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SEARCH FOR $B \to K^{(*)}\nu\bar{\nu}$ DECAYS IN BELLE II

Rapport de stage de Master

sous la direction de Isabelle RIPP-BAUDOT et Giulio DUJANY

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Abstract

The $B \to K^{(*)}\nu\bar{\nu}$ decay channel, never discovered to this day, is actively sought for in the Belle II experiment. Its branching fraction of the order of 10^{-6} could be significantly skewed by new physics, which makes it a potential probe for physics beyond the Standard Model. During this internship, we simulated and analyzed pairs of B mesons produced by SuperKEKB collisions and registrated by the Belle II detector. The goal of the analysis is to assess the event reconstruction efficiency of a key algorithm, the Full Event Interpretation, in the case where one of the two B mesons decays to an invisible state (e.g into neutrinos or unknown invisible particles).Finally, these reconstruction performances are studied with two different simulated samples for the Belle II experiment as well as on a simulated sample for the Belle experiment (Belle II's predecessor) and we investigate leads for improvement in order to improve the sensitivity for the $B \to K^{(*)}\nu\bar{\nu}$ channel.

La désintégration $B \to K^{(*)}\nu\bar{\nu}$, jamais découverte à ce jour, est activement recherché dans l'expérience Belle II. Son rapport d'embranchement, de l'ordre de 10^{-6}, pourrait être modifié de manière significative par de la Nouvelle Physique, ce qui en fait un processus très intéressant pour chercher des manifestations de physique au delà du Modèle Standard.

Pendant ce stage, j'ai simulé et analysé des paires de mésons B produites par l'accélérateur SuperKEKB et detéctées par le détecteur Belle II. Le but de l'analyse est d'estimer l'efficacité de reconstruction d'un algorithme clé : l'algorithme de Full Event Interpretation, dans le cas où l'un des deux mésons B se désintègre de manière invisible (en neutrinos ou en particules invisibles inconnues). Enfin, ces performances de reconstructions sont étudiées avec deux echantillons simulés de l'expérience Belle II et un echantillon simulé de l'expérience Belle (ancêtre de Belle II) et j'étudie de potentielles sources d'améliorations afin d'améliorer la sensibilité au canal $B \to K^{(*)}\nu\bar{\nu}$.

Acknowledgements

I wish to thank Isabelle Ripp-Baudot, who believed in me when I asked her to pursue an internship in her team during the summer of 2019 and allowed me to study such an interesting subject for my second year of masters internship. She has been an incredible support and her precious advice helped me to carry out my work in the best conditions.

I also would like to thank Giulio Dujany, who dedicated a lot of time to this internship. He taught me a lot while still letting me figure things out on my own and helped me to be able to do the best work possible in spite of the challenges brought by the epidemic situation in the spring of 2020.

I thank the whole Belle II group at the IPHC, which wanted to join for a few years now, and in particular Tristan Fillinger, who made me feel very welcomed and Jerôme Baudot for his help as the Subatomic and Astroparticle Physics masters dean and for the rock climbing discussions.

Contents

Chapter 1

Introduction

From the early days of particle physics and up yo now, theoretical considerations as well as results from successive experiments have been compiled into the Standard Model (SM) of particle physics. This theory has proven successful in making numerous predictions like the existence of the Higgs boson, which was the last missing piece of the Standard Model discovered at CERN in 2012. Several observations are indeed not described by the SM, for example the existence of dark matter and dark energy or the matter/anti-matter imbalance in the Universe. This has led to the idea of "beyond the Standard Model" (BSM) physics. However the nature of this new physics is not known but refinements of experimental setups allow us to probe the Standard Model with better precision.

The branching fraction of the $B \to K^{(*)}\nu\bar{\nu}$ decay is an excellent probe for BSM physics. Indeed, this decay, while allowed in the Standard Model, might see its branching fraction modified by BSM contributions. The study of this decay is only achievable in the Belle II experiment in Japan where a pair of B mesons are produced as the result of an electron-positron collision. This experiment is run by an international collaboration involving numerous research groups worldwide, like the Belle II group at the IPHC in which I pursued this internship.

