Nonlinear Dynamics and Applications. Vol. 29 (2023) 27 - 31

Particle Identification in SPD

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Particle identification is an important part the reconstruction procedure which will be used in the analysis of data of the future SPD (Spin Physics Detector) experiment at the NICA (Nuclotron-based Ion Collider fAcility) collider. Several identification techniques are exploited in SPD to cover the momentum range up to 2.7 GeV. In this analysis, methods of particle identification based on specific energy loss in straw tubes and time of flight measurements will be presented. The study was done using the SpdRoot framework. The results are shown for pion, kaon and proton particles.

PACS numbers: 29.90.+r
Keywords: SPD NICA experiment, PID

1. Introduction

In particle physics experiments, Particle Identification (PID) plays an important role by contributing to the better understanding of investigated physics processes and enhancing the signal-to-background ratio. For this purpose, various specialized detectors will be constructed to identify different types of particles. The SPD (Spin Physics Detector) [1], is planned to be placed at the second interaction point of the NICA collider, which is currently under construction at the Joint Institute for Nuclear Research in Dubna. The SPD setup will be a universal 4π spectrometer based on a variety of advanced technologies. The NICA facility will offer polarized proton-proton and deuteron-deuteron collisions at the maximum center-of-mass total energy of approximately 27 GeV and 13.5 GeV, respectively. The maximum luminosity for proton and deuteron collisions will be 10^{32} and 10^{31} $cm^{-2}s^{-1}$, respectively.

The detector is conventionally divided into three parts: barrel and two end-caps. The reconstruction of secondary vertices will be provided by the silicon vertex detector (VD) achieving a vertex position resolution below 100 μm. The momentum of the particle tracks will be determined in a tracking system based on straw tubes (ST) measuring the drift times in a working gas. The ST will be placed within a solenoidal magnetic field of up to 1T at the detector axis and will provide a transverse momentum resolution of $\sigma_{p_T}/p_T \approx 2\%$ for a particle momentum of 1 GeV/c. The particle track reconstruction is performed in VD and ST. The shashlyk-type electromagnetic calorimeter serves for the photon detection. The muon (range) system is intended for muon identification. The pair of beam-beam counters and zero-degree calorimeters will be used for the local polarimetry and luminosity control. Hadron identification will be accomplished by a set of subsystems, such as the time-of-flight system (TOF) based on Multigap Resistive Plate Chamber technology, an aerogel-based Cherenkov detector, and ST which will use the energy losses per unit length (dE/dx) of charged particles in the gas for PID. This work presents the simulation results for ST and TOF demonstrating its limits of applicability for particle identification in the SPD setup.

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2. Analysis techniques

The simulation of the SPD setup was done in the SpdRoot framework, based on the FairRoot software [2]. It takes into account the magnetic field and the material map in the detectors. An artificial set of particle (pions, kaons, and protons) uniformly distributed over azimuthal and polar angles with a momentum step of 0.01 GeV from 0.1 GeV to 3.5 GeV was generated. The particles were emitted from the central part of the detector. The transport of the particles through the material and magnetic field of the SPD setup was supplied by Geant4 [3]. Track fitting was performed using the GenFit toolkit [4].

The TOF has a cylindrical geometry: two end-caps and a barrel with a radius of 1 m and a length of about 3.72 m. It measures the flight times of particles with an intrinsic resolution of 60 ps. The formula for determining the mass of a particle has a form:

$$m = p\sqrt{\left(\frac{t}{L}\right)^2 - 1} \tag{1}$$

where m - mass of the particle, p - momentum of the particle, t - time of flight, L - path length of the particle track. The values of L and p are determined during the procedure of track fitting.

The ST barrel consists of 31 double layers, and the ST end-cap has 8 double layers. Each layer is made of straw tubes with a diameter of 1 cm. The dE/dx is taken from simulation by GEANT4 and described by the Bethe-Bloch formula [5]. The dE/dx of a track is measured by calculating the truncated mean of the dE/dx values associated with the track. The truncated mean is calculated by averaging over the 65% lowest energy deposit measurements in order to reduce the Landau tail.

The two most popular approaches to identifying charged particles are the n-sigma method and the Bayesian approach. The n-sigma approach is the most frequently used in particle identification due to its simplicity. In this approach, a comparison is made between the expected detector response for a particular track, assuming a specific particle species hypothesis, and the raw measurement, e.g. t_{TOF} or dE/dx, dividing by the detector resolution. This can be formulated the following way:

$$n_{\sigma^i_\alpha} = \frac{S_\alpha - \hat{S}(H_i)_\alpha}{\sigma^i_\alpha}, \quad \text{where} \quad i = \pi, K, p \quad \alpha = \text{ST, TOF} \tag{2}$$

where S_α, $\hat{S}(H_i)_\alpha$ and σ^i_α represent measured, mean expected response and detector resolution for a given detector α, respectively, while i denotes the particle species hypothesis used in the expectation. The value of n_σ is typically chosen to be 3. This means that the fraction of signal accepted by this approach is $\sim$ 99.7%. If the response is perfectly Gaussian, then it is possible to combine the n_σ values as a quadratic sum to account for multiple detectors.

