A PROJECT REPORT ON

A review on CP Violation and Belle-II Experiment

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Abstract

We review theoretical and experimental aspects of CP violation and its relation to matter-antimatter symmetry of the universe. We begin with an introduction to parity symmetry and charge conjugation symmetry, which were thought to be trivially valid before 1950s and a notion of indistinguishable mirror universe was prevalent, which was disproved by Wu's experiment and later utterly shattered by Cronin and Fitch experiment with the observation of CP violation. In 1973, CP violation was incorporated into Standard Model through Kobayashi-Maskawa(KM) Model, which predicted the existence of 6 quarks. KM model is embodied by CKM matrix, which describes the flavour mixing of quarks under weak interaction. CP violating decays being the first observed processes which asymmetrically produced matter and antimatter, its role in baryogenesis is discussed. Lastly, Belle-II detector is introduced, which studies of B-meson physics, providing: ideal system for study of CP violation, testground for Standard Model and CKM matrix elements, insights into Flavour Changing Neutral Currents (FCNCs) and a probe for discovering new physics.

Contents

Chapter 1

Introduction

1.1 Parity Symmetry (P)

Before 1956, it was taken for granted that the laws of physics were ambidextrous, meaning the mirror image of any physical process was considered just as feasible as the original process. Most physicists saw this mirror symmetry, or "parity invariance," as obvious. However, in 1956, Lee and Yang questioned whether this assumption had ever been experimentally tested. While there is enough evidence for parity invariance in electromagnetic and strong processes, there was no evidence for weak interactions. They suggested a test, which was conducted later that year by C. S. Wu to resolve the issue. In this well-known experiment, radioactive cobalt-60 nuclei were meticulously aligned so that their spins pointed in the z direction. Cobalt-60 undergoes beta decay, and Wu observed the direction of the emitted electrons. She discovered that most electrons were emitted in the "northerly" direction, which was aligned with the nuclear spin.

If we consider the mirror image of this process, the image nucleus spins in the opposite direction, with its spin pointing downward. However, in the mirror image, the electrons still appeared to be emitted upward. Thus, in the mirror image, electrons are preferentially emitted in the direction opposite to the nuclear spin. This demonstrated that parity is not conserved in weak interactions. If parity were conserved, electrons in Wu's experiment would be emitted equally in both directions ("north" and "south"), but this was not the case. Parity violation was not a small effect, nor was it limited to β-decays, it is very prominent in the behaviour of neutrino. Let us consider the contrast between the helicity (value of m_s/s is helicity) of an electron and a neutrino (which is taken to be massless here) :

Take the direction of velocity v of electron as z. The electron being a spin $\frac{1}{2}$ particle can have a helicity of $+1(m_s = \frac{1}{2})$ or $-1(m_s = -\frac{1}{2})$. The former is called "right-handed" and the latter "left-handed." However, helicity is not lorentz invariant, one can always find a frame moving faster than a right handed electron in the $+z$-direction, from which, the electron seems to be moving in $-z$ direction, but still spinning in $+z$, changing the sign of helicity to -1 and from his perspective, this electron is left-handed. In other words, we can convert a right-handed electron into a left-handed one simply by changing your frame of reference.

But this is not true in case of neutrino, unlike electron, neutrino is massless, so it travels at the speed of light, and hence there is no observer travelling faster. Establishing the fact that helicity of a neutrino (or any other massless particle) is Lorentz invariant, fixed and fundamental property. Hence, determining the helicity of a neutrino became a significant experimental question. Up until the mid-1950s, it was generally believed that neutrinos, like photons, would be equally split between left-handed and right-handed types. However, it was discovered that all neutrinos are left-handed, and all antineutrinos are right-handed.

Of course, it's tough to measure the helicity of a neutrino directly; they're hard enough to detect at all. However, there is a relatively simple indirect method using pion decay: $\pi^+ \rightarrow \mu^+ + \nu_\mu$. If the pion is at rest, the muon and the antineutrino are emitted in opposite directions. Since the pion has a spin of 0, the spins of the muon and antineutrino must be oppositely aligned. Therefore, if the antineutrino is right-handed, the muon must also be right-handed in the pion rest frame, which is confirmed by experimental observations.

1.1.1 Action of Parity on classical objects

Parity converts a right-handed system into a left-handed system and vice versa by rotating backwards and reflecting downwards : Parity = Rotation around z axis by 180°+Reflection in XY-plane

$$\begin{aligned}
\text{Scalar}: \ P(a) &= a \\
\text{Vector}: \ P(\vec{a}) &= -\vec{a} \\
\text{Pseudo or Axial Vector, } \vec{c} = \vec{a} \times \vec{b}: \ P(\vec{c}) &= \vec{c} \\
\text{Scalar triple product or Pseudoscalar, } \vec{a}.(\vec{b} \times \vec{c}): \ P(c) &= -c
\end{aligned}$$

1.1.2 Parity quantum number and Action of Parity on Particle states

Applying Parity twice, we get back to the same state, which means,

$$P^2 = \mathbb{1} \tag{1.1}$$

$\Longrightarrow$ Eigenvalues of P are ± 1. For example, scalars and pseudovectors have eigenvalue + 1, whereas vectors and pseudoscalars have eigenvalue -1. Following points illustrate how to assign quantum numbers to elementary particles and hadrons :

- According to QFT, the parity of a fermion must be opposite to corresponding antifermion. While parity of a boson is same as its antiparticle.
- Intrinsic parity of quarks is taken to be $+1$ so the antiquarks are -1.
- Parity of composite system[1] is the product of the parity of its constituents. Baryons $(qqq) \rightarrow (+1)^3 = 1$, Mesons $(q\bar{q}) \rightarrow (+1)(-1) = -1$.

In the early 1950s, it was commonly believed that parity was conserved in all interactions, including the weak interaction, just as it was in strong and electromagnetic interactions. However, the "tau-theta puzzle" presented a paradox: two mesons, called τ and θ, appeared identical in terms of mass, spin, and charge, but decayed differently—one into two pions (with parity +1) and the other into three

[1] in its ground state,in excited states an extra factor of $(-1)^\ell$ appears, where ℓ is orbital angular momentum.

pions (with parity -1) :

$$\theta^+ \to \pi^+ + \pi^0 \qquad (P = +1) \tag{1.2}$$

$$\tau^+ \to \pi^+ + \pi^0 + \pi^0 \qquad (P = -1) \tag{1.3}$$

This discrepancy led Lee and Yang in 1956 to propose that these mesons might actually be the same particle (now known as the K^+) and that parity might not be conserved in one of the decays. Their hypothesis prompted experiments to test for parity invariance in weak interactions, ultimately finding that parity is indeed violated in these processes.

