

Systematic Studies on Reconstruction Efficiency at Belle II

von

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Masterarbeit in Physik
vorgelegt dem Fachbereich Physik, Mathematik und Informatik (FB 08)
der Johannes Gutenberg-Universität Mainz
am 3. Dezember 2019

1. Gutachter: Prof. Dr. Wolfgang Gradl

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

Mainz, den 03.12.2019 [Unterschrift]

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Before the sea,
land, and heavens, which cover everything,
the entire world of nature looked the same.
They called that Chaos, a crude, confused mass,
nothing but lifeless stuff and scattered seeds
of matter not yet properly combined,
all piled up in the same place together

Ovid (~ 8 AD) -*Metamorphoses*-
Book I: -*The Primal Chaos*- Verse: 5-9
Translated by: Ian Johnston (2012)

As the proverb says, a picture is worth a thousand words...

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THE standard model of particle physics (SM) is an extraordinary successful theory which describes three out of four fundamental forces in nature. The predictions of this theory are extremely accurate within the reach of precision and energy currently available at modern experiments. Nevertheless, the standard model is far from complete because it is unable to answer fundamental questions like the origin of the matter/antimatter asymmetry, the presence of dark matter/energy and many other unanswered questions. Theories which try to answer these question have been developed suggesting physics beyond the standard model ultimately leading to new physics. Nonetheless, these theories lack experimental evidence.

The Belle II experiment is located at the electron-positron collider SuperKEKB at KEK in Tsukuba, Japan. SuperKEKB is a next-generation B factory with a design luminosity of $8 \cdot 10^{35} \text{ cm}^{-2}\text{s}^{-1}$. It is planned that SuperKEKB will ultimately have a data sample corresponding to a recorded integrated luminosity of $\sim 50 \text{ ab}^{-1}$. The Belle II detector is designed to study the properties of B and D mesons with respect to new physics. Belle II started taking physics data in early 2019. The detector consists of a vast variety of sub-detectors each fulfilling a complementary purpose like determination of the charge, trajectory reconstruction (tracking), momentum measurements, particle identification etc. For example, the purpose amongst others of the innermost sub-detectors is to reconstruct tracks created by charged particles passing through them. Of course, these sub-detectors are not able to reconstruct every charged particle as such. Therefore, one has to estimate how well they perform. This can be done by using Bhabha events. In a Bhabha event, an electron interacts with its antiparticle, a positron, by scattering or annihilation. The outgoing particles are then an electron and a positron again. Using the kinematics of this process and informations solely coming from the electromagnetic calorimeter (ECL), a sub-detector surrounding the inner sub-detectors, it is possible to select only Bhabha events. Therefore, one knows that there has to be an outgoing electron and positron in these events. Then, it is counted how often a charged particle is reconstructed as such. Finally, this number is divided by the total number of particles in all the Bhabha events. The result is a so-called tracking efficiency.

1. Introduction

In this thesis, the selection used to select only Bhabha events with ECL informations will be described. The selection will be motivated by Monte Carlo-Truth informations. These informations are the true properties of the particles generated in Monte Carlo (MC). Then, it will be shown that this selection works even without the Truth informations and can therefore, be applied on real data as well. Finally, the tracking efficiencies for different phases of the Belle II detector will be calculated and presented. The tracking efficiencies will be shown for several (transverse) momenta ranges and as a function of the polar angle θ and of the azimuthal angle ϕ . It will also differentiated between an electron tracking efficiency and a positron tracking efficiency.

Chapter 2 will present a short introduction to the standard model of particle physics. Also, Bhabha scattering will be explained briefly followed by Bhabha kinematics at Belle II.

In chapter 3 the experimental setup at SuperKEKB will be described. First, the accelerator SuperKEKB will be introduced, then the Belle II detector with all of its sub-detectors starting with the innermost.

Since, the ECL will be used as a tool to select Bhabha events, one has to be sure that it send out a trigger signal in each event which is taken into account. Therefore, the trigger and data acquisition system will be described briefly in chapter 4.

A very briefly introduction to the analysis framework at Belle II, BASF2, will be given in chapter 5.

In chapter 6 the selection used to only take Bhabha events into account, with only ECL informations, will be presented in detail.

Finally, this selection will be used to calculate the tracking efficiency of phase2 in chapter 7 and phase3 in chapter 8.

Since the same selection is used to calculate the tracking efficiency of phase2 and phase3 one can compare them. This will be done in chapter 9.

Last but not least, a short summary and conclusion will be given in chapter 10.

In this thesis, natural units are used. This means that $c = \hbar = 1$.

2 Theoretical Foundations

THE first part of this chapter will give a 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 energies reached 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 briefly 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 electrodynamic* (QED), the *electroweak theory* (EWT) and the *quantum chromodynamic* (QCD) as well as the *Higgs mechanism*.

The QED describes all phenomena caused by photons (γ) and charged point-like particles like electrons 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 flavor dynamics*, 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* (EWT) 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 chromodynamic*, QCD). This was done by Abraham Pais and Sam Treiman in 1975. The exchange particles for the strong

2. Theoretical Foundations

force are the *gluons* (g). They «*glue*» *quarks* (fundamental particles) together, forming *hadrons* like *mesons* (containing two quarks) and *baryons* (containing three quarks). [1]

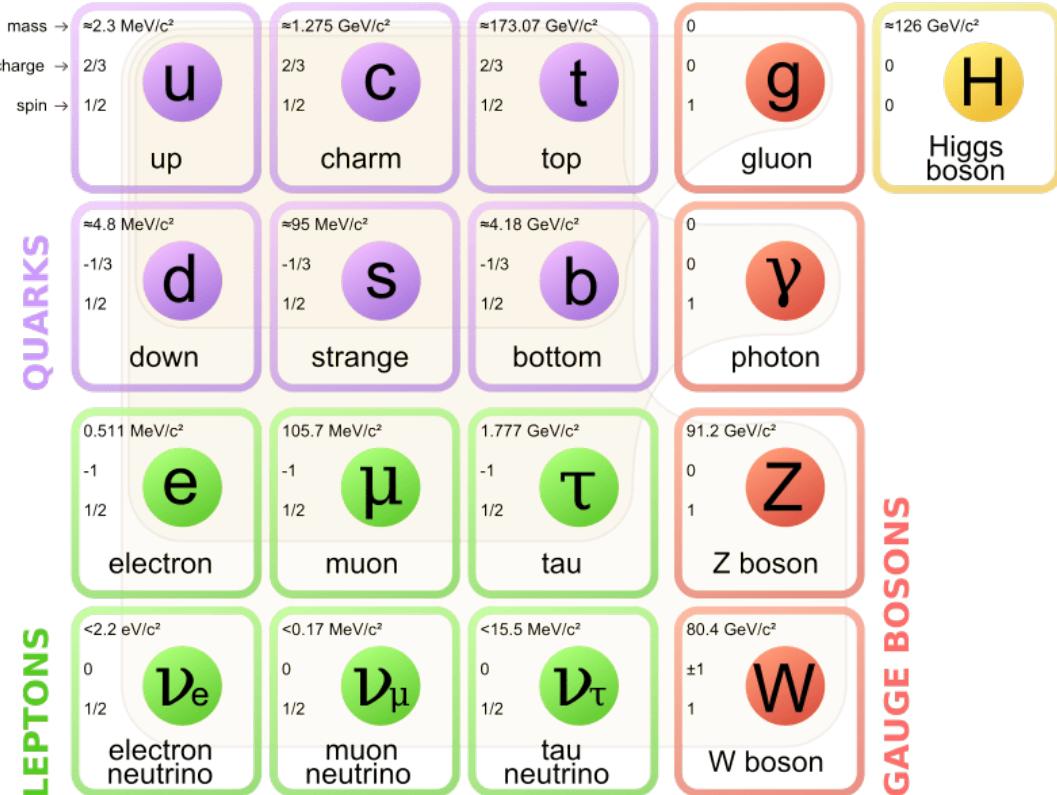


Figure 2.1.: The particles of the standard model include three families of quarks and leptons, four gauge bosons and the Higgs boson. The beige background indicates which bosons interact with which fermions. [2]

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 $2/3 e$ and d -, s - and b -quark have an electric charge of $-1/3 e$. 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 (e), the muon (μ) and the tau

2.2. Physics Beyond The Standard Model

(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*. Antiparticles 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 out 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.[3] 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 Large Hadron Collider (LHC) at Cern 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, it is not valid at energy scales approaching the Planck energy $E_P \approx 10^{19}$ GeV.[4] 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.[5]

2.3. Bhabha Scattering

In this section, we want to briefly discuss Bhabha scattering. We will start with the physics of Bhabha scattering and then discuss the Bhabha kinematics at Belle II.

2.3.1. Bhabha Process

Bhabha scattering is a quantum electromechanical process between an electron and a positron. It is named after the Indian physicist H. Bhabha who first derived the electron-positron scattering cross section in 1935.[6]

Bhabha scattering contains two different processes. Both have in common that there is an electron and positron in the initial and final state. Figure 2.2 shows the Feynman

2. Theoretical Foundations

diagrams for both Bhabha processes. The time passes from the left to the right side. In the left process, the initial electron and positron annihilate to form a virtual photon γ^* . This virtual photon then decays into an electron and a positron. The right Feynman diagram describes a classic electrodynamic scattering process. Here the incoming electron and positron are scattering by the interaction with a virtual photon. In contrast to the right diagram, the left diagram can only be explained by quantum field theory, due to the creation and destruction of particles.

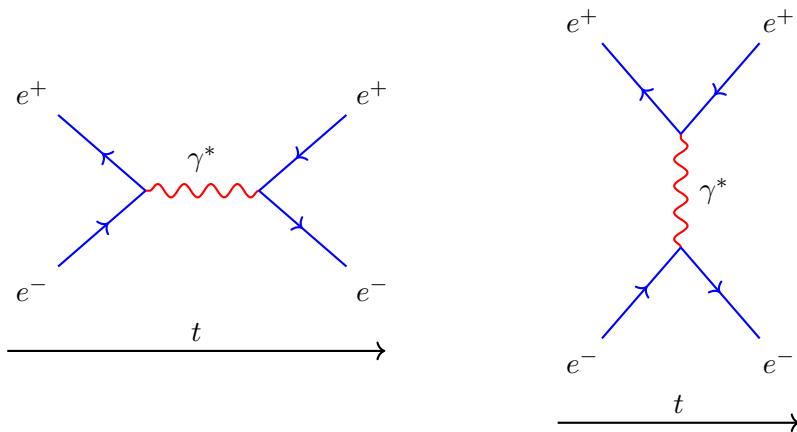


Figure 2.2.: The two Bhabha process Feynman diagrams. The left diagram describes the annihilation and pair production process, while the right diagram describes a classic electromagnetic scattering process.

2.3.2. Differential Cross Section Of Bhabha Processes

A cross section describes the probability that two particle will interact with each other when they collide. If this collision creates secondary radiation, then the intensity distribution over the spatial direction Ω is described by the differential cross section $d\sigma/d\Omega$.

The differential cross section for the electron¹ in a Bhabha process is given by equation 2.1.

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{cms}} = \frac{e^4}{32\pi^2 E^2} \left(\frac{1 + \cos^2(\theta)}{2} + \frac{1 + \cos^4(\theta/2)}{\sin^4(\theta/2)} - \frac{2\cos^4(\theta/2)}{\sin^2(\theta/2)} \right) \quad (2.1)$$

In figure 2.3 on the left, the differential cross section for electrons is plotted. Since, most incoming particles are only very slightly deflected, the cross section is very high for small angels and gets smaller with increasing angle. Equation 2.1 is also true for positrons but they are moving in the opposite direction, therefore, θ has to be replaced by $\pi - \theta$ in equation 2.1. The result is plotted in figure 2.3 on the right.

¹The electrons are moving along the x-axis. The positrons are moving in the opposite direction

2.3. Bhabha Scattering

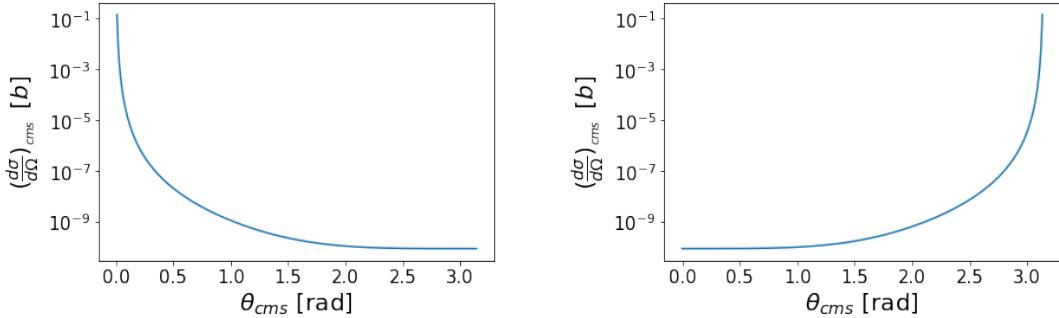


Figure 2.3.: Differential cross section for Bhabha events. Left: The Cross section for electrons is shown and on the left for positrons.
These plots were created with python3.

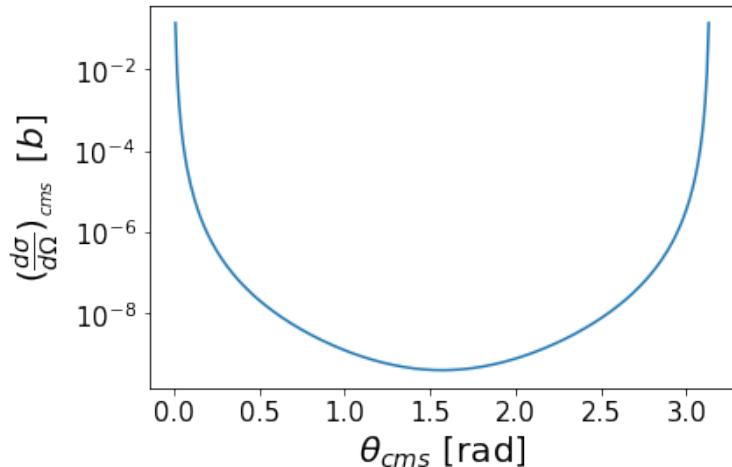


Figure 2.4.: This figure shows the differential cross section for Bhabha events.
This plot was created with python3.

To get to differential cross section for Bhabha events, one has to add the differential cross section of electrons and positrons. This is shown in figure 2.4. As you can see, most of the outgoing particles will have a very small or very large θ angle.

2.3.3. Bhabha Kinematics At Belle II

At Belle II the electron and the positron beams have different energies. Also, they are hitting each other under an angle. Therefore, it is interesting to look at the Bhabha kinematics in the lab system of Belle II.

Figure 2.5 on the left, you can see the momentum of the Bhabha particles as a function of the θ angle in the center-of-mass frame. Since the incoming electron and the positron have the same mass and they are hitting each other with the same energy, the outgoing

2. Theoretical Foundations

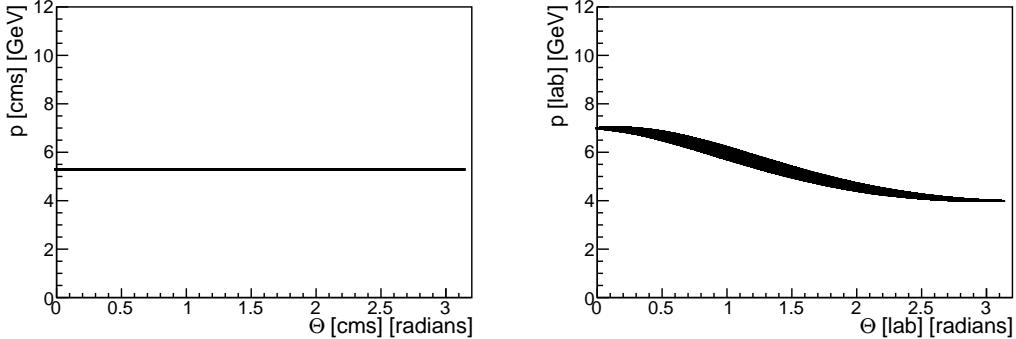


Figure 2.5.: Bhabha scattering in different frames. In the CMS the particle has the same energy in every θ -direction. Left: The θ -Energy-distribution in the CMS frame is shown. Right: The θ -Energy-distribution in the lab frame is shown.

particles always have the same momentum independent of the θ angle in the center of mass frame. In the right plot, you can see the momentum distribution after the boost in the lab system. For small θ angles a higher momentum of the outgoing particles is expected compared to high θ angles. The fanning of the distribution is caused by the fact that the beams are hitting each other under an angle at Belle II. Also, due to the fanning, we expect a range of energies at a fixed θ angle.

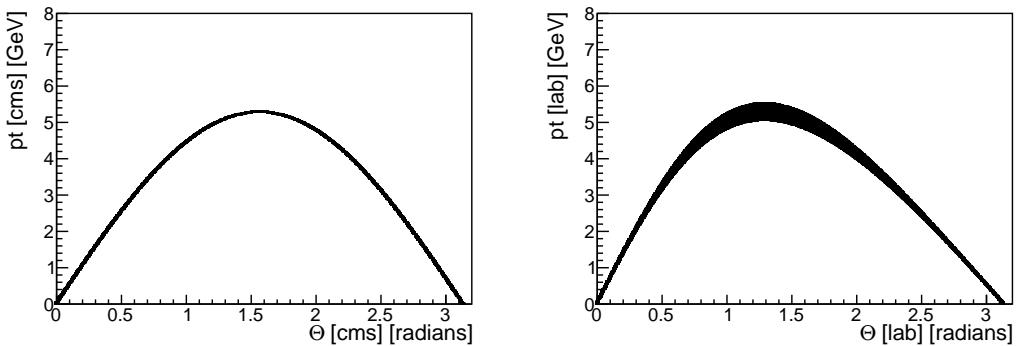


Figure 2.6.: The transverse momentum of the outgoing Bhabha particles in different frames. Left: transverse momentum in the center-of-mass frame. The highest transverse momentum is expected at an θ angle of $\pi/2$. Right: The transverse momentum in the lab frame. The highest transverse momentum is shifted a bit to smaller values of θ .

Figure 2.6 shows the transverse momentum as a function of θ for the outgoing Bhabha particles at Belle II. The left plot shows the distribution in the center-of-mass frame,

2.3. Bhabha Scattering

while the right plots shows it for the lab frame. In both frames, we expect the highest transverse momentum at a θ angle of about $\pi/2$.

