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(ԵՐԵՎԱՆԻ ՖԻԶԻԿԱՅԻ ԻՆՍՏԻՏՈՒՏ)

Ղևոնդյան Գայանե Գուրգենի

ARICH դրանցիչի ուսումնասիրությունը BELLE II գիտափորձում,
որպես լիցքավորված մասնիկների նույնականացման
հիմնական բաղադրիչներից մեկը

Ա.04.16 - «Միջուկի, տարրական մասնիկների եւ տիեզերական
ճառագայթների ֆիզիկա» մասնագիտությամբ ֆիզիկամաթեմատիկական
գիտությունների թեկնածուի գիտական աստիճանի հայցման
ատենախոսության

ՍԵՂՄԱԳԻՐ

ԵՐԵՎԱՆ – 2025

A. I. ALIKHANYAN NATIONAL SCIENCE LABORATORY
(YEREVAN PHYSICS INSTITUTE)

Gayane Ghevondyan

Study of the ARICH detector performance, as one of the essential components
of charged particle identification in the Belle II experiment

SYNOPSIS

of the Dissertation in 01.04.16 -“Nuclear, elementary particles and cosmic ray physics”
presented for the degree of candidate in physical and mathematical sciences

YEREVAN – 2025

Ատենախոսության թեման հաստատվել է Ա. Ի. Ալիխանյանի անվան ազգային գիտական լաբորատորիայի (ԵրՖԻ) գիտական խորհրդում

Գիտական ղեկավար՝
Ֆիզ. մաթ. գիտ. դոկտոր՝ Ակոպով Նորայր Զավենի (ԱԱԳԼ)

Պաշտոնական ընդդիմախոսներ՝
Ֆիզ. մաթ. գիտ. դոկտոր՝ Մկրտչյան Համլետ Գեղամի (ԱԱԳԼ)
Ֆիզ. մաթ. գիտ. թեկնածու՝ Գուլքանյան Հրանտ Ռուբենի (ԱԱԳԼ)

Առաջատար կազմակերպություն՝ Երեւանի Պետական Համալսարան (ԵՊՀ)

Պաշտպանությունը կայանալու է 2025թ.-ի փետրվարի 10-ին՝ ժամը 16:00-ին, ԱԱԳԼ-ում գործող ԲԿԳԿ-ի 024 «Ֆիզիկայի» մասնագիտական խորհրդում (Երևան, 0036, Ալիխանյան եղբայրների փ. 2):

Ատենախոսությանը կարելի է ծանոթանալ ԱԱԳԼ-ի գրադարանում:
Սեղմագիրն առաքված է 2025թ-ի հունվարի 9-ին:

Մասնագիտական խորհրդի գիտ. քարտուղար
Ֆիզ. մաթ. գիտ. դոկտոր՝ Հրաչյա Մարուքյան

The subject of the dissertation is approved by the scientific council of the A. I. Alikhanyan National Science Laboratory (YerPhI).

Scientific supervisor:
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Leading organization: Yerevan State University (YSU)

The defense will take place on the 10 February 2025 at 16:00 during the “Physics” professional council session of HESC 024 acting within AANL (2 Alikhanyan brothers str., 0036, Yerevan).

The dissertation is available at the AANL library.
The synopsis is sent out on the 9 January 2025.

Scientific secretary of the special council:
Doctor of phys-math. sciences Hrachya Marukyan

Thesis relevance

The Belle II experiment at the SuperKEKB asymmetric e^+e^- collider [1][2] in the High Energy Accelerator Research Organization (KEK, Tsukuba, Japan) is searching for CP asymmetries in different rare decays, as well as new physics (NP) beyond the standard model (BSM) and aims to collect a high statistics data set corresponding to an integrated luminosity of 50[ab^{-1}].

The primary physics goals of Belle II, as a next-generation flavor factory, are to search for NP in the flavor sector at the intensity frontier, and to improve the precision of measurements of Standard Model (SM) parameters. The SuperKEKB facility is designed to collide electrons and positrons at center-of-mass energies in the regions of the Υ resonances. Most of the data will be collected at the $\Upsilon(4S)$ resonance, which is just above the threshold for the production of B-meson pairs where no fragmentation particles are produced.

Its predecessor, the Belle experiment, was able to identify pions and kaons with momenta up to 2[GeV/c] in the forward end-cap region. However, in the Belle II experiment identification of charged particles with higher momenta i.e. up to 4[GeV/c] in the forward region is required to search for new physics. To identify high-momentum particles in the forward end-cap region, the efficient Particle Identification Detector (PID) - Aerogel Ring Imaging Cherenkov (ARICH) counter was designed for the Belle II spectrometer. The ARICH counter construction was completed in October 2018 and the detector was installed on the Belle II spectrometer in December 2018. At that point, ARICH was integrated into the operation of the Belle II spectrometer.

The main characteristics of the ARICH detector are efficiency and mis-identification probability which are essential for physics analysis. We study the Aerogel Ring Imaging Cherenkov (ARICH) detector response in terms of loglikelihood functions using decay samples of $D^{*+} \to D^0 + \pi^+$ and $D^{*-} \to \bar{D}^0 + \pi^-$ resonances. For this purpose we use experimental data corresponding to 368.091[fb^{-1}] combined integrated offline luminosity and Monte Carlo run independent sample with the integrated luminosity for each quark combination equal to 1000[fb^{-1}], which include different quark combinations like: $u\bar{u}, d\bar{d}, s\bar{s}, c\bar{c}$ as well as $B^0\bar{B}^0$, B^-B^+ pairs combined with the weights proportional to the corresponding cross section for $e^-e^+ \to q\bar{q}$ processes.

The particle identification efficiencies and mis-identification probabilities are presented in 2D momentum and the polar angle bins.

Relevance of the research topic

Modern experimental setups used for high energy physics experiments are essentially complicated and expensive. This is directly related to Belle II setup, which consists of many sub-detectors, including a set of Particle Identification Detectors (PID), where the Aerogel Ring Imaging Cherenkov (ARICH) detector[2] is one of important elements providing selection of hadrons at certain momentum and angular regions of charged particles phase space. Optimization of such a detector in the sense of providing maximal performance is very important to increase the efficiency of data taking. The present thesis is devoted to detailed studies of the mentioned problems based on the analysis of experimental data and the corresponding Monte Carlo (MC) simulations.

The aims of the thesis

The main purpose of the work done during the thesis preparation was extraction of ARICH detector efficiency and mis-identification probability based on known decays such as $D^{*+} \to D^0 + \pi^+$ and $D^{*-} \to \bar{D}^0 + \pi^-$. Obtained tabulated (parameterized) values of ARICH efficiencies and mis-identification probabilities as a function of particle momentum and polar angle are very important ingredients for any physics analysis using the global PID, for which the information provided by ARICH is necessary. The procedure of extraction includes many components, such as fitting of invariant mass spectra, estimation of possible backgrounds using the information form MC simulated spectra, knowledge and experience with complicated Belle II software, and experience with details of ARICH functioning, obtained during many performed shifts.

Scientific novelty

The studies performed during the thesis preparation related to extraction of the ARICH efficiencies and mis-identification probabilities in two-dimensional (2D) momentum and polar angle space were performed for the first time. The results obtained provided more detailed information on the kinematic dependencies for ARICH performance. In addition, a possible dependence on the multiplicity of the track (number of charged tracks) was investigated for the first time. Another novelty is detailed studies of MC simulated invariant mass spectra with very high statistics, where the limitation on statistics in 2D space existing for experimental data can be overcome. Then based on achieved good MC/Data agreement such approach allowed to extract 2D dependencies for the performance in much more fine binning over momentum and polar angle.

