Maximum likelihood reconstruction for the Daya Bay Experiment

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Abstract. The Daya Bay reactor neutrino experiment is designed to precisely determine the neutrino mixing angle θ_{13} . In this paper, we present an algorithm using the maximum likelihood (ML) method to reconstruct the vertex and energy of events in the anti-neutrino detector, based on a simplified optical model describing light propagation. The key parameters of the optical model are calibrated with ^{60}Co source, by comparing the predicted charges of the PMTs with the observed charges. With the optimized parameters, the ML reconstruction provides a uniform energy reconstruction, and a vertex reconstruction with small bias along radial direction.

1. Introduction to the optical model

The optical model is based on the structure of the antineutrino detector (AD). The AD of the Daya Bay experiment has three nested cylindrical volumes separated by concentric acrylic vessels [1]. The innermost volume holds 20 tons of Gd-liquid sintilltor[2] as the antineutrino target. The middle volume is filled with 21 tons of liquild scitillator (LS) which is the gamma catcher. There are 192 8-inch PMTs mounted on eight ladders installed along the circumference and within the mineral oil volume, which is the outer volume of AD. Two reflective panels with a film of Enhanced Specular Reflected (ESR) are placed at the top and bottom of the outer volume to increase the photon-statistics and improve the uniformity of the energy response. Three automated calibration units (ACU-A,ACU-B, ACU-C) are mounted at the top of AD. Each ACU contains a LED as well as two scaled capsules with the radioactive source that can be lowered individually into the Gd-LS along either the centreline or inner edge, or in the LS.

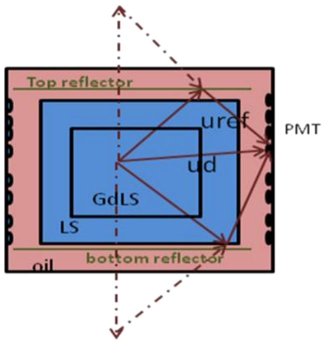

Fig. 1: An illustration of the optical model of the ML reconstruction in AD.

The optical model [3] based on the structure of the AD used in the ML reconstruction is illustrated in figure.1. The predicted charge on each photomultiplier (PMT) is the sum of the photo-electrons (PE) produced by the direct light (μ_d) and the photo-electrons produced by the reflected light (μ_r). The definition of μ_d and μ_r are in equation 1, where Φ is a normalization parameter; $f(\cos\theta_d)$ is the PMT angular response curve; θ_d is the angle between the PMT normal direction and the vector from PMT position pointing to source position; R_d is the distance between PMT and radioactive source; λ_a is the average attenuation length of the liquid scintillator ; ε^{QE} is the PMT relative efficiency; μ_r is the sum of the charges produced by mirror sources, and the subscripts j, k denotes respectively that light is the j-th order reflected by bottom reflector and the k-th order reflected by the top reflector; ε_t ε_b are the reflectivity for the top and bottom reflector, respectively; R_{jk} is the distance from the mirror source to the PMT; θ_{jk} is the angle between the PMT normal direction and the vector from the PMT position pointing to the mirror source position. A sum of μ_d and μ_r gives the total expected charge.

$$\begin{aligned}\mu_d &= \Phi\cdot\frac{f(\cos\theta_d)}{R_d^2}\cdot\exp\left(-{R_d}/{\lambda_a}\right)\cdot\varepsilon^{QE}\\ \mu_r &= \Phi\cdot\sum_{j,k}\left(\varepsilon_b^j\right)\cdot\left(\varepsilon_t^k\right)\cdot\frac{f(\cos\theta_{j,k})}{R_{j,k}^2}\cdot\exp\left(-{R_{j,k}}/{\lambda_a}\right)\cdot\varepsilon^{QE}\end{aligned} \tag{1}$$

In this optical model, the key parameters that need to be determined from calibration data are as follows:

- The average attenuation length λ_a.
- PMT angular response curve $f(\cos\theta_d)$.
- The top and bottom reflectivity ε_t , ε_b .
- The PMT relative efficiency ε^{QE} .

2. Calibration of key parameters

The calibration of the key parameters is performed by requiring the expected charge distribution on the PMTs to agree with that observed in data. We use the 2.5MeV γ emitted by ^{60}Co for calibration, except for PMT relative efficiency. The PMT relative efficiency is determined by counting the relative occupancy, when the calibration source is at ACUA. A low energy calibration source ^{68}Ge is chosen for the calibrating. With this calibration source, at most one PE is obtained by the PMT.