The response of the detector needs to be parameterized as a function of momentum for pions, kaons, and protons. For TOF, the parametrization is obtained as a function of the m^2 value versus the track momentum. For ST, the parametrization is obtained as a function of the dE/dx value versus the track momentum. The distribution response of the detector as a function of momentum can be seen in Fig. 1 where the 3σ intervals for each type of particles are indicated by lines. It can be seen from Fig. 1 that the parametrization behaves differently for tracks crossing the barrel and the end-caps. For TOF, this is due to the fact that the average particle flight length is different, $L \sim 1$ m for the barrel and $L \sim 1.86$ m for end-caps. The explanation for the ST is related to the different number of layers in the barrel and end-cap. The Table 1 shows the upper limit

Table 1: Upper limits in momentum for 3σ separation of π/K and K/p in ST and TOF

Detectors	π/K		K/p	
	Barrel	End-Cap	Barrel	End-Cap
ST	0.6 GeV	0.45 GeV	1.1 GeV	0.85 GeV
TOF	1.2 GeV	1.6 GeV	2.0 GeV	2.7 GeV

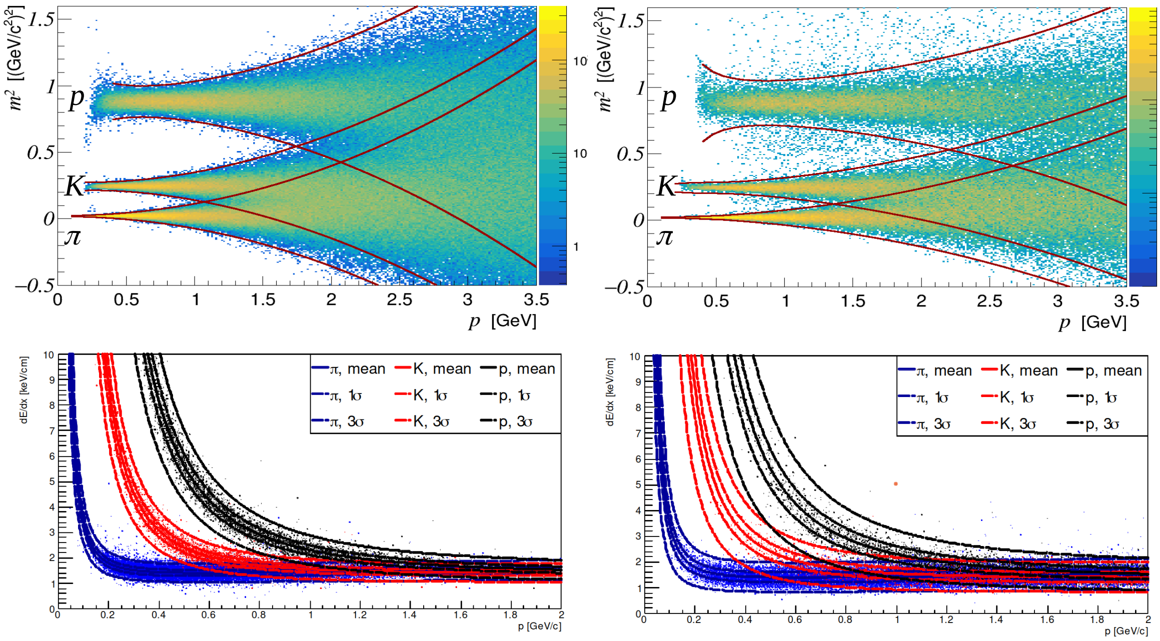

Figure 1: The upper plots show the m^2 distribution reconstructed from TOF data as a function of the track momentum for pions, kaons, and protons. The lower plots show the dE/dx truncated mean distribution reconstructed from ST data as a function of the track momentum for pions, kaons, and proton. The lines indicate the 3σ regions for each particle type. Results are shown for tracks crossing the barrel (left column) and the end-caps (right column).

in momentum for 3σ separation of π/K and K/p in ST and TOF for different parts of the SPD setup.

The Bayesian approach represents a more advanced strategy that incorporates statistical uncertainties within measurements. It works by assigning a probability to each particle species, given the measured values of the particle's momentum. Assuming a Gaussian distribution, it can be expressed as a conditional probability $P(S|H_i)$ that a particle of species H_i will produce a signal S. It is given by the following relation:

$$P(S|H_i) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}n_\sigma^2}, \tag{3}$$

where n_σ is defined in Eq. 2. The probability is described by an alternative parameterization appropriate to the detector. The probabilities from different detectors can be combined. The variable of interest is the conditional probability $P(H_i|S)$ that the particle is of species H_i, given some measured detector signal. The relation between the two probabilities can be expressed by applying the Bayes' theorem [8]

$$P(H_i|\vec{S}) = \frac{P(\vec{S}|H_i)C(H_i)}{\sum_{k=\pi,K,p} P(\vec{S}|H_k)C(H_k)}, \tag{4}$$

where $C(H_i)$ denotes the a priori probability of detecting the particle species H_i, commonly referred to as the prior, and the conditional probability $P(\vec{S}|H_i)$ is known as the posterior probability. The $\vec{S}$ means the set of detector signals. The priors act as an informed estimate of the relevant particle yields, which are influenced by the sample's conditions, such as the beam type and $\sqrt{s}$. More details about this approach can be found at [6].

