Bachelor of Physics

Bachelor research internship report

Search for various three-body charmed and charmless b-flavoured hadron decays the decay with the LHCb detector

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Contents

Abstract

This is the place where your abstract is going The purpose of this paper is to report our work during our internship at the LPC. During this intership, we are looking for new decays mode. Still, prior to moving forward, we shall commence by harvesting as much knowledge as we can concerning LHCb and the software employed; so we will dedicate a brief passage to discussing these subjects.
Subsequently, we will utilize ROOT from CERN to investigate decay modes, employ mathematical models and make use of statistics to validate our hypothesis.

Throughout this internship, a significant portion of our initial efforts was dedicated to troubleshooting and comprehending the ROOT framework. Nevertheless, we managed to allocate time to finalize and validate certain hypotheses. We successfully uncovered novel decay modes; however, upon further investigation, it became evident that a number of these had been documented in prior publications.

Nevertheless, discoveries were made. While their significance in physics might be relatively minor, their identification is a crucial aspect of the mission to contribute to the compendium of natural knowledge.

Acknowledgements

Though is paper will be a very brief read, we spent two month working with on the side of the LPC team. Some where a great source of inspiration, other where a crucial help.
First and foremost, we express our gratitude to the LPC team for providing us with this internship opportunity, and to Stéphane MONTEIL for his mentorship throughout its duration who has made a lot of effort to make himself available and guide us toward the conclusion of our research. We want to thanks others, for their presence or their help, including Lars ROHRIG , Regis LEFEVRE , Jean ORLOFF , Eric COGNERAS.

1 Introduction

Since decades physicists are using the standard model to describe and carry their theories and projects.

2 Physics Motivations

2.1 The Standard Model of Particle Physics

Figure 1 displays the components of the subatomic world. There are 3 main categories to classify these objects.

- Quarks cannot be observed directly, but can be observed as components of observable matter such as neutrons of protons. Quarks interact with each other thanks to strong interaction. There are 6 quarks (and 6 anti quarks). They can have a charge of $\frac{1}{3}e$ or $\frac{2}{3}e$.
- Leptons are different from Quarks mainly because they are not sensible to strong force or colors.
- Bosons are part of a different category composed of particles whose spin is a integer value. They all have a different role. Gluons are at the origin of strong force and interactions for example.

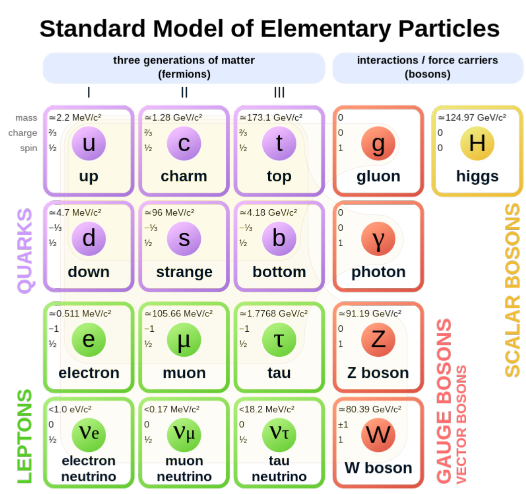


Figure 1: Standard model

2.2 Invariant mass

Invariant mass is one of the main property of a quantum object (among spin and charge). In order to determinate the invariant mass, we must know about the pulse and the energy of a particle. Moreover, this rest mass is the same in every frame of reference As we will see, the LHCb is designed to determine these variables, and after some weeks, a lot of data about masses are available for further analysis. In special relativity, the only way to find the mass of a particle knowing the pulse and the energy is to use the formula : $E = \sqrt{p^2 + m^2}$ (c=1).
Knowing the invariant mass of the object created by a collision, we can discover new decay modes of baryons and mesons.

2.3 Beauty production

In a collision between gluons there are tree dominant mechanisms for the creation of a pair of beauty $b\bar{b}$. This interaction leads to an angular distributions of the beauty pair.

So, when there are a collision in the LHCb, the products continue their way only towards the pipe, with a 50% chance of leaving either side. If we have many collisions for the detector it's possible to take care only one side of the collision and have results. That explain the topology in cone of the LHCb which will be described in the next section.