1.2 Charge Conjugation Symmetry (C)

Classical electrodynamics maintains its symmetry under the reversal of all electric charges; the potentials and fields change sign, but a compensating charge factor in the Lorentz force law ensures the forces remain the same. In elementary particle physics, this concept is generalized by the operation known as charge conjugation, C, which transforms a particle into its antiparticle:

$$C|p\rangle = |\bar{p}\rangle \tag{1.4}$$

The term "charge conjugation" might be misleading, as C can be applied to neutral particles (e.g., converting a neutron to an antineutron). Charge conjugation changes the sign of all internal quantum numbers—such as charge, baryon number, lepton number, strangeness, charm, beauty, and truth—while leaving mass, energy, momentum, and spin unaffected. As with P, application of C twice brings us back to the original state:

$$C^2 = \mathbb{1} \tag{1.5}$$

and hence the eigenvalues ± 1. But unlike P, most of the particles in nature are not eigenstates of C, because if $|p\rangle$ is an eigenstate of C, from (1.4),

$$C|p\rangle = \pm|p\rangle = |\bar{p}\rangle \tag{1.6}$$

which means p and $\bar{p}$ represent the same physical state. Thus only those particles that are their own antiparticles can be eigenstates of C. This leaves us the photon, as well as all those mesons which lie at the center of their Eightfold Way diagrams: π^0, η, η', ρ^0, ϕ, ω, J/ψ, and so on. Since the photon is the quantum particle of the electromagnetic field, which reverses sign under C, it logically follows that the photon's charge conjugation number is -1. It can be demonstrated that a system comprising a spin-$\frac{1}{2}$ particle and its antiparticle, arranged with orbital angular momentum l and total spin s, forms an eigenstate of C with an eigenvalue of $(-1)^{l+s}$.

$$\text{For pseudoscalars : } l = 0, s = 0 \implies C = +1$$
$$\text{For vectors : } l = 0, s = 1 \implies C = -1$$

C is a multiplicative quantum number, and, like parity, it is conserved in the strong and electromagnetic interactions. Thus, for example, the π^0 decays into two photons:

$$\pi^0 \to \gamma + \gamma \quad (C = +1 \text{ before and after}) \tag{1.7}$$

but it cannot decay into three photons. (For a system of n photons, $C = (-1)^n$.) Similarly, the ω goes to $\pi^0 + \gamma$, but never to $\pi^0 + 2\gamma$. Because so few particles are eigenstates of C, its direct application in elementary particle physics is rather limited. Its power can be somewhat extended if we confine our attention to the strong interactions by combining it with an appropriate isospin transformation. A rotation by 180° about the number 2 axis in isospin space will carry π^+ into π^-, for instance.
If we then apply the charge conjugation operator, we come back to π^+. Thus the charged pions are eigenstates of this combined operator, even though they are not eigenstates of C alone. For some reason the product transformation is called "G-parity":

$$G = CR_2, \quad \text{where } R_2 = e^{i\pi I_2} \tag{1.8}$$

All mesons that carry no strangeness (or charm, beauty, or truth) are eigenstates of G, for a multiplet of isospin I the eigenvalue is given by,

$$G = (-1)^I C \tag{1.9}$$

For a single pion, $G = -1$, and for a state with n pions :

$$G = (-1)^n \tag{1.10}$$

This result tells us how many pions can be emitted in a particular decay. For example, the ρ mesons, with $I = 1, C = -1 \implies G = +1$, can go to two pions, but not to three, whereas the ϕ, the ω, and the J/ψ can go to three, but not to two.

Chapter 2

CP Violation : Early Observations

2.1 Study of π^+ decays : C, P and CP

Weak interactions are NOT invariant under Charge Conjugation (**C**) and Parity transformation (**P**), the cleanest evidence are pion decays :

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \tag{2.1}$$

Above produced Antimuon and Neutrino are LEFT-HANDED. On performing **P**, the handedess of μ^+ and ν_μ should be inverted, But Right-Handed Neutrinos DO NOT exist! This decay with right handed neutrino is not found in nature. Similarly, this is the charge conjugated version of pion decay :

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu \tag{2.2}$$

Since Charge conjugation preserves handedness, the muon and antineutrino produced are LEFT-HANDED, but all antineutrinos are right handed, consequently, this decay is not found in nature.

Whereas, applying **P** followed by **C** on (1.1), that is, **CP** we get :

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu \tag{2.3}$$

This time, the produced Muon and Antineutrino are RIGHT-HANDED, and this decay is found in observed.

From this example, it was concluded that **CP** is a symmetry of weak interaction. However, this is not true.

2.2 CP Violation in Neutral Kaon Systems

Gell-Mann and Pais pointed out the dramatic implications of CP violation on Neutral K Mesons, they observed :

$$K^0 \rightleftharpoons \bar{K}^0 \tag{2.4}$$

K^0 with strangeness $+1$ changes to $\bar{K}^0$ with strangeness -1 through weak interactions of second order.

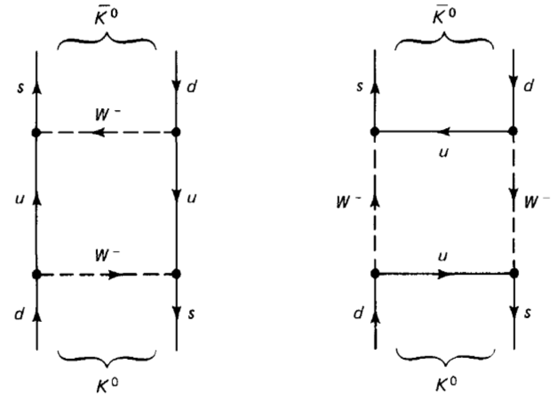

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Figure 2.1: Feynman diagrams corresponding to the second order weak interactions responsible for $K^0 \rightleftharpoons \bar{K}^0$ [5]

Since, K^0 and $\bar{K}^0$ keep interchanging to each other, what we actually see is a linear combination of these particles.

