Search for the decay $B_c^+ \longrightarrow J/\psi D_s^+$ in LHCb

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Internship in the LAL (Bât 200, 91440 Orsay), framed by Yiming Li and Patrick Robbe

Greetings

I would like to thank every person in the team of the LAL for their sympathy especially Patrick Robbe, my tutor for having accepted me, Alexis Vallier and Benoit Viaud too, who have shared their office with me.
Finally, I wish to thank Yiming Li, for her welcomed advices, her constant support and her framings.

Abstract

In particles physics we want to observe the particles predicted by the standard model. This model describes all particles physics and presents, like a bestiary, the different particles existing. We are interested by a specific decay, and we observe only the daughter particles in the Large Hadron Collider. By several computing, we can obtain some distribution of differents variables of a some particle thanks to the data collected, and we can do the same for the mother particles.
The topic of this report, and thus my internship, is to highlight the different particles of the decay thanks to the data collected by the LHCb and explain the method used.

The following report contains mainly two parts about the decay $B_c^+ \longrightarrow J/\psi D_s^+$. The first one is about the general theory necessary for the study ; the second is about the treatment of data and their analysis.

Résumé

En physique des particules nous cherchons à observer les particules prédites par le modèle standard. Ce modèle décrit toute cette physique et présente, tel un bestiaire, les différentes particules existant. Nous nous intéressons à une désintégration bien particulière, et ne pouvons observer dans le Large Hadron Collider que ses particules filles. Par divers calculs, nous pouvons remonter à partir des données collectées à des distributions de la masse, par exemple, sur le nombre d'événements mesurés, et ce, même pour les particules mères des désintégrations.
L'objet de ce présent rapport, et donc du stage, est de mettre en évidence les différentes particules de la désintégration à partir des données collectées par le LHCb et d'expliquer les méthodes utilisées.

Le rapport de stage suivant contient principalement deux parties traitant de la désintégration $B_c^+ \longrightarrow J/\psi D_s^+$. L'une concernant la théorie générale nécessaire à l'étude ; la seconde concernant le traitement des données et leur analyse.

Contents

1 Introduction

During the last century, particles physics has known a great growth. The development of the theory has given an experimental dimension at this domain. Hence, a lots of laboratories and experiments were set up, like for example, respectively, the Laboratory of Linear Accelerator (LAL), and the Large Hadron Collider (LHC). My internship takes place in this laboratory about this experiment, and particularly, the LHCb experiment, which is a detector for meson on the LHC.

The LHC makes collision between particles at high energy, like for example two protons. A such collision produces meson B, and a decay of it follows. We obtain thus some products more stable than their mother particle, and we detect it in the LHCb. It is the work of Yiming Li and Patrick Robbe to analyse the data collected of some decays. Indeed, like only the last products are stable, only them can be measured, it is necessary to rebuilt the decay to understand every mechanism, and detect new particles, like the Higgs boson.

How can we rebuild a decay ?

The decay studied during my internship is $Bc^+ \longrightarrow J/\psi D_s^+$, and it is the subject of the following report.
In a first part we will present the different theoretical elements what we need, and a brieve part about the experiment. Then, we will present the data collected by LHCb ; to finish with their analysis.

2 Generalities

2.1 Elements of theory

2.1.1 The Standard Model

All elementary particles and the fundamental interactions are described by a model, the Standard Model in which every interaction corresponds to a particle, for example the electromagnetic corresponds to a photon. This model is a relativistic quantum theory (QFT) about particles, based on the local gauge symmetry SU(3)$\otimes$ SU(2)$\otimes$ U(1) with symmetry broken.

With this model, the physical matter is thus composed of fermions (spin $\frac{1}{2}$), and bosons (spin 1) which are vectors of interactions. Currently, there exist twenty-four species of fermions, including quarks, leptons and the antiparticles associated. We can resume it in the following table :

$$\begin{pmatrix} u & d \\ c & s \\ t & b \end{pmatrix} \begin{pmatrix} e^- & \nu_e \\ \mu^- & \nu_\mu \\ \tau^- & \nu_\tau \end{pmatrix}$$

$$\begin{pmatrix} \bar{u} & \bar{d} \\ \bar{c} & \bar{s} \\ \bar{t} & \bar{b} \end{pmatrix} \begin{pmatrix} e^+ & \bar{\nu_e} \\ \mu^+ & \bar{\nu_\mu} \\ \tau^+ & \bar{\nu_\tau} \end{pmatrix}$$

On the right, there are quarks, **u**p, **c**harm, **t**op, **d**own, **s**trange, **b**ottom, and the antiquarks associated. On the left, the leptons and antileptons associated : electron (e^-), muon (μ^-), tauon (τ^-), and the neutrinos associated.
An antiparticle is the twin of a particle with an opposite charge ; each quark and lepton has an antiparticle. Another important thing, free quarks don't exist in the nature, they are necessarly grouped with others, hence, we know a quark and an antiquark form a meson, three quarks a baryon. For example, a proton (baryon) of charge +e is composed of two quarks up and one quark done, i.e, **uud**. Indeed, u, c, t have a charge $\frac{2}{3}$e and d, s, b, -$\frac{1}{3}$e, where e is the elementary charge.