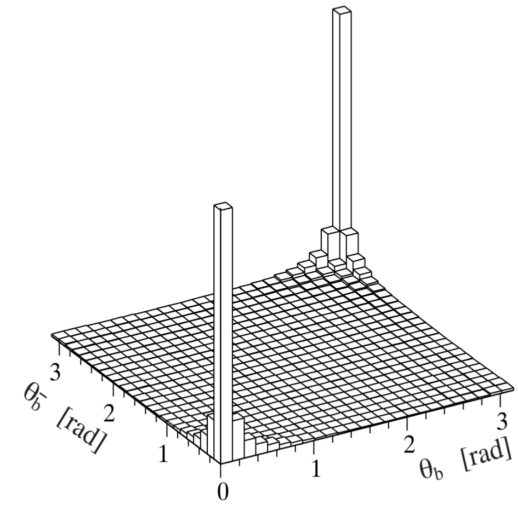


Figure 2: Angular distribution of the pair beauty production to the ridge axis in proton collisions at the LHCb

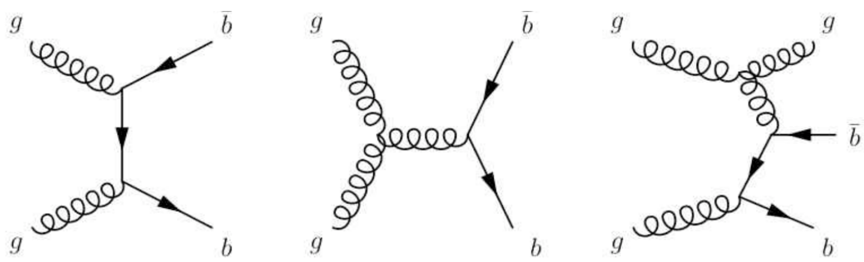


Figure 3: Feynman diagram of the dominant production of the beauty pair $b\bar{b}$

2.4 Radiative Energy Loss

This phenomenon is also knowws as the Stopping Power of materials and is a crucial element we must take in account. This energy loss may lead to miss-matching particles with others in some cases.
The stopping power concern both charged and uncharged particles ; while penetrating matter (so detectors in LHCb) particles may lose more or less energy depending of the properties of the material

2.5 Symmetries

In physics, symmetries provides a important amount of information. For example, and important symmetry is the CP one; it is a transformation that switches a particle into her corresponding antiparticle (changing all charges related to force). It's useful to look at the symmetry of physics law under this transformation. For now, the C symmetry is mainly a concern in cosmology because of the dominance of matter in the universe.
P symmetry consist of an inversion of space : $P(x, y, z) \to (-x, -y, -z)$, a "mirror image" transformation. In quantum mechanics, a wave function that stay unchanged after a P transformation is named a "even" function, while those that change signs are called "even". The P symmetry involve the special orthogonal group : SO(3) and the special unitary group : SU(2).
The last important physics symmetry is the T symmetry : $T : t \to -t$, the inversion of time. The same way than P or C transformation, the image by this transformation can be odd or even. For example, $\vec{x}$, or $\vec{a}$ for a particle are even under a T transformation, on the other hand, t, $\vec{B}$ or $\vec{v}$ will be even (so inverted).
It was until the 1960s that physicist assumed every known particles were CP symmetrics because none of them violated CP. But it was while studying K mesons that CP-violation was monitored the first time. The violations was then observed on beauty mesons in 2001, as the Top and Bottom quarks were discovered and whose could possibly be a major anomaly concerning CP symmetry.

2.6 Discovering new decay modes

There are infinite possibilities of decays mode for mesons and baryons. Each of them have their own probability of happening : the branching fraction. Most of them so rare that studying them is rarely interesting, and obtaining data may prove to be scarce or even non-existent.
But given enough data, we are able to look for new and not so uncommon decays mode. It is with this mind that LHCb and other detectors produces millions of collision, harvesting terabytes of data to ensure that the community will be able to quantify physics.

In this paper, our primary objective is to examine some possibly unexplored decay processes:

- $\Xi_b^0 \to p\pi K_S$
- $\Lambda_b^0 \to p\pi K_S$
- $\Xi_b^0 \to pKK_S$
- $\Lambda_b^0 \to pKK_S$
- $\Xi_c^+ \to pK_S$

In the following sections, we will review the hardware and software employed, as well as the mathematical techniques used to validate the majority of these hypotheses.

3 LHC and LHCb spectrometer

3.1 LHC

The LHC (Large Hadron Collider) is a circular particle collider located on the France-Swiss border at CERN (European Organisation for Nuclear Research). It is one of the main tool for researchers to study particles. The LHC is specialised on proton-proton collision, and are accelerated to energies up to 7 TeV.
Theses protons (or other Hadrons) are accelerated through a 27km tube, thanks to 8T magnets. Afterwards, the collision occurs in one of the 8 detectors across the LHC.
Today, the LHC is mainly associated with the discovery of the Higgs's Boson. The former LEP wasn't powerful enough to make such discoveries, although it was useful to study the properties of W and Z bosons, and the top quark.
The main motivation behind the upgrade was the exploration of higher energies, in order to detect the Higgs' Boson and new particles.

