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Charged Particle Identification Using Calorimetry and Tracking at the Belle II Experiment

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Abstract

Particle identification (PID) is a critical procedure carried out in high energy physics experiments in search of new physics. When particles of matter (i.e., an electron) and antimatter (i.e., a positron) collide, new types of particles may form given certain conditions. Such particles may be classified as hadrons–which feel the strong nuclear force–and leptons–which do not. Identifying particles at the Belle II experiment is done by combining the measurement of energy deposited in the calorimeter with the measurement of track momentum in the tracker. In a tau lepton (τ) decay sample, particles such as electrons, muons, and pions may be separated and identified using such measurements.

The Belle II Detector

Elementary particles in the Belle II experiment are created as a result of colliding an electron and a positron at nearly the speed of light. Both the electron and the positron are said to be annihilated, meaning that these particles are destroyed and new particles are produced. As energy and momentum are conserved in this annihilation, any leptons and hadrons that are produced will have a unique value of energy and momentum, and the sum of all these energies and momenta will be equal to that of the initial electron-positron collision.

These quantities are measured using the Belle II experiment's detector. Each particle produced by the annihilation would follow its own path at its own speed with its own energy. However, because the number of particles produced per collision differs and owing to the presence of invisible particles such as neutrinos, there is great variability in the momentum and energies each visible particle may possess. As such, the detector needs to be able to track a particle's speed, path, and energy to a high precision, and must be able to measure them for millions of events. The Belle II detector is built of several components to measure such quantities [1].

- Closest to the point of collision (the vertex) are several layers of silicon detectors. These detectors record the path newly formed charged particles take. These are labeled as PXD and SVD in Figure 1.
- Outside the silicon detectors is the central drift chamber [2]. The trajectory of particles is tracked within a magnetic field. The radius of curvature and the magnetic field strength is known, so momentum of the charged track is derived. This is labeled as CDC in Figure 1.
- Surrounding the central drift chamber are two Cherenkov counters. Particle velocities are tracked in these counters, labeled as TOP and ARICH in Figure 1.
- An electromagnetic calorimeter measures and absorbs all energy of emitted photons and electrons [3]. This is labeled as ECL in Figure 1.
- The largest and outermost detector identifies particles with long lifetimes, such as muons, which pass through the entire length of the detector. This is labeled as KLM in Figure 1.

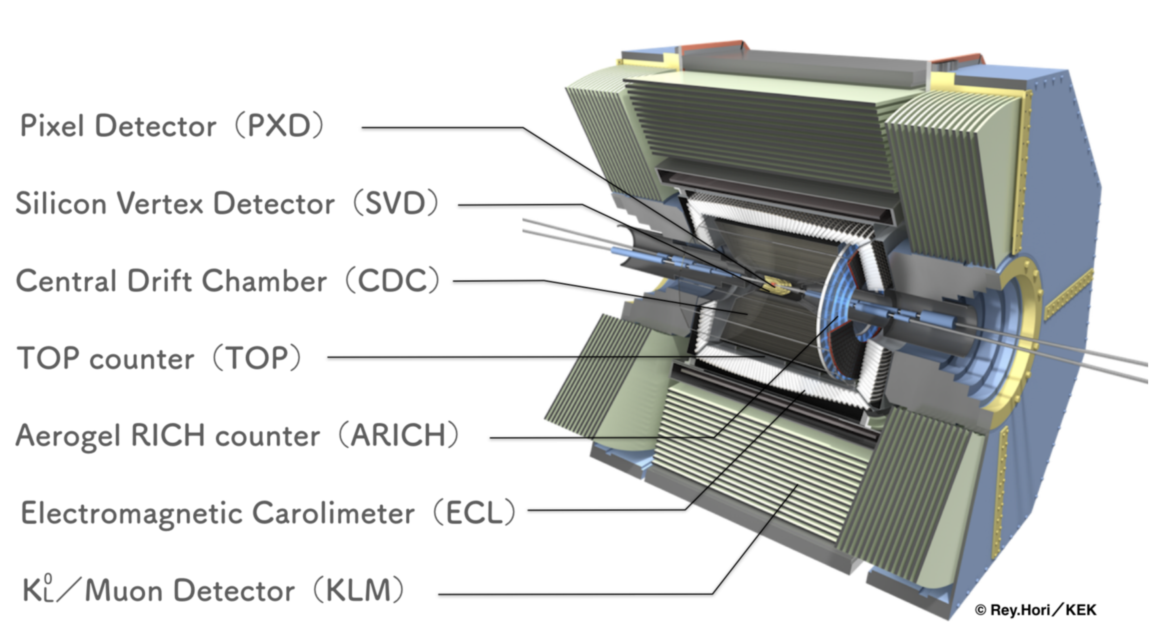

Fig. 1: The Belle II detector with labeled components.

