EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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Project report

Monitoring of the RICH detector performance during the NA62 data taking

Abstract

The goal of this project was improving the existing tools for monitoring of the RICH detector. First part of the project was related to improving the existing electron selection, for better estimation of the B/S ratio. After changes we made, the B/S ratio dropped from $(4.0 \pm 0.2)\%$ to $(0.09 \pm 0.03)\%$. Second part of the project was dedicated to making a new tool for monitoring: study of the spurious hits in the detector. With our analysis we were able to spot some discrepancies between the Monte-Carlo samples and data. The last part of the project was looking for residual momentum dependence in the electron parameters. The conclusion is that for the ring radius we can approximate it as independent of the momentum, but for the number of hits there is a nonlinear dependence on the momentum of the electron.

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1 Introduction

The NA62 experiment at CERN is aimed at studying the very rare decay $K^+ \to \pi^+\nu\bar{\nu}$. The rejection of one of the main backgrounds coming from the $K^+ \to \mu^+\nu_\mu$ decays is done by the Ring Imaging Cherenkov[1] (RICH) detector, which plays a key role in particle identification, specifically in distinguishing between electrons, muons, and pions from kaon decays. Separation of pions from muons and electrons with the RICH detector is relying on the properties of the Cherenkov effect: the ring radius (measured by the RICH detector) is related to the $\beta = \frac{v}{c}$ of the charged particle. Using momentum of the charged particle that is obtained from the STRAW spectrometers, and combining it with the ring radius obtained from the RICH, we can separate different particles by their mass, using the formula [2, 3]:

$$m^2 = m^2(p, R) = p^2 \cdot \left(\frac{F^2 \cdot n^2}{F^2 + R^2} - 1 \right) \tag{1}$$

where $F = 17020\ mm$ is the focal length, and n is the refractive index inside the detector (which is filled with neon gas).

Monitoring of the performance of the RICH detector is done by studying a specific decay mode of the positively charged kaon: $K^+ \to \pi^0 e^+ \nu_e (Ke3)$. This specific channel is chosen because of its kinematic properties. On the figure 1 we can see the reconstructed radius from the RICH as a function of the track momentum, for different particles as product of the kaon decay. One can see that the distribution for the positron is independent of the momentum of

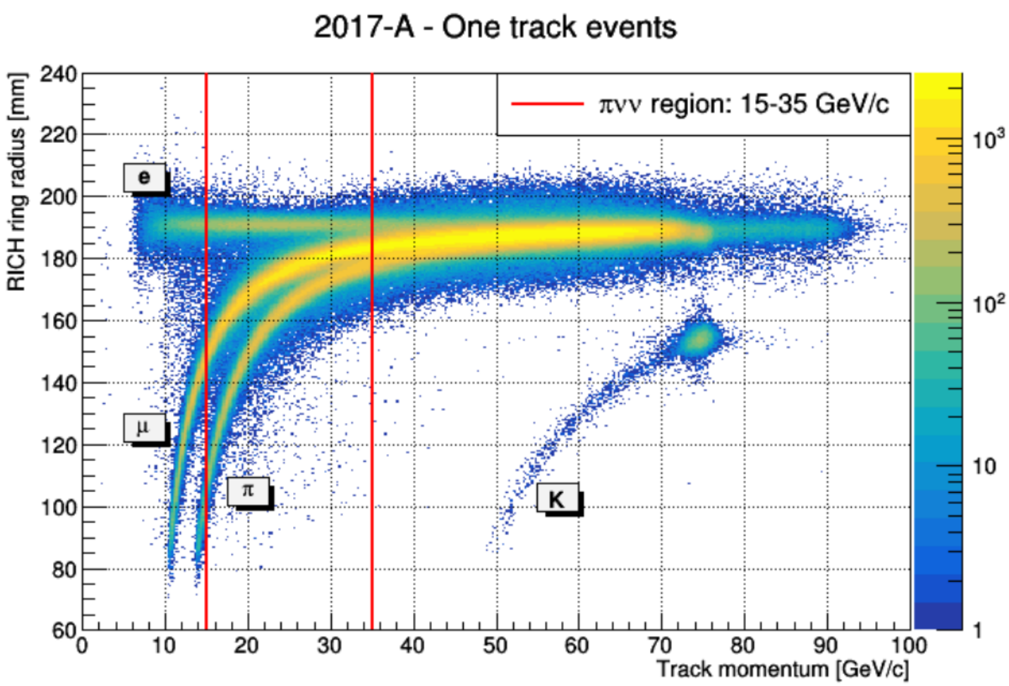

Figure 1: Reconstructed ring radius in the RICH as a function of the track momentum in 2017 data. The different distributions of positrons, muons, pions and kaons are visible.[2]

the track (is approximately constant) and that is because in this decay the e^+ is ultrarelativistic - has β close to 1. Consequently, e^+ mass is negligible and from the equation (1) we can see how the ring radius is approximately independent of the momentum of the particle with $m << p$:

$$R^2 = \frac{F^2 \cdot n^2}{\frac{m^2}{p^2} + 1} - F^2 \approx \frac{F^2 \cdot n^2}{1} - F^2 = F^2(n^2 - 1) \tag{2}$$

This makes a great tool for ensuring the RICH detector functions optimally, as we can see a clean dependence of the ring radius on the index of refraction. The next step is selecting the *Ke3* events. The main objective is reducing contamination from backgrounds processes such as $K^+ \to \pi^+\pi^0(K2\pi)$, $K^+ \to \mu^+\nu_\mu(K\mu2)$ and $K^+ \to \pi^0\mu^+\nu_\mu$ $(K\mu3)$. The goal of this project was to reduce the expected background/signal ratio with improving the *Ke3* selection. Inspecting the analyser we were able to find possible improvements in the code for the selection, and also introduced some new cuts in the selection, trying to keep as much signal as possible.