The goal of this internship is to study the efficiency with which the Full Event Interpretation (FEI) algorithm reconstructs the collision event when one of the two B mesons decays into neutrinos or unknown invisible particles (= undetected). The FEI takes as input the tracks and calorimeter clusters left by the stable (at the scale of the detector) particles in the detectors and combines them to reconstruct the most probable chain of decay from the origin of the event to these stable particles. The main issue with B mesons decaying into invisible particles is that no tracks are seen in the detectors, thus the only "track" of our signal is missing energy inferred from the energy balance, known in leptonic collisions.Thich means that all the information from the collision has to be extracted from the other B meson (reconstructed with the FEI).

After assessing the FEI efficiency for invisible decays, we aim to study the parameters of the FEI which might enhance the efficiency, in order to be able to reconstruct most of the "missing energy" decays (including $B \to K^{(*)}\nu\bar{\nu}$), the first step to be able to study them.

Chapter 2

Scientific motivation and experimental context

2.1 Beyond the Standard Model

The Standard Model is the theory currently used in particle physics to describe elementary particles and their interactions. This theory has been probed to the highest precision up to date and has proven to hold extremely well to such scrutiny.

However, some experimental observations cannot be explained by the Standard Model, like the asymmetry between matter and anti-matter in the universe or the existence of dark matter.

This has led particle physicists to postulate the existence of physics ”Beyond the Standard Model” or BSM physics, that could explain these anomalies.

To this day, BSM physics has not yet been observed at energy levels described by the Standard Model. However, even if hypothetical BSM particles are several orders of magnitude higher in mass than Standard Model particles, they could manifest themselves in known Standard Model processes as *virtual* particles. In this case, these new particles could significantly skew the probability of a given process (fig.2.1).

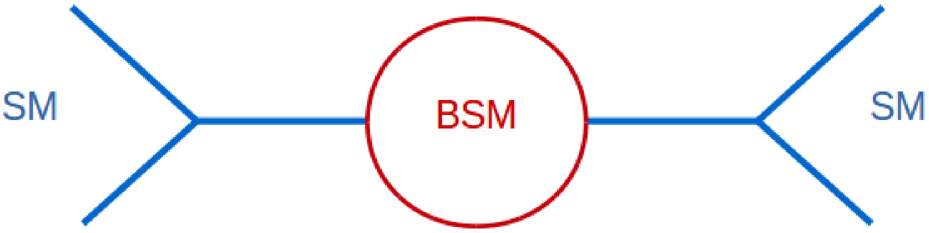


Figure 2.1: Standard Model processes could be altered by virtual manifestations of BSM physics

The search for BSM physics is a very active field of research nowadays, as any observation could help us to better discriminate between the many BSM models proposed.

2.2 The Belle II experiment

The Belle II experiment [1],[7], based in Tsukuba, Japan, is dedicated to the precision study of the Standard Model and the search for BSM physics. Specifically, the international Belle II collaboration, which revolves around the experiment, aims to study rares B meson decay channels sensitive to BSM physics, CP violation, precision measurements of CKM matrix parameters and lepton number violating decays.

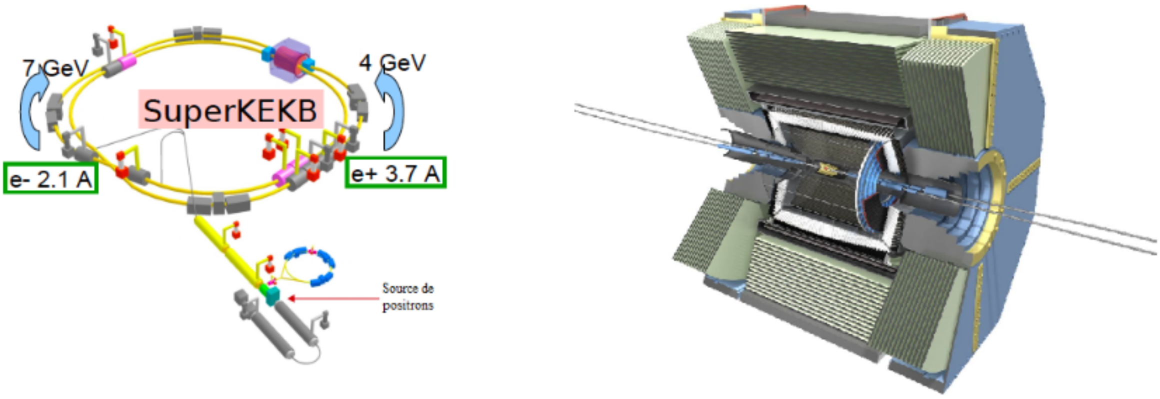


Figure 2.2: The SuperKEKB accelerator (left) and the Belle II detector (right)

