with the first prominent afterpulse peak  
121 occurring at approximately 600 ns [7]. The spread in the afterpulse time is dependent on  
122 the position of photocathode, the charge to mass ratio of the ion produced, and the electric  
123 potential distribution [16]; whereas the size of the afterpulse is related to the momentum and  
124 species of the ionized gas and composition of the photocathode [17].

125 • **Pre-pulses.** If an incident photon passes through the photocathode without interaction and  
126 strikes one of the dynodes, it can eject an electron that is only amplified by the subsequent  
127 stages, resulting in a lower measured charge (lower by a factor of approximately 25). For the  
128 IceCube PMTs, the pre-pulses were found to arrive approximately 30 ns before the signal  
129 from other photoelectrons from the photocathode [7].

130 • **MultiPE contamination.** When multiple photoelectrons arrive at the first dynodes within  
131 several nanoseconds of each other, they can be reconstructed by the software as a single,  
132 multiPE pulse.

133 • **Electronic noise.** This refers to the fluctuations in the analog-to-digital converters (ATWDs  
134 and FADC) and ringing arising from the electronics.

135 Beyond the physical phenomena above that modify the measured charge distribution, there is  
136 also a lower limit to the smallest charge that can be extracted. For IceCube, the discriminator limits  
137 the trigger pulse to be above approximately 0.25PE, and subsequent pulses in the readout time  
138 window are subject to a software defined threshold. The software threshold was set conservatively  
139 to avoid extracting pulses that originated from electronic noise. This threshold can be modified to  
140 gain access to lower charge pulses, and will be discussed in Sec. 2.2.

141 The standard charge distribution model used by the IceCube collaboration (known as the  
142 TA0003 distribution [7]) represented the above effects as the sum of an exponential plus a Gaussian,

143 where the exponential represented charge of poorly amplified pulses, and the Gaussian represented  
 144 the spread in statistical fluctuations due to the cascade multiplication. The TA0003 distribution was  
 145 previously used to describe all the PMTs in the IceCube and DeepCore detectors.

146 Recently, IceCube has performed several lab measurements using the R7081-02 PMTs with in-  
 147 time laser pulses, demonstrating that the in-time charge distribution includes a steeply falling low  
 148 charge component below the discriminator threshold. To account for this, a new functional form  
 149 including a second exponential was introduced. This form of the charge distribution,  $f(q)_{SPE} =$   
 150  $Exp_1 + Exp_2 + \text{Gaussian}$ , and is referred to as the *SPE template* in this report. Explicitly:

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

151 Where  $q$  represents the measured charge;  $E_1$ ,  $E_2$ , and  $N$  represent normalization factors of  
 152 each components;  $w_1$  and  $w_2$  are the exponential decay widths; and  $\mu$ ,  $\sigma$  are the Gaussian mean  
 153 and width respectively. This is the assumed functional shape of the SPE charge distributions and  
 154 the components of Eq. 1.1 are determined in this report for all in-ice DOMs. IceCube defines 1PE  
 155 as the location of the Gaussian mean ( $\mu$ ) and calibrates the gain on the individual PMTs during the  
 156 start of each season to meet this definition. This definition comes from the Gaussian fit component  
 157 aiming to model the statistical fluctuations of the cascade multiplication process assuming the  
 158 central limit theorem (see Sec. 1.1).

## 159 1.2 IceCube datasets and software definitions

160 The largest contribution to the IceCube trigger rate comes from down-going muons produced in  
 161 cosmic ray induced showers [18]. Cosmic ray muons stopping in the detector cause the individual  
 162 trigger rate to decrease at lower depths. Further, during the formation of this ice sheet, there have  
 163 been several periods of colder climate that have caused different optical properties in the ice at  
 164 different depths. The optical properties also affect the trigger rate, in particular, the “dust layer”  
 165 from 2100 to 2200 m (optical modules 32 to 38 in the IceCube detector) below the surface is a  
 166 region in the ice with a relatively large scattering and absorption coefficient [19].

167 An induced signal in the PMT that passes through the AC coupling toroid located on the base of  
 168 the PMT, is compared to a discriminator threshold. If two DOM within two DOM distances observe  
 169 a passing of the discriminator, a *Hard Local Coincidence* (HLC) is initiated and the corresponding  
 170 waveforms are sampled 128 times and readout on the three ATWDs.

171 After waveform digitization, there is a correction applied to remove the measured DC base-  
 172 line offset. The signal droop and undershoot introduced by the toroidal transformer AC coupling  
 173 is compensated for in software (during waveform calibration) by adding the expected temperature  
 174 dependent reaction voltage of the undershoot to the calibrated waveform. Conditions where the  
 175 undershoot drops below 0 ADC counts are zeroed and then compensated for once the waveform is  
 176 above the minimum ADC input. Scaled single photoelectron pulse shapes (that take into account  
 177 the version of the AC coupling) are then fit to the waveforms using software referred to as WaveDe-  
 178 form (Waveform unfolding process), which determines the individual pulse time stamp and charge,  
 179 and populates a pulse series [20].

