Lifetime measurement of the Ξ_c^0 baryon.

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Abstract. New detectors and technologies are employed for the detection of new exotic particles using higher and higher energies, in hope of finding new theories to support existing models or improve the theoretical frameworks as they are determined today. A high precision measurement of the Ξ_c^0 baryon's lifetime may reveal inconsistencies between the experimental results and the theoretical predictions. This could be an indication of the need to improve the current theory supporting the measurements. Data from the second run of the LHCb experiment at the Large Hadron Collider, CERN, with an integrated luminosity of 300 pb^{-1} is used for this report, in order to analyse and determine the differentiation between signal and background in the mass range of the Ξ_c^0 baryon. A background of the theoretical prediction is presented, together with previous experimental results. It contains the methods used for the candidate selection, which were developed by using a multi- variate analyser and concludes with the numerical fidings. A blinded lifetime value for the Ξ_c^0 baryon of $\tau_{\Xi c}{}^0 = 0.1335 \pm 0.0029$ ps is found, with an uncertainty of 2.2% which is a considerable improvement on the current world average uncertainty of $\sim$ 10%. Some further considerations are also presented with recommendations for future projects such as the need for a full analysis containing systematic uncertainties to support the results.

1. Introduction

The lifetime of a particle, denoted 'τ' , is the average proper time after which a heavy particle will decay into a number of lighter ones, by different types of interaction. The absolute lifetime of a particle is of great importance, as it contains information on every possible decay channel for it, and thus if a certain decay mode is enhanced or supressed by physics beyond the Standard Model, this will affect the lifetime.

The aim is to measure the lifetime of the Ξ_c^0 baryon, in order to identify any differences from previous experimental measurements, as well as any diversions from the theoretical predictions. As will be explained further in detail, the decay of the Ξ_c^0 baryon is dominated by a weak interaction, which has a time constant of $\sim 10^{-12}$ s. Therefore, the particle will fly a measurable distance before decaying. Its lifetime, can then be calculated in terms of this distance and in terms of its mass and momentum as

$$\tau = \frac{(FD)m}{p} \tag{1}$$

where FD is the flight distance , m the mass and p the momentum. The lifetime was measured by using LHCb data from 2015 with an integrated luminosity of 300 pb^{-1}. It was done in Python by using the ROOT framework, together with TMVA for multivariable analysis and RooFit for fitting the plots.

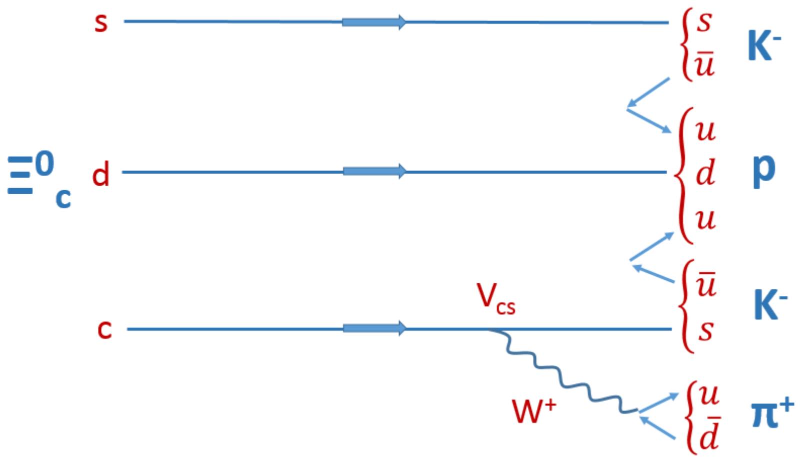


Figure 1: Leading order Feynman diagram for the decay $\Xi_c^0 \to pK^-K^-\pi^+$.

2. Theoretical framework of the charmed hadrons

2.1. Theory of the Ξ_c^0 baryon.

The Standard Model, contains two classes of particles, the quarks and the leptons, with each class having three generations of particles, and also the force carriers or gauge bosons; namely gluons, photons, the Z, W and Higgs bosons. The known quarks are six in total, or, in other words, come in six flavors; the up (u) and down (d), the charm (c) and strange (s), and the top (t) and bottom (b) quarks. The u, c and t quarks have a charge of $+\frac{2}{3}e$, where e is the electron charge (1.602×10^{-19} C). The d, s and b quarks have a charge of -$\frac{1}{3}e$. In addition to the electromagnetic charge, there are also 'colour' charges associated with the strong interaction, and there are three of them ($N_c = 3$), namely, Red, Green and Blue [4]. All quarks have a spin of $\frac{1}{2}$. Associated with them are their corresponding antiparticles, i.e. $\bar{u}, \bar{d}, \bar{c}, \bar{s}, \bar{t}, \bar{b}$, that have the opposite charge.

Quarks combine into hadrons bound by the strong force, mediated by gluons. Hadrons come in two groups; mesons, for example a pair of quark- antiquark, and baryons that are made by three quarks or antiquarks [1]. In the case of a (d, s, c) combination, the product is the Ξ_c^0 baryon, which has a neutral charge as indicated by its superscript, and with a subscript 'c' showing the presence of the charm quark, whose existence is therefore fundamental in the overall decay process of the baryon. It has a mass of $2470.85 \pm^{0.28}_{0.40}$ MeV [2]. The decay channel that is used for the lifetime measurement is $\Xi_c^0 \to pK^-K^-\pi^+$, or in terms of quark combination $(dsc) \to (uud) + (\bar{u}s) + (\bar{u}s) + (u\bar{d})$. As it is shown in figure 1, this decay mode requires a change in quark flavour and hence it has to proceed through a weak interaction so that the quark conservation is valid.

