

Systematic Studies on Reconstruction Efficiency at Belle II

von

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Ich versichere, dass ich die Arbeit selbstständig verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt sowie Zitate kenntlich gemacht habe.

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But it doesn't do anything
No, it does nothing

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Dieses Dokument richtet sich an Studierende am Fachbereich 08 im Studiengang Bachelor of Science (Physik). Sie finden hier Beispiele für eine mögliche Gliederung Ihrer Arbeit und Hinweise zur Strukturierung des Inhalts. Selbstverständlich sollen Sie diese Gliederung nach den Gegebenheiten Ihrer Bachelorarbeit anpassen. Besprechen Sie rechtzeitig mit Ihrem Betreuer, ob Ihr Entwurf sinnvoll ist. Holen Sie sich auch Anregungen zur Gestaltung von Abschlussarbeiten aus der Literatur ().

Sofern Sie sich dazu entscheiden, Ihr Dokument in \LaTeX zu erstellen, können Sie diese Datei als Vorlage verwenden. Fast die gesamte Literatur in der Physik verwendet \LaTeX , vor allem wegen der ausgezeichneten Möglichkeiten für das Formelschreiben.

In der Einleitung Ihrer Bachelorarbeit sollte das Thema der Arbeit möglichst allgemeinverständlich eingeführt werden. Gehen Sie dabei auch auf das weitere Umfeld der Arbeit ein und erläutern Sie, warum Aufgabenstellung und Herangehensweise interessant sind. Auch die weitere Gliederung kann angesprochen werden, um dem Leser einen ersten Überblick über den nachfolgenden Text zu geben.

CHAPTER 2 Theoretical Foundations

THE first part of this chapter will give short introduction to the standard model of particle physics. The standard model of particle physics (SM) is a theory that describes three of the four fundamental known forces in the universe: the electromagnetic, the weak and the strong force.

At the current level of experimental precision and the reached energies so far, it is the best theory describing these forces.

Unfortunately the standard model fails to explain a variety of different observations and since gravitation is not included in the standard model, it is easy to see that the standard model is not complete.

Finally this chapter will shortly describe the electron-positron scattering process, also known as Bhabha scattering, which plays a very important role in this thesis.

2.1. The Standard Model

The standard model is based on the idea that matter is made of particles with no internal structure. These particles can interact with each other by exchanging other particles which are associated to the fundamental forces. The standard model includes the *quantum electrodynamics* (QED), the *electroweak theory* (EWT) and the *quantum chromodynamics* (QCD) as well as the *Higgs mechanism*.

The QED describes all phenomenons caused by photons (γ) and charged point-like particles like electron and positrons. In the 1920s Paul Dirac laid the foundation for the QED while computing the coefficient of spontaneous emission of an atom. The description of the weak force (*quantum flavordynamics*, QFD) and the QED got merged by Sheldon Glashow in the early 1960s. The exchange particles of the weak force are the Z and W^\pm *bosons*. A few years later, Steven Weinberg and Abdus Salam independently proposed a theory that included the *Higgs mechanism* whereby the *electroweak theory* (EQT) emerged. The Higgs mechanism is the reason why the *gauge bosons* have mass. Finally the standard model reached its modern form after combining the EWT and the theory of the strong interaction (*quantum chromodynamics*, QCD). This was done by Abraham Pais and Sam Treiman in 1975. The exchange particles for the strong force are the *gluons* (g). They «glue» *quarks*

2. Theoretical Foundations

(fundamental particles) together, forming *hadrons* like *mesons* (even number of quarks) and *baryons* (odd number of quarks). [19]

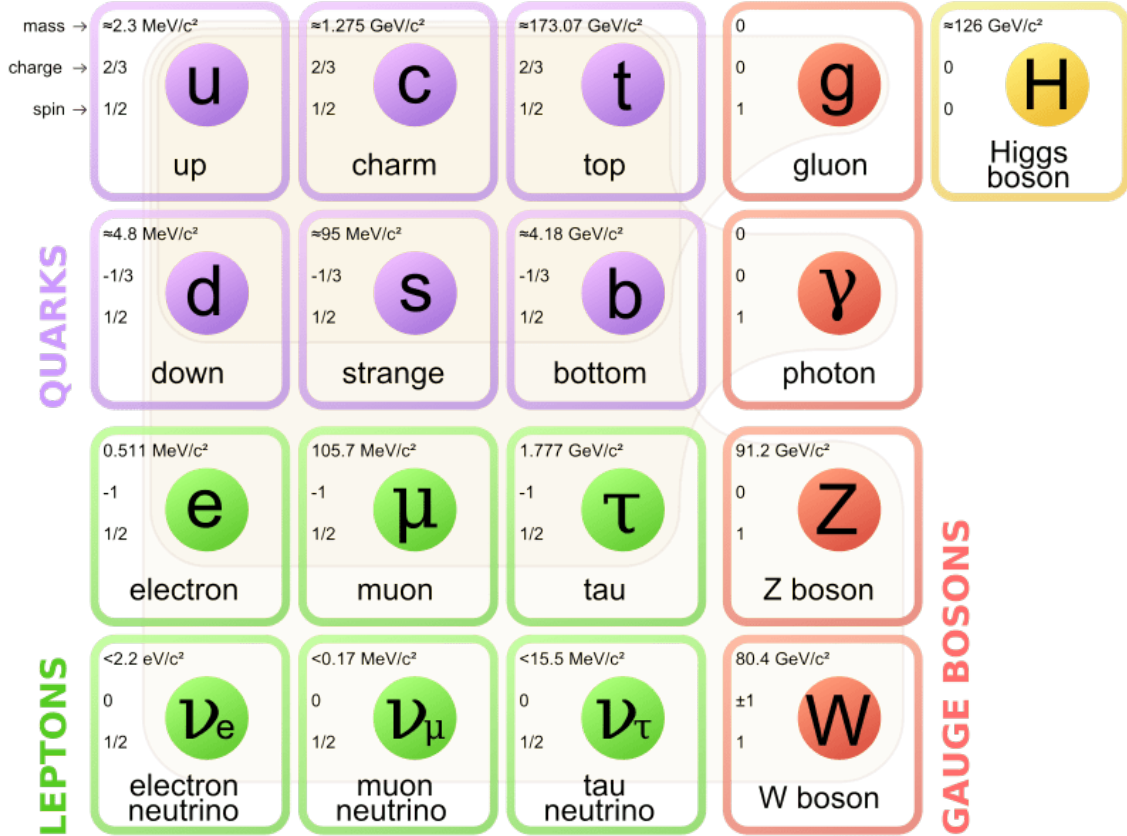


Figure 2.1.: The particles of the Standard Model include three families of quarks and leptons, four gauge bosons and the Higgs boson. The beige background indicates which bosons interact with which fermions. [14]

Figure 2.1 shows the fundamental particles of the standard model. It includes three families of quarks and leptons so-called *fermions*, four *gauge bosons* and the Higgs *boson*. Fermions and bosons differ by the spin. Spin is a degree of freedom, which had to be introduced to conserve the angular momentum in the Dirac equation. The matter forming fermions have a half-integral spin (in units of the reduced Planck constant \hbar) and the bosons (the exchange particles as well as the Higgs particle) have an integer spin. The fermion family can be sectioned into two families. The quark and the lepton family. The quark family consist of up- (u), down- (d), strange- (s), charm- (c), bottom- (b) and top- (t) quark. Quarks have fractional electric charge values. u-, c- and t-quark have an electric charge of $2/3e$ and d-, s- and b-quark have an electric charge of $-1/3e$. As indicated in figure 2.1 by the beige background, quarks can interact with all four gauge bosons. The lepton family is made of the electron

2.2. Physics Beyond The Standard Model

(e), the muon (μ) and the tau (τ) and their corresponding neutrinos ν_e, ν_μ and ν_τ . The neutrinos can only interact via the weak exchange particles (W^\pm and Z bosons). Since the electrons, muons and taus are charged, they can also interact with photons. All fermions also have so-called *antiparticles*. Antiparticle have the same mass as their corresponding particle but they have opposite charge. For example, the antiparticle of the electron is the positron. Both have the same mass and the same spin but the electron has an electric charge of $-1e$ and the positron has an electric charge of $+1e$. When a particle collides with its antiparticle annihilation can occur. In an annihilation process the incoming particles are destroyed to produce other particles. The final particles carry the same energy and momentum as the initial particles.

All visible matter in the universe is made of fermions from the first family. For example, atoms consist of protons and neutrons, each of which is a combination of up and down quarks. In the electron shell of an atom the eponymous electrons are located. Pauli proposed the neutrino in the 1930 to explain the energy spectrum of electrons in β -decays. Since neutrinos are only weak interacting particles, they were not observed until 1956.[23] With increasing energy, the second and third family have been gradually discovered, first from cosmic ray experiments in the 1930s up to the discovery of the Higgs boson at the LHC in 2012. Parallel to the experimental discoveries, the theory also evolved, partially explaining the results and in part motivating new experiments through predictions.

2.2. Physics Beyond The Standard Model

Despite the success of the standard model as an effective theory, it fails answering a lot of open questions. As already mentioned, the standard model only includes three out of four fundamental forces. It does not include gravity, therefore, the standard model is not valid at energy scales approaching the Planck energy $E_P \approx 1.22 \cdot 10^{19}$ GeV.[26] It is also unable to explain dark matter, dark energy and the matter/antimatter asymmetry in the universe which is directly linked to charged-parity violation.[15]

2.3. Bhabha Scattering

In this section we want to shortly discuss Bhabha scattering.