The part which interests us is the decay of a meson, formed by a quark and an antiquark, b and $\bar{c}$. That will be the object of the next part.

2.1.2 The decay $Bc^+ \longrightarrow J/\psi D_s^+$

Like we have seen before a pair quark-antiquark forms a meson. The object of our study is the decay of a meson produced in the Large Hadron Collider (LHC), and detect by the LHCb detector, where the adjective b corresponds to the bottom quark, which is studied in the decay.
The meson is Bc^+, formed with a bottom antiquark and a charm quark, coming from a proton-proton collision. This meson decays after an important time of

life (0.5 fs), in two others mesons J/ψ thanks to a boson W^- (weak interaction), and D_s^+. The first is composed of a pair quark-antiquark charm and so its decay is very fast. It appears two muons of opposite charge.
The D_s^+ meson is composed of a quark charm and an antiquark strange. It has a certain time of life, and decay in three others mesons, the pions. Two of them are charged positively, the other negatively to respect the conservation of charge.

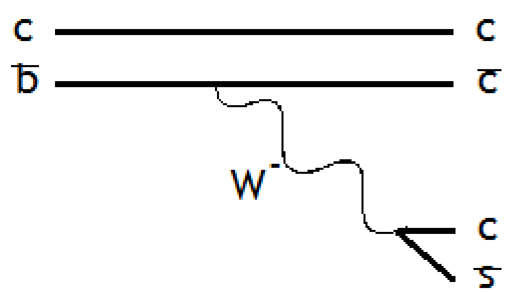

Figure 2.1 : Scheme of the decay studied, c and $\bar{b}$ represents the meson Bc^+, c, $\bar{c}$, the meson J/ψ, and c and $\bar{s}$ the meson D_s^+.

We know that mesons obtained during the first decay (Bc^+ decay) will decay in others particles. We detect mainly these particles because they have a long time of life. To recreate the decay, the idea is to use the conservation of the quadrivector energy-momentum, expressed by :

$$\begin{pmatrix} \text{E/C}_{mother} \\ \text{P}_{xmother} \\ \text{P}_{ymother} \\ \text{P}_{zmother} \end{pmatrix} = \begin{pmatrix} \text{E/C}_{daughter1} \\ \text{P}_{xdaughter1} \\ \text{P}_{ydaughter1} \\ \text{P}_{zdaughter1} \end{pmatrix} + \begin{pmatrix} \text{E/C}_{daughter2} \\ \text{P}_{xdaughter2} \\ \text{P}_{ydaughter2} \\ \text{P}_{zdaughter2} \end{pmatrix}$$

By this way, we can find, for example, the mass of the mother particle knowing all parameters of the daughter particles. Indeed, we know that the norm of this quadrivector is equal to m^2C^2, and has for expression $E^2/C^2 - (P_x^2 + P_y^2 + P_z^2)$. We can obtain E, P_x, P_y and P_z of the mother particle thanks to the vectorial equation before. So, the mass is given by :

$$m = \sqrt{\frac{E^2 - \vec{P}^2.C^2}{C^4}}$$

Where $\vec{P}$ is the momentum of the particle whose components are P_x, P_y and P_z.

We know how to determine the mass of the mother particle since we have parameters about daughter particles. How can we have information about these particles, how can we detect it ? The next part is about the LHCb experiment and the detector associated.

2.2 The LHCb experiment

2.2.1 The Large Hadron Collider

In 20^{th} century, a new physic appears governed by Relativity and Quantum theory. These two theories concern high velocity for the first, and small scale for the second. To study the phenomenon in this conditions, great accelerators were built. In 2008, the Large Hadron Collider (LHC) started its experiments. The most important result for Particles Physics coming from these works is the detection of the Higgs boson, which permits to explain the existence or the absence of mass for some particles. Its aim is to give answers in Cosmology and Particles Physics. For example, underscore the supersymmetry.

NB : A hadron is a particle composed with quarks and antiquarks, like for example a proton.

The LHC is located next to Genève, and built underground. It is composed by two circular accelerator with a girth of 26.7 km. Currently, there are four detectors on the LHC, CMS, ALICE, ATLAS and LHCb. Among its characteristic, the most important is the center-of-mass energy (7 TeV) of the proton-proton (pp) collision. Since 2015, this energy is re-evaluated at 12 TeV.
Another feature, the luminosity. During a pp collision, the visible number of interactions per second is given by $N_{visible} = L.\sigma_{visible}$, where $\sigma_{visible}$ is the visible cross-section and L, the instantaneous luminosity of the machine depending only of the bean parameters.