Looking at the behavior of K's under **C**, **P** and **CP**, we find,

$$K\text{'s being pseudoscalars}: \; P|K^0\rangle = -|K^0\rangle \tag{2.5}$$

$$P|\bar{K}^0\rangle = -|\bar{K}^0\rangle \tag{2.6}$$

$$\text{From the definition of } \mathbf{C}: \; C|K^0\rangle = |\bar{K}^0\rangle \tag{2.7}$$

$$C|\bar{K}^0\rangle = |K^0\rangle \tag{2.8}$$

$$\implies CP|K^0\rangle = -|\bar{K}^0\rangle \tag{2.9}$$

$$CP|\bar{K}^0\rangle = -|K^0\rangle \tag{2.10}$$

Clearly, K^0 and $\bar{K}^0$ are not the eigenstates of **CP**, and its not difficult to see that K_1 and K_2 defined by :

$$|K_1\rangle = \frac{1}{\sqrt{2}}(|K^0\rangle - |\bar{K}^0\rangle) \tag{2.11}$$

$$|K_2\rangle = \frac{1}{\sqrt{2}}(|K^0\rangle + |\bar{K}^0\rangle) \tag{2.12}$$

are eigenstates of **CP** with eigenvalues -1 and $+1$ respectively,

$$CP|K_1\rangle = |K_1\rangle \tag{2.13}$$

$$CP|K_2\rangle = |K_2\rangle \tag{2.14}$$

Now, assuming **CP** is invariant under weak interaction from our previous intuition about π^+ decays, we conclude,

$$K_1 \text{ can only decay into a state with } CP = +1$$
$$K_2 \text{ can only decay into a state with } CP = -1$$

Neutral Kaons decay into 2 or 3 pions and we know that $C = +1$ for both configurations and $P = +1$ for 2π and $P = -1$ for 3π configurations,

$$\implies K_1 \rightarrow 2\pi$$
$$K_2 \rightarrow 3\pi$$

Now, 2π decays are much faster which is attributed to the greater energy release in the process. Which means, if we start with a beam of K^0's :

$$|K^0\rangle = \frac{1}{\sqrt{2}}(|K_1\rangle + |K_2\rangle) \tag{2.15}$$

Near the source, we should see a lot of 2π events but farther along, we expect only 3π decays (from a pure beam of K_2's). In fact, the decay lifetimes of K_1 and K_2 were measured in 1956, by Lederman and his collaborators,

$$\tau_1 = 0.89 \times 10^{-10} s$$
$$\tau_2 = 5.20 \times 10^{-8} s$$

$\implies$ K_1's are gone after a few centimeters, while K_2's can travel many meters.

Now, this effect can be exploited to test **CP** invariance. Which is what Cronin and Fitch[1] did.

2.3 Observation of CP Violation : Cronin and Fitch's Idea

Idea : By using a long enough beam, we can easily produce an arbitrarily pure sample of long lived(K_2) species. Hence, at the end of the beam, if we observe 2π decays, we shall know that **CP** has been violated.

Results : At the end of a 57 feet long beam, **45 2π decays** were observed in total of 22700 decays. Now, this is a clear evidence for CP Violation.

$\implies$ Long lived Neutral Kaon is not a perfect eigenstate of CP, but contains a small admixture of K_1 :-

$$|K_L\rangle = \frac{1}{1+\epsilon^2}(|K_2\rangle + \epsilon|K_1\rangle) \tag{2.16}$$

[1] Experimental setup to be discussed in subsequent sections.

where, ϵ contains the information about how much the nature deviates from **CP** invariance and its experimentally measured value is :

$$\epsilon = 2.3 \times 10^{-3}$$

Moreover, there was no natural way at that time to accomodate Charge-Parity Violation into Standard Model because the effect is so small that its very difficult to generalize unlike Parity violation.

The Cronin-Fitch experiment destroyed the last hope for any form of exact mirror symmetry in nature. Further studies in semileptonic decays of $|K_L\rangle$ gave even more dramatic evidence and implications of **CP** Violation. It was observed that 34% of $|K_L\rangle$ decay by the 3π mode as usual, but 39% decay as either of :

$$\pi^+ + e^- + \bar{\nu_e} \tag{2.17}$$

$$\pi^- + e^+ + \nu_e \tag{2.18}$$

If **CP** was conserved and $|K_L\rangle$ was a pure eigenstate of CP, both of these should be equally probable, but the latter is more probable (by a fractional difference of 3.3×10^{-3}). A list of observations and implications :

- This was the first ever observed distinction in treatment of matter and antimatter.
- Unambiguous, convention free definition of the positive charge : It is the charge carried by the lepton preferentially produced in the decay of long lived Neutral K-aon.
- The fact that **CP** Violation permits unequal treatment of particles and antiparticles suggests that it may be responsible[2] for the dominance of matter over antimatter in the universe.

[2]Implications of CP violation in Baryogenesis are discussed in chapter 4

Chapter 3

Cronin and Fitch Experiment

3.1 Experimental Setup and Description

In this measurement, K^0 mesons were produced at the Brookhaven AGS in an internal Be target bombarded by 30 GeV protons. A neutral beam was defined at 30 degrees relative to the circulating protons by a collimator. The charged particles were swept out of the beam by a bending magnet, while most of the photons were removed by passing it through a 4cm thick block of lead.

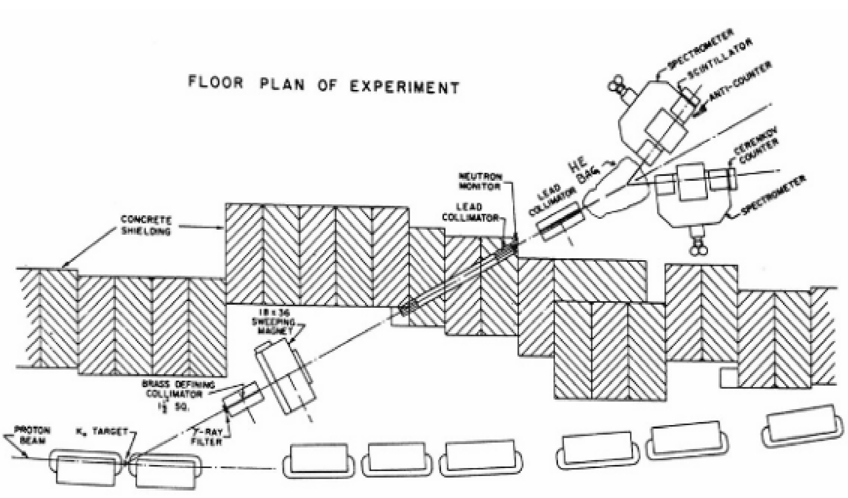

Figure 3.1: Schematic view of the arrangement for the CP run [4].