2.3.1. Bhabha Process

Bhabha scattering is a quantum electromechanical process between a particle and its antiparticle. It is named after the Indian physicist H. Bhabha.[24]

2. Theoretical Foundations

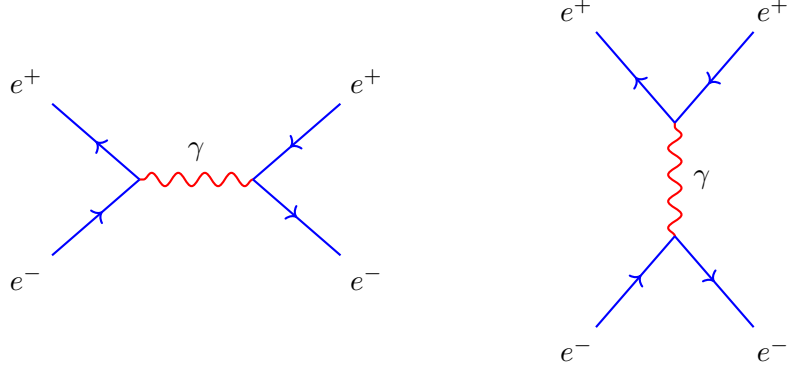


Figure 2.2.: The two Bhabha process feynman digrams.

$$\left(\frac{d\sigma}{d\Omega}\right)_{cms} = \frac{e^4}{64\pi^2 2E^2} \left(\frac{1 + \cos^2(\theta)}{2} + \frac{1 + \cos^4(\theta/2)}{\sin^4(\theta/2)} - \frac{2\cos^4(\theta/2)}{\sin^2(\theta/2)} \right) \quad (2.1)$$

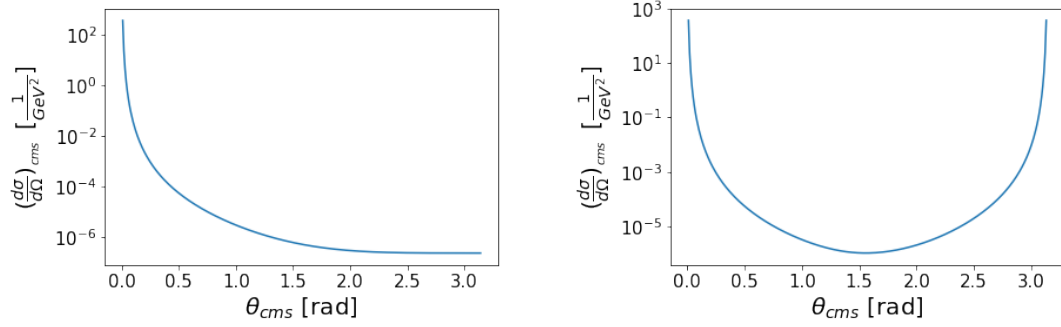


Figure 2.3.: Differential cross-section for Bhabha events. Left: Cross-section for **text**. These plots were created with python3.

2.3.2. Bhabha Kinematics At Belle II

2.3. Bhabha Scattering

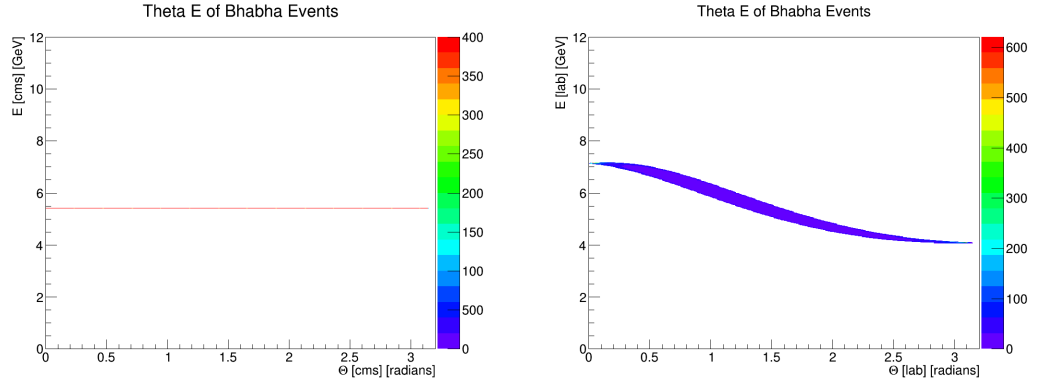


Figure 2.4.: Bhabha scattering in different frames. In the cms the particle has the same Belle II energy in every θ -direction. Left: The θ -Energy-distribution in the cms frame is shown. Right: The θ -Energy-distribution in the lab frame is shown.

3 Experimental Setup At SuperKEKB

SUPERKEKB is an two-ring, asymmetric¹, electron positron accelerator, which is located at KEK (*High Energy Accelerator Research Organization*) in Tsukuba Japan. The electron beam has an energy of 7 GeV and the positron beam has an energy of 4 GeV. These beams collide with a center-of-momentum energy of about 10.58 GeV, which is close to the mass of the $\Upsilon(4S)$ resonance. Therefore SuperKEKB is a so-called *B-factory*. The decay products are then detected by the Belle II detector to study the properties of these B mesons with high precision. In early 2018 Belle II started taking data. One goal of Belle II is to study CP-Violation with respect to new physics.[4]

3.1. KEKB And SuperKEKB

This section will only provide a rough overview of the SuperKEKB accelerator since the focus of this work is on the analysis.

SuperKEKB is an upgrade of the KEKB accelerator. KEKB was also an asymmetric electron positron accelerator in the period from 1998 to 2010, but the energies were different compared to SuperKEKB. At KEKB the electrons were accelerated to an energy of 8 GeV and the positrons to an energy of 3.5 GeV. KEKB was also a B-factory and the reaction products were then detected in the Belle detector. In 2009 KEKB achieved an instantaneous luminosity of $2.11 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. This was the world record at that time. KEKB was discontinued after more than 10 years, to be upgraded to SuperKEKB.[1]

In figure 3.1 you can see the schematic layout of the SuperKEKB accelerator. The electrons are start at the Low emittance gun. They are then accelerated in the *J*-shaped linear particle accelerator (linac). Due to lack of space, the linac has to have this special form.[3] After the curve and a second acceleration stage the electrons hit the positron production target, where the positrons are created. After this target there are more acceleration stages, before the two beam are then injected into their independent storage rings. The electrons are stored in the high-energy ring (HER)

¹asymmetric means that there is an energy difference between the two colliding beams

3. Experimental Setup At SuperKEKB

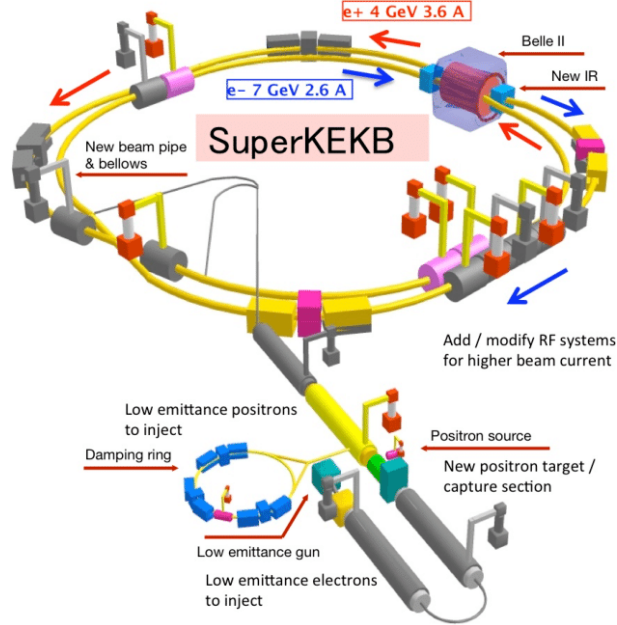


Figure 3.1.: The SuperKEKB collider.[11]

and the positrons are stored in the low-energy ring (LER). Each of these rings has a circumference of about 3 km. Both beams collide at the interaction region (IR). The products of the collisions are then detected by the Belle II detector, an upgraded version of the Belle detector.[4] (See chapter 3.2)

SuperKEKB uses a smaller asymmetry in the beam energies compared to KEKB. This allows the usage for higher beam currents and better focusing magnets. This can then result into a higher luminosity. The goal is to achieve a 40 times higher luminosity with SuperKEKB compared to KEKB. An integrated luminosity of 50 ab^{-1} will be achieved by 2025.[4]

The instantaneous luminosity \mathcal{L} specifies the performance of the collider. Knowing \mathcal{L} and the cross section σ one can calculate the events per second for a process by the following formula.

$$\frac{dN}{dt} = \mathcal{L} \cdot \sigma \quad (3.1)$$

To increase the event rate one has to increase the instantaneous luminosity since σ is given by the processes. The instantaneous luminosity can be calculate by

$$\mathcal{L} = \frac{N_{e-} N_{e+} f_c}{4\pi\sigma_x\sigma_y} \cdot S \quad (3.2)$$

assuming that both beams have a Gaussian profile of horizontal and vertical size σ_x and σ_y . In equation 3.2 N_{e-} is the number of particles in an electron bunch and N_{e+} is the number of particles in a positron bunch. f_c is the average crossing rate, which

3.2. The Belle II Detector

can be calculated by $f_c = n \cdot f_r$. Where n is the number of bunches and f_r is the revolution frequency. S is a reduction factor which takes geometrical effects linked to the finite cross section and bunch length into account.[17] SuperKEKB increased the luminosity by a factor of two compared to KEKB by increasing the number of bunches and the number of particles per bunch.