Another part of the project was a study on spurious hits in the RICH detector. Spurious hits are signals in the detector which do not correspond to genuine Cherenkov rings, and could be a consequence of background radiation, bad mirror reflection, chromatic dispersion .. Studying spurious hits can help with understanding what is happening in the detector and could be useful for monitoring.

Additional study was done on residual momentum dependence of the electron parameters. Since we rely on the fact that there shouldn't be any dependence on the momentum of the positron for the radius of the ring and the number of hits per ring, identifying some residual dependence could be a sign for the need of a better description.

2 Event selection

As it is explained in the introduction, for monitoring of the performance of the RICH detector we are collecting a positron sample from the $K^+ \to \pi^0 e^+\nu_e(Ke3)$ decay events. The selection criteria rely on single track selection, particle ID, kinematics of the decay and the RICH selection[1]. The first task of this project was to improve the background/signal ratio for the selection of the *Ke3* events. We are not going to go in details about the whole selection, just explain the improvements made in the code.

The first step was calculating the acceptances of the selection for each of the relevant decay channels of K^+: $K2\pi$, $K\mu2$, $K\mu3$ (background) and *Ke3* (signal). This was done using the Monte-Carlo samples for each of these events. For the purpose of calculation, a histogram filling the number of events after every cut was made: "Number of events left after each cut". An example of this histogram can be seen on the figure 2. With it, we were able to calculate the

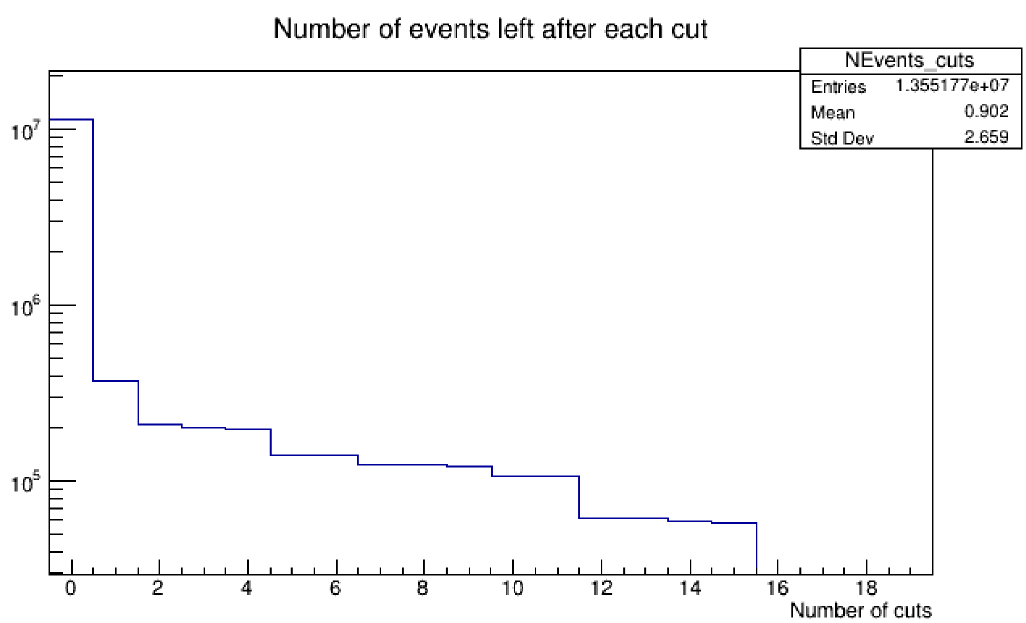

Figure 2: Number of events left after each cut from 1 run in 2018

ratio between the number of events that passed the whole selection with the number of events before the selection. The condition for the events to be counted was that they happen in the fiducial volume - for the calculation we only used events that have between $110 - 180\ m$ for the true Z coordinate of the decay. Initial acceptance of relevant channels for the *Ke3* selection and the B/S ratio can be seen in tables 1 and 2, where ϵ stands for efficiency of the selection (acceptance), and σ stands for uncertainty.

Channel	ϵ	$\epsilon \cdot BR$
Ke3	$(204.31 \pm 0.09) \times 10^{-4}$	$(10.358 \pm 0.005) \times 10^{-4}$
$K2\pi$	$(3.14 \pm 0.06) \times 10^{-5}$	$(6.49 \pm 0.12) \times 10^{-6}$
$K\mu2$	$(5.27 \pm 0.05) \times 10^{-5}$	$(3.35 \pm 0.04) \times 10^{-5}$
$K\mu3$	$(4.65 \pm 0.05) \times 10^{-5}$	$(1.56 \pm 0.02) \times 10^{-6}$

Table 1: Initial results for the acceptances

Channel	**Ratio**
$BKG_{K2\pi}$ / SIG	$(6.26 \pm 0.12) \times 10^{-3}$
$BKG_{K\mu2}$ / SIG	$(32.32 \pm 0.34) \times 10^{-3}$
$BKG_{K\mu3}$ / SIG	$(1.50 \pm 0.02) \times 10^{-3}$
All B/S	$(4.01 \pm 0.16)\%$

Table 2: Initial background to signal ratios for different channels

We see that before the improvements in the code, the B/S ratio for the *Ke3* selection was $(4.0 \pm 0.2)\%$. The objective of this project was to reduce this ratio, so that we are left with a cleaner sample of real *Ke3* events.