Particle Identification

There are methods in which the mass of a particle can be calculated indirectly from these quantities, however the data on individual particles may vary by considerably large amounts due to detector resolution. As a result, PID must be approached by means of likelihood.

Likelihood probability is used in particle detection in order to distinguish groups of particles based on unique, predicted, past trends. It is important to consider all relevant likelihood values depending on the detectors in which the particles pass through.

While there are certain methods used for likelihoods in the KLM and Cherenkov counters, it is outside the scope of this presentation and will not be covered. Instead, there will be a focus primarily on the ECL and CDC for energy and track measurement, respectively.

Let p be the the momentum of a charged particle reconstructed as tracks in the CDC (a virtual image of the tracker is provided in Figure 2). And let E be the energy deposited into the calorimeter (a photograph of the calorimeter is provided in Figure 3). E/p would then be the energy of a particle per unit momentum, and is an effective quantity in PID for its highly distinguishable likelihood values of particles. From an accumulation of measured E/p values, likelihood may be measured relatively and particles may be identified.

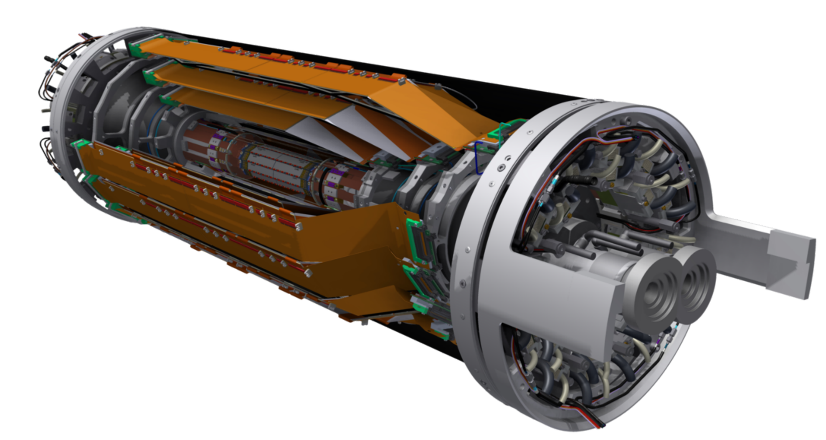

Fig. 2: The solenoid magnet of the Belle II detector, which measures momentum through tracking a decayed particle's path within a 1.2-1.5T magnetic field.

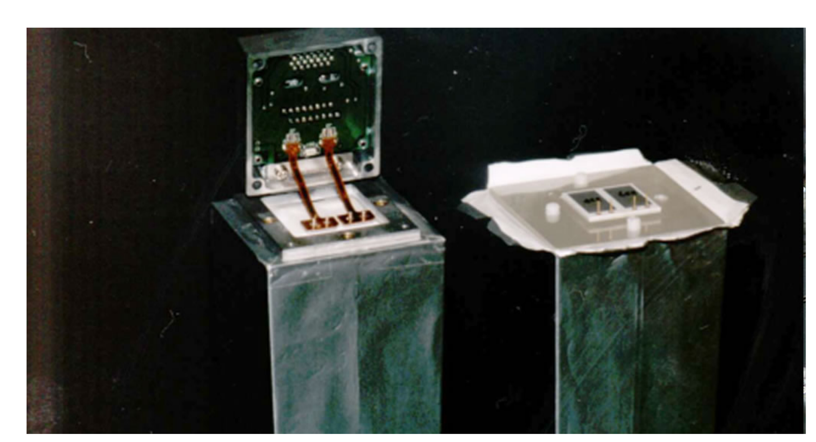

Fig. 3: A detector crystal of the electromagnetic calorimeter of the Belle II detector.