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

- 181 1. The **MinBias dataset**. This dataset records the full waveform readout of randomly triggered  
182 HLC events at a rate that corresponds on average to 1/1000 events. The largest contribution  
183 to the IceCube trigger rate comes from down-going muons produced in cosmic ray induced  
184 showers [18] and therefore is the largest signal component in this dataset. These muons tend  
185 to have small energies when they reach the detector, thus they produce minimal MPE con-  
186 tamination. The full waveform of these events allows us to extract the raw information about  
187 the individual pulses. This will be used to measure the individual PMT charge distributions.
- 188 2. The **BeaconLaunch dataset**. This is a forced trigger (not triggered by the discriminator) fil-  
189 ter that is typically used to monitor the individual DOM baseline. It includes the full ATWD  
190 window waveform readout. Since this dataset is forced triggered, the majority of these wave-  
191 forms represent baseline fluctuations with minimal contamination from the occasional coin-  
192 cidental pulse that makes it into the readout window. This dataset will be used to examine  
193 the noise contribution to the charge distributions. Note: when using this datasets, the weight  
194 of every pulse is scaled by a factor of 28.4 to account for the livetime difference between  
195 the MinBias dataset and the BeaconLaunch dataset. Weight, in this context, refers to the  
196 equivalent number of photons in the MinBias dataset that one photon in the BeaconLaunch  
197 dataset is proportional to in order for both datasets to have the same equivalent livetime.

198 This analysis uses the full MinBias and BeaconLaunch datasets from IceCube season 2011  
199 to 2016 (subsequently referred to as IC86.2011 to IC86.2016). Seasons in IceCube typically start  
200 in June of the labeled year and end approximately one year later. Calibration is performed at the  
201 beginning of each season.

## 202 2. Extracting the SPE templates

### 203 2.1 Single photoelectron pulse selection

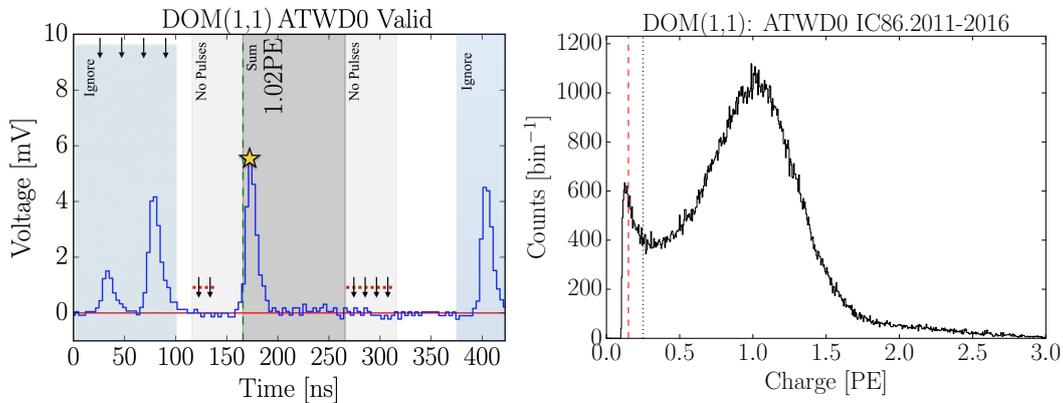
204 The pulse selection is the method used to extract candidate, unbiased, single photoelectron pulses  
205 from data, while minimizing the multiPE contamination. It avoids collecting afterpulses, rejects  
206 late pulses from the trigger, reassembles late pulses, accounts for the discriminator threshold,  
207 reduces the effect of droop and baseline undershoot, and gives sufficient statistics to perform a  
208 season-to-season measurement. An illustrative diagram of the pulse selection is shown in the left  
209 side of Fig. 2, while a description of the procedure is detailed below.

210 In order to trigger a DOM, the input to the front-end amplifiers must exceed the discriminator  
211 threshold. To avoid the selection bias of the discriminator trigger, we ignore the trigger pulse as  
212 well as the entire first 100 ns of the time window. Ignoring the first 100 ns has the added benefit  
213 of also removing late pulses that could be attributed to the triggering pulse. To ensure we are not  
214 accepting afterpulses into the selection, we also enforce that the pulse of interest (POI) is within  
215 the first 375 ns of the ATWD time window. This also allows us to examine the waveform up to  
216 50 ns after the POI (the ATWD time window is  $\approx 425$  ns). In the vicinity of the POI, we check  
217 that WaveDeform did not reconstruct any pulses up to 50 ns prior to the POI, or 100 to 150 ns after  
218 the POI (the light gray region of Fig. 2 Left). This later constraint is to reduce the probability of  
219 accidentally splitting a late pulse in the summation window.

220 Restrictions are put on the full ATWD waveforms as well, such as ensuring that the trigger  
 221 pulse does not exceed 10 mV (to reduce the effect of the subsequent baseline undershoot due to  
 222 the AC coupling or other artifacts from large pulses) and a global constraint that the time window  
 223 cannot contain any waveform that exceeds 20 mV (recall that a properly amplified SPE pulse is  
 224  $\approx 6$  mV).

225 If a pulse is reconstructed between 100 and 375 ns after the time window is opened and the  
 226 voltage criteria are met, it is accepted as a candidate photoelectron and several checks are performed  
 227 on the waveform prior to and after the pulse. The first check is to ensure that the waveform is near  
 228 the baseline just before to the rising edge of the POI. This is accomplished by ensuring that the  
 229 waveform does not exceed 1 mV, 50 to 20 ns prior to the POI, and eliminates cases where the POI  
 230 is a late pulse. We also ensure the waveform returns to the baseline by checking that no ADC  
 231 measurement exceeds 1 mV, 100 to 150 ns after the POI (these constraints are illustrated as the  
 232 horizontal red dotted lines and black arrows in the left side of Fig. 2).

