Low-momentum charged hadron identification using SVD

The Belle II Collaboration

Abstract
We report a particle identification (PID) framework developed using energy loss information in the silicon-strip vertex detector (SVD) of Belle II for charged pions, kaons and protons using $D^{*+} \rightarrow D^0[\rightarrow K\pi^+]\pi^+$ and $\Lambda \rightarrow p\pi^-$ decay samples. The study is based on $e^+e^-$ collision data recorded at the $\Upsilon(4S)$ resonance by Belle II and the results are compared with that of a Monte Carlo sample. The introduction of additional information from the SVD is found to improve the overall PID performance in the low momentum region.
1. INTRODUCTION

Particle identification (PID) plays a central role in the physics program of Belle II. Low-momentum charged particles having a transverse momentum $p_T \lesssim 65 \text{ MeV}/c$ are unable to reach the central drift chamber (CDC), the main tracking system of the experiment, owing to their highly curved trajectories. Our goal is to exploit specific ionization ($dE/dx$) by these low-momentum particles in the silicon-strip vertex detector (SVD) towards identifying them. Even if the particles have a $p_T$ greater than 65 MeV/c and are thus able to reach the CDC, the $dE/dx$ values measured in the SVD can provide complementary information to that obtained from the main PID detectors of Belle II: CDC, TOP, and ARICH.

We use clean samples of $D^{*+} \rightarrow D^0(K^-\pi^+)\pi^+$ and $\Lambda \rightarrow p\pi$ decays to first obtain the SVD $dE/dx$ calibration for charged pions, kaons and protons. Later we check the impact of $dE/dx$ information on overall PID performance using the same decay channels. We have also verified the $dE/dx$ values to be independent of the mass of traversing particles depending only on their $\beta \gamma$ values. The study is based on $e^+e^-$ collision data recorded at the $\Upsilon(4S)$ peak by Belle II and the results are compared with that of a Monte Carlo (MC) sample.

To assess the impact of SVD $dE/dx$ information on the overall PID performance, we plot the identification efficiency and fake rate as a function of momentum applying a requirement on the binary PID likelihood $L(i/j) > 0.5$. The efficiency is defined as:

$$\epsilon_i = \frac{\text{# charged particle tracks identified kinematically as well as with PID requirement under the hypothesis } i}{\text{# charged particle tracks identified kinematically under the hypothesis } i},$$

and the fake rate is given by:

$$f_{j \rightarrow i} = \frac{\text{# charged particle tracks identified kinematically as well as with PID requirement under the hypothesis } i}{\text{# charged particle tracks identified kinematically under the hypothesis } j}.$$

2. RESULTS

In the following, we will have a series of plots describing various aspects of the study.
FIG. 1. Fitted distributions of $D^*-D^0$ mass difference ($\Delta m$) from the $D^*$ sample in data (left) and MC (right) events. We require the charged particle tracks to have a transverse (longitudinal) impact parameter less than 0.5 cm (2.0 cm). These tracks must have at least one SVD hit and a track-fit $\chi^2$ value greater than $10^{-5}$. To further purify the sample, we require the reconstructed $D^0$ mass to lie between 1.85 and 1.88 GeV/$c^2$, corresponding to a $\pm 3\sigma$ window around the nominal $D^0$ mass. The reconstructed $D^*$ mass must be within 1.95 and 2.05 GeV/$c^2$. We apply a loose criterion on kaon and pion PID likelihoods, calculated without SVD information, to remove low-momentum secondary pions and kaons produced due to hadronic interaction in the detector material. We model the signal and background $\Delta m$ shape by a sum of two Gaussian functions with a common mean and a threshold function, respectively. The $\textit{a}Plot$ [1] technique is used to subtract the residual background contributions.
FIG. 2. Fitted $M_{p\pi}$ distributions from the $\Lambda$ sample in data (left) and MC (right) events. We require the reconstructed $p\pi$ invariant mass of $\Lambda$ candidates to be in the range $[1.10, 1.13]$ GeV/c$^2$, and they are further subjected to a vertex fit. The distance between the interaction point and the vertex of the $\Lambda$ candidates is required to be greater than 1 cm and the vertex fit $\chi^2$ must be greater than $10^{-3}$ to remove the random combination of two tracks. We also require at least one SVD hit for both daughter tracks of $\Lambda$ candidates. We suppress the contamination of charged pions coming from the $K^0_S$ decay by rejecting events that have the $M_{\pi^+\pi^-}$ value in the range $[488, 508]$ MeV/c$^2$, corresponding to a $\pm 3\sigma$ window around the nominal $K^0_S$ mass. Similarly, events with electrons from converted photons are suppressed by excluding $M_{e^+e^-} < 50$ MeV/c$^2$, a veto decided by the figure-of-merit optimization. We impose an additional requirement of at least one CDC hit and a loose criterion on the proton PID calculated without SVD information to remove low-momentum secondary pions produced due to hadronic interaction with the detector material. We model the signal shape with the sum of a Gaussian and two asymmetric Gaussian functions of a common mean and the background shape with a second-order Chebyshev polynomial. The $\chi^2$-Plots technique is used to subtract the residual background contributions.