Practical and experimental significance

The results for extraction of ARICH performance parameters in 1D and 2D phase space are already and will be intensively used by BELLE II collaboration in many analyses based on the necessity of hadrons separation with the set of PID detectors, where the ARICH is one of essential components. Also, in many other large experiments, where ARICH-like detectors are used and will be used, the obtained results and developed methods can be applied effectively.

Approbation of the work

The results used for this thesis were reported on international conferences (workshops), main meetings of Belle II collaboration, as well on many seminars at AANL. The results obtained were also presented during international conferences: in the "11th International Workshop on Ring Imaging Cherenkov Detectors" (Sept. 12-16, 2022, Edinburgh, UK) and in the "Recent Advances in Fundamental Physics" school and workshop(Sept.24-Oct.1, 2022, Tbilisi, Georgia).

Structure of the thesis

The dissertation work consists of an introduction, 5 chapters, a conclusion, an acknowledgment, a list of codes, and a list of references used. Altogether, it consists of 130 pages, includes 20 tables, and 300 plots. The thesis contains 40 publications.

The introduction describes the Belle II experiment [1][2], gives some information about the structure of the setup with some details of various sub-detectors. Furthermore, it gives us information about the physics goals of the Belle II experiment and explains which gaps in modern physics can be covered with the help of Belle II experiment.

Chapter 1 gives information about the BELLE II experiment, shows the overall setup of the SuperKEKB accelerator, describes different sub-detectors and presents the importance of this experiment as one of the most important experiments in particle physics and in the B-factory.

§**1.1** describes the SuperKEKB accelerator and the physical goals of it. SuperKEKB is a circular collider with a circumference of approximately 3 km, located 11 meters beneath the surface. It accelerates beams of electrons and positrons to nearly the speed of light, causing them to collide. Together with the Belle II detector, SuperKEKB serves as a facility aimed at exploring new physical phenomena that could provide insights into the fundamental mysteries surrounding the origins of the universe.

§**1.2** represents the BELLE II experiment. The physical characteristics of it and gives information about its sub-detectoral structure. Various detector components are arranged cylindrically around the beamline. The detector components can detect the individual degradation end products of the decay (such as electrons, muons, pions, and other particles).

§**1.2.1** reveals about "Inner and Tracking detectors" in Belle II experiment. The VerteX Detector (VXD) system which consists of two inner layers of a silicon PiXel Detector (PXD) followed by four layers of a Silicon Vertex Detector (SVD) is fundamental for reconstructing the vertex of B-mesons decays. The central drift chamber (CDC) that measures the trajectories, momenta, and dE/dx information of the charged particles.

§**1.2.2** demonstrates the electromagnetic calorimeter (ECL) which provides the detection of photons and particles π^0 from the decays of the B-meson. The ECL's energy resolution is crucial for distinguishing signal and background events, especially in high-energy collisions.

§**1.2.3** depicts the identification of muons and K_L mesons in the largest Belle II sub-detector which is KLM (K-Long-Muon). It is positioned in the gaps of the magnet yoke. Due to the distance between the interaction point and the metal in the yoke, only muons and K_L particles can penetrate and reach the KLM effectively.

§**1.2.4** illustrates trigger-and-data-acquisition in the Belle II experiment, which is used to select and store interesting events while reducing the data flow.

§**1.2.5** portrays the Particle Identification detectors used in the Belle II experiment. A barrel-shaped array of Time-Of-Propagation (TOP) counters reconstructs in spacial and time coordinates, the ring-image of Cherenkov light cones emitted from charged particles passing through quartz radiator bars. The Time-Of-Propagation (TOP) counter in the Belle II detector distinguishes pions from kaons, crucial for identifying B meson decays.

Another ring-imaging Cherenkov counter with aerogel radiator in the forward end-cap (A-RICH), is used to identify charged particles in the front-end endcap region of the Belle II spectrometer. Its main objective is to separate kaons from pions in the full kinematical region of the experiment (about 0.5-4.0 GeV). About ARICH we will talk in the next section.

Chapter 2 describes the principle and the design of the Belle II Aerogel RICH counter.

§**2.1** outlines the principles of Cherenkov radiation and Cherenkov detectors. The dedicated particle identification Cherenkov counters detect charged particles through the effect of Cherenkov radiation. Cherenkov radiation arises when a charged particle moves in a dielectric material faster than the light travels in the same material where the number of emitted photons depends on the charge of the particle.

§**2.2** presents the principle of particle identification in the Aerogel RICH counter. The fundamental operating principle of all Cherenkov detectors is consistent. They require a radiator material where Cherenkov photons are produced along with a medium where these photons can travel (often aided by mirrors or lenses to focus the photons). In addition, sensors are needed to detect photons. The design and choice of materials for the detector are determined by factors such as spatial constraints, desired signal resolution, and the need to differentiate between particles across a specific momentum range. In particle physics, momentum is typically used in place of velocity, so the focus is on the relevant momentum range for operation.

A schematic representation of the ARICH detector and its operation is shown in Fig.1.

§**2.3** describes the main components of the ARICH counter which are: re a double layer aerogel radiator for Cherenkov photon emission, an empty space for a Cherenkov light-cone ex- pansion, the Hybrid Avalanche Photo-Detector(HAP

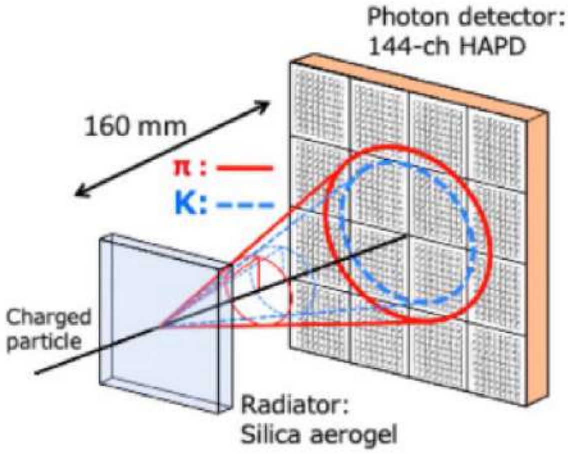


Figure 1: *The principle of the particle identification with the ARICH counter*

D) sensor plane and the read-out electronics, which were developed for the Belle II experiment [3][4].

§**2.2.1** gives insight into the radiator and explains the preferences of using the dual layer scheme which is adopted to improve angle resolution without reducing the number of detected Cherenkov photons [5][6][7].

§**2.2.2** gives the physical characteristics of a photon detector which is capable of single-photon detection and tolerance to the high magnetic field. As a photon detector, the HAPD Avalanche Photo Diode was developed [8][9].

§**2.2.3** describes the readout electronics for the ARICH system comprise Front End Boards (FEBs) and Merger Boards (MBs). In the ARICH system, the primary function is to measure the image of the ring, and only hit information is collected [10][11][12].

§**2.2.4** depicts Aerogel material and its properties. Aerogel is an extremely lightweight material known for its high optical transparency. Its structure resembles that of a gel, but the liquid component is replaced by gas. Aerogels vary depending on factors such as molecular structure, density, water interaction, and more.

Chapter 3 describes the performance of the Belle II Aerogel RICH counter [13]

§**3.1** informs us about the PID method [14]. For each charged track passing through ARICH, the value of the likelihood function for six particle hypotheses is evaluated: electron, muon, pion, kaon, proton, and deuteron. The separation between kaons and pions is performed by imposing selection criteria on the logarithms of likelihood ratios.

