

# Calibration algorithms of RPC detectors at Daya Bay Neutrino Experiment

5 Ning Zhe<sup>1,3,7</sup>, Zhang Qingmin<sup>2</sup>, Xu Jilei<sup>3</sup>, Logan Lebanowski<sup>4</sup>, Zhang Jiawen<sup>1,3</sup>,  
Yang Changgen<sup>3</sup>, He Miao<sup>3</sup>, Zhao Jie<sup>1,3,7</sup>, Zou Jiaheng<sup>3</sup>, Viktor Pěč<sup>5</sup>, Shih-Kai Lin<sup>4</sup>,  
Guan Mengyun<sup>3</sup>, Hao Huifeng<sup>6</sup>, Zheng Lei<sup>6</sup>, Ji Xiaolu<sup>1,3</sup>, Li Fei<sup>1,3</sup>, Kwong Lau<sup>4</sup>,  
Vit Vorobel<sup>5</sup>

(1. State Key Laboratory of Particle Detection and Electronics, Institute of High Energy Physics,  
CAS, Beijing 100049;

10 2. School of Nuclear Science and Technology, Xi'an Jiaotong University, Xi'an 710049;

3. Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049;

4. Department of Physics, University of Houston, Houston, TX 77204-5005, USA;

5. Faculty of Mathematics and Physics, Charles University, Prague 12116, Czech Republic;

6. Department of Modern Physics, University of Science and Technology of China, HeFei 230026;

15 7. School of Physics, University of Chinese Academy of Sciences, Beijing 100049)

**Abstract:** During the commissioning of RPC detector systems at the Daya Bay Reactor Neutrino  
Experiment, calibration algorithms were developed and tuned, in order to evaluate and optimize the  
performance of the RPC detectors. Based on a description of the hardware structure of the RPC  
detector systems, this paper introduces the algorithms used for detector calibration, including trigger  
20 rate, efficiency, noise rate, purity and muon flux.

**Keywords:** RPCs; muon veto detectors; calibration; Daya Bay

## 0 Introduction

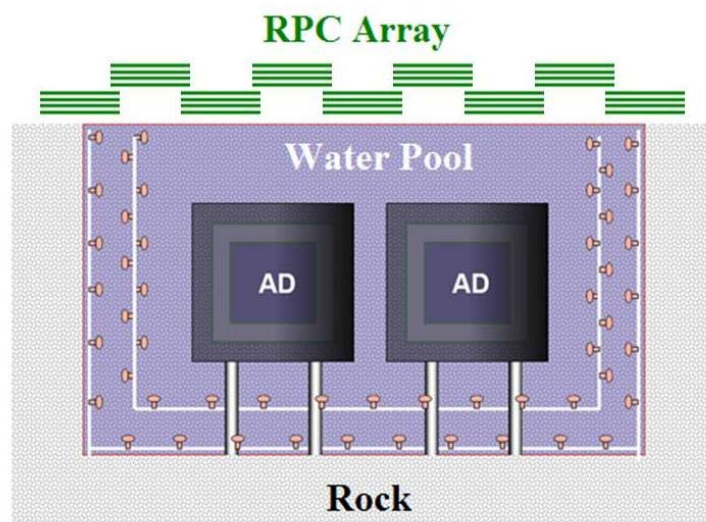
The Daya Bay Reactor Neutrino Experiment [1] aims at the precise measurement of the  
25 neutrino mixing angle  $\theta_{13}$  by comparing observed Inverse Beta Decay (IBD) event rates at both  
near and far baselines from six nuclear reactors. At Daya Bay, there are three Experiment Halls  
(EHs): two halls (EH1 and EH2) nearer to the reactors and one hall (EH3) farther from the  
reactors. The most recent result from the Daya Bay experiment is  $\sin^2 2\theta_{13} = 0.089 \pm 0.010$  (stat.)  $\pm$   
0.005 (syst.) [2,3]. The majority of the systematic uncertainty is due to backgrounds induced by  
30 cosmic-ray muons. To minimize these uncertainties, the Antineutrino Detectors (ADs) are  
deployed underground with redundant muon veto systems. A muon veto system consists of a  
water Cherenkov pool and an RPC detector array. As shown in Fig. 1, the ADs [4] are immersed  
in the water pool, which tracks muons and shields from ambient radioactivity. The RPCs are  
located above the water pool and independently detect muons.