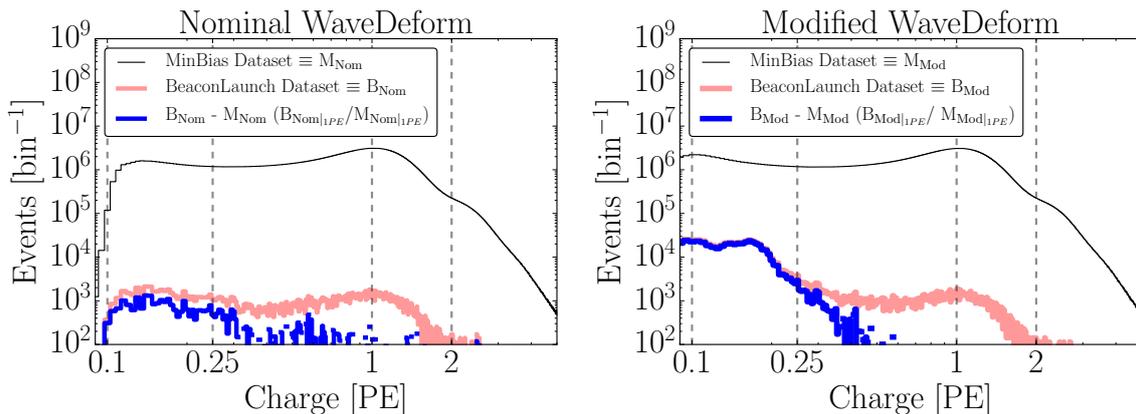
233 If all the above criteria are met, we sum the reconstructed charges from the POI time (given  
 234 by WaveDeform) to +100 ns (the dark gray area of in Fig. 2 Left). This ensures that any nearby  
 235 pulses are either fully separated or fully added. WaveDeform may occasionally split a SPE pulse  
 236 into multiple smaller pulses, therefore it is always critically important to perform a summation of  
 237 the charge within a window. The 100 ns summation also means that the pulse selection we will  
 238 occasionally be accepting MPE events.



**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 the 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 semiopaque regions. The POI is reported to have a charge of 1.02PE, 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 data set collected from IC86.2011 to IC86.2016 that pass the pulse selection. The discriminator threshold at 0.25PE is represented as a dotted black vertical line. For visual purposes, a vertical dashed red line is also included at 0.15PE.

239 **2.2 Characterizing the low charge region**

240 Fig. 2 (right) shows the charge distributions of the selected pulses that pass the single photoelec-  
 241 tron pulse selection for string 1, optical module 1 (DOM (1,1)). In the low charge region (below  
 242 0.25PE), we see a steep rise (in agreement with the in-time laser tests mentioned in Sec. 1.1), then  
 243 a second threshold at approximately 0.13PE. This is a software defined threshold that comes from  
 244 a gradient-related termination condition in WaveDeform. The threshold was set to avoid electronic  
 245 noise being interpreted as PMT pulses and contaminating the low charge region. This section will  
 246 examine the effect on the charge distribution and noise contribution by lowering the WaveDeform  
 247 threshold. The aim will be to explore the low charge region.



**Figure 3.** The cumulative charge distributions (IC86.2011 to 2016) of all DOMs for the MinBias and BeaconLaunch datasets. The blue histogram shows the expected contribution from noise (found by subtracting the shape of the MinBias dataset from the BeaconLaunch dataset). Left: The charge distributions for the standard WaveDeform settings. Right: The charge distributions for the modified WaveDeform settings.

248 Fig. 3 (left) shows the charge distributions for the MinBias (black) and the BeaconLaunch  
 249 (red) datasets using the default settings on WaveDeform. As mentioned in Sec. 1.2, occasionally  
 250 a photoelectron will be coincident with the forced BeaconLaunch time window and populate a  
 251 single photoelectron distribution. Subtracting the shape of the MinBias charge distribution from the  
 252 BeaconLaunch dataset yields an estimate of the amount of electronic noise contamination (blue).  
 253 The bin with the largest signal-to-noise ratio (SNR) above 0.1PE was found to have 0.0013. The  
 254 SNR for the the full distribution was found to be 0.0005. Fig. 3 (right) shows the same data after  
 255 lowering the WaveDeform threshold. Correspondingly, the bin with the largest SNR was found to  
 256 be 0.0017, whereas the total SNR was found to be 0.0015.

257 **2.3 Fitting procedure**

258 The fit assumes that there is a negligible three-PE contribution, which is justified by the lack of  
 259 statistics in the 3PE region as well as the significant scale difference between the 1PE and 2PE  
 260 region, as shown in Fig. 2 (right). The 2PE charge distribution is assumed to be the 1PE charge  
 261 distribution convolved with itself [21]. A python-based piece of software called the "convolutional

262 fitter" is used to determine the components of Eq. 1.1 from the measured charge distribution that  
 263 includes the multiPE contamination.