2.2.2 The LHCb detector

The LHCb detector is a spectrometer dedicated to b hadrons physics. The LHC is the largest source of B meson all around the world, indeed its $b\bar{b}$ production cross-section is 500μb at a center-of-mass energy of 14 TeV.
The pp collision is done in LHCb at a luminosity of $10^{32}cm^{-2}s^{-1}$ and at 14 TeV. With these values,we can expect 10^{12} $b\bar{b}$ pairs produced in one year of data taking. Among all detectors on LHC, the luminosity of LHCb is the lowest. However, there exist some advantages with this "weak" luminosity :

- The number of interactions per bunch crossing is limited, for LHCb is 5, for ATLAS, 20. It is important because with high number of pp interaction, the analysis is more complicated.
- The occupancy in the detector remains low.
- The radiation damage on the detector is reduced.

The all detector is shown on the figure 2.3. During all the presentation, we will call the z axis, the axis following the beam.
The LHCb detector has a unique detector acceptance with a forward angular coverage from 10 to 300 mrad (horizontally), and 250 mrad (vertically). This geometry is due to the fact that b and $\bar{b}$ hadrons are produced in the same forward or backward region. A large fraction of B hadrons are thus distributed according to the LHCb geometrical acceptance.

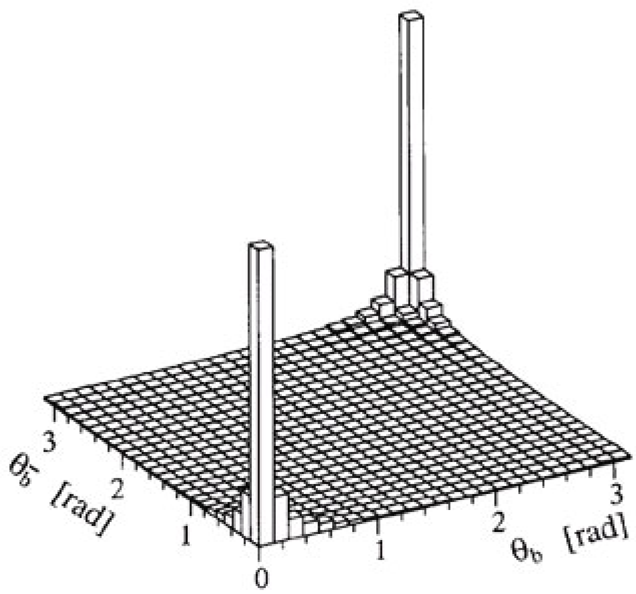

Figure 2.2 : Angular distribution of the b and $\bar{b}$ hadrons.

The next paragraphs concern the technical part of the LHCb detector, we will present the main parts of this detector and their operating principle.

To measure the momentum of charged particles in LHCb detector, a warm magnet is used. The integrated magnetic field is 4 T.m. We can inverse the polarity of this magnet to study the asymmetry of the LHCb detector. We measure the magnetic field in three regions of the detector, the region of VELO, the region of TT and the magnetic shielding of RICH detectors. All these acronyms will be explained thereafter.

In LHCb there is a tracking system, composed of the vertex locator (VELO) around the collision point, a trigger tracker (TT) and three tracking stations (T1-T3). This tracking system is responsible for the track reconstruction of charged particles and the measurement of their momentum. a good resolution for momentum is very important to reconstruct the mass of B mesons for example. Indeed, since the quadrivector is conserved like we have seen it in the previous part, we can obtain the mother particle mass. VELO permits to reconstruct precisely the primary vertex of the pp collision, which corresponds to the collision point, and the second vertex, corresponding to the decay of Bc^+.

2.2.3 Particle Identification

This part concerns anothers detectors of the LHCb, RICH (Ring Imaging CHerenkov), two calorimeters (electromagnetic (ECAL) and hadronic (HCAL)) and MUON. These detectors allow us to identify particles.
There are two RICH systems in LHCB, RICH1 and RICH2, which are dedicated to hadrons identification, based on Cherenkov effect (cf Annex.1). The calorimeters contribute to the trigger and measurement for electrons and photons.