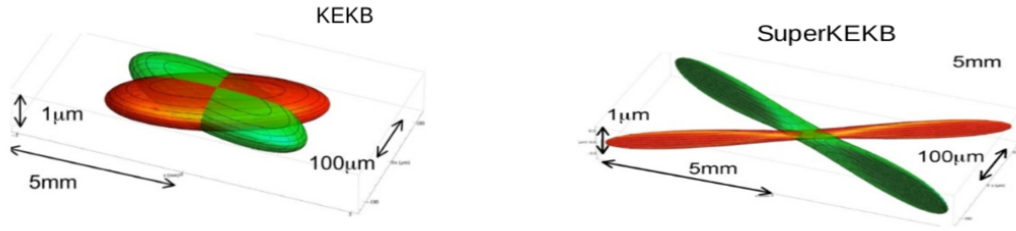


Figure 3.2.: Sketch of the beam crossing at KEKB (left) and SuperKEKB (right). At KEKB the size of the interaction region was about 10 mm. At SuperKEKB it is about 0.5 mm

Also the size of the interaction region at SuperKEKB is just one twentieth of what it was at KEKB, resulting in a vertical beam size of $\sigma \approx 50$ nm. This can be seen in figure 3.2. This decrease in beam size, along with the increase in the beam currents, it results in a overall 40-fold increase in luminosity. [2] [4]

3.2. The Belle II Detector

The Belle II detector is an upgraded version of the Belle detector which was a solid-angle magnetic spectrometer located at the interaction region of KEK. In figure 3.3 a sketch of the Belle II detector is shown. The detector contains of a variety of sub-detectors, each fulfilling a specific purpose.

In the innermost of the detector, three tracking sub-detectors are located, surrounding the IR. These sub-detectors are in a axial magnetic field of 1.5 T, provided by a solenoid, to be able to reconstruct the tracks of charged particles.

The vertex detectors, consisting of the silicon vertex detector (SVD), an upgraded version of the SVD used in Belle, and the pixel detector (PXD), a new detector designed for Belle II, are used to measure the momenta of charged particles and to reconstruct decay vertices and particles with a momentum too low to reach the central drift chamber (CDC).

The CDC also already existed in the Belle detector and has been upgraded for Belle II. The CDC scans the trajectories of charged particles. From these trajectories the charge, momentum and energy loss can be determined by ionization.

These three innermost tracking detectors are surrounded by a barrel. The time-of-propagation (TOP) detector, which also got an upgrade for Belle II, surrounds the inner detectors parallel to the beam-pipes. The TOP detector, as the name suggests,

3. Experimental Setup At SuperKEKB

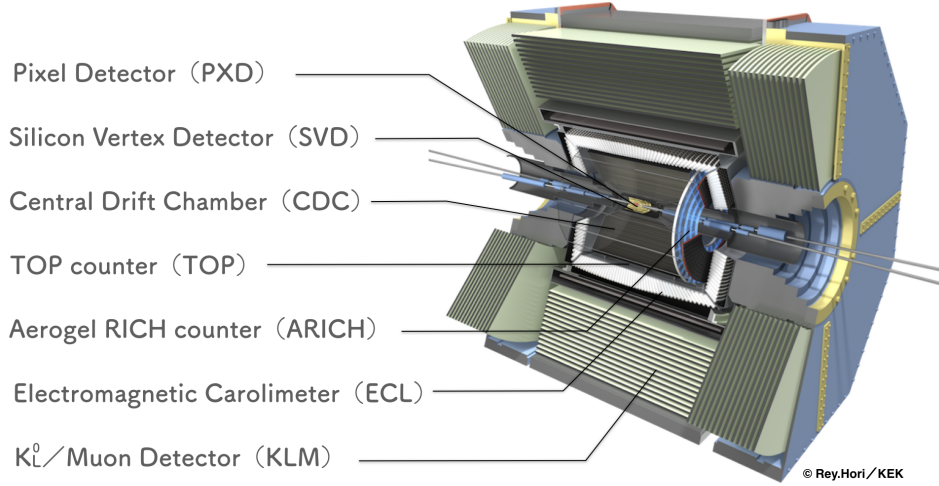


Figure 3.3.: Schematic view of the Belle II detector. The different detector elements are labeled. Also the beam pipes for the electrons and positrons with their corresponding energies are shown. [13]

measures the flight-time of charged particles. Knowing the flight-time and the momentum of the charged particles, it is possible to conclude their mass and to identify them. In the forward end-cap of the barrel are closed with an Aerogel Ring-Imaging Cerenkov detector (ARICH) which also identifies charged particles.

The next outer detector is the electromagnetic calorimeter (ECL). It surrounds all the previously mentioned detectors, and was already installed in Belle. With the ECL the energy of electromagnetically interacting particles, especially photons and electrons, can be measured.

The task of the outermost detector the K_L^0 and muon detector (KLM) is to identify K_L^0 and muons. The KLM also got upgraded for Belle II. [4]

3.3. Coordinate System

For clarification, I want to explain the coordinate system of Belle II, before I describe to the detectors in more detail.

A sketch of the coordinate system is shown in figure 3.4. The origin of the coordinate system corresponds to the interaction region. For the Cartesian coordinate system: The z -axis points in the direction of the magnetic field. This is also the so-called forward direction. The y -axis points up to the upper part of the detector. The x -axis points along the radial direction of the accelerator. In figure 3.4 also the spherical coordinate system is shown. Here θ corresponds to the polar angle and ϕ to the azimuthal angle.[25]

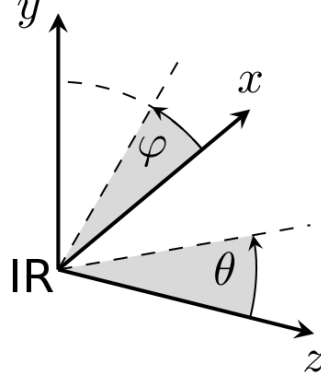


Figure 3.4.: A sketch of the coordinate system of Belle II

3.4. Vertex detector

The vertex detectors (VXD) is able to make precise measurements of the tracks of particles close to the interaction region. This allows the reconstruction of decay-vertices of long-lived particles. For this it is very important to determine the distance and the spatial resolution of the first measured hit, and the effect of multiple scattering. The VXD consists of the pixel vertex detector and the silicon vertex detector, both can be seen in figure 3.5. These two detectors complement each other.

3.4.1. Pixel Vertex Detector

The purpose of the PXD is to reconstruct the spatial position of the decay vertices of B , D and τ . The PXD is based on Depleted P-channel Field-Effect Transistor (DePFET) technology. This technology allows the sensors of the PXD to be very thin ($50\text{ }\mu\text{m}$).

As you can see in figure 3.6, the PXD consists of two layers of sensors. The inner layer is made out of eight planar sensors (ladder), each has a width of 15 mm and an effective length of 90 mm. This layer has a radius of 14 mm. The second layer consists of 12 planar sensors. These sensors also have a width of 15 mm, but a length of 123 mm. The radius for the second layer is 22 mm. The PXD provides a spatial resolution of about $1.2\text{ }\mu\text{m}$. [2]

Due to the vicinity of the PXD to the interaction region, the quantum-electrodynamics background is very high, so the sensors must withstand high radiation. The DePFET technology fulfills this condition. [2] [20]

DePFET is a semiconductor detector concept invented in 1987 by J. Kemmer and G. Lutz of the MPI for Physics. This concepts combines detection and amplification in one single device. [2]

3. Experimental Setup At SuperKEKB

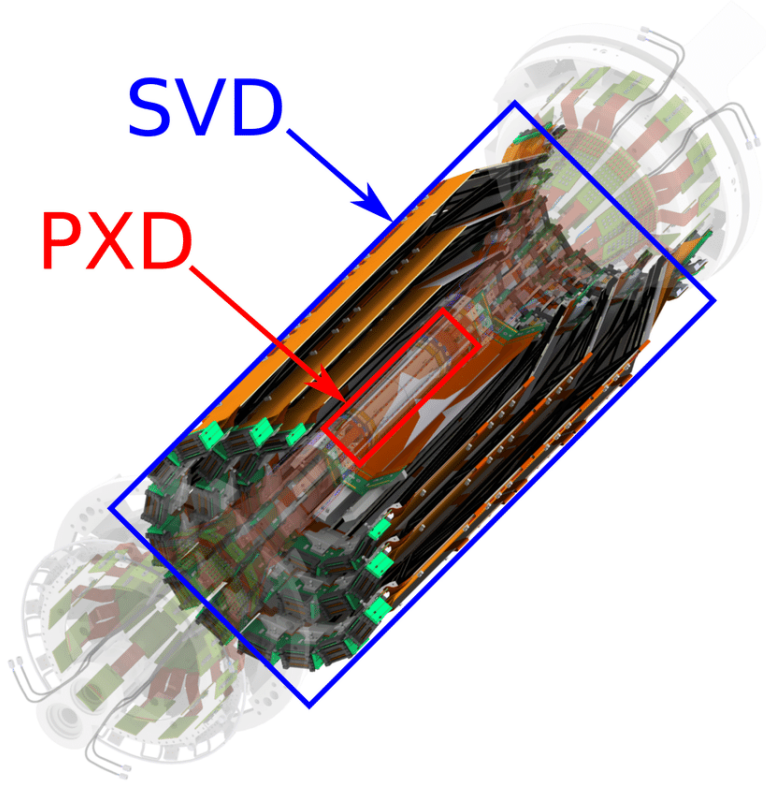


Figure 3.5.: Sketch of the vertex detectors. The vertex detector itself consists of two sub-detectors. The PXD is surrounded by the SVD. [5]

A cross section of the device is shown in figure 3.7. The structure of a DePFET cell consists of fully depleted silicon. In this silicon substrate depleted by a high negative voltage a p -channel MOSFET (metal oxide semiconductor field effect transistor) or a JFET (junction field effect transistor) is integrated. The field effect transistors act as a first pre-intensification. When radiation or a particle hits the detector, electron-hole pairs are created. These pairs get separated by the potential field of the sidewall depletion. The positive charged holes drift to the negatively charged back contact. The negative charged electrons are collected in the potential minimum. The so-called internal gate. Above the internal gate a field emission transistor is located. The signal charge is amplified right above the position where it was generated. This avoids the leakage of lateral charge transfers. One of the most important main features of the DePFET is that the internal gate has a very small capacitance. This makes it possible to measure events affected by low noise even at room temperature.[2]