A χ^2 function is built to calibrate the attenuation length λ_a 、 the reflectivity ε_t ε_b and the PMT angular response curve $f(\cos\theta_d)$ simultaneously, as shown in equation (2).

$$\chi^2 = \sum_j^{Num}\left(\sum_i^{192}\frac{\left(\overline{n_{ij}}-\mu_{ij}\right)^2}{\overline{n_{ij}}}\right) \tag{2}$$

In equation (2), $\overline{n_{ij}}$ is the average observed charge, μ_{ij} is the expected charge and is a function about the parameters to be calibrated $\mu_{ij}\left(\lambda_a,\varepsilon_t,\varepsilon_b,f(\cos\theta)\right)$, 192 is the number of PMTs, *Num* is the total number of calibration sources that locate at different position in the AD, $f(\cos\theta_d)$ is parameterized as $f(\cos\theta)=p_0+p_1\cos\theta+p_2\cos^2\theta$. Optimal parameters are determined by minimizing χ^2 .

Figure 2 shows the ratio of observed charge to expected charge as a function of the incident angle θ and the distance from the PMT to the radioactive source. θ is the angle between the PMT normal direction and the vector from PMT position pointing to source position. The performance of the optical model with the optimized parameters is much better than that with the initial parameters as figure 2 indicates. The initial parameters were measured independently before the assembling of AD.

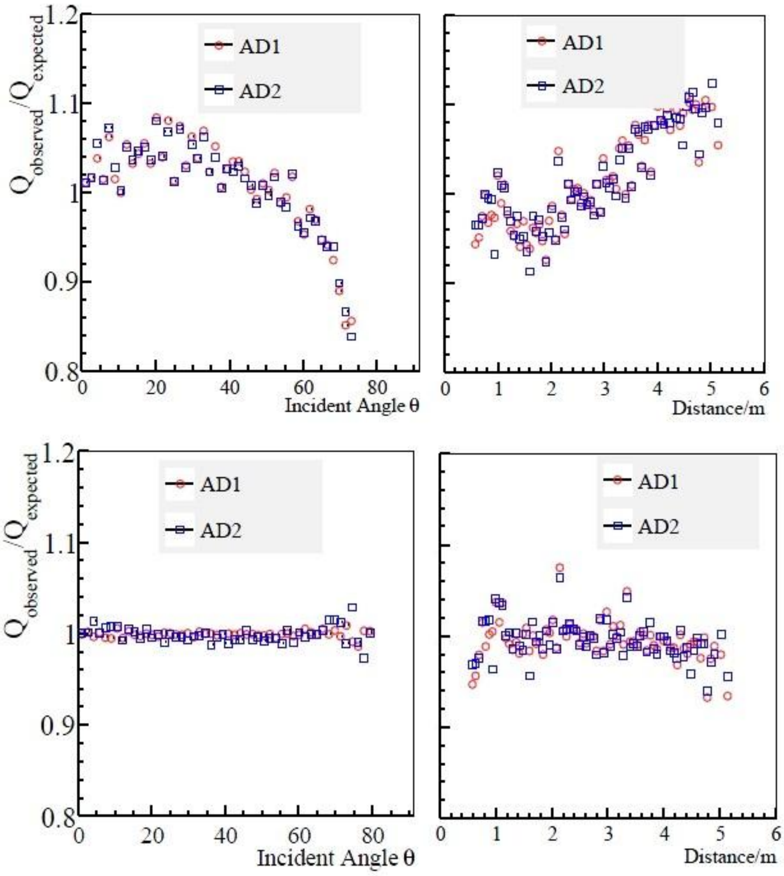

Fig 2: Top: The ratio of observed charge to the expected charge as a function of θ and distance for the old parameters; Bottom: The ratio of observed charge to expected charge as a function of θ and distance for the optimized parameters.

3. Performance of the ML reconstruction

Energy and vertex of events are reconstructed by minimizing the joint likelihood. The joint likelihood is a function of the observing charge pattern and the predicted charge pattern [3]. The predicted charge pattern is calculated with energy E and vertex $\vec{x}$. In this paper, the performance of the ML reconstruction is studied by using the Am-C neutron source; the source was deployed in the detector along various vertical axes and radial directions.

