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Particle Identification in Belle II Silicon Vertex Detector

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We report a particle identification (PID) tool developed using energy-loss information in the silicon-strip vertex detector (SVD) of Belle II for charged pions, kaons, and protons using $D^{*+} \to D^0[\to K^-\pi^+]\pi^+$ and $\Lambda \to p\pi^-$ 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.

KEYWORDS: *dE/dx*, SVD, PID

1. Introduction

Particle identification (PID) plays an important role in the physics program of the Belle II experiment [1]. Low-momentum charged particles having a transverse momentum $p_{\mathrm{T}} \lesssim 65\,\mathrm{MeV}/c$ 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) [2] towards identifying them. Even if the particles have a p_{T} greater than $65\,\mathrm{MeV}/c$ and reach the CDC, the dE/dx values measured in the SVD can provide complementary information to that obtained from the main PID subdetectors of Belle II, namely CDC, time-of-propagation counter, and aerogel ring-imaging Cherenkov counter.

We use clean samples of $D^{*+} \to D^0(K^-\pi^+)\pi^+$ and $\Lambda \to p\pi$ decays to first obtain the SVD dE/dx calibration for charged pions, kaons, and protons. Towards that end, we extract the dE/dx value from each SVD hit for these particles. In order to combine the hit-level dE/dx information for reconstructing the track-level dE/dx value, we find a simple arithmetic mean to be insufficient since the hit-level distribution follows a Landau function [3] for which the mean is undefined. Thus, a truncation is applied while combining the individual hit-level dE/dx measurements; basically the energy of all clusters except for the two highest ones are used in the calculation. Later we check the impact of dE/dx information on overall PID performance using the above two 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 [4].

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 $\mathcal{L}(i/j) > 0.5$. 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:

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

2. SVD *dE/dx* calibration

The $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$ decay is used to calibrate the pion and kaon PID based on dE/dx information in SVD. 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 χ^2 probability value greater than 10^{-5}. To further purify the sample, we require the reconstructed D^0 mass to lie between 1.85 and $1.88\,\mathrm{GeV}/c^2$, corresponding to a $\pm 3\sigma$ window around the nominal D^0 mass. The reconstructed D^* mass must be within 1.95 and $2.05\,\mathrm{GeV}/c^2$. 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 shape in the D^*–D^0 mass difference (Δm) by a sum of two Gaussian functions with a common mean and a threshold function, respectively. Results of the fit are presented in Fig. 1. The ${}_s\mathcal{P}lot$ [5] technique is used to subtract the residual background contributions.

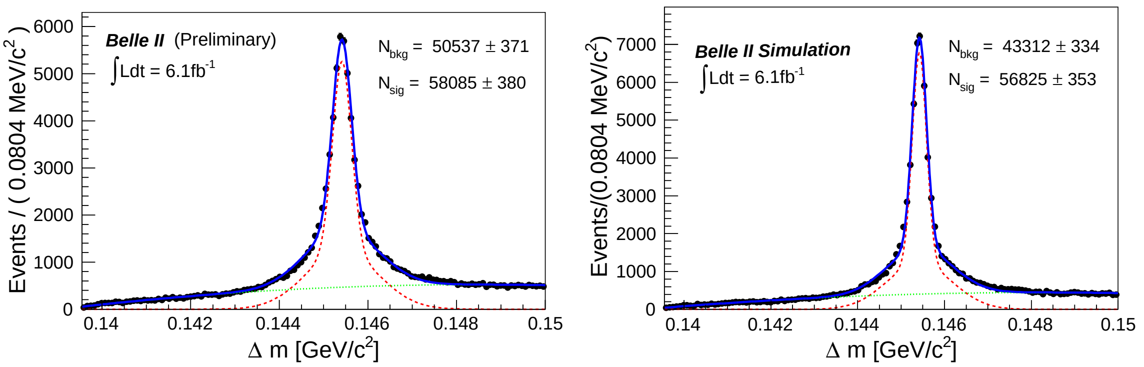

Fig. 1. Fitted distributions of Δm from the D^* sample in data (left) and MC (right) events.