The first issue that was found was related to the application of the veto for muons. This condition was included in the definition of goodness of the track, and the number of the good tracks in one event was required to be exactly one. In this case, an event with both a muon and an electron track could pass these selection criteria. On the other hand, a standard $K\mu2$ event doesn't even pass the one track condition, even if the muon track is reconstructed well, as it is visible on the *Number of good tracks* histogram on figure 3. In order to prevent this, the particle identification condition (veto for muons) is moved after counting the number of good tracks and is applied only to the good track found in the selected event. With this change, we are able to

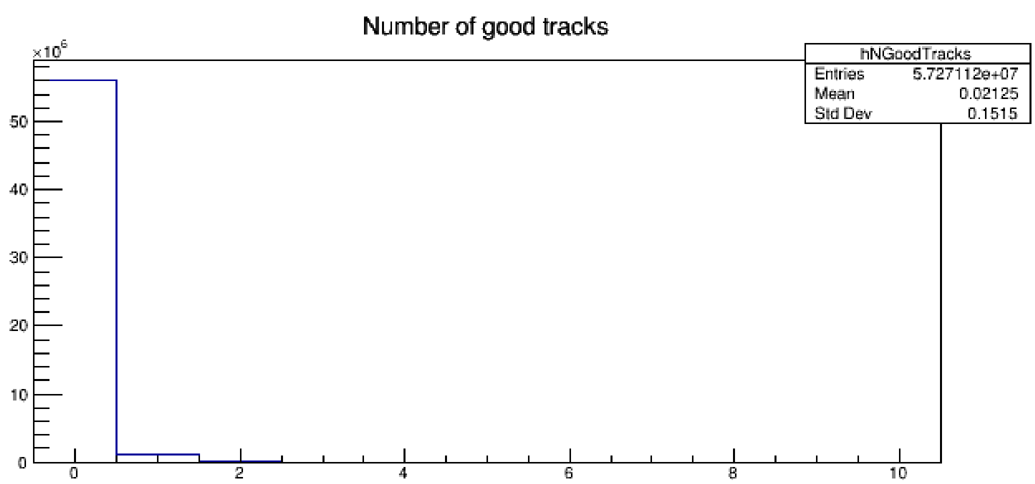

Figure 3: Number of good tracks per event, from $K\mu2$ MC sample

estimate the B/S ratio better:

$$B/S = (3.2 \pm 0.2)\%$$

The second attempt for improving the selection we made was trying to separate background from overlay. We saw with the $K\mu2$ MC sample that a lot of overlay events survive because of the peak around 0 in the squared missing mass in *Ke3* hypothesis, which shouldn't be the case with the real $K\mu2$ events[1](see figure 4). One way to see if the majority of events that survive

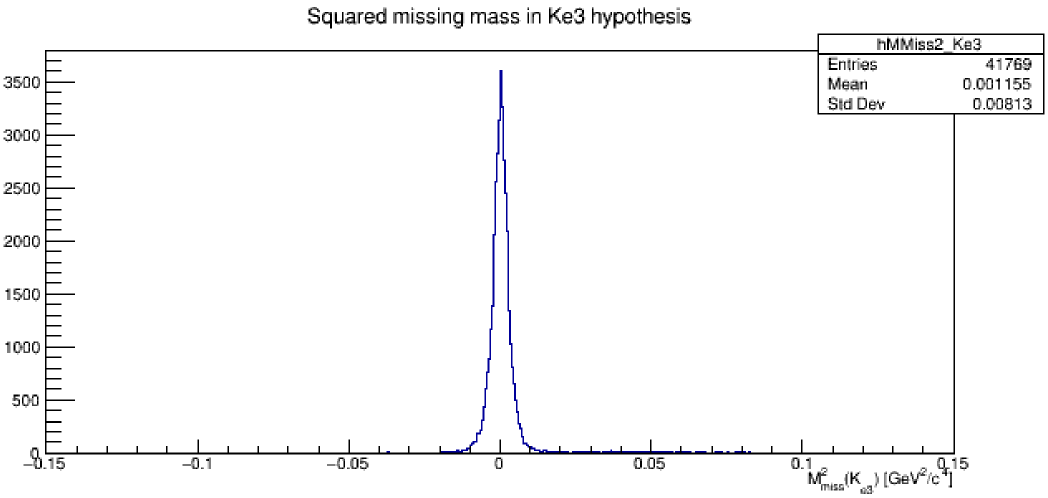

Figure 4: Squared missing mass in *Ke3* hypothesis, from a $K\mu2$ MC sample

come from the overlay, is to see what is the time of those tracks compared to the reference time. We made a plot to check that. A *GoodTrackTime - RefTime* histogram was added: on the x axis is the difference between the time of the track that is considered "good" and the trigger reference time. For the $K\mu2$ sample, we expected to see a lot of events whose times don't align with the reference time, while for the *Ke3* sample we expected a peak around 0. The results are shown on the figures 5 and 6.

