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Abstract: There are two types of PMT hung in center of each cell of WCDA. In order to achieve an optimal energy reconstruction, and cosmic ray background suppression, we develop an off-line method to calibrate number of photoelectrons of signals. By matching signals caught by different kinds of PMT, we bridge their linear measurement range to obtain equivalent NPE of signals up to more than 8000000 PEs for WCDA-1, and more than 150000 PEs for WCDA-2. Besides, detector monitoring and various measurements show the PMT among cells are slightly different in quantum efficiency and collection efficiency, and the light attenuation and depth of water in the pool are also varying with time, especially in the very beginning of the operation. Above inhomogeneity and instability influences the detection efficiency of cells on secondary air shower particles. A flexible efficiency calibration method of Constant Rate Scaling is under study. The analysis method and the calibration results of the first two pools are presented in this paper.

1. Introduction: LHAASO-WCDA is a ground-based air-shower detector array based on water cherenkov technique. As a major component of LHAASO project, it focus on VHE gamma-ray astronomy 0.1 TeV to 30 TeV[1]. As shown in Fig. 1, WCDA consists of three fully enclosed cubic pools. Each pool is divided into cells with area of $5\text{m} \times 5\text{m}$. There is an 8-inch photomultiplier tube (PMT) and 1.5-inch PMT in each cell of WCDA-1, while a 20" PMT and 3" PMT are hung in each cell of WCDA-2 and WCDA-3. This combination of the two covers a wide dynamic range in terms of charge of signals, e.g. 1 PE to 8000000 PEs for combination of 8-inch and 1.5-inch, which allows a better measurement of secondary particle density distribution in the shower core without saturation. As shown in Fig. 2, attenuation length of WCDA-1 changes over time. The detection efficiency on secondary air shower particles is time dependent according to monitoring of attenuation length. And that is the motivation that lead us to develop a method named as Constant Rate Scaling (CRS) to calibrate detection efficiency of the cells.

2. Calibration of number of photoelectron :

2.1 SPE and D/A ratio

One of running modes of data acquisition system (DAQ) of LHAASO-WCDA is single-channel mode. In this mode, all hits of each cell are saved. The peak around 25 ADC counts in single channel charge spectrum of 8-inch PMT is mainly formed by single photon signals and its peak position is used to convert charge of signals from ADC counts to number of photoelectrons (NPEs). The 8-inch PMT is read out from both anode and 8th dynode to cover a range from 1 PE to 4000 PEs. The range covered by anode channel is up to 130 PEs, with a non-linearity of less than 5% [2]. Saturation exists when the anode signal exceeds 4096 ADC counts. The calibration of the dynode signals is performed by comparing them with the corresponding anode signals in the overlapping region. The ratio between the two signals denoted as D/A , can be extracted by fitting in the region of anode signals between 2400 and 3000 ADC counts. Distribution of D/A ratio of 900 8-inch PMTs in WCDA-1 is presented in Fig. 3(a). A similar method is used to calibrate the D/A ratio of three other kinds of PMT. By combining 6th dynode with anode, dynamic range of 1.5inch PMT is 20 PEs – 200000 PEs, and non-linearity within this range is less than 5% [3]. Distribution of D/A ratio of 900 1.5-inch PMT in WCDA-1 are shown in Fig. 3(b). Performance of four types of PMTs in LHAASO-WCDA are listed in Tab.1, in which SPE and D/A ratio are mean value of 900 PMTs in WCDA-1 or WCDA-2.

2.2 Ratio of 8-inch/20-inch PMT signals to 1.5-inch/3-inch PMT signals

The calibration of 1.5-inch/3-inch PMTs has been performed by matching signals, which are produced by the same air shower event, with 8-inch/20-inch PMTs in the same cell. The A_{plus}/D ratio is given by linearly fitting the overlapping region of square root of dynode signals of 8-inch/20-inch PMTs and that of anode signals of 1.5-inch/3-inch PMTs. The overlapping region is 2500 ADC counts - 3025 ADC counts for a combination of 8-inch PMT and 1.5-inch PMT and 2601 ADC counts - 3136 ADC counts for 20-inch PMT and 3-inch PMT. The mean value of A_{plus}/D is **0.0240** and **0.0242**, as shown in Fig. 4.