2.2. Theory of charm quark and theoretical prediction of $\tau_{\Xi_c}{}^0$

Charm quarks can decay into a strange or a down quark through the emission of a $W^\pm$ boson, which will further decay into leptons i.e. a semi- leptonic decay, or into quarks i.e. a non leptonic decay [3]. Its lifetime can be theoretically calculated as

$$\tau_{\text{theory}} = \frac{1}{\Gamma_c} \tag{2}$$

where Γ_c is the inclusive decay rate given as

$$\Gamma_c = \frac{G_f^2 m_c^5}{192\pi^3} |V_{cs}|^2 c_{3,c} \tag{3}$$

[3], with m_c being the mass of the charm quark, G_f the Fermi coupling constant, V_{cs} the CKM matrix element that measures the probabillity that a charm quark will decay into a strange one and $c_{3,c}$ a numerical coefficient [3] given by

$$\begin{aligned} c_{3,c} = {} & g\left(\frac{m_s}{m_c}, \frac{m_e}{m_c}\right) + g\left(\frac{m_s}{m_c}, \frac{m_\mu}{m_c}\right) + N_c |V_{ud}|^2 h\left(\frac{m_s}{m_c}, \frac{m_u}{m_c}, \frac{m_d}{m_c}\right) + N_c |V_{us}|^2 \left(\frac{m_s}{m_c}, \frac{m_u}{m_c}, \frac{m_s}{m_c}\right) \\ & + \left|\frac{V_{cd}}{V_{cs}}\right|^2 \left[g\left(\frac{m_d}{m_c}, \frac{m_e}{m_c}\right) + g\left(\frac{m_d}{m_c}, \frac{m_\mu}{m_c}\right) + N_c |V_{ud}|^2 h\left(\frac{m_d}{m_c}, \frac{m_u}{m_c}, \frac{m_d}{m_c}\right)\right. \\ & \left. + N_c |V_{us}|^2 h\left(\frac{m_d}{m_c}, \frac{m_u}{m_c}, \frac{m_s}{m_c}\right)\right] [3] \end{aligned} \tag{4}$$

The factor N_c in equation (4) is related to the colour charges. The values of $|V_{ud}|$, $|V_{us}|$, $|V_{cd}|$ and $|V_{cs}|$, come from the semileptonic decay rates of hadrons with different properties (strangeness, flavour etc.) and are given as $|V_{ud}| = 0.97425 \pm 0.00022$, $|V_{us}| = 0.2252 \pm 0.0009$, $|V_{cs}| = 0.1006 \pm 0.023$ and $|V_{cd}| = 0.230 \pm 0.011$ [4]. So, if one sets $|V_{ud}|^2 + |V_{us}|^2 \approx |V_{ud}|^2 + |V_{cs}|^2 \approx 1$ and substitute also for the values of the phase space factors g and h (for two and three massive particles respectively) which describe how momenta are shared between the decay products [3], then the $c_{3,c}$ component can be calculated, and consequently, the numerical value for the $|V_{cs}|^2 c_{3,c}$ product too. Therefore, the inclusive decay rate can be derived which in turn gives a theoretical value of the charm quark lifetime of $\tau_{\text{charm-theory}} = 1.70$ ps [3]. This result for the charm quark is of the right scale, though the lifetime of the D^0 meson ($c\bar{u}$), the decay of which is also dominated by the charm quark decay, is 0.4101 ps [3]. The difference is due to the interaction between the c and the $\bar{u}$ quarks in the decay process, and that is the reason why the lifetime of ${\Xi_c}^0$ is much smaller than the one of the D^0. Taking the theory of the inclusive decay rates as a basis for lifetime calculations, the theoretical prediction for $\tau_{\Xi_c}{}^0$ is 0.087 ps , assuming a charm quark mass of $m_c = 1.4$ GeV [5].

3. Lifetime experimental measurements

3.1. Previous results

The Ξ_c^0 has been previously measured during experiments at Fermilab and CERN. The NA32 experiment at CERN gave a value of $\tau = 82^{+59}_{-30}$ fs [6] by using events for the decay mode $\Xi_c^0 \to pK^-\bar{K}^{*0}$. Another experiment at Fermilab (E687) published a $\tau = 101^{+25}_{-17}(stat) \pm 5$ (sys) fs [7], for a decay mode of $\Xi_c^0 \to \Xi^-\pi^+$. The last FOCUS experiment, again at Fermilab , used the modes $\Xi_c^0 \to \Xi^-\pi^+$ and $\Xi_c^0 \to \Omega^- K^+$ to find a lifetime of $118^{+14}_{-12}(stat) \pm 5$ (sys) fs [8]. The world average is currently 112^{+13}_{-10} fs [2].

The uncertainty value of the world average ($\sim 10\%$) is still large, but because charmed hadrons are produced at very high rates at CERN, the LHCb experiment is very well placed to improve on this.

3.2. The LHCb experiment

At LHCb (shown in figure 2), two proton beams collide in order to produce b and c hadrons. The main parts of LHCb are the Vertex Locator and two Ring Imaging Cherenkov (RICH) detectors, and also other components located before and after the dipole magnet that yield high precision momentum measurements, such as electric and hadronic calorimeters and muons

Table 1: Previous experimental measurements and the current world average value.