The separation between kaons and pions is performed by imposing selection criteria on the logarithms of likelihood ratios which are defined as

$$R_{K/\pi} = \frac{lnL_K}{lnL_K + lnL_\pi} \tag{1}$$

$$R_{\pi/K} = \frac{lnL_\pi}{lnL_K + lnL_\pi} \tag{2}$$

§**3.2** describes the probability density function(PDF) which is constructed from two parts: track-correlated and uncorrelated components. First, the track-correlated part is built as a function of the reconstructed Cherenkov angle, which corresponds to the Cherenkov angle for unscattered Cherenkov photons. The expected number of hits on a specific channel (denoted as ($n_{h,i}$)) is determined by projecting the correlated part of the PDF onto the photon-detector plane and integrating it over the surface of the pixel i. Additionally, the uncorrelated part of the PDF is added to this calculation

§**3.3** presents efficiency determination. The registration efficiency of ARICH detector as well as the mis-identification probability as a function of a particle momentum and polar angle are very important characteristics for any Particle Identification Detector (PID) in measuring of physical observables such as the cross-section, branching fractions and others. Usual approach to calculate the efficiency is based on usage of well-known resonance decays with pions, kaons, and protons in the final state. Identification performance is discussed in terms of identification efficiency ϵ and the mis-identification probability η. Both are determined as a ratio of the number of reconstructed D^* decays obtained with and without the identification selection criteria applied, i.e.:

$$\epsilon_K = \frac{number\ of\ K\ tracks\ after\ R_{K/\pi} > R_{cut}}{number\ of\ K\ tracks} \tag{3}$$

$$\epsilon_\pi = \frac{number\ of\ \pi\ tracks\ after\ R_{\pi/K} > R_{cut}}{number\ of\ \pi\ tracks} \tag{4}$$

$$\eta_K = \frac{number\ of\ K\ tracks\ after\ R_{\pi/K} > (R_{cut})}{number\ of\ K\ tracks} \tag{5}$$

$$\eta_\pi = \frac{number\ of\ \pi\ tracks\ after\ R_{K/\pi} > (R_{cut})}{number\ of\ \pi\ tracks}, \tag{6}$$

where $R_{\pi/K}$ and $R_{K/\pi}$ are defined by Eq.(1, 2) and R_{cut} is fixed after dedicated studies with typical values $R_{cut} = 0.6$.

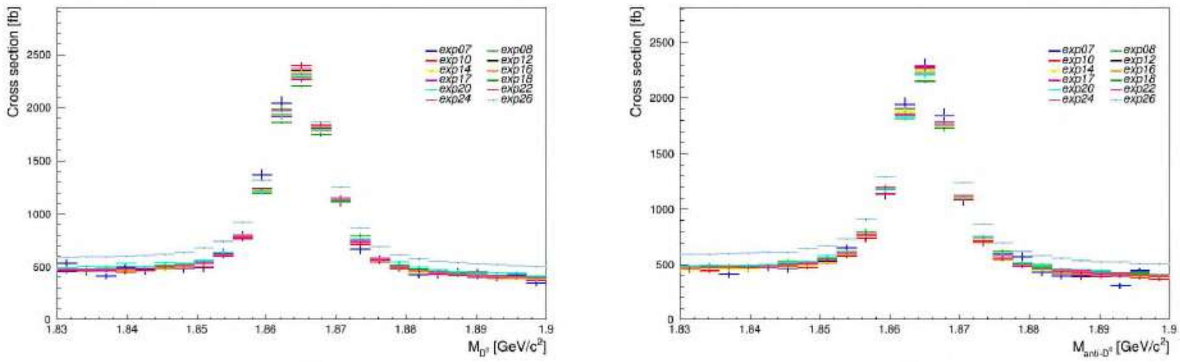
Chapter 4 describes the dataset that was used for our studies.

§ **4.1** refers to the selection of events for this thesis. To evaluate particle identification performance $D^{*\pm} \to D^0(\bar{D}^0)\pi^\pm \to (K^\mp\pi^\pm)\pi^\pm$ decays were used. Certain kinematic and geometric restrictions were applied to the decay product in order to have a more clean sample.

§ **4.2** indicates the dataset which was used as a Data sample. A subset of the Moriond 2023 dataset was used for this study. In the Belle II experiment, some amount of data collections is called an *experiment*. The compatibility between different data samples(*experiments*) was checked.

Fig. 2 shows the invariant mass distributions for D^0 and $\bar{D}^0$ where different colors correspond to different experiments and normalization was performed through cross sections.

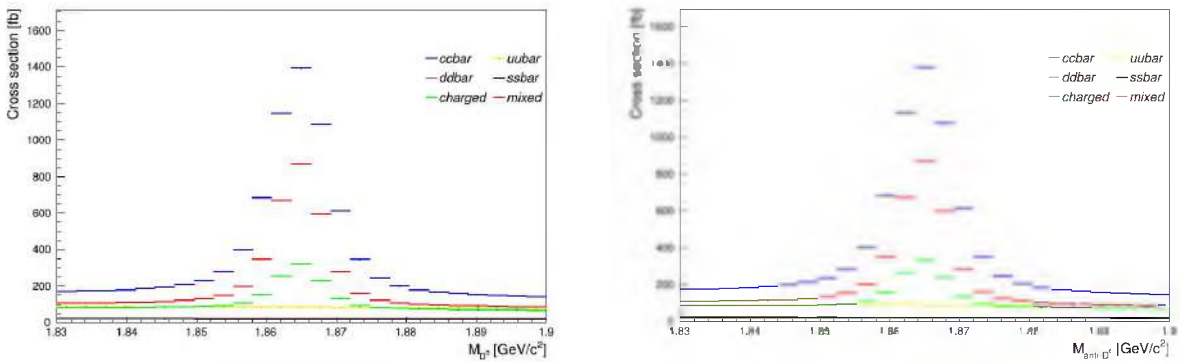
For final results, the combined sample was used with combined integrated offline luminosity 368.091 [fb^{-1}].



(a) (b)

Figure 2: *The invariant mass distributions for D^0 (a) and $\bar{D}^0$ (b).*

§ **4.3** portrays the dataset that was used for the MC sample and includes different combinations of quarks like $u\bar{u}, d\bar{d}, s\bar{s}, c\bar{c}$ as well as $B^0\bar{B}^0$, B^-B^+ pairs. With the integrated luminosity for each quark combination equal to 1000[fb^{-1}]. Since the reconstruction of the $D^{*-} \rightarrow D^0 + \pi^-$ and $D^{*+} \rightarrow \bar{D}^0 + \pi^+$ samples was done separately the compatibility between those samples was checked. The invariant mass distributions of the D^0 and $\bar{D}^0$ particles for different MC samples are shown in Fig. 3.



(a) (b)

Figure 3: *The invariant mass distribution for D^0 (a) and $\bar{D}^0$ (b).*

§ **4.4** shows the previous studies about ARICH efficiency and mis-identification probability studies [15] [16].

§ **4.5** indicates the technical steps that were taken to obtain these results. To perform this analysis a python code was written which allows us to reconstruct necessary particles. In this case $D^{*\pm} \rightarrow D^0(\bar{D}^0)\pi^\pm \rightarrow (K^\mp\pi^\pm)\pi^\pm$

decay was reconstructed. The slight changes on fallowing code may allow for the reconstruction off different particles, and also similar studies for other sub-detectors.