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**Foundations:** 1) Specialized Research Fund for the Doctoral Program of Higher Education (No.20120201120061);  
2) China National Science Foundation (No.2006CB808102, No.Y2118M005C); 3) Scientific Research Support Plan  
for New Teachers at Xi'an Jiaotong University (No.0103-08142036); 4) Czech Science Foundation  
(No.MSM0021620859, No.ME08076, No.202/08/0760)

**Brief author introduction:** Ning Zhe, (1985-), Male, Ph.D Student, High Energy Physics.

**Correspondance author:** Zhang Qingmin, (1981-), Male, Associate Professor, Particle Detector R&D and Particle  
Physics Experiment. E-mail: zhangqingmin@mail.xjtu.edu.cn



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Fig. 1 Layout of sub-detectors at one site

The RPC has been widely applied in high energy physics experiments such as BaBar [5], Belle [6], ALICE [7], ATLAS [8], CMS [9,10] since its invention in the 1980s [11]. It continues to be studied as a candidate active medium for a digital hadron calorimeter [12, 13, 14, 15, 16]. Bakelite RPCs, developed by Institute of High Energy Physics (IHEP), Chinese Academy of Sciences (CAS), have been successfully applied to BESIII as a muon identifier [17, 18, 19, 20, 21], and were further developed for neutron detection [22] and a digital hadron calorimeter [23] later on. Based on the experience from BESIII and studies implemented to meet the specific requirements of Daya Bay, RPC technology was adopted to construct an underground cosmic-ray detector [24, 25, 26, 27, 28, 29].

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## 1 Components of the RPC detector system

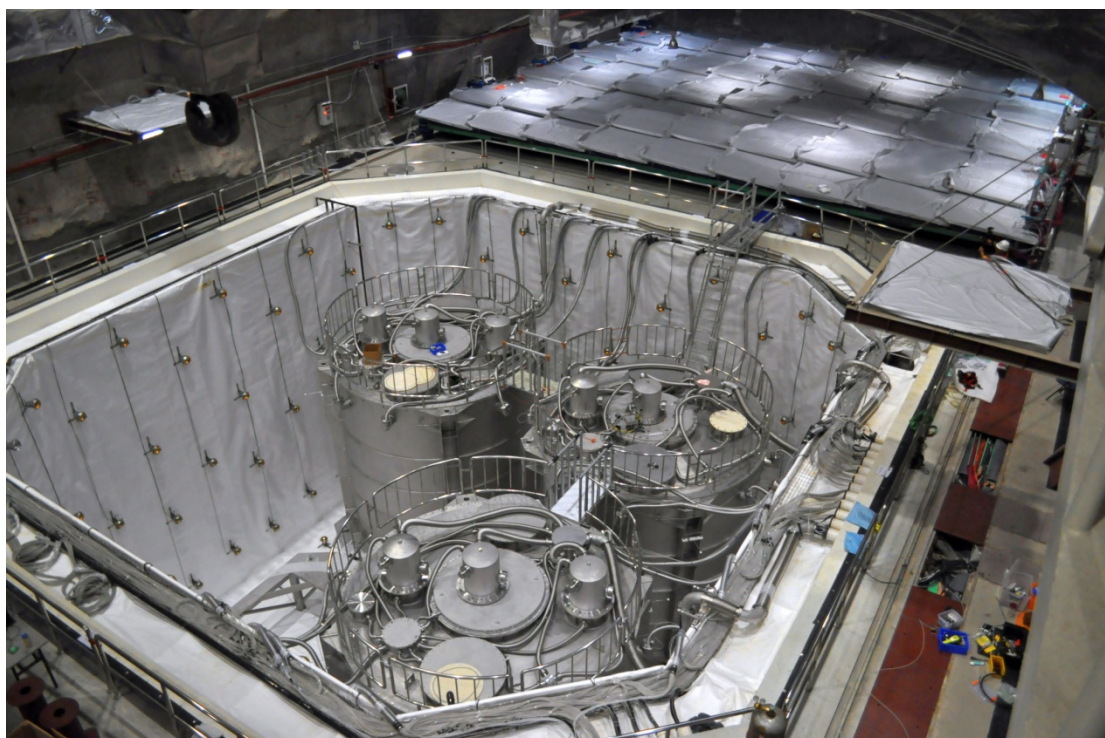
An RPC detector system is composed of RPC modules, a gas system, a high voltage (HV) system and an electronic readout system. In addition, a Detector Control System (DCS) is used to monitor and control the gas and HV systems as well as monitor environmental temperature, pressure and humidity.

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### 1.1 RPC modules

The RPC arrays in both EH1 and EH2 consist of  $6 \times 9$  modules ( $9 \times 9$  modules in EH3). The RPC modules are deployed on a movable support structure as seen in Fig. 2. During commissioning, an RPC array stayed in an ‘RPC hall’ to the side of the pool, while it was moved into the designed position along the RPC support railway for normal data taking. At each site, two supplementary “telescope” RPC modules are installed at two opposing banks of the water pool, approximately 2 m above the top of the RPC array (see Fig. 2).