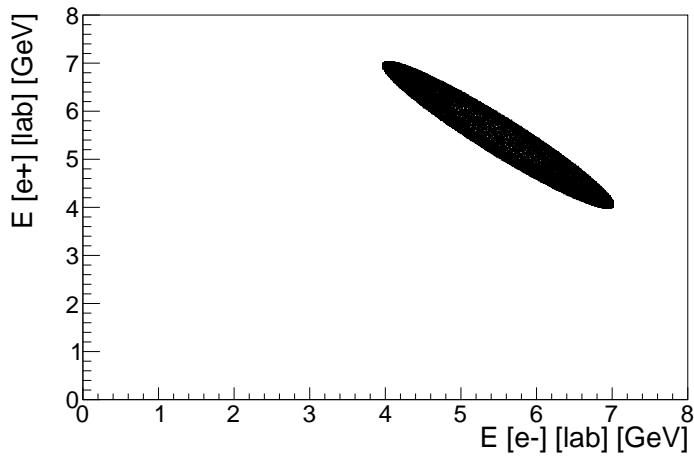


Figure 2.7.: The energy of the two outgoing Bhabha particles in the lab frame at Belle II.

In figure 2.7 the energy of the outgoing Bhabha particles in the lab frame at Belle II are plotted against each other. As you can see, if for example the electron has an energy of 7 GeV than the positron will have an energy of just about 4 GeV and vice versa.

3

Experimental Setup At SuperKEKB

SUPERKEKB is a 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.[7]

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 $\mathcal{L} = 2.11 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$. This was the world record at that time. KEKB was discontinued after more than 10 years, to be upgraded to SuperKEKB.[8]

In figure 3.1 you can see the schematic layout of the SuperKEKB accelerator. The electrons 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.[10] 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

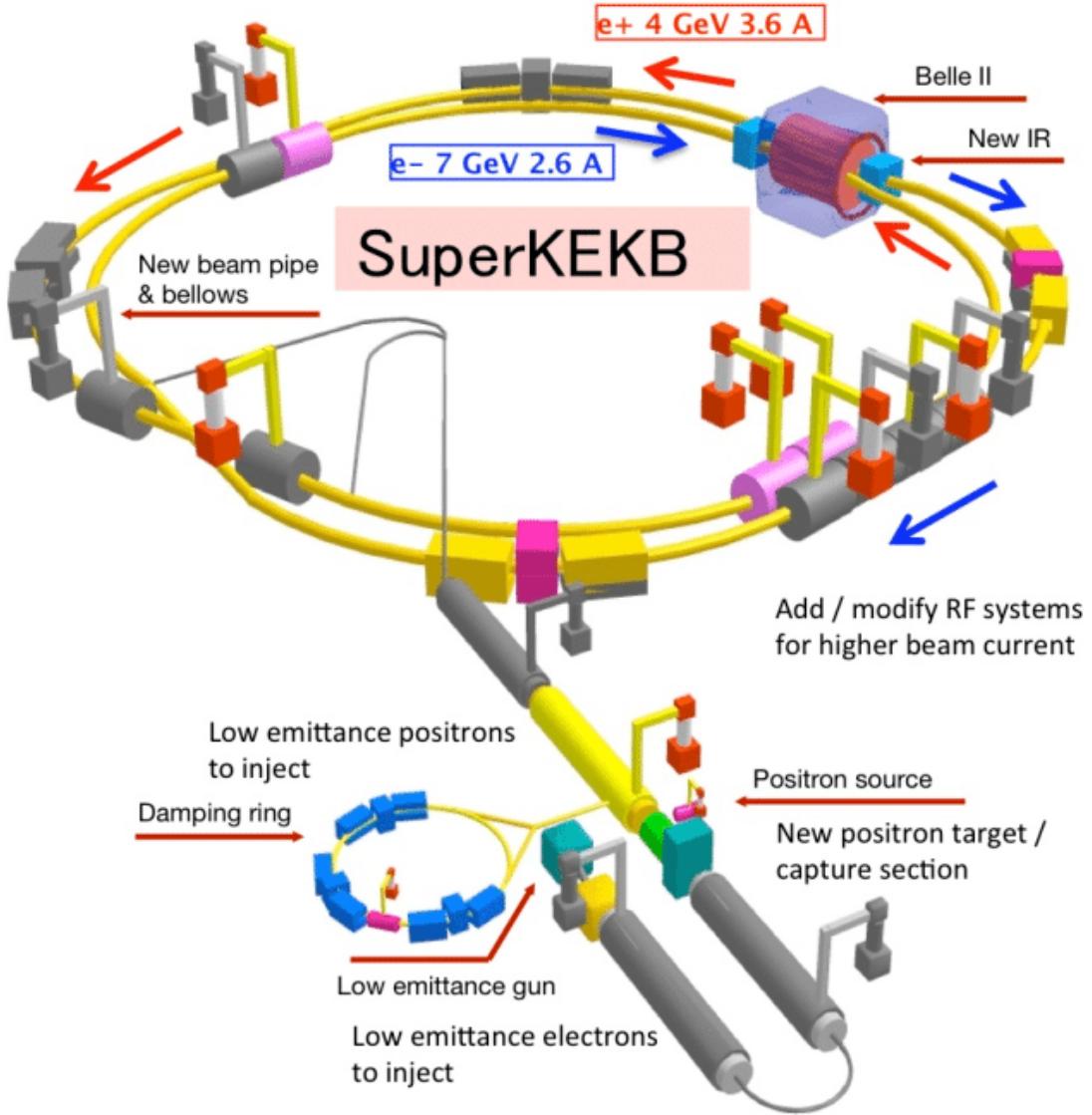


Figure 3.1.: The SuperKEKB collider.[9]

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.[7] (See section 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. Ultimately, this will result into a higher luminosity. The goal is to achieve a 40 times higher

3.2. The Belle II Detector

luminosity with SuperKEKB compared to KEKB. An integrated luminosity of 50 ab^{-1} will be achieved by 2025.[7]

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 calculated by the following equation.

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

One has to assume 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 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.[11] 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.

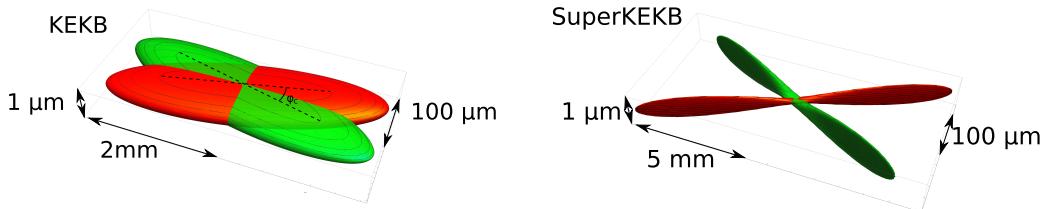


Figure 3.2.: Sketch of the beam crossing at KEKB (left) and SuperKEKB (right). At KEKB the size of the interaction region in z -direction was about 10 mm. At SuperKEKB it is about 0.5 mm.[12] This figure was edited in order to make the axis more readable.

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 $\sigma \approx 50 \text{ nm}$. This can be seen in figure 3.2. This decrease in beam size along with the increase in the beam currents results in a overall 40-fold increase in luminosity. [13] [7]

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 a variety of sub-detectors, each fulfilling a specific purpose.

3. Experimental Setup At SuperKEKB

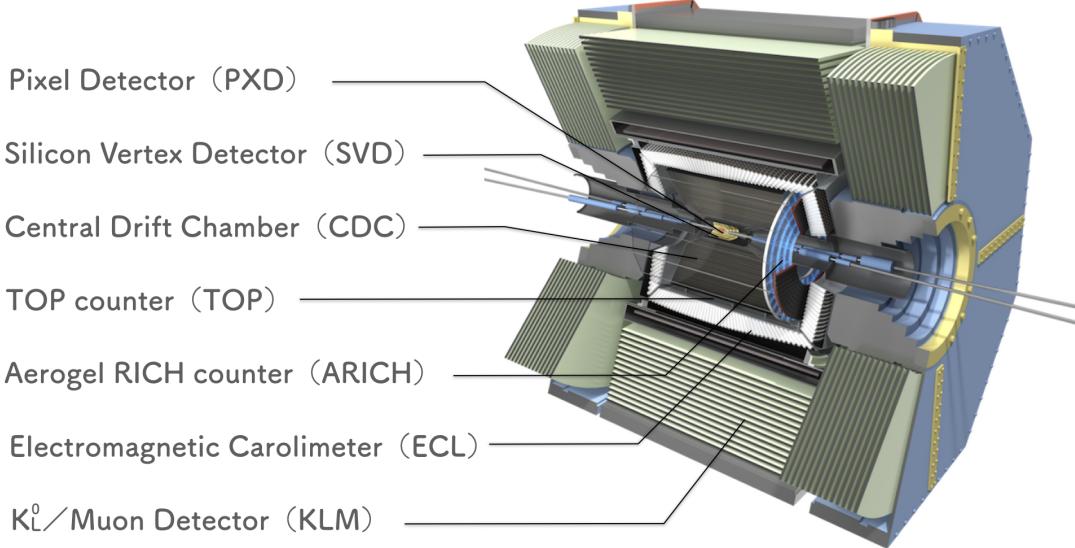


Figure 3.3.: Schematic view of the Belle II detector. The different detector elements are labeled. Also the beam pipes for the electrons and positrons with their corresponding energies are shown. [14] This figure was modified in order to make the text more readable.

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 trajectories (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, 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. The forward end-cap of the barrel is 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. The ECL is able

3.3. Coordinate System

to measure the energy of electromagnetically interacting particles, especially photons and electrons.

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. [7]

3.3. Coordinate System

For clarification, the coordinate system of Belle II will be described in this section, before the detectors are explained in more detail.

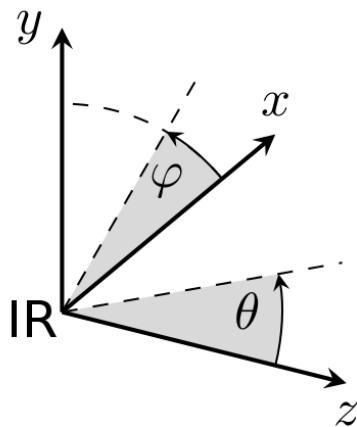


Figure 3.4.: A sketch of the coordinate system of Belle II. The original figure was modified to make the coordinate system more visible. [15]

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. The electrons are moving roughly along the positive z axis, while the positrons are moving in the opposite direction. In figure 3.4 also the spherical coordinate system is shown. Here θ corresponds to the polar angle and ϕ to the azimuthal angle.[16]

3.4. Vertex detector

The vertex detectors (VXD) are 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. Experimental Setup At SuperKEKB

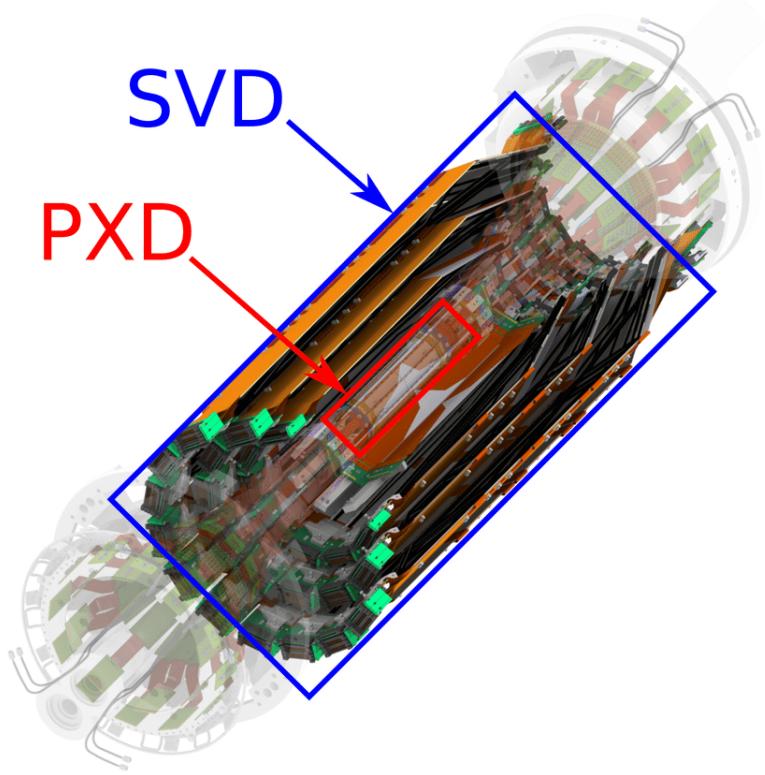


Figure 3.5.: Sketch of the vertex detectors. The vertex detector itself consists of two sub-detectors. The PXD is surrounded by the SVD. [17]

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 ($\sim 50 \mu\text{m}$).

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 $1.2 \mu\text{m}$.[13]

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. [13] [18]

3.4. Vertex detector

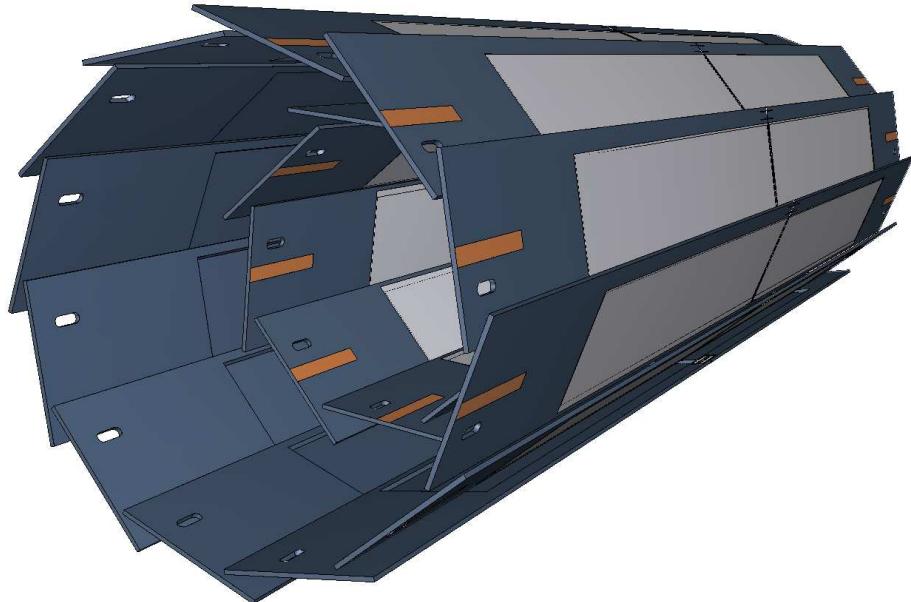


Figure 3.6.: Sketch of the complete PXD [13]

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. [13]

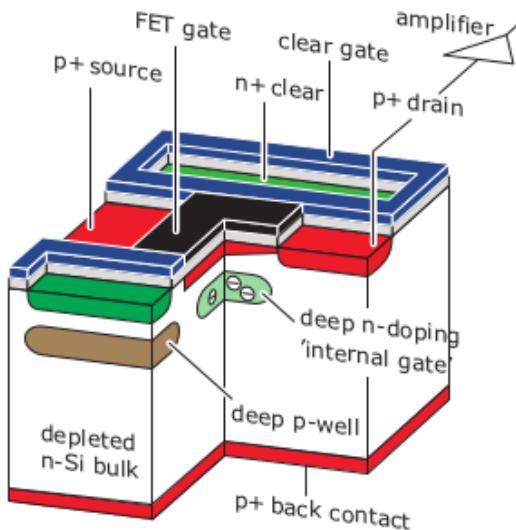


Figure 3.7.: Illustration of the DePFET technology.[13]

3. Experimental Setup At SuperKEKB

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) of 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 sidewards 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.[13]

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 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 trapeze to 57.6 mm on the long side of the trapeze times a length of 122.8 mm.[13] An illustration of the SVD can be seen in figure 3.8.

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.[13] [20]

3.5. Central Drift Chamber

The CDC surrounds the SVD. It consists of 14336 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

3.5. Central Drift Chamber

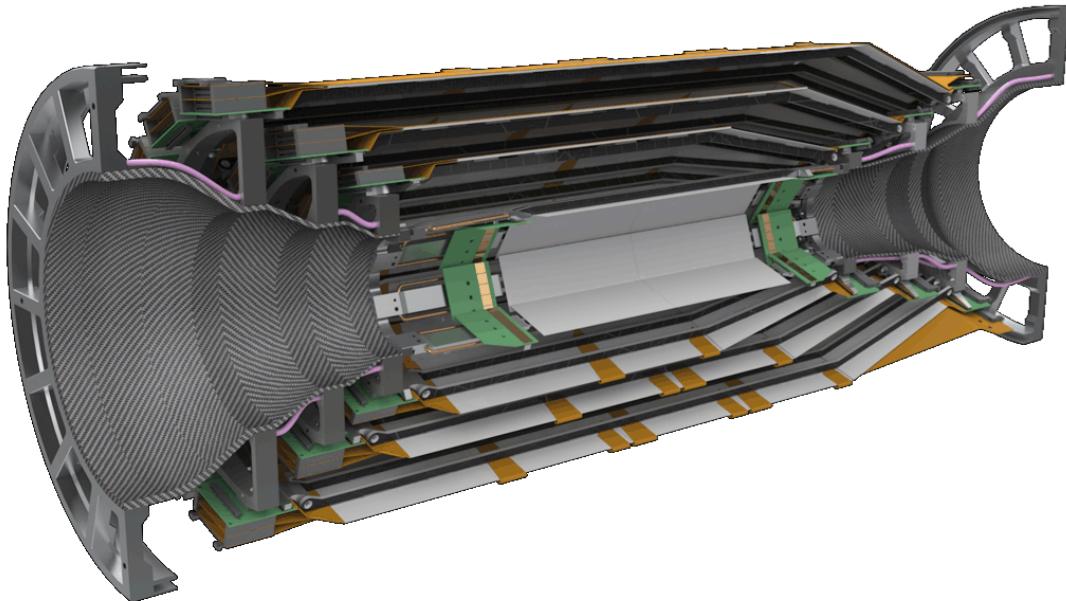


Figure 3.8.: Cross section of the silicon vertex detector[19]

device. The CDC also acts as a reliable trigger for charged particles.[13] A small cross section of the CDC is shown in figure 3.9.

