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TRIGGERING POSSIBILITIES WITH AN UPGRADED BELLE II VERTEX DETECTOR

Rapport de stage de Master
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Abstract

The Belle II experiment is a high intensity particle physic experiment, which aims to collect $50\,\mathrm{ab}^{-1}$ of integrated luminosity within 15 years. In order to collect this amount of luminosity, the experiment relies on the SuperKEKB collider, an accelerator at the edge of intensity, producing currently the world's highest instantaneous luminosity near $5 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. However, at this rate the amount of data generated by the collider is so important that the acquisition system cannot store it. Thus, the first-level trigger is used. The trigger is a key component of high intensities particle physics experiments. Its role is to determine whether an event is of interest, and thus to store it. The trigger relies on the various information provided by the detectors, such as the tracking provided in Belle II only by the Central Drift Chamber (CDC). The current luminosity is expected to increase by almost an order of magnitude in the coming years. In this context of increasing the quantity of data produced by SuperKEKB, the experiment intends to improve its detection capacities, starting with the most internal detector, its vertex detector. The VerteX Detector (VXD) is currently used in Belle II. It has high position resolution for charged particle, but is not used for the first-level trigger (L1 trigger). The VerTeX detector (VTX) is being envisioned as its successor. It will have higher position and time resolution, providing more precise informations to the different system. Thus this work focuses on the capacity of this new information to contribute to the L1 trigger of the experience.

L'expérience Belle II est une expérience de physique des particules à haute intensité, qui vise à collecter $50\,\mathrm{ab}^{-1}$ de luminosité intégrée en l'espace de 15 ans. Pour collecter cette quantité de luminosité, l'expérience s'appuie sur le collisionneur SuperKEKB, un accélérateur à la frontière de l'intensité, qui produit actuellement la luminosité instantanée la plus élevée au monde, proche de $5\times10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. Cependant, à ce rythme, la quantité de données générées par le collisionneur est si importante que le système d'acquisition ne peut pas les stocker. C'est pourquoi le déclencheur de premier niveau est utilisé. Le déclencheur est un élément clé des expériences de physique des particules à haute intensité. Son rôle est de déterminer si un événement est intéressant, et donc de le stocker. Le déclencheur s'appuie sur les diverses informations fournies par les détecteurs, telles que la trajectométrie fournie dans Belle II uniquement par la Central Drift Chamber (CDC).
La luminosité actuelle devrait augmenter de près d'un ordre de grandeur dans les années à venir. Dans ce contexte d'augmentation de la quantité de données produites par SuperKEKB, l'expérience a l'intention d'améliorer ses capacités de détection, en commençant par le détecteur le plus interne, son détecteur de vertex.
Le VerteX Detector (VXD) est actuellement utilisé dans Belle II. Il a une haute résolution de position pour les particules chargées, mais n'est pas utilisé pour le déclenchement de premier niveau (L1 trigger). Le détecteur VerTeX (VTX) est envisagé comme son successeur. Il aura une résolution de position et de temps plus élevée, fournissant des informations plus précises aux différents systèmes. Ce travail se concentre donc sur la capacité de ces nouvelles informations à contribuer au déclenchement L1 de l'expérience.

Acknowledgements

I'd like to thank my internship supervisor, Jérôme Baudot, for all the discussions we had and for all the advice he gave me. Although I can't convey my ideas clearly orally, he was always ready to listen to me and help me move forward with my work.
I would also like to thank Isabelle Ripp-Baudot, for the opportunity to join the Belle II laboratory at IPHC for this internship, and for the immense honor of supporting my application for an internship in Japan last year. I think that without her help, my situation would have been very different.
Tomoyuki Shimasaki, who worked on the same subject but on a different detector [5], was invaluable in helping me to carry out this work, pointing out the mistakes not to be made in this study.
I'd also like to thank the other members of the laboratory; Petros and Pere for their invaluable help with the basf2 software, Christian and Giulio for their explanations of the various detector simulation files, as well as Merna for our long discussions, Jacopo for his help in understanding this great software called Notilus and Corentin for the power of apple juice.
It goes without saying that all these people made it possible for me to carry out my work in very pleasant conditions.