264 The  $\text{Exp}_2$  component (as well as the  $\text{Exp}_1$ ) of Eq. 1.1, represents poorly amplified photoelec-  
 265 trons and we do not allow it to extend beyond the high charge region of the Gaussian component.  
 266 In particular, we include a constraint on the the parameter  $w_2$  to ensure that it falls off with the  
 267 Gaussian component:

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

268 This equation was found by setting the  $\text{Exp}_2$  to be  $1/e^2$  that of the Gaussian component at two  
 269 sigma (the  $\text{Exp}_1$  is neglected from this equation since it falls off in the low charge region). Eq. 2.1  
 270 is used as a constraint during the fit to the charge distributions.

271 Pulses that fall below the WaveDeform threshold and are not reconstructed contribute to an  
 272 effective efficiency of the individual DOMs. This analysis assumes the same shape of the steeply  
 273 falling exponential component ( $\text{Exp}_1$ ) for all DOMs in the detector to avoid large fluctuations in  
 274 the individual DOM efficiencies. The modified WaveDeform data will strictly be used to determine  
 275 the  $\text{Exp}_1$  component. Specifically, using the modified WaveDeform, we will background subtract  
 276 the BeaconLaunch distribution from the MinBias data, fit the resulting distribution to determine  
 277 the components of Eq. 2.1, and only use the measured shape and normalization of  $\text{Exp}_1$  in all  
 278 subsequent non-modified WaveDeform fits.

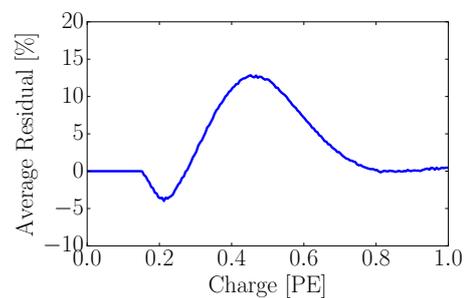
279 Upon fitting the MinBias data (with the predetermine values for  $\text{Exp}_1$ ), the residual of each  
 280 fit is calculated by measuring the percentage difference between the fit and the data. The average  
 281 residual will then be used as a global scaling factor for all SPE templates to account for difference  
 282 between the chosen model (Eq. 2.1) and the actual data.

283 Failed fits (DOMs removed from service (109 DOMs) and DOMs that fail any one of several  
 284 validity checks on the goodness of fit (6 DOMs)) are not included in this report. In the IceCube  
 285 MC simulation chain, the these DOMs are assigned the average SPE template.

## 286 2.4 SPE template fit results

287 Using the background subtracted modified WaveDe-  
 288 form dataset, the steeply falling exponential compo-  
 289 nent was determined by fitting from 0.1PE to 3.5PE  
 290 to be  $E_1 = 6.9 \pm 1.5$  and  $w_1 = 0.032 \pm 0.002\text{PE}$ . The  
 291 shape of the steeply falling exponential is then used to  
 292 describe the low-PE charge region for all subsequent  
 293 fits.

294 Using the MinBias dataset with the value for  
 295  $\text{Exp}_1$  described above, the SPE templates are extracted  
 296 for every DOM, separately for each IceCube season  
 297 (IC86.2011 to IC86.2016). An average fit was also  
 298 performed in which all the data for a given DOM was  
 299 summed together (labeled as "AVG"). The fit range



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

300 for  $\text{Exp}_2$  and the Gaussian components are selected to be between 0.15PE and 3.5PE. The average  
 301 residual for all DOMs from 0 to 1PE is shown in Fig. 4.

302 An example fit is shown in Fig. 5 for the cumulative charge distribution for DOM (1,1). The  
 303 collected charge distribution is shown in the black histogram, while the convolutional fit is shown  
 304 as the black line (scaled by the residual). The extracted SPE template (also scaled by the residual)  
 305 for this DOM is shown in red. The 2PE component from the fit is shown in blue.

306 The mean value and  $1\sigma$  spread of the fit parameters, excluding  $\text{Exp}_1$ , for the IceCube and  
 307 DeepCore detectors are shown in Table 1 and Table 2 respectively.

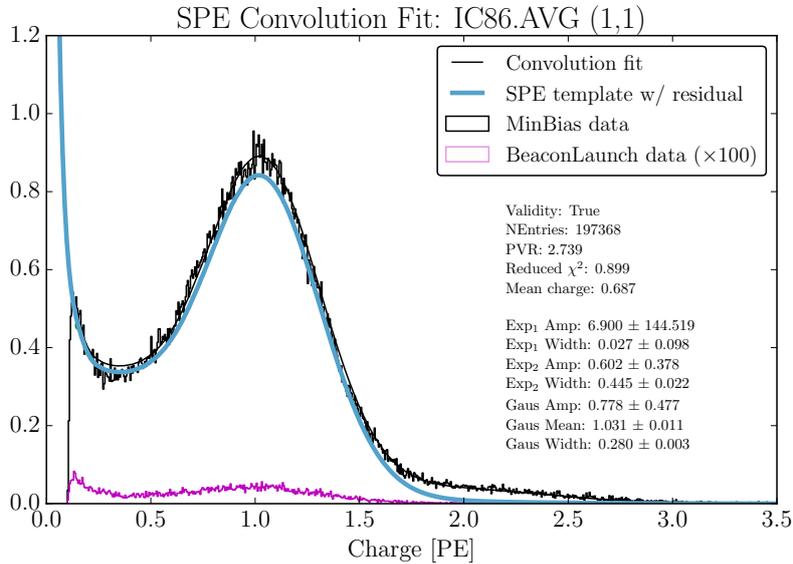
308 The individual DOM SPE templates were then examined between IceCube seasons for a time  
 309 dependence on the fit parameters. For every DOM, the change over time of each fit parameter  
 310 (excluding  $\text{Exp}_1$ ) was calculated.