Experiment	Laboratory	Lifetime (fs)
NA32	CERN	82^{+59}_{-30}
E687	Fermilab	101^{+25}_{-17}
FOCUS(E831)	Fermilab	118^{+14}_{-12}
World average		112^{+13}_{-10}

tracking stations which are used to identify muons and neutral particles. The Vertex Locator (VELO), as its name suggests, is used to locate vertices of interactions and thus measures the decay or flight distances [10]. RICH detectors identify the particular type of particle. RICH1 is assigned to low momentum and RICH2 to high momentum particles [11].

For the event selection, LHCb uses a trigger system. Many of the trigger lines, use variables that are biasing tau, as they have good discriminating power. For this analysis, variables from the trigger have been selected in a way that the lifetime is not biased, in order to minimise the need for acceptance corrections. The key is not to use any variables that depended on the distance between the Primary Vertex (PV) of the interaction and the daughter tracks, as this is correlated to the decay time of the mother particle. Instead, tracks that are identified with a high probability of being tracks of protons, Kaons or a pions are used. These have high momentum and form a good quality vertex, i.e. their trajectories pass closely to each other, and their invariant mass as calculated from the four- vector sum of their momenta, is within 80 MeV of the known Ξ_c^0 baryon mass [12]. But even when using these variables, the level of background is still large, something that obviously needs to be at minimal levels [13]. The task here is to retain the signal while minimising the background, in a way that does not bias the lifetime distribution of the baryon.

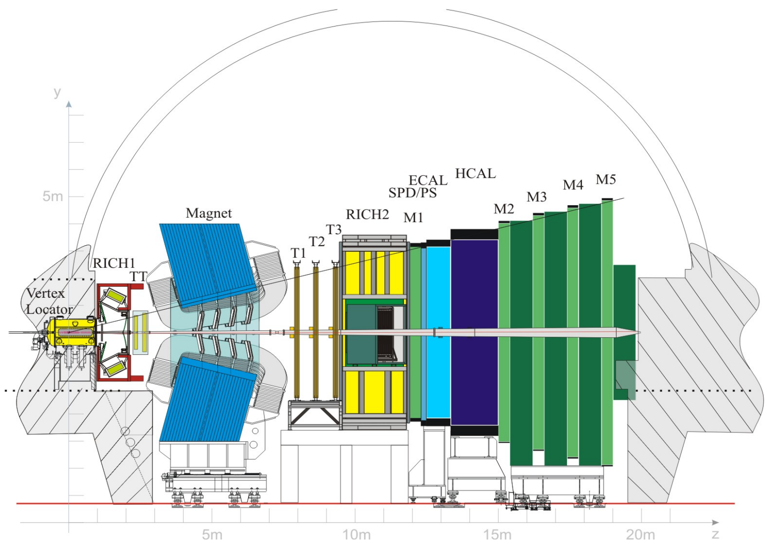


Figure 2: The LHCb detector at CERN [9]

4. Data analysis

4.1. Method of analysis

The analysis was performed on a dataset of 16 million candidates from the second run of LHCb in 2015. This data was used to train a Multivariate Data Analyser (TMVA), using the CERN's ROOT framework. This machine- learing technique determined correlations between different variables and also output a tool for an optimal cut value that was to be used on the dataset in order to eliminate the background in a way that was not biasing the decay time distribution. The updated dataset with the reduced background was then used for a fit of the mass distribution of the baryon. The signal yield was then used to fill a histogram with bins of decay time intervals and an exponential fit was made on this histogram. From the exponential fit, the decay constant was determined and therefore the lifetime of the Ξ_c^0 baryon, together with the uncertainties on the measurements.

4.2. Establishing the existence of signal candidates

The first task was to determine whether or not the raw data could reveal a signal before attempting any non- biasing selection of variables. A small signal was retrieved by applying a cut on the variables that were correlated with the impact parameter χ^2 of the daughter particles with the primary vertex PV. These variables show the χ^2 of the hypothesis that the track originates from this vertex. Larger values indicate lower probability of the tracks being produced there, or a higher probability that they are produced by a long lived particle. That technique gave a distinct peak on top of the background around the Ξ_c^0 mass of 2470 MeV as shown in figure 3.