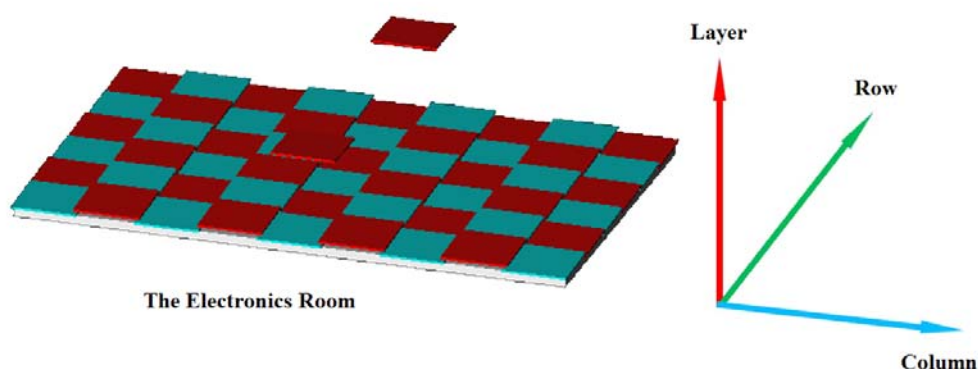
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60 Fig. 2 EH3: RPC array in the RPC hall. It moves to/away from the top of the water pool by motor and railway.

Fig. 3 shows the relative positions of RPC modules on a support structure. The 10 cm overlap on all sides among adjacent modules aims to minimize dead regions [28]. Module dimensions are 2.17 m × 2.20 m × 0.08 m. The inner structure of modules is shown in Fig. 4. Each module consists of 4 layers and each layer contains one ‘small’ RPC (1.00 m × 2.10 m) and one ‘big’ RPC (1.10 m × 2.10 m), as shown in the top right diagram of Fig. 4. In addition, the placement of the two RPCs varies among layers to reduce overlapping dead regions due to RPC edges (0.024 m × 2.10 m). The RPCs themselves are bakelite RPCs with a single 2.0 mm-thick gas gap, and the total area of RPC is 3200 m<sup>2</sup>.

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Fig. 3 Layout of RPC modules

RPC signals are read out from copper-clad sheets of FR-4. Each sheet is divided into four readout strips, 2.1 m × 0.26 m in size and with a zigzag design as shown in the bottom right diagram of Fig. 4. The performance of this type of readout strip is equivalent to one with dimensions of 8.4 m × 6.25 cm. This zigzag design changes the impedance to give a higher and narrower pulse, which would otherwise require more readout channels [26]. One end of each strip is connected to the input of a Front-End Circuit (FEC), while both ends are connected to a clean

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(DAQ) system. The resulting data are buffered in the ROM before being transmitted to the DAQ system by VME bus. The data packages are read out by the means of polling and sorting online according to time stamps [31]. The locally generated 3/4 triggers read out a single RPC module only. Additionally, in order to measure RPC noise rate, a periodic forced trigger reads out all hit information from all FECs at 10 Hz during normal data taking.

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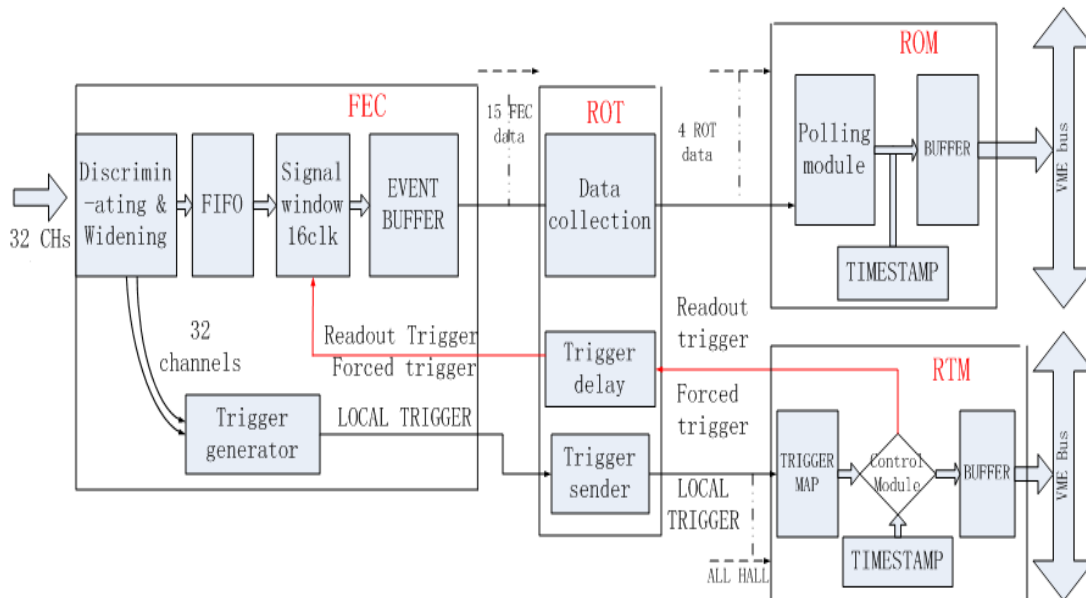