311 Fig. 6 shows the change in a given fit parameter (represented in percentage deviation from the  
 312 mean value), per year, of each DOM in both the IceCube (left) and DeepCore (right) detectors.  
 313 The spread in the fit parameters were found to be consistent with statistically scrambling the yearly  
 314 measurements. The average fit parameters are found to deviate less than 0.5% per year in both  
 315 detectors, which is in agreement with the stability checks performed in Ref. [8].

### 316 3. Discussion

#### 317 3.1 Correlations between fit parameters and DOM hardware differences

318 As noted in Sec. 1, there are two DOM related hardware differences: the subset of HQE DOMs and



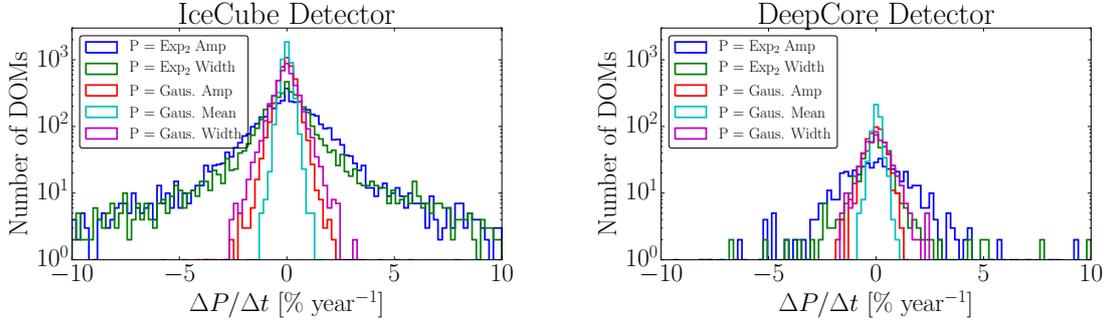
**Figure 5.** An example fit including the residual correction for DOM (1,1) using the WaveDeform dataset for seasons IC86.2011 to IC86.2016. The result from the convolutional fitter is shown as a solid black line. The extracted SPE template is shown blue. The purple histogram is the full detector (all DOMs and all seasons summed together) BeaconLaunch dataset, scaled to the livetime of the MinBias data and further multiplied by a factor of 100 in order to be visible on this plot.

IceCube	Exp <sub>2</sub> Amplitude	Exp <sub>2</sub> Width	Gaus. Amplitude	Gaus. Mean	Gaus. Width
IC86.2011	0.601 ± 0.101	0.457 ± 0.070	0.736 ± 0.061	1.022 ± 0.030	0.296 ± 0.033
IC86.2012	0.595 ± 0.100	0.462 ± 0.065	0.740 ± 0.062	1.020 ± 0.034	0.295 ± 0.033
IC86.2013	0.602 ± 0.101	0.452 ± 0.071	0.736 ± 0.060	1.021 ± 0.033	0.298 ± 0.032
IC86.2014	0.597 ± 0.099	0.453 ± 0.071	0.736 ± 0.059	1.019 ± 0.030	0.299 ± 0.030
IC86.2015	0.604 ± 0.099	0.457 ± 0.067	0.735 ± 0.061	1.024 ± 0.032	0.296 ± 0.032
IC86.2016	0.600 ± 0.101	0.460 ± 0.063	0.736 ± 0.060	1.024 ± 0.030	0.295 ± 0.031

**Table 1.** The average values and  $1\sigma$  spread of each fit parameter for the IceCube detector. The active DOMs in the IceCube detector are 99.4% normal quantum efficiency and 31.0% of the DOM have the old method of AC coupling. Correspondingly, there are 0.6% HQE DOMs and 69.0% of the DOM have the new version of AC coupling.

DeepCore	Exp <sub>2</sub> Amplitude	Exp <sub>2</sub> Width	Gaus. Amplitude	Gaus. Mean	Gaus. Width
IC86.2011	0.519 ± 0.095	0.462 ± 0.099	0.763 ± 0.073	1.023 ± 0.031	0.307 ± 0.038
IC86.2012	0.517 ± 0.095	0.467 ± 0.098	0.763 ± 0.074	1.024 ± 0.032	0.306 ± 0.038
IC86.2013	0.520 ± 0.092	0.461 ± 0.096	0.763 ± 0.073	1.024 ± 0.030	0.306 ± 0.037
IC86.2014	0.522 ± 0.093	0.459 ± 0.098	0.765 ± 0.073	1.021 ± 0.031	0.306 ± 0.038
IC86.2015	0.525 ± 0.095	0.458 ± 0.099	0.763 ± 0.072	1.023 ± 0.031	0.307 ± 0.038
IC86.2016	0.522 ± 0.095	0.464 ± 0.098	0.763 ± 0.074	1.024 ± 0.031	0.305 ± 0.038

**Table 2.** The average values and  $1\sigma$  spread of each fit parameter for the DeepCore detector. The active DOMs in DeepCore are 12.4% NQE DOMs and 0.2% of the DOM have the old method of AC coupling. Correspondingly, the DeepCore detector contains 87.6% HQE DOMs and 99.8% of the DOM have the new version of AC coupling.