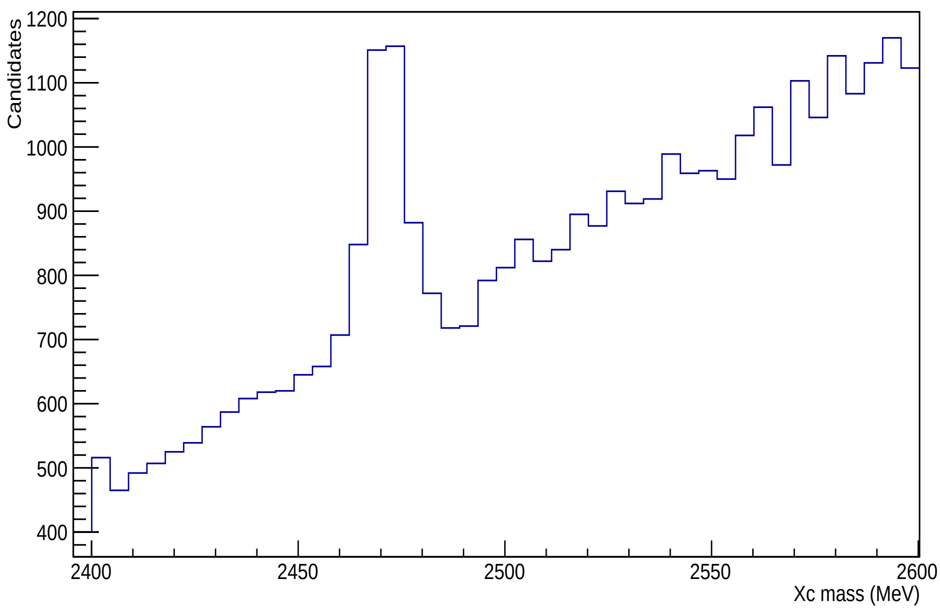
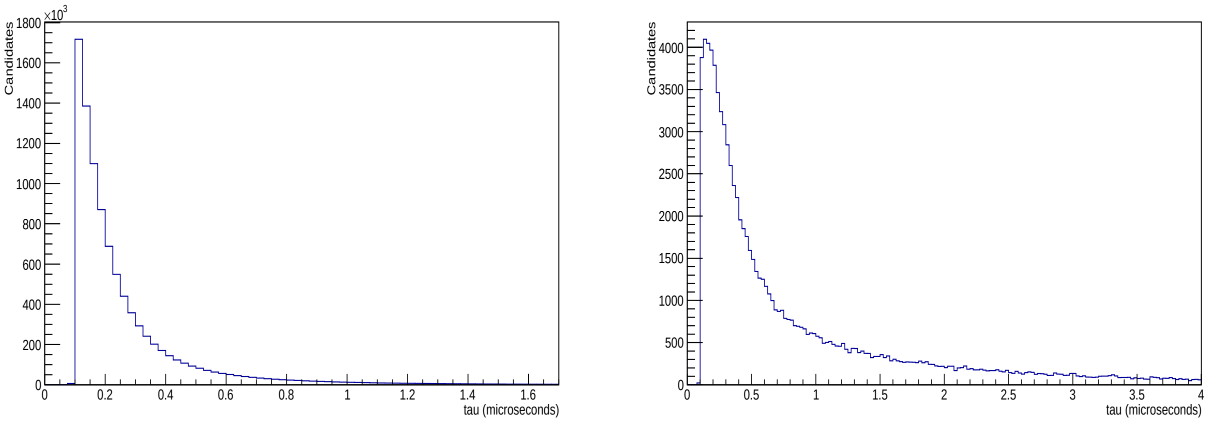


Figure 3: Mass distribution of Ξ_c^0 with initial selection applied. A signal was

Using these variables preferentially selects longer lived candidates, and so, biases the decay time distribution towards larger decay times. This biasing effect was obvious when plotting the distribution of the τ variable of the mother particle, which is the decay time of the candidates, with and without the cuts, as shown in figure 4.



(a) Decay time before cuts. (b) Decay time after cuts.

Figure 4: The effect of the initial selection on decay time distribution. The selected variables bias the tau of the mother particle.

Having established that the data did contain some signal, the next step was to find a selection of cuts that were not associated with the decay time of the mother particle. Some potentially useful variables are worthwhile to be mentioned; the endvertex χ^2, which measures how good a vertex the daughter tracks make, essentially how close they are passing each other. Additionally, the momentum and the transverse momentum of the mother and all daughter particles, that should generally be larger for signal than background. Furthermore, variables showing the probability that the daughter particle tracks are actually the type of particle they should be and not misidentified ones, and also other variables measuring the probabilty that the track was a 'ghost' i.e. not corresponding to a real particle but being just random combinations of hits in the detector. These variables were chosen as a starting point, as they were uncorrelated to the decay time of the mother particle.

At this point, simulated Monte Carlo datasets with the above selection applied, were used for the signal, in order to be passed for MVA training as will be discussed later.

4.3. TMVA analysis

Since the need of finding a non- biasing selection is obvious, the use for a multivariate technique for this purpose is necessary. TMVA, which stands for 'Toolkit for Multi-variate Data Analysis', is a software package for ROOT that performs machine learning, based on pre- defined criteria passed on by the user. It can train algorithms allowing for determination of the variables' significance used as a selection on a data sample. The list of these variables can be seen in the Appendix A, and they are not associated with the decay time distribution.

During the training process and after the selection criteria were applied, the simulated Monte Carlo which contained the same trigger selection as the real data, was passed as an input to the TMVA which used it as the signal file, whilst the real data coming from the mass region away from the signal peak, i.e. the sideband region, was used as the background file. The important variables were then declared in order for the TMVA to recognise what variables should be used for training. The analyser can use a variety of training methods, such as Cuts- based selection techniques, and others like 'BDT' or 'BDTG' (Boosted Decision Trees) [14]. At this stage more variables were added, and others were removed in order to make the training more efficient. The output of the training process was the calculation of the distributions of the variables for signal and background. It comes in the form of a weight file that can then be used to any real dataset with an unknown mixture of signal and background, after the best method is determined. This weight is applied to every candidate in the dataset as a single, method specific variable, eg. 'BDTG' variable or 'BDT' variable.

4.4. MVA training stage- Determining the best method

TMVA's interface gives a plethora of options when it comes to providing graphical representations of the training outcome. One has the possibility of knowing which method is best to use for a particular dataset. Figure 5 shows that the best method at rejecting background while retaining the signal was the BDT (Boosted Decision Tree) as it was the method that gave the largest area under the relevant plot. BDT method is based on repeated boolean decisions starting from an initial single node, depending on whether or not a criterion is satisfied. This procedure goes on until it ends up with a single decision for each variable that is classified as a signal or a background event [14]. Figure 6 shows a sample tree of this kind.