3.2 Luminosity at LHCb

In experimental physics, the most import thing in an experience is this reproduction, the number of events. Here the event is the collision between two hadrons is defined thanks to a number call Luminosity :

$$\mathcal{L} = \frac{N_1 N_2 k_b f \gamma F}{4\pi\beta^* \epsilon} \tag{1}$$

Where N_1 and N_2 are the number of protons in a packet, k_b the number of packet crossings in one machine revolution at the point of intersection, f the frequency of revolution of the LHC. γ the Lorentz factor, ϵ the emittance, is the length of the pipe at the collision point. β^* is the capacity of the magnet to concentrate the beam into the interaction point. And F is a factor that accounts the angle at which the two beams cross.

In the LHC we have $\mathcal{L} = 2.10^{32} cm^{-2}s^{-1}$.

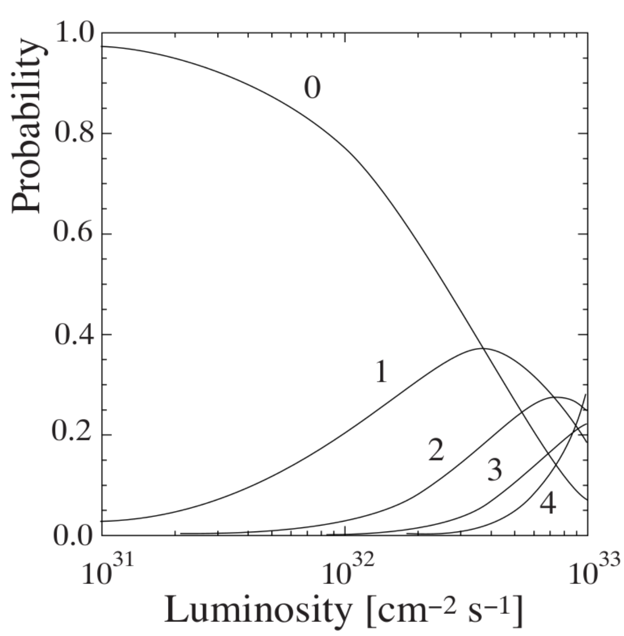


Figure 4: Probability of collision

luminosity plays a crucial role as it exhibits a strong correlation with the amount of data accessible for our analysis. The higher the luminosity, the more data we will have at our disposal for investigation.

3.3 LHCb

For reason we are going to develop later, the study of the Beauty Quark could carry much importance to understand many deficiencies in our understanding of particle physics and cosmology.
For this purpose, the Large Hadron Collider Beauty Experiment was a detector optimised to harvest properties on Flavours and Beauty Quarks and b quark-composed Hadrons.

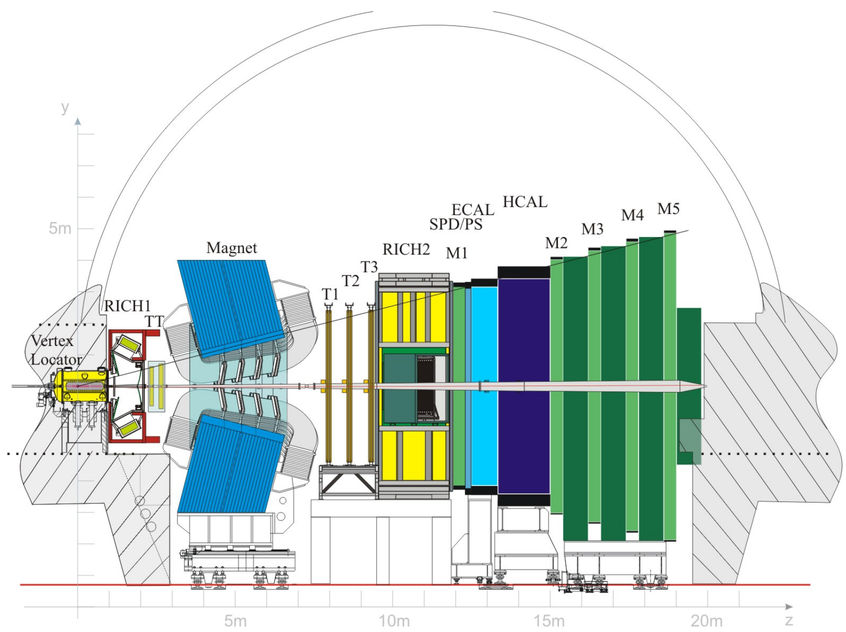


Figure 5: Side overview of the LHCb with his detectors

The conic structure of the LHCb detector is sufficient due to the trajectory of our beauty charmed particles. We will develop this point later in this paper. The LHCb is made of many detectors, all of them useful in a way to get more data about the decay.
In the logical order, here are the function of every parts of the LHCb detector :

The tube is leading our protons toward the detectors. It is made of beryllium, a good choice of material due to the properties of the metal ; Beryllium is a non-magnetic material, so it won't interfere with charged particles. The tube narrows down near the collision point where billions of collision will occurs per second, depending on factors such as luminosity and the quality of the vacuum inside the tube. Then, after the collision, the many detectors will come into play .