Contents

Chapter 1

Introduction

1.1 Presentation of the laboratory

My internship took place in the IPHC (Institut Pluridisciplinaire Hubert Curien) within the Belle II group. The IPHC is an UMR (Unité Mixte de Recherche) based in Strasbourg, divided in 3 laboratories :

- **DEPE** : Département d'écologie, physiologie et éthologie; studies the adaptive strategies of animal species in the face of natural or anthropogenic environmental constraints.
- **DSA** : Département de sciences analytiques; aims to develop new analysis tools that will allow us to better understand the interactions of humans with their environment (pollution, food, etc.) and to diagnose and image the diseases that affect us.
- **DRS** : Département de recherches subatomiques; attempts to understand worlds from the infinitely large to the infinitely small. This field of investigation, theoretical and experimental, explores areas as varied as nuclear physics, particle physics and astroparticle physics.

The Belle II group is one of the group part of the DRS laboratory. It participates in the international Belle II experiment, which analyzes leptonic collisions produced by SuperKEKB in Japan.

1.2 Scientific context

In this section we will present the facilities of the Belle II experiment.

1.2.1 SuperKEKB

The SuperKEKB accelerator is a state-of-the-art electron-positron (e^+e^-) collider with a circumference of 3 kilometers. In collider terminology, a collider refers to a facility where two beams travel in opposite directions and are brought to collision. SuperKEKB is an upgrade of the previous KEKB accelerator, which operated from 1998 to 2010 as an asymmetric electron-positron collider. This asymmetry pertains to the differing energies of the colliding particles; in SuperKEKB, electrons are accelerated to a kinetic energy of 7 GeV, while positrons are accelerated to 4 GeV. The SuperKEKB collider can be divided into three key components of interest:

- **Linear Accelerator (LINAC)** : It generates and accelerates electrons and positrons to their target energies and spans a length of 700 meters.

- **Positron Dampling Ring (DR)** : It produces a low-emittance positron beam and has a circumference of 136 meters.
- **Main Ring (MR)** : It consists of two rings: the High Energy Ring (HER) for electrons and the Low Energy Ring (LER) for positrons. These two rings intersect at one point, the Interaction Point (IP), located at the heart of the Belle II detector. The entire system has a circumference of 3016 meters.

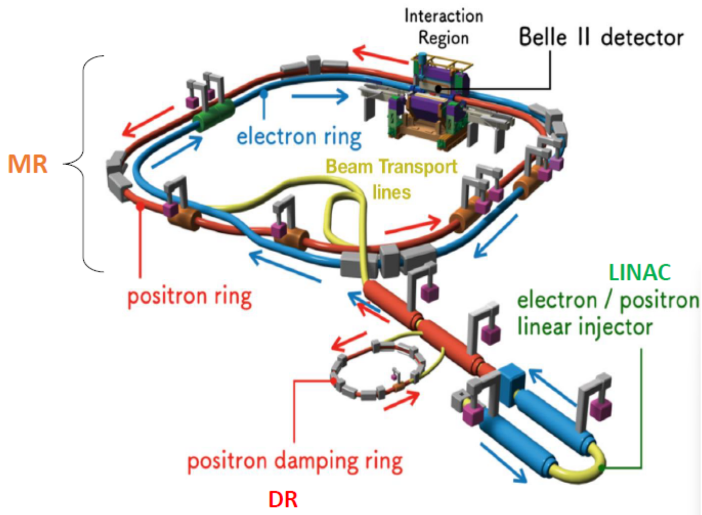

Figure 1.1: Diagram of the SuperKEKB collider

1.2.2 Belle II

The Belle II experiment, established in 2015 at the Tsukuba Hall site of the SuperKEKB accelerator, aims investigate the fundamental properties and interactions of elementary particles, with a particular focus on B mesons. The accelerator is specifically designed to maximize the production of B mesons; the electron-positron collision energies are optimized to create the $\Upsilon(4S)$ resonance, which subsequently decays into pairs of B mesons. The Belle II detector comprises several subsystems, each with a distinct role [1]. Our focus will be on the innermost detectors, which are dedicated to determine particle trajectories in the experiment:

- **VXD** : **V**erte**X** **D**etector, relies on silicon sensors. It is composed of :
  - PXD : **P**i**X**el **D**etector, is the most inner one. It is made of 2 layers of silicon pixels, based on the DEPFET technology.
  - SVD : **S**ilicon **V**ertex **D**etector is made of 4 layers of silicone strips.
- **CDC** : **C**entral **D**rift **C**hamber, relies on field and anode wires, which will generate a drift of the charged particle.