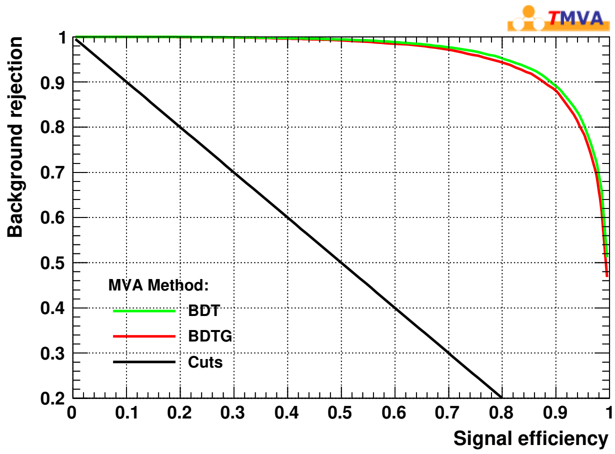


Figure 5: Area under curve determines BDT as the best training method at rejecting background.

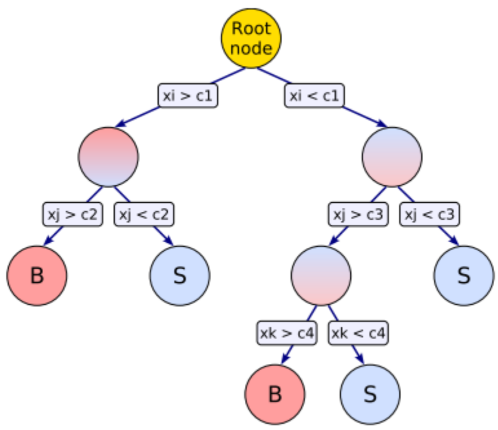


Figure 6: The Boosted Decision Tree schematic [14].

4.5. Importance of different variables

The TMVA process begins with a number of variables that the user passes on to the software in order for it to start the training process. These variables were chosen carefully as the most appropriate in order to give the best discrimination between signal and background events. MVA output then ranked the variables depending on their importance (see Appendix A). The most important of them, were the pion momentum, the identification variables for the two Kaons, and the χ^2 of the track vertex related with the degrees of freedom. A selection of these variables is shown in figure 7 as an example, where the signal is in blue and the background is in red.