Fig. 5 The architecture of the RPC electronics system

## 120 2 Calibration algorithms

The calibration algorithms were developed and tuned in order to evaluate and optimize the performance of the RPC detectors. Based on the previous description of the hardware structure of the RPC detector systems, this section introduces the algorithms for detector calibration including efficiency, noise rate, purity and muon flux. The algorithms are tuned by using experimental data and theoretical models, and implemented within RPC software. The RPC software includes both online and offline components. The former is used to monitor detector performance during data taking and the latter is used for detector calibration and physics analysis. Here, only the calibration algorithms of the offline software are discussed.

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### 2.1 Offline software

RPC offline software includes simulation [25], detector calibration and event reconstruction [29], and runs in the Daya Bay offline software framework, called NuWa, which is developed based on Gaudi [32]. Muon simulation data is generated using Geant4 according to the surveyed mountain geometry. Experimental data, including event time, trigger type (3/4 or 2/4 trigger type, the latter being from the original design and unused) and lists of hits with coordinates, are used to reconstruct physics events. Physics events are analyzed based on the LAF (Lightweight Analysis Framework) [33] and used to calibrate detector performance and reconstruct muon information (incident positions or/and tracks). Simulation results and calibration algorithms are validated and tuned by comparison with experimental data.

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### 2.2 Detector calibration

The offline calibration of RPC performance includes determination of the efficiency and noise rate of each layer in an RPC module. The calibration algorithms were developed to account

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for the structure of an RPC module, the layout of RPC modules, the readout mechanism and the anchoring position of an RPC array, and will be described in the following sections.

### 2.2.1 Trigger rate

145 As mentioned above, RPC data is sorted online by the DAQ system and then packed following these criteria: RTM triggers within a time window of three clock cycles (75 ns) are treated as belonging to the same event, and a matching is performed between an RTM trigger and FEC data if their time difference is within one clock cycle. Under these criteria of online sorting, the 3/4 trigger rate of a module is calculated precisely as follows:

$$150 R_{3/4} = \frac{N_{3/4}}{A \times \Delta T},$$

where  $N_{3/4}$  is the number of events which have 3 layers or all 4 layers with hits,  $A$  is the effective area of a layer ( $2.08 \text{ m} \times 2.06 \text{ m} = 4.28 \text{ m}^2$ ), and  $\Delta T$  is the time length of data-taking. Similarly, the 4/4 trigger rate of a module is also calculated precisely as follows:

$$R_{4/4} = \frac{N_{4/4}}{A \times \Delta T},$$

155 where  $N_{4/4}$  is the number of events which have all 4 layers with hits.

The 3/4 trigger rates in EH1, EH2, and EH3 are 200, 130, and 40 Hz, respectively. Fig. 6 shows the dependence of the 3/4 trigger readout rate on trigger latency in EH1. According to the setting of the electronics, the width of the plateau should be the width of signal window ( $T_w$  is 16 clock cycles), which is consistent with the observation in Fig. 6. It is clearly seen that data loss occurs when the latency is out of the range (45, 60) clock cycles. Accordingly, a latency value of 54 clock cycles was chosen, which is almost in the middle of the usable range.