3.4 Vertex Locator

First of all there are the Vertex Locator (or VELO), is enables to track the trajectory of the b- and c-hadrons thanks to a disposition of silicon modules. This system have any impact on the particles. All of silicon modules have two sides, one for track the distance from the centre of the modules (R sensor) and the other side track the angle (θ sensor). Also we know the length between every module. Here we are on a cylindrical coordinate system.

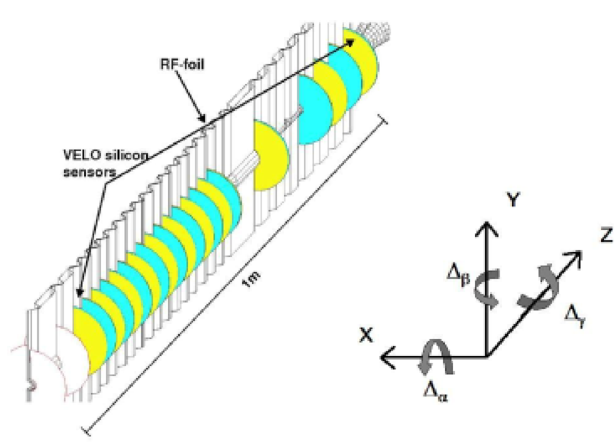


Figure 6: Silicon modules

3.5 RICH 1 and 2

In this part of the LHCb, after the VELO, the polar angles of the particles decrease. So it's more difficult to find the momentum spectrum. In answer for that problem, there are two Ring Imager Cherenkov (RICH1 and RICH2). Thanks to the Cherenkov effect we can find the speed of a particles which exceeds the speed of light in a medium, because we have a relation between the open angle of the light cone and the speed of the particle :

$$cos(\theta) = \frac{1}{\beta n} \tag{2}$$

with β the ratio between the speed of the particle and the limit speed of the relativity theory (c), and n the refractive index of a medium.
The medium here is gas, we have the C_4F_{10} and Aerogel for the RICH1 and the CF_4 for the RICH2. The RICH1 covers the low momentum charged particles range (1-6 GeV/c) and the RICH2 covers the high momentum range (15-100 GeV/c).

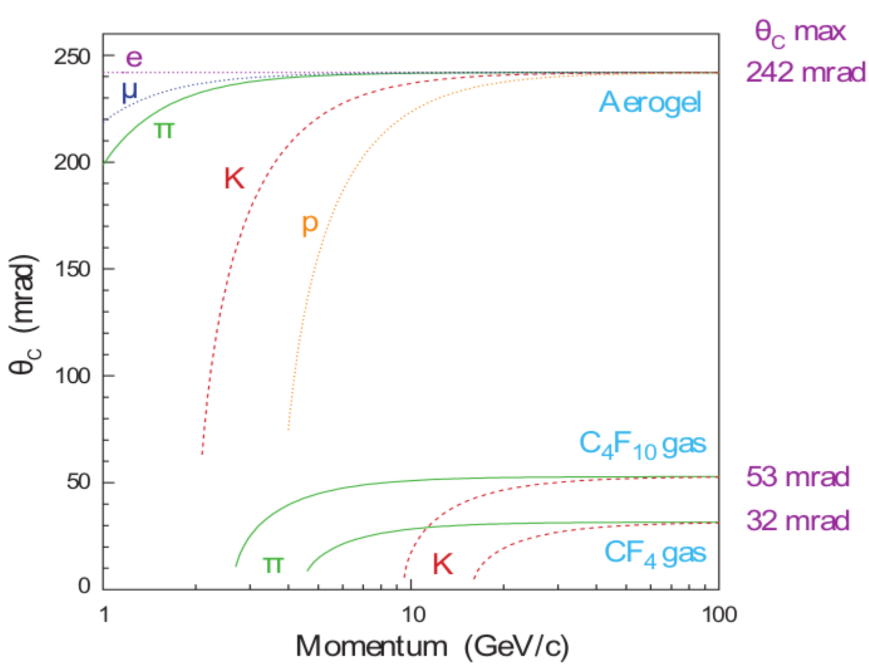


Figure 7

The light cone is redirected via mirrors to the edges of the LHCb so as not to interfere with other detectors