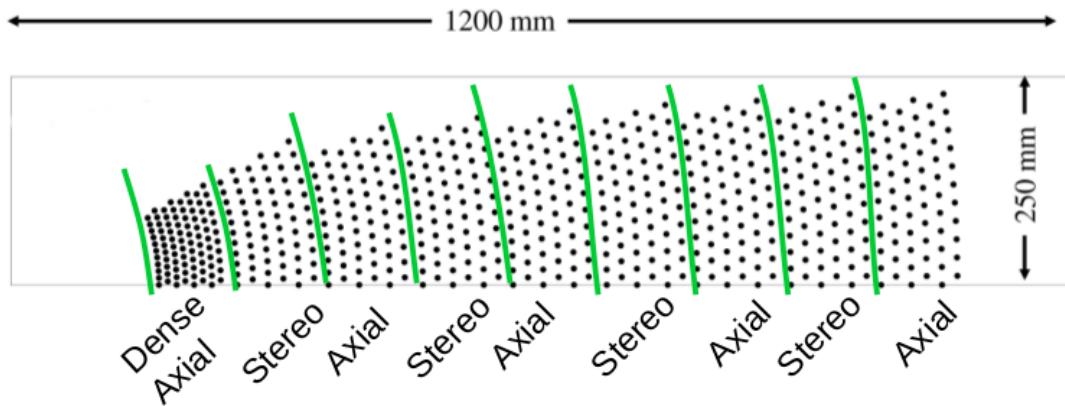


Figure 3.9.: Cross section and only a small part of the CDC. Each dot represent a wire. Also the area for the different superlayers are separated by the green line. All of these wires are immersed in a helium-ethane mixture.[21]

When a charged particle passes through the CDC it losses energy due to ionization of the gas. This produces electron-ion pairs, which are then separated by the electric field provided by 42240 aluminum field wires, with a diameter of $125 \mu\text{m}$. The signal

3. Experimental Setup At SuperKEKB

is then read out by the sense wires. These have a radius of $30\mu\text{m}$ and are made out of gold-plated tungsten.[13]

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 gives 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 superlayer. The four stereo superlayer subdivide into two stereo superlayer (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* and 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 $100\mu\text{m}$.[13]

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 reflective index n then this particle emits Cerenkov radiation under the angle θ_C .[22]

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

The Cerenkov angle is given by:[22]

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

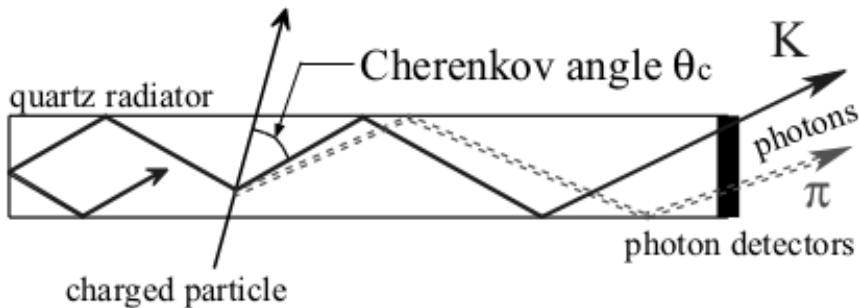


Figure 3.10.: Operating mode of a TOP detector.[13]

3.6. TOP And ARICH

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 .[13]

The TOP counter consists of 32 quartz bars. They have a length of 1250 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 %. [13]

The ARICH detector is located in the forward end-cap 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.

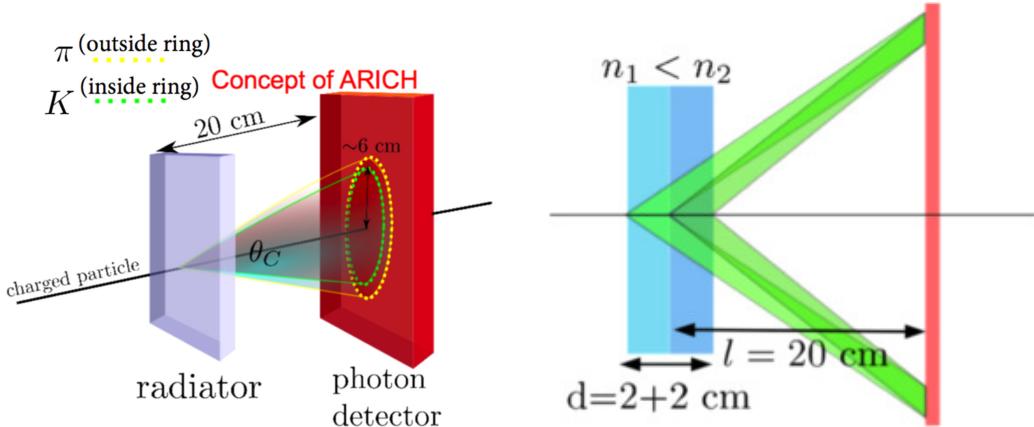


Figure 3.11.: Left: Illustration of the working principle of the ARICH detector. The yellow Cerenkov ring on the photon detector is produced by a π meson, the green ring by a K meson. Right: The radiator is shown in more detail. The radiator consists of two aerogel layers with different reflective index. [23]

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 reflective indexes and emits Cerenkov photons under a Cerenkov angle θ_C . Behind the radiator, an extension volume, for the Cerenkov rings to form, is located. At a distance of 20 cm behind the radiator is the photon detector.[13] 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. Experimental Setup At SuperKEKB

3.7. Electromagnetic Calorimeter

One of the main tasks of the ECL is the detection of photons with a high efficiency, it determines the energy and the angular coordinates of these photons with high 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 end-caps 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 end-caps. The barrel section of the calorimeter consists of 6624 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 end-caps consist of 2122 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 by:[13] [24]

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

The energy E is in GeV.

Photons and electromagnetic particles are creating electromagnetic cascades when they pass through material.[25] 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 velocity changes in an the electric field of a nuclei, they generate photons through Bremsstrahlung. These processes are repeated and an 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:[25]

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

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

²Thallium activated Cesium Iodide

3.8. K_L^0 And Muon Detector

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.[25]

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. Therefore, they initiate more ionization, 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 end-caps.

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.[13][26]

4 Trigger And Data Acquisition System

In this chapter a short introduction to the trigger system and the data acquisition system at Belle II is provided.

4.1. Trigger

The online event selection system (trigger) for Belle II makes it possible to acquire data from the detector based on information from a set of sub-detectors. The individual triggers are structured in an hierarchy. Each sub-trigger system provides the trigger information from the corresponding sub-detector to the global decision logic (GDL). This global trigger finally decides whether the event should be written out or not. [13] A schematic overview of this trigger hierarchy can be found in figure 4.1.

The trigger system has to fulfill the following requirements:[13]

0. high efficiency for hadronic events from $\Upsilon(4S) \rightarrow B\bar{B}$ and from continuum
1. a maximum average trigger rate of 30 kHz
2. a fixed latency of about $5\ \mu s$
3. a timing precision of less than 10 ns
4. a minimum two-event separation of 200 ns
5. a trigger configuration that is flexible and robust

At SuperKEKB bunch crossing occurs almost continuously, since the radio-frequency (RF) is about 508 MHz and every second or third period produces an event.[13] The total cross section and trigger rates at a luminosity of $\mathcal{L} = 8 \cdot 10^{35} \text{ cm}^{-2}\text{s}^{-1}$ for various physics processes is shown in table 4.1.

The luminosity is measured by using Bhabha and $\gamma\gamma$ events. These events are also used to calibrate the detector response. Due to their high cross section, these events are very dominant. That is the reason why there is a prescaling factor of 100 on these

4. Trigger And Data Acquisition System

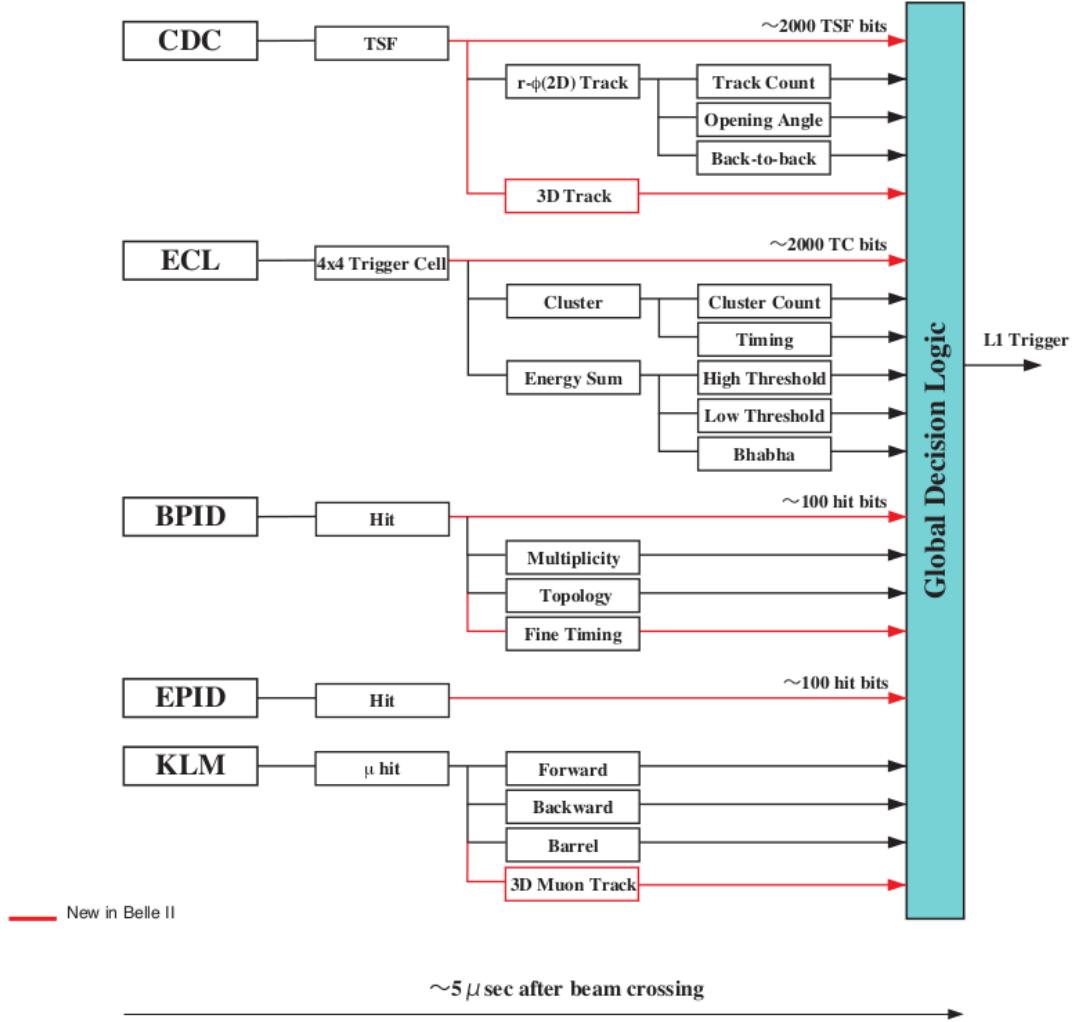


Figure 4.1.: Schematic overview of the Belle II trigger system. The four sub-trigger systems send their outputs to the Global Decision Logic. The GDL then performs the final on-line trigger decision. [27]

events. This means that a predetermined fraction of these events are accepted after satisfying the trigger requirements. After a beam collision, the GDL decides within about $5 \mu\text{s}$ if the event should be accepted and if it should be written out. Since the GDL is the first module to make a decision, and since it is dead time free, it is also called Level-1 trigger.[13]

4.2. Data Acquisition System

The data acquisition system (DAQ) reads out the detector signals once the Level-1 trigger decision is given by the trigger system. Starting from the front-end electronics,

4.2. Data Acquisition System

Table 4.1.: Total cross section and trigger rates for $\mathcal{L} = 8 \cdot 10^{35} \text{ cm}^{-2}\text{s}^{-1}$ from various physics processes at the $\Upsilon(4S)$.[27]

Physics process	Cross section (nb)	Rate (Hz)
$\Upsilon(4S \rightarrow BB)$	1.2	960
$e^+e^- \rightarrow \text{continuum}$	2.8	2200
$\mu^+\mu^-$	0.8	640
$\tau^+\tau^-$	0.8	640
Bhabha ($\theta_{\text{lab}} \geq 17^\circ$)	44	350 ^a
$\gamma\gamma$ ($\theta_{\text{lab}} \geq 17^\circ$)	2.4	19 ^a
2γ processes ($\theta_{\text{lab}} \geq 17^\circ, p_t \geq 0.1 \text{ GeV}/c$)	~ 80	~ 15000
Total	~ 130	~ 20000

^aThe rate is pre-scaled by a factor of 1/100

DAQ transfers the data through multiple steps of data processing to the storage system. With the exception of the PXD, all sub-detectors are read out by the unified data link system called the Belle2Link. The working principle of the DAQ can be seen in figure 4.2.

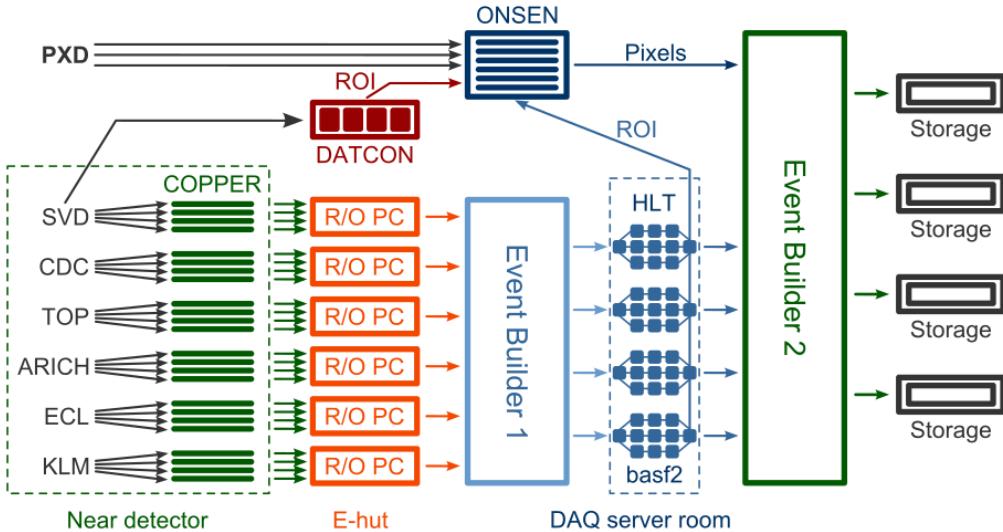


Figure 4.2.: Working principle of the Belle II DAQ. The data is transferred by about 300 COPPER boards to about 30 R/O PCs. The data is then put together by the first event builder and the events are reconstructed by the HLT afterwards. The HLT contains $O(10)$ units with about 400 cores each. Then, the reconstructed data is merged with the data coming from the PXD. Finally, the data is saved on about 10 storage units. [28]

4. Trigger And Data Acquisition System

The first part of the Belle2Link is the common readout platform (COPPER). This platform transforms the different data formats coming from the sub-detectors into a common data format. The COPPER boards then send their output signal to the event builder, which merges the data coming from the same collision to an event. With the information from the fully reconstructed events, the high level trigger (HLT) is able to finally decide whether the event should be stored or not. If the event should be recorded, it is then merged with the information coming from the PXD data in the second event builder.

Once the PXD receives the trigger signal, the readout starts. These data are stored on on-line selector nodes for up to 5 s. Meanwhile, the HLT performs the event reconstruction. Based on information coming from the SVD and CDC, the charged tracks, reconstructed in the HLT, are transferred back to the PXD and regions of interest (ROI) are formed. Only pixels of the PXD within the ROI are kept and considered in the second event builder. Complementary to the HLT, the data concentrator also searches for RIOs. The HLT is optimized for high momentum and the data concentrator is optimized for low momentum particles. Both systems require hits in all SVD layers. [13]

THE software framework used at Belle II is called BASF2 (Belle Analysis Framework). It is designed to prosecute off-line and analysis tasks. The majority of the code is written in C++, but python scripts are used for framework execution. The user specifies a sequence of modules in the python steering file which than process events. It also provides access to external libraries like ROOT which allows processing, statistical analysis, visualization and storage of common data and Geant4 for simulating the full detector.[29]

For the off-line reconstruction to work it has to take into account that the Belle II detector consists of a set of sub-detectors. Each sub-detector has a different geometry, dimension and is made out of different materials buried in a magnetic field. It also exploits the informations on the interactions of the particles with the matter. These informations are then used to reconstruct the particle trajectories (tracks) and the signal they generate in the detectors. This is done using algorithm that model particle propagation.

6 Preparation For Calculating The Tracking Efficiency Of Phase2

THIS chapter will provide an overview on how the cuts where chosen and which selection was applied in order to calculate a reasonable tracking efficiency on phase2 data. We will start with a definition of the tracking efficiency we want to calculate. Then the reconstruction and selection of the Bhabha events using only ECL informations will be described. The same selection and cuts used on phase2 will also be used on phase3 later on.

6.1. Phase2

Phase2 data were taken in the time between March 2018 and July 2018. During this time, only a small azimuthal fraction of the vertex detector was installed at $\phi \approx 0$. A sketch of the installed VXD can be found in the appendix figure B.1. The main focus of this phase was to study the background of the newly installed Belle II detectors, in order to be certain that the operation of the vertex detector is compatible with the much higher luminosity expected for physics data taking. Also, hardware controls were tested in this phase.

6.2. 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 track associated, 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:

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

6. Preparation For Calculating The Tracking Efficiency Of Phase2

To calculate an efficiency according to equation 6.1 one needs two histograms. One histogram filled particle information in the case that both particles are charged, and a histogram filled with particle information in the case that at least one particle in the event is reconstructed as a charged particle. The first will be referred to as *enumerator* histograms and the later will be referred to as *denominator* histograms.

The particle we investigate will be called *probe*. The other particle will be called *tag*. We know that *tag* is always reconstructed as a charged particle. Therefore, we will calculate the efficiency for two different cases:

- Electron: *tag* is reconstructed as a positron
- Positron: *tag* is reconstructed as an electron

6.3. Reconstructing Bhabha Events With Basf2

To analyze a Monte Carlo (MC) or 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 whole steering file is located on KEKCC at:

/home/belle2/msobotzi/bhabha/bhabha_vpho.py

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 then 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 a 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 and MC.

```
1 fillParticleList('gamma:all', 'clusterE > 0.01', path=mypath)
2 fillParticleList('e+:all', 'clusterE > 0.01', path=mypath)
3
4 reconstructDecay('vpho:gamma -> gamma:all', '', path=mypath)
5 reconstructDecay('vpho:elec -> e+:all', '', path=mypath)
6
7 copyLists(outputListName = 'vpho:ECLObjectUnranked' ,inputListNames=['vpho:
8     ↪ elec', 'vpho:gamma'], path=mypath)
9
10 rankByHighest('vpho:ECLObjectUnranked', 'daughter(0,clusterE)', path=mypath)
11 cutAndCopyList('vpho:ECLObject', 'vpho:ECLObjectUnranked', '', path=mypath)
12
13 reconstructDecay('vpho:bhabha -> vpho:ECLObject vpho:ECLObject', '',
14     ↪ mypath)
15
16 variablesToNtuple('vpho:bhabha', variables, treename = 'vpho_bhabha',
17     ↪ filename = output.root, path=mypath)
```

6.3. Reconstructing Bhabha Events With Basf2

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. Therefore, a cut is applied to the cluster energy and not on the energy of the particles.