The Belle II experiment succeeded to the Belle experiment, which ran at the KEKB accelerator from 1998 to 2010. Belle II started its physics program in 2019.

The collaboration studies the electron-positron collisions generated by the SuperKEKB particle accelerator (FIg.2.2). SuperKEKB is an upgrade of KEKB, the accelerator used by the Belle experiment. It holds the current world record for instantaneous luminosity ($2.1 \times 10^{35}\mathrm{cm}^2\mathrm{s}^{-1}$) which should provide, by 2027, the largest data sample ever (50 ab^-1)(fig.2.3).

This will be crucial to study a channel as rare as $B \to K^{(*)}\nu\bar{\nu}$, especially if we want to be sensitive to BSM physics effects.

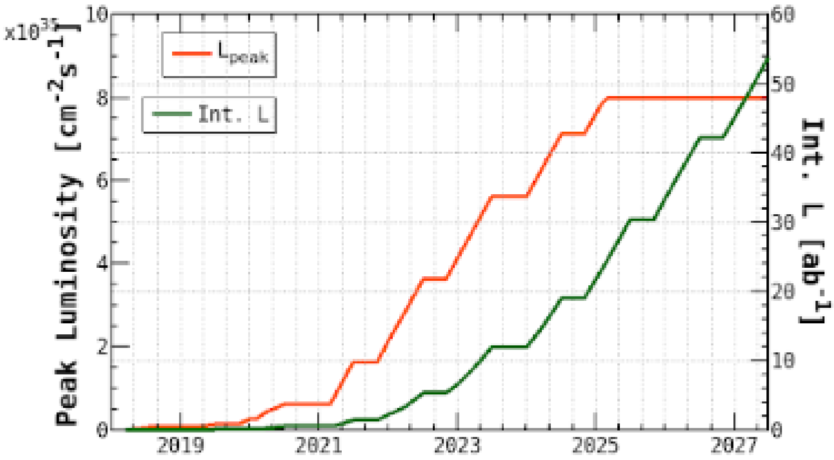


Figure 2.3: SuperKEKB instaneous (green) and integrated (red) luminosities

2.3 Motivation

Searches for rare B decays with missing energy in the final state have been a long standing motivation for past experiments like Belle and Babar [3]. They primarily focused on $B \to h\nu\bar{\nu}$ decays as a way to study Flavour Changing Neutral Currents (FCNC) in $b \to s$ quark transitions.

Because of too low statistics and a reconstruction efficiency too small, these collaborations were only able to put upper limits on the $B \to h\nu\bar{\nu}$ decays branching fractions[8][5]. FCNC have also been studied in the Belle II and LHCb experiments in $B \to l^+l^-$ and $B \to K^{(*)}l^+l^-$ where l^+ and l^- are charged leptons. The goal of these stud ies to measure kinematic variables, angular distribution and Wilson coefficients of these already known decays to detect possible discrepancies with predicted SM values. These discrepancies could be due to BSM physics manifestations.

These analyses found intriguing anomalies [2]. Taken alone each of this anomaly is not enough to claim the discovery of BSM physics. Togher however they suggest a coherent picture in which lepton universality, one of the hypothesis of the Standard Model, is violated. It is thus important to study similar FCNC processes as they could confirm the presence of BSM physics and help define its nature.

