BESIII barrel time-of-flight (TOF) calibration using cosmic ray data*

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Abstract The principle of the method for the BESIII TOF calibration using cosmic ray data without magnetic field are reported in this paper. After applying calibration constants, the single-end readout time resolution could reach about 150 ps, and the time resolution for one layer is achieved to be about 110 ps. The paper also described the extraction scheme for the event start time of cosmic events.

Key words time-of-flight detector, offline calibration, time resolution, cosmic ray

PACS 29.40.Mc, 29.85.Fj

1 Introduction

The upgraded Beijing Electron Positron Collider (BEPCII) [1] is a double-ring, multi-bunch collider with a designed luminosity of 1×10^{33} cm$^{-2}\cdot$s^{-1} at 1.89 GeV, an improvement of a factor of 100 times with respect to the BEPC. The Beijing Spectrometer (BESIII) [2, 3] which will operate at BEPCII, is designed for high-precision measurements and new physics searches at τ-charm energy region. It consists of a beryllium beam pipe, a helium-based small-cell drift chamber (MDC), the time-of-flight (TOF) counters for particle identification, a CsI(Tl) crystal calorimeter (EMC), a super-conducting solenoidal magnet with the field of 1 T, and a muon identifier of Resistive Plate Counters (MUC) interleaved with

Received 7 May 2009, Revised 23 June 2009
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the magnet yoke plates.

Particle identification (PID) plays a key role in the study of τ-charm physics. The TOF capability of PID depends on the time resolution of the predicted and measured time difference of particles of different types. The scheme of barrel TOF calibration is studied using cosmic ray data acquired on BESIII without magnetic field in this paper. The TOF offline calibration and reconstruction software are based on the BESIII offline software system (BOSS) [4].

2 Barrel TOF detector and cosmic ray data taking

The time-of-flight sub-detector, made of plastic scintillator bars and read out by fine-mesh phototubes, is placed between the drift chamber and the electromagnetic calorimeter. The Barrel TOF consists of two layers of 88 plastic scintillator elements arranged in a cylinder of the mean radius of about 870 mm. Each scintillator bar has a length of 2380 mm, a thickness of 50 mm and a width of 50 mm; it is read out at each end by a fine-mesh PMT. The target of the time resolution for one layer for muons is about 100–110 ps. The momentum of 2σ K/π separation can go up to 0.8 GeV or 0.9 GeV for single layer and double layers respectively [2, 5].

After the construction of the BESIII, cosmic ray events without magnetic field have been collected and used for calibration and alignment as well as detector tuning. The cosmic ray incident at the top of the terrestrial atmosphere includes muons, stable charged particles and nuclei with lifetimes of order 10^6 years or longer [6]. A large amount of cosmic ray sample with broad momentum range is acquired by the BESIII detector with about 20 Hz trigger rates during the data taking. In the cosmic ray sample, muons are the most numerous charged particles, hadrons and other electromagnetic particles are filtered by the iron yoke, only a few percent ($<1\%$) of the hadron background remains [7].

In general, a single cosmic ray would pass the detector as a straight line without a magnetic field, and it is reconstructed as a pair of tracks in MDC [8], as shown in Fig. 1. The event selection of the cosmic ray for TOF calibration proceeds as follows: Two tracks are required to be well reconstructed in MDC, that is χ^2 of track fitting less than 150 and the number of hit layers greater than 35. In order to get a high-quality reconstructed track with good position resolution, each track must pass the internal region of the detector, which is defined to be within 5 cm of the beam line in the transverse plane and within 35 cm of the interaction point along the beam direction. The deposited energy in EMC should be less than 0.3 GeV for each track. The hit position of each track reconstructed using deposited energy in barrel EMC crystals is required to be consistent with that of the MDC track extrapolated. In order to filter low momentum muons and other particles, the reconstructed track is also required to hit more than 5 layers in the downside region of MUC.