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, the 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[30]:

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

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 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 6.4.

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. The first daughter will be referred to as `Hc1E` and the second daughter as `Lc1E`. You can see that the `Hc1E` daughter has always a higher energy than the `Lc1E` daughter in figure A.1. Here the `clusterE(Lc1E)` is subtracted from the `clusterE(Hc1E)` and only positive values remain. Therefore, `Hc1E` 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. Preparation For Calculating The Tracking Efficiency Of Phase2

6.4. Best Candidate Selection On Phase2 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 on KEKCC at:

```
/belle/MC/release-01-00-02/DB00000294/MC10/prod00004668/s00/e1002/4S/  
r00000/3600520000/mdst/sub00/mdst_000050_prod00004668_task10010000050.root
```

The generated file is located at:

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

6.4.1. CDC-Cut

Due to the fact that charged particles are reconstructed using informations coming from the CDC detector, we are only interested in events which would pass the CDC. So, we apply a θ -cut on the generated daughters (generated daughters means the true generated Monte Carlo daughters).

$$0.296706 < \theta_{HclE,LclE} < 2.617990 \quad (6.3)$$

All the events which survive this cut are written into a list (*mcEvtCDC*). We know that the Monte Carlo file contains 140000 generated Bhabha events. After this cut, only 24286 Bhabha events remain. In section 2.3.1, we saw that Bhabha events have a very high cross section in forward and backward direction. So, we expect that most of the generated daughters are not passing the CDC.

Now, we will take a look at the reconstructed Monte Carlo events. All of these reconstructed events have to appear in the *mcEvtCDC* list because we know that only in these events both daughters are passing the CDC. A total of 24100 events have at least one reconstructed candidate.

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.

6.4. Best Candidate Selection On Phase2 Monte Carlo

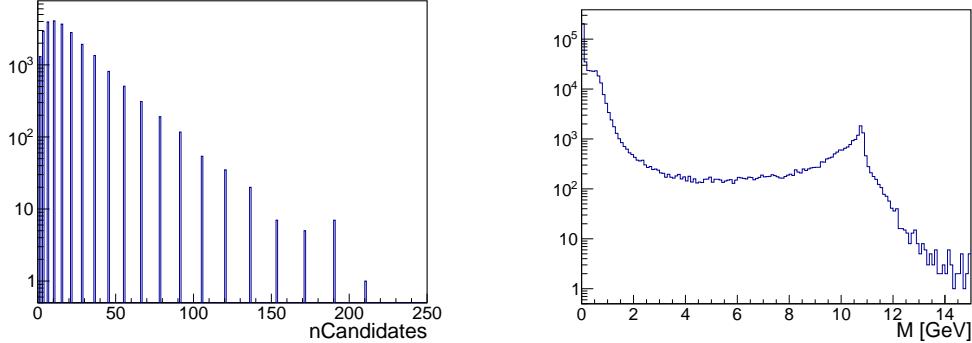


Figure 6.1.: Left: The number of reconstructed candidates per event is shown. We select 24100 events. Right: The invariant mass of the reconstructed candidates is shown. We select 417899 candidates.

6.4.2. 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.

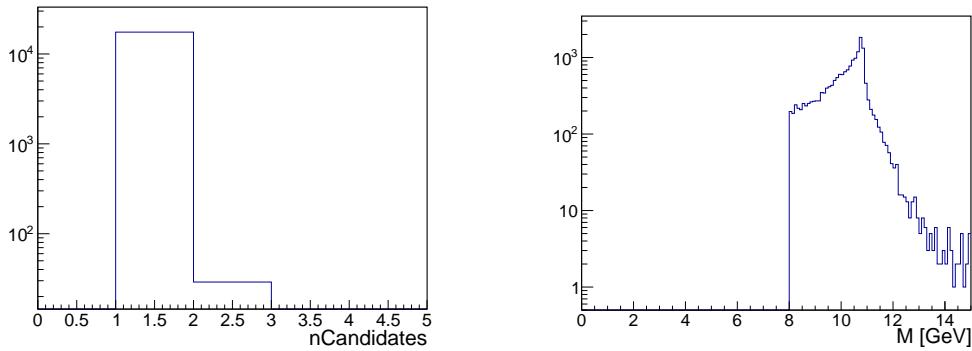


Figure 6.2.: A cut on the invariant mass is applied. The reconstructed invariant mass has to be bigger than 8 GeV. Left: The number of reconstructed candidates per event is shown. We select 17539 events. Right: The invariant mass of the reconstructed candidates is shown. We select 17558 candidates.

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

6. Preparation For Calculating The Tracking Efficiency Of Phase2

candidates per event and consequently, we have to introduce some more additional cuts.

6.4.3. 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.

Table 6.1.: Some examples for events with cluster splitting. mcE is the same for LclE and HclE. The energies are in GeV.

Event Number	HclE				LclE			
	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

As you can see, the Monte Carlo generated energy (mcE) for both HclE and LclE is the same and the reconstructed energy (E) of the HclE and the LclE particle sum up roughly to their respectively mcE. You can also see that the generated particle is always an electron or positron and that the *additionally* reconstructed particle is always a photon.

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 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 particle and for the other cluster no track is left, therefore, it is labeled as a photon. This effect will be referred to as *cluster splitting*.

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 2.3.3 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 almost 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. Also, due to the kinematics at Belle II, we can require that one of the outgoing particles

6.4. Best Candidate Selection On Phase2 Monte Carlo

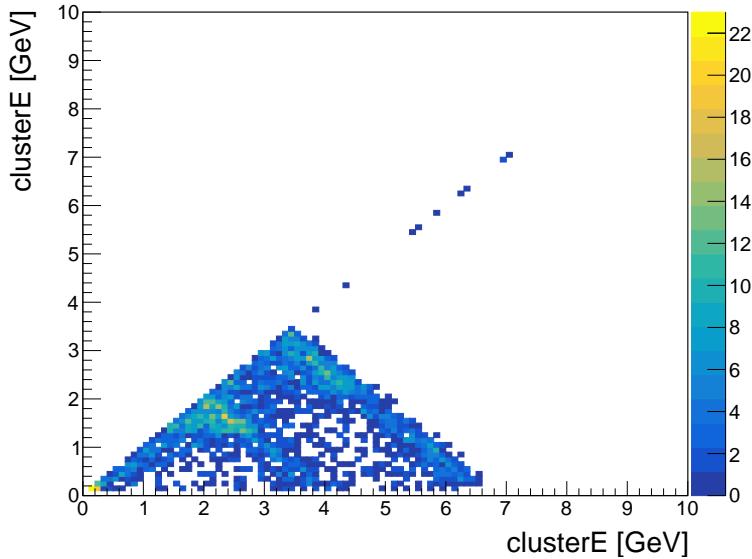


Figure 6.3.: Cluster Energy vs. Cluster Energy in the case that both particles are associated to the same Monte Carlo particle. Here, no cuts are applied. The total number of entries is 2891.

has an cluster energy of at least 4.5 GeV. This is required due to the trigger we will add in section 6.7. (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 charged particles per event (The cut is called `Mc1E2HnT`). This number should not be greater than six.

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 Number	M	Energy(Hc1E)	Energy(Lc1E)	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

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 also has to be smaller than 12 GeV.

6. Preparation For Calculating The Tracking Efficiency Of Phase2

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.

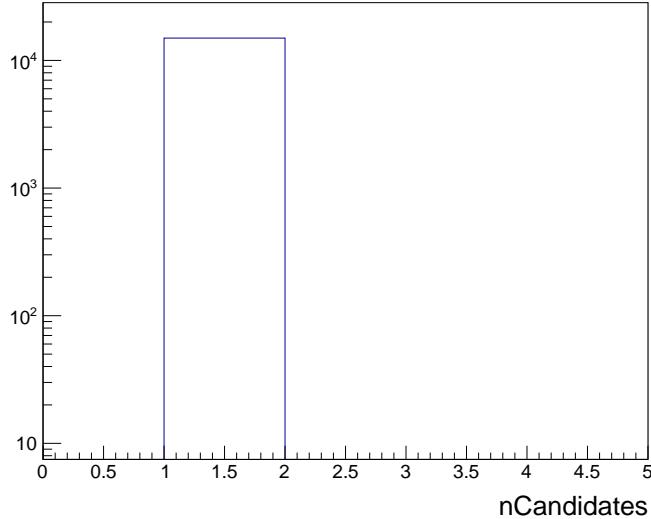


Figure 6.4.: Number of candidates per event after applying all cuts. $n = 14545$

After applying all mentioned cuts, the number of candidates per event is shown in figure 6.4. As you can see, now, we only select one candidate per event. Therefore, we select 14545 events and candidates.

There is no cut on the interaction point since this would require a backtracking of the particles.

6.4.4. 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.

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

¹The cut that requires that the generated particles have to pass the CDC is still applied $\rightarrow n_{\text{total}} = 24100$

6.5. Best Candidate Selection on Phase2 Data

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. The total number of entries in the *mcEvtCDC*-list is 24286.

Cut	Number Of Events	Relative Efficiency	Total Efficiency
No Cut	24100	1.0000	1.0000
M	17529	0.7273	0.7273
Mc1E	14903	0.8502	0.6183
Mc1E2H	14896	0.9995	0.6180
Mc1E2HnT	14896	1.0000	0.6180
Mc1E2HnTSumE	14545	0.9764	0.6035

Table 6.3 shows the relative and total efficiency of the cuts. As you can see, after all cuts a total of about 62% generated Bhabha events are reconstructed.

6.4.5. No MC-Truth Information

In the previous sections we saw that we are able to select only one candidate in a Bhabha event under the condition that we know that both daughters are hitting the ECL. Unfortunately, we do not have this information on phase2 data. Therefore, we also check how many candidates we reconstruct if we do not have MC-Truth information. We will analyze the same MC-file as before to compare the number of reconstructed events.

In figure 6.5 we see that we reconstruct a total number of 14581 events. Therefore, we reconstruct only 36 events more with no MC-Truth information. Also, we are still able to select only one candidate per event.

Since we only reconstruct a few more events and still only one candidate per event, we can be very confident that we only select almost exclusively Bhabha events.

6.5. Best Candidate Selection on Phase2 Data

Until now we only ran on MC, but ultimately we want to calculate the tracking efficiency on phase2 data. Therefore, we have to test the selection also on phase2 data. The same steering file as described in section 6.3 is used and run over the following files located at:

```
/ghi/fs01/belle2/bdata//Data/release-03-00-03/DB00000528/proc00000008/e0003/
4S/r02608/all/mdst/sub00/*.root
```

The generated file is located on KEKCC at:

```
/home/belle2/msobotzi/bhabha/bhabha_vpho_data_608.root
```

6. Preparation For Calculating The Tracking Efficiency Of Phase2

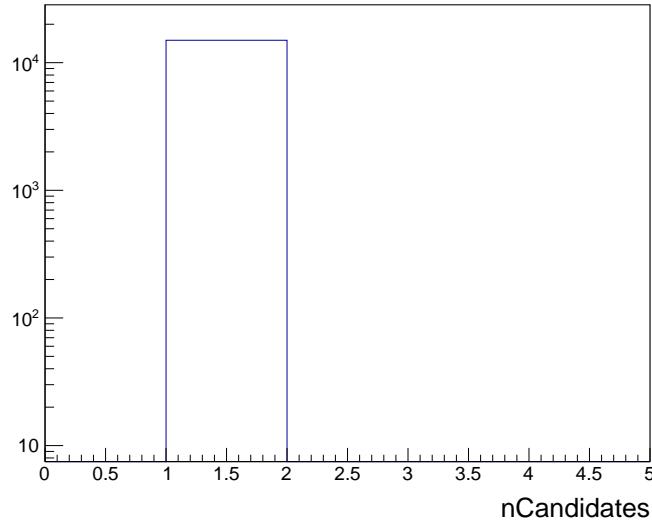


Figure 6.5.: Number of candidates per events with no MC-Truth information and all cuts. Same MC file as before. We also select just one candidate per event. The total number of selected events is 14581.

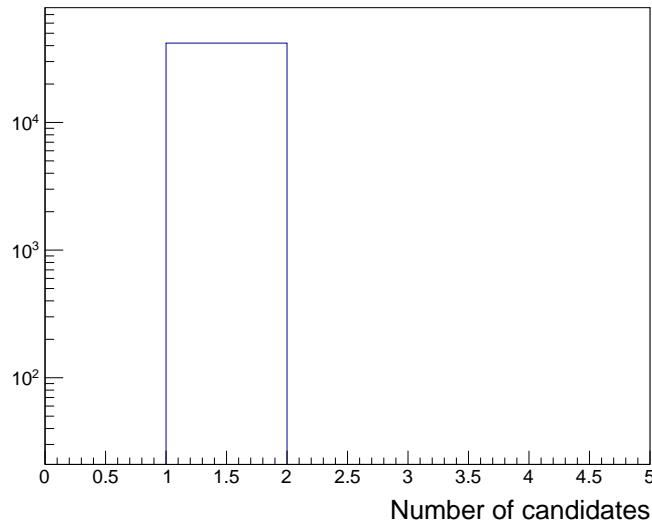


Figure 6.6.: Number of candidates per event for phase2 data. We also select only one candidate per event on phase2 data. A total number of 41853 events and candidates is selected.

Figure 6.6 shows the number of reconstructed candidates on phase2 data after the `Mc1E2HnTSumE` cut. You can see that we reconstruct only one candidate per event even on phase2 data.

6.6. Selecting Bhabha Events

Now, that we are satisfied with the selection of events and candidates we need to be sure that we only select $ee \rightarrow ee$ events and not for example $ee \rightarrow \gamma\gamma$. This is important on phase2 data since there are no $ee \rightarrow \gamma\gamma$ events on Monte Carlo. To do this we can use the so-called b2b-variable (back-to-back).

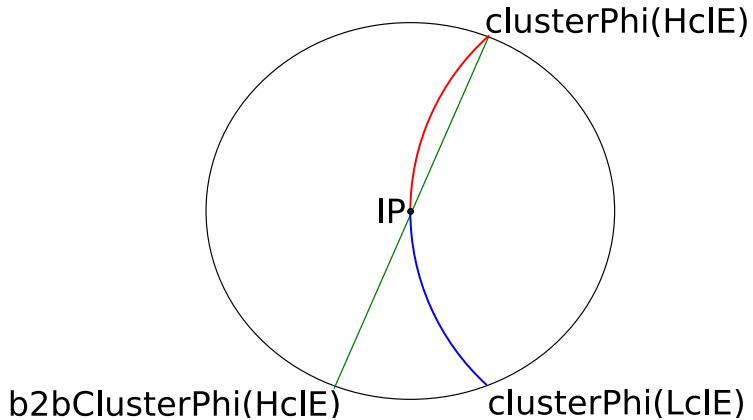


Figure 6.7.: Simplified representation of the b2bClusterPhi variable. The track of charged particles are bend in the detector. This sketch was created with Inkscape. The colors have no deeper meaning.

A simplified sketch of the b2bClusterPhi variable is shown in figure 6.7. This sketch shows the ECL in beam direction, so the magnetic field in the ECL is pointing into the paper. At the interaction point an electron (in this example the red line) and a positron (in this example the blue line) are created. Since both particles are charge their trajectories are bended by the magnetic field. The electron hits the ECL and creates a cluster with at the ϕ -angle clusterPhi. As described in section 2.3.3 the center-of-momentum frame at Belle II has a non zero $x - y$ fraction. Therefore, the b2bClusterPhi variable is not just clusterPhi $- \pi$ (as in the sketch). To calculate the b2bClusterPhi variable we have to boost the particle in the center-of-momentum frame then calculate clusterPhi $- \pi$ and finally boost back in the lab frame. With this variable we can predict the clusterPhi angle of the other particle.

In the sketch you see that there is a difference between the predicted and the true clusterPhi angle due to the magnetic field. This also means that in an $ee \rightarrow \gamma\gamma$ event the predicted and the true clusterPhi angle are the same because the trajectory of photons are not bend in the magnetic field. Therefore, we are able to differ between $ee \rightarrow ee$ and $ee \rightarrow \gamma\gamma$.