In 2019 the Belle II group at the IPHC in Strasbourg tried to assess if a first observation of the $B \to K^{(*)}\nu\bar{\nu}$ decay channel was possible in a near future in the Belle II experiment. They used a simulation of the experiment developed by the collaboration and concluded that the event reconstruction efficiency was too low to expect such results in the next three years. However, recent studies by the collaboration have shown that the simulation used in 2019 was flawed, and corrections and enhancements were applied during the past year.
This internship allowed us to quantify the effect of these corrections and to investigate new ways to improve the event reconstruction efficiency.

Chapter 3

Principle of measurement

3.1 Signal reconstruction

In the Belle II experiment, the e^+ e^- collisions produce different kinds of events. What we are interested in are the collisions that produce an $\Upsilon(4S)$ decaying into a pair of B mesons ($B^0\bar{B}^0$ or B^+B^-) where one of the B mesons decays in our channel (fig.3.1).

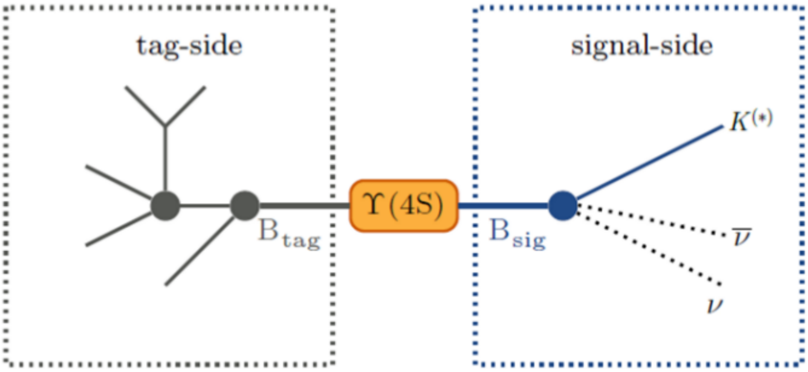


Figure 3.1: The $\Upsilon(4S)$ (orange) decays into the B_{sig} and B_{tag}.

The B meson that decays in our channel ($B \rightarrow K^{(*)}\nu\bar{\nu}$) is labelled B_{sig} and its daughter particles make up the *signal side* of detection. The other B meson decaying in any of the other possible decay channels is called B_{tag} and its decay products compose the *tag side.*

In our case, there is a significant challenge to detect the signal: the neutrinos do not interact with the matter of the detectors, meaning that they are not "seen". In this case, the only way to identify the signal is by the presence of a $K^{(*)}$ or K meson, which is a fairly common final state particle. Because of that, the presence of neutrinos has to be inferred from the totally reconstructed event. Indeed, if the signal $K^{(*)}$ and the B_{tag} are correctly detected, one can use the conservation of the $\Upsilon(4S)$ energy-momentum (known) to measure the neutrinos energy. This means that the *tag side* has to be perfectly reconstructed.

In order to accurately reconstruct the B_{tag}, we have to make sure that the final state particles can come from a generated B meson (*i.e* following a known decay chain, respecting the B meson invariant mass, etc...). To do that we use a specialized algorithm: the $Full\ Event\ Interpretation$ (FEI) algorithm.