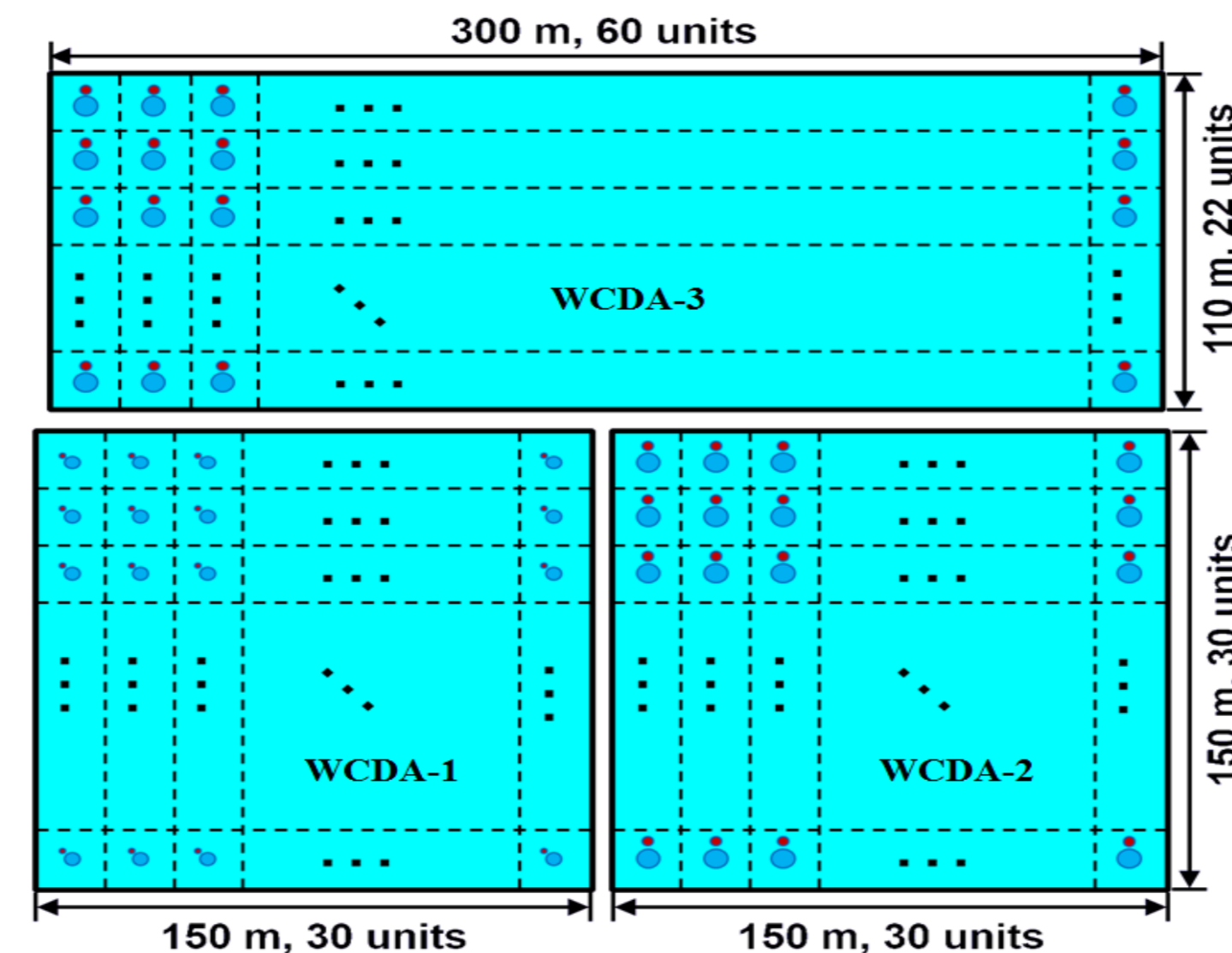


Fig. 1: Schematic of the LHAASO-WCDA layout.