The result plots look like we expected - we see a lot of out of time events for the $K\mu2$ sample, which suggests that a lot of overlay events survive the selection. For this reason, we added a cut: $|GoodTrackTime - RefTime| < 3ns$ which removes the out of time events. When this cut is applied on data, less than 1% of signal statistics is lost, which allows the use of it. Applying the cut on data is useful for better estimation of the expected B/S ratio. After applying this cut, the relevant calculated acceptances and the B/S ratio can be seen in the tables 3 and 4:

Channel	ϵ	$\epsilon \cdot BR$
Ke3	$(198.78 \pm 0.09) \times 10^{-4}$	$(10.078 \pm 0.005) \times 10^{-4}$
$K2\pi$	$(3.3 \pm 0.7) \times 10^{-7}$	$(6.9 \pm 1.3) \times 10^{-8}$
$K\mu2$	$(1.36 \pm 0.09) \times 10^{-6}$	$(8.7 \pm 0.6) \times 10^{-7}$
$K\mu3$	$(6.7 \pm 0.5) \times 10^{-7}$	$(2.2 \pm 0.2) \times 10^{-8}$

Table 3: Final results for the acceptances

With the changes made to the code, the selection improved from having B/S ratio of 4% to around 0.1%, with loosing only 2.43% in statistics.

[1]we would expect a missing mass not peaked at 0, because there is no π_0 in a $K\mu2$ event