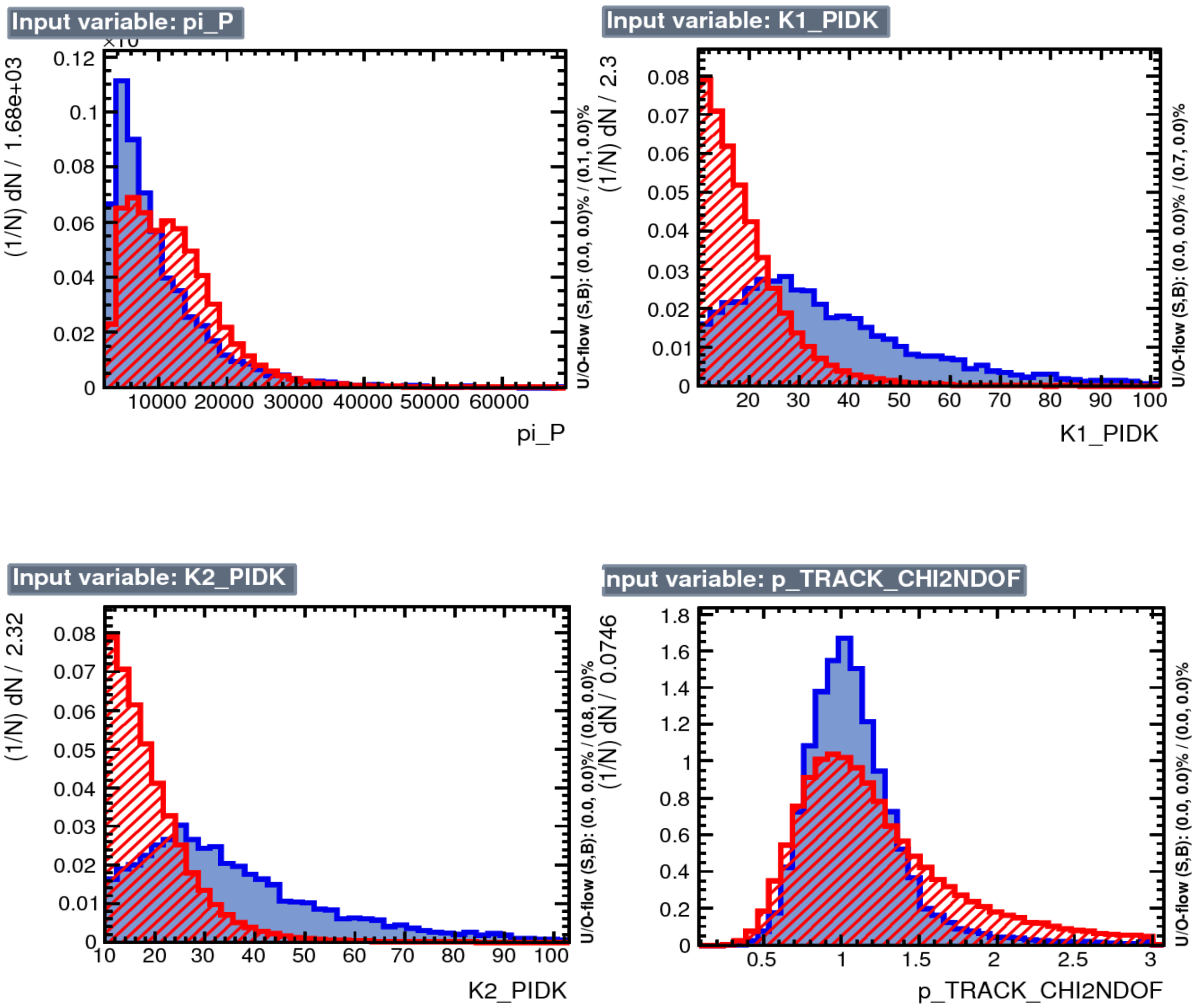


Figure 7: Signal and background distributions for some of the most highly ranked variables.

4.6. BDT classifier and optimal cut value

As mentioned earlier, the most efficient method of the MVA training was the BDT. It comes as a single classifier variable and can be calculated for each candidate in the real dataset. One can have a rough estimation of the range of the optimal cut value, by looking at the classifier response output from the TMVA. We expect a peak starting to be visible at a cut around -0.1 and a sharp drop off for values above 0.2 (figures 8 and 9). The exact BDT cut value though, is more complicated to define as it requires knowing how much signal and how much background there is in the data sample. To determine that, the best way was to apply the training to the real data and gradually increase the cut value to see how the signal peak varied.

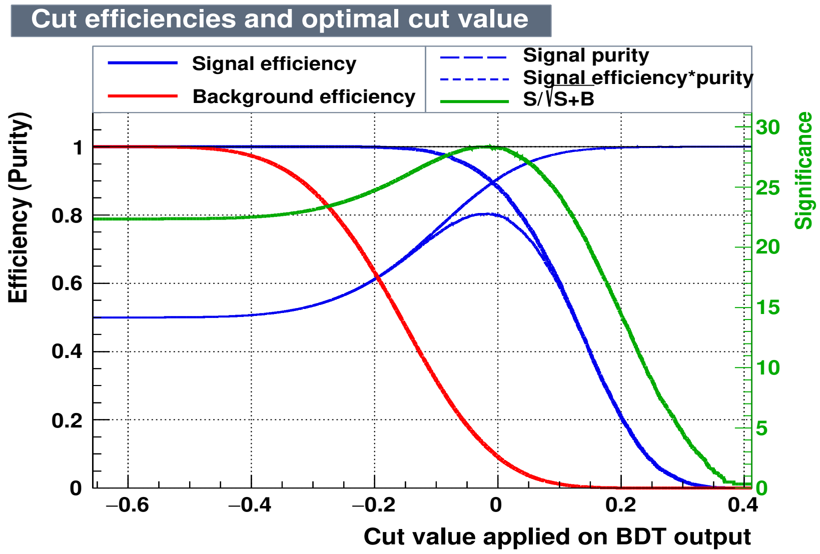


Figure 8: Cut efficiency levels for the BDT classifier, provides a tool for determining the range within which one may expect to find the greatest signal significance.

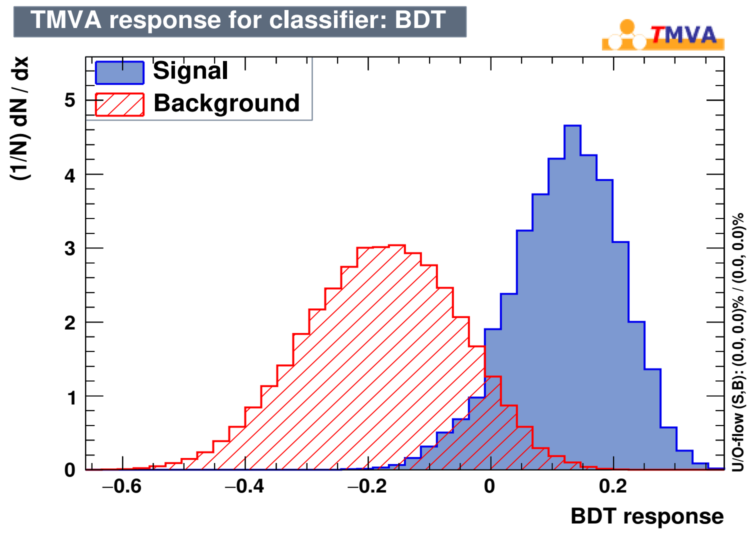


Figure 9: TMVA response for the BDT method, can provide a rough estimation for a range of optimal BDT values. The expectation is, that the maximum number of signal candidates would be given for a BDT value greater than 0 and less than 0.2.

4.7. Mass distribution with optimal cuts applied

For each BDT cut value, the significance was calculated as $\frac{s}{\sqrt{s+b}}$ where s and b are the signal and background levels respectively. The maximum significance would then give the optimal BDT output value to be applied as a cut on the whole data. A first mass fit was made to simulate the signal with a Gaussian and the background with a Chebyshev polynomial. For the first fit, a BDT cut value that gave the most decent peak by visual approximation was selected. Then the mean and the sigma for the Gaussian was fixed, so one could scan over all the cut values and fit only for the number of signal and background, and also the background shape parameters i.e. the Chebyshev polynomial gradient. The fit would then still be stable, even if the signal peak was not clear since the signal shape was fixed. Looping over small intervals of BDT value, gave a maximum significance when the BDT had a value of 0.01.