3.1. Energy reconstruction

The accuracy of the energy reconstruction is investigated by comparing the peaks of the reconstructed energy and the true energy of neutron capture events. The energy peaks are determined by fitting the energy spectrum with Double Crystal Ball function as shown in figure 3.

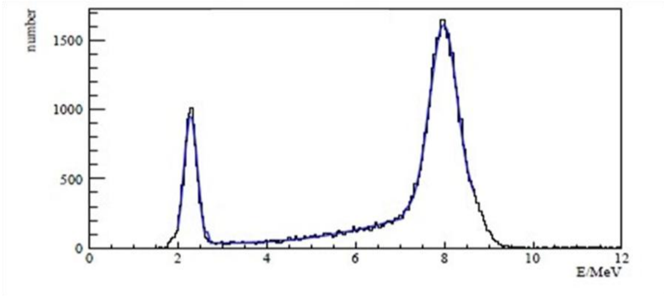

Fig.3.: Energy distribution of the Am-C neutron events.

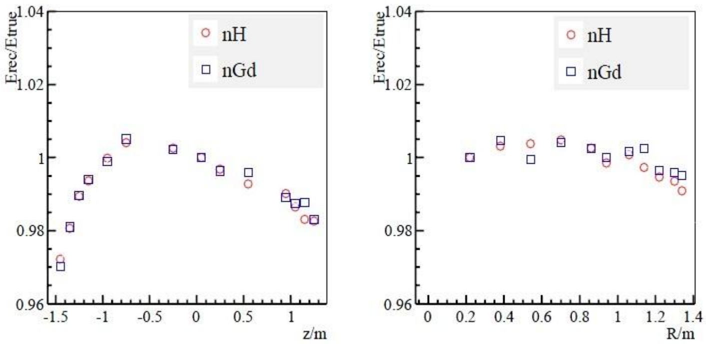

Fig.4.:The vertical (left) and radial (right) energy non-uniformity after ML reconstruction.

From figure 4, the non-uniformity along vertical direction of the energy reconstruction is within 4% for the neutron capture on Hydrogen (nH) events and the neutron capture on Gadolinium (nGd) events. The reconstructed energy is very uniform along the radial direction as shown in figure 4 for neutron source.

3.2. Vertex reconstruction

The bias of the vertex reconstruction is defined as the mean value of differences between the reconstructed vertex and the true vertex in both vertical and radial directions.

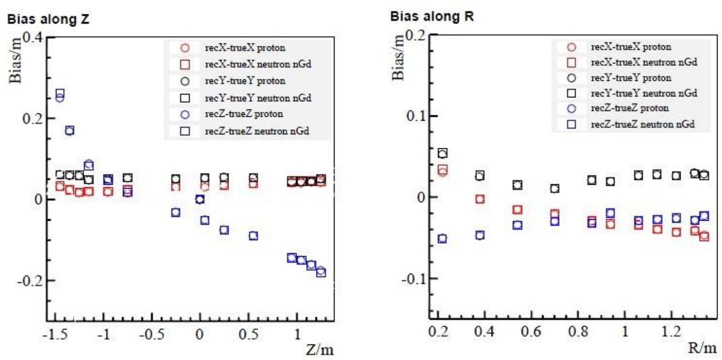

Fig.5.: Bias of the vertex reconstruction along vertical and radial direction.

The bias increases when events are close to the top and bottom reflectors. The maximum Z bias is about 20cm and the bias in X,Y is within 10cm along vertical direction. The bias is within 5cm along radial direction, as shown in figure5.

4. Conclusions

Using the calibration data of ^{60}Co and ^{68}Ge , we optimized the key parameters of the optical model of the ML reconstruction for the Daya Bay experiment. The optical model is improved, and the predicted charge is more consistent to the observed charge. With the optimized parameters, the ML provide a uniform energy reconstruction and a vertex reconstruction without bias along radial direction. The non-uniformity of the energy reconstruction and the bias of the vertex reconstruction along vertical direction are within 4% and 25cm respectively.

References

[1] An F P *et al*. (Daya Bay collabration), Nucl.Instr.Meth.A, (2012),**685**: 78-97.
[2] Ding Y Y *et al*., Nucl.Instr.Meth.A, (2008), **584**: 238.
[3] Wen L J *et al*., Nucl.Instr.Meth.A, (2011), **629**: 296-302.