The beam, initially containing both K_S and K_L mesons (and neutral background particles), through a collimator reached the detection apparatus 18 m away. By that time, the short-lived K_S component had completely decayed, leaving a beam that consisted mainly of K_L particles and background neutrons, together with a few background photons that had penetrated the lead block.

The K_L beam entered a helium-filled bag (suppressing background from beam interactions in a bag gas) through a lead collimator. The CP-violating decays in the shaded region in Bag were detected by the symmetrically spaced spectrometers, containing a pair of spark chambers separated by a magnet. The spark chambers, recording tracks, have been triggered by the coincidence of scintillation counters

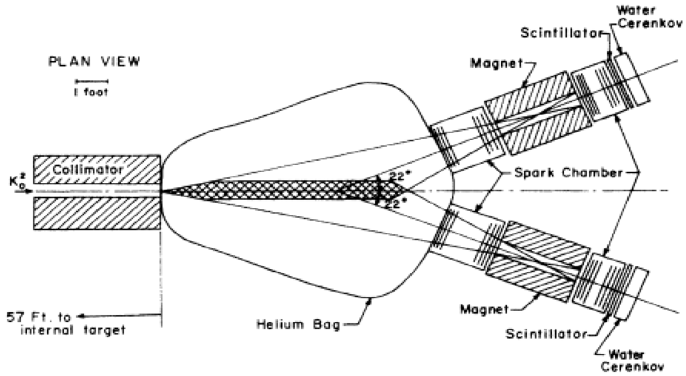

Figure 3.2: Plan view of the detector arrangement [3].

and water-filled Cerenkov counters, recording charged particles with velocities greater than $0.75c$. This trigger eliminated background events involving slow-moving particles produced, for example, due to the collisions of neutrons. The analysis program computed the vector momentum of each charged particle observed in the decay and the invariant mass, m^*, assuming each charged particle had the mass of the charged pion.

Defining the components at one single place for reference :

- **Collimator**: A collimator narrows a beam of particles or waves by aligning motion directions or reducing the beam's spatial cross section.
- **Spark Chamber** : A spark chamber is a sealed box filled with metal plates filled with helium or neon gas. A charged particle moves through the box, ionizing the gas between plates. Electronics detect this, and a high voltage is applied, causing sparks.
- **Scintillator** : A scintillator is a material that exhibits scintillation, a luminescence property, when excited by ionizing radiation, absorbing and re-emitting the energy in light.
- **Water Cerenkov** : It counts the number of charged particles that move faster than light in water as a medium, i.e, greater than $0.75c$.

3.2 Results

Mass distribution of all K_L decays in He gas is plotted in fig 2.3, broad peak is obtained due to 3-body decays :

$$K_L \to \pi^+ \ell^- \nu_\ell \tag{3.1}$$

$$K_L \to \pi^- \ell^+ \bar{\nu}_\ell \tag{3.2}$$

$$K_L \to \pi^+ \pi^- \pi^0 \tag{3.3}$$

there is no signature of decays to two pions recognizable (i.e. no sharp peak around $m^* = m_K \approx$ 498MeV)

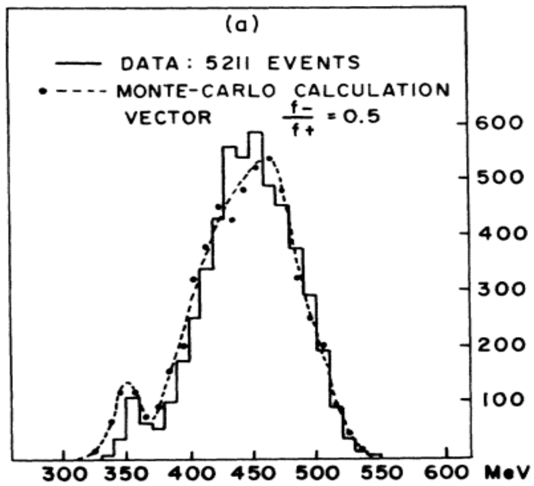

Figure 3.3: For the K_2 decays in He gas, the experimental distribution in m^* compared with Monte-Carlo calculation [4].

In Fig 2.4, the decay events occur only at zero angles to the beam and at an invariant mass of $498MeV/c^2$, and background events have a smooth dependence on this angle and on the invariant mass. There is a peak in the beam direction $\theta = 0^{\circ}$ for the invariant mass range $494 < m^* < 504GeV/c^2$, which is from the CP-violating decay $K_L \rightarrow \pi^+\pi^-$.

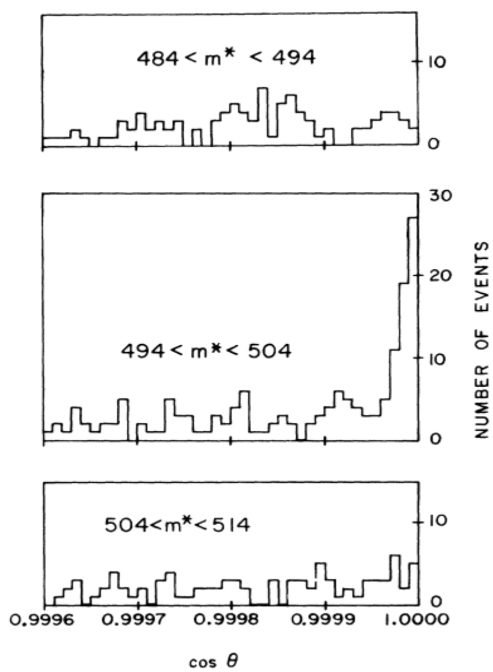

Figure 3.4: Angular distribution in three mass ranges for events with $cos\theta > 0.9995$ [4]

45 ± 9 were obtained at the forward peak after subtraction of background out of a total corrected sample of 22700 K_2 decays.