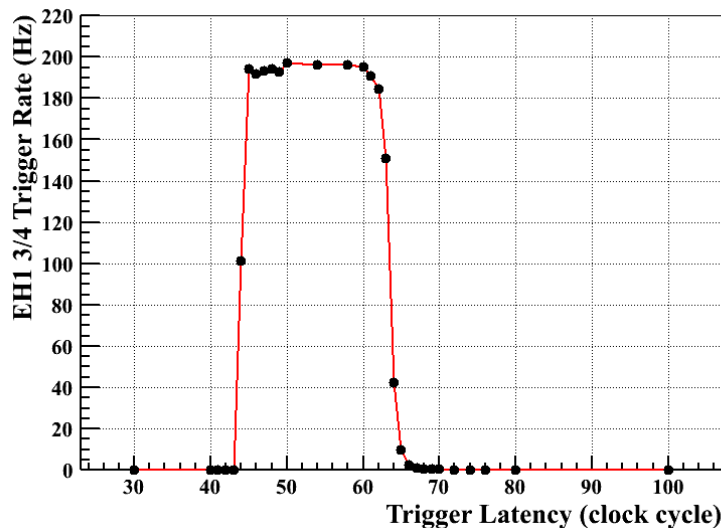


Fig. 6 The trigger rate versus trigger latency in EH1

### 165 2.2.2 Efficiency

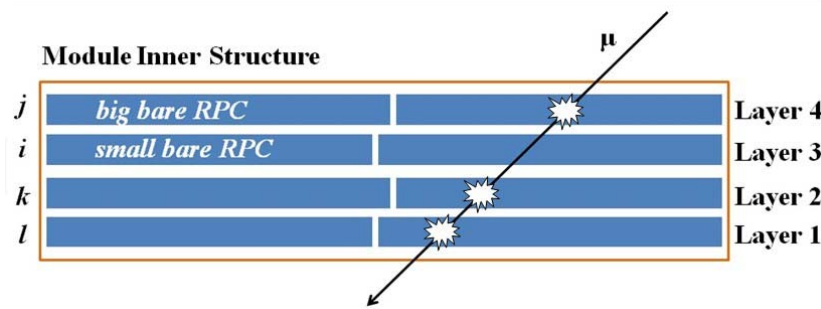
#### Layer efficiency

Since the RPC detector is used as an anti-coincidence detector for muons at Daya Bay, it is critical to determine the muon detection efficiency precisely. The RPC layer efficiency is calculated as follows:

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$$\mathcal{E}_i = \frac{N_{ijkl,R1,R2}}{N_{jkl,R1,R2}},$$

where  $i, j, k, l \in \{1, 2, 3, 4\}$  and none of  $i, j, k$  and  $l$  are equal,  $\mathcal{E}_i$  is the efficiency of layer  $i$  in a given module,  $N_{ijkl,R1,R2}$  is the number of 4-fold coincidences involving all 4 layers and  $N_{jkl,R1,R2}$  is the number of 3-fold coincidences of layers  $j, k$  and  $l$ . The meanings of R1 and R2 are explained below. Fig. 7 (not to scale) illustrates one example of a  $N_{jkl,R1,R2}$  event.



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Fig. 7 Example of a 3-fold event used in the calculation of the efficiency of layer  $i$

In order to select muons with high purity, two requirements are introduced. The first requirement (R1), which aims to suppress cross-talk, is that no more than two strips are fired in each layer of the triggered modules (the two fired strips should be adjacent). The second requirement (R2) is that the Water Cherenkov Pools tag a muon within 600 ns of an RPC 3/4 trigger. R2 reduces the effect of underestimating the efficiency due to accidentals and all other purely RPC-related backgrounds, which are more significant in underground measurements than at sea level. Before R2 is applied, the calculated average efficiencies of three randomly selected layers in three randomly selected modules from EH1, EH2 and EH3 are  $(96.42 \pm 0.03)\%$ ,  $(95.9 \pm 0.03)\%$  and  $(80.77 \pm 0.25)\%$ , respectively. However, when R2 is applied, the corresponding efficiencies are  $(97.04 \pm 0.03)\%$ ,  $(96.88 \pm 0.03)\%$  and  $(97.06 \pm 0.13)\%$ , which are consistent with the test results at sea level in IHEP, Beijing [28]. The larger difference of 17% in EH3 is due to the lower muon flux (muon flux is discussed in section 2.2.5). Fig. 8 shows the effect of R2 in EH3 for each layer of RPCs.

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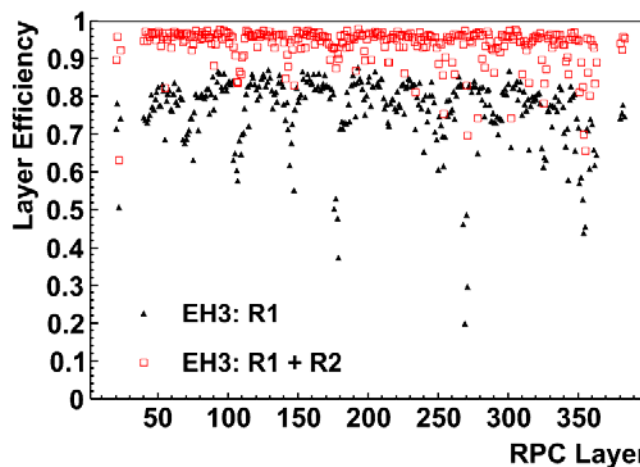


Fig. 8 Comparison of calculated layer efficiencies with and without R2

Given that R2 makes use of the water pool, there is a concern that a muon angle selection bias may cause a bias in calculated efficiency. Due to the limited spatial resolution and selection