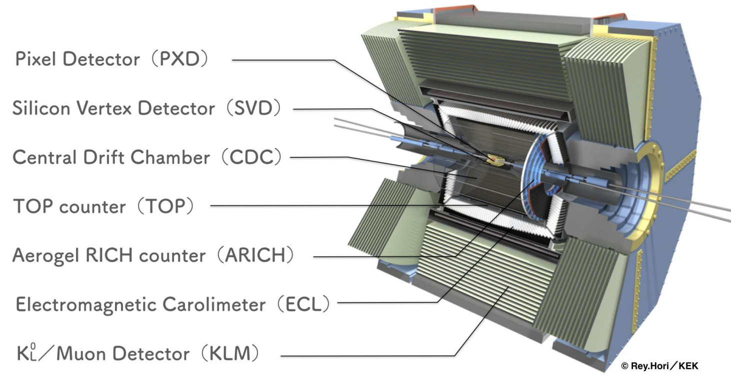

Figure 1.2: View of the different layers of detectors in the Belle II experiment

1.2.3 Trigger

In particle physics experiments, a trigger is a crucial system responsible for rapidly selecting and recording events of interest from the vast number of particle collisions occurring within the detector. The Belle II experiment employs a sophisticated multi-level trigger system to manage the high collision rates produced by the SuperKEKB accelerator. The Level 1 Trigger (L1 Trigger), in particular, plays a vital role by making initial, real-time decisions about which events are potentially significant and should be further analyzed and stored for deeper investigation. It operates with stringent timing constraints to ensure only the most relevant data is kept. Currently, the L1 Trigger in Belle II relies only on information from the Central Drift Chamber (CDC) to identify particle tracks and provide essential data on momentum and charge.

1.3 Activities of the group

The group studies flavor changes between quarks to discover new processes not described by physical theories. It focuses in particular on measurements sensitive to additional sources of violation of CP symmetry that could explain the disappearance of antimatter in the universe, and tests the fundamental principle of lepton universality, accepted until now but questioned by several recent measures. The group's other field of action is on the Belle II silicon detector, one of the most precise in the field, as well as the development of the next generation of such detectors.

1.4 My activity

My work focused on these new generations of silicon detectors. It is planned that the current VXD will be replaced by a new full pixelised silicon detector based on the CMOS technology,the VTX detector. As previously described , the VXD is not providing any tracking information to the trigger; only the CDC does. So the integration of improved vertex detector data, with its superior spatial and temporal resolution, could enhance the trigger's precision and efficiency, ultimately contributing to more effective and accurate particle identification and event reconstruction in the Belle II experiment. So my work aims to determine if this new vertex detector could contribute to the trigger decision. To do so, the first chapter introduced the context of my internship, the second chapter will describe the new detector and its sensor as well as the experiment software, the third chapter will present the methods I used to develop my track reconstruction algorithm, and the fourth chapter will show the results. The last chapter will conclude this report and present the perspectives of my work.

Chapter 2

Experimental Groundwork

This chapter will outline the foundational elements of my work. It will be divided into two parts: the first part will detail the improvements made to the vertex detector, and the second part will introduce the simulation software used in the Belle II experiment.

2.1 VXD Upgrade

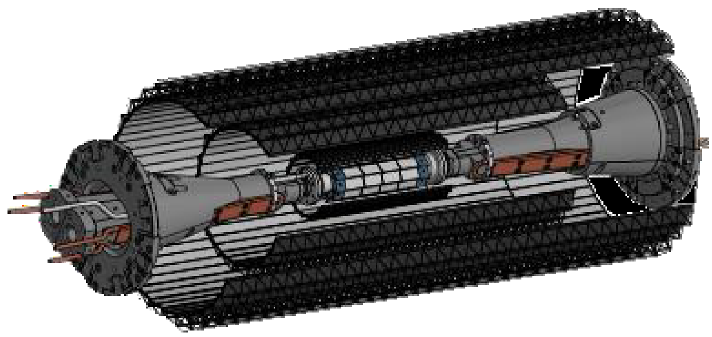

Figure 2.1: Schematic view of the VTX Detector

To collect the amount of data required by the experiment, the SuperKEKB collider will increase its instantaneous luminosity in the future. This increase will boost the quantity of data relevant for physics but will also raise the background noise of the experiment. The specifications of this new detector are:

- Better tracking robustness against background
- Improved track reconstruction for low momentum particles
- Higher vertex position resolution
- Conserved performance for physics with respect to the previous detector

The VTX detector (Figure 2.1) is the one envisionned to replace the VXD [3]. The structural characteristics of the detector are listed in the Table 2.1. However, these characteristics depend on the type of sensor chosen.