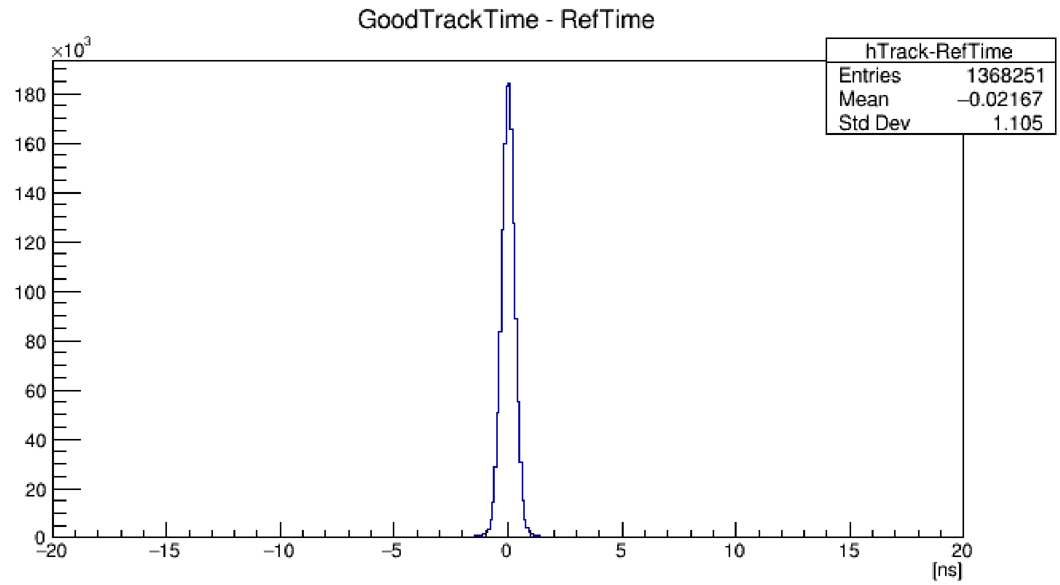

Figure 5: Distribution of *GoodTrackTime - RefTime* for a *Ke3* MC sample

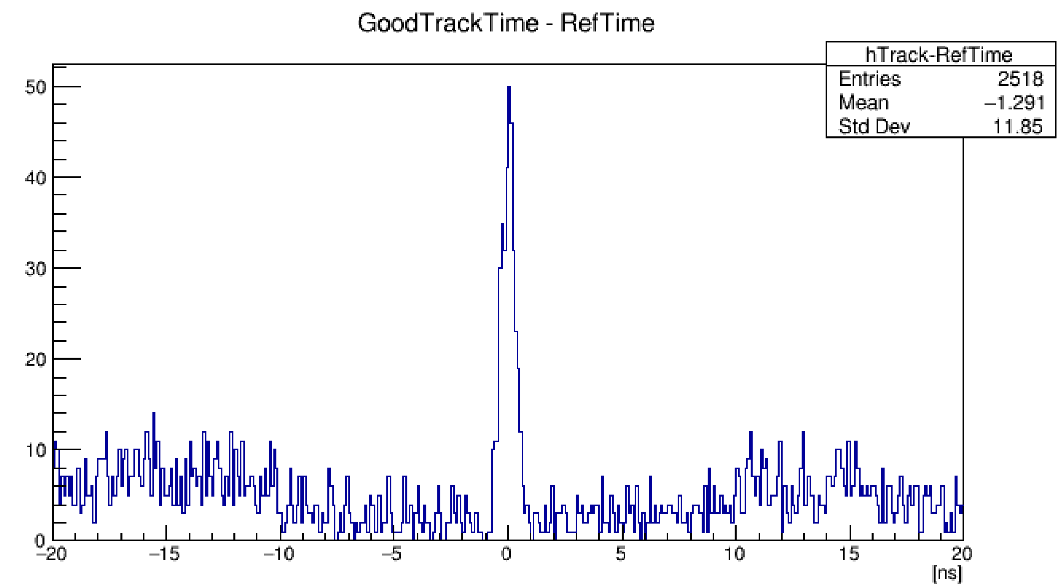

Figure 6: Distribution of *GoodTrackTime - RefTime* for a $K\mu2$ MC sample

Channel	**Ratio**
$BKG_{K2\pi}$ / SIG	$(6.8 \pm 1.3) \times 10^{-5}$
$BKG_{K\mu2}$ / SIG	$(86 \pm 6) \times 10^{-5}$
$BKG_{K\mu3}$ / SIG	$(2.2 \pm 0.2) \times 10^{-5}$
All B/S	$(0.09 \pm 0.03)\%$

Table 4: Final background to signal ratios for different channels

3 Study of the spurious hits

The goal of the second part of this project, the spurious hits study, was making a new monitoring tool. Spurious hits in the detector can be a consequence of electronic noise or can come from some unwanted events in the detector. In this study, we define as a "spurious" hit every hit that lies 15 mm outside of the ring. A spurious hits histogram can be seen on Figure 7. The histogram is filled with all the RICH hits in the event that happen within ± 1 ns from the RICH time. Out of time hits and supercell hits are removed. On figure 8 we can see the distribution of the difference between hit time and RICH time, for every hit that is not a supercell hit. With a Gaussian fit of the distribution, we get $\sigma = 0.1625 \pm 0.0002$, so we can see that with the cut at 1ns we are cutting at more than 5σ. With this cut we are removing around 34% of all hits. On the x axis is the distance between hit point and the Single Ring centre taken from the RICH Candidate reduced by the ring radius:

$$x = \sqrt{(X_{hit} - X_{centre})^2 + (Y_{hit} - Y_{centre})^2} - R_{ring} \tag{3}$$

Hits with $|x| > 15mm$ are considered spurious. The fraction of spurious hits for the data reported in the plot (from 2018 dataset) $(5.11 \pm 0.03)\%$.

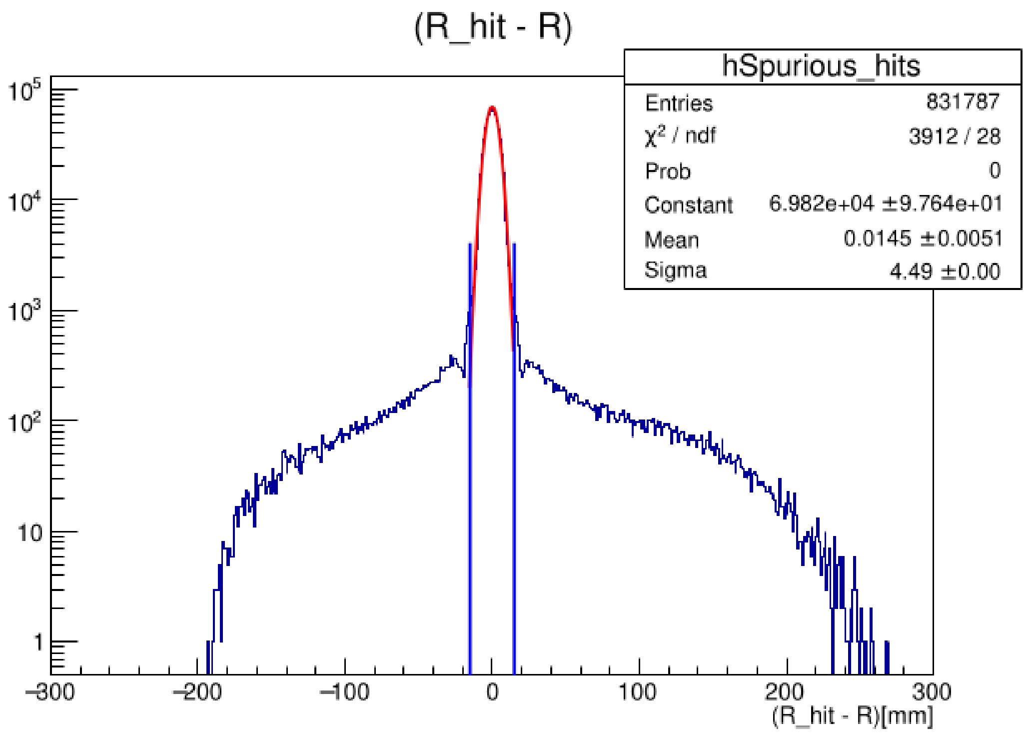

Figure 7: Distribution of the variable x defined in (3)
for hits in the detector. Hits outside the blue lines are considered spurious.