Chapter 4

The CKM matrix and the Kobayashi-Maskawa mechanism

4.1 Historical background

In the early 20th century, only a few "elementary" particles were known: the proton, the electron, and the photon. The first major addition to this list came when W. Pauli proposed the existence of the neutrino in 1924. This idea was a significant breakthrough, leading to Enrico Fermi's development of a theory of weak interactions in 1934. Fermi's work provided a framework to understand the roles of hadrons and leptons and the nature of particle interactions. This also resulted in a clear formulation of "weak" versus "strong" interactions and the understanding of interactions as an exchange of mediating particles. Around this time, Hideki Yukawa predicted the existence of such a particle, leading to the discovery of the pion. Additionally, the muon was discovered, initially mistaken for a pion but later identified as a separate particle. The term "flavor" was introduced much later, but the beginning of quark flavor physics can be traced back to the discovery of strange particles by Rochester and Butler in 1947. These particles had unusually long lifetimes into non-strange particles for their decays to be classified as strong decays, leading to the introduction of the strangeness quantum number by Gell-Mann in 1953. This number is conserved in strong decays but can change in weak decays. As more particles were discovered, they were organized using Gell-Mann's "eightfold way" in 1962, which extended isospin symmetry to the SU(3) group. The decays of strange particles, especially kaons, advanced our understanding of particle physics. Before 1954, it was believed that the discrete symmetries C (charge conjugation), P (parity), and T (time reversal) were individually conserved. This belief, based on electromagnetic interactions, led to the $\theta - \tau$ puzzle. Two particles, then known as θ and τ, had identical masses and lifetimes but different parities: θ decayed into two pions (even parity) and τ into three pions (odd parity). Lee and Yang resolved this puzzle in 1956 by proposing that parity is not conserved in weak interactions, revealing that θ and τ are actually the same particle, now known as the charged kaon. After many breakthrough experiments, it was established that parity is not the mirror symmetry we were looking for. However, the combination of two discrete transformations, namely CP, still seemed to be conserved (π decay in first chapter).

Another puzzle related to kaon decays was the relative coupling strength. It turned out that the coupling strength of strangeness-changing processes is much smaller than that of strangeness-conserving transitions. This finding eventually led to the parameterization of quark mixing by Cabibbo (1963).

In modern language, the up quark u couples to a combination $d\cos\theta_C + s\sin\theta_C$ of the down quark d and the strange quark s. The value $\theta_C \sim 13°$ for the Cabibbo angle explained the observed pattern of branching ratios in baryon decays. Experiments during that period only investigated the three lightest quarks, and the reason for the significant suppression of flavor-changing neutral current (FCNC) decay was unknown, consider the decay :

$$\frac{\Gamma(K^+ \to \pi^+\ell^+\ell^-)}{\Gamma(K^+ \to \pi^0\ell^+\bar{\nu})} \sim 10^{-6}$$

The resolution of this puzzle was found by Glashow, Iliopoulos, and Maiani (1970): one includes the **charm** quark, with the same quantum numbers as the up quark, and coupling to the orthogonal combination $-d\sin\theta_C + s\cos\theta_C$. FCNC processes are suppressed by the "GIM mechanism." In the kaon system, this involves the transition of an s quark to a d quark, achieved through two successive charged current processes. These processes involve either the up or charm quark as an intermediate state, with the amplitudes considering Cabibbo mixing as :

$$\begin{aligned} A(s \to d) &= A(s \to u \to d) + A(s \to c \to d) \\ &= \sin\theta_C \cos\theta_C [f(m_u) - f(m_c)] \end{aligned}$$

If the up and charm quark masses were equal, the function f(m) would be the same for both, resulting in no $K^0 - \bar{K}^0$ mixing or other kaon FCNC processes. However, their masses aren't degenerate, and these effects are observed.

With the proposal of existence of c, the term "particle family" was coined and it was indeed discovered, in 1974, which completed the second quark family. It also introduced a 2×2 quark mixing matrix into the phenomenology of weak interactions :

$$\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} \cos\theta_C & \sin\theta_C \\ -\sin\theta_C & \cos\theta_C \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix} \tag{4.1}$$

Further, the discovery of the τ lepton in 1975 and the bottom quark in 1977 confirmed the existence of a third generation of quarks and leptons. The third generation was incomplete for many years because the top quark, being very heavy, wasn't discovered until 1995 at Fermilab's Tevatron. Furthermore, the bottom quark turned out to be quite long-lived, indicating a small mixing angle between the first and second generation. This fact is the experimental foundation of using B decays to study CP violation. The first hint of the large top-quark mass was the discovery of $B^0 - \bar{B}^0$ oscillations (also known as mixing) by ARGUS (Albrecht et al., 1987b). In fact, if the top mass had been significantly smaller, ARGUS could not have observed $B^0 - \bar{B}^0$ oscillations. The GIM mechanism for down-type quarks leads generally to suppression factors of the form :

$$\text{CKM factor} \times \frac{1}{16\pi^2}\frac{m_t^2 - m_u^2}{M_W^2} \tag{4.2}$$

and hence the GIM suppression for the bottom quark is much weaker than in the up-quark sector, where the corresponding factor is :

$$\text{CKM factor} \times \frac{1}{16\pi^2}\frac{m_b^2 - m_d^2}{M_W^2} \tag{4.3}$$

Hence FCNC decays of B-mesons ($B^0 \equiv d\bar{b}$) have branching ratios in the measurable region, while FCNC processes for D-mesons ($D^0 \equiv u\bar{c}$) are heavily suppressed.

4.2 CP violation and baryogenesis

Over the past thirty years, particle physics experiments have confirmed the Standard Model (SM) at the quantum level, including quark mixing and CP violation. However, the observed matter-antimatter asymmetry in the universe suggests there must be additional sources of CP violation, as the CP violation predicted by the CKM mechanism alone is insufficient to account for the observed asymmetry. In fact, the excess of baryons over antibaryons in the universe :

$$\Delta = n_B - n_{\bar{B}} \tag{4.4}$$

is small compared to the number of photons : the ratio is measured to be $\Delta/n_\gamma \sim 10^{-10}$. While it's possible to imagine regions in the universe made of antimatter, similar to our matter-dominated neighborhood, no known mechanism could have generated regions of matter or antimatter as vast as those observed since the Big Bang. Additionally, efforts to detect photons from matter-antimatter collisions, which would indicate large antimatter regions, have been unsuccessful. Sakharov (1967) outlined the prerequisites for the dynamic emergence of a non-zero baryon asymmetry (Δ) from an initially symmetric state ($\Delta = 0$). He identified three essential components necessary for this process, called as **Sakharov Conditions for Baryogenesis**:

- **Baryon Number Violation :** Interactions that violate baryon number conservation, allowing for the creation or destruction of baryons and antibaryons, mathematically, $H_{\text{eff}}(\Delta B \neq 0) \neq 0$.
- **C and CP Violation :** CP-violating interactions are essential. If CP symmetry were intact, each process $i \to f$ mediated by $H_{\text{eff}}(\Delta B \neq 0)$ would have an identical probability for its CP-conjugate process, which would erase any matter-antimatter asymmetry. Hence, these violations are need in order to have differences between the behaviors of particles and their antiparticles, contributing to the asymmetric creation of matter and antimatter.

$$\Gamma(i \to f) \neq \Gamma(\bar{i} \to \bar{f}) \tag{4.5}$$

- **Out-of-Equilibrium Dynamics :** The universe must have been out of thermal equilibrium. Under the assumption of locality, causality, and Lorentz invariance, CPT is conserved. Since in an equilibrium state, time becomes irrelevant on the global scale, CPT is reduced to CP, which according to second condition will imply symmetric production of matter and antimatter.