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bias of muon tracks supplied by all detectors, the angle selection bias of R2 must be investigated theoretically. Daya Bay RPCs work in streamer mode; therefore, theoretically only primary ionizations generated within a distance  $d_0$  from the inner surface of the cathode plate can produce a detectable streamer signal as shown in Fig. 9. Accordingly, the dependence of efficiency ( $\varepsilon$ ) on muon incident angle ( $\theta$ ) can be written as

$$\varepsilon(\theta) = 1 - P(X = 0|\theta) = 1 - e^{-\frac{nd_0}{\cos\theta}}$$

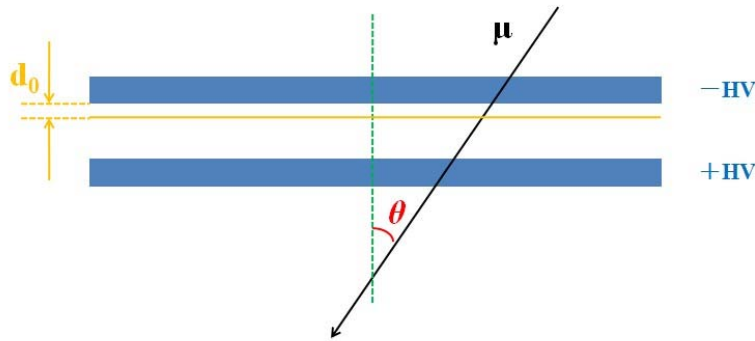


Fig. 9 Estimation of efficiency bias due to angle selection of muons

where  $P(X=0|\theta)$  denotes the Poisson probability that there are no primary ionizations within the distance  $d_0$ , and  $n$  is the average number of ionizations per unit track length.

If the efficiency for vertical muons ( $\theta = 0$ ) is known, the formula takes the form

$$\varepsilon(\theta) = 1 - e^{-\frac{\ln(1-\varepsilon(0))}{\cos\theta}}$$

Assuming  $\varepsilon(0) = 95\%$ , we can get the dependence of efficiency on incident angle  $\theta$ . For each experimental hall, the angular distribution of muons is known from simulation. The bias is estimated by simulation with the detector's survey geometry and the angular distribution. As Fig. 10 shows for EH3, the simulation predicts a bias that ranges from about - 0.55% to + 0.55% with an average of - 0.07%. Ultimately, any discrepancy in the estimated bias will be small and worth the improvement in calculated efficiency (2% for EH1 and EH2 and 17% for EH3).

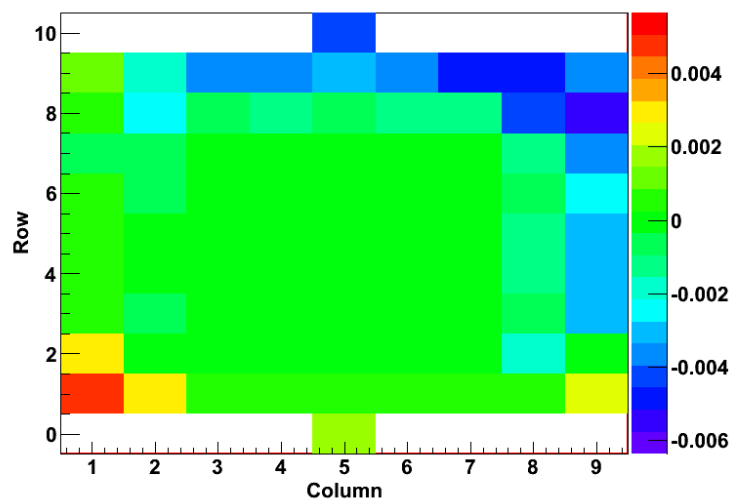


Fig. 10 Estimation of efficiency bias due to the angle selection bias of R2 when  $\varepsilon(0) = 95\%$  in EH3

The aforementioned algorithm for calibrating layer efficiency is not directly validated by an independent measurement. We have validated it implicitly by comparing a computation of overall RPC array efficiency using the calibrated layer efficiencies with a measurement of overall RPC array efficiency. The overall efficiency of the RPC module array cannot be determined analytically due to the overlap among RPC layers and RPC modules, gaps between RPC modules and the spatial relationships between the RPC detectors, water Cherenkov pools and Antineutrino detectors. Therefore, it is estimated by simulating the real detector geometry with the calibrated layer efficiencies. This result is compared with a measurement made by selecting muons that pass through the inner half (closer to the RPC array) of either of the two telescope RPC modules and a water pool, which ensures that these muons pass through the RPC array. The computed and measured efficiencies in EH3 are  $95.3\% \pm 0.6\%$  and  $95.8\% \pm 0.7\%$ , respectively, which are in agreement.