FIG. 3. Scatter plot of $dE/dx$ values of charged pions and kaons as a function of their momentum for data (left) and MC (right) events from the $D^*$ sample. The two-dimensional distributions of $dE/dx$ vs. momentum show a clear separation between different particles in the low momentum region, and are uploaded to the calibration database.
FIG. 4. Scatter plot of $dE/dx$ of proton and pion as a function of their momentum in data (left) and MC (right) events from the $\Lambda$ sample. The two-dimensional distributions of $dE/dx$ vs. momentum show a clear separation between different particles in the low momentum region, and are uploaded to the calibration database.

FIG. 5. The $\beta\gamma$ universality curve obtained in data with $D^*$ and $\Lambda$ samples. As the specific ionisation depends only on the velocity ($\beta$) of traversing particles, we check the $\beta\gamma$ universality of $dE/dx$ values obtained from $D^*$ and $\Lambda$ samples. The minimum energy loss occurs at $\beta\gamma \approx 3$ regardless of the particle type. We get a flat curve beyond that threshold, as the relativistic rise of energy loss is suppressed by the density effect in silicon.
FIG. 6. $K$ efficiency and $\pi$ fake rate vs. momentum without (left) and with (right) SVD $dE/dx$ information. To assess the impact of this information to the overall PID, we plot the efficiency and fake rate as a function of momentum applying a requirement on the PID likelihood $\mathcal{L}(K/\pi) > 0.5$. The study shows an improvement in kaon efficiency after adding SVD $dE/dx$ information.

FIG. 7. $p$ efficiency and $\pi$ fake rate vs. momentum without (left) and with (right) SVD $dE/dx$ information. To assess the impact of this information to the overall PID, we plot the efficiency and fake rate as a function of momentum applying a requirement on the PID likelihood $\mathcal{L}(p/\pi) > 0.6$. The study shows an improvement in proton efficiency after adding SVD $dE/dx$ information.
FIG. 8. $\pi$ efficiency vs. $K$ fake rate (left) and $K$ efficiency vs. $\pi$ fake rate (right) with and without SVD for $p < 1$ GeV/c. We plot the efficiency vs. fake rate to better appreciate the improvement in PID performance by adding the SVD $dE/dx$ information. The PID likelihood criterion is varied from 0 to 1 in order to produce these plots. Our study confirms that addition of $dE/dx$ information improves the pion (kaon) efficiency for a given kaon (pion) fake rate in the low momentum region.

FIG. 9. $p$ efficiency vs. $\pi$ fake rate (left) and $p$ efficiency vs. $K$ fake rate (right) with and without SVD for $p < 1$ GeV/c. We plot the efficiency vs. fake rate to better appreciate the improvement in PID performance by adding the SVD $dE/dx$ information. The PID likelihood criterion is varied from 0 to 1 in order to produce these plots. Our study confirms that addition of $dE/dx$ information improves the proton efficiency for a given pion or kaon fake rate in the low momentum region.