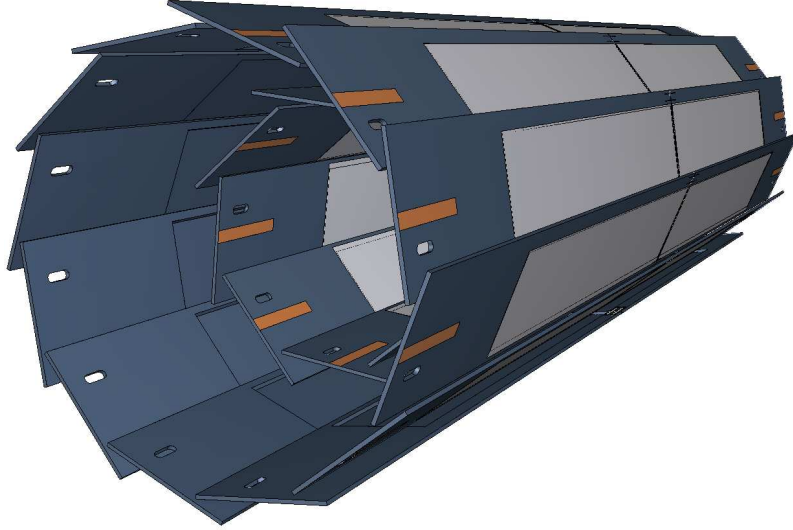


Figure 3.6.: Sketch of the PXD [2]

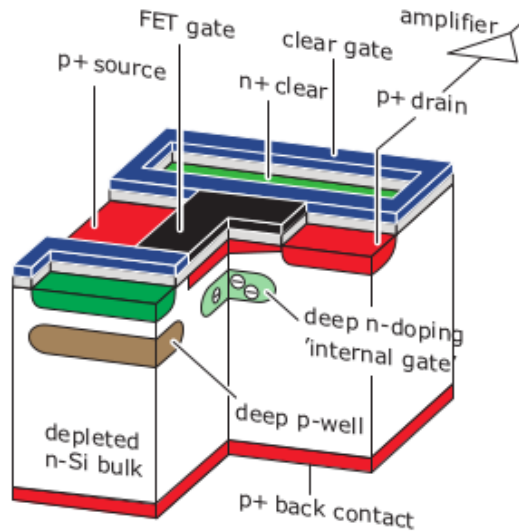


Figure 3.7.: Illustration of the DePFET technology.[2]

3.4.2. Silicon Vertex Detector

The SVD consists of four layers of double-sided strip detectors. The layers are located at radii of 38, 80, 115 and 140 mm. There are two different shapes of these sensors. The rectangular sensors are used in the barrel part and the trapezoidal sensors are used in the forward region of the SVD. Each sensor has a thickness of $320\ \mu\text{m}$ but the sensors have different dimensions depending on the layer they are located. The barrel

3. Experimental Setup At SuperKEKB

sensors in the most inner layer of the SVD have a dimension of $38.4 \times 122.8 \text{ mm}^2$. The size for the barrel sensors of the other layers is $57.6 \times 122.8 \text{ mm}^2$. The trapezoidal sensors have a dimension of 38.4 mm on the small side of the trapez to 57.6 mm on the long side of the trapez times a length of 122.8 mm.[2] An illustration of the SVD can be seen in figure 3.8.

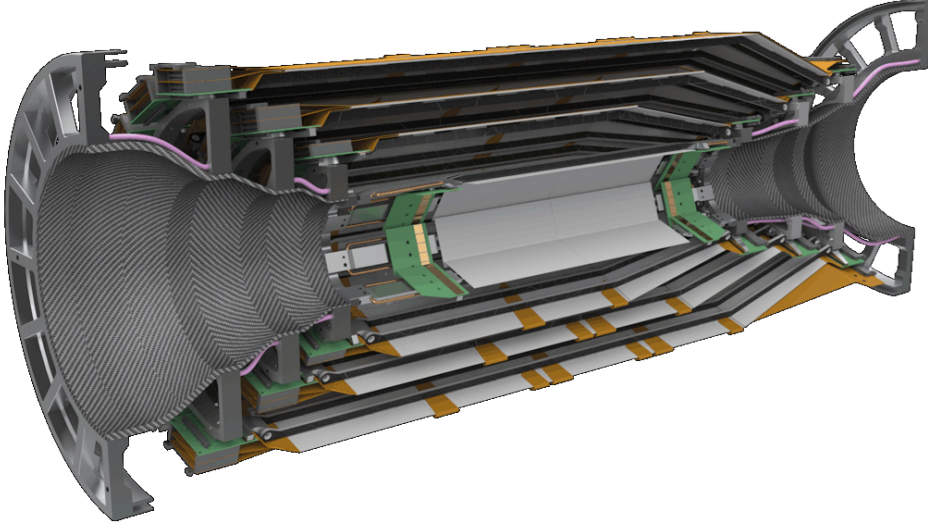


Figure 3.8.: Cross section of the silicon vertex detector[10]

In the barrel region the p -side of the double-sided-strip sensors is arranged parallel to the beam axis and facing the interaction region. The n -side is facing outside the detector and the n -strips are perpendicular arranged to the beam axis.

When a particles travels through the sensors it creates electron-holes pairs along its path by ionization. The electrons then propagate to the n -strips and are accumulated there. The holes propagate to the p -strips and are collected there. The sensors then produce a signal from which the coordinate of the particle position can be read out. The p -side provides the z -direction and the n -side provides the $r - \theta$ direction.[2] [8]

3.5. Central Drift Chamber

The CDC surrounds the SVD. It consists of 14,336 wires arranged in 56 layers and has an inner radius of 16 cm and an outer radius of 113 cm. The volume is filled with a 50 % helium and an 50 % ethane gas mixture. The purpose of the CDC is to reconstruct the momenta and tracks of charged particles, to identify these particles by measuring their specific energy loss within the gas volume. The CDC alone is able to identify low-momentum tracks, which are unable to reach the particle identification device. The CDC also acts as a reliable trigger for charged particles.[2] A small cross section of the CDC is shown in figure 3.9.

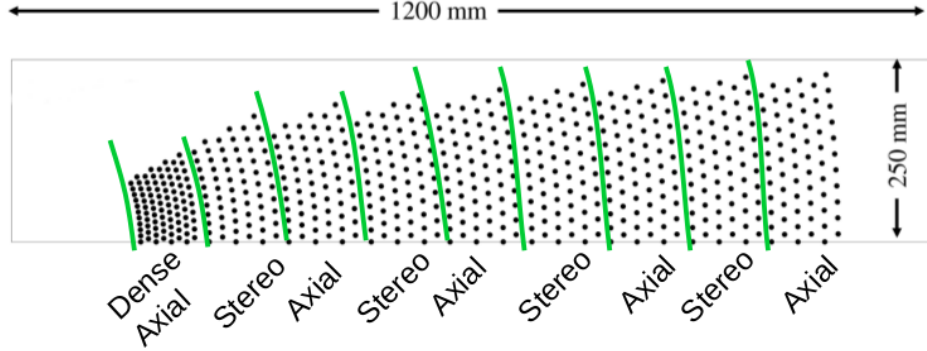


Figure 3.9.: Cross section and only a small part of the CDC. Each dot represent a wire. Also the area for the different superlayers is shown by the green line. All of these wires are immersed in a helium-ethane mixture.[16]

When a charged particle passes through the CDC it loses energy due to ionization of the gas. This produces electron-ion pairs, which are then separated by the electric field provided by 42,240 aluminum field wires, with a diameter of $125\text{ }\mu\text{m}$. The signal is then read out by the sense wires. These have a radius of $30\text{ }\mu\text{m}$ and are made out of gold-plated tungsten.[2]

As indicated in figure 3.9 there are different superlayers in the CDC. The Dense Axial and Axial sense wires allow the reconstruction of the track in the $r - \phi$ plane. The stereo sense wires give information about the z direction. These stereo wires are tilted in respect to the z direction. Six layers of sense wires are combined to a superlayer. The CDC consists of five axial superlayers (A), and four stereo superlayers. The four stereo superlayers subdivide into two stereo superlayers (U) with a positive stereo angle and two stereo superlayers (V) with a negative stereo angle. Starting with the innermost superlayer, every second superlayer is an axial superlayer. The stereo superlayers are between them, alternating between U and V. In total there are nine superlayers. The innermost superlayer is called *small-cell chamber* has a total of eight superlayers. (compared to the other superlayers with just six layers) This was done to lower the influence of the background, which is higher in the innermost superlayer due to the vicinity to the interaction region. The CDC has a spatial resolution of about $100\text{ }\mu\text{m}$. [2]

3.6. TOP And ARICH

There are two additional detectors for particle identification, the TOP and the ARICH. The TOP counter is located in the barrel part and it uses a combination of time-of-flight and Cerenkov angle measurements. When a charged particle with the velocity β is faster than the speed of light c_n in a medium with a refractive index n then this particle emits Cerenkov radiation under the angle θ_C . [9]

3. Experimental Setup At SuperKEKB

$$c_n = \frac{c_0}{n} \leq \beta \quad (3.3)$$

The Cerenkov angle is given by:[9]

$$\cos(\theta_C) = \frac{1}{n\beta} \quad (3.4)$$

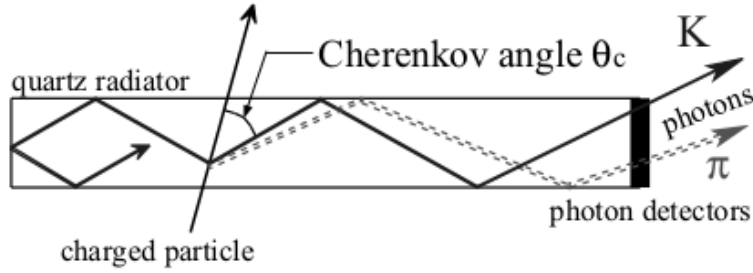


Figure 3.10.: Operating mode of a TOP detector.[2]

Figure 3.10 shows an illustration of the functionality of a TOP bar. The charged particle emits Cerenkov light when it passes the quartz crystal. These photons then travel inside the crystal due to reflection until they are detected by a photon detector. Measuring the time difference between the emitted photons it is possible to calculate the position of the track of the charged particle. The outgoing photons are then focused by mirrors and are then detected by PMTs. Cerenkov photons with different θ_C will be detected by different PMTs. Therefore, the TOP reconstructs the Cerenkov ring image using the information of time, x and y . [2]

The TOP counter consists of 32 quartz bars. They have a length of 1,250 mm, a width of 45 mm and a depth of 20 mm. There are two quartz bars per module. The TOP counter has a K/π separation of over 99 %. [2]

The ARICH detector is located in the forward endcap region. It is designed to distinguish between kaons and pions over most of their momentum spectrum. It is also able to identify particles with a momentum below 1 GeV.

