Nuclear Instruments and Methods in Physics Research A 766 (2014) 237–240

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Performance studies of the Belle II TOP counter

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ARTICLE INFO

Available online 12 June 2014

Keywords:
TOP counter
Particle identification
Extended likelihood method

ABSTRACT

We present the performance studies of the Belle II time-of-propagation (TOP) counter. The studies are performed with the Belle II software that includes Geant4 full detector simulation, realistic digitizers, track finding and fitting, and other reconstruction algorithms. We also compare a Geant4 based Monte Carlo simulation with the recently taken test beam data.

1. Introduction

At the Belle II detector [1] a time-of-propagation (TOP) counter will be used for particle identification (PID) in the barrel region. The TOP counter is a novel type of PID device that combines time-of-flight with the Cherenkov ring imaging technique. A single counter module consists of a long quartz bar within which the Cherenkov photons are emitted along the charged particle trajectory and then transported to the bar exit window by means of total internal reflections. The two-dimensional information about the Cherenkov ring image is obtained by measuring the time of arrival and the impact position of photons at the quartz bar exit window. The time of arrival is measured relative to the bunch crossing time and thus includes the time-of-flight of the particle. In its basic configuration the detector module consists of a quartz bar with a cross-section of typically 2 cm $\times$ 40 cm, and an array of fast photon detectors connected to the exit window. The other end can be equipped either with another array of photon detectors or with a mirror.

The dispersion, which is the dominant contribution to the resolution of this detector, can be accounted for by focusing the Cherenkov light onto the photon detector with a focusing mirror and by measuring the second coordinate of the photon impact position. To further improve the resolution, a small expansion prism can be added at the bar exit window.

The imaging TOP counter with a spherical mirror in the forward and an expansion prism in the backward direction has been chosen as the configuration for the Belle II barrel hadron identification system [2,3]. Sixteen 2.7 m long modules will be positioned in the space between the central drift chamber and the electromagnetic calorimeter.

The extended likelihood method that is used for particle identification has already been presented at the RICH workshops [4,5]. The method has become the standard tool in the Belle II reconstruction software. Presently, the Belle II software includes a Geant4 based full detector simulation, event generators like EvtGen and Pythia, realistic digitizers for all detector components, track finding, track fitting and other reconstruction algorithms, and thus enables to perform realistic Monte Carlo (MC) based studies.

In this contribution we present recent studies of the performance of the Belle II TOP counter that are based on the existing Belle II software and we compare the MC simulation with recently taken test beam data.

2. Measurements with a test beam

The Belle II TOP detector will be of cylindrical shape, with 119 cm radius and 2.7 m length. It will consist of 16 modules, of which each is essentially a 2 cm thick, 45 cm wide and 2.6 m long quartz plate. At one end of the plate is a spherical mirror (f=3.25 m), while the other end has a small, 10 cm long expansion prism and an array of position sensitive, single photon counters (MCP PMT Hamamatsu SL-10, two rows of 16 PMT/module) [3,6]. A charged particle traversing the plate with a velocity greater than the speed of light in the medium will emit Cherenkov radiation at a characteristic angle. Such Cherenkov photons would undergo a total internal reflection at the boundaries of the plate and would then be detected by the photon detectors. By measuring not only the position of the Cherenkov photon hit, but also its time of arrival (i.e. the time of propagation=TOP), one observes an interesting but complicated pattern. In Fig. 1 we compare a measured, a simulated and an analytically calculated pattern. The measurement was performed with one module using a narrow 2.1 GeV positron beam at the Spring-8 facility in Japan. For

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http://dx.doi.org/10.1016/j.nima.2014.06.017
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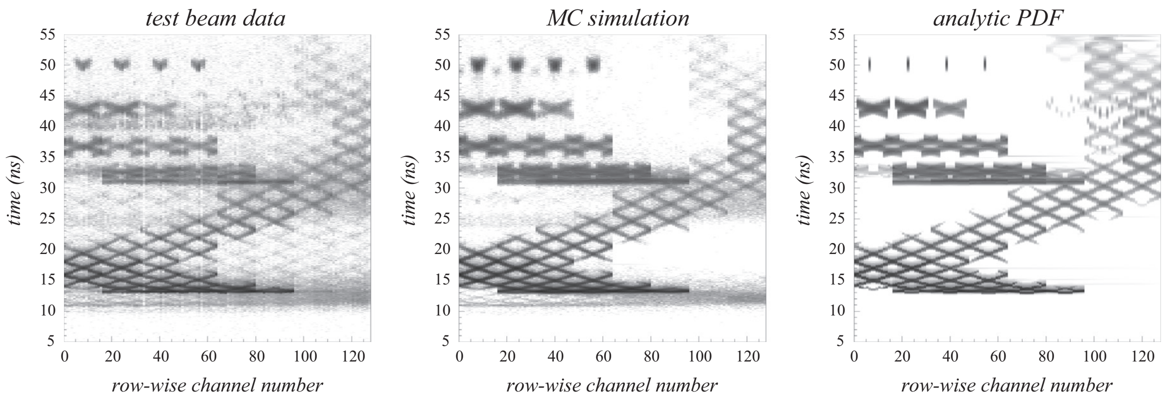

Fig. 1. A measured, a simulated and an analytically calculated distribution of Cherenkov photons in time and channel number.