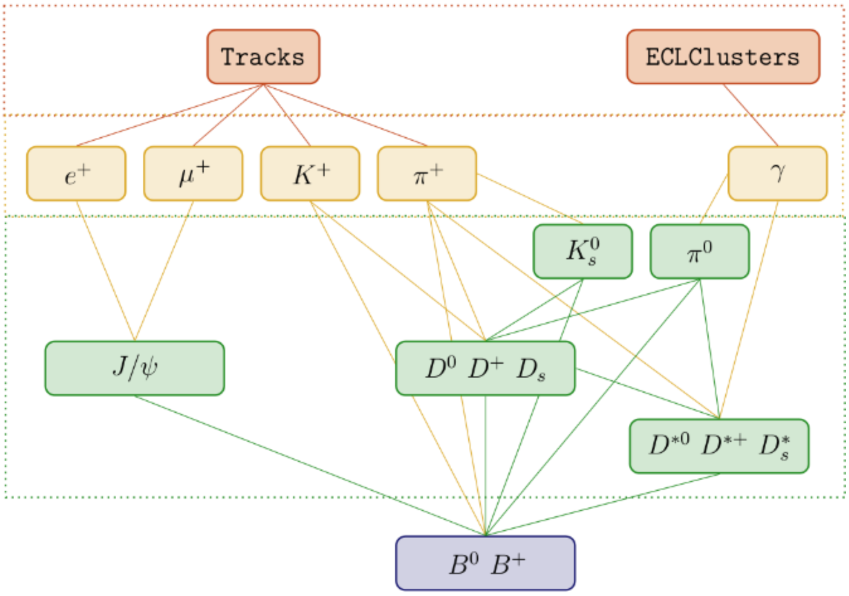


Figure 3.2: Schematic view of the FEI hierachical approach, from the tracks and clusters left in the detectors t the B meson.

The FEI algorithm is an artificial intelligence algorithm designed to reconstruct the most probable B meson decay chain, from the final state particles to the original B meson.

To do so, the FEI operates in a hierarchical approach [6], it first takes the tracks left in the detectors by charged particles and energy clusters deposited by neutral particles and associates it to final state particles candidates ($e^{\pm}$, $\mu^{\pm}$, $K^{\pm}$, $\pi^{\pm}$, K_L^0 and γ). It then combines them into intermediate particles (J/Ψ, π^0, K_S^0, D and D^*) that are finally used to reconstruct the B meson (fig.3.2). This is a very complex process with some challenges:

1. The *signal side* and *tag side* overlap in the detector rest frame, making assigning particles to a given B meson harder.

2. Several decay channels give the same (or very close) final state.
3. Some particles leave similar tracks in the detectors which leads to misidentification (ex : taking a K^+ for a $\pi^\pm$).
4. Only a fraction of the possible B meson decay channels are implemented in the FEI ($\mathcal{O}(10\,000)$ different decay chains), which means that in our case a significant portion of events cannot be processed because the B_{tag} decays in a non-implemented way.

To counteract this, the algorithm is trained and uses a set of variables to optimize its reconstruction (spatial distribution of decay products, kinematic considerations, etc).
Several *candidates* are reconstructed for each B meson and ranked by their probability to be a correct interpretation of the B meson decay.

3.2 BTAG Reconstruction efficiency

The total number N of reconstructed events is given by :

$$N = \mathcal{L} \times \sigma \times \mathcal{B}(B \to K^{(*)}\nu\bar{\nu}) \times \epsilon \tag{3.1}$$

with :

- $\mathcal{L}$ the accelerator integrated luminosity.
- σ the $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ production cross section.
- $\mathcal{B}(B \to K^{(*)}\nu\bar{\nu})$ the branching fraction of the signal decay.
- ϵ the event reconstruction efficiency.

Given that $\mathcal{L}$ is a fixed experimental constraint and σ, $\mathcal{B}(B \to K^{(*)}\nu\bar{\nu})$ are physical constants, ϵ is the key parameter that we can improve to maximize our results.
ϵ depends on the reconstruction of the full event and can be evaluated as follow :

$$\epsilon \simeq \epsilon_{sig} \times \epsilon_{tag} \tag{3.2}$$

With ϵ_{sig} and ϵ_{tag} the reconstruction efficiencies of the B_{sig} and B_{tag} mesons respectively.
However, in our case the *signal side* is only a $K^{(*)}$ so there is not much room for improving ϵ_{sig}, so the key parameter to our discovery is ϵ_{tag}.

3.3 Production of data for the analysis

In order to measure the *tag side* reconstruction efficiency, we want a set of events where we know the B_{tag} actual decay so we can compute how much are correctly reconstructed. This is not a possibility with experimental data. Instead, we generated and simulated our data, in order to be able to know precisely what was the real whole decay chain of a reconstructed B_{tag} candidate. This was achieved with the basf2 analysis framework of the Belle II collaboration
As we saw earlier, the total reconstruction efficiency depends on both ϵ_{sig} and ϵ_{tag}. In order to measure ϵ_{tag} without convoluting it to ϵ_{sig} we choose to study B meson pairs where the B_{sig} decays in the $B^0 \to \nu\bar{\nu}$ channel. The reason behind that is that the final state of $B^0 \to \nu\bar{\nu}$ is totally invisible to the detectors, meaning that the only detected signal is from the *tag side*.
Using the two Belle II last simulation versions, we produced 12×10^6 $B^0\bar{B^0}$ pairs with one B decaying in the $B^0 \to \nu\bar{\nu}$ channel , we also produced 12×10^6 $B^0\bar{B^0}$ pairs in the Belle experiment in order to compare the performances of the FEI in Belle II with regards to Belle.
In our study, we only consider B_{tag} being reconstructed in the hadronic decay channels by the FEI. Another version of the FEI is dedicated to leptonic decay channels.
A 16×10^6 $B^0\bar{B^0}$ pairs sample with the appropriate *signal side* had already been simulated by the collaboration in 2019, we applied the hadronic FEI on this sample as well.