3. Results of comparison of two methods

In order to compare the capabilities of the two above-described PID methods, their performance is described in terms of the efficiency $E(i,p)$ and the contamination $K(i,p)$. For this study, proton-proton collisions were simulated at a center-of-mass energy $\sqrt{s} = 27$ GeV using the Pythia 8 generator [7] with the 'soft QCD processes' option enabled. The $E(i,p)$ and the $K(i,p)$ for the particle type i (pions, kaons and protons) in each momentum p bin are defined as $E(i,p) = N_{good}(i,p)/N_{true}(i,p)$ and $K(i,p) = N_{fake}(i,p)/N_{ID}(i,p)$, where N_{good} is the number of particles of type i correctly tagged as i, N_{true} is the number of generated particles of type i, N_{fake} is the number of particles tagged as i without being of type i and N_{ID} is the total number of tracks identified as i.

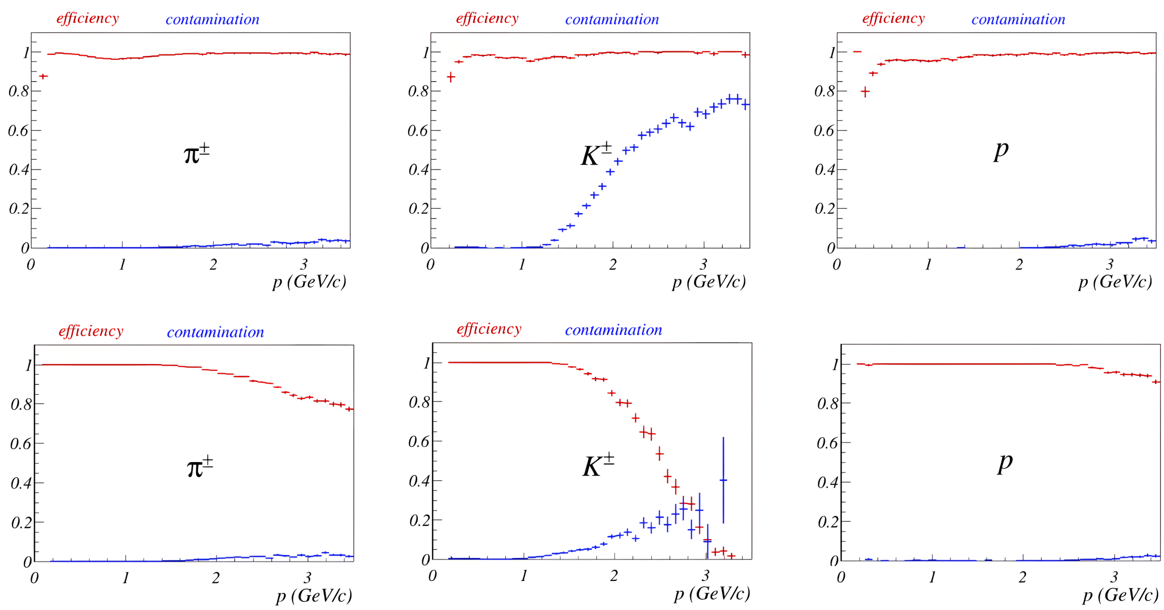

Figure 2: Efficiency (red points) and contamination (blue points) as a function of the track momentum for pions (left column), kaons (middle column), and protons (right column). The top row plots show results for the combined n-sigma method, the bottom row plots show results for the Bayesian approach.

Results for $E(i,p)$ and $K(i,p)$ are shown in the Fig. 2 for combined n-sigma method, $n_\sigma = \sqrt{(n_\sigma^{ST})^2 + (n_\sigma^{TOF})^2}$ and Bayesian approach. The n-sigma method is a simple and effective way to identify charged particles. However, it can be less accurate than the Bayesian approach in some cases. The Bayesian approach takes into account the probability of each particle species being present in the event, as well as the uncertainty in the measurements. It is more accurate, especially at low momenta where the statistical uncertainties are larger. This makes the Bayesian approach more accurate, but it is also more computationally expensive.

4. Conclusion

Two particle identification methods, the n-sigma and the Bayesian approach, have been adapted to the reconstruction procedure of the SPD experiment. The maximum applicability limits of particle separation for the straw tracker and the time-of-flight system have been determined and presented in the Table 1. Results are shown separately for tracks crossing the barrel and the end-caps.

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