In figure 6.8 the difference between the predicted and the reconstructed clusterPhi angle for phase2 data is shown. In the left plot the reconstructed clusterPhi angle of the LcIE particle is subtracted by the b2bClusterPhi angle of the HcIE particle. In the right plot it is vice versa. In both plots we have three peaks. The middle peaks are $ee \rightarrow \gamma\gamma$ events since the predicted and the reconstructed clusterPhi angle is the

6. Preparation For Calculating The Tracking Efficiency Of Phase2

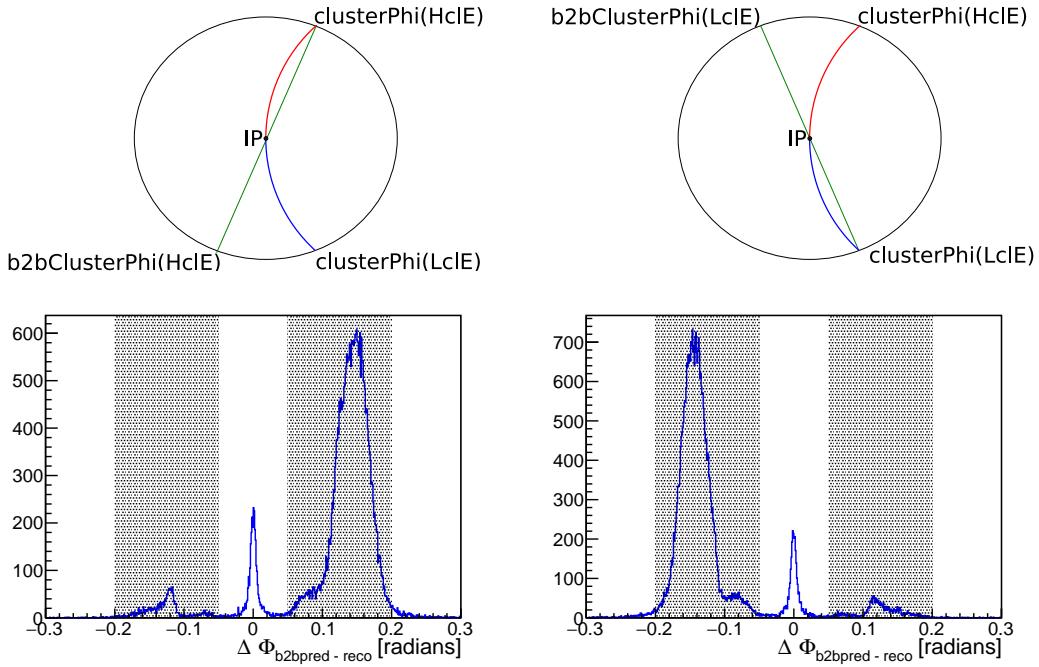


Figure 6.8.: Left: Predicted clusterPhi(HclE) - Reconstructed clusterPhi(LclE). Right: Predicted clusterPhi(LclE) - Reconstructed clusterPhi(HclE). Only particles within the gray area are taken into account. Both plots are created with phase2 data. The variable to get the predicted clusterPhi value is the b2bclusterPhi variable which was described earlier. The two top sketches represent what is calculated.

same. So these are events we want to cut away. The left peak is caused by electrons (most of the HclE particles are electrons, therefore the left peak on the right plot is significantly higher²), the right peak by positrons. This means that if for example we only cut on the left peak we are only selecting electron particles even if they are wrongly reconstructed as photons, using ECL information only. Therefore, the last cut we will add is a cut on the b2bClusterPhi angle. We will only consider events in with:

$$0.05 \leq \text{abs}(\text{b2bClusterPhi(HclE)} - \text{clusterPhi(LclE)}) \leq 0.2 \quad \text{and} \quad 0.05 \leq \text{abs}(\text{b2bClusterPhi(LclE)} - \text{clusterPhi(HclE)}) \leq 0.2$$

A special case occurs for $\Phi \approx \pi$ or $\Phi \approx -\pi$. It can happen that the reconstructed clusterPhi angle is around π but the b2bClusterPhi angle is calculated to be around $-\pi$, then the difference between the predicted and reconstructed clusterPhi angle is around 2π . This can be seen in figure A.3

²As described in section 6.3, the HclE daughter is the daughter with the higher cluster energy

6.7. ECL-Trigger

Finally, the b2bClusterPhi variable cut can be summarized in the following three conditions. Each event has to fulfill one of them to be taken into account.

- (a) $0.05 \leq \text{abs}(\text{b2bClusterPhi(HclE)} - \text{clusterPhi(LclE)}) \leq 0.2 \&\& 0.05 \leq \text{abs}(\text{b2bClusterPhi(LclE)} - \text{clusterPhi(HclE)}) \leq 0.2$
- (b) $2\pi - 0.2 \leq \text{abs}(\text{b2bClusterPhi(HclE)} - \text{clusterPhi(LclE)}) \leq 2\pi - 0.05 \&\& 0.05 \leq \text{abs}(\text{b2bClusterPhi(LclE)} - \text{clusterPhi(HclE)}) \leq 0.2$
- (c) $0.05 \leq \text{abs}(\text{b2bClusterPhi(HclE)} - \text{clusterPhi(LclE)}) \leq 0.2 \&\& 2\pi - 0.2 \leq \text{abs}(\text{b2bClusterPhi(LclE)} - \text{clusterPhi(HclE)}) \leq 2\pi - 0.05$

These cuts are visualized by the gray area in figure 6.8. Only particles within these areas are taken into account.

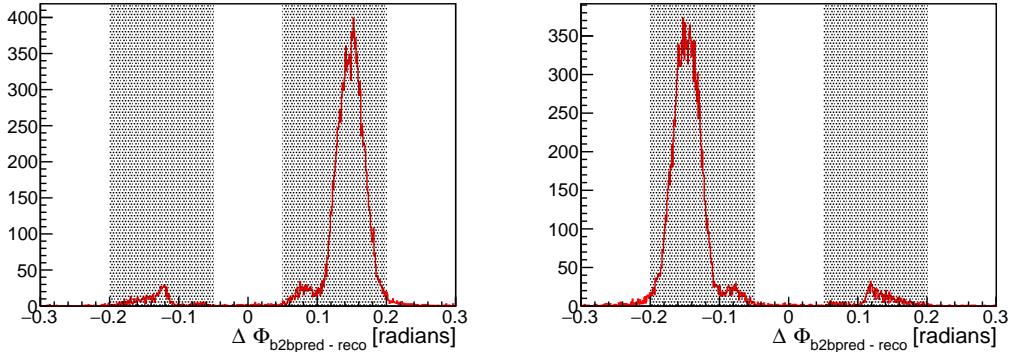


Figure 6.9.: Left: Predicted clusterPhi(HclE) - Reconstructed clusterPhi(LclE). Right: Predicted clusterPhi(LclE) - Reconstructed clusterPhi(HclE). Only particles within the gray area are taken into account. Both plots are created with phase2 MC. There is no middle peak because only ee → ee events were generated.

Figure 6.9 shows the same plots as figure 6.8 but with phase2 MC. Note that there is no middle peak because only ee → ee events were generated. In figure A.4 the b2bClusterPhi plot with full range is shown for MC.

6.7. ECL-Trigger

Last but not least, we need to be sure that each event has a trigger signal coming from the ECL. Otherwise, the trigger signal could come only from the tracking detectors. Then, there would be a bias on the efficiency, since the tracking detectors require at least one track. Therefore, a cut on the trigger called `bhabha` is introduced. This trigger requires a signal coming from the ECL and some additional conditions. Both reconstructed particles have to have an energy of at least 2.5 GeV each and one of

6. Preparation For Calculating The Tracking Efficiency Of Phase2

them has to have at an energy of 4 GeV or more. Also, two additional conditions have to be fulfilled.

- $160^\circ < \sum \theta_{cms} < 200^\circ$
- $140^\circ < \Delta\phi_{cms} < 220^\circ$

The **bhabha** trigger returns a 1, only if all three conditions are fulfilled. [31]

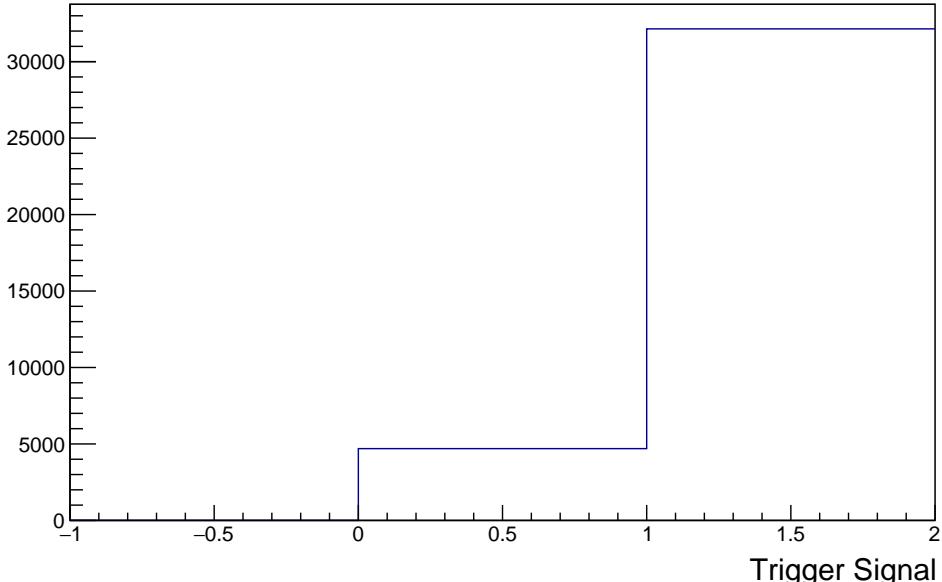


Figure 6.10.: **bhabha** trigger signal for a single phase2 data file after the selection.

Trigger Signal == 0 means that there was no trigger signal in the event.
 Trigger Signal == 1 means that there was a trigger signal in the event.
 (Trigger Signal == -1 means that there are no trigger informations in the file.) As you can see, in most of the selected events there is a trigger signal coming from the ECL.

In figure 6.10 you can see the **bhabha** trigger signal for a single phase2 data file after the selection. Most of the time, there was an ECL trigger signal and in only about 8 % of the events there was no trigger signal coming from the ECL. These events have to be cut out.

This is not done for phase2 Monte Carlo, since the trigger does not work reliable on MC and we only look at events we want to consider. Therefore, a trigger cut is only done for phase2 data (and phase3 data in chapter 8). This is also the reason why the cuts on the cluster energy were chosen as they are. Otherwise, a comparison between phase2 MC and phase2 data would be impossible.

6.8. More Events

6.8. More Events

The efficiency errors are calculated with the following equation:

$$\Delta\epsilon = \sqrt{\frac{\epsilon(1-\epsilon)}{n}} \quad (6.6)$$

In equation 6.6, ϵ is the calculated efficiency and n is the total number reconstructed particles with and without an associated track in the investigated bin. This equation is only true for large n , since according this equation, an efficiency of 1 has always an error of zero. Therefore, the efficiency will be calculated by the root class TEfficiency. This class is able to calculate the right efficiency error even for small n . [32]

To reduce the error on the calculated efficiency, n has to be as big as possible. Therefore, more phase2 data and phase2 MC files are needed. For Monte Carlo we will consider all files located at KEKCC:

```
/belle/MC/release-01-00-02/DB00000294/MC10/prod00004668/s00/e1002/4S/
r00000/3600520000/mdst/sub00
```

Also, we will take all available phase2 data files into account. They are located on KEKCC at:

```
/ghi/fs01/belle2/bdata//Data/release-03-00-03/DB00000528/proc00000008/e0003/
4S/r0*/all/mdst/sub00/*.root
```

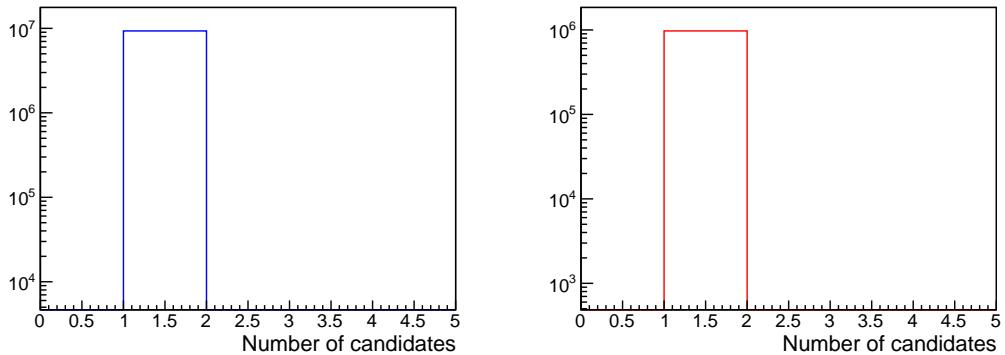


Figure 6.11.: The number of candidates per event after the selection is shown. Left: Phase2 Data. Right: Phase2 MC. A total of 9323903 candidates are selected for phase2 data and 973181 candidates are selected for phase2 MC.

6. Preparation For Calculating The Tracking Efficiency Of Phase2

In figure 6.11, you can see the number of candidates per event after the selection. You can see that we reconstruct only one virtual photon per event on both phase2 data and phase2 MC.

6.9. Dividing The ECL In Areas Of Interest

As described in section 3.7, the ECL is divided in three areas, the barrel, the forward end-cap and the backward end-cap. Therefore, we will take a look at the efficiency of these areas separately. The first area will only contain the forward end-cap. This means, only particles with a predicted θ angle of $0^\circ < \theta < 32^\circ$ will be taken into account. The second area of interest is the barrel. Here, the predicted θ angle of the investigated particle has to be $32^\circ < \theta < 130^\circ$. The last area of interest is the backward end-cap with an cluster θ angle of $130^\circ < \theta < 180^\circ$.

In section 2.3.3, we saw that the azimuthal angle and the momentum of the particles are correlated in the lab frame. Therefore, we need to look at momentum intervals. Otherwise, it would be impossible to interpret the calculated efficiencies. For example, a low efficiency in ϕ could be the results of an inefficient forward end-cap or created by momentum dependencies.

In figure 6.12 you can see the *denominator* histograms for the electron. In these plots, the predicted θ and ϕ angles for different momenta for phase2 MC are shown. Also, the three areas of interest are indicated in these plots by a pink line. Phase2 MC was used to determine the momenta ranges because the statistics are lower on phase2 MC compared to phase2 data.

Figure A.5 shows the same plots but for phase2 data. Small differences for momenta between 4 GeV and more at an ϕ angle of about 0° are probably caused by the geometry of the vertex detector. As already mentioned in section 6.1, only a small azimuthal fraction at $\phi \approx 0$ was installed. The corresponding phase2 data plots for positrons are shown in figure A.8.

In these four figures, one can also see that it makes sense to look only at some momenta for different areas of interest. The different momenta regions are listed in table 6.4.

Table 6.4.: Momenta ranges for different *probe* cases and different areas of interest.

	e^-	e^+
Forward End-Cap	4 GeV – 8 GeV	/
Barrel	4 GeV – 7 GeV	3 GeV – 7 GeV
Backward End-Cap	/	2 GeV – 6 GeV

The same is done for the transverse momenta for the three different cases. The denominator plots of phase2 MC for the electrons can be seen in figure 6.14. Figure 6.15 shows the denominator plots for phase2 MC positrons. The different transverse momenta regions are listed in table 6.5.

6.9. Dividing The ECL In Areas Of Interest

Table 6.5.: Transverse Momenta ranges for different *probe* cases and different areas of interest.

	e^-	e^+
Forward End-Cap	1 GeV – 4 GeV	/
Barrel	2 GeV – 6 GeV	3 GeV – 6 GeV
Backward End-Cap	/	1 GeV – 4 GeV

We will also look at the tracking efficiency as a function of θ . For this, we also have to choose momenta regions. They can be determined by the same plots as before. The selected ranges can be found in table 6.6.

Table 6.6.: Momenta and transverse momenta ranges for the tracking efficiency as a function of θ .

	e^-	e^+
Momentum	4 GeV – 9 GeV	2 GeV – 7 GeV
Transverse Momentum	1 GeV – 6 GeV	1 GeV – 6 GeV

6. Preparation For Calculating The Tracking Efficiency Of Phase2

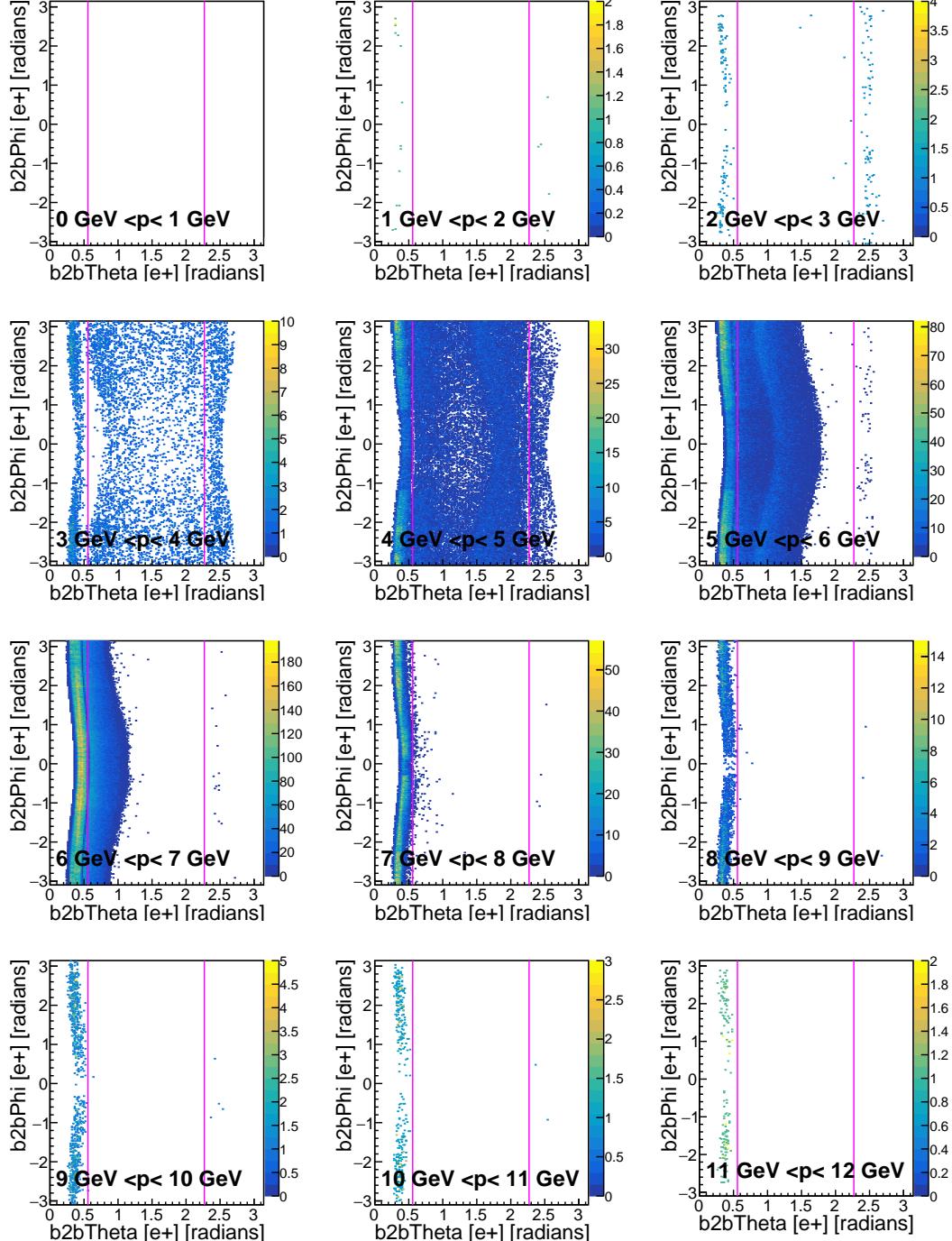


Figure 6.12.: Predicted θ and ϕ denominator histograms of the electron for different momenta for phase2 MC are shown. The different areas of interest are indicated by the pink line.