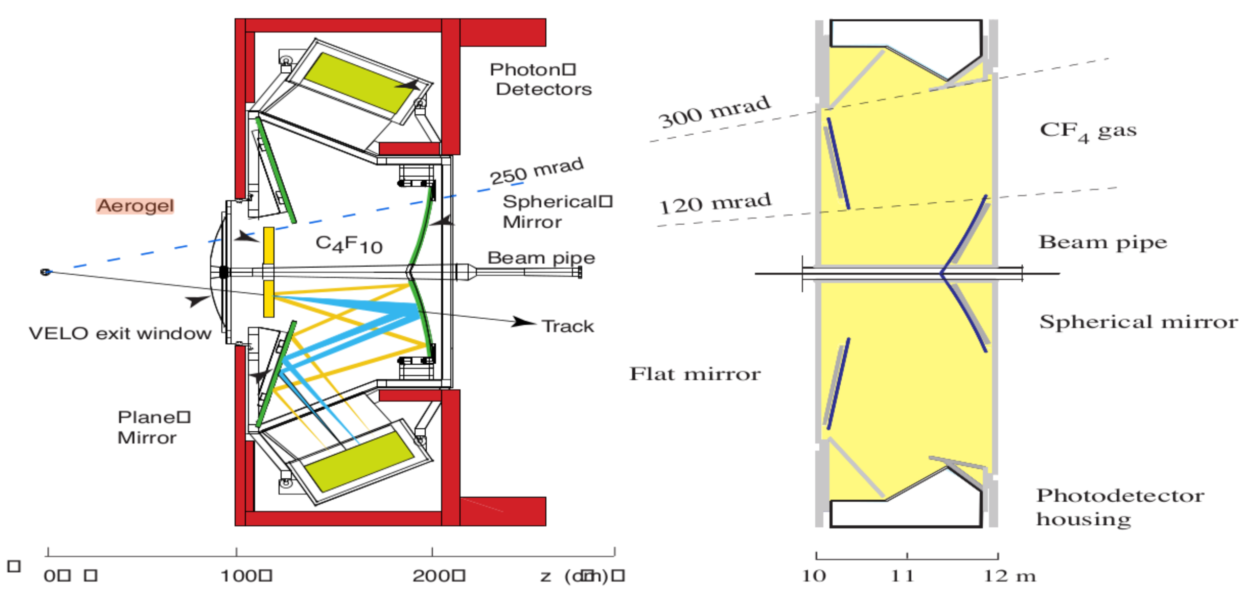


Figure 8: RICH1 and RICH2 layouts

3.6 Magnet

The main function of this magnet is to measure the momentum of incoming particles. It as a magnetic field of 4T generated by aluminium coils. It's shape is adapted for pp collision, which requires a free aperture of ±300 mrad horizontally and ±250 mrad vertically. To get data about the momentum of particles, it will be interesting to periodically change the direction of the magnetic field using the formula $Bqv = \frac{mv\check{s}}{r}$ and a tracking system.

3.7 Silicon Trackers

In the LHCb there are two silicon tracker, one before the magnet (TT) and the second after the magnet (IT, or T1 T2 and T3). They try to track particles the most closest possible from the pipe of hadrons. They are made up of silicon micro-strip sensors with a resolution of 50 μm for one hit. Each station consists of four detection layers (x-u-v-x) grouped by peer with an angle of ±5° for a reconstruction in three dimensions of the trajectory of particles.

We have the propiety that when a charged particles hit silicon, the paricles interact with the atom, generating ionization. This interaction creates electron holes that are captured by electrodes and converted into an electrical signal. Due to its lighter mass than the silicon atom, the particle loses almost no energy as it continues its adventure at the run in the LHCb.