Later, codes were sent to the GRID system and after being done were downloaded to AANL, Belle local machine. In order to continue further studies *ROOT* and *JupiterNotebook* programs were used. We also wrote a code for fitting procedures as well as another code for checks of different distributions for different variables.

Chapter 5 shows the results obtained during these studies.

§ **5.1** indicates the comparison that was done between Data and MC run independent samples. Furthermore, the comparison quality dependence of different variables was shown and the most optimal restrictions were chosen for further studies. Fig. 4 shows the comparison between Data vs. MC samples for $D^0\bar{D}^0$ invariant mass distributions.

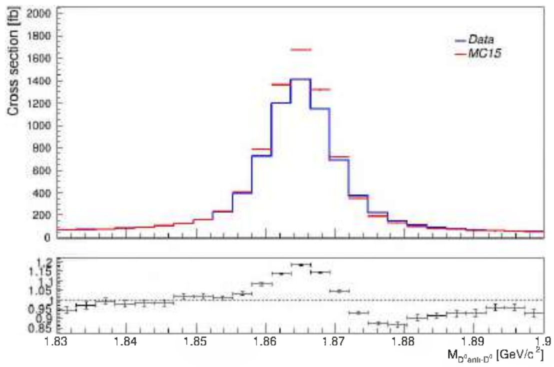


Figure 4: *The invariant mass distribution of $D^0\bar{D}^0$ for Data and MC samples.*

§ **5.1.1** since the Data vs MC15ri(run independent) samples had some difference in signal region, it was decided to generate the MC15rd (run dependent) sample and compare it with the MC run independent and Data samples. The comparison shows (Fig. 5) that there is a good agreement between MC15ri vs. MC15rd samples but still not a good agreement between Data vs. MC15rd samples in the signal region.

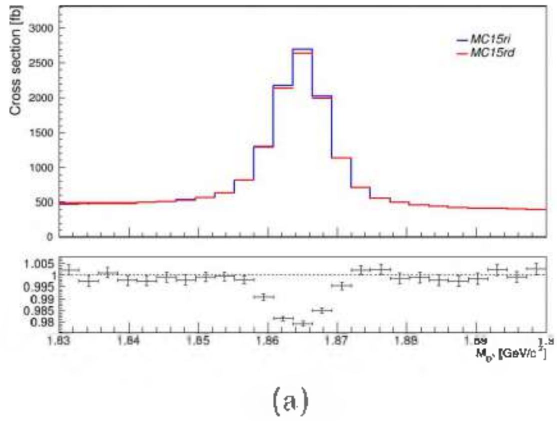


Figure 5: *The invariant mass distribution for $D^0\bar{D}^0$ for MCrd vs. MCri vs. Data samples.*

§ **5.2** describes the RooFit tool, which was used to perform a large amount of necessary fitting procedures. Different fit options were checked, and the best one was chosen for further studies which is Double Gaussian and Chebyishev polynomial.

Fig. 6 shows an invariant mass fit of $D^0\bar{D}^0$ with double Gaussian and 1^{st} order of the Chebyshev polynomial.

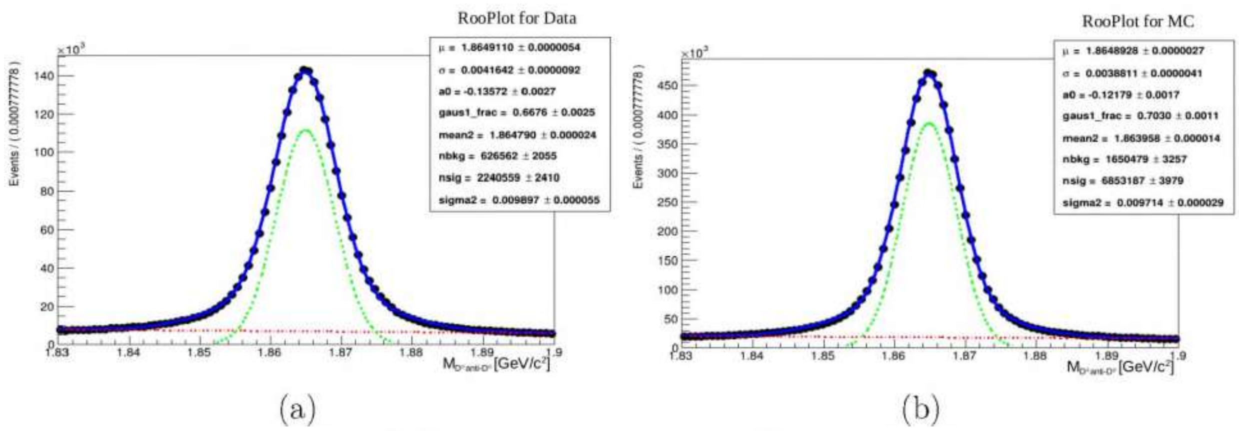


Figure 6: *The fitted $D^0\bar{D}^0$ invariant mass distributions for Data (a) and MC (b) with double Gaussian + 1^{st} order of Chebyshev polynomial.*

§ **5.3** shows the calculated efficiency and mis-identification probabilities for kaons and pions for Data and MC samples in momentum and polar angle bins. For these studies 6×6 two-dimensional binning over momentum and polar angle was used as shown in Table 1:

p bins [GeV/c]	θ bins [rad]
[0.3;1.0]	[0.30;0.36]
[1.0;1.7]	[0.36;0.39]
[1.7;2.4]	[0.39;0.42]
[2.4;3.1]	[0.42;0.45]
[3.1;3.8]	[0.45;0.49]
[>3.8]	[0.49;0.53]

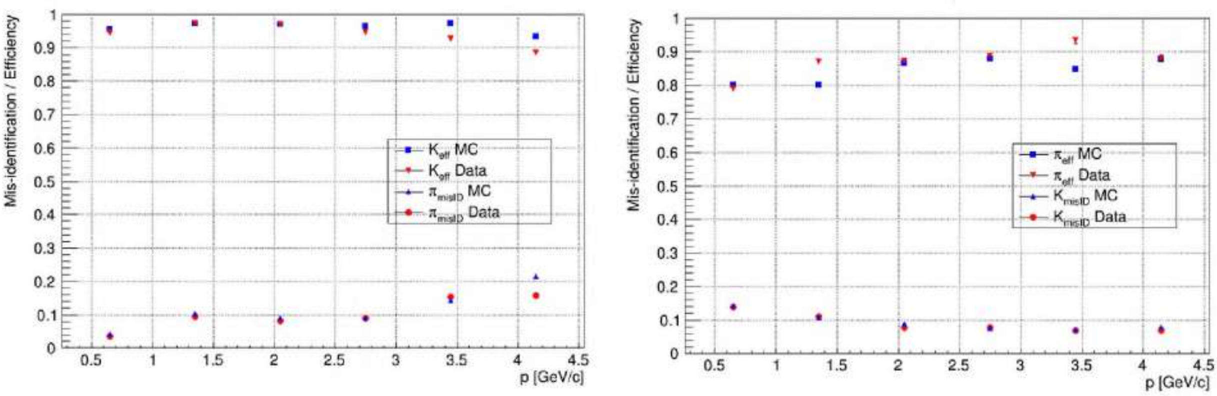
Table 1: *2D bining for kaons and pions*

Using Eq.(3-6) we calculated the efficiency and mis-identification probability values for kaons and pions obtained for Data and MC. For this purpose, we use the binning over momentum and the polar angle shown in Table 1.