	inner VTX		outer VTX		
Layer	1	2	3	4	5
Ladder	6	10	30	40	31
Sensor per Ladder	4	4	12	16	2×24
Distance to IP (mm)	14.1	22.1	69.1	89.5	140.0
Max Hit Rate ($\mathrm{MHz\,cm^{-2}}$)	120	51.6	6.4	2.1	1.2

Table 2.1: VTX characteristics with OBELIX sensor

2.1.1 OBELIX sensor

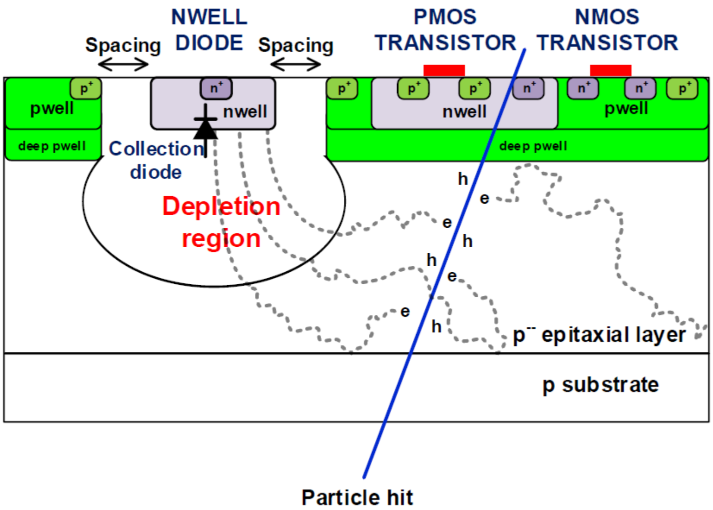

Figure 2.2: Diagram of the operation of a silicon detector

A silicon detector consists of a thin layer of silicon, typically doped to create a p-n junction, which is a boundary or interface between p-type and n-type silicon. When charged particles (such as electrons or ions) pass through the silicon layer, they ionize the silicon atoms, creating electron-hole pairs (free electrons and positive holes). The p-n junction is reverse biased, meaning a voltage is applied across it that widens the depletion region, a zone where no free charge carriers exist. This region is crucial for the detection process as it ensures the generated electron-hole pairs are swiftly separated and collected. The electric field in the depletion region causes the electrons to move towards the n-side and the holes towards the p-side. This movement generates a current pulse, which is proportional to the energy deposited by the incident particle.

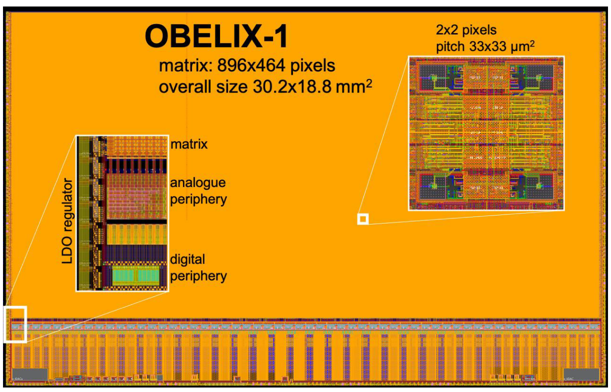

Figure 2.3: Design of the OBELIX sensor

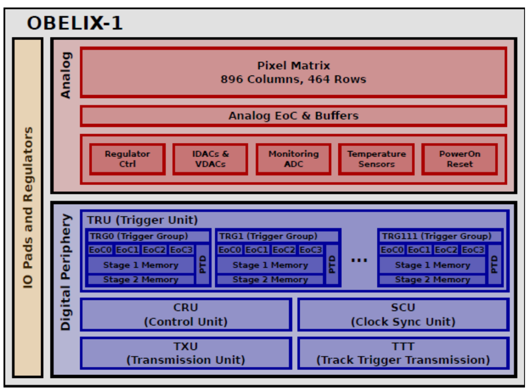

Figure 2.4: OBELIX Block diagram

The **O**ptimized **BEL**le II monolithic p**IX**el sensor (OBELIX) is the monolithic active pixel sensor (MAPS) based on CMOS technology, proposed to equip all VTX layers [2]. Figure 2.3 shows the OBELIX sensor, and Table 2.2 lists its properties. The pixel information is read using the column-drain mechanism, but the time required to read each pixel in a column is comparable to the trigger delay (a few microseconds), which is too long for pixel information to contribute effectively to the trigger. Figure 2.4 presents the different sensor modules in the Digital Periphery part. Among these modules, the TRU and the TTT are designed to contribute to the experiment's trigger system.