In figure 3.11 the working principle of the ARICH detector is shown. A charged particle passes through two layers of an aerogel radiator with different refractive indexes and emits Cerenkov photons under an Cerenkov angle θ_C . Behind the radiator is an extension volume for the Cerenkov rings to form. At a distance of 20 cm behind the radiator is the photon detector. [2] Once the Cerenkov ring is reconstructed, the radius of the ring can be determined and, knowing the distance and the radius, the Cerenkov angle can be calculated.

3.7. Electromagnetic Calorimeter

One of the main tasks of the ECL is the detection of photons with a high efficiency. It also determines the energy and the angular coordinates of these photons with high

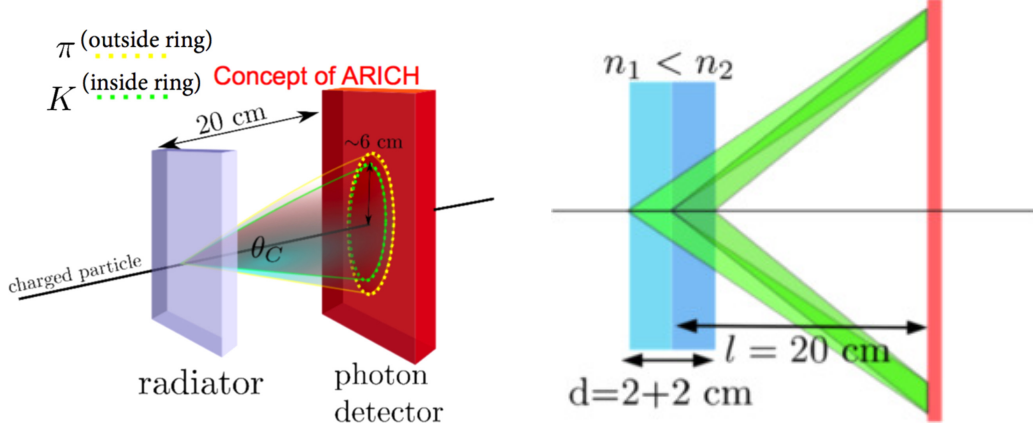


Figure 3.11.: Left: Illustration of the working principle of the ARICH detector. The yellow Cerenkov ring on the photon detector is produced by a π , the green ring by a K . Right: The radiator is shown in more detail. The radiator consists of two aerogel layers with different reflective index. [27]

precision. It is also used for electron identification and the generation of a proper signal for the trigger. The ECL consists of a 3 m long barrel section with an inner radius of 1.25 m. The circular endcaps are located at a distance of $z = 1.96$ m in the forward direction and $z = -1.02$ m in the backward direction from the interaction point. The ECL covers a polar angle region of $12.4^\circ < \theta < 155.1^\circ$. Due to construction, there are two $\sim 1^\circ$ wide gaps between the barrel and the endcaps. The barrel section of the calorimeter consists of 6,624 CsI(Tl)² crystals with 29 distinct shapes. Each of these crystals is a truncated pyramid with an average size of about $6 \times 6 \text{ cm}^2$ in cross section and 30 cm in length. The length of these crystals corresponds to around 16.1 radiation lengths X_0 . The endcaps consist of 2,122 CsI crystals of 69 shapes. At the end of each crystal, photo-multiplier are mounted to detect the excitation of the scintillators. The detected number of photons corresponds directly to the energy released by absorbed particles. The energy resolution of the calorimeter can be approximated as:[2] [7]

$$\frac{\sigma_E}{E} = \sqrt{\left(\frac{0.066\%}{E}\right)^2 + \left(\frac{0.81\%}{\sqrt[4]{E}}\right)^2 + (1.34\%)^2} \quad (3.5)$$

The energy E is in GeV.

Photons and electromagnetic particles are creating electromagnetic cascades when they pass through material.[18] When a high energetic photon passes through a material it creates an electron-positron pair by pair production. For this, the photon must have at least an energy of $2 \cdot m_{e^-} = 1.022 \text{ MeV}$. This energy is evenly distributed between the two particles. Because these two particles are charged and their

²Thallium activated Cesium Iodide

3. Experimental Setup At SuperKEKB

velocity changes in an the electric field of a nuclei, they generate photons through Bremsstrahlung. These processes are repeated and a electromagnetic shower is created. The energies of the particles continue to decrease until the critical energy E_c is reached. At the critical energy, the energy loss due to Bremsstrahlung is as high as the energy loss due to ionization.

If the average energy of an electron becomes E_0/e then the distance the electron traveled is called radiation length X_0 .

Assuming that the electromagnetic particles and photons interact after one radiation length and that they loose half of their energy each time they do, the total number of particles and their energy after t cascades can then be calculated by:[18]

$$N \simeq 2^t \quad (3.6)$$

$$E(t) \simeq \frac{E_0}{2^t} \quad (3.7)$$

This shower both spreads longitudinally and transversely. The transverse propagation can be described by the Molière radius. It can be calculated by:

$$R_M = 21 \text{ MeV} \cdot \frac{X_0}{E_c} \quad (3.8)$$

95 % of all particles of a shower are within two Molière radii.[18]

3.8. K_L^0 And Muon Detector

The KLM consists of an alternating sandwich structure of a 4.7 cm thick iron plates and resistive plate chambers (RPC) in between.

RPCs consist of two glass sheets, separated by a thin gas volume. These sheets act as high voltage electrodes. When a particle passes through the volume, they create ion-electron pairs which are then accelerated by the strong electric field. They therefore initiate more ionizations, which leads to a streamer between the electrodes. This causes a voltage drop in the nearby electrodes, which is detected by pick-up strips, located on both sides of the chamber. These strips are a few centimeters wide and are placed orthogonal on each side. Therefore, the particle track can be localized in z/ϕ for the barrel region and ϕ/θ for the endcaps.

To distinguish between muons and hadrons, the KLM takes advantage of the high penetration power of muons. Hadrons deplete their energy through hadronic showers in the ECL and KLM. Electrons have a shorter radiation length and are therefore absorbed by the ECL, most of the time. K_L^0 create clusters in the ECL and the KLM. These clusters are than grouped and geometrically matched to charged tracks which are detected by the inner detectors. If no corresponding charged track can be found by geometrical matching, the detected particle is then treated as a K_L^0 candidate.[2][6]

CHAPTER

4

Trigger And Data Acquisition System

THIS chapter will give a short introduction on the three most important tools that were used in this thesis: Root, Basf2 and GridKa.

5.1. Root

Entsprechend kann es bei einer theoretischen Arbeit sinnvoll sein, die Lösungsmethoden in einem eigenen Kapitel zu beschreiben.

5.2. Basf2

Hauptteil Ihrer Arbeit ist das Kapitel (oder die Kapitel) mit den Ergebnissen. Bei einer theoretischen Arbeit kann damit auch die Herleitung von Formeln oder die Beschreibung eines Computerprogramms gemeint sein.

5.3. GridKa

IN this chapter the tracking efficiency studies will be presented. We will start with a definition of the tracking efficiency we want to calculate. Then the reconstruction and selection of the Bhabha events will be described. Finally the tracking efficiency for MC and for beamtime data will be calculated.

6.1. Definition Of Tracking Efficiency

First of all, a definition of efficiency has to be declared, since there are different ways to define a tracking efficiency. The physics case we are considering is Bhabha events $e^+e^- \rightarrow e^+e^-$. As described in chapter 3, charged particles leave a track in the detector. So, when we look at an outgoing particle with a track, then we know that the other particle should also have a track. If the other particle has no charge, then this is an inefficiency. If both particles have a track associated, then this is the efficient case.

So for this work we will use the following definition for the tracking efficiency:

$$\epsilon = \frac{\text{Number of Bhabha events with exactly reconstructed 2 tracks}}{\text{Number of Bhabha events with 1 or more reconstructed tracks}} \quad (6.1)$$

6.2. Reconstructing Bhabha Events With Basf2

To analyze a Monte Carlo/data file, a python script using Basf2 has to be written. The following code is a simplified version of the steering file I wrote. The goal of this steering file is to reconstruct the virtual photon in a Bhabha event. This virtual photon decays into two daughters which hit the ECL. Since we want to calculate the tracking efficiency. We need to be able to reconstruct the virtual photon from two daughters both associated with an track, and two daughters one associated with a track (reconstructed as a charged particle by the framework) and one with no track associated (reconstructed as a photon by the framework).