The $\Lambda \to p\pi$ decay is used to calibrate the proton PID based on dE/dx information in SVD. We require the reconstructed $p\pi$ invariant mass of Λ 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 Λ candidates is required to be greater than 1.0 cm and the vertex-fit χ^2 probability 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 Λ candidates. We suppress the contamination of charged pions coming from the K_S^0 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_S^0 mass. Similarly, events with electrons from converted photons are suppressed by excluding $M_{e^+e^-} < 50$ MeV/c^2. 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 in $M_{p\pi}$ 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 (see Fig. 2). Again the $_s\mathcal{P}lot$ [5] technique is used to subtract the residual background contributions.

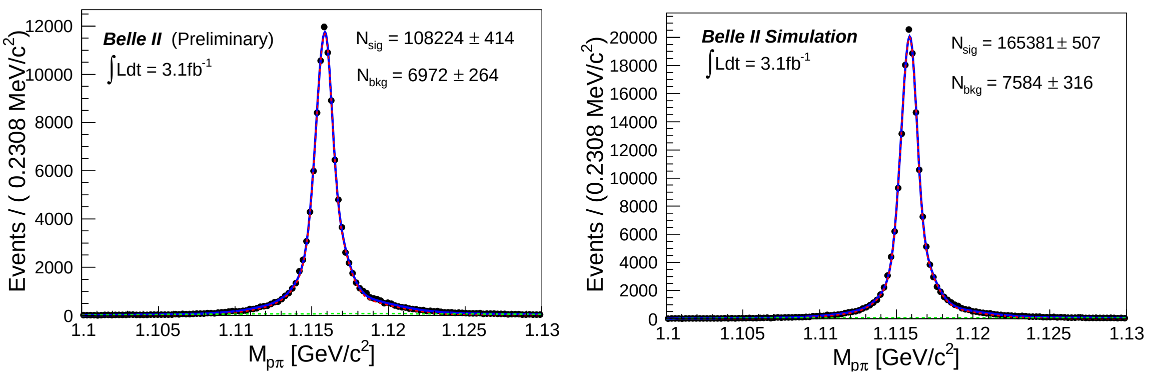

Fig. 2. Fitted distributions of $M_{p\pi}$ from the Λ sample in data (left) and MC (right) events.

The two-dimensional distributions of dE/dx vs. momentum (see Figs. 3 and 4) show a clear separation between different particles in the low momentum region, and are uploaded to the calibration database.

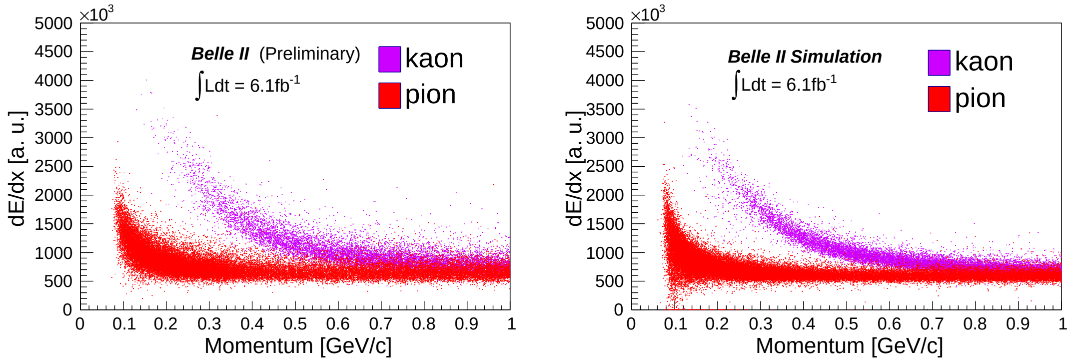

Fig. 3. Scatter plot of dE/dx values of charged pions and kaons as a function of their momentum for data (left) and MC (right) events from the D^* sample.