Following the electron-positron collision, τ leptons may be produced, which can quickly decay into electrons, muons, and pions. Measuring the E/p of the visible daughters of a τ decay may be used in separating decayed particles from each other.

By accumulating several thousand events which contain information from different particle decays, the variety in recorded E/p values may create a probability distribution. A sample of E/p from visible daughters of τ decays is given in Figure 4, and is further explained in the next section.

τ particles are produced in pairs in electron-positron annihilations. For this study, we choose an event sample where a τ^+ always decays into a positive pion, π^+ and the τ^- is allowed to decay into either an electron, e^-, or a negative muon, μ^-, each with a probability of 50%. To distinguish between e^-, μ^-, and π^+, a probability density function over E/p may be used; and by evaluating relative likelihoods, decayed particles may be identified.

E/p Distribution

Figure 4 shows distribution of the variable E/p for particles π^+, μ^-, and e^- obtained from decays of $\tau^-\tau^+$ events. These τ-pairs were the product of the initial e^- and positron (e^+) annihilation. The process $e^-e^+ \to \tau^-\tau^+$ was simulated with the use of Monte Carlo truth information in the Belle II software environment, and the data created is based on the geometry of the Belle II detector. 50,000 events of $\tau^-\tau^+$ decays were used.

For the E/p measurement, the graphs that have been plotted have been normalized to unit area. Hence, the graphs represent the probability density function for different types of particles. While separation of particles is not possible over the entire range of E/p, there are regions which are dominated by certain particles. These regions define the identity of such particles.

In Figure 4,

- for 0.8 < E/p < 1.1 the spectrum is dominated by e^-,
- for 0.4 < E/p < 0.6 it is dominated by π^+, and
- for 0.1 < E/p < 0.2 the μ^- dominates.

The characteristics of these E/p regions distinguish π^+, μ^-, and e^- in τ-pair decays. Note that for other regions of the E/p spectrum, the signature of e^-, μ^- and π^+ starts to overlap. In such regions, the E/p likelihood becomes less effective and likelihoods of other measurements are used for particle identification.

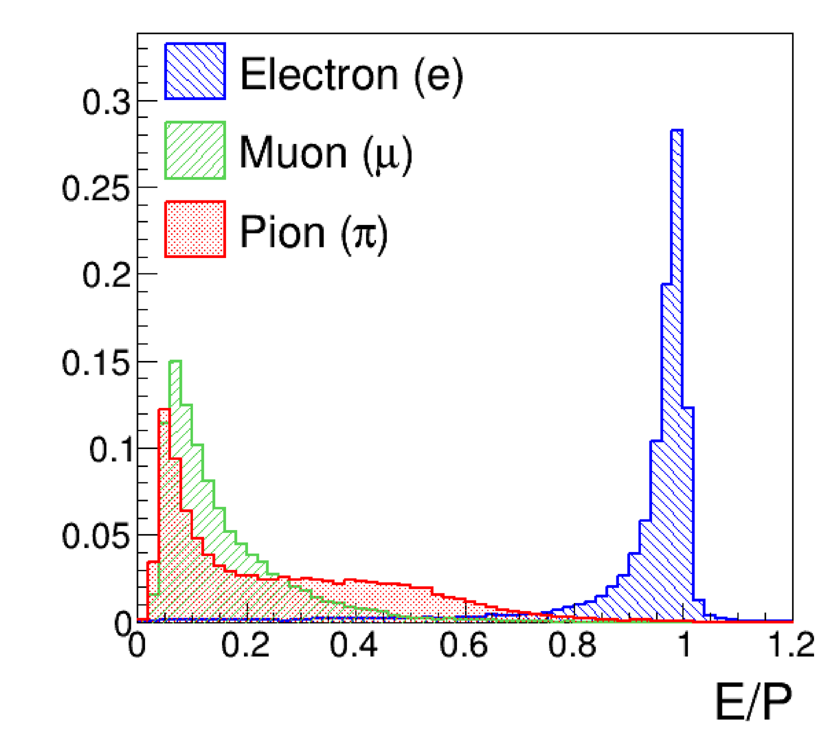

Fig. 4: Probability functions of τ decay samples are plotted over E/p measurements of decayed particles.

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