	Design
Sensitive Area	$4.53\,\text{cm}^2$
Pixel Pitch	$33\,\mu\text{m}$
Integration Time	50 to 100 ns
Trigger delay	$<10\,\mu\text{s}$
Latency	100 ns

Table 2.2: OBELIX Specifications

2.1.2 Track Trigger Transmission (TTT) Module

The TTT is a module of VTX designed to create an alternative data output channel to contribute to the trigger. The primary constraint is the speed of transmitting information to the decision algorithm. As mentioned previously, the column-drain mechanism does not allow information to be obtained quickly enough. However, we can take advantage of a fast signal for each column of the matrix, corresponding to the OR of all pixel outputs along the column. Instead of reading each pixel sequentially from the top to the bottom of the column and generating information for each pixel, we can generate a signal indicating that the column has been hit as soon as any pixel in the column registers a hit. This approach allows us to produce information quickly enough to contribute to the decision logic.

2.2 The Belle II Software

The basf2 (Belle II Analysis Software Framework 2) software plays a critical role in the Belle II experiment, facilitating the processing, simulation, and analysis of data collected from particle collisions. Technically, BASF2 is built using C++ and Python, combining high performance with the use of C++, and employs a Python-based configuration language for flexible workflow customization. The framework is highly modular, incorporating various components such as event generators, detailed detector simulation using Geant4, sophisticated particle reconstruction algorithms, and optimized analysis tools. These features enable the efficient handling of large data volumes, detailed modeling of particle interactions, and robust statistical analyses. Moreover, basf2's simulation capabilities are particularly valuable for studying and developing new detectors, allowing researchers to optimize and enhance the performance of the Belle II detector components.
The simulation as well as the response of VTX were developed on the basf2 software. My work was based on this simulation to develop my own segmentation (for execution speed) and track identification algorithms.

Chapter 3

Development of VTX trigger reconstruction algorithm

This chapter covers the methods I used to determine if the new detector could contribute to the trigger from a software perspective. The first two sections describe the sensor segmentation and track reconstruction algorithm, while the last section presents the performance metrics used to answer the initial question of this work. All these methods were coded by me in Python.

3.1 Look-Up Table Method

As part of the trigger, track reconstruction aims to determine whether or not the reconstructed track[1] comes from the interaction point (IP) in order to separate the tracks produced by physically interesting particles from the tracks coming from particles that we call background noise [4]. Subsequently, On-IP particles will refer to interesting particles, those to keep, and Off-IP particles to background ones.
To do this, it was decided after a discussion with the person responsible for the experiment trigger to use the so-called Look-Up Table method. This method was chosen because it is quick to execute and is easily implemented in an FPGA, the reference hardware component for the trigger.
It consists of two steps:

1. Beforehand, **the learning step** : Creation of a reference table from simulated On-IP events, the characteristics of which are recorded. The informations of this table will be stored within the FPGA.

2. During experiment operation, **the usage step** : After reconstructing tracks from the different hits seen in the detector, this tracks will be compared to the reference table. Thus, if a reconstructed track coincides with a table track, the algorithm will return that this track must be kept, otherwise reject it.

The speed of the method is therefore correlated to the size of the recorded table; the larger the latter, the more time the algorithm will take. However, the size of the table depends on how the tracks are described and therefore how hits are described.

[1]A track is a collection of 3 hits, 1 hit per oVTX layer (iVTX layers cannot be taken into account due to their hit rate being too high)

3.2 Macropixels Segmentation

As explained in Section 2.1.2, in order to achieve quick information, the TTT minimal hit information to transmit needs to be the column hit. Therefore, the hit information could take a value up to the number of columns in the sensor (896). Since the detector is made of almost 2000 sensors, each column will be assigned a unique address, which represents approximately 1.7 million different addresses. Thus, a track will be represented by the combination of 3 unique column addresses. Nevertheless, the number of combinations associated with these unique column addresses is extremely large. This number is directly linked to the size of the table to store, as said in Section 3.1. This is why we introduce a new segmentation, macropixel segmentation.
Column segmentation makes it possible to generate information in the time required by the trigger; macropixel segmentation makes it possible to create an efficient and rapid LUT. This new segmentation uses the same OR logic as for pixels, but at the column scale. Thus, if one of the columns that is part of the macropixel is hit, it activates the macropixel. The granularity chosen to carry out a first test is 8 macropixels per sensor, meaning a macropixel is made up of 112 columns.
These changes in information segmentation are represented in Figure 3.1, illustrating the evolution of the segmentation methods discussed.