The same steering file is used for data, MC and MC on GridKa.

```
1 fillParticleList('gamma:all', 'clusterE > 0.01', path=mypath)
```

6. Tracking Efficiencies

```

3 fillParticleList('e+:all', 'clusterE > 0.01', path=mypath)
reconstructDecay('vpho:gamma -> gamma:all', '', path=mypath)
5 reconstructDecay('vpho:elec -> e+:all', '', path=mypath)

7 copyLists(outputListName = 'vpho:ECLObjectUnranked' ,inputListNames=['vpho:
  ↳ elec', 'vpho:gamma'], path=mypath)

9 rankByHighest('vpho:ECLObjectUnranked', 'daughter(0,clusterE)', path=mypath)
cutAndCopyList('vpho:ECLObject', 'vpho:ECLObjectUnranked', '', path=mypath)
11 reconstructDecay('vpho:bhabha -> vpho:ECLObject vpho:ECLObject', '', path=
  ↳ mypath)
13 variablesToNtuple('vpho:bhabha', var_vpho, treename = 'vpho_bhabha', filename
  ↳ = outputname, path=mypath)

```

In the first line of code all particles which hit the ECL and have no track associated are filled into a gamma list called `gamma:all`. The clusters created by those particles must have an energy (clusterE) of at least 0.01 GeV. In the second line a list called `e+:all` is created. All particles with an associated track are filled in this list independently of their charge. Therefore, this list contains for example electrons, positrons and even muons. Again, a cut is applied to the cluster energy.

Due to the fact, that we want to calculate the efficiency of the tracking, we need to somehow combine the `e+:all` and the `gamma:all` lists. As mentioned earlier, we need to be able to reconstruct the virtual photon from particles reconstructed as electrons/positrons and photons. Unfortunately, the Basf2 framework prevents a combination of two different particle lists, like `e+:all` and `gamma:all`. Therefore, we need to use a trick. This is shown in lines four and five. In line four, we tell the framework that the reconstructed gamma is the only daughter of a virtual photon called `vpho:gamma`. The same is done for the electron list. Here, the virtual photon is called `vpho:elec`.

Now, these two lists can be combined to one list called `vpho:ECLObjectUnranked`. This is done in line seven.

In line nine and ten the daughters in the `vpho:ECLObjectUnranked` list are sorted by their cluster energy and filled in a list called `vpho:ECLObject`.

In line twelve, a virtual photon of the bhabha event is reconstructed from the ECL objects in the `vpho:ECLObject` list. The number of reconstructed virtual photon candidates per event n_{cand} is determined by the following equation[22]:

$$n_{\text{cand}} = \frac{n_p(n_p + 1)}{2} \quad (6.2)$$

n_p is the number of reconstructed particles per event. Equation 6.2 is also known as the equation to calculate *triangular numbers*. For example, if four ECL particles are reconstructed in a single event then ten virtual photon candidates are reconstructed

6.3. Selecting Bhabha Events On Monte Carlo

according to equation 6.2. Since we only expect one virtual Bhabha photon per event, we have to select the best candidate in each event. This will be done in section 6.3. Since the entries in the `vpho:ECLObject` list are sorted by energy, the first daughter of the reconstructed virtual bhabha photon always has a higher energy than the second daughter. I will refer to the first daughter as `tag` and the second daughter as `probe`. You can see that the `tag` daughter has always a higher energy than the `probe` daughter in figure A.1. Here the `clusterE(probe)` is subtracted from the `clusterE(tag)` and only positive values remain. Therefore, `tag` is the daughter with the higher energy. Finally, in the last line of code, all variables of the candidates like mass, momentum, cluster energy of each daughter, does the daughter have a track and so on are written in a tree `vpho_bhabha` in a file. The `outputname` of the output file depends on whether the steering file is running on data or MC.

6.3. Selecting Bhabha Events On Monte Carlo

We use Monte Carlo simulation due to the fact that on MC we know everything about the generated and reconstructed particles. So on MC we can select Bhabha events which hit the ECL and with this knowledge we can introduce cuts in such a way that we only reconstruct these Bhabha events. To calculate an efficiency it is extremely important to select only Bhabha events. At first, we are also running on only one $e^+e^- \rightarrow e^+e^-$ MC file which is located at:

```
/belle/MC/release-02-00-01/DB00000411/MC11/prod00006731/s00/e1002/4S/  
r00000/3600520000/mdst/sub00/mdst_000278_prod00006731_task10010000499.root
```

The generated file is located at:

```
/home/belle2/msobotzi/bhabha/bhabha_vpho_mc.root
```

6.3.1. ECL-Cut

Due to the fact that we can verify a Bhabha event with only ECL informations and we are therefore only interested in events which hit the ECL, we apply a θ -cut on the generated daughters (generated daughters means the true generated Monte Carlo daughters).

$$0.296706 < \theta_{tag,probe} < 2.617990 \quad (6.3)$$

All the events which survive this cut are written into a list (`mcEvtECL`). We know that the file Monte Carlo file contains 140,000 generated Bhabha events. After this cut, only 24,286 Bhabha events remain. In section 2.3.1, we saw that Bhabha events have a very high cross-section in the endcap direction. So we expect that most of the generated daughters are not hitting the ECL.

6. Tracking Efficiencies

Now we will take a look at the reconstructed Monte Carlo events. All of these reconstructed events have to appear in the mcEvtECL list because we know that only in these events both daughters are hitting the ECL. A total of 24,100 events have at least one reconstructed candidate.

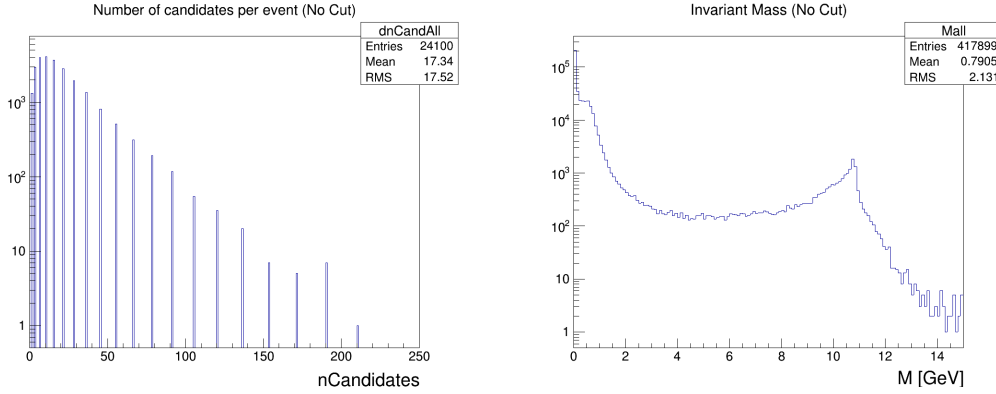


Figure 6.1.: Left: The number of reconstructed candidates per event is shown.
Right: The invariant mass of the reconstructed candidates is shown.

In figure 6.1 on the left, we see the number of reconstructed candidates per event. Since we do not have a cut on the reconstruction, the number of reconstructed candidates n_{cand} follows equation 6.2. On the right, we see the invariant mass of the reconstructed candidates. Note that we are now looking at candidates and as we can see on the left we oftentimes have more than one candidate per event. Therefore the numbers of entries for the mass is way higher then for the number of candidates per event. Consequently, we need some cuts to select the best candidate in each event and thereby reduce the number of candidates per event to one.

6.3.2. Mass-Cut

The first cut to reduce the number of reconstructed candidates per event is a mass cut (The cut is called M). As we saw in figure 6.1 a lot of candidates are reconstructed with an low invariant mass and we know from section 2.3.1 that the mass of the reconstructed candidate should be the invariant mass of the collider. For Belle II this is around 10.58 GeV. Due to some acceptance for reconstruction error the mass cut is with an lower-cut of 8 GeV rather loose.

As you can see in figure 6.2 on the right, all reconstructed candidates with an invariant mass below 8 GeV are neglected. Therefore the number of candidates per event is reduced. We see this in the left plot. Unfortunately, sometimes we still have two candidates per event and consequently, we have to introduce some more additional cuts.

6.3. Selecting Bhabha Events On Monte Carlo

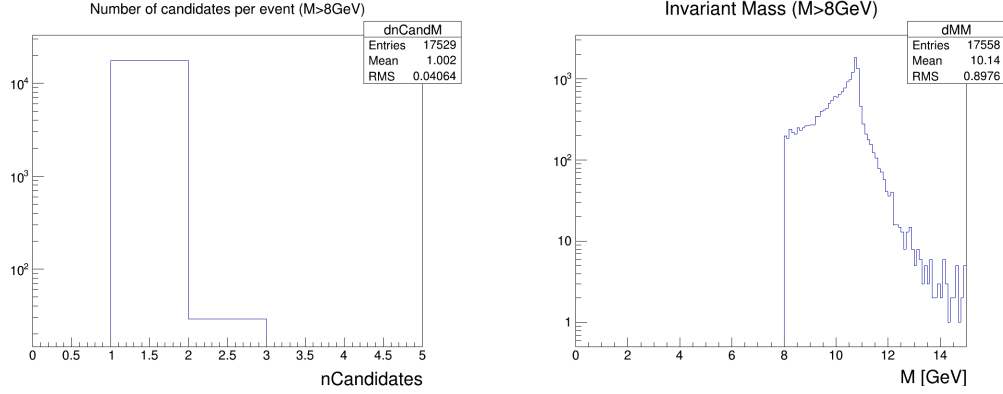


Figure 6.2.: A cut on the invariant mass is applied. The reconstructed invariant mass has to be bigger than 8 GeV. Left: The number of reconstructed candidates per event is shown. Right: The invariant mass of the reconstructed candidates is shown.

6.3.3. Additional Cuts

To reduce the number of candidates per event to one, some additional cuts are needed. Sometimes it can happen that two reconstructed particles are associated to one Monte Carlo particle. Some examples of this effect can be seen in table 6.1. As you can see, the Monte Carlo generated energy (mcE) for both tag and probe is the same and the reconstructed energy (E) of the tag and the probe particle sum up roughly to their respectively mcE. You can also see that the generated particle is always a electron/positron and that the *additionally* reconstructed particle is always a photon.

Table 6.1.: Some examples for events with cluster splitting. The energies are in GeV.