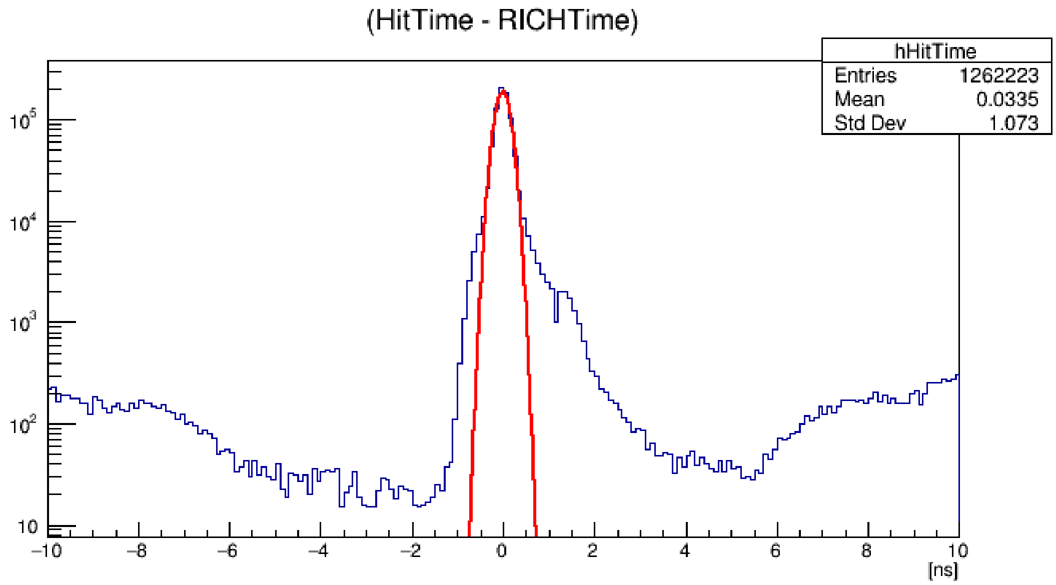

Figure 8: Distribution of the difference between hit time and RICH time. The cut is applied at 1ns.

We compared the fraction of spurious hits that we get from Ke3 Monte-Carlo sample with the fraction of spurious hits from the data. The data used is from 1 run in 2018. The fraction of spurious hits in the MC sample was:

$$(4.42 \pm 0.01)\%$$

And for the 2018 data the fraction we get is:

$$(5.11 \pm 0.03)\%$$

The plots are shown on figures 9 and 10. It is obvious from the fraction of spurious hits that there is some disagreement between MC and data. This study can be helpful for improving the existing Monte-Carlo simulation of the real events. The final thing we checked in this part of the project is how stable the fraction of spurious hits is through time. The results for the fraction of spurious hits across runs in years 2016, 2017, 2018, 2021, 2022 and 2023 are shown in table 5:

Date of the Runs	Fraction of spurious hits(%)	Uncertainty (%)
2016	5.14	0.05
2017	5.12	0.03
2018	5.11	0.03
2021	5.32	0.03
2022	5.28	0.03
2023	5.36	0.03

Table 5: Fraction of spurious hits for data from 2016 to 2023.

The results presented are calculated from a single run in each of the years. We can see that the portion of spurious hits is stable across runs in 2016, 2017 and 2018. After restarting the runs at 2021 we see a little rise in the fraction of spurious hits, and then it stays more or less stable again until 2023.