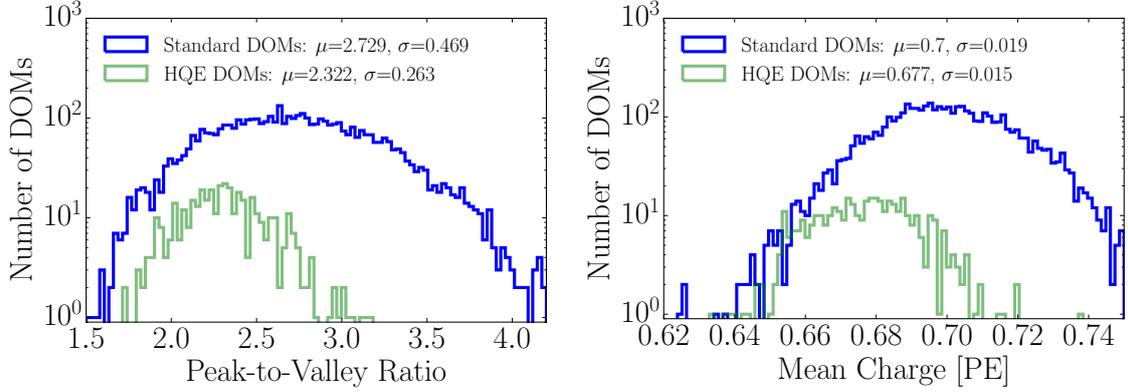
**Figure 6.** The change in individual DOM fitted parameters over time (Left: IceCube, Right: DeepCore). The change in the fit value is represented in percentage deviation from the mean fit parameter value.

319 the version of AC coupling used to couple the signal from the PMT anode to the front-end ampli-  
320 fiers. Correlations between the different hardware configurations were examined for correlations  
321 with the SPE template fit components.

322 The HQE DOMs were found to have a larger Exp<sub>2</sub> component (2.3% lower  $w_2$  component,  
323 and a 19.9% higher  $E_2$ , described in terms of Eq.1.1) than the standard DOMs<sup>2</sup>. Consequently, the  
324 HQE DOMs have an 14.9% lower peak-to-valley ratio and a 3.3% lower mean charge. These distri-

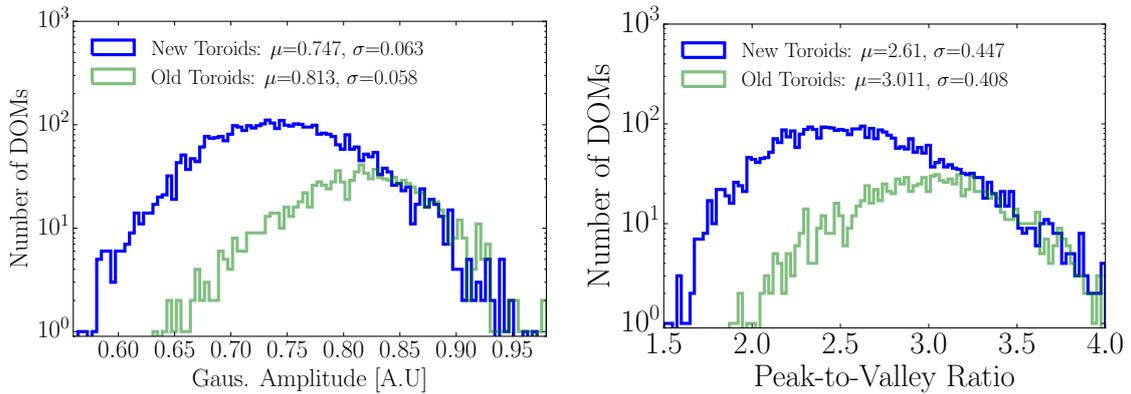
<sup>2</sup>This difference is still observed when comparing the DOMs at similar depths in the detector.

325 butions are shown in Fig. 7. The change in the mean charge for the HQE DOMs is compensated for  
 326 in simulation by increasing the HQE DOM efficiency by the equivalent amount. This ensures that  
 327 the total amount of charge collected by the HQE DOMs remains the same after the SPE templates  
 328 are implemented.



**Figure 7.** 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 templates.

329 The subset of NQE DOMs with the old AC coupling transformer were found to have a 6.1%  
 330 narrower Gaussian width and an 8.0% larger Gaussian amplitude ( $\sigma$  and  $N$  in Eq. 1.1). The expo-  
 331 nential component  $\text{Exp}_2$  was also found to have a 7.5% lower  $E_2$  component, and a 3.0% higher  
 332  $E_2$  component. Although the old toroid DOMs were deployed into ice earlier than the new toroid  
 333 DOMs, the difference above is still noted when examining individual deployment years, therefore  
 334 the shape differences are not attributed to the change in the DOM behavior over time. However,  
 335 the DOMs with the old toroids used the first PMTs to be manufactured by Hamamatsu, so this  
 336 difference may also be attributed to a gradual change in the process parameters over the course  
 337 of the PMT manufacturing change in the production procedure rather than the actual AC coupling  
 338 version.



**Figure 8.** Comparison between the AC coupling version used on the NQE DOMs. Left: The distribution of the measured Gaussian amplitudes. Right: The distribution of the measured Peak-to-Valley ratios.