The efficiency and mis-identification probability values are determined as $\epsilon = A \pm \sigma_A / B \pm \sigma_B$, where A, σ_A, B, σ_B is defined from fitting procedures. For this purpose, bin-by-bin fitting was performed. Furthermore, the efficiency and mis-identification uncertainty values σ_ϵ were determined from the equation:

$$\sigma_\epsilon = \frac{1}{B}\sqrt{\epsilon^2\sigma_B^2 + \sigma_A^2 - 2\epsilon^{2/3}\sigma_A\sigma_B} \tag{7}$$

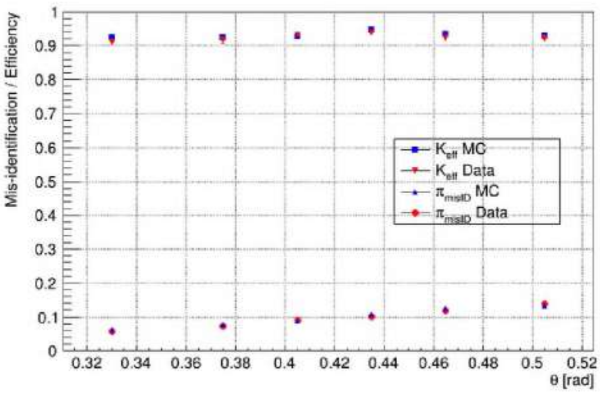
The efficiencies and mis-identification probability values in the one-dimensional frame over momentum binning can be seen in Fig. 7.



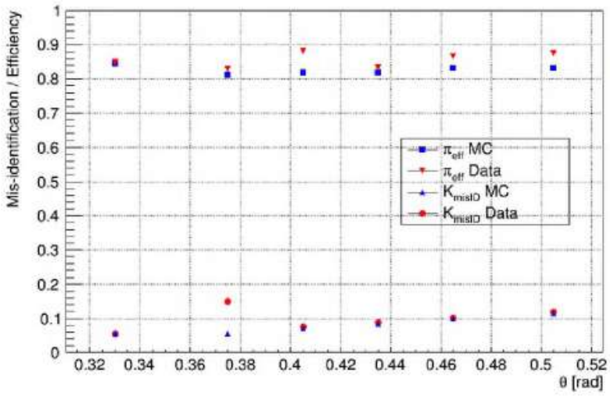
(a) (b)

Figure 7: *Efficiencies and mis-identification dependencies in momentum binning.*

And Fig. 8 shows the calculated efficiencies and mis-identification probabilities for kaons and pions for Data and MC samples over polar angle bins.



(a)



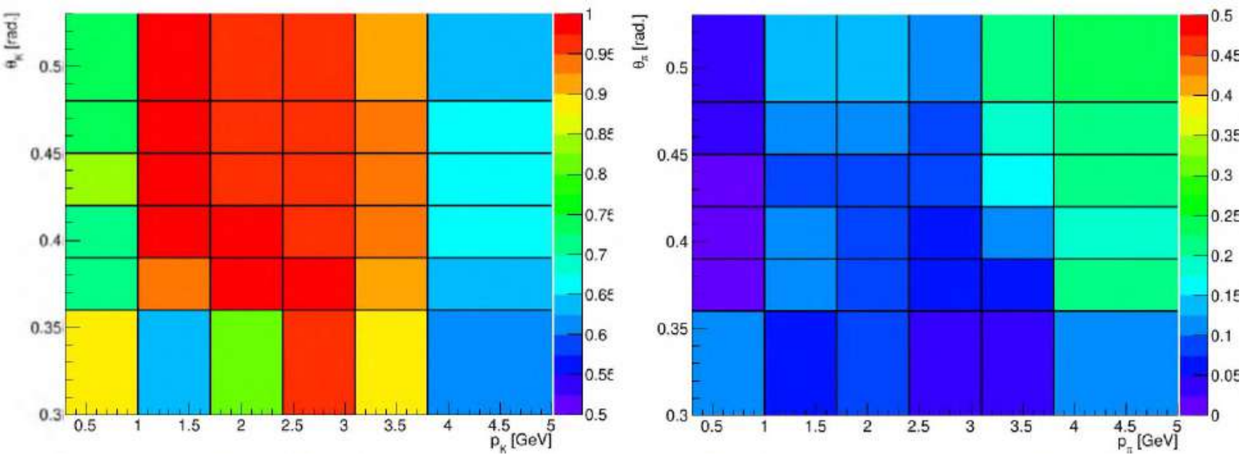
(b)

Figure 8: *Efficiencies and mis-identification dependencies over polar angle binning.*

As can be seen from the obtained results, in general there is good agreement between the Data and MC samples. *Kaon* detection efficiency for all bins in the above bins from 90% and defers from 91-94%. Meanwhile, *pion* detection efficiency is higher than 80% and is delayed from 81-87%. Furthermore, the mis-identification probability for *kaon* is changed from 5-12%. It reaches its minimum value for the small momentum bins and its highest value for higher momentum bins. For the *pion* mis-identification probability is lowest for the smallest momentum bins and about 6% but reaches its maximum for highest momentum bins until 13%.

§ **5.3.2** indicates the calculated 2D efficiency and mis-identification probability values for kaons and pions for Data and MC samples in the momentum and polar angle bins with respect to each other.

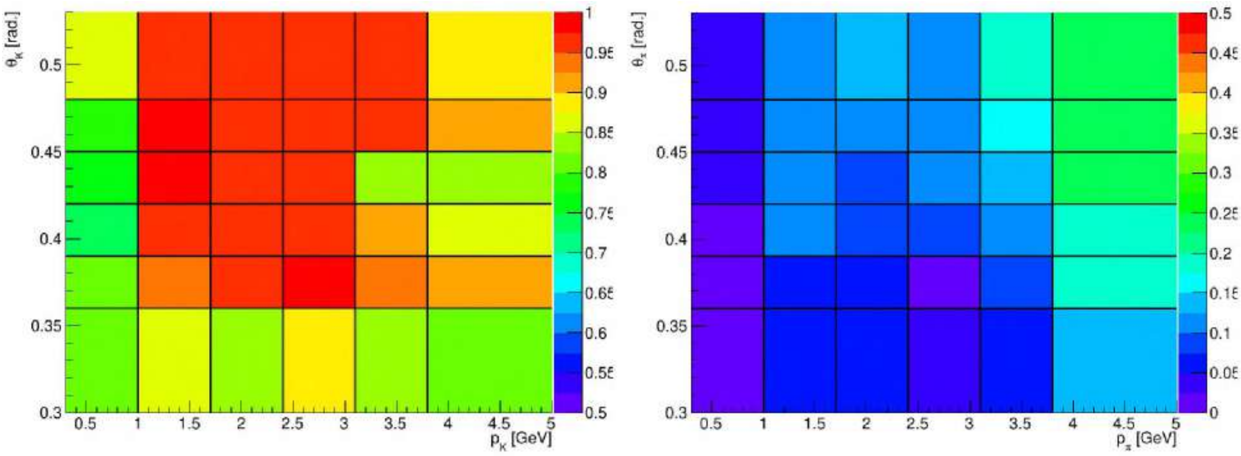
Fig. 9 shows the 2D efficiency frame for kaons and mis-identification frame for pions based on Data results.