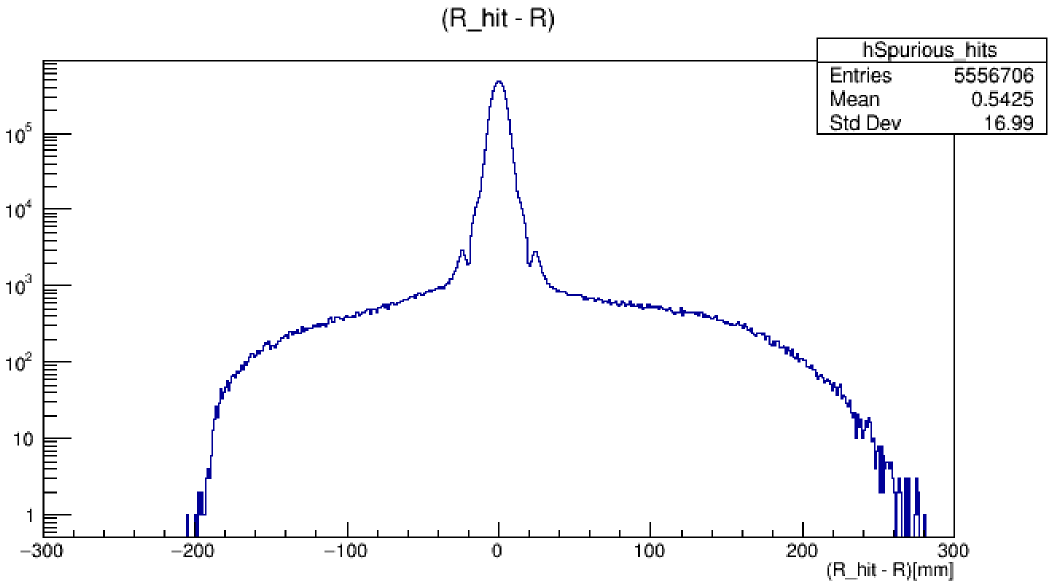

Figure 9: Distribution of spurious hits of the Ke3 Monte-Carlo sample

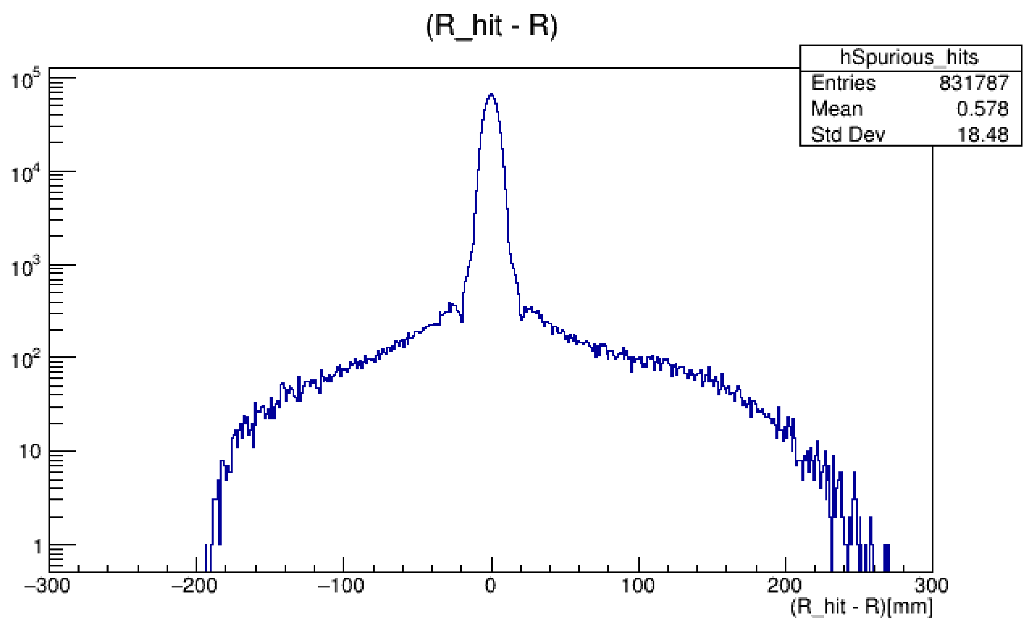

Figure 10: Distribution of spurious hits of the 2018 single run data

4 Residual momentum dependence

The last part of this project was studying whether there is a residual momentum dependence of the electron parameters for the *Ke3* events. As explained in the introduction, since the electrons can be assumed to be ultrarelativistic, the ring radius and the number of hits shouldn't be dependent on the momentum of the electron, but it turns out that there is some residual dependence that has to be studied in more details. We were looking at plots from the 2018 data; number of hits vs. momentum - *"NHits vs P - standalone iterative single fit"* and ring radius vs. momentum - *"Radius vs P - standalone iterative single fit"*. By using *Profile X* on these plots, we are able to see how the ring radius and number of hits per ring depend on the momentum (see figures 11 and 12.