### 230 **Module efficiency**

Given that a trigger must have three or more layers with hits, the 3/4 efficiency of a module,  $\varepsilon_{3/4}$ , is calculated as follows:

$$\varepsilon_{3/4} = \prod_{i=1}^4 \varepsilon_i + \sum_{i=1}^4 \left( (1 - \varepsilon_i) \prod_{\substack{j=1 \\ j \neq i}}^4 \varepsilon_j \right).$$

The 4/4 efficiency,  $\varepsilon_{4/4}$ , is simply the first term in the expression for  $\varepsilon_{3/4}$ , i.e.,

$$235 \quad \varepsilon_{4/4} = \prod_{i=1}^4 \varepsilon_i.$$

Given that the layer efficiencies of a randomly selected module are  $(95.36 \pm 0.15)\%$ ,  $(97.56 \pm 0.11)\%$ ,  $(95.76 \pm 0.14)\%$  and  $(97.02 \pm 0.12)\%$  for layers 1, 2, 3 and 4,  $\varepsilon_{3/4}$  is  $(99.28 \pm 0.03)\%$  and  $\varepsilon_{4/4}$  is  $(86.43 \pm 0.24)\%$ .

### 2.2.3 Noise rate and accidentals

240 The RPC noise level is indicated by noise rate and dark current. The layer noise rate, which can be used for detector monitoring and the estimation of accidentals and purity (see section 2.2.4), is defined as

$$f_i = \frac{N_i}{A \times n \times T},$$

245 where  $f_i$  is the noise rate of layer  $i$  in one module,  $N_i$  is the number of noise hits in layer  $i$  during forced triggers (if a layer has much cross-talk, it is significant to apply R1 in counting  $N_i$ ),  $n$  is the number of forced triggers, and  $T$  is the sampling time of each forced trigger ( $T = \text{width of signal window } (T_w) + \text{typical width of digitized RPC signal } (T_s) = 400 \text{ ns} + 150 \text{ ns} = 550 \text{ ns}$ ).

250 Accidental events are one type of event that reduces the purity of RPC triggers. The rate of accidental coincidence of three out of four layers in a module can be estimated using the following formula:

$$R_{3/4, Acc} = \frac{1}{T_s} \left( 4 \prod_{i=1}^4 AT_s f_i + 3 \sum_{i=1}^4 \left( (1 - AT_s f_i) \prod_{\substack{j=1 \\ j \neq i}}^4 AT_s f_j \right) \right),$$

where the typical width of a digitized RPC signal,  $T_s$ , is taken to be 150 ns.

The rate of accidental coincidence of four out of four layers is estimated as follows:

$$R_{4/4,Acc} = 4A^4T_s^3 \prod_{i=1}^4 f_i.$$

255 Given that the layer noise rates of the same module as in section 0 are  $575.8 \pm 13.8$ ,  $524.9 \pm 13.2$ ,  $559.2 \pm 13.6$  and  $587.1 \pm 14.0$  Hz/m<sup>2</sup> for layers 1, 2, 3 and 4, the estimated accidental rates of 3 out of 4 layers and 4 out of 4 layers are  $0.0150 \pm 0.0005$  and  $(4.5 \pm 0.2) \times 10^{-7}$  Hz/module, respectively. As mentioned in section 0, R2 minimizes the effects of accidentals and all other RPC-related backgrounds when calculating layer efficiency.

260 **2.2.4 Purity**

The purity of RPC module triggers is the fraction of real muon events in the triggers. It is calculated as follows:

$$Purity = \frac{N_{3/4,R2}}{N_{3/4}} \times \frac{N_{4/4}}{N_{4/4,R2}},$$

265 where  $N_{3/4,R2}$  and  $N_{4/4,R2}$  are the number of 3/4 and 4/4 events under R2, respectively, and the definitions of  $N_{3/4}$  and  $N_{4/4}$  can be seen in Section 2.2.1. This calculation is based on the assumptions that: 1)  $N_{4/4}$  counts only muons (which is reasonable because the 4 out of 4 accidental rate is  $(4.5 \pm 0.2) \times 10^{-7}$  Hz/module); 2) Both  $N_{3/4,R2}$  and  $N_{4/4,R2}$  count only muons (that are also sampled by the water pool); 3) The ratio of the number of muons in 3/4 events to  $N_{3/4,R2}$  is equal to the ratio of  $N_{4/4}$  to  $N_{4/4,R2}$ . Backgrounds enter the calculation of purity through  $N_{3/4}$  in the denominator, because 3 layer coincidences are relatively more sensitive to backgrounds.  
270 Consequently, the purity of triggers of a randomly selected module in EH1 is about 97.4%.