### 3.2 Quantifying observable changes when modifying the PMT charge distributions

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

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

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

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

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

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

$$Q_{0.25} = \eta_0 \int_{0.25q_{pk}}^{\text{inf}} qf(q) dq \quad (3.3)$$

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

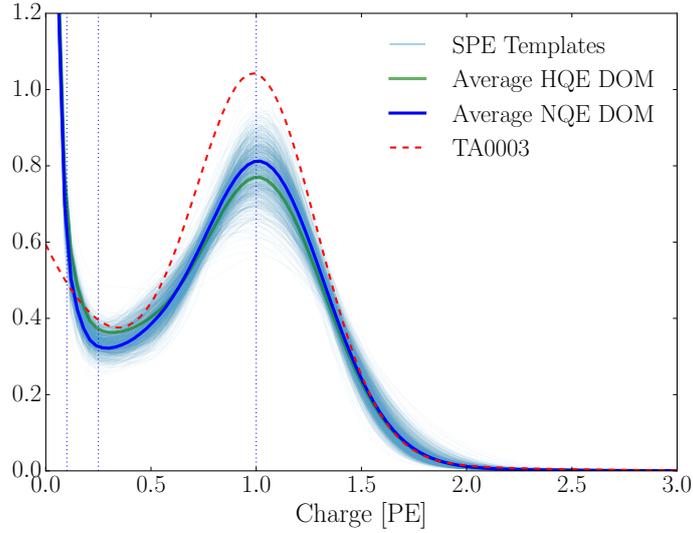
**Semi-bright source measurements** Once the ATWD window is open, subsequent pulses are not limited by the discriminator threshold. WaveDeform introduces a software termination condition at 0.1PE (described at the end of Section 2.1). The average charge of an individual pulse that arrive within the time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

$$Q_{0.10} = \eta_0 \int_{0.10q_{pk}}^{\text{inf}} qf(q) dq \quad (3.4)$$

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

$$Q_0 = \eta_0 \int_0^{\text{inf}} qf(q) dq \quad (3.5)$$

As such the total charge is directly proportional to the average charge of the SPE template, having a strong dependence on the steeply falling exponential.



**Figure 9.** A comparison between the SPE templates (light blue) and the TA0003 (dashed red) distribution. The average SPE template for the NQE and HQE DOMs is shown as the thick blue and green line, respectively. The SPE templates include the residual correction and all curves are normalized.

### 368 3.2.1 Model comparison

369 When the charge distribution model is changed in a way that preserves agreement with the mea-  
 370 sured  $\eta_{0.25}$  or  $Q_{0.25}/q_{pk}$ , i.e.  $\eta_0$  is adjusted properly for changes in  $f(q)$ , the physical effect can  
 371 be summarized by the change in the bright-to-dim ratios  $Q_0/Q_{0.25}$ , and  $Q_0/Q_{0.10}$ . Conveniently,  
 372 these ratios depend only on the shape of  $f(q)$ . Table 3 compares these ratios in terms of the previ-  
 373 ous charge distribution (TA0003) and the SPE templates described here. It is shown that there are  
 374 percent level differences in the physically observable bright-to-dim ratios.

Model	Detector	$Q_0/Q_{0.25}$	$Q_0/Q_{0.10}$	$\eta_{0.25}/Q_{0.25}$
TA0003	IceCube and DeepCore	1.017	1.003	0.969
SPE Templates	IceCube	$1.031 \pm 0.003$	$1.013 \pm 0.001$	$0.971 \pm 0.006$
SPE Templates	DeepCore	$1.034 \pm 0.002$	$1.014 \pm 0.001$	$0.965 \pm 0.006$

**Table 3.** The distribution in bright-to-dim ratios for the previous charge distribution (TA0003) and the individual DOM SPE templates for the IceCube and DeepCore detector.

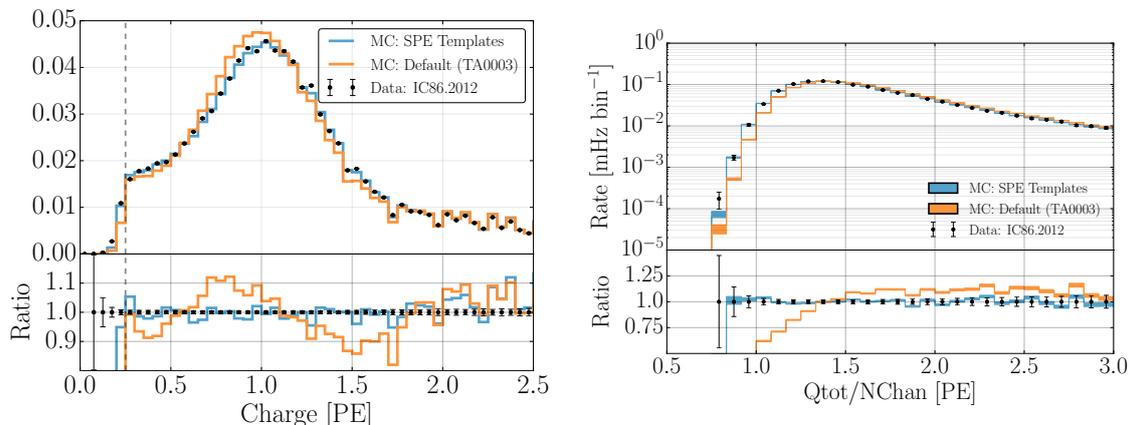
375 Fig. 9 shows the shape difference between the TA0003 distribution and all the SPE templates  
 376 measured in this report. The shape difference is attributed to a better control of the low charge  
 377 region, the difference in functional form (described in Section 1.1), as well as the fact that the SPE  
 378 templates sample uniformly over the entire photocathode at random incident angles. We have also  
 379 separated the DOMs into the subsets of NQE and HQE DOMs to illustrate their average shape  
 380 differences.