6.9. Dividing The ECL In Areas Of Interest

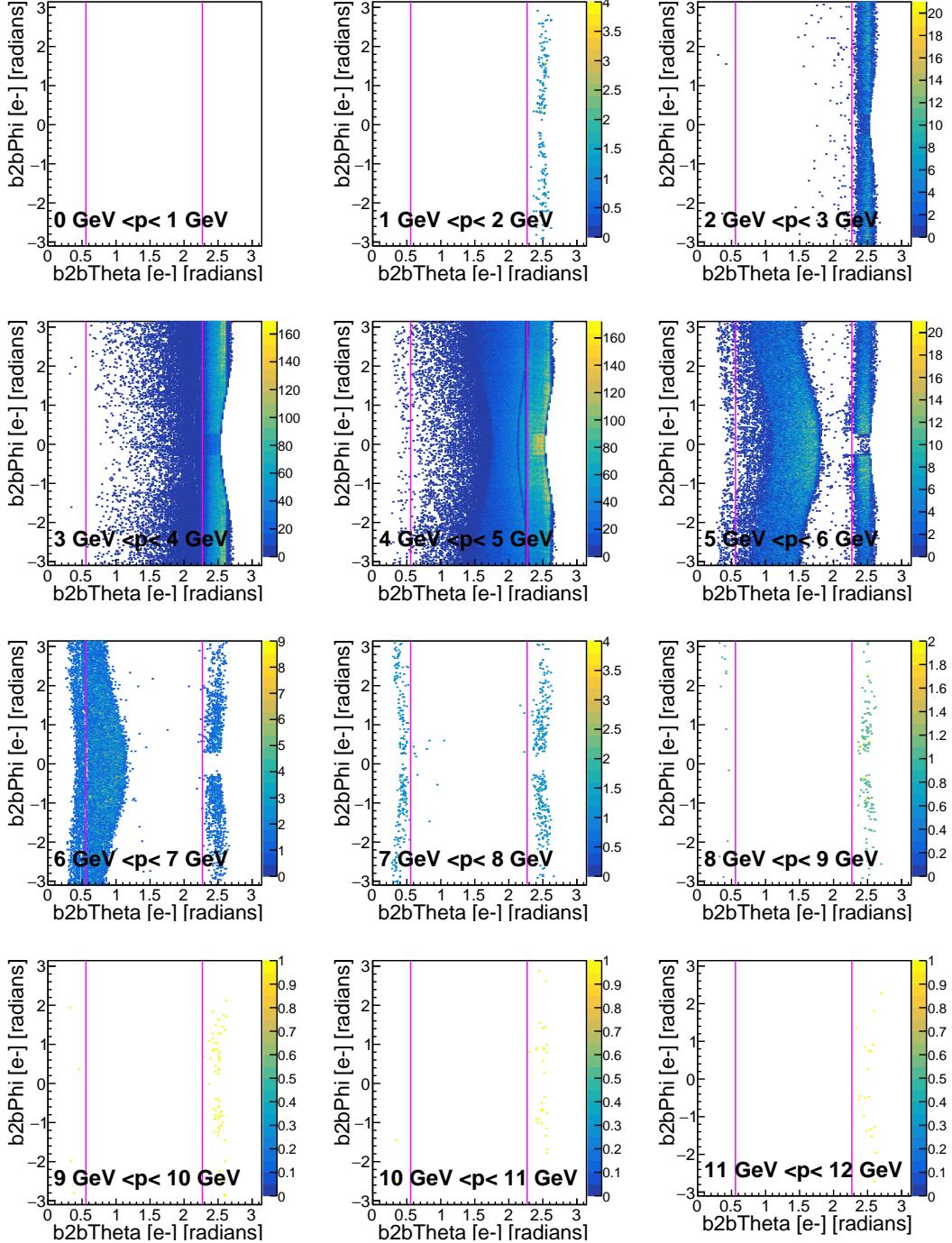


Figure 6.13.: Predicted θ and ϕ denominator histograms of the positron for different momenta phase2 MC are shown. The different areas of interest are indicated by the pink line.

6. Preparation For Calculating The Tracking Efficiency Of Phase2

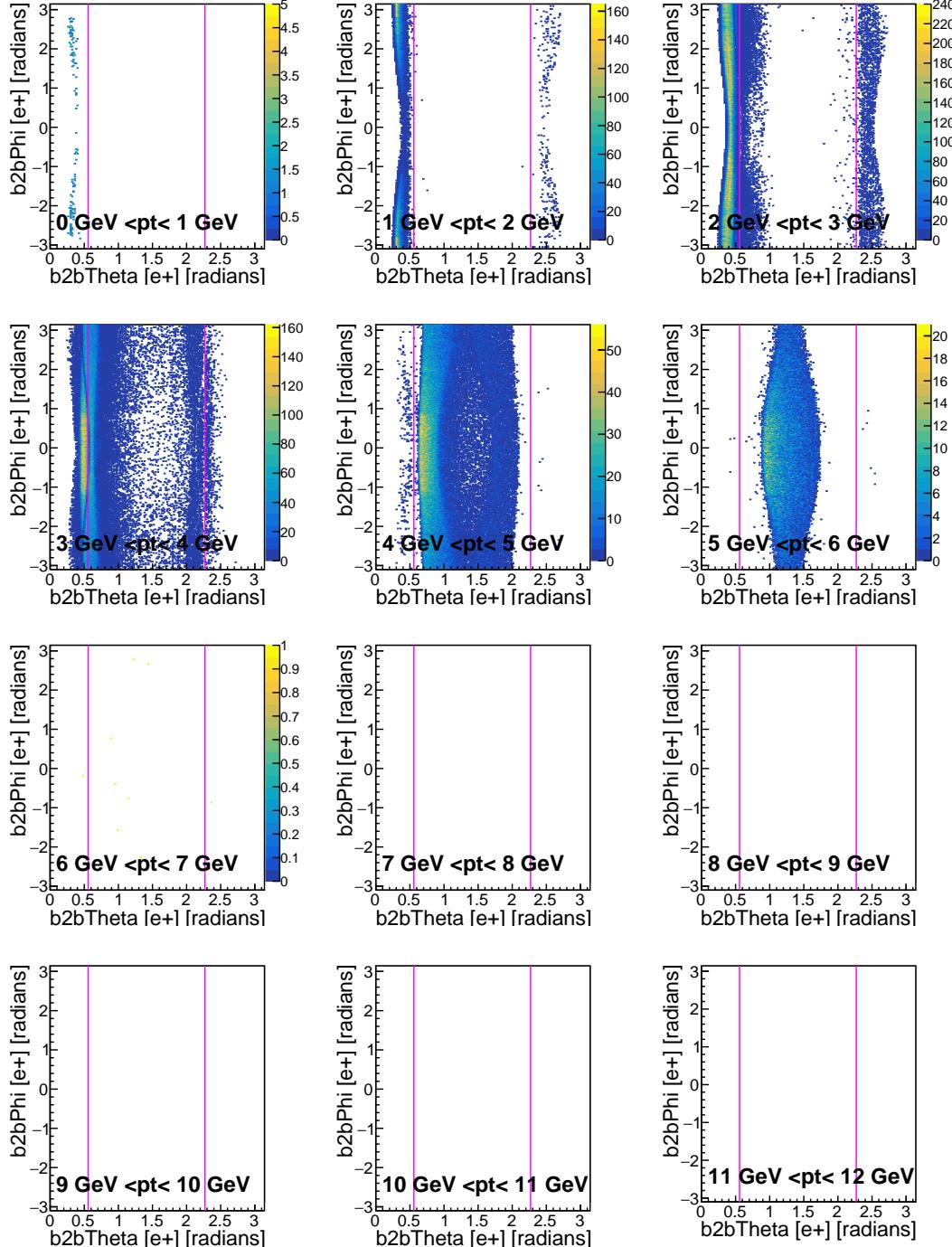


Figure 6.14.: Predicted θ and ϕ denominator histograms of the electron for different transverse momenta for phase2 MC are shown. The different areas of interest are indicated by the pink line.

6.9. Dividing The ECL In Areas Of Interest

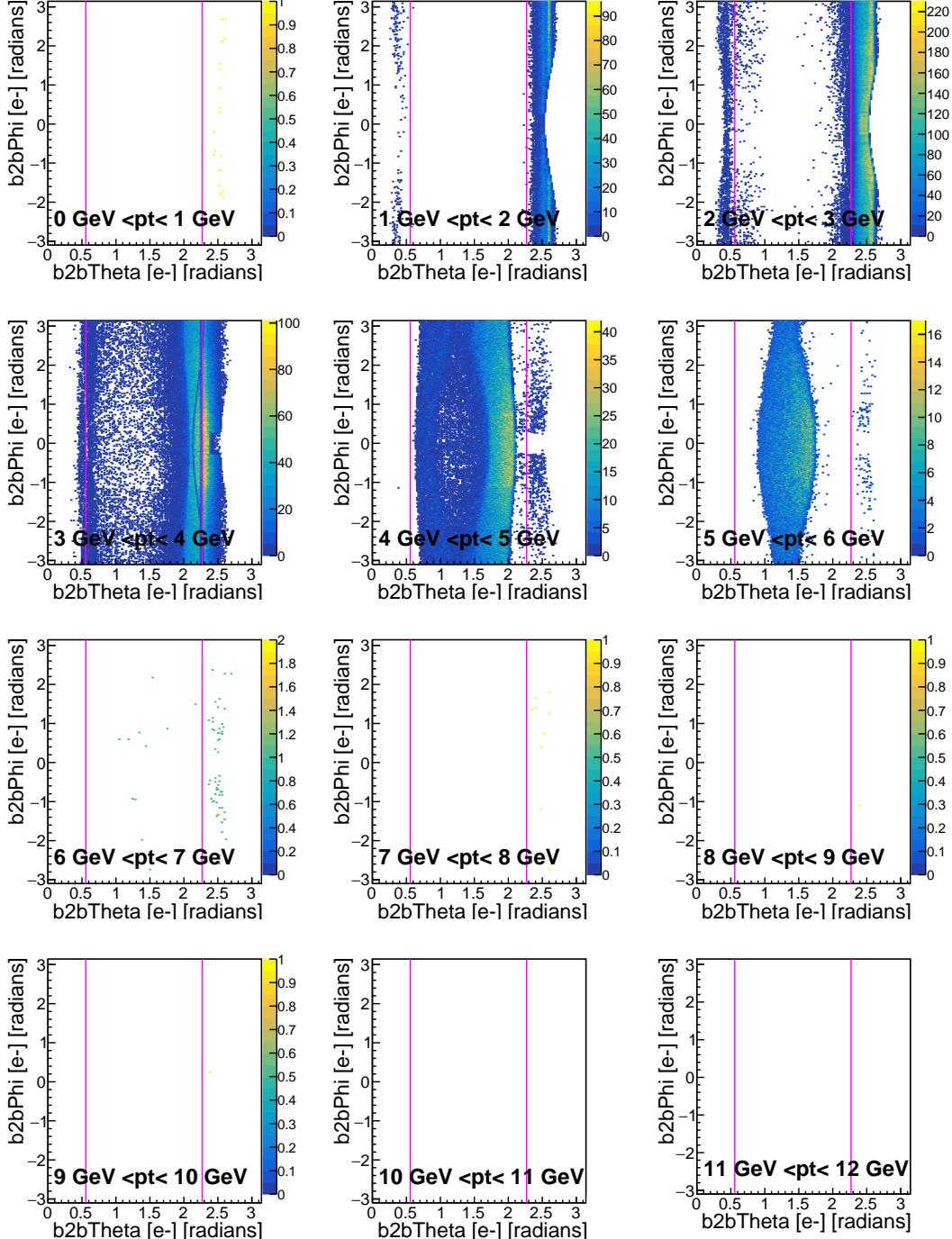


Figure 6.15.: Predicted θ and ϕ denominator histograms of the positron for different transverse momenta for phase2 MC are shown. The different areas of interest are indicated by the pink line.

In this chapter the tracking efficiency studies on phase2 will be presented. The selection described in chapter 6 will be applied in this chapter. Phase2 data in blue and phase2 Monte Carlo in red will be shown together, in order to make comparison between these two easier. The individual tracking efficiencies can be found in the appendix chapter B. Also, only tracking efficiencies with $\Delta\epsilon < 0.4$ are plotted to make the plots more easy to read.

We will see that the tracking efficiencies for phase2 MC will be higher than the tracking efficiencies for phase2 data. This is expected because if you want to generate Monte Carlo files, you have to simulate the detector as a whole and it is impossible to consider every aspect of the structure of the detector like cabling, screws and even impurities of the material which we have in reality. These additional materials can interact with the outgoing particles, and these particles could scatter an additional or be absorbed by the material, for example. In addition, there is no dead time of the detector in MC. Each event is simulated individually. This is another error source for real data. Also, in MC, the detector is working with optimal conditions. Only one event is happening at a time, there are no fluctuations in the power supplies etc. For real data, all of these issues result in a lower tracking efficiency. Therefore, phase MC should have a higher tracking efficiency compared to phase2 data. Otherwise, it will be noted. This is also true for phase3.

7.1. Momentum Efficiencies

7.1.1. Forward End-Cap

In figure 7.1 you can see the calculated electron tracking efficiency for different momenta. As expected, the tracking efficiency for phase2 data is almost all of the time worse than the efficiency for phase2 MC for all momenta. For momenta between 4 GeV and 5 GeV, phase2 MC and phase2 data have a similar efficiency. In both cases, the lowest efficiency occurs at $\phi \approx 0$. According to figures 6.12 and A.5, we expect that most electrons have a momentum between 5 GeV and 8 GeV. For momenta between 5 GeV and 6 GeV phase2 data and phase2 MC have some differences in the calculated tracking efficiency. Phase2 MC has an efficiency between 0.80 and 0.95 with an ex-

7. Phase2 Tracking Efficiency

ception of an efficiency drop at $\phi \approx 0$. This drop also appears on phase2 data, but for $\phi > \text{abs}(1.5)$ the efficiency on phase2 data is much worse than phase2 MC. Here the efficiency falls partially below 0.7 for phase2 data. The biggest difference occurs for momenta between 6 GeV and 7 GeV. For phase2 MC, the tracking efficiency ranges between 0.90 and almost 1.00. But the efficiency oscillates heavily between 0.7 and 0.95 for phase2 data. In both cases the highest efficiency occurs at $\phi \approx 0$. For momenta between 7 GeV and 8 GeV, phase2 MC has a tracking efficiency of above 0.98 for all ϕ angles. Except for $\phi \approx 0$. Here the efficiency is still high but the errors are bigger. For phase2 data, the efficiency is also very high for $\phi > \text{abs}(1)$. But for $\phi < \text{abs}(1)$ the efficiency falls down by over 10 %.

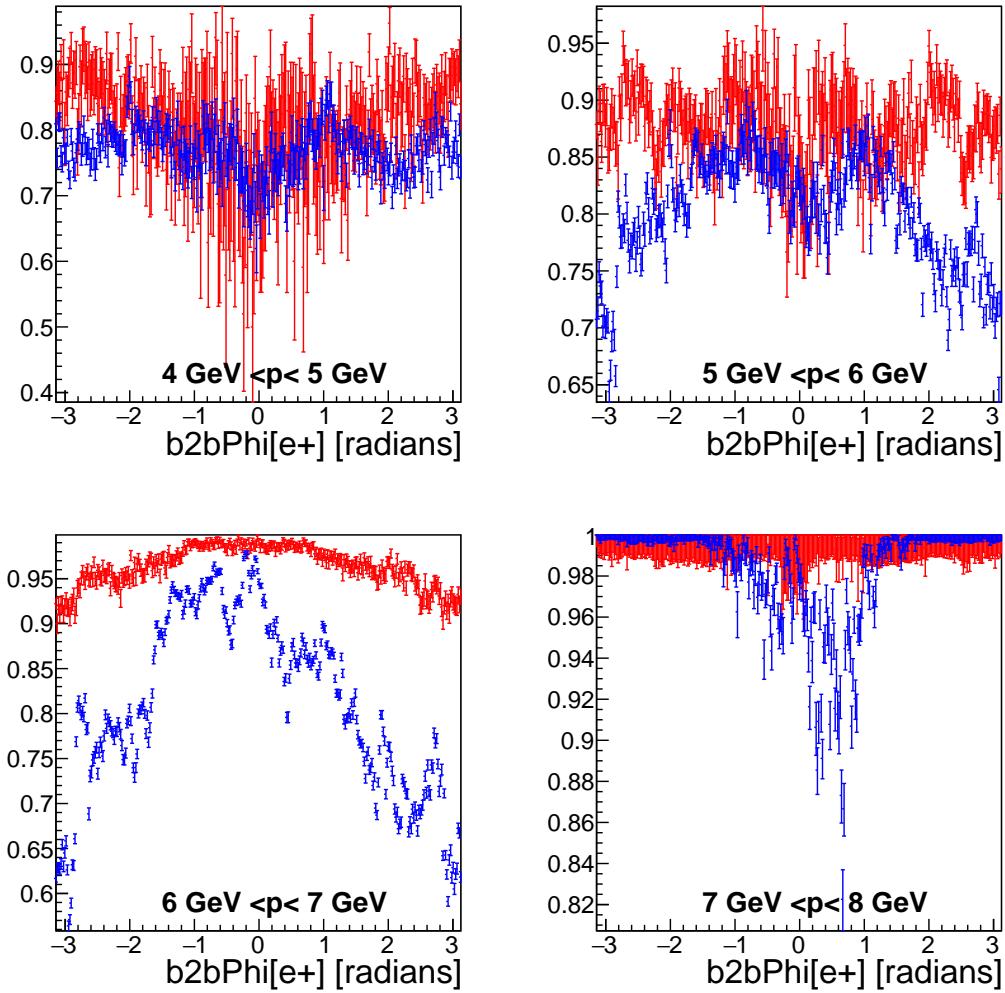


Figure 7.1.: Electron ϕ tracking efficiency plots in the forward end-cap. The tracking efficiency for phase2 data is shown in blue and phase2 MC in red.