(a) (b)

Figure 9: *2D efficiency plot for kaon(a) and mis-identification plot(b) for pion based on Data results.*

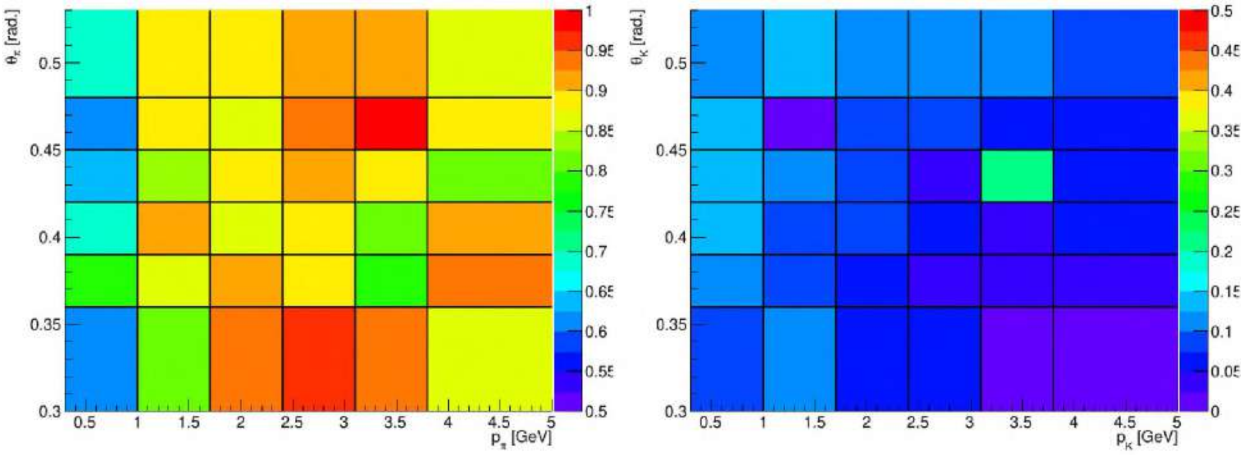
Fig. 10 shows the 2D efficiency frame for kaons and mis-identification frame for pions based on MC results and Fig. 11 shows the 2D efficiency frame for pions and mis-identification frame for kaons based on Data results.



(a) (b)

Figure 10: *2D efficiency plot for kaon(a) and mis-identification plot(b) for pion based on MC results.*

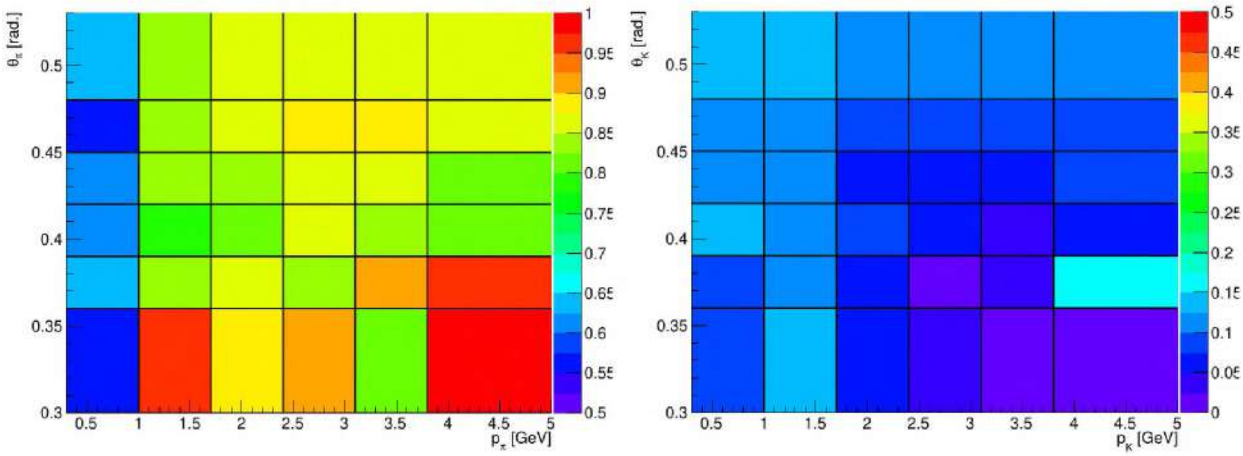
As can be seen in Figs. 9 (a) and 10 (a), the kaon efficiency is low for low- and high-momentum bins, meanwhile, it is higher for middle-momentum and high-polar angle bins. Furthermore, as can be noticed in Figs. 9 (b) and 10 (b), the pion mis-identification probability is low for small momentum bins and higher for high momentum bins, which explains the low kaon efficiency in high-momentum bins. Moreover, there is good agreement between Data (Fig. 9) and MC (Fig. 10) samples for the kaon detection efficiency and pion mis-identification probability values in the 2D frame.



(a) (b)

Figure 11: *2D efficiency plot for pion(a) and mis-identification kaon(b) for pion based on Data results.*

Fig. 12 shows the 2D efficiency frame for pions and mis-identification frame for kaons based on MC results.

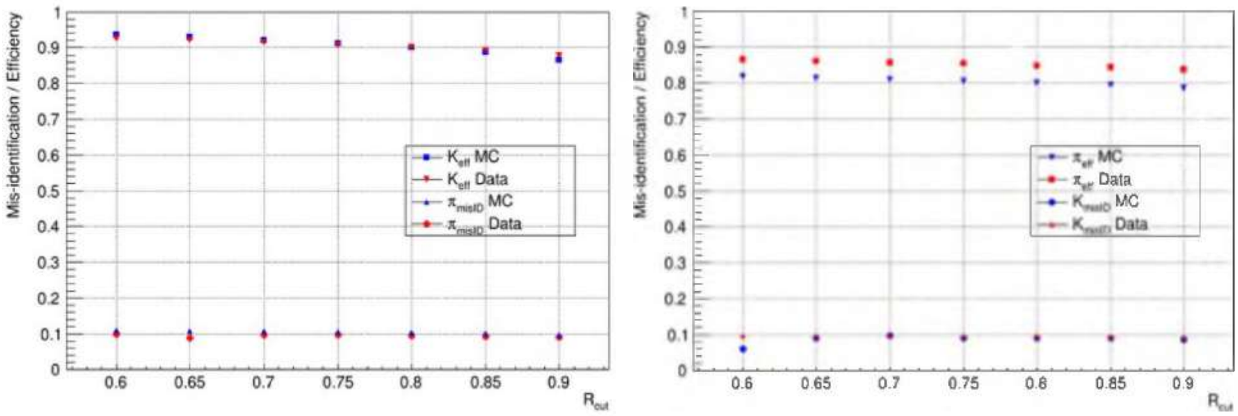


(a) (b)

Figure 12: *2D efficiency plot for pion(a) and mis-identification plot(b) for kaon based on MC results.*

As can be seen in Figs. 11 (a) and 12 (a), the pion efficiency is low for low-momentum bins, meanwhile, it is higher for middle- and high-momentum bins. Moreover, those 2D results prove the noticeable difference between Data and MC for pion efficiencies which was caused due to a release problem. Furthermore, as can be noticed in Figs. 11 (b) and 12 (b), the pion mis-identification probability is low for all momentum bins and there is good agreement between Data and MC samples for kaon mis-identification.

§ **5.3.3** refers to the efficiency and mis-identification probability values with respect to the dependence of the R variable which is the ratio of two loglikelihood functions. Fig. 13 shows the efficiency and mis-identification probability dependencies of the koan and pion over the R variable.