### 381 3.3 SPE templates in simulation

382 The IceCube Monte Carlo simulation chain assigns a charge to every photoelectron generated at  
 383 the surface of the photocathode. The charge is determined by sampling from a normalized charge  
 384 distribution probability density function. A comparison between describing the charge distribution  
 385 using the SPE templates and the TA0003 distribution follows.

386 Two simulation sets consisting of the same set of events were processed through the IceCube  
 387 Monte Carlo simulation chain to the final level of the multiyear High Energy Sterile Analysis.  
 388 At analysis level, the events that pass the cuts are  $>99.9\%$  pure up-going (directed upwards rel-  
 389 ative to the horizon) secondary muons produced by charged current muon neutrino/antineutrino  
 390 interactions. The muon energy range of this event selection is between 500 GeV and 10 TeV  
 391 (reconstructed quantities).

392 Fig. 10 (left) shows the distribution of the total measured charge in a single DOM during each  
 393 event. The data is shown for the full IC86.2012 season, but statistically equivalent to any of the  
 394 other seasons. The simulation set using the TA0003 charge distribution is shown in orange, and the  
 395 SPE Templates is shown in blue. The bottom of the plot shows the ratio of the measured quantity  
 396 relative to data. Fig. 10 (right) shows the distribution of the measured total charge on a DOM (after  
 397 noise removal) divided by the number of channels, or DOMs, that participated in the event. Both  
 398 plots in Fig. 10 have been normalized such that the area under the histograms is the same.



**Figure 10.** A comparison between the SPE 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.

399 The SPE templates clearly improve the overall MC description of these two variables. IceCube  
 400 includes a systematic uncertainty in all analyses, which scales the DOM efficiency to account for  
 401 effects that change the total observed charge. This systematic compensates for the overall mean  
 402 charge shift introduced using the SPE templates, however, the SPE templates now introduce DOM-  
 403 to-DOM differences. This is not expected to change the IceCube physics results since analyses are  
 404 sensitive to the overall detector performance rather than the individual DOM variations.

### 405 **3.4 SPE templates for calibration**

406 The gain setting on each DOM is calibrated at the beginning of the season such that the Gaussian  
407 mean charge distribution corresponds to a gain of  $10^7$  (equivalently labelled as 1PE). Since the  
408 method used to extract the Gaussian mean described in this report is different from the previous  
409 method used for calibration of the DOMs, the total measured charge from a DOM is expected to  
410 change with the updated calibration.

411 As shown in Tables ??, the Gaussian mean component of the fit of every year is found to be  
412 on average 2.2% higher than unity, corresponding to a systematic overestimation of the measured  
413 charge in the detector. This correction to the measured charge can be implemented retroactively by  
414 dividing the reported charge from WaveDeform by the corresponding Gaussian mean for a given  
415 DOM. Alternatively, the MC can account for this difference by simply inserting the SPE templates  
416 with Gaussian mean matching the values found in the data. Both of these solutions will be used in  
417 future IceCube data/MC production.

## 418 **4. Conclusion**

419 This report outlines the procedure used for collecting a relatively pure sample of single photoelec-  
420 tron charges for each of the in-ice DOMs in IceCube. MPE contamination was removed using the  
421 assumption that the MPE contamination is the convolution of the SPE distribution multiple times.

422 The SPE templates were extracted for each DOM and each season in the IceCube and Deep-  
423 Core detectors, and investigated for correlations with hardware related features. Both detectors do  
424 not show more than a 0.5% deviation in any of the fitted parameters over the investigated seasons,  
425 in agreement with Ref. [8]. Yearly variations in the fit parameters are consistent with statistical  
426 fluctuations. The HQE DOMs located in the IceCube and DeepCore detectors were found to have  
427 a distinguishable  $\text{Exp}_2$  component from the standard DOMs. Similarly, DOMs with the old method  
428 of AC coupling were found to have a narrower and larger Gaussian component. This was not found  
429 to be due to a manufacturing process and is still under investigation.

430 The SPE templates were introduced into the MC simulation production and the result was  
431 compared to the default charge distribution. A significant improvement in the description of the  
432 low level variables, total charge per DOM and total charge per event over the number of channels,  
433 was shown. IceCube includes a systematic that scales the bare efficiency of the DOMs to maintain  
434 agreement with a quantity known from lab or in-ice measurements. After accounting for this shift  
435 the effect on physics analysis, as shown by the bright-to-dim ratios, is expected to be minimal  
436 (percent level changes in the measured charge).

437 The new method for extracting the calibration constant that determines the gain setting on each  
438 of the PMTs (the Gaussian mean of the fit), has been revised and shows that the average gain was  
439 approximately  $2.2\% \pm 3.1\%$  higher than expected. This will be implemented in future IceCube data  
440 reprocessing.

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