A final cut for the mother particle impact parameter χ^2 variable was used with a default value just lower than 5. The reason is, that a fraction of the the Ξ_c^0 baryons is produced in decays of b hadrons which tend to fly a significant distance from the PV before decaying. Since these are not produced at the primary vertex, they have a larger impact parameter χ^2 value, so we minimise the contribution of this background by requiring candidates to have a small IP χ^2 which removes most of this background from secondaries (but not all).

The plot of the mass fit with full cuts (for BDT and secondaries) applied, is shown in figure 10. It is clear that the background has been decreased significantly. The entries were reduced to 98443, with a signal yield of 2308.8 events. The mean of the Gaussian was at 2471.57 ± 0.47, in agreement with the baryon's known mass [2].

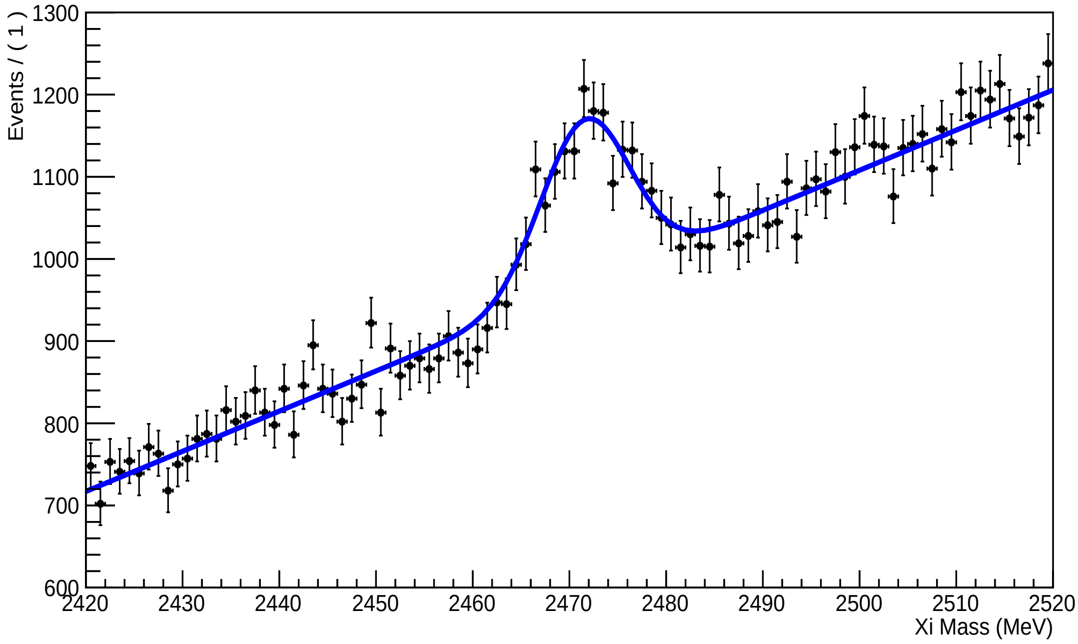


Figure 10: Mass distribution of the Ξ_c^0 baryon with full cuts applied. The background has been decreased and the signal peak is much more prominent.

4.8. Lifetime measurement

After the fit of the mass distribution was made, the signal yield, i.e. the number of remaining candidates that were representing signal events, was determined in bins of decay time intervals. The resulting histogram was to be used in order to calculate the Ξ_c^0 directly by fitting an exponential. In order to fit an exponential to the histogram, a blinded analysis approach was used, i.e. the decay constant of the exponential was declared as a blinded value by using a blind offset in the form of a scale parameter of about 20%. In addition to that, the error on the signal values for each bin was caculated. The purpose of the blinded analysis was that the result was not revealed until the full analysis was done. That was to avoid any biasing towards the result from the experimenter's perspective. If the final result is way off the expectation, one can then try to improve any problematic approaches in his experimental methods [15].

Figure 11 shows the exponential fit on the histogram. The blinded decay constant was output from the software, and the blinded lifetime was then calculated as 1/(Decay constant). The error on the lifetime was finally determined as (decay constant error)/(decay constant squared). The results gave a decay constant A $= 7490 \pm 170$, a lifetime of $\tau_{\Xi_c}{}^0 = 0.1335 \pm 0.0029$ ps, that was translated in a 2.23% error, which is about 4 times better than the error of the world average value which is currently 10% [2], so the improvement on that was significant.