To illustrate the first two Sakharov conditions, a simple example is considered. Assume that in the early universe, there was a particle X that could decay to only two final states $|f_1\rangle$ and $|f_2\rangle$, with baryon numbers $N_B^{(1)}$ and $N_B^{(2)}$ respectively, and decay rates

$$\Gamma(X \to f_1) = \Gamma_0 r \quad \text{and} \quad \Gamma(X \to f_2) = \Gamma_0(1-r),$$

where Γ_0 is the total width of X. Taking the CP conjugate, the particle $\bar{X}$ decays to the state $\bar{f}_1$ with baryon number $-N_B^{(1)}$ and $\bar{f}_2$ with baryon number $-N_B^{(2)}$; the rates are

$$\Gamma(\bar{X} \to \bar{f}_1) = \Gamma_0 \bar{r} \quad \text{and} \quad \Gamma(\bar{X} \to \bar{f}_2) = \Gamma_0(1-\bar{r}),$$

where Γ_0 is the same as for X due to CPT invariance. The overall change ΔN_B in baryon number induced by the decay of an equal number of X and $\bar{X}$ particles is

$$\Delta N_B = rN_B^{(1)} + (1-r)N_B^{(2)} - \bar{r}N_B^{(1)} - (1-\bar{r})N_B^{(2)} = (r-\bar{r})\left(N_B^{(1)} - N_B^{(2)}\right) \tag{4.6}$$

For matter-antimatter symmetry, we need :

$$\Delta N_B \neq 0 \tag{4.7}$$

$$\implies r \neq \bar{r} \textbf{ : CP Violation} \tag{4.8}$$

$$\text{and, } N_B^{(1)} \neq N_B^{(2)} \textbf{ : Baryon Number Violation} \tag{4.9}$$

Electroweak baryogenesis is another consideration. The electroweak interaction introduces CP violation through the CKM mechanism. Additionally, baryon number is conserved only classically, with electroweak quantum effects violating baryon number while conserving $(B-L)$. However, despite having all necessary ingredients, this mechanism cannot account for the observed baryon asymmetry (Δ), as the CP violation provided by the CKM matrix is several orders of magnitude too small.

Considering the solid evidence for non-zero neutrino masses, there might be new sources of CP violation in the lepton sector and possibly even lepton-number violation, though the latter has not been observed yet. This could result in baryon number violation through leptogenesis, with the surplus of leptons transferred to the baryonic sector via interactions that conserve the $B-L$. Regardless, there is a necessity for an extra source or sources of CP violation beyond what the CKM matrix phase provides (as elaborated in the next section) to explain the matter-antimatter asymmetry in the universe. This quest for new interactions is a key driving force behind flavor-physics experiments.

4.3 The CKM Matrix

In 1973, when only three quarks were known, Kobayashi and Maskawa (KM) introduced a six quarks hypothesis in order to naturally accommodate CP violation to the theory of weak interaction. The subsequent discovery of the c, b and t quarks strongly suggested the validity of the KM model for CP violation. In the Standard Model, the quark mass eigenstates are not the same as the weak eigenstates, and the matrix relating these states for six quarks was given by Kobayashi and Maskawa. Conventionally, the mixing is expressed in terms of the 3×3 unitary Cabibbo-Kobayashi-Maskawa (CKM) matrix :

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \tag{4.10}$$

where,

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = V_{CKM} \tag{4.11}$$

Here the V_{ij} are the couplings of quark mixing transitions from an up-type quark $i = u, c, t$ to a down-type quark $j = d, s, b$.

In the Standard Model, the CKM matrix is unitary by construction. Using the freedom of phase redefinitions for the quark field, the CKM matrix has $(n-1)^2$ physical parameters for n families. Among these parameters, $n(n-1)/2$ represent real rotation angles, and $((n-3)n+2)/2$ are phases responsible for inducing CP violation. When $n=2$, no CP violation can occur, whereas for $n=3$, a single phase emerges, constituting the sole source of CP violation in the Standard Model, assuming the absence of strong CP violation.

The CKM matrix for three families can be depicted by three rotations and a matrix that generates the phase:

$$U_{12} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}, \quad U_{13} = \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix}, \quad U_{23} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}, \quad U_{\delta} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i\delta_{13}} \end{pmatrix} \tag{4.12}$$

where $c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$, and δ is the complex phase responsible for CP violation. Conventionally, the mixing angles θ_{ij} are chosen to lie in the first quadrant to ensure that s_{ij} and c_{ij} are positive. Then, following Chau and Keung (1984), the CKM matrix V_{CKM} is given by:

$$V_{\text{CKM}} = U_{23}U_{\delta}^{\dagger}U_{13}U_{\delta}U_{12} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \tag{4.13}$$

The elements of the CKM matrix exhibit a clear hierarchy. The diagonal elements are close to one, while the off-diagonal elements are significantly smaller, for example, $V_{ud} \gg V_{us} \gg V_{ub}$. In terms of the angles θ_{ij}, we have $\theta_{12} \gg \theta_{23} \gg \theta_{13}$. This hierarchy is often represented using the Wolfenstein parameterization, which can be viewed as an expansion in $\lambda = |V_{us}|$. Up to order λ^3, it reads:

$$V_{\text{CKM}} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4) \tag{4.14}$$

One can obtain an exact parameterization of the CKM matrix in terms of A, λ, ρ, and η, for example, by following the convention of Buras, Lautenbacher, and Ostermaier (1994), where,

$$\lambda = s_{12}, \tag{4.15}$$

$$A = \frac{s_{23}}{\lambda^2}, \tag{4.16}$$

$$A\lambda^3(\rho - i\eta) = s_{13}e^{-i\delta} \tag{4.17}$$

The modern convention for Wolfenstein's parameters (Charles et al., 2005),

$$\bar{\rho} + i\bar{\eta} = -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} \tag{4.18}$$

holds at all orders. The difference from the previously defined parameterization appears only at higher orders in the Wolfenstein expansion. The connection between this scheme and the earlier one is given by:

$$\rho + i\eta = (\bar{\rho} + i\bar{\eta})\frac{\sqrt{1 - A^2\lambda^4}}{\sqrt{1-\lambda^2}[1 - A^2\lambda^4(\rho + i\eta)]} \tag{4.19}$$