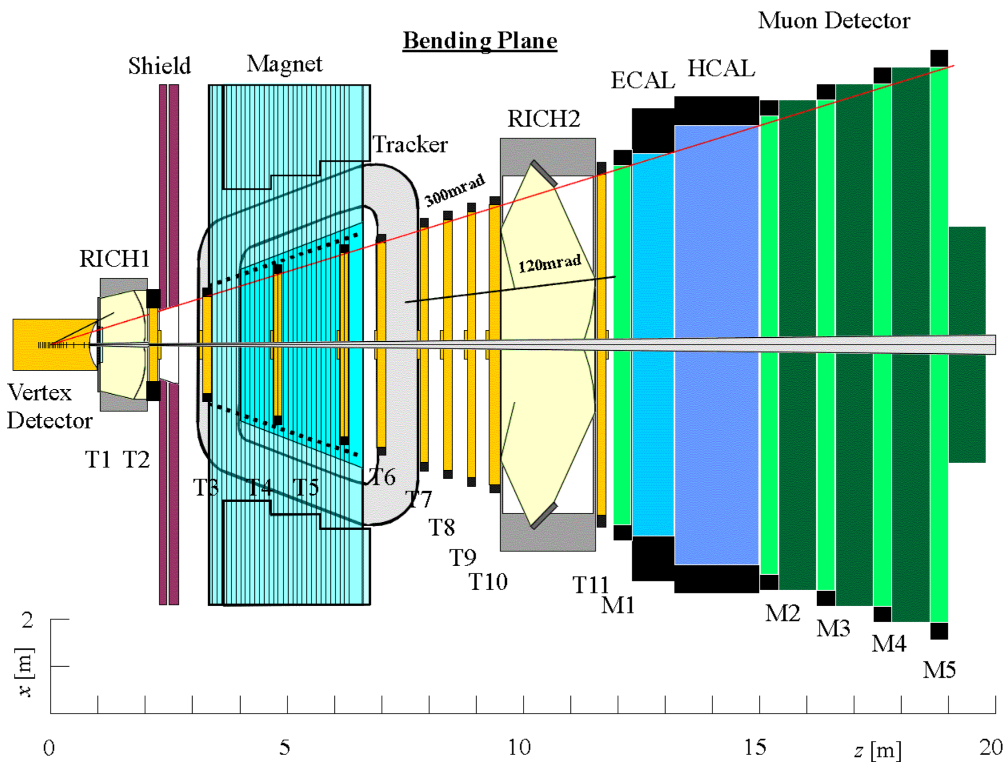

Figure 2.3 : Scheme of the LHCb detector.

3 Data

3.1 Presentation

Like we have seen before, thanks to the LHCb detector we can measure a big number of events, onwhich we can associate a lot of variables like the momentum, the position or others geometrical variables. We have four pieces of data collected because the magnet can be set in up polarisation or down polarisation, and a piece for 2011 (collision at 7 TeV), and for 2012 (collision at 8 TeV).

3.1.1 Real data

The data collected by the detector form that we call the real data. It concerns all events detected. Among these real data, we have two parts ; we have taken data in the LHCb with no proton-proton collision, i.e. we have just measured the pure background. On the other hand, we have done a measurement during the collision and so, we can expect that there are some B_c mesons in the data collected. We recall that for these two parts, we have the four pieces : up 2011, up 2012, down 2011, down 2012.

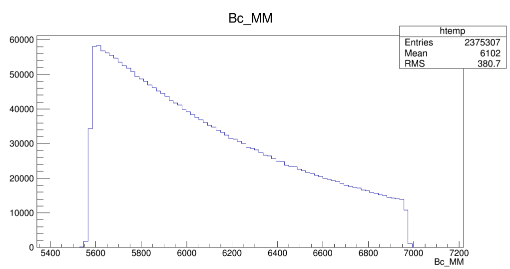

Figure 3.1 : Distribution of invariant mass of the meson B_c in real data, there is no singularity or peak in this distribution, just a continuum.

3.1.2 Simulation from Monte Carlo method

Beyond the real data, we have simulated data coming from the theory, i.e. the conservation of momentum and the Monte-Carlo method. So, we have a number of events for each variables corresponding to a pure signal.

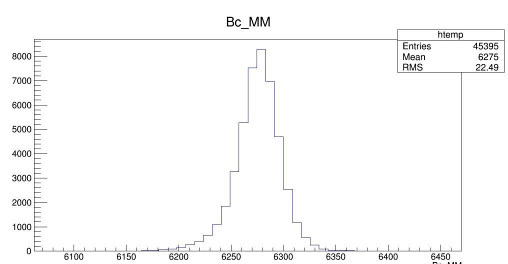

Figure 3.2 : Distribution of invariant mass of the meson B_c in simulated data, we can observe a gaussian with mean-value 6275 MeV/C^2.

The two last figures show us an important thing. The majority of events measured in real data are background, indeed, we can't see any singularity in the distribution. So, we need to define precisely the pure background, the pure signal and the data. It's why we have three differents data corresponding to them. We need to know how we can separate background and signal, it may be possible that some variables could be discriminating between them.

3.2 Discriminating variables

3.2.1 How can we find it ?

The general idea to find the discriminating variables is to use the simulated data and the pure background to compare them. We have the distribution for all events for each variable. To recall it, in our data, we have a pure signal, a pure background and the measurement of the decay. We want to observe a singularity in the distribution of mass in the measurement. To do it, we have to compare the pure signal and the pure background to exhib the characteristics of signal and background.
Moreover, the pure signal teach us about the range where can be the potential particle. So, for example, on B_c invariant mass, we have made a cut on it in the pure background, which corresponds here to a cut at 6275 +/- 20 MeV/C^2.
If we plot all distributions for each variables with pure background with cut (which will be called the sideband), pure background and pure signal, we can identify the discriminating variables like the plot where pure signal and pure background are radically different. In the sideband, we are sure that there is no particle. Like on the following figure.