(a) (b)

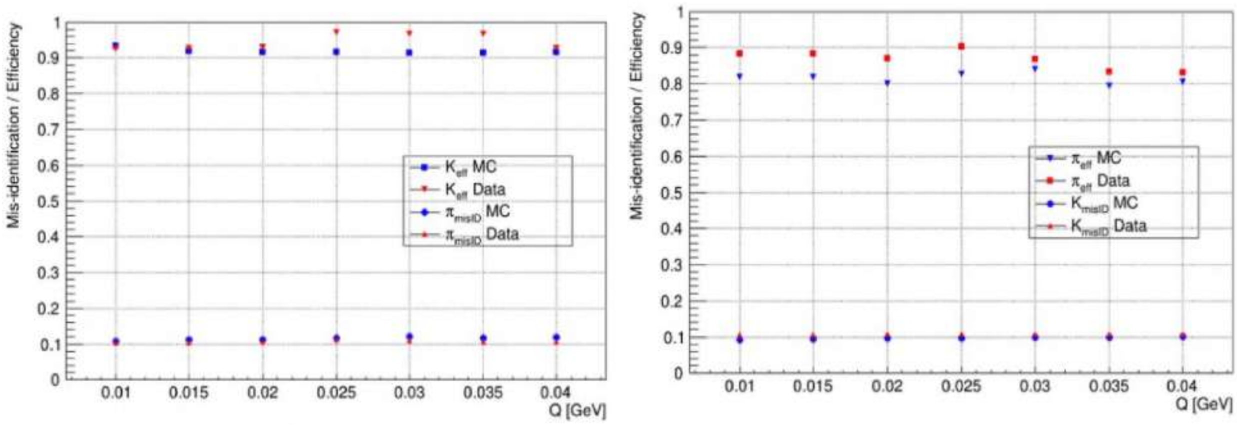
Figure 13: *Koan and pion efficiency and mis-identification probability dependence over R variable.*

As we can see from obtained results there is a good agreement between Data and MC samples for kaon efficiencies and pion mis-identification probabilities(Fig. 13(a)).

Meanwhile, for pion detection efficiency (Fig. 13(b)) we see a shifted results between Data and MC. Detection efficiency for Data on average estimated about 4-5% is higher from the MC results. This phenomenon has been noticed in other Belle II analyses and was related to *release*06. This problem exists only in *release*06 and was fixed in higher releases. Whereas the kaon mis-identification probability is mainly constant and in average it is about 9-10%.

§ **5.3.4** refers to the efficiency and mis-identification probability values with respect to the dependence of the Q variable, which is the energy released in decay.

Fig. 14 shows the dependence of the koan and pion efficiency and the mis-identification probability on the Q variable.



(a) (b)

Figure 14: *Koan and pion efficiency and mis-identification probability dependence over Q variable.*

As we can see from the results obtained there is mainly a good agreement between Data and MC samples for kaon efficiencies(figure 14(a)) except for few points where we see that the efficiency obtained for Data is higher than that for the MC. Meanwhile, from (Fig. 14(b)) we see slightly shifted results for pion efficiencies between Data and MC samples. As was explained above, this is a release problem and was fixed in later releases. Furthermore, for pion(figure 14(a)) and kaon (figure 14(b)) mis-identification probabilities we see a good agreement between Data and MC. In general, kaon efficiency varies from 91.4-97.13% and for pions its 80-90%. Overall, the kaon mis-identification probability in average is about 9.2-10%, meanwhile for pions it is about 11-12%.

Conlusion briefly presents the information presented throughout the thesis and states its main results:

Main results

The efficiency and mis-identification probabilities via momentum and polar angle binning for Belle II ARICH counter were calculated for pions and kaons. The results obtained for Data and MC samples are in good agreement with each other and match the previous obtained results in Belle II.

Conclusion

The physical program of the Belle II experiment requires prompt reconstructions of different decaying particles, which means the separation of final-state hadrons. This is provided with the set of PID detectors, including the ARICH-aerogel Cherenkov detector, which is one of the most important ones. Separation is performed with the combined PID information from all PID sub-detectors. Thus, the studies of ARICH performance performed during the preparation of this thesis are very important to provide an effective global PID. The efficiencies and mis-identification probabilities determined as a function of charged particle momentum or polar angle, as well as two-dimensional values of mentioned characteristics determined for both: momentum and angle, are essential ingredients for look-up tables used to be included into the final criteria of global PID. In order to extract the performance dependencies, well-known decays like $D^{*\pm} \to D^0(\bar{D}^0)\pi^\pm \to (K^\mp\pi^\pm)\pi^\pm$ were reconstructed from Belle II data, also necessary Monte Carlo studies were performed to estimate possible backgrounds. In addition to momentum and polar angle dependencies, possible influence on track multiplicity has also been investigated.

Author’s relevant published papers

- G. Ghevondyan, "Performance study of the aerogel RICH at the Belle II experiment". Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Volume 1056, November 2023, 168584 https://doi.org/10.1016/j.nima.2023.168584

- N. Akopov, G. Ghevondyan, V. Muradyan, G. Karyan "Investigations of Characteristics for Arich Detector with D*±-Mesons Decay at Belle II Experiment Using the Monte Carlo Method". J. Contemp. Phys. 58, 24–30 (2023). https://doi.org/10.1134/S1068337223010036

- L. Santelj, I. Adachi, ..., G. Ghevondyan et al. "Recent developments in data reconstruction for aerogel RICH at Belle II", Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Volume 1055, October 2023, 168502 https://doi.org/10.1016/j.nima.2023.168502

- I. Adachi, ... N. Akopov, ..., G. Ghevondyan et al. (Belle II Collaboration). “Measurement of branching fractions and direct CP asymmetries for $B \to K\pi$ and $B \to \pi\pi$ decays at Belle II”. In: Physical Review D 109, 012001 (2024). https://doi.org/10.1103/PhysRevD.109.012001

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ARICH գրանցիչի կատարողականության ուսումնասիրությունը, որպես լիցքավորված մասնիկների նույնականացման կարեւոր բաղադրիչներից մեկը BELLE II գիտափորձում

Ամփոփագիր

Բարձր էներգիաների արագացուցիչների հետազոտությունների կազմակերպության (KEK, Ցուկուբա, Ճապոնիա) SuperKEKB ասիմետրիկ կոլայդերի վրա իրականացվող Belle II գիտափորձը նպատակ ունի գտնել CP-ասիմետրիա տարբեր հազվադեպ տրոհումներում, ինչպես նաև Նոր ֆիզիկա, որը դուրս է գալիս Ստանդարտ Մոդելի սահմաններից: Գիտափորձը նախատեսում է բարձր վիճակագրությամբ՝ մինչեւ 50[ab^{-1}] ինտեգրալ լուսատվությամբ տվյալների հավաքագրում: Դրան նախորդող Belle գիտափորձը թույլ էր տալիս հայտանաբերել եւ գրանցել մինչև 2 [GeV/c] իմպուլսներով պիոններ և կաոններ գրանցիչի առաջնային շրջանում: Սակայն Belle II գիտափորձում, Նոր ֆիզիկայի որո-նումների համար, օրինակ՝ $B\rightarrow\rho\gamma(\rho\rightarrow\pi\pi)$ պրոցեսներում, անհրաժեշտ է հայտնաբերել եւ գրանցել ավելի բարձր իմպուլսներով լիցքավորված մասնիկներ՝ մինչև 4 [GeV/c]:

Նշված խնդիրը լուծելու համար Belle II սպեկտրոմետրին ավելացվել է մասնիկների նույնականացման (PID) լրացուցիչ գրանցիչ, որը կոչվում է Aerogel Ring Imaging Cherenkov (ARICH): ARICH գրանցիչի կատարողա-կանության արդյունավետությունը և սխալ նույնականացման հավանականությունը կախված մասնիկի իմպուլսից եւ բեւեռային անկյունից կարևոր բնութագրեր են, որոնք խիստ կարևոր են ֆիզիկական վերլուծության համար: Ընդհանրապես, արդյունավետության հաշվարկի մոտեցումը հիմնված է հայտնի ռեզոնանսների տրոհումների վրա, որոնց վերջնարդյունքում ստացվում են պիոններ, կաոններ և պրոտոններ:

Այս ուսումնասիրության մեջ գնահատվել է ARICH գրանցիչի կողմից $D^{*\pm}\rightarrow D^0(\bar{D}^0)\pi^\pm\rightarrow(K^\mp\pi^\pm)\pi^\pm$ տրոհումից առաջացած պիոնների և կաոնների գրանցման արդյունավետությունը եւ կեղծ նույնականացումը, որպես ֆունկցիա իմպուլսից և բևեռային անկյունից: Նշված աշխատանքում մշակվել է կոդ, որը թույլ է տալիս վերականգնել $D^{*\pm}$ մասնիկները՝ հիմնվելով փորձից ստացված տվյալների և Մոնտե-Կառլո մոդելավորման արդյունքների վրա: Ստացված փորձարարական և Մոնտե-Կառլո տվյալները համեմատվել են իրար հետ և ստուգվել է դրանց միջեւ համապատասխանությունը: Մասնիկների ինվարիանտ զանգվածների սպեկտրները ենթարկվել են ֆիթինգի, որի արդյունքում ընտրվել է առավել համապատասխան տարբերակը, այն է կրկնակի Գաուսյան և Չեբիշևի պոլինոմիալ ֆունկցիաներ:

Հաշվարկվել է նաև պիոնների և կաոնների սխալ նույնականացման հավա-նականությունը ըստ իմպուլսի և բևեռային անկյան տարբեր արժեքների, որի արդյունքում ստացվել են մեկչափանի եւ երկչափ

պատկերներ: Ստացված արդյունքները համընկնում են նախկինում ստացված արդյունքների հետ: Դիսերտացիայի ժամանակ ստացված երկչափ արդյունքները ըստ իմպուլսի եւ բեւեռային անկյան, որոնք վերաբերում են ARICH գրանցիչի կողմից կաոնների ու պիոնների արդյունավետ գրանցմանն ու կեղծ նույնականացման հավանականությանը, կատարվել են առաջին անգամ: Ստացված արդյունքները տրամադրել են ավելի մանրամասն տեղեկություններ ARICH-ժ գրանցիչի կատարողականության կինեմա-տիկական կախվածությունների մասին: Իրադարձության տոպոլոգիայից (լիցքավորված հետքերի քանակից) հնարավոր կախվածությունը նույնպես ուսումնասիրվել է առաջին անգամ: Մեկ այլ նորություն է Մոնտե Կառլո սիմուլյացիայից ինվարիանտ զանգվածի սպեկտրների մանրամասն ուսումնասիրությունը շատ բարձր վիճակագրությամբ, որտեղ հաղթահարելի է փորձարարական տվյալների համար գոյություն ունեցող երկչափ տարածության վիճակագրության սահմանափակումը:

ARICH գրանցիչի կատարողականության պարամետրերի ստացման արդյունքները միաչափ և երկչափ Ֆազային տարածություններում այժմ էլ կիրառվում են եւ լայնորեն կկիրառվեն BELLE II համագործակցության կողմից բազմաթիվ վերլուծություններում, որոնք պահանջում են հադրոնների բաժանում: Բազմաթիվ այլ փիտափորձերում, որտեղ օգտագործվում են ARICH գրանցիչի տիպի գրանցիչներ, ստացված արդյունքները և մշակված մեթոդները կարող են արդյունավետ կիրառվել:

Изучение производительности детектора ARICH, как одного из основных компонентов идентификации заряженных частиц в эксперименте Belle II

Резюме

Эксперимент Belle II на асимметричном e^+e^- коллайдере SuperKEKB в Исследовательской организации ускорителей высоких энергий (KEK, Цукуба, Япония) нацелен на поиск CP-асимметрии в различных редких распадах, а также на новую физику, выходящую за пределы Стандартной Модели, и предполагает набор данных с высокой статистикой, соответствующей интегральной светимости 50 ab^{-1}. Его предшественник, эксперимент Belle, позволял идентифицировать пионы и каоны с импульсами до 2 [ГэВ/с] в передней области детектора. Однако, в экапериментe Belle II для поиска новой физики в таких процессах, как $B \to \rho\gamma(\rho \to \pi\pi)$, необходима идентификация заряженных частиц в передней области с более высокими значениями импульсов вплоть до 4 [ГэВ/с]. Для реализации этой проблемы к спектрометру Belle II было добавлен дополнительный детектор идентификации частиц (PID), называемый черенковским счетчиком изображений аэрогелевого кольца (ARICH). Эффективность и вероятность ложной идентификации сигналов детектора ARICH в зависимости от импульса частицы и угла являются основными характеристиками, существенными для физического анализа. Обычный подход к расчету эффективности основан на использовании известных распадов резонансов с пионами, каонами и протонами в конечном состоянии.

В указанной работе была оценена эффективность регистрации детектором ARICH пионов и каонов в расспаде $D^{*\pm} \to D^0(\bar{D}^0)\pi^\pm \to (K^\mp\pi^\pm)\pi^\pm$, как функция от импульса и полярного угла. На предварительном этапе работы был разработан код, позволяющий восстанавливать $D^{*\pm}$ частицы на основе данных, полученных в результате эксперимента и моделирования Монте-Карло. Полученные экспериментальные данные и данные Монте-Карло сравнивались между собой и проверялось соответствие между ними. Спектры инвариантных масс частиц были подвергнуты подгонке, в результате которой были выбраны наиболее подходящие варианты в виде функции Гаусса и полинома Чебышева. Были рассчитаны эффективность и вероятность ложной идентификации пионов и каонов по бинам импульсов и полярных углов, в результате чего были получены одномерные и двумерные изображения. Результаты эффективности и ложной идентификации также рассчитывались в зависимости от других параметров. Полученные результаты согласуются с ранее полученными результатами.

Исследования, проведенные во время подготовки диссертации, связанные с извлечением эффективностей детектора ARICH и вероятностей оши-

бочной идентификации в двумерном (2D) пространстве импульса и полярного угла, были выполнены впервые. Полученные результаты предоставили более подробную информацию о кинематических зависимостях для производительности детектора ARICH. Также впервые была исследована возможная зависимость от топологии события (количества заряженных треков). Еще одной новинкой являются подробные исследования моделируемых MC инвариантных массовых спектров с очень высокой статистикой, где ограничение на статистику в 2D пространстве, существующее для экспериментальных данных, может быть преодолено.

Результаты по извлечению параметров производительности детектора ARICH в 1D и 2D фазовом пространстве уже использовались и будут интенсивно использоваться коллаборацией BELLE II во многих анализах, основанных на необходимости разделения адронов с помощью набора детекторов PID, где ARICH детектор является одним из основных компонентов. Также, во многих других больших экспериментах, где используются и будут использоваться детекторы типа ARICH, полученные результаты и разработанные методы могут быть эффективно применены