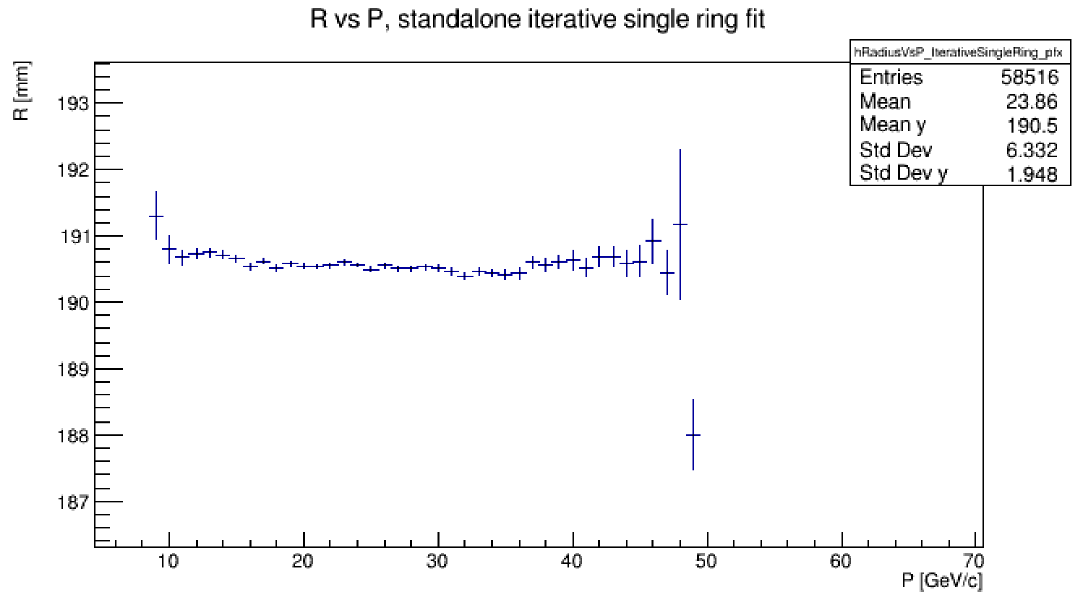

Figure 11: Profile X of the Ring radius vs. Momentum

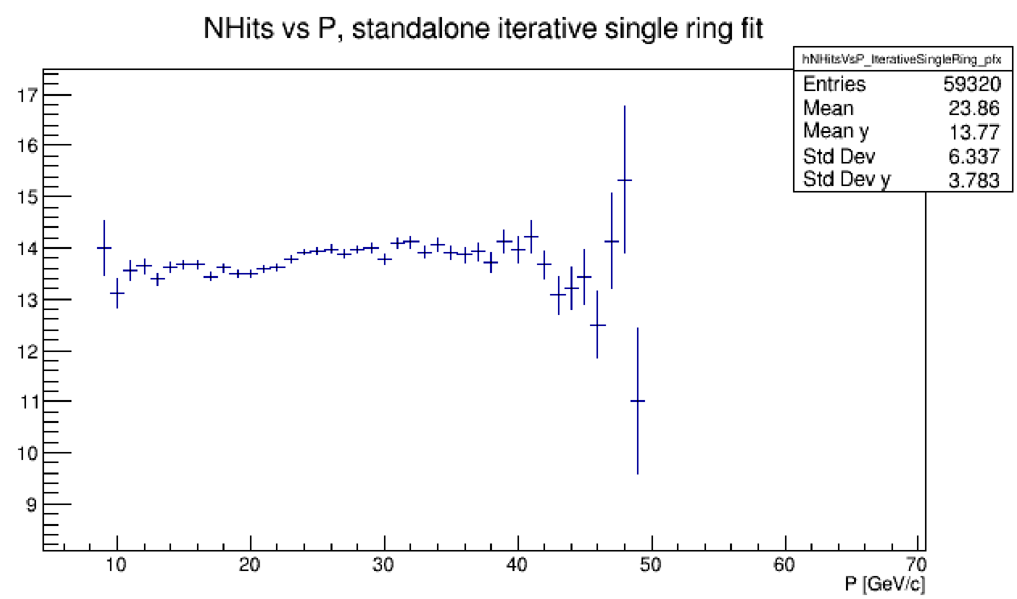

Figure 12: Profile X of the number of hits vs. momentum

Parameter	$f(x) = p_0$	$f(x) = p_1 x + p_0$	$f(x) = p_2 x^2 + p_1 x + p_0$	$f(x) = p_3 x^3 + p_2 x^2 + p_1 x + p_0$
Reduced χ^2	44.1/25	29.2/24	27.6/23	24.4/22
p_0	190.533 ± 0.009	190.67 ± 0.04	190.85 ± 0.15	189.9 ± 0.6
p_1	—	$(-5.7 \pm 1.5) \times 10^{-3}$	-0.020 ± 0.011	0.10 ± 0.07
p_2	—	—	$(2.8 \pm 2.2) \times 10^{-4}$	$(-4.4 \pm 2.6) \times 10^{-3}$
p_3	—	—	—	$(5.9 \pm 3.3) \times 10^{-5}$

Table 6: Reduced χ^2 and parameter values for different models of fitting the dependence of the ring radius on the momentum

Parameter	$f(x) = p_0$	$f(x) = p_1 x + p_0$	$f(x) = p_2 x^2 + p_1 x + p_0$	$f(x) = p_3 x^3 + p_2 x^2 + p_1 x + p_0$
Reduced χ^2	146.9/25	59.3/24	51.3/23	39.0/22
p_0	13.78 ± 0.02	13.12 ± 0.07	12.36 ± 0.28	15.99 ± 1.07
p_1	—	$(2.71 \pm 0.29) \times 10^{-2}$	0.089 ± 0.022	-0.36 ± 0.13
p_2	—	—	$(-1.22 \pm 0.43) \times 10^{-3}$	$(1.66 \pm 0.51) \times 10^{-2}$
p_3	—	—	—	$(-2.26 \pm 0.65) \times 10^{-4}$

Table 7: Reduced χ^2 and parameter values for different models of fitting the dependence of the number of hits on the momentum

We tried to fit these distributions to polynomial distributions of various degrees. In tables 6 and 7 the parameters resulting from the fits are shown. From the results, one can see that there is some small dependence of the ring radius of the momentum of the electron, since the parameters of order higher than 0 we get are not 0 within the uncertainty. For example, for the linear fit model (p_1), we see that the result for the parameter p_1 is 3.8σ away from 0. But since the χ^2 of the constant fit (p_0) is less than 2, it may be enough to consider just that one, and conclude that the ring radius is more or less independent of the electron momentum. Fitting to higher degree polynomials doesn't make much sense, since it would be overfitting the data.

For the number of hits, the dependence is more noticeable. The χ^2 is 5.88 for the fit to a constant function, so using this fit may not be justified. The only fit with χ^2 less than 2 is the one to the third degree polynomial, and we see that the parameters are all around 3σ away from 0, which means that there is around 1% chance that the parameters of the fit are really 0. So, there seems to be a nonlinear dependence of the number of hits of the electron momentum, unlike with the ring radius.

References

[1] G. Anzivino et al. "Precise mirror alignment and basic performance of the RICH detector of the NA62 experiment at CERN". In: *JINST* 13.07 (2018), P07012. DOI: 10.1088/1748-0221/13/07/P07012. arXiv: 1809.04026 [physics.ins-det].

[2] Francesco Brizioli. "Measurement of $Br(K^+ \to \pi^+ \nu \bar{\nu})$ with the NA62 experiment at CERN". Presented 26 Apr 2021. Perugia U., 2020. URL: http://cds.cern.ch/record/2765463.

[3] Francesco Brizioli. "The RICH detector of the NA62 experiment at CERN". In: *2019 IEEE Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC)*. 2019, pp. 1–6. DOI: 10.1109/NSS/MIC42101.2019.9059969.