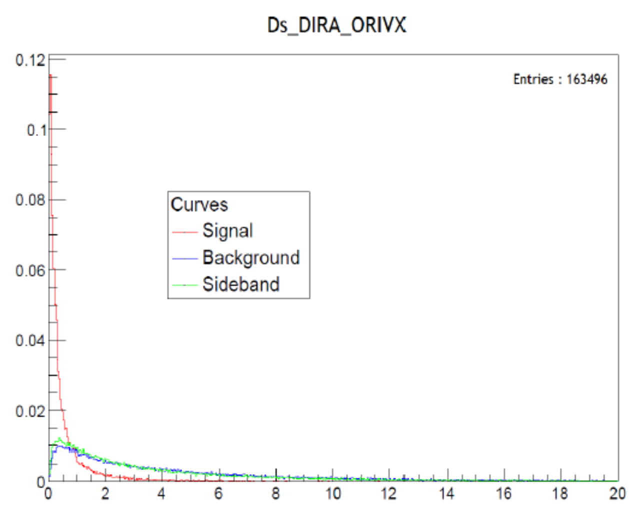

Figure 3.3 : Example of comparison between the pure background (blue), the sideband (green) the pure signal (red).

3.2.2 List of discriminating variables

In this paragraph, we make a list of the discriminating variables that will be use to select the signal in the data.
We have three types of variables, some are just geometrical considerations, like angular dispersion or flight distant, or are kinematic variables like the transverse momentum, or even variables about the vertex quality.

	Kinematic	Geometrical	Vertex quality
D_s	Transverse momentum	Angular dispersion / Impact parameter / Flight distant	Vertex position
B_c	Transverse momentum	Angular dispersion / Impact parameter	Vertex position
Pion	Transverse momentum		
J/ψ	Transverse momentum		

Figure 3.4 : List of discriminating variables.

4 Analysis

4.1 To identify the different events

4.1.1 Boosted Decision tree (BDT)

In the previous part we have presented the discriminating variables. All our analysis concerned one particle, D_s, it's why, among the variables we use only the D_s variables.
The analysis is done by a software called Root (developped by the CERN), and a plug-in, Toolkit for MultiVariate Analysis (TMVA). The general pattern of the analysis is described in the following picture.

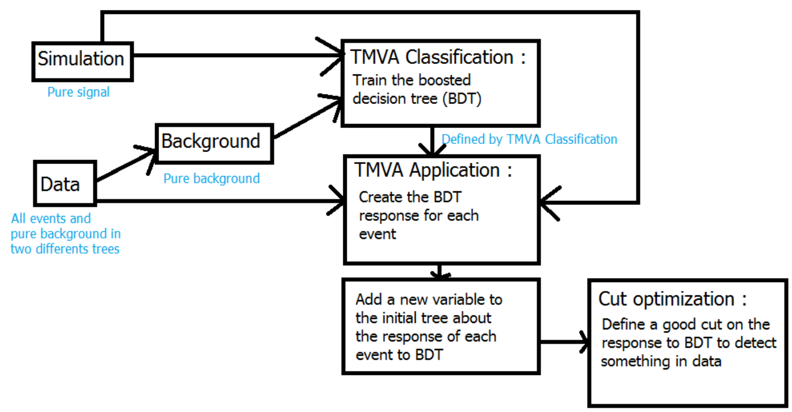

Figure 4.1 : General pattern used during the analysis.

From the pure signal and the pure background, we train the boosted decision tree (BDT). It permits to observe the link between all variables and evaluate each characteristic. It's an algorithmic method.
About the BDT, we can create a response to it for every variables. The study of this response allows us to know where is the particle for a given variable (invariant mass for example, and it is used in the following parts), indeed, it is linked to every discriminating variables. The following picture is about the response to BDT for the pure background and the pure signal. We can notice that there is a real difference between the both. It's why we use this method to separate signal and background precisely.