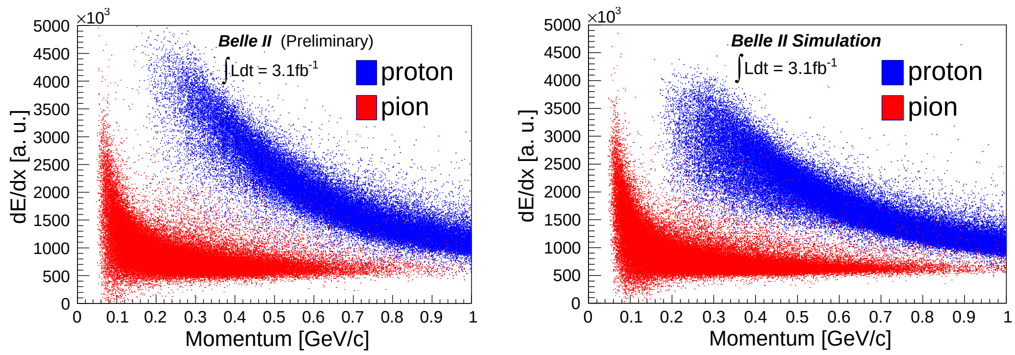

Fig. 4. Scatter plot of dE/dx of proton and pion as a function of their momentum in data (left) and MC (right) events from the Λ sample.

As the specific ionisation depends only on the velocity (β) of traversing particles, we check the $\beta\gamma$ universality of dE/dx values (Fig. 5) obtained from D^* and Λ 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.

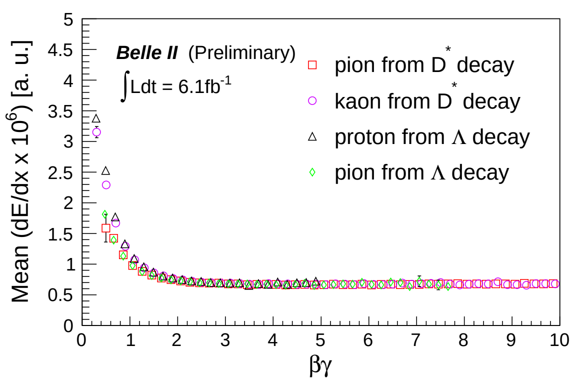

Fig. 5. $\beta\gamma$ universality curve obtained in data for pions, kaons and protons obtained with D^* and Λ samples.

3. PID performance

We also use $D^{*+} \to D^0(K^-\pi^+)\pi^+$ and $\Lambda \to p\pi$ decays for performance studies. To assess the impact of the SVD dE/dx information to the overall PID, we plot the efficiency and fake rate (see Figs. 6 and 7) as a function of momentum applying a requirement on the PID likelihood $\mathcal{L}(K/\pi) > 0.5$ and $\mathcal{L}(p/\pi) > 0.6$. The study shows an improvement in kaon and proton identification efficiency after adding SVD dE/dx information.