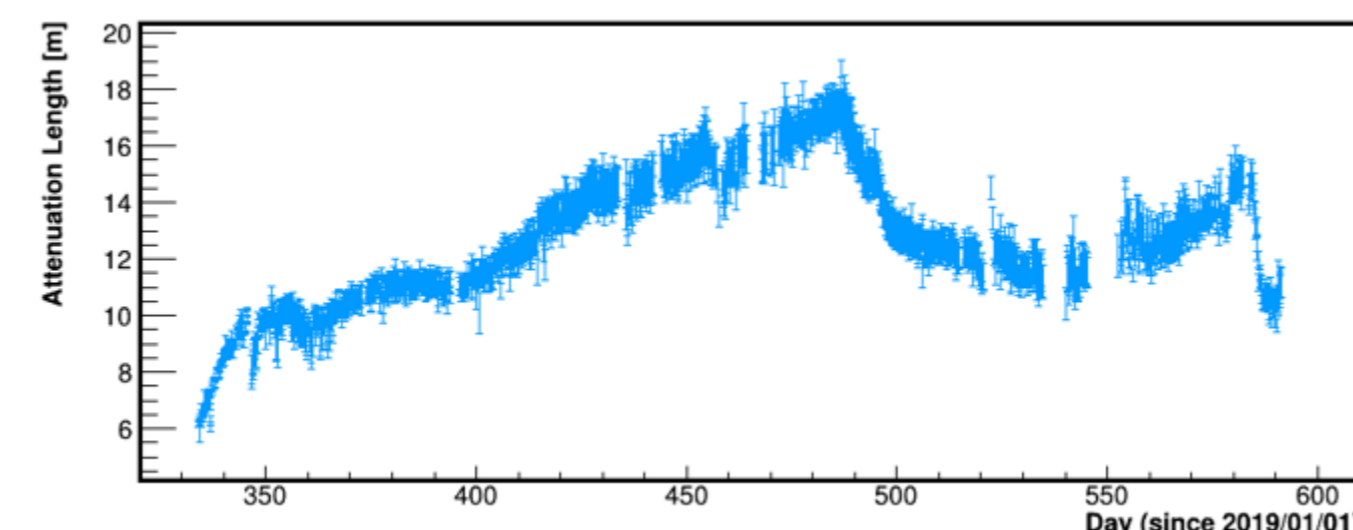


Fig. 2: Change of attenuation length of WCDA-1 from 2019/12/01 to 2020/08/14

PMT	SPE [count]	Dynamic range (PEs)	D/A ratio
8-inch	26.7	1 - 4,000	0.0225
1.5-inch	-	20 - 200,000	0.0186
20-inch	41.9	1 - 1,800	0.0505
3-inch	-	1 - 3,000	0.0286

Table 1: Performance of four types of PMTs in LHAASO-WCDA.

2.3 Ratio of signals of cells in WCDA-1 and that of cells in WCDA-2

The final step is to connect signals of 20-inch PMTs in WCDA-2 to that of 8-inch PMTs in WCDA-1. Air shower events, of which core position falls in the middle of WCDA-1 and WCDA-2, are chose to calibrate the ratio. The secondary particle density at the same distance from the core in the shower plane is considered to be statistically approximately equal. Therefore, in the case of no difference in water, the ratio of signal of a cell in WCDA-2 to that of a cell in WCDA-1 is the ratio of the corresponding 20-inch PMT to 8-inch PMT if the two cells are equal in distance from the core. Specifically, hits of one event are divided into nine groups according to the distance from the core. Each group of hits falls within the same loop centered on the core. In the same loop, parts of hits are in WCDA-1 and others are in WCDA-2. For each pool, hits within the same loop are sorted by NPEs and tagged with *rank* from 0 to 1. $\log_{10}(NPEs)$ of pairs of hits with same *rank* are filled in a histogram. The ratio in each loop is obtained by linear fitting of the corresponding histogram. The final result is an average of the five closest of the nine ratios. Analyzing data from a single day in April 2021 yields a ratio of **11.78**.