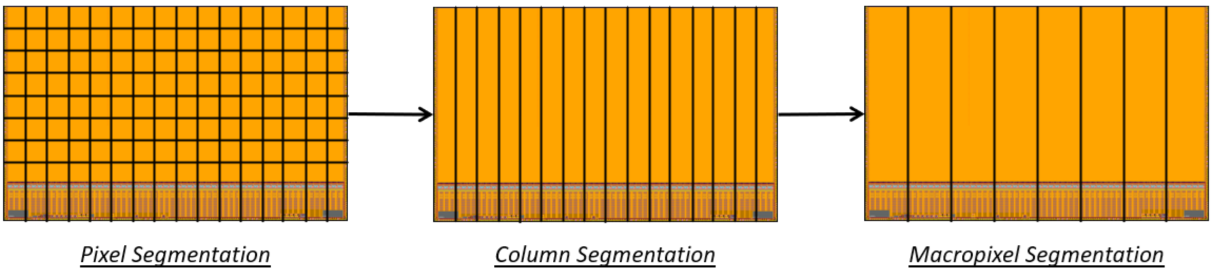

Figure 3.1: Schematic view of the segmentation evolution

3.3 Figure of merits

It is necessary to determine performance metrics in order to answer the question of the software feasibility of the TTT module. After the comparison with the LUT, we can associate the characteristics recorded in the table with each accepted track. Thus, the output of our TTT module will correspond to the recognized particles with its characteristics. In order to anticipate a possible breakdown of the CDC, two different output modes were considered:

- **Standalone mode** : returning the number of tracks; corresponding to the number of tracks associated to the same event, The Z-vertex; which represents the origin point of the track according to the Z coordinate (beam axis), and the spherical angle ϕ of the track
- **Matching to CDC trigger mode** : returning the spherical angle ϕ of the track as well as the track timing; information on the time at which the particle exited the VTX volume

I was asked to focus on standalone mode, a prerequisite before looking at potential matching with CDC. The performance metrics associated with this mode are the Z-vertex discrimination power of On-IP particles and the resolution of the ϕ angle.
The Z-vertex discrimination power is defined as the Z coordinate range where the efficiency probability to reconstruct a track is greater than 1%. The smaller the discrimination range, the better the Off-IP rejection rate.

The ϕ angle resolution is defined as $|\phi^{LUT} - \phi^{data}|$, corresponding to the difference between the ϕ angle stored in the LUT and the true ϕ angle of the test track. The lower this value, the better the resolution.
Track reconstruction efficiency, which is a trigger-specific performance metric is also studied. The efficiency is defined as $\frac{\text{Number of reconstructed tracks}}{\text{Number of generated tracks}}$. The higher this value, the better the algorithm. For this study, it was decided to begin with the study of single track events. Thus, the number of tracks is not monitored.

Chapter 4

Perfomance evaluation

This chapter presents the results obtained for the various performance metrics discussed above. It is divided into three parts; each part presenting the results obtained for one of the performance metrics. In order to obtain results, it was necessary to generate datasets; a dataset to create our reference table of physical tracks, and several test datasets representing the data to compare to the table. Here, the table is generated from 10^6 events described in Table 4.1 and the test datasets are composed of 10^5 events with the same characteristics as table events for the efficiency test, and with characteristics described in the Table 4.2 for the Z-vertex test. It is important to note that in this study, the particles are generated by a particle gun, and that each event only includes one particle.

Particle	$\mu^{\pm}$
Production Point	$(x = 0, y = 0, z = 0)$
Range of momentum	$0.2 \leq p \leq 3.0$
Range of θ angle	$0° \leq \theta \leq 180°$
Range of ϕ angle	$0° \leq \phi \leq 360°$

Table 4.1: Table events and efficiency test events characteristics

Particle	$\mu^{\pm}$
Production Point	$(x = 0, y = 0, z \in [-10, 10])$
Range of momentum	$0.2 \leq p \leq 3.0$
Range of θ angle	$0° \leq \theta \leq 180°$
Range of ϕ angle	$0° \leq \phi \leq 360°$

Table 4.2: Z-vertex discrimination power test events characteristics

4.1 Efficiency of the track reconstruction

The first test concerns the efficiency of the algorithm in reconstructing tracks. This efficiency can be represented based on different parameters, such as emission angles or transverse momentum. The simulation provides us with all the information on the particles, including their emission angles or momentum. This information is saved in the table for table tracks, but it is also possible to obtain it for test datasets. So here is an example of how to read Figure 4.1: Out of 100 tracks generated at 0.1 Gev/c from our test dataset, 47 were recognized by the trace reconstruction algorithm. The targeted average efficiency is $\geq 95\%$, which is the CDC trigger algorithm efficiency.