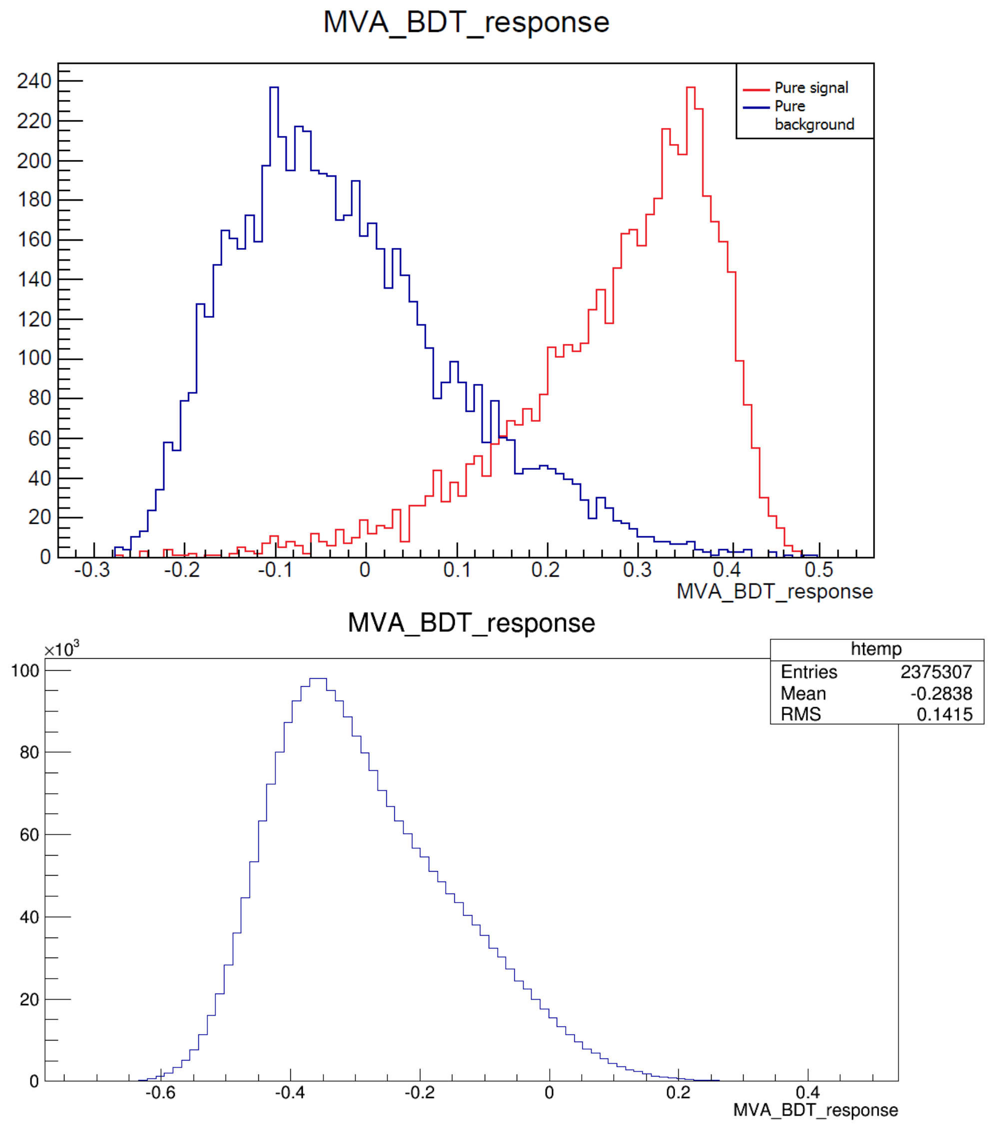

Figure 4.2 : Response to BDT (up) for background (blue), and signal (red). The two data have a different number of events (2 millions and 15000 respectively), so the two histograms have been normalized. Response to BDT (down) for real data, the histogram looks like to the pure background.

The response is known, but where can we apply the cut to save a good number of events concerning the signal and delete the most of background. The cut should be apply where the response for signal is bigger than the response for background. In the following part we will optimize this cut.

4.1.2 Optimization of the cut

To optimize the cut we use the significance f which is linked to the efficiency of the cut. It is explicited by the following relation in a range around two sigmas of the invariant D_s mass mean-value.

$$f \, \alpha \, \frac{N_{puresignal}(after)}{N_{puresignal}(before)} \text{ x } \frac{1}{\sqrt{N_{realdata}(after)}}$$

We have plotted the significance distribution ont he following picture. And it returns that the cut is optimized for a cut on response at 0.3.

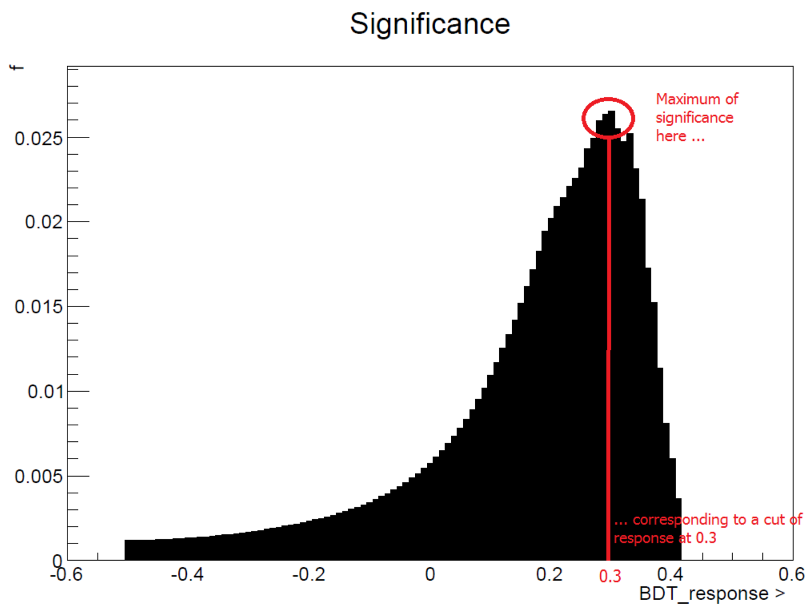

Figure 4.3 : Significance distribution.

4.2 Preliminary results

4.2.1 Presentation

Hence, we can apply a cut on response to BDT at 0.3, for D_s invariant mass, after a merge of data corresponding to the both polarizations and center-of-mass energy.
We can thus fit a gaussian on the mass distribution. The result of this fitting has for mean-value 1968.2 MeV/C^2, and for sigma 20.1 MeV/C^2.