3. Efficiency calibration

The feasibility of using single particle peak to calibrate cell's detection efficiency for secondary particles has been revealed in previous studies [2]. In this article, the focus will be on the Constant Rate Scaling method. Under such assumption that integral energy flux detected by different cells is same over the same period of time, charge spectrum from single-channel data of two different cells should be exactly same if detection efficiency of the two cells is same. In fact, comparison of single channel charge spectrum shows that the detection efficiency of the cells in one pool is obviously different, mainly due to the difference of quantum efficiency and collection efficiency of PMTs and the inhomogeneity of water quality. Therefore, we can quantitatively analyze the relative differences of detection efficiency based on the single channel charge spectrum. Specific to the CRS method, process of calculating the efficiency of "cell1" relative to the reference "cell0" is divided into three steps:

- (1) a threshold in PEs (denoted as th_i) is set for each cell, and th_1 is equal to th_0 ;
- (2) adjust th_1 until integral count rate above threshold of the two cells is equal;
- (3) the efficiency of "cell1" relative to the reference "cell0" is equal to th_1/th_0 .

According to the change of water quality over time and single-channel hits rate, the cell 371 on 20190820 and cell 1458 on 20201110 are chose to be the reference of WCDA-1 and WCDA-2, respectively. The th_0 are set to 15PEs and 200PEs. Preliminary results are shown in the Fig. 5. The results show that the relative difference between 900 cells is $0.0565/1.034 =$ **5.46%** and $0.1189/1.006 =$ **11.82%** for WCDA-1 and WCDA-2.

References:

- [1] Z. Cao, A future project at tibet: the large high altitude air shower observatory (LHAASO), *Chin. Phys. C*, 34 (2)(2010): 249-252.
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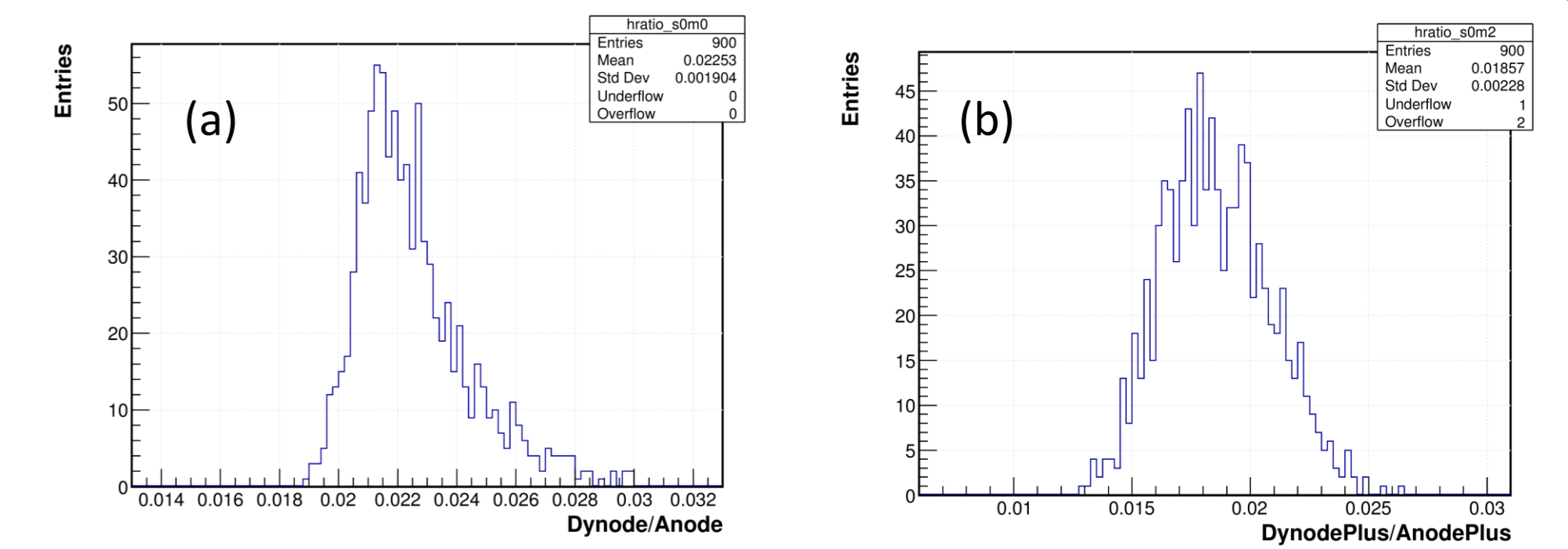


Fig. 3: (a) Distribution of D/A ratio of 900 8-inch PMTs in WCDA-1. (b) Distribution of D/A ratio of 900 1.5-inch PMTs in WCDA-1.