We call the newest(from 2020) simulation sample MC13 and the oldest (from 2019) MC9. MC9 corresponds to the (flawed) simulation what was used in 2019 by the Belle II group to evaluate the reconstruction efficiency and MC13 corresponds to the corrected 2020 simulation (see 2.3).

Chapter 4

Results

4.1 FEI performances characterization

After reconstructing the events with the FEI, we first aim to characterize the algorithm performances for the three simulations. The results can be found in tab.4.1

	Belle	MC9	MC13
Simulated sample size	12×10^6	16×10^6	12×10^6
number of correctly reconstructed B_{tag}	6467	8352	21324
fraction of FEI implemented decay chains reconstructed	$(4.0 \pm 0.2)\%$	$(4.3 \pm 0.3)\%$	$(10.0 \pm 0.4)\%$
reconstruction efficiency for B_{tag} decaying in an implemented channel	$(1.87 \pm 0.01) \times 10^{-2}$	$(0.71 \pm 0.01) \times 10^{-2}$	$(2.43 \pm 0.02) \times 10^{-2}$
ϵ_{tag}	$(0.54 \pm 0.01) \times 10^{-3}$	$(0.52 \pm 0.01) \times 10^{-3}$	$(1.78 \pm 0.01) \times 10^{-3}$

Table 4.1: Markers of the FEI performances and ϵ_{tag} for the three simulations

The number of correctly reconstructed B_{tag} is assessed by checking for how many events the best B_{tag} candidates matches the actual B_{tag} produced.

To assess the percentage of FEI implemented decay chains reconstructed, we first had to measure the total number of decay chains implemented in the FEI. This number is not known *a priori* because the different decay chains are not implemented verbatim, rather, a set of possible decays is given for each particle (e.g $B^0 \to D^-\pi^+\pi^-\pi^+$, $K_S^0 \to \pi^0\pi^0$, etc...). Based on these decays, we devised a program that automatically generates all possible decay chains (ex : $B^0 \to D^-(K^+\pi^-\pi^-)\pi^+\pi^-\pi^+$ from $B^0 \to D^-\pi^+\pi^-\pi^+$ and $D^- \to K^+\pi^-\pi^-$). In the end we expect 6165 unique decay chains reconstructible by the FEI.

To be able to count how many unique decay chains are reconstructed we need to be able to access the reconstructed decay chain for each B_{tag} candidate, which is not given by the FEI by default. We developed another program to get the decay mode of each reconstructed particles from the FEI and reconstruct the whole decay chain.

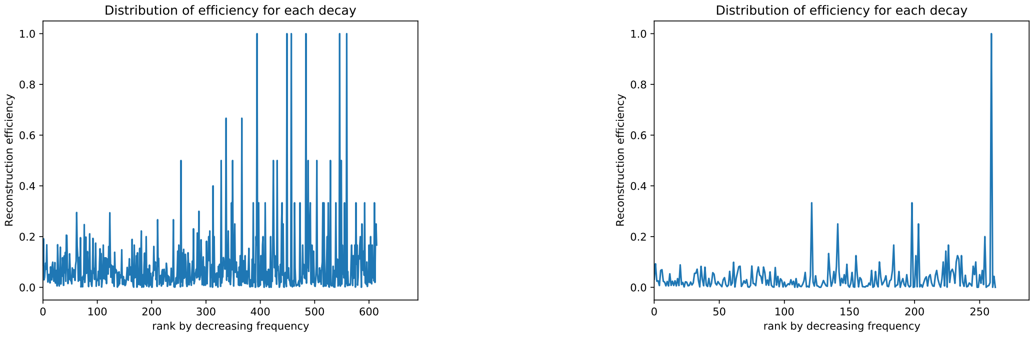
We are then able to measure the reconstruction efficiency when considering only B_{tag} decaying in one of these chains. Comparing this value to the actual ϵ_{tag} (for which we look at the number of correctly reconstructed B_{tag} out of the whole generated sample) is interesting, because ϵ_{tag} should converge to it as more decay chains are implemented into the FEI.