4.4 The Unitarity Triangle

The unitarity relations $V_{\text{CKM}} \cdot V^{\dagger}_{\text{CKM}} = \mathbb{1}$ and $V^{\dagger}_{\text{CKM}} \cdot V_{\text{CKM}} = \mathbb{1}$ result in six independent conditions corresponding to the off-diagonal zeros in the identity matrix. These conditions can be visualized as triangles in the complex plane, with each triangle having the same area, signifying that there is only one irreducible phase in a three-family system. A triangle with non-zero angles indicates CP violation, proportional to the common area of the triangles. Among the triangles, only two have sides of comparable length, meaning they are of the same order in the Wolfenstein parameter λ. The corresponding relations are:

$$V_{ud}V^*_{ub} + V_{cd}V^*_{cb} + V_{td}V^*_{tb} = 0 \tag{4.20}$$

$$V_{ud}V^*_{td} + V_{us}V^*_{ts} + V_{ub}V^*_{tb} = 0 \tag{4.21}$$

In order to form the unitarity triangle in Fig 3.1, we divide (4.20) by $V_{cd}V^*_{cb}$ so that the base of the triangle is of unit length,

$$1 + \frac{V^*_{ud}V_{ub}}{V^*_{cd}V_{cb}} + \frac{V^*_{td}V_{tb}}{V^*_{cd}V_{cb}} = 0 \tag{4.22}$$

Due to the significant angles involved, significant CP asymmetries in B decays are anticipated in

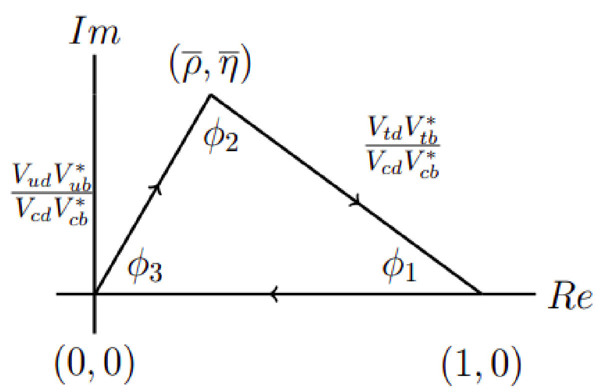

Figure 4.1: The unitarity triangle. [1]

the Standard Model (SM). It's important to note that both unitarity-triangle relations involve CKM matrix elements associated with the top quark. Specifically, V_{td} and V_{ts} can only be indirectly accessed through FCNC decays of bottom quarks. The angles of the Unitarity Triangle are defined as :

$$\phi_1 = \beta \equiv \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right], \tag{4.23}$$

$$\phi_2 = \alpha \equiv \arg\left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right], \tag{4.24}$$

$$\phi_3 = \gamma \equiv \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]. \tag{4.25}$$

The presence of CP violation in the CKM matrix leads to non-zero values for these angles ($\phi_i \neq 0°, 180°$), indicating a non-zero area for the Unitarity Triangle. Specifically, all triangles formed from the unitarity relation have the same area, which is proportional to the quantity $\Delta = \mathrm{Im}\,(V_{cs}^* V_{us} V_{cd} V_{ud}^*)$, independent of the phase convention. It's important to note that all other rephasing-invariant fourth-order combinations of CKM matrix elements, which cannot be reduced to products of second-order invariants, can be linked to Δ, making it unique.

Chapter 5

The Belle-II detector

Although CP violation was first discovered in the K-system in 1964, in recent years most experimental and theoretical developments in the field of flavour physics occur in the B-system and as a result the term "B-physics" is intimately related to flavour physics. Many observables in B-physics are dominated by higher order diagrams, and therefore, these measurements are extremely sensitive to extra contributions from new, virtual, heavy particles. That is why we need modern detectors like Belle-II [1] and LHCb [2], which operate at higher energy scales and are equipped with advanced technology to measure CP violation in B mesons with high precision.

5.1 Introduction

The new generation (super) B-factory will use the Belle II detector as its primary instrument for discoveries. The new detector, featuring a superconducting soleniod magnet with an iron return yoke, has been significantly upgraded or newer compared to its predecessor.

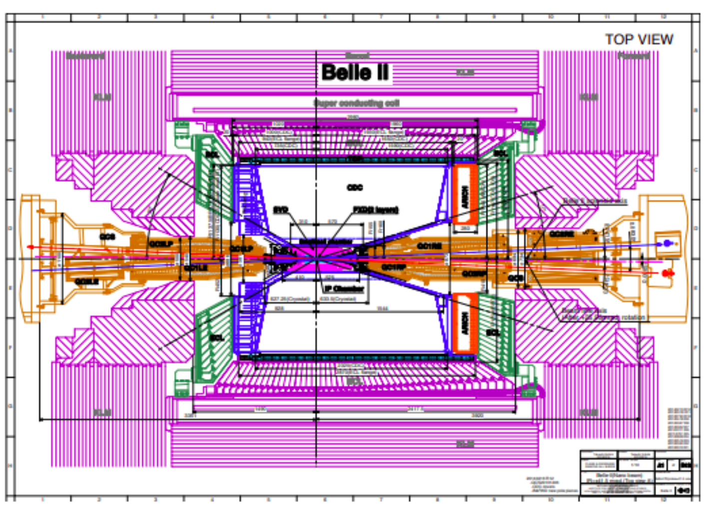

Figure 5.1: Top view of Belle-II. [1]

The Belle II detector, compared to Belle, operates at 40 times higher luminosity with background rates elevated by a factor of 10 to 20. To maintain performance, it must mitigate background effects, reduce occupancy and radiation damage, and avoid fake hits and neutron-induced hits. Modifications to trigger, data acquisition, and computing are needed for higher event rates, improved hadron identification, and improved hermeticity.

The requirements for a B factory detector are summarised as follows :

- Excellent vertex resolution.
- Very high reconstruction efficiencies for charged particles.
- Very good momentum resolution over the whole kinematic range of the experiment.
- Precise measurements of photon energy and direction.
- Highly efficient particle identification system to separate pions, kaons, protons, electrons and muons over the full kinematic range of the experiment.
- Cover almost the full solid angle around the collision point, that is, large hermeticity.
- Fast and efficient trigger system, as well as a data acquisition system capable of storing large quantities of data.