7.1. Momentum Efficiencies

7.1.2. Barrel

In figure 7.2 the calculated electron tracking efficiency in the barrel is shown. For momenta between 4 GeV and 5 GeV the tracking efficiency is between 0.75 and 0.96 for phase2 MC and between 0.77 and 0.93 for phase2 data. For phase2 data the efficiency has its minimum at $\phi \approx 0$. For momenta between 5 GeV and 6 GeV, the efficiency gets better. The tracking efficiency ranges between 0.90 and 0.99 for phase2 MC and between 0.91 and 0.98 for phase2 data. The structure of this efficiency is very similar compared to the tracking efficiency for momenta between 4 GeV and 5 GeV. In both cases the lowest efficiency occurs at $\phi \approx 0$ for phase2 data. The best tracking efficiencies for electrons in the barrel appear at momenta between 6 GeV and 7 GeV. Here the efficiency for phase2 MC is between 0.98 and 1 and for phase2 data between 0.955 and 0.995. Again, the lowest calculated tracking efficiency occurs at $\phi \approx 0.5$. Without this drop, the tracking efficiency of phase2 data is between 0.980 and 0.995. The calculated tracking efficiencies for positrons in the barrel can be found in figure 7.3. You can see that for momenta between 3 GeV and 4 GeV, the calculated tracking efficiency is between 0.7 and 0.98 for phase2 MC and between 0.7 and 0.92 for phase2 data. The efficiency for phase2 MC stays more or less the same over all values of ϕ . For phase2 data, there is an efficiency drop at $\phi \approx 0$.

For momenta between 4 GeV and 5 GeV the tracking efficiency is between 0.97 and 1 for phase2 MC and between 0.96 and 0.99 for phase2 data. Phase2 data has almost always a lower calculated tracking efficiency than phase2 MC. The biggest difference between phase2 data and phase2 MC appears at $\phi \approx 0.5$. Here, the efficiency for phase2 data falls down significantly. For momenta between 5 GeV and 6 GeV, the tracking efficiency ranges between 0.93 and 1 for phase2 MC and 0.95 and 0.99 for phase2 data. The tracking efficiency for phase2 MC is higher by 0.02 compared to phase2 data for almost all ϕ angles. For momenta between 6 GeV and 7 GeV, the phase2 MC tracking efficiency ranges between 0.75 and 1. This wide range is a result of the low statistic for positrons at this momentum. The calculated tracking efficiency for phase2 data ranges between 0.9 and 1. For all tracking efficiencies with momenta between 4 GeV and 7 GeV, you can see a dip at $\phi \approx 0.5$.

7. Phase2 Tracking Efficiency

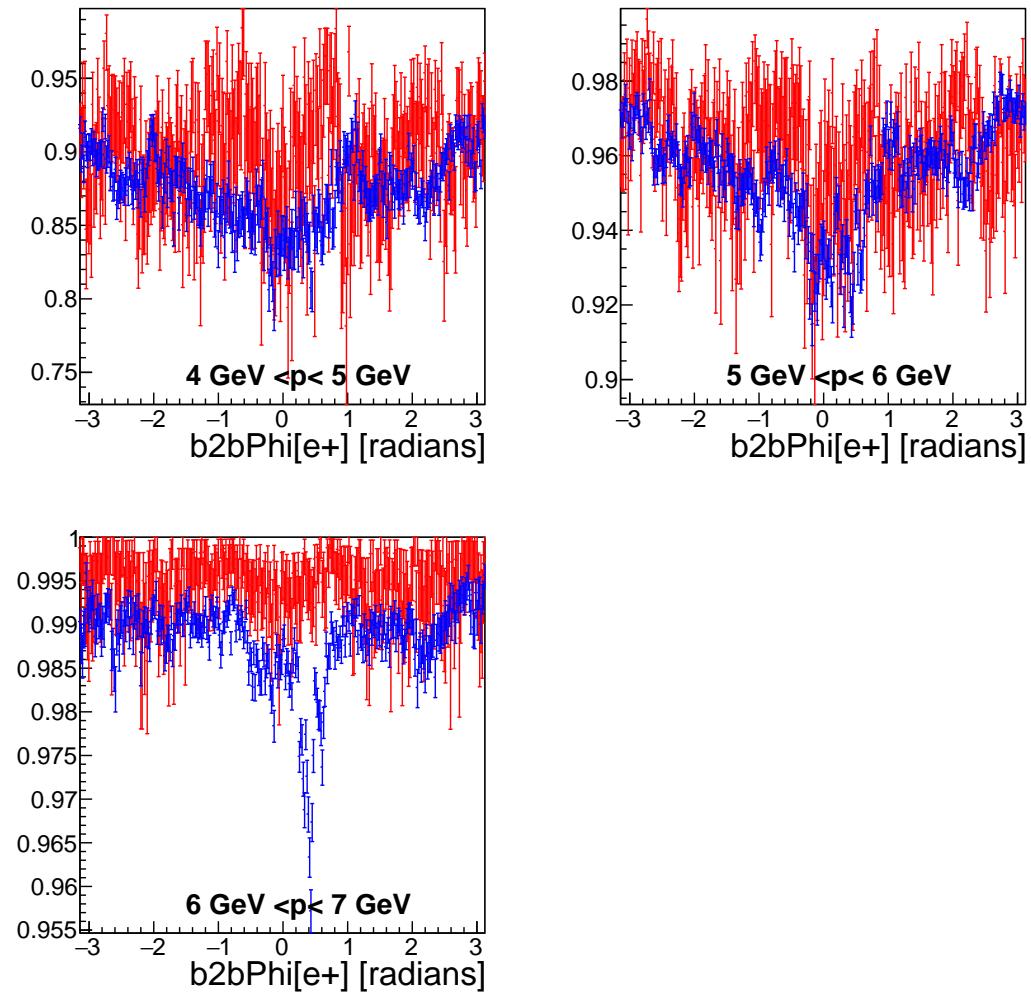


Figure 7.2.: Electron ϕ tracking efficiency plots in the barrel. The tracking efficiency for phase2 data is shown in blue and phase2 MC in red.

7.1. Momentum Efficiencies

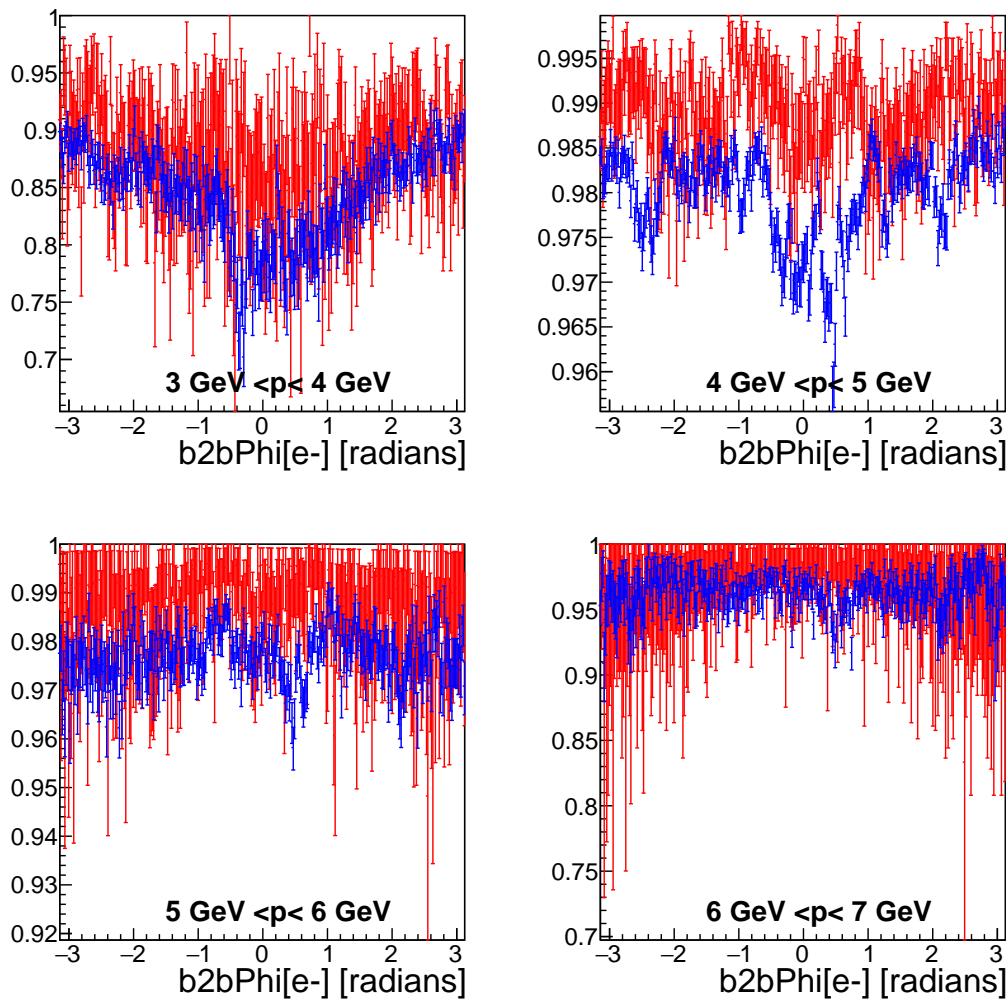


Figure 7.3.: Positron ϕ tracking efficiency plots in the barrel. The tracking efficiency for phase2 data is shown in blue and phase2 MC in red.

7. Phase2 Tracking Efficiency

7.1.3. Backward End-Cap

In figure 7.4 you can see the calculated positron tracking efficiency for different momenta in the backward end-cap. Due to the kinematics at Belle II, almost no electrons are detected in the backward end-cap. For momenta between 2 GeV and 3 GeV, the calculated tracking efficiency is between 0.95 and 1 for phase2 data and between 0.85 and 1 for phase2 MC. An exception occurs at $\phi \approx 0$, here the error bars for phase2 MC are noticeably large. For momenta between 3 GeV and 4 GeV the tracking efficiency covers a very large range. For phase2 MC the efficiency is between 0.4 and 0.95 and for phase2 data between 0.2 and 0.85. For $\phi < -1$, the efficiency is slightly higher for phase2 data compared to phase2 MC. A strange structure occurs at $\phi \approx 0$ for phase2 data. Starting at around $\phi \approx -1.7$ the efficiency goes up from 0.4 to 0.65 at $\phi \approx -0.8$, then it goes back down to 0.4 before it reaches a maximum of 0.8 at $\phi \lesssim 0$. At $\phi = 0$ the efficiency is down to ~ 0.6 . At $\phi \gtrsim 0$, the efficiency is back to a maximum of 0.85 before it falls back down to ~ 0.4 . After that, the efficiency stays constant until it starts to fall down again at $\phi \approx 1.5$. It reaches its minimum at $\phi \approx 2$. For phase2 MC the calculated tracking efficiency starts similar to phase2 data at around 0.5 and it slowly increases until $\phi \approx -1$. Then it starts to vary from phase2 data. For phase2 MC the efficiency increases rapidly until it reaches its maximum at $\phi = 0$. Then it falls back to 0.6 at $\phi \approx 1$. A similar structure can be found for momenta between 4 GeV and 5 GeV. The only difference is that the efficiency is higher compared to the lower momenta. For example, phase2 MC reaches a calculated tracking efficiency of almost 1 at $\phi = 0$. For momenta between 5 GeV and 6 GeV the efficiency is above 0.9 for phase2 MC and above 0.98 for phase2 data with the exception of $\phi \approx 0$. Here, the error of the calculated efficiencies are very large in both cases due to the low statistics.

7.1. Momentum Efficiencies

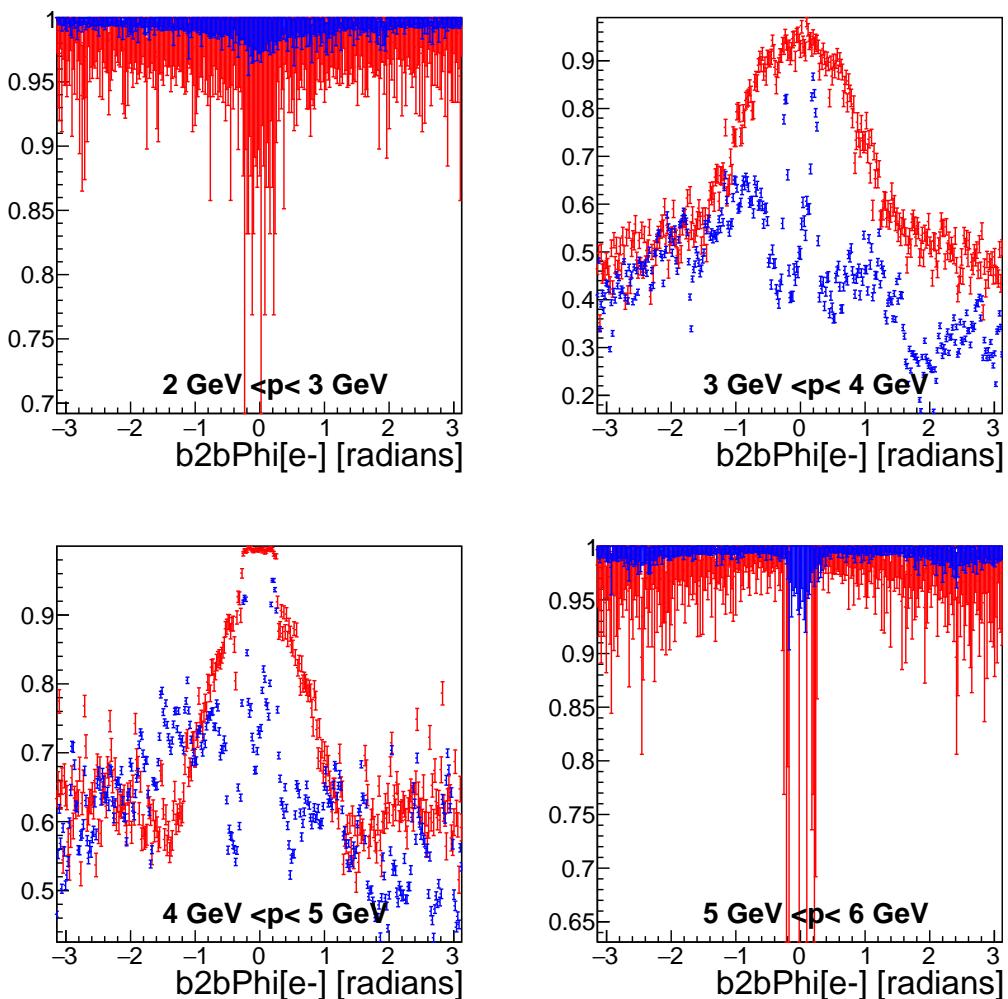


Figure 7.4.: Positron ϕ tracking efficiency plots in the backward end-cap. The tracking efficiency for phase2 data is shown in blue and phase2 MC in red.

7. Phase2 Tracking Efficiency

7.1.4. θ Efficiencies

This section will present the calculated tracking efficiencies as a function of the polar angle θ . The pink lines in each of the following plots will indicate the different areas of the ECL.

Figure 7.5 shows the calculated electron tracking efficiency for different momenta as a function of the polar angle. For momenta between 3 GeV and 4 GeV, the calculated tracking efficiency starts rather high for small θ angles. For phase2 MC and phase2 data the highest efficiency is in the forward end-cap with over 0.9. But it falls down very quickly with increasing θ . At the transition between the forward end-cap and the barrel, the efficiency has a local minimum of only 0.2 for phase2 data and almost 0 for phase2 MC. For $0.5 < \theta < 0.7$, the efficiency goes back up to 0.6 very quickly. After this, the efficiency increases slowly to around 0.85 for phase2 data and 0.9 for phase2 MC at $\theta \approx 2.2$. At roughly this angle the barrel ends and the backward end-cap begins. In the backward end-cap the efficiency goes up to over 0.9 at first for phase2 MC before it falls down to 0 rather quickly. In contrast, phase2 data falls down strictly monotonic in the backward end-cap. For momenta between 4 GeV and 5 GeV, the structure of the efficiency is similar to the momentum region we just looked at. The only differences are that the efficiency drops at the forward end-cap to barrel transition is not as dominant as before. Here, the efficiency only falls down to 0.6. Also, phase2 MC has a higher tracking efficiency in the forward end-cap compared to phase2 data. In addition, the highest efficiency is reached in the barrel at $1.7 < \theta < 2.3$ for phase2 MC and $1.7 < \theta < 2.2$ for phase2 data. The biggest difference between phase2 MC and phase2 data occurs again in the backward end-cap. Here the phase2 data tracking efficiency falls down noticeably earlier compared to phase2 MC. The phase2 data tracking efficiency is lower compared to phase2 MC for almost all θ . For momenta between 5 GeV and 6 GeV, there is no dip in the efficiency at the transition between forward end-cap and barrel. In the forward end-cap the efficiency of phase2 data starts lower compared to the phase2 MC efficiency. But they meet at $\theta \approx 0.4$ and increase up to approximately 0.95 and more at $\theta \approx 1$. For higher θ values the efficiency in the barrel stays more or less the same. One can argue that there is a small dip in phase2 data at $\theta \approx 1.9$. In the plot for the momentum range between 6 GeV and 7 GeV, the efficiency for phase2 data starts lower compared to phase2 MC efficiency. In the barrel both efficiencies stay above 0.98 with an exception of a small dip for phase2 data at $\theta \approx 1.25$. For momenta between 7 GeV and 8 GeV the tracking efficiency for phase2 MC is about 0.99. This was already discussed in section 7.1.1. For phase2 the tracking efficiency is slightly lower. Again for phase2 data, a small dip in the tracking efficiency at $\theta \approx 0.4$ appears. For the last momentum range, similar to the previous momenta range the tracking efficiency for phase2 MC and phase2 MC are above 0.95.

In figure 7.6 the calculated tracking efficiency for positrons as a function of the polar angle θ is shown. For momenta between 2 GeV and 3 GeV, almost all positrons are detected in the backward end-cap, with a tracking efficiency of over 0.98 for phase2 MC and phase2 data. For momenta between 3 GeV and 4 GeV, the tracking efficiency

7.1. Momentum Efficiencies

increases slowly in the barrel with increasing values of θ . It reaches its maximum of ~ 0.9 at $\theta \approx 2.2$. Then the tracking efficiency falls down for phase2 data and it continues to fall in the backward end-cap. For phase2 MC the efficiency has a small peak in the backward end-cap before it also falls down. For momenta between 4 GeV and 5 GeV, the tracking efficiency has a similar structure compared to the previous momenta range except it is overall higher. The calculated tracking efficiency also slowly increases in the barrel until it reaches its maximum of over 0.95 for phase2 MC and phase2 data at $\theta \approx 1.6$. The tracking efficiency stays more or less constant with increasing θ in the barrel. As soon as the backward end-cap starts the phase2 data efficiency drops down. Phase2 MC tracking efficiency stays very high up to $\theta \approx 2.4$. For momenta between 5 GeV and 6 GeV, the calculated tracking efficiency also gets higher in the barrel. It reaches its maximum at $\theta \approx 1$. After this it stays more or less the same, even in the backward end-cap. At $\theta \approx 1.9$ there is a small dip for phase2 data. We saw this also for electrons at the same momenta range. The last positron momenta range is between 6 GeV and 7 GeV. Here, the calculated tracking efficiency increases rapidly in the forward end-cap. It reaches its maximum of over 0.95 for phase2 MC and around 0.95 for phase2 data in the barrel. In contrast to the forward end-cap and the barrel, the tracking efficiency in the backward end-cap is higher for phase2 data compared to phase2 MC. Similar to the phase2 tracking efficiency for electrons with the same momenta range, there is a small dip at $\theta \approx 1.25$.