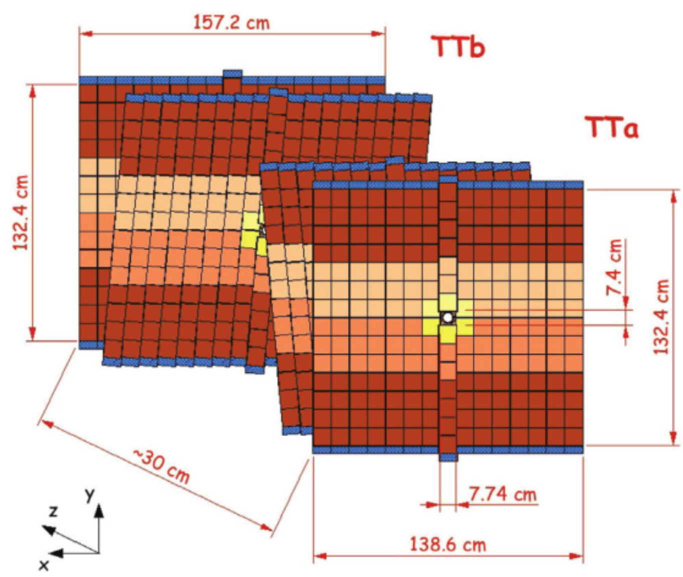
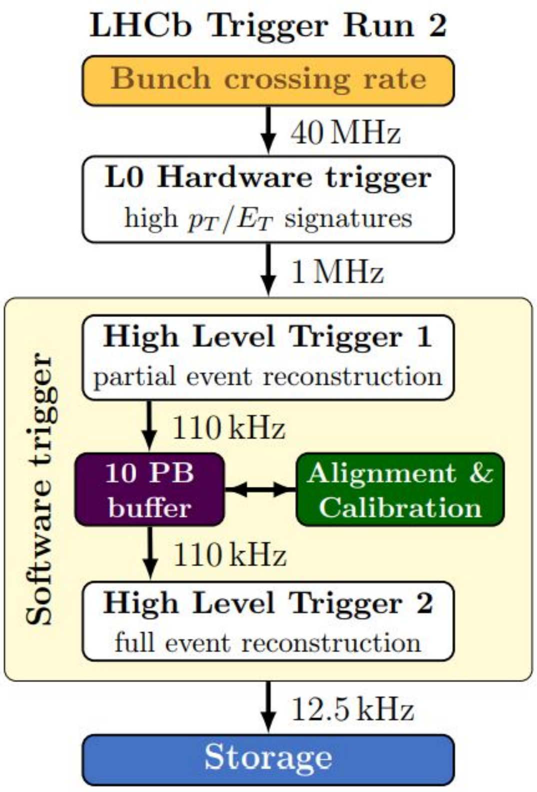


Figure 9: Composition of the TT

3.8 The LHCb Trigger System

Collision generate an enormous amount of data and uninteresting particle. It becomes a main issue for data analysis and it is essential to build a system to differentiate interesting event from basic one (background). It's with this aim that a Trigger system was created and integrated inside the detector.
The first one is named the L0 Trigger implemented in hardware, it is followed by a software trigger named the High Level Trigger (HLT). L0 Trigger was implemented into the Calorimeter and the Muons detector, and it is the first step into detecting the event of interest of the experiment. It work at a high frequency (1Mhz for a bunch crossing rate of 40MHz) and is has been designed to take quick decisions. Then, if the collision is deemed important, it will be transmitted to the HLT for further analysis.

The HLT runs on a very powerful "computer" named the Even Filter Farm, multiprocessor PCs. It consist of 2 stages (HLT1 and HLT2).Their function may vary depending on the current status or objective of the detector. In the figure above, we have the Run 2 configuration of the HLT. It will read the data fromthe L0 and generate 70kHz of Data. The HLT2 will lower this rate to 3kHz (2011).
Eventually, the data will be saved on a disk, after being filtered in through the HLT algorithm. In a nutshell,the L0 Trigger system is here to delete the background and uninteresting collisions very quickly using basic maths and simple algorithms. On the other hand, the HLT will run more complex physics test on the kept data, and powerful machines are needed to do so .



Due to technology and current electronics limitations, about 1 of 15 collisions are monitored, due to the very high collision rate. But latency can make this ratio even lower.
It will use the data from the many detectors to keep high transverse momentum and high transverse energy particles. We will further describe these physics points later. With this unit, we are going from >10Mhz of data to <1Mhz of data. The calorimeter part of the L0 Trigger uses data from the SPD, PS, ECAL and HCAL, and the decision will be transferred to a single unit named the "Readout Supervisor Board" before getting sent to the HLT.
The muons L0 Trigger system : It will select event containing a single Muon with $p_T > 1.76GeV/c$ or a pair of Muons with $p_{T1} \times p_{T2} > (1.6GeV/c)^2$.

4 Analysis

4.1 Data Analysis

In order to analyse and classify a million of recorded collision, we much use really optimised programs,it was for this purpose ROOT was created. It enables the visualisation of a large amount of data, and was made to be used with C++, Python or Java.
Root is the abbreviation of "Residual Object Oriented Tree", it's effectiveness shine thanks to the efficient data structure used : TTree and Tchain allowing the access of large data-set quickly. It has a plotter included with a lot of customisation options and allows 3D visualisation. Multi threading support is, too, very important.
As a result, we can monitor the mass of mesons, like b charmed mesons . In our case, we will focus on RUN 2 (2016/17/18) data.

In the reconstruction of the K_S^0 with an π^+ and an π^- in final state, there are two categories of reconstruction. The "Long" is the one that has hits in the vertex detector and the tracking stations downstream of the dipole magnet. The second category includes decays into pions that have not been detected by the vertex, and use only the tracking stations downstream of the vertex detector for found them. These two categories are two different types of data offered to us. The probability density function (PDF) in each invariant mass distribution is defined as the sum of several components (which will be detailed in paragraph 4.2).