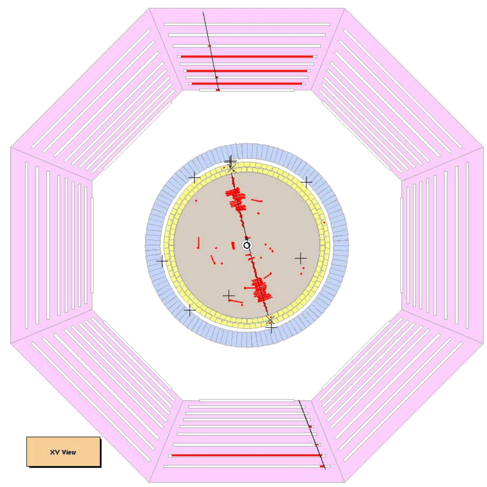

Fig. 1. The illustration of one cosmic ray goes through the BESIII detecter.

3 TOF calibration

The TOF calibration is proceeded by comparing the measured time ($t_{\rm mea}$) against the predicted time ($t_{\rm pre}$).

$$\Delta t = t_{\rm mea} - t_{\rm pre}, \qquad (1)$$

the $t_{\rm pre}$ can be expressed as,

$$t_{\rm pre} = \frac{L}{\beta \cdot c}, \qquad (2)$$

where L is the corresponding path of flight measured by the MDC and extrapolated the track trajectory from the outer radius of the MDC to the scintillator [9], c is the velocity of light in vacuum, the flight velocity of charged particle, $\beta = p/\sqrt{p^2+m^2}$, p is the measured momentum by MDC and m is the mass of the particle. Since cosmic ray data are acquired without magnetic field, no precise momentum measurement is available. The number of fired layers of MUC is required to be greater than 5 to ensure that the flight velocity of the particle is close to the velocity of light with $\beta \approx 0.99$.

The $t_{\rm mea}$ is obtained as,

$$t_{\rm mea} = TDC - t_0 - t_{\rm cor}, \qquad (3)$$

where TDC is the raw measured time recorded by electronics, t_0 is the event start time and $t_{\rm cor}$ is the correction term. The term $t_{\rm cor}$ is a function of pulse height Q and hit position z along the scintillator, the following empirical form [10] is taken from BESⅡ:

$$t_{\rm cor} = P_0 + \frac{P_1 + P_2\cdot z + P_3\cdot z^2}{\sqrt{Q}} + P_4\cdot Q + P_5\cdot Q^2 + P_6\cdot Q^3 + P_7\cdot z + P_8\cdot z^2 + P_9\cdot z^3 + \frac{P_{10}}{R^2+z^2}, \quad (4)$$

where R is the radius of the layer of TOF detector, P_i ($i = 0, 1, \cdots, 10$) are the calibration constants: P_0 is delay time (cabling, etc.); P_1–P_3 is time walk effect; P_4–P_6 is saturation of PMTs; P_7–P_9 is effective velocity of light in the scintillator; P_{10} is different depths of charged track traversing in the scintillator.

A χ^2 minimization method is applied by defining a set of

$$\chi^2[\text{counter, readout unit}] = \sum^{\text{event}} (t_{\rm mea} - t_{\rm pred})^2, \quad (5)$$

in each readout unit and counter by counter independently. The calibration constants, P_0 to P_{10}, are obtained from cosmic ray data by setting the derivative of Eq. (5) with respect to P_i to zero.

4 Event start time determination

4.1 The principle of event start time determination

In the case of beam collision events, BEPCⅡ will be operated in the two-ring and multi-bunch colliding mode, 93 bunches with the bunch spacing of 8 ns will be filled in each storage ring. The time measurement system of TOF adopts the CERN HPTDC (High Performance Time to Digital Converter) chip. The trigger cycle is 24 ns, which equals the duration of 3 bunches. When two bunches collide and generate a good event, the measured TDC got from TOF is the time interval of the start time to the arrival time of the detector's hit signal. This time interval may differ from the time interval between the collision and the arrival time of the hit signal in the detector. The interval of the start time to the real collision time, described as event start time t_0, depending on the event is created at a particular bunch [11]. Since the incident time of the cosmic ray which hits the detector is stochastic, it would not have a relatively accurate event start time as collision events. In this analysis, the event start time of the cosmic ray event is defined as the time when the cosmic ray passes the midpoint of the trajectory in MDC. Then the event start time of the cosmic ray event is expressed as:

$$t_0 = TDC - t_{\rm sig} \mp t_{\rm tof}, \quad (6)$$

where TDC is the measured time of TOF, and $t_{\rm sig}$ is the time interval from the time when the cosmic ray hits TOF scintillator, which is expressed as t_1 or t_2 for "up" or "down" track respectively in Fig. 2, to the arrival time of the hit signal. $t_{\rm tof}$ is the time of flight of charged particle, it can be obtained as $t_{\rm pre}$ in Eq. (2). The positive or negative sign of $t_{\rm tof}$ is for "up" or "down" track respectively. $t_{\rm sig}$ is described by the following equation:

$$t_{\rm sig} = t_{\rm pro} + t_{\rm PMT} + t_{\rm elc}, \quad (7)$$

$t_{\rm pro}$ is the light propagation time in the scintillator, which corresponds to the P_7 term in the empirical time calibration formula Eq. (4),

$$t_{\rm pro,forward/backward} = \frac{l/2 \mp z}{v_{\rm eff}}, \quad (8)$$

where l is the length of scintillator, z is the hit position along z-axis, $l/2 \mp z$ are the displacements for forward and backward PMT respectively. And $v_{\rm eff}$ is the effective velocity of light propagation in scintillator. It is easily found that the light propagation time would be a Gaussian like distribution when summing up $t_{\rm pro}$ for forward and backward PMTs of particular scintillator. $t_{\rm PMT}$ is the transmit time of the photoelectron signal in PMT and $t_{\rm elc}$ is the delay-time of the electronic signal. $t_{\rm PMT}$ and $t_{\rm elc}$ are the contribution of term P_0 of time calibration formula Eq. (4). The assumption is taken that $t_{\rm PMT}$ and $t_{\rm elc}$ are constants. The measured time diagram of cosmic ray for BESIII TOF system is shown in Fig. 2.

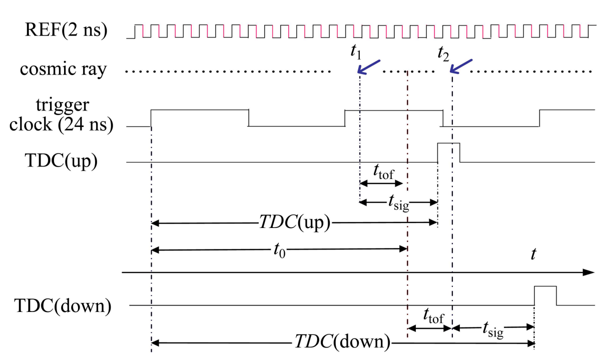

Fig. 2. The illustration of TOF time system.

4.2 Time difference

The TOF counter has an intrinsic readout time difference between each other, which includes the difference of light propagation time in scintillator, transmit time of photoelectron signal in PMT and delay-time of electronics signal. For the same hit signal, the measured times of different TOF counters would not be the same. This discrimination should be corrected before the event start time extraction and time calibration and it is named as the time difference of TOF counter, which is described as follows,

$$t_{\rm diff} = t_{\rm sig,forward} + t_{\rm sig,backward} = t_{\rm pro,scin} + t_{\rm PMT,forward} + t_{\rm elc,forward} + t_{\rm PMT,backward} + t_{\rm elc,backward}, \quad (9)$$

where $t_{\rm pro,scin} = t_{\rm pro,forward} + t_{\rm pro,backward} = l/v_{\rm eff}$.

The distribution of the sum times of forward and backward PMT readout of one counter $(TDC_{\rm forward} + TDC_{\rm backward})/2$ is shown in Fig. 3(a). It is fitted with a cumulative distribution function (CDF) [12]:

$$\varphi_{\mu,\sigma^2}(x) = \frac{1}{\sigma\sqrt{2\pi}}\int_{-\infty}^{x} \exp\left(\frac{-(t-\mu)^2}{2\sigma^2}\right){\rm d}t, \quad (10)$$

where μ and σ^2 are the mean and variance of the normal distribution respectively. The distribution of mean values, half-height of the rise time, versus TOF counter numbers is shown in Fig. 3(b).