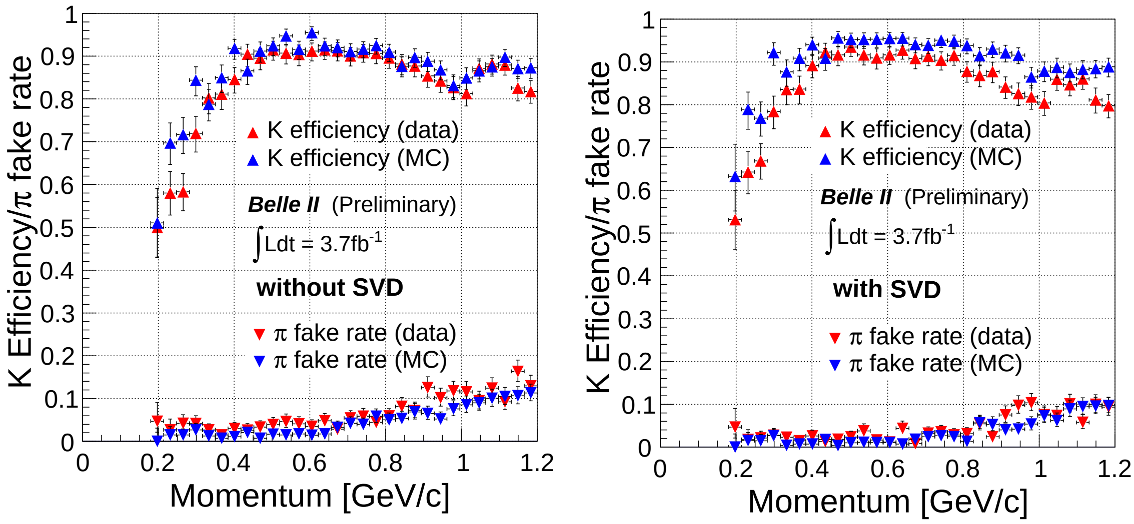

Fig. 6. K efficiency and π fake rate vs. momentum without (left) and with (right) SVD dE/dx information.

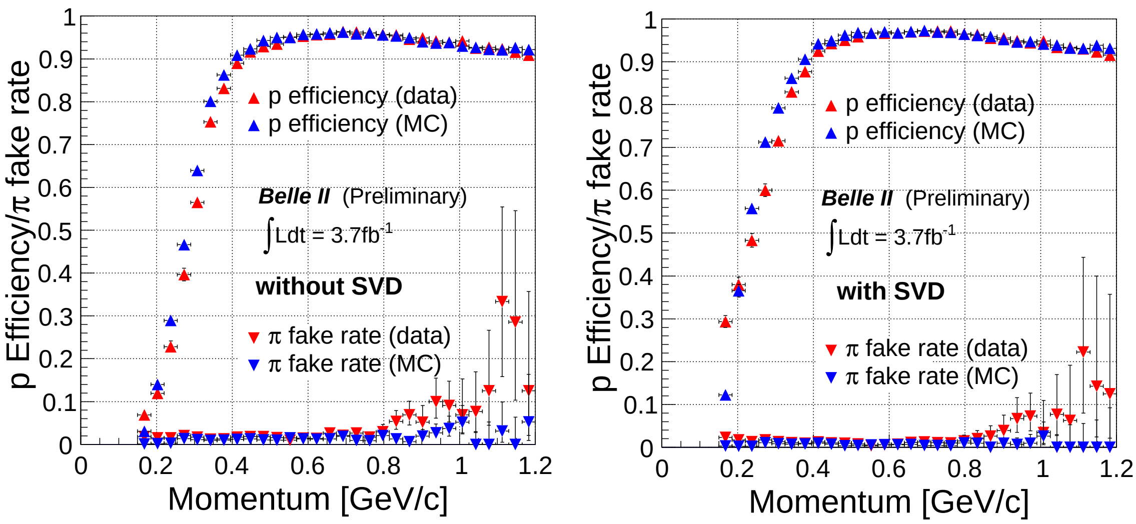

Fig. 7. p efficiency and π fake rate vs. momentum without (left) and with (right) SVD dE/dx information.

We plot the efficiency vs. fake rate (see Figs. 8 and 9) 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 for a given fake rate the addition of *dE*/*dx* information improves the efficiency in the low momentum region. For example, if we fix the π fake rate at 4%, we get an overall 4% improvement in the kaon efficiency. We find some data-MC difference in performance, which arises due to imperfect simulation of the cluster energy distribution.