References

4.2 Modelization of the signal

In order to validate our hypothesis concerning an interisting signal, we must compare it with a mathematic model that follow some specific physics laws. The choice of the mathematical model depends on the particular phenomenon under investigation. This model aims to encapsulate the fundamental physical principles; in our case, we want to modulate decays.
To study decay modes, we are interesting into a normal law which is frequently used to describe the statistical behavior of experimental data, including decay events. Furthermore, this normal law will allow us to take into account the statistical errors and the fluctuations ; indeed, fluctuations in data is going to cluster around a central value, that may be our most likely mass.
Unfortunately, particles going through the detectors, magnetics fiels and many intruments are going to lose energy, and their mesured invariant mass will be lower than predicted : this is called the radiative energy loss. We must incorporate this phenomenon in our models because they are essential for accurately modeling the expected outcomes of particle decay processes. In order to do that, we make use a the Crystal Ball Function (CB) defined as:

$$f(x;\ \alpha,\ n,\ ,\ \sigma) = \begin{cases} N \cdot e^{-\frac{(x-\bar{x})^2}{2\sigma^2}}, & \text{if } \frac{x-\bar{x}}{\sigma} > -\alpha \\ A \cdot (B - \frac{x-\bar{x}}{\sigma})^{-n}, & \text{if } \frac{x-\bar{x}}{\sigma} \leq -\alpha \end{cases}$$

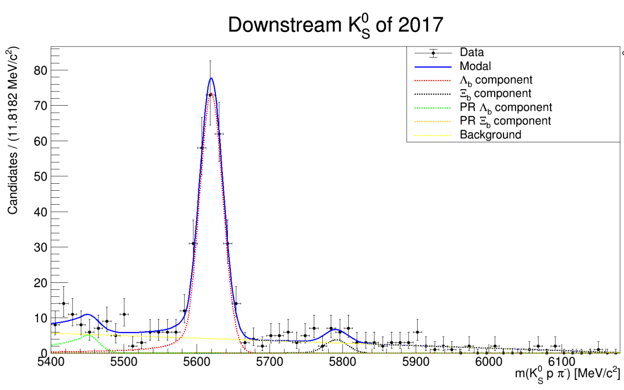
Essentially, this function leverages a power law to capture the effects of radiative energy loss. This form aligns well with the distribution of particle energies when radiative energy loss is a prominent factor. Combining this power law with a normal distrubution provides a more accurate representation of experimental data.

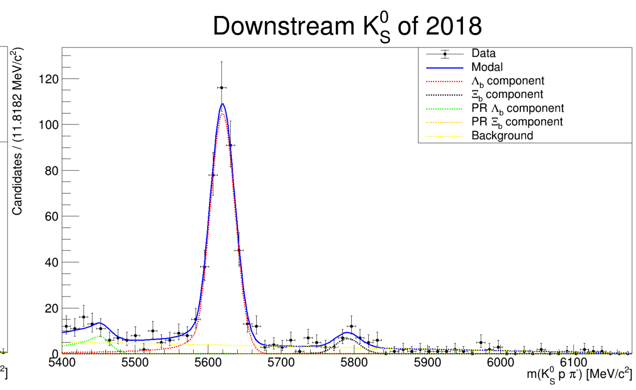
Normally, to describe background noise we use an exponential, but in our data we've observed that we can approximate the exponential by a straight line since we have few combinatorial background candidates. And more precisely by.... To properly model our data, we had to add the fact that certain four-body particle decays could be detected as 3-body decays. The ..... decays can be recorded as a 3-body decay because the π^0 will not be detected, only the other 3 particles. To integrate this decay into our model, we have added two crystal balls (for and), (it remains to say that we have subtracted the mass).