In the end we can see that the overall B_{tag} reconstruction efficiency value ϵ_{tag} is $\simeq 3$ times better in MC13 compared to MC9 and Belle. The difference between the MC13 and MC9 values can be explained by the corrections and enhancement brought to the simulation between the two generations. On the other hand, the difference between Belle and MC13 can be linked to the upgrades between the Belle and Belle II detector. The fact that the ϵ_{tag} values for Belle and MC9 are very close to each other is a coincidence. To be convinced of that, one can compare the reconstruction efficiencies for the implemented chains in Belle and MC9. The MC9 value is lower than the Belle and MC13 values because some issues were found in the way the FEI was trained for it.

4.2 Efficiency of individual decay chains

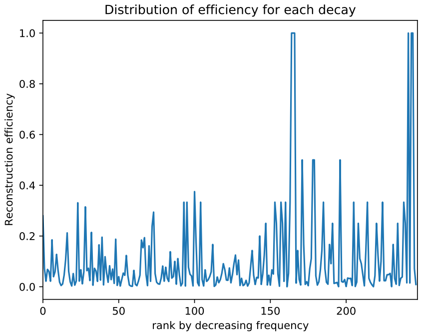
After measuring the overall reconstruction efficiency for the B_{tag}, we propose to study ϵ_{tag} for each reconstructed decay chain. This idea comes from the fact that the set of reconstructed decay chains is very heterogeneous in the number of particle decays composing them and the number of tracks in the final state.

To do so, we look at how many times each decay chain is simulated and we compare it to the number of time it is correctly reconstructed by the FEI. The results of this analysis can be found in fig.4.1



(a) MC13

(b) MC9



(c) Belle

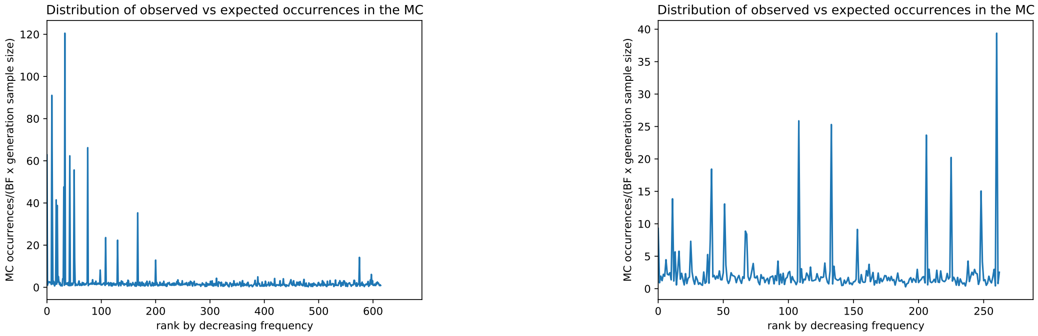
Figure 4.1: ϵ_{tag} for each decay chains in the different samples

This study "by chain" is done here for the first time in the Belle II collaboration. It appears that the reconstruction efficiency is not constant for all decay chains, understanding why some chains are better reconstructed than others can help us figure out ways to improve the FEI.
Moreover, it appears than the chains most seen in the reconstructed sample are not the ones with the highest branching fraction. However, this does not seem to stem from a bias induced by the FEI as these chains are not reconstructed with an efficiency higher than the others.
This leads us to question whether this bias comes from the simulation (*ie* before the FEI reconstruction).