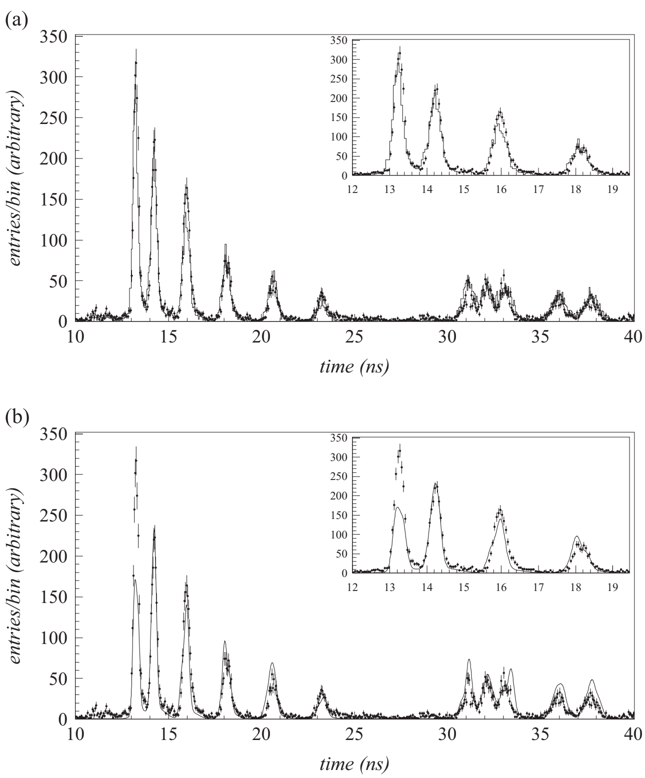

Fig. 2. A comparison of the test beam measurement in a single PMT channel with the MC simulation (a) and with the analytic PDF (b). Points with error bars represent measured data, the histogram in (a) is from MC simulation and the solid curve in (b) is the analytic PDF. Insets show the enlarged regions around the first four peaks of the distribution.

the Monte Carlo generated pattern, the full Belle II software has been used. The details of the analytic calculation have been described in one of our previous publications [5].

The pattern shown in Fig. 1 was measured with a beam perpendicular to the quartz plate and with its impact point close to the plate center. The net-like pattern from bottom-left to top-right originates from photons flying toward the MCP PMT's, while the cross-like pattern at the upper-left quadrant is due to photons reflected at the spherical mirror. The time distribution of photons in one of the PMT channels is shown in Fig. 2, where we compare the measurement with the MC simulation and with the analytic PDF. Both have been normalized to the number of measured beam particles. As seen from Fig. 2a the simulation agrees well with the measurement concerning positions, widths (time resolution) and heights (photon yield) of the peaks. Somewhat less good, but still

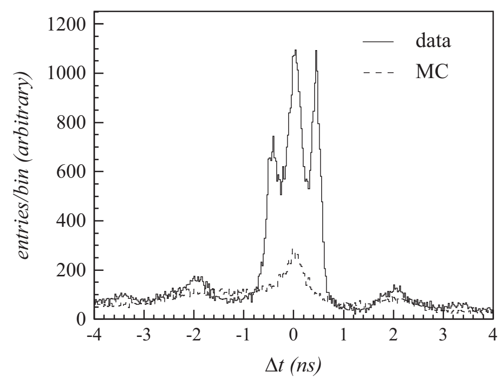

Fig. 3. Distributions of the time difference of signals in two adjacent MCP PMT channels from the test beam measurement (solid line) and from MC simulation (dashed line).

reasonable is the agreement of the analytic PDF with the measurement shown in Fig. 2b.

Charge sharing and electronic cross-talk between channels of a single MCP PMT have been studied on the test beam data by histograming the time difference Δt between signals from two different channels of the same MCP PMT. Presently, these effects are not modeled with the MC simulation. The effects are found to be considerable only between adjacent channels and show up as an excess of events at $|\Delta t| < 1$ ns (Fig. 3). To prevent double counting in the determination of photon yields, the following removal procedure is applied when two or more channels of a single MCP PMT detect a signal. The signals are first ordered according to time and then a signal is removed from further analysis if it is delayed relative to the leading signal by less than 1 ns. This procedure has been used also for the plots in Figs. 1 and 2. It removes 9.9% of the photon hits from the measured data and 5.1% from the simulation; the difference of 4.8% can therefore be attributed to charge sharing and electronic cross-talk.

This removal procedure has been used to compare the overall photon yields in data and in MC simulation. We counted the number of photons in the regions of signal and of background, which were defined by means of the analytic PDF as shown in Fig. 1; the signal region corresponds to the gray-colored pattern and the background region to the remaining white-colored area. The results are shown in Fig. 4. The measured and simulated yields in the signal region are in good agreement: the mean numbers of photons are 23.6 (data) and 23.8 (MC). In the background region we measure on average 6.1 photons, while the simulation gives 3.1 photons. The excess on the background in the data is attributed to the accompanying particles from showers produced by positrons in the upstream material of the LEPS spectrometer that has not been included in the simulation.