5.2 Components of the Detector

Subsequent sections discuss the different components of Belle-II detector and the improvements made in comparison to Belle.

5.2.1 Vertex Detector (VXD)

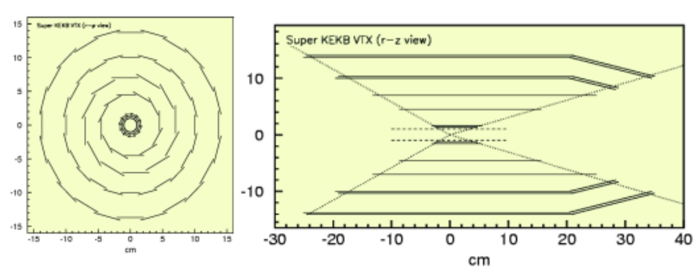

Figure 5.2: A schematic view of the Belle II vertex detector with a Be beam pipe, two pixelated layers and four layers with silicon strip sensors. [1]

The new vertex detector is comprised of two devices, the Silicon Pixel Detector (PXD) and Silicon Vertex Detector (SVD), with altogether six layers around a 10 mm radius Be beam pipe. The first two close packed layers will use pixelated sensors, the remaining four layers will be equipped with double-sided silicon strip sensors.

On comparison with Belle vertex detector, it has a beam pipe and first two detector layers closer to the interaction point, while the outermost layer has a larger radius, implying a significant improvement with respect to Belle in the vertex resolution, and in the reconstruction efficiency, since $K_S^0 \to \pi^+\pi^-$ decays with hits in the vertex detector.

5.2.2 Central Drift Chamber (CDC)

The CDC is the main device for tracking and identification of charged particles for Belle-II experiment. It focuses on high spatial resolution and the provision of z-direction information for triggering and it measures the momentum and dE/dx (Energy lost per unit distance). To be able to operate at high

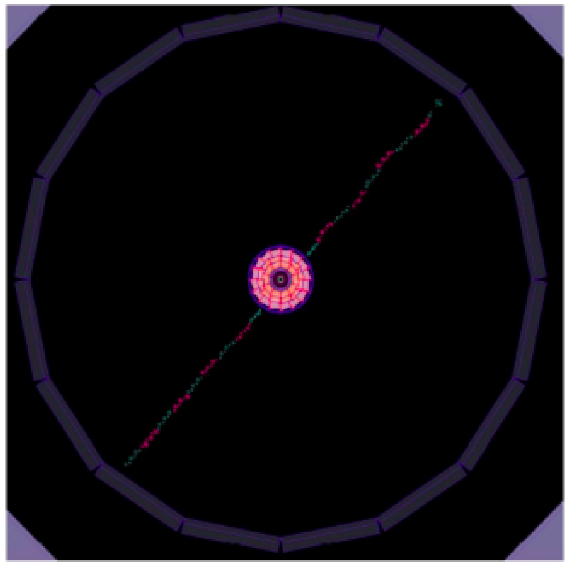

Figure 5.3: A cosmic muon as recorded by the Belle II CDC. [1]

event rates with increased background levels, the chamber has smaller drift cells than the one used in Belle. The 14336 sense wires that make up the CDC are stacked in 56 layers and are either oriented in a "axial" manner, which is parallel to the solenoidal magnetic field, or in a "stereo" orientation, which is skewed in relation to the axial wires. A complete 3D helix track can be recreated by fusing data from the axial and stereo layers. The chamber gas is comprised of a $He - C_2H_6$ 50:50 mixture with an average drift velocity of 3.3 cm/μs and a maximum drift time of about 350 ns for 17 mm cell size.

5.2.3 Particle Identification (TOP and ARICH)

TOP : Time-of-Propagation counter is an advanced PID system, which is designed to distinguish between charged particles. It operates by measuring the time it takes for Cherenkov radiation, emitted by particles as they pass through quartz bars, to reach photon detectors. This precise timing information allows for accurate particle identification, essential for reconstructing B-meson decays. Compared to the older TOF and threshold Cherenkov systems used in the Belle detector, the TOP counter offers more precision, efficiency, and a more compact design, improving the Belle-II's performance.

ARICH : The Aerogel Ring-Imaging Cherenkov detector enhances particle identification, especially at higher momentum ranges. It works by utilizing aerogel as a medium where charged particles emit Cherenkov radiation, forming a cone of light. This light is detected by an array of sensitive photon detectors, forming a ring pattern whose radius helps identify the type of particle. ARICH provides high-resolution and functions effectively across a wide range of momenta, crucial for studying B-meson decays. Compared to the Belle detector, the inclusion of the ARICH in Belle-II represents a significant upgrade, improving precision and efficiency in particle identification.

5.2.4 Electromagnetic Calorimeter (ECL)

The electromagnetic calorimeter is used to detect gamma rays as well as to identify electrons, i.e. separate electrons from hadrons, in particular pions. It is a highly-segmented array of thallium-doped caesium iodide CsI(Tl) scintillating crystals. All three detector regions, barrel as well as the forward and backward end-caps, are instrumented with a total of 8736 crystals, covering about 90% of the solid angle in the centre of mass system. This configuration ensures that photons and electrons from particle decays are efficiently detected.

CsI(Tl) crystals emit light when struck by high-energy photons or electrons, and the amount of light is proportional to the energy deposited by the particle, allowing for accurate energy measurement. Moreover, by analyzing the distribution of light in adjacent crystals, the position and direction of the incoming particles and position of particle interaction can be reconstructed.

5.2.5 K_L^0-Muon Detector (KLM)

As the name suggests, it detects long lived neutral K-mesons and muons. Located on the outermost layer of the Belle-II detector system, surrounding ECL, it consists of alternating layers of iron plates and active detector elements. The iron plates serve as absorbers to filter out other particles, while the active layers detect muons and K_L^0 mesons. Active detector elements here are scintillators, instead of RPCs (Resistive Plate Chambers) in Belle experiment, because in Belle-II the background rates are much higher than its prequel, which leads to fake muon identification, which renders such counters useless.

Muons are highly penetrating particles that can pass through the inner layers of the detector and the iron plates in KLM. As muons travel through the KLM, they excite the scintillators, generating detectable signals, pattern and timing of which is used to reconstruct the Muon's path. While K_L^0 are neutral and do not ionize directly. However, they can interact with the nuclei in the iron plates, producing secondary particles (such as pions) that can be detected.

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