For the "up" part TOF counters, the mean value includes the time difference of the counter and a multiple of the whole trigger cycles which are the same for different TOF modules; for the "down" part TOF counters, the time of flight which the cosmic ray passes the TOF detector is also included. The path of flight could be calculated from the fit to the hits in MDC and extrapolation, and the time of flight would be easily obtained. After the correction of time of flight for the "down" part TOF counters, the distribution of the time difference counter-by-counter is shown in Fig. 3(c). Since most of the cosmic rays are incident perpendicularly, the statistics of the horizontal counters are insufficient to do the study of TOF calibration, and the results of those TOF counters are not shown in the plots. Time delay for each readout PMT would not be consistent with each other, and for the counters which are close to horizon, the contaminant is more serious. Then the sum of measured times of one counter with time difference correction can be expressed as $t_{\rm sum}$, which is:

$$t_{\rm sum} = TDC_{\rm forward} + TDC_{\rm backward} - 2\times t_{\rm diff}. \quad (11)$$

After $t_{\rm diff}$ correction, the propagation time in the scintillator, the transmit time of photoelectron signal in PMT and cable length time delay have been excluded. The time walk effect, the saturation of PMT, and the auxiliary item which describe the light propagation time in the scintillator and other minor contribution still remain in $t_{\rm sum}$.

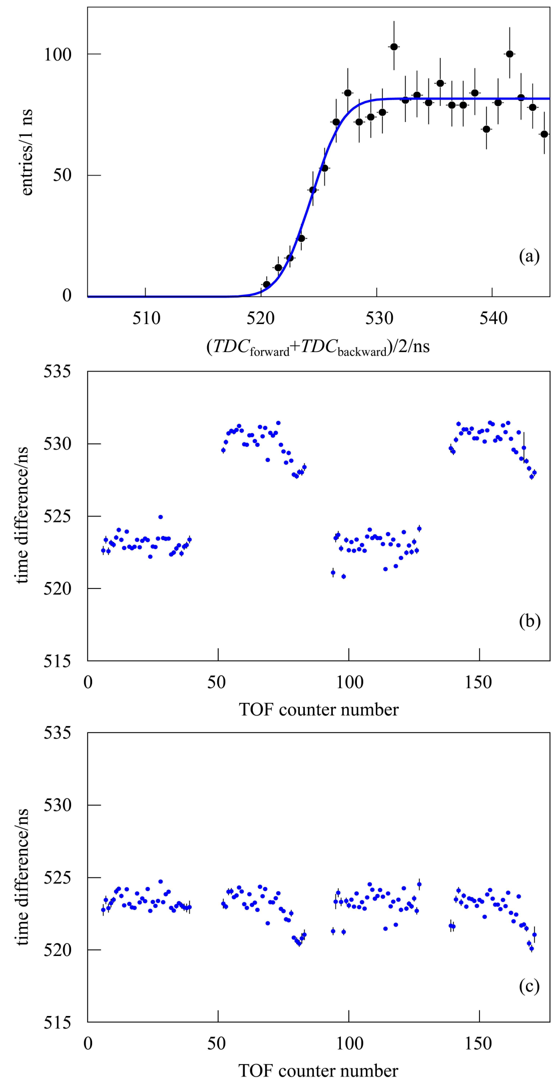

Fig. 3. (a) The distribution of the sum times of forward and backward PMT readout of one counter, (b) The distributions of half-height of the rise time versus TOF counter numbers before time of flight correction, (c) The distributions of time differences versus TOF counter numbers after time of flight correction.

4.3 Event start time extraction

For collision events, the preliminary result of event start time calculated by TOF using a Monte Carlo simulation sample is shown in Fig. 4(a), it could be easily found that the events from different bunches separated clearly, and the intrinsic TOF time resolution, time walk effect and other effects would contribute to the time resolution of the event start time. Since 8 ns is the bunch time interval, the time resolution would only impact the judgement of which bunch the event belongs to, and would not introduce additional uncertainty for the event start time.

For a cosmic event, the event start time t_0 is obtained with the average value of the four PMT readout times with the time difference correction of one layer,

$$t_0[\text{layer}] = \frac{1}{2}\sum_{\text{pos}} t_{\text{sum}}, \tag{12}$$

t_0 is a function of layer(inner or outer), and the subscript "pos" represents the "up" or "down" track. In order to avoid the correlation of measured time of the two layers of the barrel part of TOF, this event start time is calculated using only one layer. The distribution of t_0 for cosmic events is shown in Fig. 4(b), it is a uniform distribution within a trigger cycle, about 24 ns, which is caused by the L1 latency of trigger system. The error of event start time caused by the uncertainty from t_{sum} could not be simply removed as collision events. And this error would be transferred into the measured time t_{mea} calculated using Eq. (3), which could not be neglected. Fortunately the main contribution of uncertainty of raw measured time TDC from light propagation and delay time have been excluded using t_{diff} correction.