**2.2.5 Muon flux**

To minimize contamination from backgrounds in the calculation of muon flux, only the events in which all 4 layers of a module have hits are chosen. Corrections for efficiency, dead time  
275 and 4 out of 4 accidental coincidences from noise are taken into account when calculating the muon flux for each module.

$$F_{\mu} = \frac{\frac{R_{4/4}}{1 - R_{3/4} \times A \times T_w} - R_{4/4,Acc}}{\mathcal{E}_{4/4}},$$

where the width of the readout trigger,  $T_w$ , is 400 ns.

280 In fact, 3/4 trigger events produce negligible dead time in one second ( $= R_{3/4} \times A \times T_w = \sim 1$  Hz/ m<sup>2</sup>  $\times 4.28$  m<sup>2</sup>  $\times 400 \times 10^{-9}$  s =  $\sim 2 \times 10^{-6}$ ), and the contribution from 4 out of 4 accidentals is even smaller. However, these two factors may be significant for modules with RPCs that have higher noise rates or hot spots. The muon flux in each near (far) hall is obtained by averaging over all 56 (83) RPC modules.

285 Table 1 comparison of muon fluxes by simulation and measurement using data in all 3 EHs

	EH1	EH2	EH3
Simulation (Hz/m <sup>2</sup> )	0.88 ± 0.09	0.69 ± 0.07	0.039 ± 0.004
Measured by RPC (Hz/m <sup>2</sup> )	0.90 ± 0.06	0.69 ± 0.08	0.046 ± 0.004

The muon fluxes in the experimental halls predicted by simulation are compared with

measurements in Table 1. Good agreement is seen for EH1 and EH2, and over-estimation in  
measurement is seen for EH3 due to the difficulty of rejecting background events, considering its  
larger background-to-signal ratio.

### 3 Summary

The offline calibration algorithms of the RPC detector systems of the Daya Bay Reactor  
Neutrino Experiment have been developed, including trigger rate, efficiency, noise rate, purity and  
muon flux. The calculated results are cross-checked by using Monte Carlo simulation and  
theoretical estimation.

### Acknowledgements

Institute of High Energy Physics, Chinese Academy of Sciences is supported by the China  
National Science Foundation and the Ministry of Science and Technology of the People's  
Republic of China (2006CB808102). This work is also implemented under Project Y2118M005C  
supported by the National Natural Science Foundation of China, Project 20120201120061  
supported by Specialized Research Fund for the Doctoral Program of Higher Education (New  
Teachers) and the Scientific Research Support Plan for New Teachers (0103-08142036) at Xi'an  
Jiaotong University. The University of Houston is supported by the United States Department of  
Energy. Charles University is supported by projects MSM0021620859 and ME08076 of the  
Ministry of Education, Youth and Sports of the Czech Republic, and 202/08/0760 of the Czech  
Science Foundation.

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## 大亚湾中微子实验 RPC 探测器刻度算法

宁哲<sup>1,3,7</sup>, 张清民<sup>2</sup>, 徐吉磊<sup>3</sup>, Logan Lebanowski<sup>4</sup>, 张家文<sup>1,3</sup>, 杨长根<sup>3</sup>, 何苗<sup>3</sup>,  
赵洁<sup>1,3,7</sup>, 邹佳恒<sup>3</sup>, Viktor Pěč<sup>5</sup>, 林世凯<sup>4</sup>, 关梦云<sup>3</sup>, 郝慧峰<sup>6</sup>, 郑磊<sup>6</sup>, 季筱璐<sup>1,3</sup>,  
李飞<sup>1,3</sup>, Kwong Lau<sup>4</sup>, Vit Vorobel<sup>5</sup>

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(1. 中国科学院高能物理研究所核探测与核电子学国家重点实验室, 北京 100049;

2. 西安交通大学核科学与技术系, 西安 710049;

3. 中国科学院高能物理研究所, 北京 100049;

4. 美国休斯顿大学物理系;

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5. 捷克查尔斯大学数学物理系;

6. 中国科学技术大学近代物理系, 合肥 230026;

7. 中国科学院大学物理学院, 北京 100049)

**摘要:** 在大亚湾中微子实验 RPC 探测器试运行期间, 发展了一套刻度算法用于评估和优化 RPC 探测器的性能。基于 RPC 探测器的组成描述, 此论文介绍了用于 RPC 探测器刻度的算法, 可以用来刻度出触发率、效率、噪声水平、纯度和宇宙线流强。

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**关键词:** 粒子物理与原子核物理; 阻性板室探测器; 宇宙线反符合探测器; 刻度; 大亚湾中微子实验

**中图分类号:** O572.21+2;O572.21+3;TL811