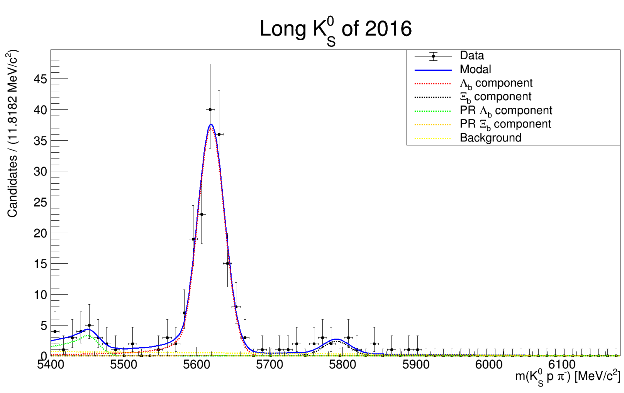
4.3 Fit of the model

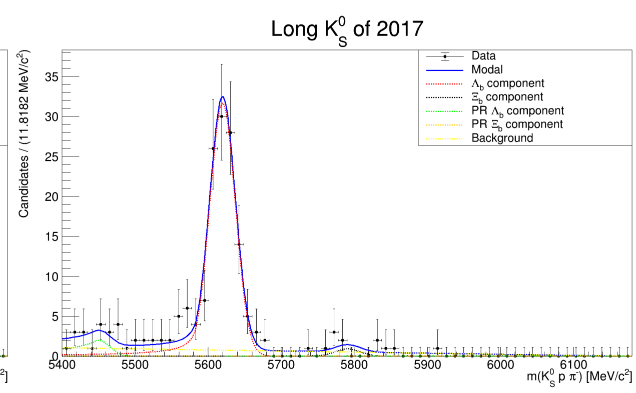
To make our fit more efficient, we decided to have all our yields determined simultaneously. This will help us to maximise the relevance of our signals.

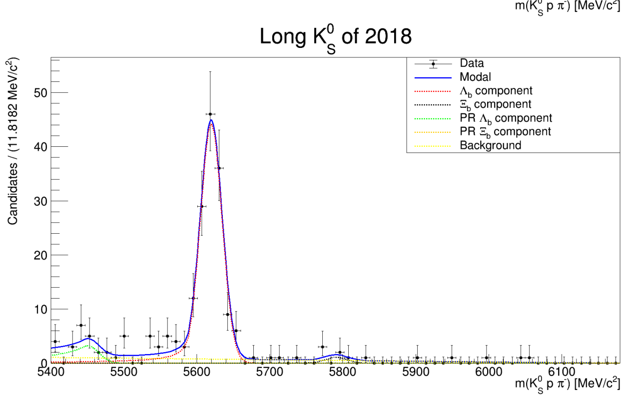
For the $\Xi_b^0(\Lambda_b^0) \to p\pi K_S$ decays our fit is :



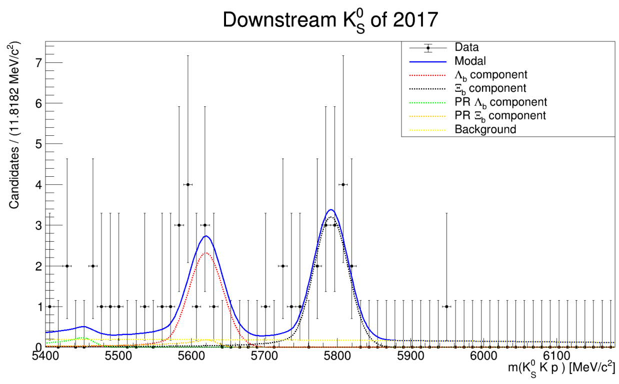


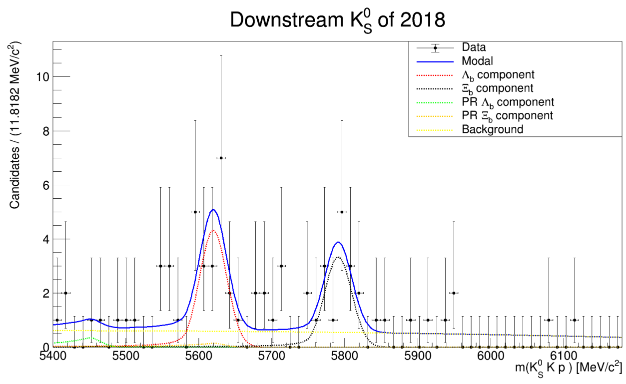






Here are our fits for the $\Xi_b^0(\Lambda_b^0) \to pKK_S$ decays :





4.4 Standard deviation measurement

To measure the statistical significance of our measure, we use Wilk's theorem. This is a hypothesis test in cases where the desired disintegration is not possible, and therefore does not exist. To do this, we need to calculate the likelihood function of our measure ;

Decays	Standard deviation
$\Xi_b^0(\Lambda_b^0) \to pKK_S$ 2017	5.53 (3.65)
$\Xi_b^0 \to pKK_S$ 2018	4.39 (5.10)
$\Xi_b^0 \to p\pi K_S$ Long (Downstream) 2017	1.40 (2.79)
$\Xi_b^0 \to p\pi K_S$ Long (Downstream) 2018	1.63 (4.49)
$\Xi_b^0 \to p\pi K_S$ Long 2016	3.48

5 Conlusion

Going through data analysis for the first time has been (most of the time) difficult though we managed to get good standard deviations at the end.
The most interesting part was to get more cultured about fundamentals of physics.