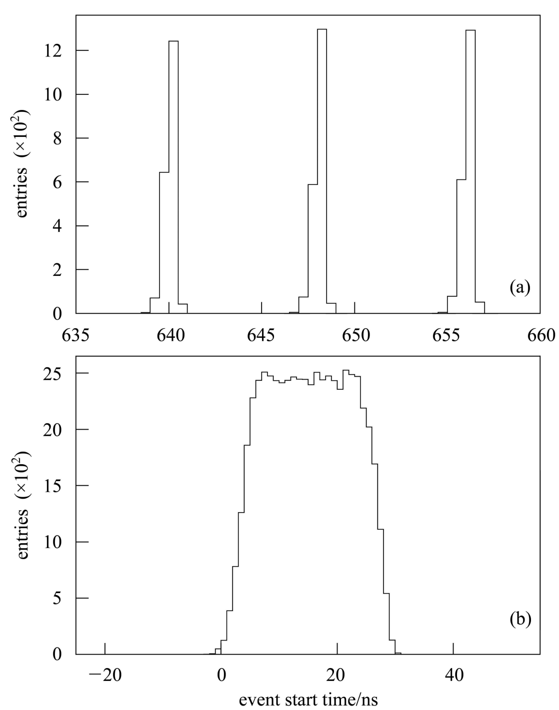

Fig. 4. (a) Event start time distribution for collision events using Monte Carlo sample. (b) The distribution of event start times for cosmic events.

A method is adopted in this analysis that repeated the iteration of TOF time calibration and successive approximation to the accurate event start time of cosmic events. The calibration of raw measured time of the other layer is done using this t_0 in Eq. (3), and more precise observed times of the other layer with time walk effect and other effects correction are obtained. These times could be used to calculate a more accurate event start time for repeated iteration,

$$t_0[\text{layer}] = \frac{1}{4}\sum_{\text{PMT,position}} t_{\text{mea}}, \tag{13}$$

where the subscript "PMT" represents forward or backward PMT. The uncertainty of event start time is suppressed. After several times alterant iteration of measured time calibration of the inner and outer layers, the χ^2 of Eq. (5) would be convergent. Fig. 5 shows the distribution of χ^2 versus the iteration number. The iteration number is chosen as 15 in this analysis.

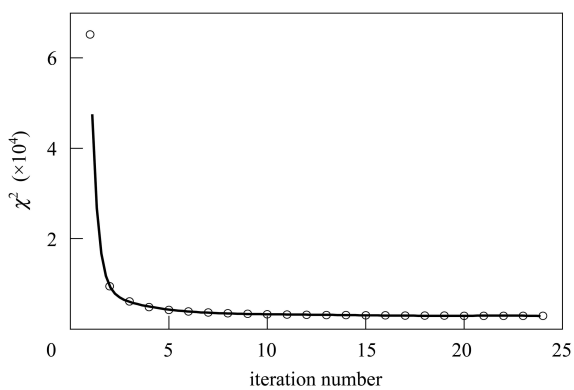

Fig. 5. The variation of χ^2 versus iteration number.

5 Results

Using the selected cosmic ray data, the single-end time resolution of the barrel TOF counters is about 2.6 ns as shown in Fig. 6(a) before calibration. Each raw measured time is subtracted from the time difference which corrects the inconsistency of TOF counters. Since there is no magnetic field, the cosmic ray is reconstructed as a straight line in MDC, the z hit position and path of flight are obtained from the extrapolated MDC reconstructed track. The predicted time is calculated as Eq. (2).

After applying the repeated iteration and successive approximation of the t_0 process, the single-end readout time resolution is about 150 ps as shown in Fig. 6(b). The weighted time resolution combining two end PMT readout units is about 110 ps as shown in Fig. 6(c). The distributions of time resolutions for single-end and for one layer of the barrel TOF versus counter numbers are shown in Fig. 6(d).