Event Number	tag				probe			
	E	mcE	PDG	mcPDG	E	mcE	PDG	mcPDG
41890065	0.9432	4.1278	11	11	3.1900	4.1278	22	-11
41890118	1.5993	4.3465	22	11	2.6462	4.3465	-11	-11
41890668	3.1758	6.8878	22	-11	3.1059	6.8878	11	11
41891214	2.3290	6.1585	22	-11	3.9079	6.1585	11	11
41892596	1.4193	4.2997	22	11	2.9673	4.2997	-11	-11

In figure A.2 you can see the angular distribution of this effect. For this plot there were no cuts on the reconstruction. It was just checked if exactly two reconstructed particles have the same generated Monte Carlo particle associated. Then the clusterPhi- and clusterTheta-values of these particles were filled into their histograms. On the left you can see that the both reconstructed particle have the same clusterTheta angle. On the right you can see that they have a slightly different clusterPhi angle. Therefore, the one *original* cluster is separated into two clusters with the same θ -angle and a different Φ -angle. One cluster is associated with a track produced by the generated

6. Tracking Efficiencies

particle and for the other cluster is no track left, therefore, it is labeled as a photon. I will refer to this effect as *cluster splitting*.

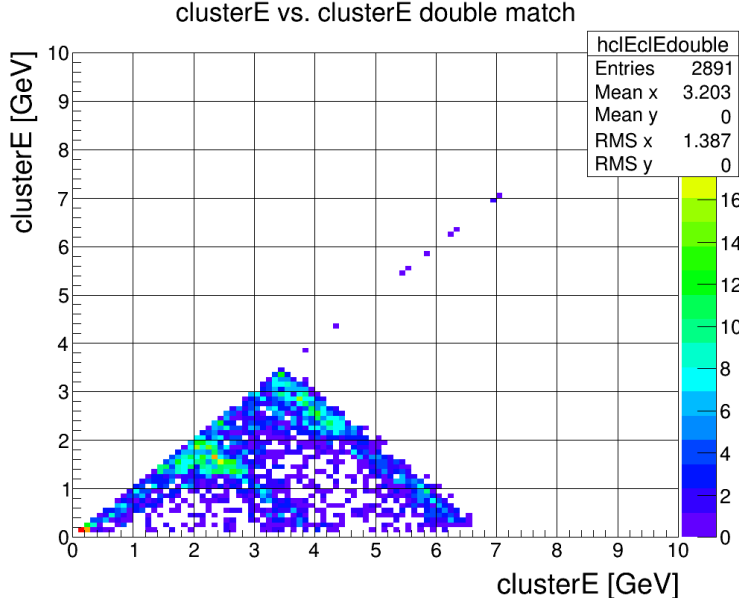


Figure 6.3.: Cluster Energy vs. Cluster Energy in the case that both particles are associated to the same Monte Carlo particle. Here, no cuts are applied.

In figure 6.3 you can see the energy of the particles in a cluster splitting process. Since we only want to select Bhabha events, we want to neglect these kinds of events. In section 2.3.2 we saw that the particles have an energy of at least 4 GeV. Therefore we are able to apply a cut on the cluster energy. We are now requiring a cluster energy of at least 3.5 GeV (The cut is called `Mc1E`). With this cut all events with cluster splitting should be neglected.

Next, we require that we have exactly two clusters per event, each with an energy of at least 3.5 GeV, since we only expect two high energetic particles in the ECL (The cut is called `Mc1E2H`).

As an additional safety net, a cut on the number of reconstructed tracks per event is applied. On data it can happen that there are way more than two tracks reconstructed per event. To select only *clean* events we apply a cut on the number of reconstructed particles per event (The cut is called `Mc1E2HnT`). This number should not be greater than six.

As you can see in table 6.2, sometimes the invariant mass of the reconstructed candidates is way bigger than 10.58 GeV. To neglect these candidates an upper cut on the reconstructed invariant mass is introduced. Now, the reconstructed invariant mass has to be smaller than 12 GeV.

Also, sometimes the total energy in the ECL is way higher than expected. To exclude these events an upper cut on the total energy per event in the ECL is added (The cut is called `Mc1E2HnTSumE`). The total energy in the ECL must not exceed 15 GeV.

6.3. Selecting Bhabha Events On Monte Carlo

Table 6.2.: Some examples for events with too much energy in the ECL.

Note: Here the energy of the particles is shown not clusterE.

Event	M	Energy(tag)	Energy(probe)	Total Energy ECL
41890917	30.6657	33.8368	7.2455	41.0823
26574414	108.4056	235.3918	13.0644	248.4563
21222871	11.6553	2.1733	15.6648	17.8381
26372406	10.3229	0.2465	190.2663	194.5971

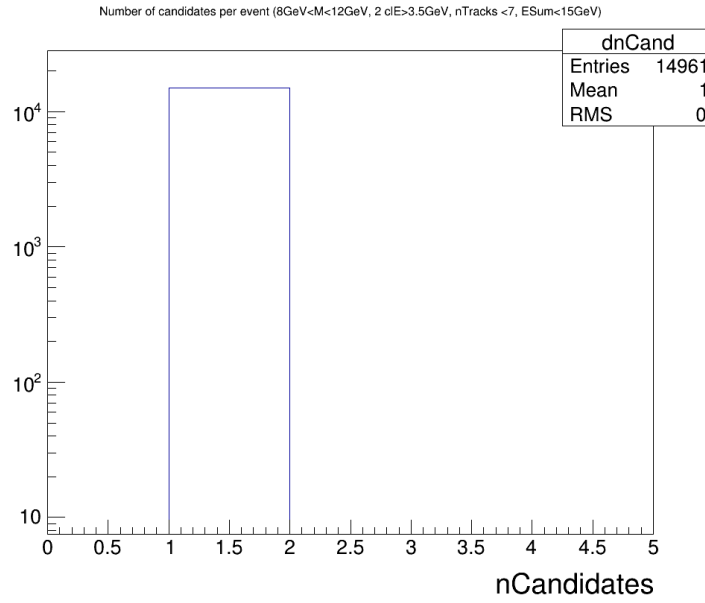


Figure 6.4.: Number of candidates per event after applying all cuts.

After applying all the cuts mentioned, the number of candidates per event is shown in figure 6.4. As you can see, now, we only select one candidate per event.

6.3.4. Cut Efficiency

In this section we want to discuss different efficiencies of the previously introduced cuts. We will take a look at the relative and the total efficiency. The results can be seen in table 6.3.

$$\epsilon_{\text{tot}} = \frac{n_{\text{cut}}}{n_{\text{total}}} \quad (6.4)$$

To calculate the total efficiency of a cut we have to use equation 6.4. Here the number of events after a cut n_{cut} is divided by the total number of events n_{total} before all cuts¹.

¹The cut that requires that the generated particles have to hit the ECL is still applied $\rightarrow n_{\text{total}} = 24,100$

6. Tracking Efficiencies

$$\epsilon_{\text{rel; Cut B}} = \frac{n_{\text{Cut B}}}{n_{\text{Cut A}}} \quad (6.5)$$

Equation 6.5 shows the equation used to calculate the relative efficiency. To calculate the efficiency of cut B we have to divide the number of events after cut B by the number of events after the previous cut A. The relative efficiency with no cut is defined as 1.

Table 6.3.: A table with the total number of events after the respective cuts. Also the relative and the total efficiency of these cuts is shown.

Cut	Number Of Events	Relative Efficiency	Total Efficiency
No Cut	24,100	1.0000	1.0000
M	17,529	0.7273	0.7273
Mc1E	15,330	0.8746	0.6361
Mc1E2H	15,320	0.9993	0.6357
Mc1E2HnT	15,320	1.0000	0.6357
Mc1E2HnTSumE	14,961	0.9766	0.6208

Table 6.3 shows the relative and total efficiency of the cuts. Describe the table

6.3.5. No MC-Truth Information

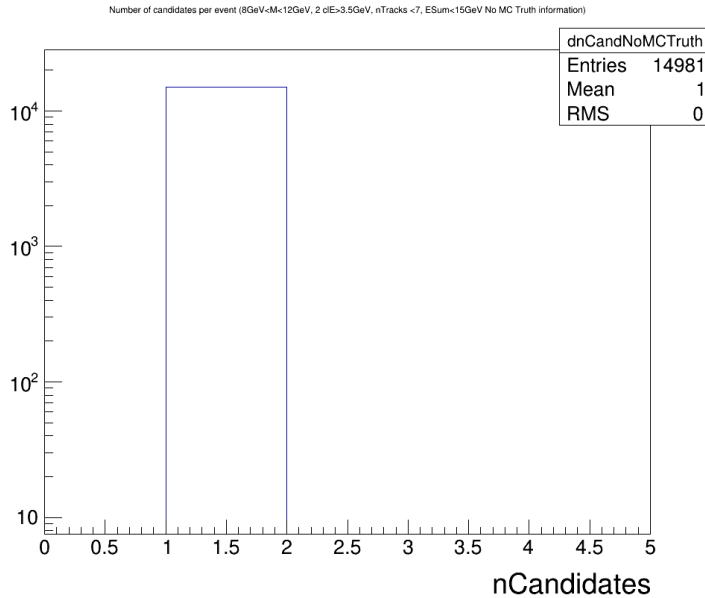


Figure 6.5.: Number of candidates per events with no MC-Truth information. Same MC file as before.