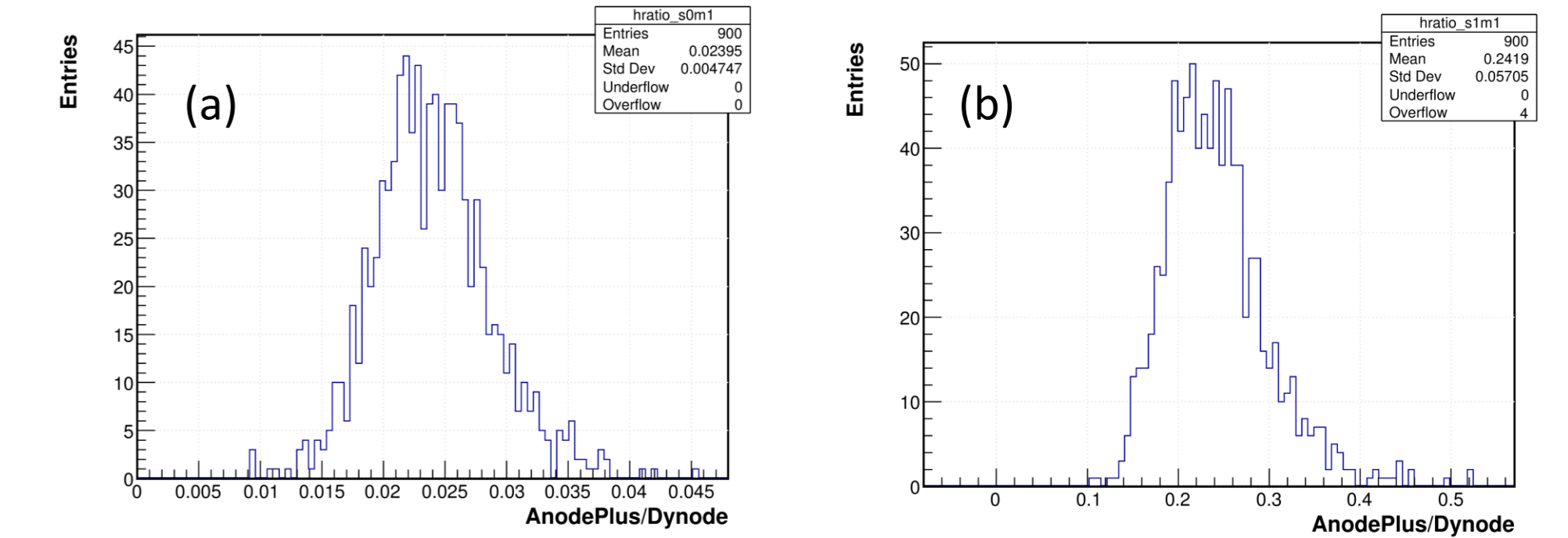


Fig. 4: (a) Distribution of A_{plus}/D ratio of 900 cells in WCDA-1. (b) Distribution of A_{plus}/D ratio of 900 cells in WCDA-2.