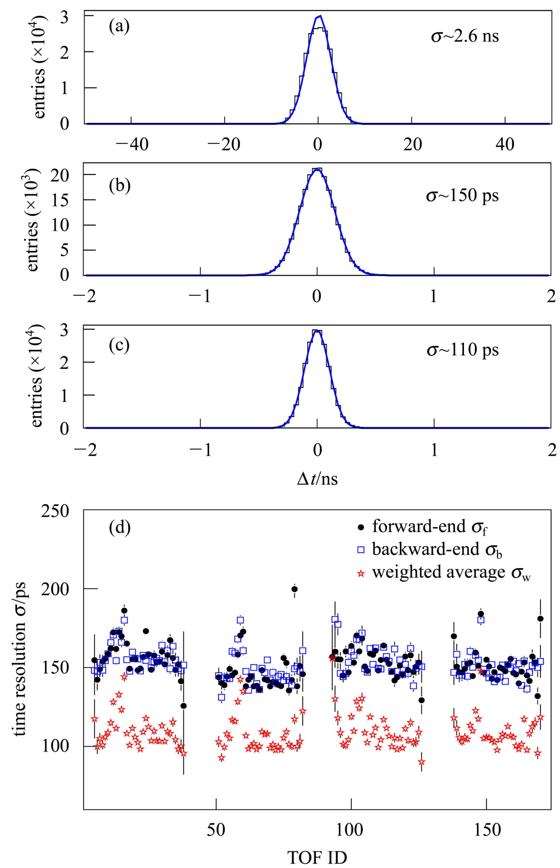

Fig. 6. $\Delta t = t_{\rm mea} - t_{\rm pre}$ distributions for single-end readout time before (a), after repeated iteration of time calibration and successive approximation of event start time (b), and for one layer (c); (d) the distributions of time resolutions for single-end and for one layer of the barrel TOF versus counter numbers.

A quadratic polynomial is used as the weighted function,

$$f_1 = w_1 + w_2 \times z + w_3 \times z^2, \quad f_2 = 1 - f_1. \tag{14}$$

The measured time of one layer, weighted average time of two single-end readouts, is expressed as:

$$t_w = f_1 \times (t_1 - t_{\rm pre}) + f_2 \times (t_2 - t_{\rm pre}) + w_4, \tag{15}$$

where $f_i (i{=}1{,}2)$ are the weights and w_i $(i = 1, 2, 3, 4)$ are the parameters. The distributions of time resolution for forward and backward single-end and for one layer versus z hit position are shown in Fig. 7 respectively. It is caused by measured pulse height saturation that the distribution of single-end time resolution versus z hit position is flat in PMT's far end range.

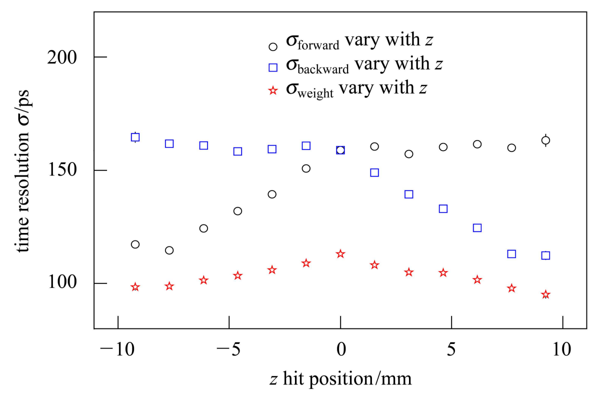

Fig. 7. The distributions of time resolution for forward and backward single-end and for one layer versus z hit position.

6 Summary and discussion

The capability of particle identification by TOF detector requires a good time resolution. In this paper, the performance check of TOF detector and the stability study of the improved TOF offline calibration and reconstruction software are presented. Using the cosmic ray data without magnetic field, we achieved about 150 ps for single end readout time resolution and about 110 ps for one layer. Since there were no precise momentum measurements and relatively accurate event start times, the resolution still contained uncertainties introduced by these approximations. It is capable of confronting the challenge of the colliding data. A better time resolution of the TOF calibration is expected using the Bhabha and Dimuon sample with a magnetic field of the collision events.

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