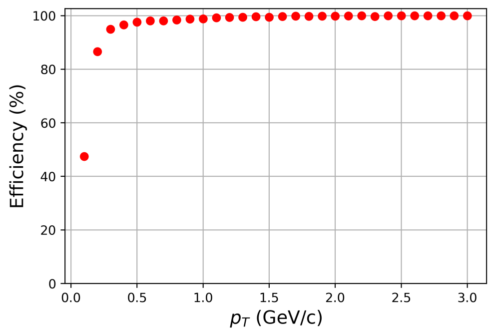

Figure 4.1: Trace reconstruction efficiency as function of p_T

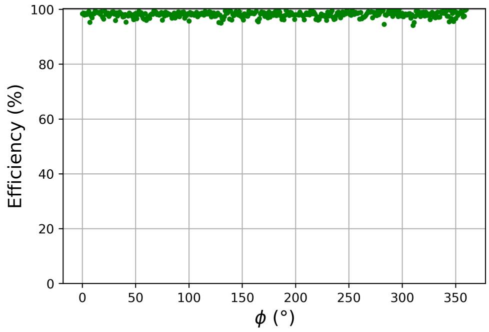

Figure 4.2: Trace reconstruction efficiency as function of ϕ

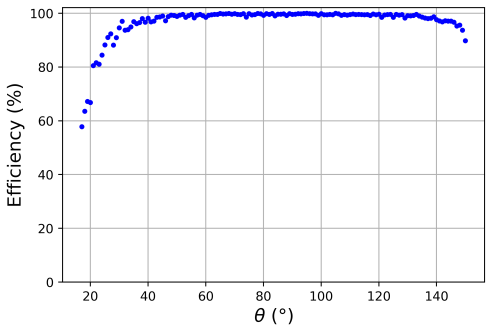

Figure 4.3: Trace reconstruction efficiency as function of θ

Reconstruction efficiency oscillates between 94% and 100% as a function of ϕ angle, while for θ angle we observe a decrease in efficiency at small and large θ. This seems to be consistent with the detector's properties: it covers 360° in ϕ, but only angles in θ between 17° and 150°. This acceptance explains why no tracks below these angles were recognized. For the decrease at low and high θ, the explanation is not yet established (a much greater decrease is observed at low θ than at high θ). Efficiency as a function of p_T also decreases at low p_T. This remains to be investigated.

Finally, the average efficiency of the algorithm is $\mathbf{98.14 \pm 0.03}\%$.

4.2 Z-vertex discrimination power

The second test focuses on the discrimination power in Z of the algorithm. By definition, Off-IP particles are produced outside the interaction point. Thus, the discrimination region in Z makes it possible to estimate the capacity of the algorithm to reject tracks produced by Off-IP particles. Since we're representing a reconstruction efficiency here, the method for reading the figure is the same as before. However, here, a low efficiency for particles with a Z value different from 0 — since our On-IP particles are produced at Z=0 — is a good thing, as it means that no track has been recognized for this Z value. The targeted discrimination range is < 5cm, which is 3 times lower than that of the CDC. As the VTX is closer to the IP, we expect a lower discrimination range.