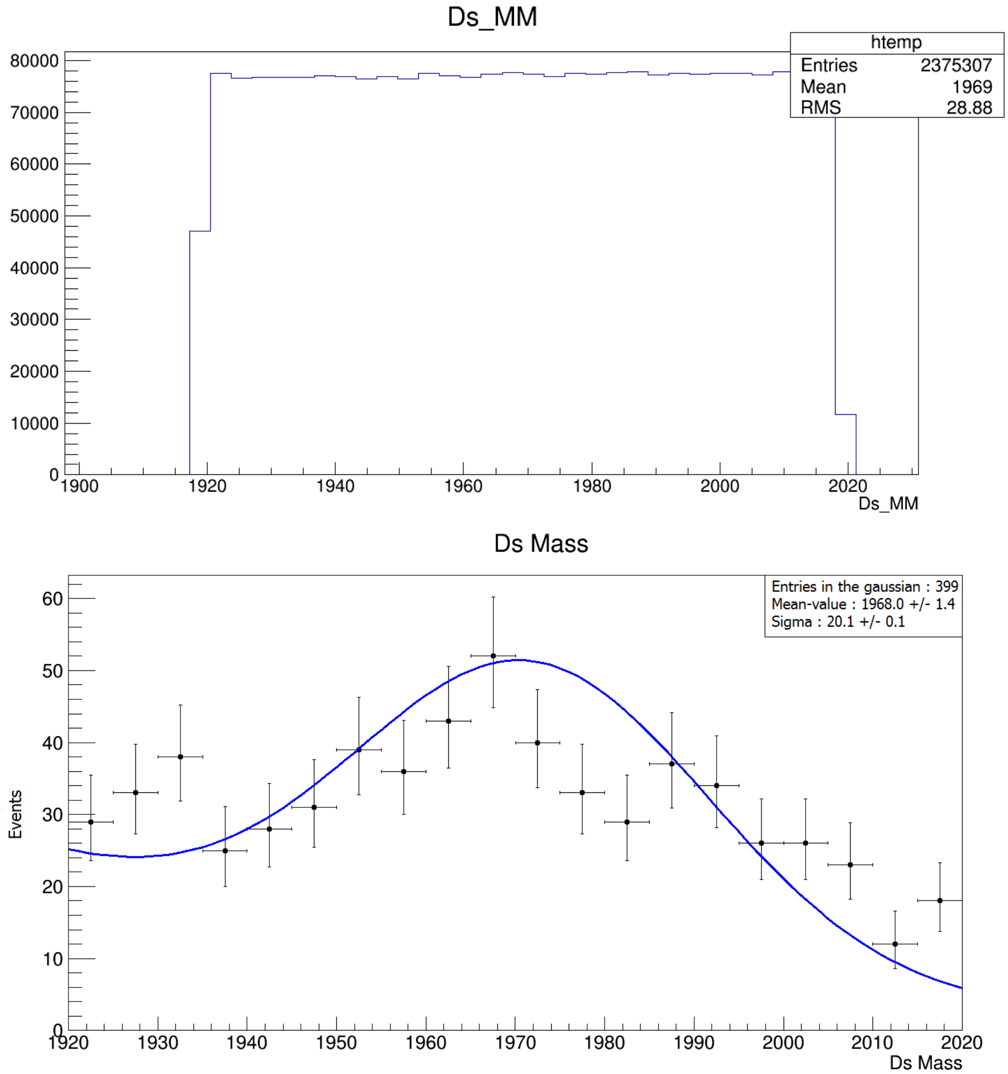

Figure 4.4 : The D_s mass invariant of real data (up). The D_s mass invariant with the gaussian fitting (down).

4.2.2 Review

If we see the simulation, our result agrees with it. However, there are a point lightly different. If we fit a gaussian on the simulation, we obtain indeed a mean-value near to the result, 1968.1 MeV/C^2, but a sigma very different. In the simulation, it is only 6.5 MeV/C^2, whereas in our result, 20.1 MeV/C^2. How can we explain this difference ?

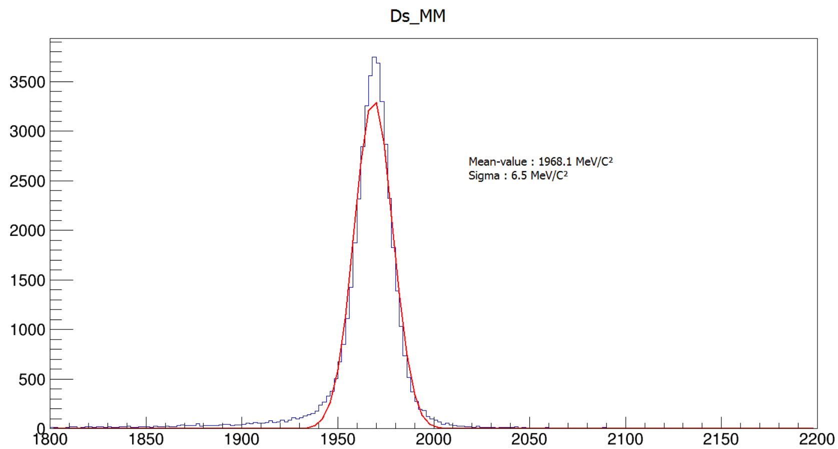

Figure 4.5 : Simulation with gaussian fit.