6.4. Selecting Bhabha Events on Beamtime Data

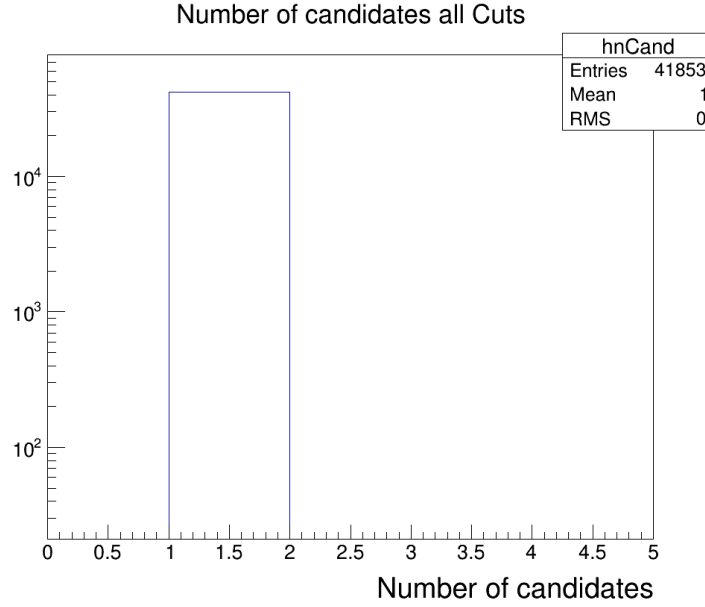


Figure 6.6.: Number of candidates per event for beamtime data.

6.5. Selecting Electron-Positron Pairs

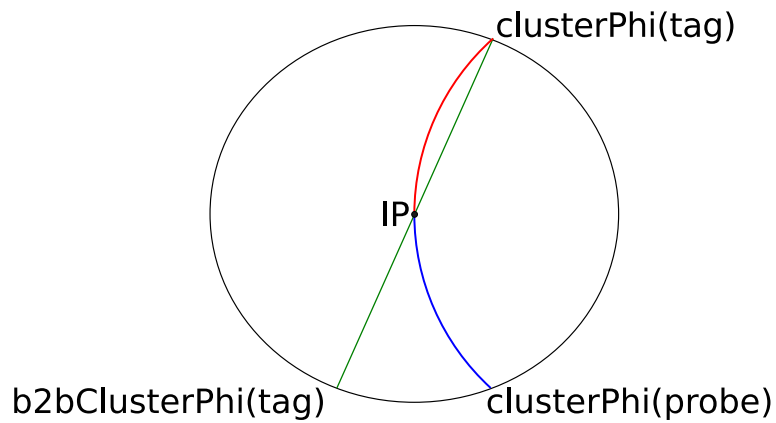


Figure 6.7.: Simplified representation of the b2bClusterPhi variable. The track of charged particles are bend in the detector. This sketch was created with Inkscape

6. Tracking Efficiencies

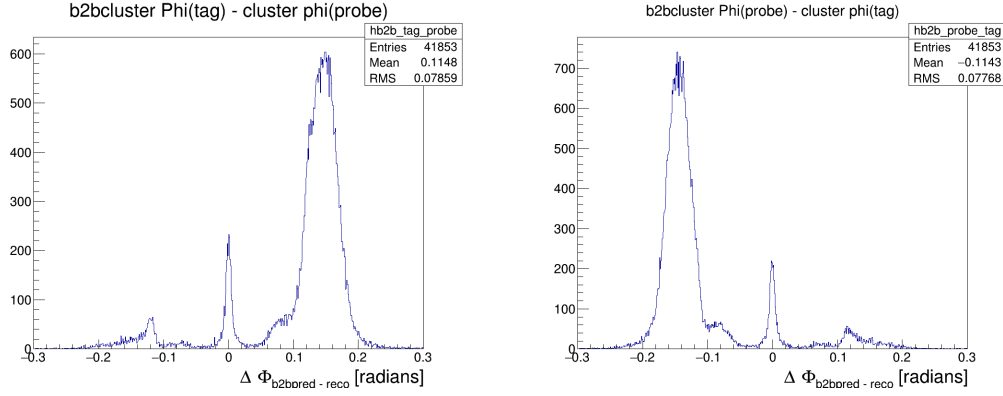


Figure 6.8.: Left: Predicted clusterPhi(tag) - Reconstructed clusterPhi(probe). Right: Predicted clusterPhi(probe) - Reconstructed clusterPhi(tag). Both plots are created with beamtime data. The variable to get the predicted clusterPhi value is the b2bclusterPhi variable which was described earlier.

6.6. Tracking Efficiency

In der Zusammenfassung sollten Sie in knapper Form die Aufgabenstellung und die wichtigsten Ergebnisse rekapitulieren. Es ist für die Gutachter hilfreich, wenn Sie ausdrücklich beschreiben, worin Ihre eigenen Beiträge liegen. Scheuen Sie sich auch nicht davor auszusprechen, welche Untersuchungen durch die Zeitbegrenzung der Bachelorarbeit nicht möglich waren und nutzen Sie dies als Überleitung zu einem Ausblick auf mögliche weitergehende Arbeiten an der Aufgabenstellung.

A Appendix

A.1. Additional Plots and Tables

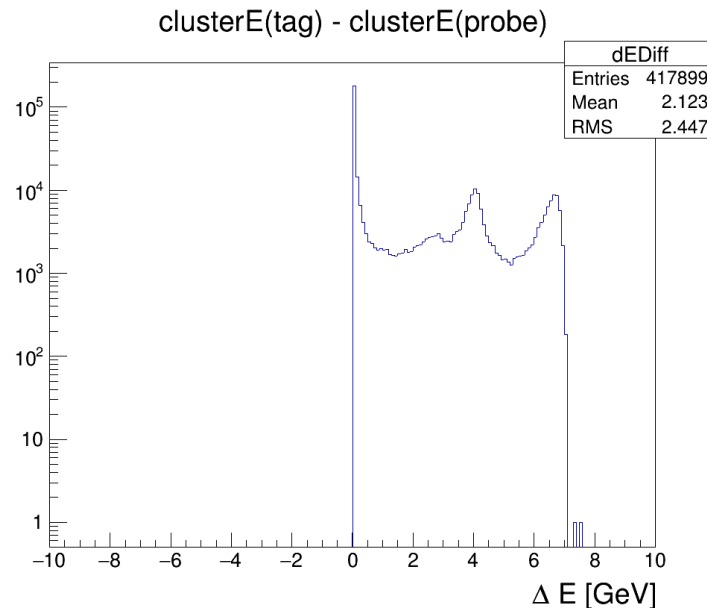


Figure A.1.: clusterE(tag) - clusterE(probe) of the reconstructed candidates. This shows that the tag daughters has always a higher cluster energy than the probe daughter.

A. Appendix

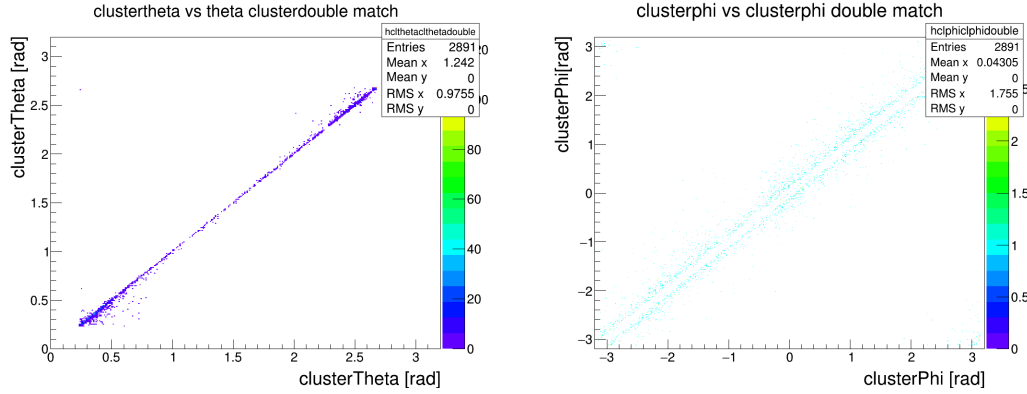


Figure A.2.: Left: The number of reconstructed candidates per event is shown. Right: The invariant mass of the reconstructed candidates is shown.

A.2. Tabellen und Abbildungen

In der Regel sind die in Tabellen und Abbildungen enthalten Informationen so wichtig, dass sie im Hauptteil der Arbeit erscheinen sollten. Unter Umständen sind aber ergänzende Tabellen und Abbildungen gut in einem Anhang aufgehoben. Wie im Hauptteil sollten Sie auch hier darauf achten, dass die in Tabellen und Figuren (siehe Abb. ??) dargestellte Information im Text angesprochen wird und selbsterklärende Legenden vorhanden sind.

A.3. Weiterführende Details zur Arbeit

Manch wichtiger Teil Ihrer tatsächlichen Arbeit ist zu technisch und würde den Hauptteil des Textes unübersichtlich machen, beispielsweise wenn es um die Details des Versuchsaufbaus in einer experimentellen Arbeit oder um den für eine numerische Auswertung verwendeten Algorithmus geht. Dennoch ist es sinnvoll, entsprechende Beschreibungen in einem Anhang Ihrer Bachelorarbeit aufzunehmen. Insbesondere für zukünftige Arbeiten, die an Ihre Bachelorarbeit anschließen, sind dies manchmal hilfreiche Informationen.

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Machen Sie genaue Angaben, so dass die verwendeten Literaturstellen eindeutig identifiziert und aufgefunden werden können. Bei Lehrbüchern ist es sinnvoll, den Titel anzugeben, eventuell auch die Ausgabe. Bei Artikeln in Fachzeitschriften ist es üblich, nur die gebräuchlichen Abkürzungen für den Titel der Zeitschrift, Band, Erscheinungsjahr und Seite anzugeben. Unter Umständen kann es auch sinnvoll sein, im Internet aufgefundene Informationsquellen anzugeben, zum Beispiel für Software oder zu den Details von Ergebnissen großer experimenteller Kollaborationen. Es ist selbstverständlich, dass Sie auch Bachelor, Diplom- oder Doktorarbeiten angeben, wenn Sie diese in Ihrer eigenen Arbeit verwendet haben.

Im folgenden Beispiel werden die in der Datei enthaltenen Anweisungen als Stilvorlage verwendet. Andere Möglichkeiten für die Gestaltung eines Literaturverzeichnisses findet man im Internet: <http://janeden.net/bibliographien-mit-latex>.

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