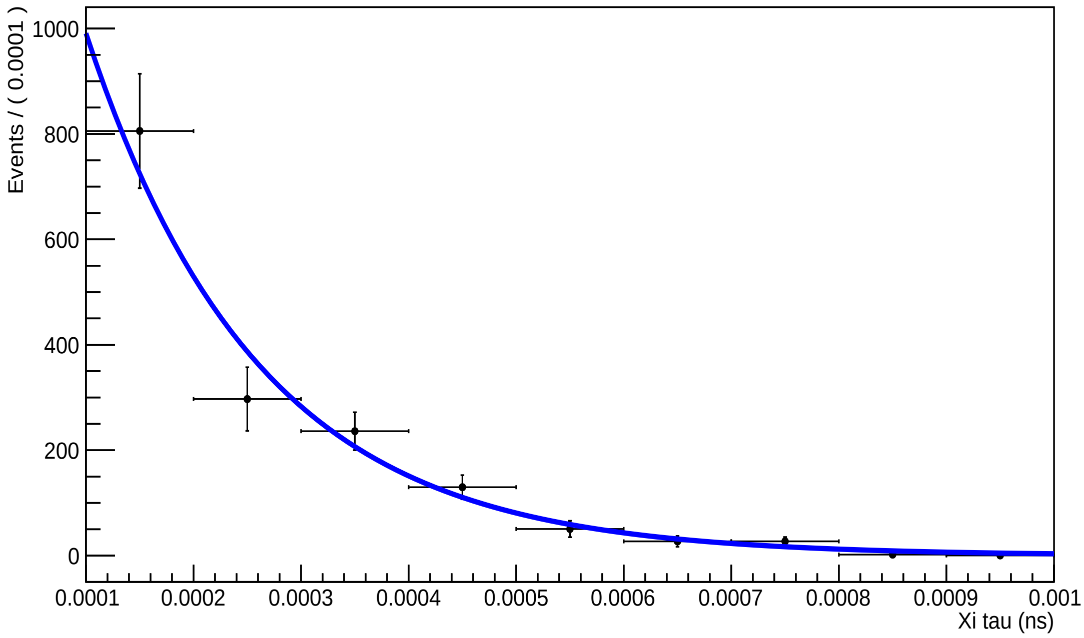


Figure 11: Exponential fit to the decay time distribution, giving a lifetime value of 0.1335 ± 0.0029 ps for the Ξ_c^0 baryon. The uncertainty precision (2.23%), is four times better than the current world average.

4.9. Systematic uncertainties

As mentioned in the previous sections, the exponential fit was done on a histogram that contained signal values in decay time intervals with a cut on IP χ^2 that was required to be less than 5 in value. Having calculated the effects of different cut values of this parameter, it is clear that it was one of the contributing factors of lifetime fluctuations.

Lower values of the IP χ^2 cut, means that the particle is more likely to have been produced at the primary vertex. Starting from the default value of <5 , when the cut became tighter, that reduced the lifetime a little, as the effect from secondaries was reduced, while as the cut was loosened, the lifetime increased significantly, due to higher secondaries contribution. The size of the variation in the lifetime demonstrates that the contamination of secondaries is significant for looser cuts, and relatively small for tighter cuts. The results indicate that it might be better to tighten the cut slightly from its current value, as loosening it only to <6 causes a big shift in the lifetime, while the difference between cutting at <5, <3 and <1 is smaller than the statistical uncertainty. In other words, since the difference between the lifetime value caused by the default

Table 2: The effect of the χ^2 cut on the results

IP χ^2	Lifetime(ps)	Error (%)
<1	0.1318 ± 0.0046	3.5023
<3	0.1330 ± 0.0033	2.4577
<5	0.1335 ± 0.0029	2.2394
<6	0.1391 ± 0.0031	2.2527
<12	0.1438 ± 0.0032	2.2397

cut that was used for the measurement (<5), and the one caused by the tighter cut that removes most of the secondaries (<1) is 1.7 fs, the systematic uncertainty can be estimated to be in the order of 2 fs, which is within the range of the 2.9 fs of the statistical error.

5. Further considerations and improvements

Apart from determining the most optimal IP χ^2 cut, in order to remove the secondaries and secure that the lifetime measurement is unbiased, it would also be useful to double check the efficiency of the selected variables before the MVA training. And even assuming optimal selection, one could also consider the different training methods and classifiers of the TMVA.

Furthermore, different binning techniques can be tried in creating the histogram of the signal yield in decay time intervals, eg. non canonical intervals or an increased amount of bins with shorter intervals.

So, a full analysis including proper systematic uncertainties considerations during a longer project, is necessary in order to further support the results found.

6. Conclusion

During this project the lifetime of the Ξ_c^0 was measured by using data taken from the 2015 run of the LHCb experiment. The analysis was done with Python using ROOT, TMVA and RooFit, and it included several different steps in order to minimise the background and isolate the events that were best describing the signal. A methodical approach was used to consider only those variables that were not biasing the decay time distribution, in order to have more accurate results. A type of blind analysis was used during the extraction of the lifetime from an exponential fit, and so the methodology was not biased in that respect. The final result gave a value of $\tau_{\Xi c}{}^0 = 0.1335 \pm 0.0029$ ps with an error of 2.23% which is already a very big improvement on the current world average of 10% [2]. Further improvements can be made, with a full calculation of the systematic uncertainties in order for the findings to form the basis for a longer investigation.

Appendix A. List of variables used for TMVA training listed by their importance

Rank	Variable	Importance
1	pi_P	$8.976e-02$
2	K1_PIDK	$8.542e-02$
3	K2_PIDK	$6.496e-02$
4	pi_TRACK_CHI2NDOF	$6.480e-02$
5	p_TRACK_CHI2NDOF	$6.385e-02$
6	pi_PIDK	$6.255e-02$
7	K1_TRACK_CHI2NDOF	$6.221e-02$
8	K2_TRACK_CHI2NDOF	$6.150e-02$
9	Xc_P	$5.800e-02$
10	p_PIDp-p_PIDK	$5.780e-02$
11	p_P	$5.731e-02$
12	Xc_DIRA_OWNPV	$5.652e-02$
13	p_PT+K1_PT+K2_PT+pi_PT	$5.628e-02$
14	K2_P	$5.627e-02$
15	Xc_ENDVERTEX_CHI2/Xc_ENDVERTEX_NDOF	$5.604e-02$
16	K1_P	$4.674e-02$
17	1000.*Xc_TAU	$0.000e+00$

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