- A first explanation could come from the meson J/ψ. This particle is observable without any cut because it's just the reconstruction of two muons. With it, we can define precisely the background for J/ψ, and so define a second background which can be separate from the data like and with the preceeding background.
- A second, but less likely hypothesis, could come from the pions of the D_s decay. D_s can also decay in two pions and a kaon, another meson. But, this kaon has a bigger mass than a pion, and so when we want to reconstruct the mass of the mother particle we obtain more events with a smaller mass (if we consider that all decays give three pions), and so the distribution of D_s mass is larger.

5 Conclusion

To conclude this report, on a scientific plane firstly, we have identified a particle, or just constrain a range where can be the particle. However, there exists some uncertainties like we have seen before.
The next step of this intership could be make the same analysis for all particles of the decay, and compare the result with the theory. If the result doesn't correspond to the theory, we could determine why, and search some explanations.

On a personal point of view, this internship was very nice, with a good team of research, and a kind and very involved tutor, Yiming Li. With her, I learned lots of thing about the theory in particles physics and about her work like researcher. That gave me more informations and more interest about this career inwhich I want to work.
However, I think I don't want to work in this domain of research because, it's not my project of life, and I prefer others domains like Cosmology.

6 Bibliography

- Measurements of the B meson production cross-sections at LHCb, Liu, 2012
- The LHCb detector at the LHC, 2010

7 Annex

7.1 The Cherenkov Effect

The Cherenkov effect is a phenomenon which appears when a charged particle is moving in a dielectric middle with a velocity greater than the light velocity in this middle. It is characterized by a luminous flash. An example, the blue halo in the water around a nuclear reactor coming from it.
In a material middle, the light has a velocity $C_n = \frac{C}{n}$, where n is the refraction index of the middle. A charged particle can move at a velocity bigger than C_n, since n is bigger than 1. This particle interacts during its movement with the middle and disturb temporarly the polarisation of electronic shells of atoms met, creating a radiative emission. The wave emitted by each excited atom has a velocity C_n, which is less than the velocity of the particle. Hence, there is a constructive interference between the emitted waves. The frequence of this new wave corresponds to the Cherenkov effect.

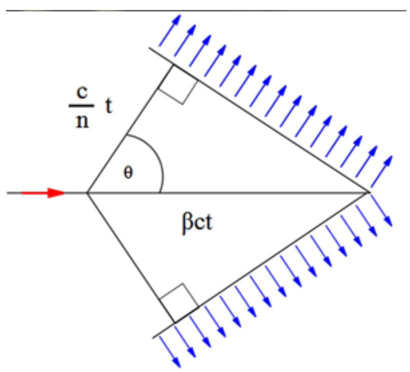

Figure 7.1 : Schematic diagram of Cherenkov radiation.

7.2 The Monte-Carlo method

The Monte-Carlo method is a method used to determine a numerical value with a probabilistic approach. A good example to explain it, is to determine the aera of a lake in a field whose the area is known.

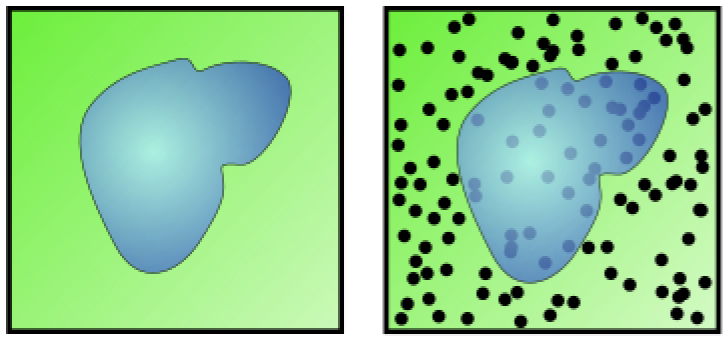

Figure 7.2 : Example of using of Monte-Carlo method.

We launch a big number of pebbles in the field, but never at the same place. When a pebble is in the lake we hear a noise, if not we don't hear. The ratio of the area of the field over the lake is thus given by the number of pebbles launched over the number of pebbles with no noise. This ratio is the best when the number of pebbles is increasing.

7.3 Topology of a decay

The general scheme of a decay is the following. We call a vertex, the point where the decay appears, i.e, for example on the following figure, the point between the three particles.

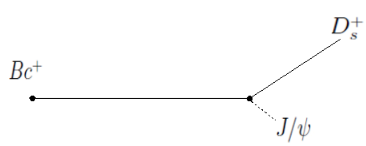

Figure 7.3 : Scheme of the decay.

The impact parameter is define between the direction of the mother particle and the daughter particle. We can define by the same way the angular dispersion. The flight distant is just the distance done by the particle before its decay.