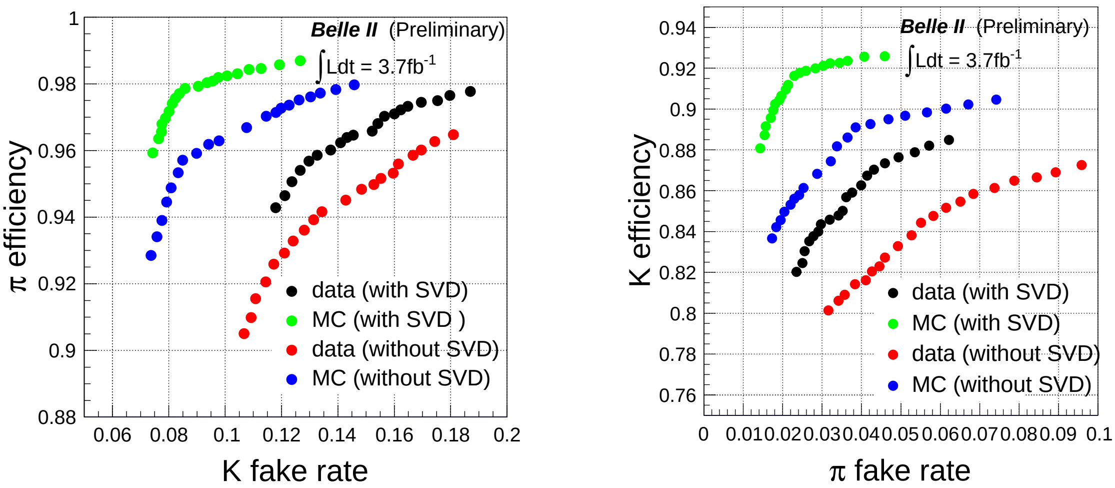

Fig. 8. π efficiency vs. K fake rate (left) and K efficiency vs. π fake rate (right) with and without SVD for $p < 1$ GeV/c.

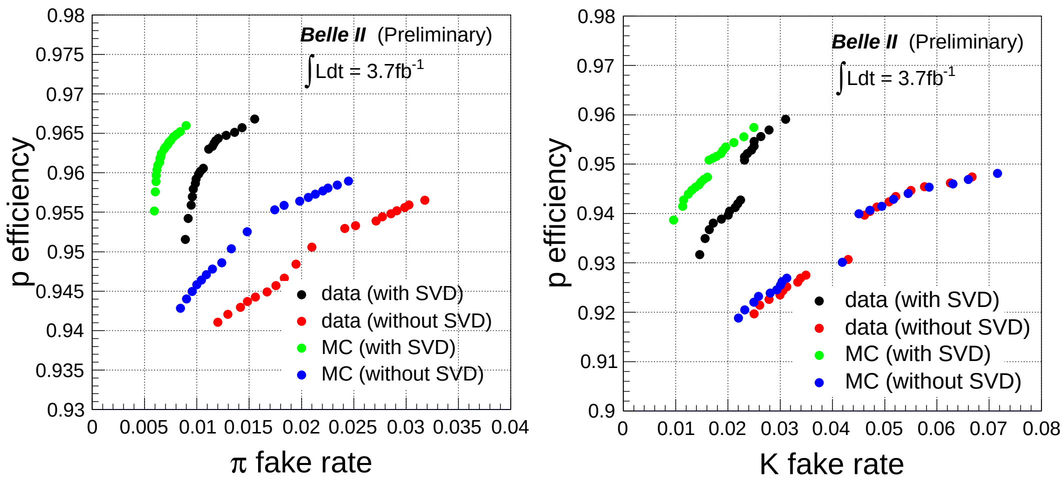

Fig. 9. p efficiency vs. π fake rate (left) and p efficiency vs. K fake rate (right) with and without SVD for $p < 1$ GeV/c.

4. Conclusion

We have developed an SVD *dE*/*dx* based PID tool for charged pions, kaons, and proton using $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$ and $\Lambda \to p\pi^-$ decay samples. The study shows that by adding the SVD information we can improve the overall PID performance in the low momentum region.

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