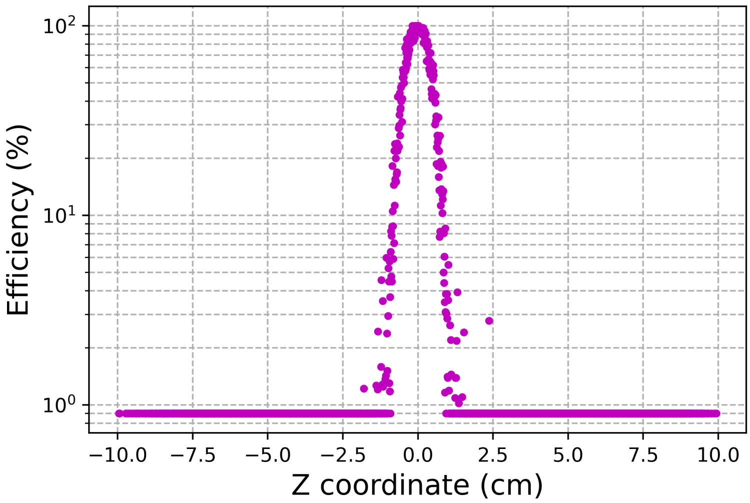

Figure 4.4: Reconstruction efficiency as a function of Z coordinate trace origin

To highlight low efficiencies, the y-axis has been scaled logarithmically. In logarithmic scale, however, it is not possible to represent the value 0, so we added 0.9 to all efficiencies equal to 0 to visualize them on Figure 4.4. So, as explained in Section 3.3, the extremities of the discrimination zone are defined by efficiencies greater than 1%. Thus, the most extreme points with an efficiency greater than 1% are located at -1.80 cm and 2.37 cm. The figure shows that the point at 2.37 cm is isolated. In fact, the point with an efficiency greater than 1% before it is located at 1.53 cm, a difference of more than 0.8 cm. The point at -1.80 cm is spaced 0.41 cm apart, which is smaller. It might be interesting to refine the criteria for selecting the extreme points of the discrimination range.
The discrimination range obtained in this test is $[\mathbf{-1.80}, \mathbf{2.37}]$cm.

4.3 Resolution of the ϕ angle

The last test carried out concerns the precision of the ϕ angle estimated by our algorithm. This angle is crucial because it allows us to estimate the trajectory of the particle and thus where it will impact the other detectors. That's why the ϕ angle is crucial as an output of the algorithm in the two modes mentioned in Section 3.3. To calculate this resolution, it is necessary to consider the predicted value of the ϕ angle from the table as well as the true value from the test dataset. With these values, we can obtain the residual, i.e., the difference between the predicted value and the true value. The residuals obtained for all the reconstructed tracks are represented in a density histogram. From this density histogram, we can attempt to fit a probability density function (PDF) that models the underlying distribution of the residuals. The precision of the ϕ angle is defined as the standard deviation (σ) of this PDF. The targeted resolution is not currently defined as it depends on the VTX mode to be used.

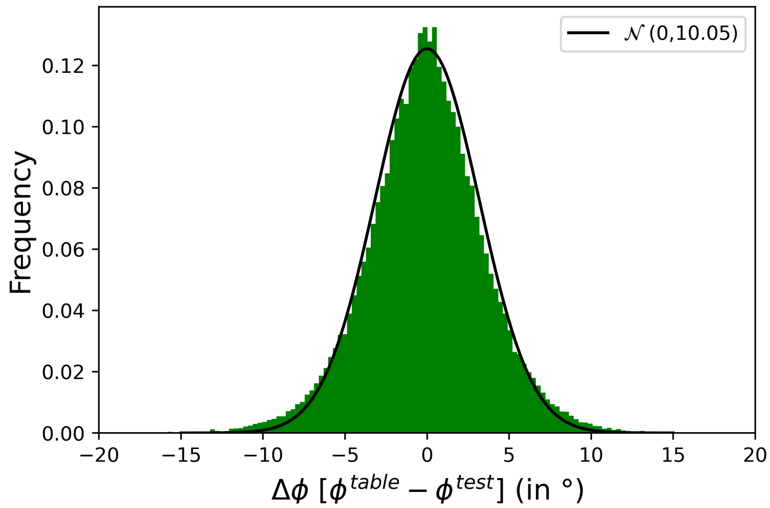

Figure 4.5: Residuals of $\Delta\phi$

In this case, we have determined that a Gaussian distribution provides a good fit for the histogram. The Gaussian curve $\mathcal{N}(\mu, \sigma^2)$ is characterized by two values, its mean μ and its variance σ^2. The mean indicates where the majority of the data points are located and serves as the reference point for the distribution's symmetry and central tendency. The variance describes the degree to which the data points are spread out around the mean. The figure shows the Gaussian approximating our curve.
Its mean is 0 and its variance is 10.05 . So the resolution in ϕ is $\sigma = \mathbf{3.17}°$.

Chapter 5

Conclusion

Initial results are very encouraging. They show that the algorithm developed in this study would be able to provide useful information for the overall decision logic of the Belle II experiment. The results of the trace reconstruction algorithm are an average efficiency greater than 98% and a discrimination zone < 2.4cm, with the expectations being $\geq 95\%$ for the efficiency and <5cm for the discrimination zone. However, these results are obtained in a well-controlled setting, with only single track events.

This summer, it is planned that I will continue this work to investigate situations closer to the reality of the detector in operation. The next step is to analyze multi-track events. This analysis will then enable me to obtain another important performance metric for the trigger: the estimation of the fake trigger rate.

As my work focuses solely on the algorithmic aspect, it will also be necessary to carry out a study of the experiment's hardware capabilities. Additionally, a study is planned for this summer on how the algorithm might be implemented on the trigger's data acquisition boards, the FPGAs.

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