4.3 Simulation agreement with expected results from theory

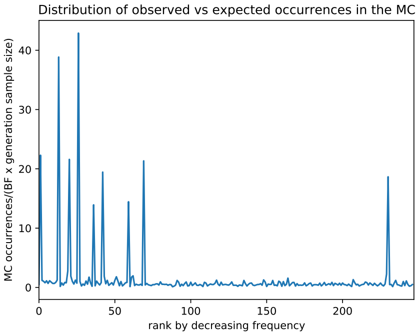
In order to study the apparent sur-representation of some decay chains in the reconstructed sample, we generate a new set of data, formed by the events where the B_{tag} decays in a decay chain known by the FEI, but before the FEI is applied to reconstruct them.
We then compare the number of times a decay chain is seen in this sample to the number of event in the generated sample (12×10^6 or 16×10^6).

We expect this ratio to be equal (within statistical fluctuations) to the theoretical probability for each decay chain. However, this probability has to be computed for each decay chain based on the branching fractions of all the decays that comprise it.



(a) MC13

(b) MC9



(c) Belle

Figure 4.2: Study of the simulation for each decay chain in the three samples

It appears (fig.4.2) that some of the most seen decay chains are generated more times than expected (some with a factor > 20).

This bias might come from the *decay table*, a file used by the simulation to estimate the correct number of times a decay has to be simulated to be coherent with the theory.

These results were submitted to the Belle II international collaboration and met with interest, this bias should be corrected in the near future.

Chapter 5

Summary and outlooks

5.1 Summary

The Full Event Interpretation algorithm will be of the utmost importance to make the first discovery of the $B \to K^{(*)}\nu\bar{\nu}$ decay. It is only with this algorithm coupled to the clean collisions and precise detector of the Belle II experiment that we can expect to measure the $B \to K^{(*)}\nu\bar{\nu}$ branching fraction with enough precision to be sensitive to potential physics beyond the Standard Model.

One key performance indicator for the FEI is the reconstruction efficiency. We showed here that this efficiency, while better than what was previously estimated, can still be enhanced and we present several leads to make such enhancements.

During the lifetime of the SuperKEKB accelerator, the reconstruction efficiency will continue to be refined in parallel to the data taking.

The experiment should collect roughly 1 ab^{-1} of data in the next year. With current performances, there should not be any signal detected for Standard Model expectations, however, the $B \to K^{(*)}\nu\bar{\nu}$ branching fraction could be significantly enhanced by BSM physics. In this case it could be possible to make an observation in this time frame.

Within three years, the accelerator should deliver 4 ab^{-1} of data, based on previous studies done by the BaBar and Belle collaborations, a first measurement of the branching fraction with 30% uncertainty could be made within the Standard Model.

The experiment should reach its maximum integrated luminosity by 2027. With this data sample, an extremely precise measurement of the branching fraction will be possible, with the ability to precisely study BSM physics contribution to this decay. This could allow to discard or favor certain BSM physics models.

However, if these results are in agreement with the Standard Model, it would still allow us to better understand rare B meson decays and constrain or exclude the possible BSM physics.

5.2 Conclusion

The research work done during this internship, which is part of a global effort to discover $B \to K^{(*)}\nu\bar{\nu}$ decays, has allowed us to evaluate the enhancement of the Full Event Interpretation algorithm reconstruction efficiency since 2019.

It appears that this efficiency has gone up by a factor $\simeq 3$ and is now equal to $(1.78 \pm 0,01)10^{-3}$. It is estimated that the current measured value of efficiency is still three times lower than what is needed to discover the decay channel in the next three years, but it has been enhanced by a factor three in the past year alone, which is very encouraging.

Moreover, we discovered a bias in the simulation used to train the algorithm which, once corrected, should improve the efficiency even more. We also found some promising leads in the search for new way of optimizations in studying this efficiency for each available decay chains.

I am lucky to be a member of the QMat graduate school and to prepare the "Magistère de Physique Fondamentale" diploma, which extends my internship by a few weeks. This could allow me to study the reasons behind the distribution of efficiency for each decay chain more deeply and to start applying my analysis to events where the *signal* B decays to $K^{(*)}\nu\bar{\nu}$.

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