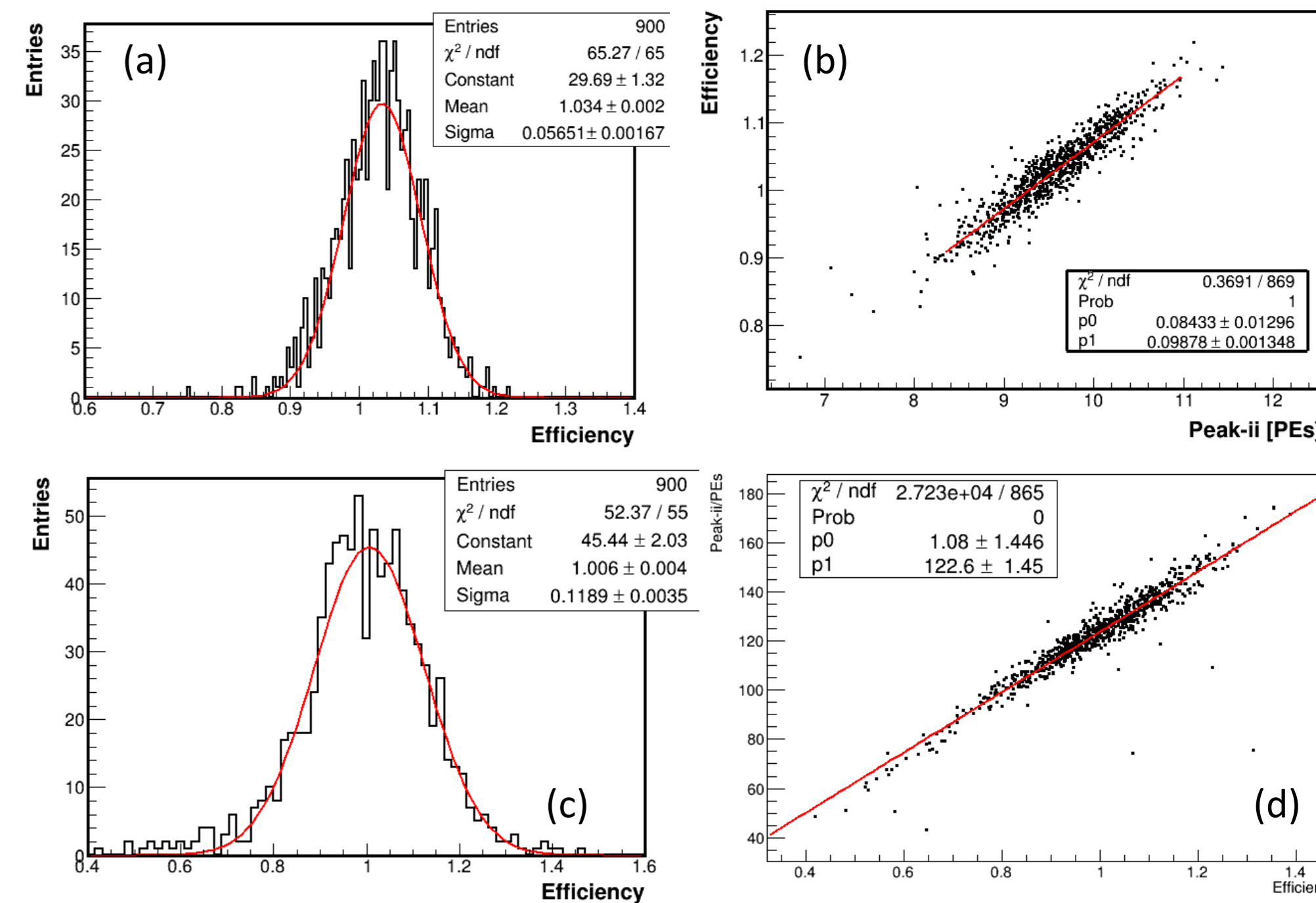


Fig. 5: (a) Distribution of CRS efficiency of 900 cells in WCDA-1 on 20190820. The red line is the result of Gaussian fitting. (b) Efficiency versus single particle peak of WCDA-1. (c) Distribution of CRS efficiency of 900 cells in WCDA-2 on 20201110. (d) Efficiency versus single particle peak of WCDA-2.

4. Summary: We developed a relatively complete off-line charge calibration method, which can accurately connect signals of four types of PMTs, so as to achieve the purpose of combining three pools into one detector array. In addition, the comparison with the single particle peak shows that CRS method can effectively calibrate the efficiency. The application of results of CRS to subsequent data analysis is under study.

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 [4] H.Y. Zhang, Y.H. Yu et al., Photomultiplier tube performance of the WCDA++ in the LHAASO experiment, *Nuclear Inst. and Methods in Physics Research*, A958 (2020) 162079