7. Phase2 Tracking Efficiency

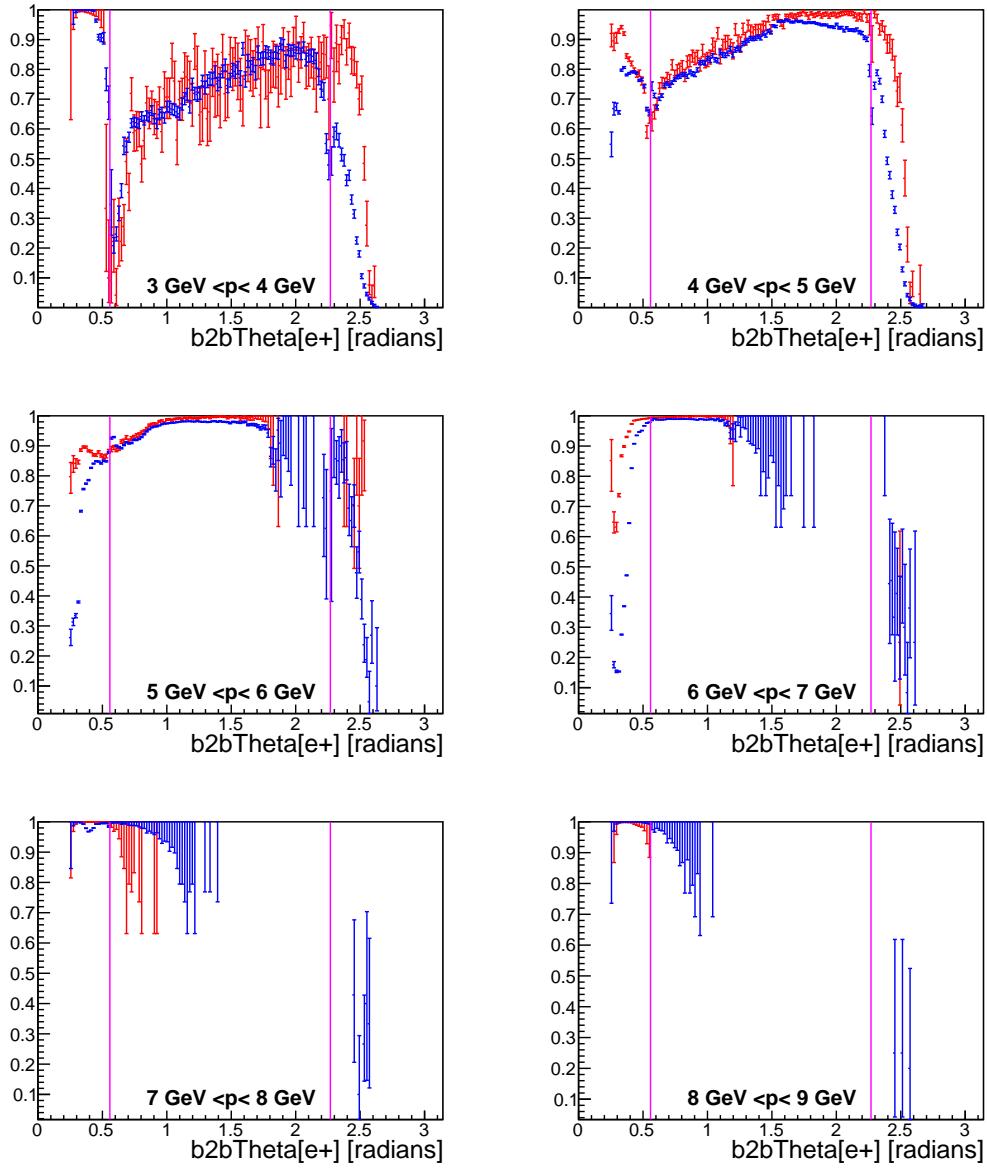


Figure 7.5.: Electron θ momentum tracking efficiency plots. The tracking efficiency for phase2 data is shown in blue and phase2 MC in red. The pink line indicates the different sectors of the ECL.

7.1. Momentum Efficiencies

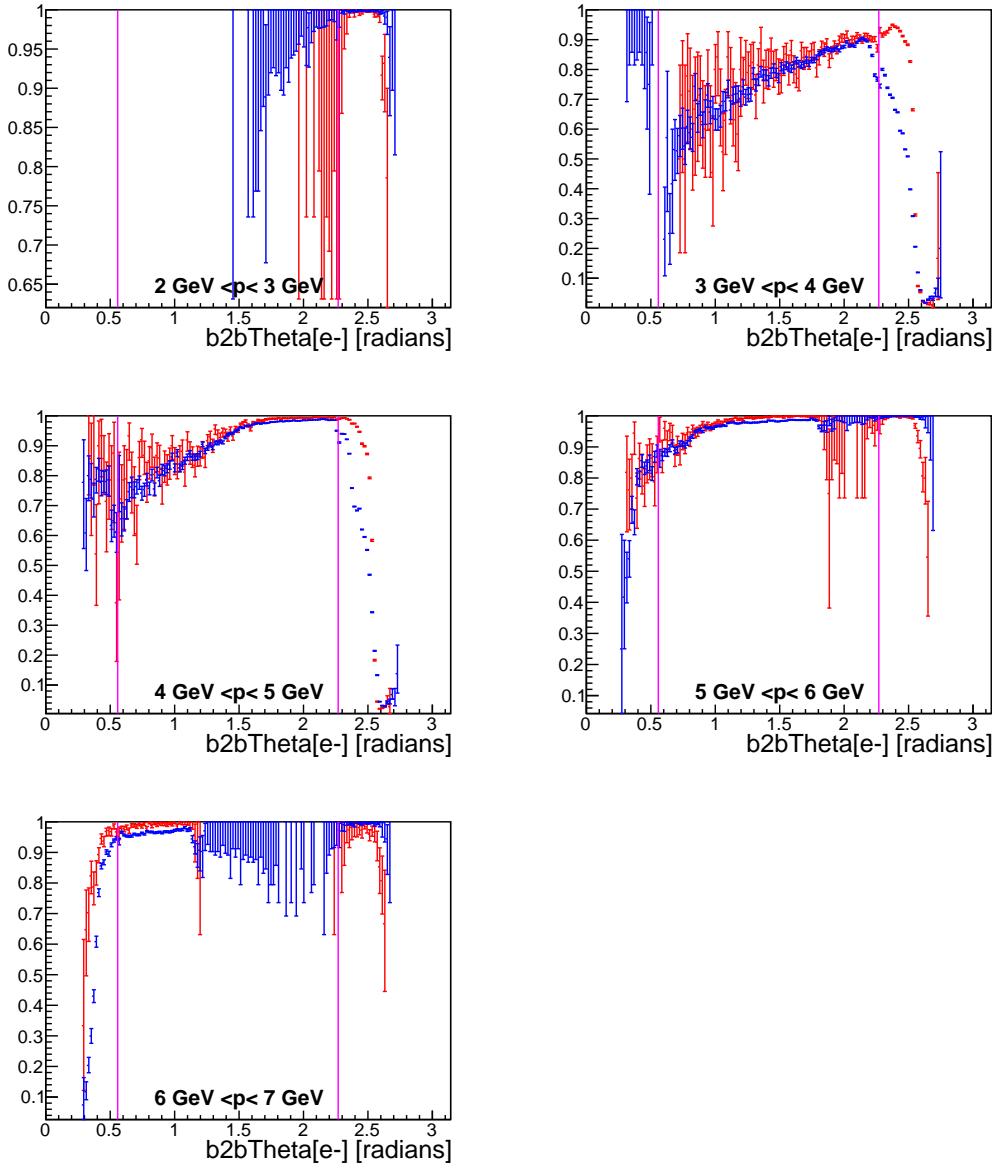


Figure 7.6.: Positron θ momentum tracking efficiency plots. The tracking efficiency for phase2 data is shown in blue and phase2 MC in red. The pink line indicates the different sectors of the ECL.

7. Phase2 Tracking Efficiency

7.2. Transverse Momentum Efficiencies

7.2.1. Forward End-Cap

In figure 7.7 you can see the calculated tracking efficiency for electrons in the forward end-cap with different transverse momenta. For transverse momenta between 1 GeV and 2 GeV, the biggest differences between phase2 MC and phase2 data occur at $\text{abs}(\phi) \gtrsim 1$. For these angles the phase2 data efficiency is noticeably worse compared to phase2 MC. The phase2 data tracking efficiency is between 0.4 and 0.95 and between 0.4 and 1 for phase2 MC. For transverse momenta between 2 GeV and 3 GeV, the tracking efficiency for phase2 MC stays above 0.9 for all values of ϕ . For phase2 data, the structure of the tracking efficiency looks more random. The lowest efficiency of approximately 0.65 occurs at $\text{abs}(\phi) \approx 3$ and the highest efficiency with 0.9 at $\phi \approx 0$. Also, the efficiency has a lot of local minimums and maximums. For transverse momenta between 3 GeV and 4 GeV, phase2 MC has an efficiency of over 0.97 for almost all values of ϕ . The tracking efficiency for phase2 data also has an efficiency of over 0.97 for most ϕ values with the exceptions of $\text{abs}(\phi) \approx 0.5$, $\phi \approx 1$ and $\phi \approx 2.9$. In all of these cases the tracking efficiency drops down significantly and in the $\phi \approx 0.5$ case even down to 0.92.

7.2. Transverse Momentum Efficiencies

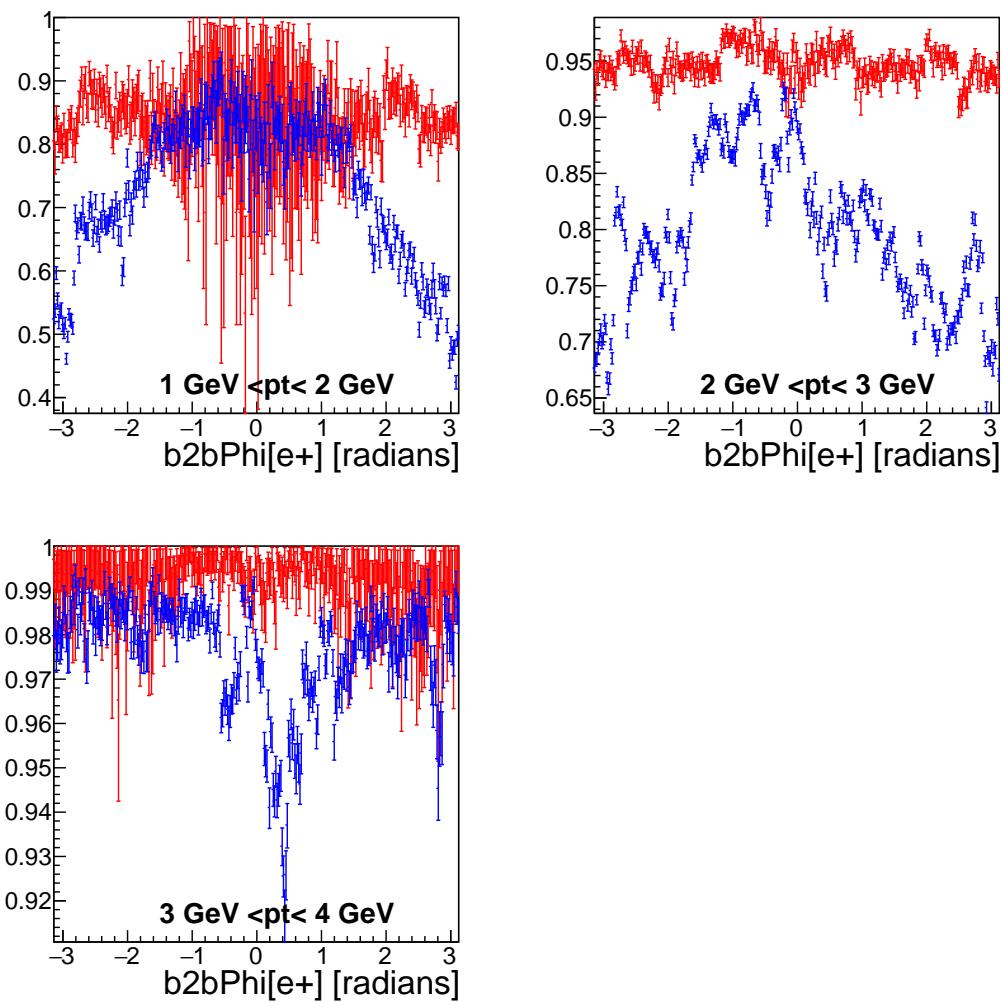


Figure 7.7.: Electron ϕ transverse momentum tracking efficiency plots in the forward end-cap. The tracking efficiency for phase2 data is shown in blue and phase2 MC in red.

7. Phase2 Tracking Efficiency

7.2.2. Barrel

Figure 7.8 shows the calculated phase2 electron tracking efficiency for different transverse momenta in the barrel. For transverse momenta between 2 GeV and 3 GeV, the tracking efficiency of phase2 MC and phase2 data has a very similar structure. In both cases the lowest tracking efficiency occurs at $\phi \approx 0$. For transverse momenta between 3 GeV and 5 GeV, the structure of the efficiency of phase2 MC and phase2 data differ. For phase2 MC the tracking efficiency is above 0.92 and for phase2 data above 0.91. The tracking efficiency becomes higher with increasing transverse momentum. The highest tracking efficiency occurs at transverse momenta between 5 GeV and 6 GeV. The efficiency of phase2 MC and phase2 data never falls below 0.95. For phase2 data, the lowest tracking efficiency appears at $\phi \approx 0$. The error bars for phase2 MC are smaller for $\phi \approx 0$ due to the kinematics at Belle II. The electron and positron beams are hitting each other under an angle and therefore there is more statistics at $\phi \approx 0$. Figure 7.9 shows positrons tracking efficiencies in the barrel for different transverse momenta. For transverse momenta between 3 GeV and 4 GeV, the calculated tracking efficiency is above 0.94 for both phase2 MC and phase2 data. The error bars are too big to see a structure in the efficiency for phase2 MC. The tracking efficiency for phase2 data is lower compared to phase2 MC for almost all values of ϕ . There are also some noticeable dips in the efficiency at $\phi \approx -2.2, \lesssim 0, \approx 0.5$ and ≈ 2.2 . For transverse momenta between 4 GeV and 5 GeV, the structure of the phase2 data efficiency looks similar to the structure of the lower transverse momenta with the exception that the tracking efficiency is overall higher with at least 0.96 and the dips on phase2 data are not that dominant. For transverse momenta between 5 GeV and 6 GeV, the phase2 data tracking efficiency is almost always above 0.96. Again, there is a small dip at $\phi \approx 0.5$. For phase2 MC the tracking efficiency is almost always above 0.95.

7.2. Transverse Momentum Efficiencies

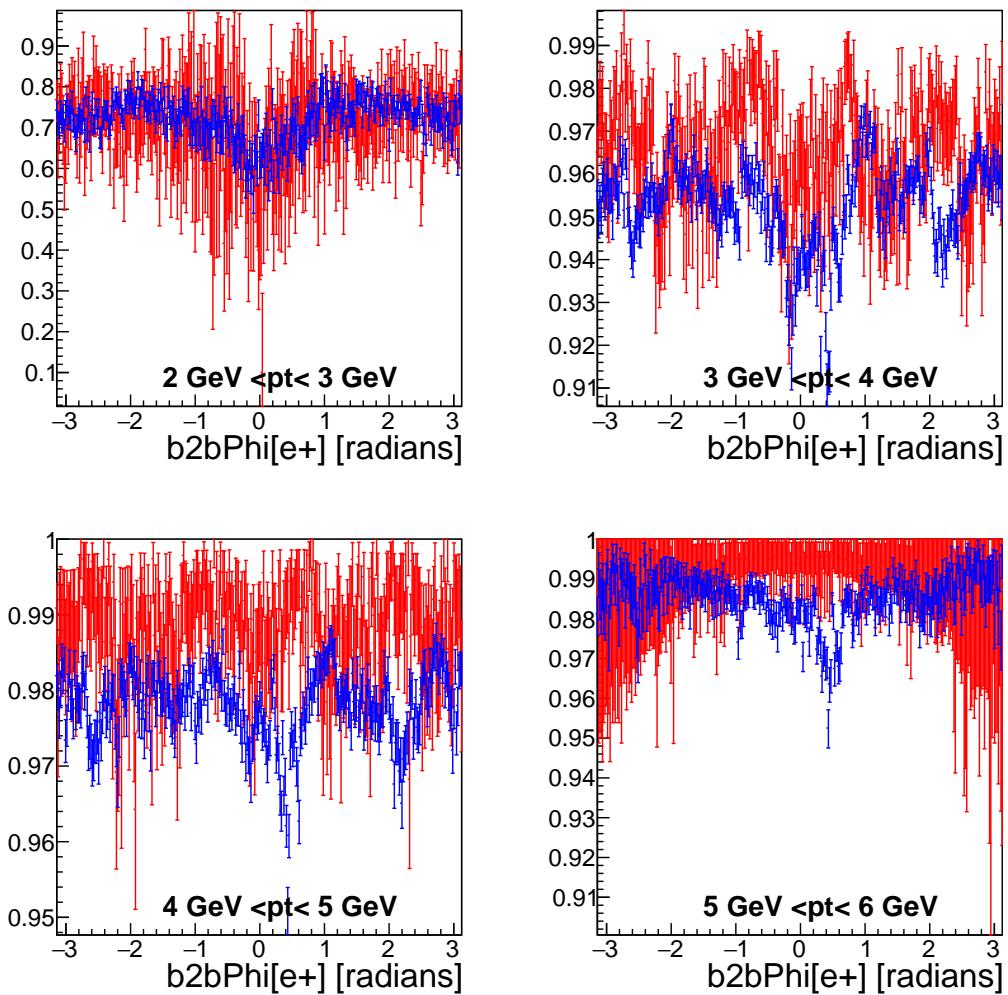


Figure 7.8.: Electron ϕ transverse momentum tracking efficiency plots in the barrel.
The tracking efficiency for phase2 data is shown in blue and phase2 MC
in red.

7. Phase2 Tracking Efficiency

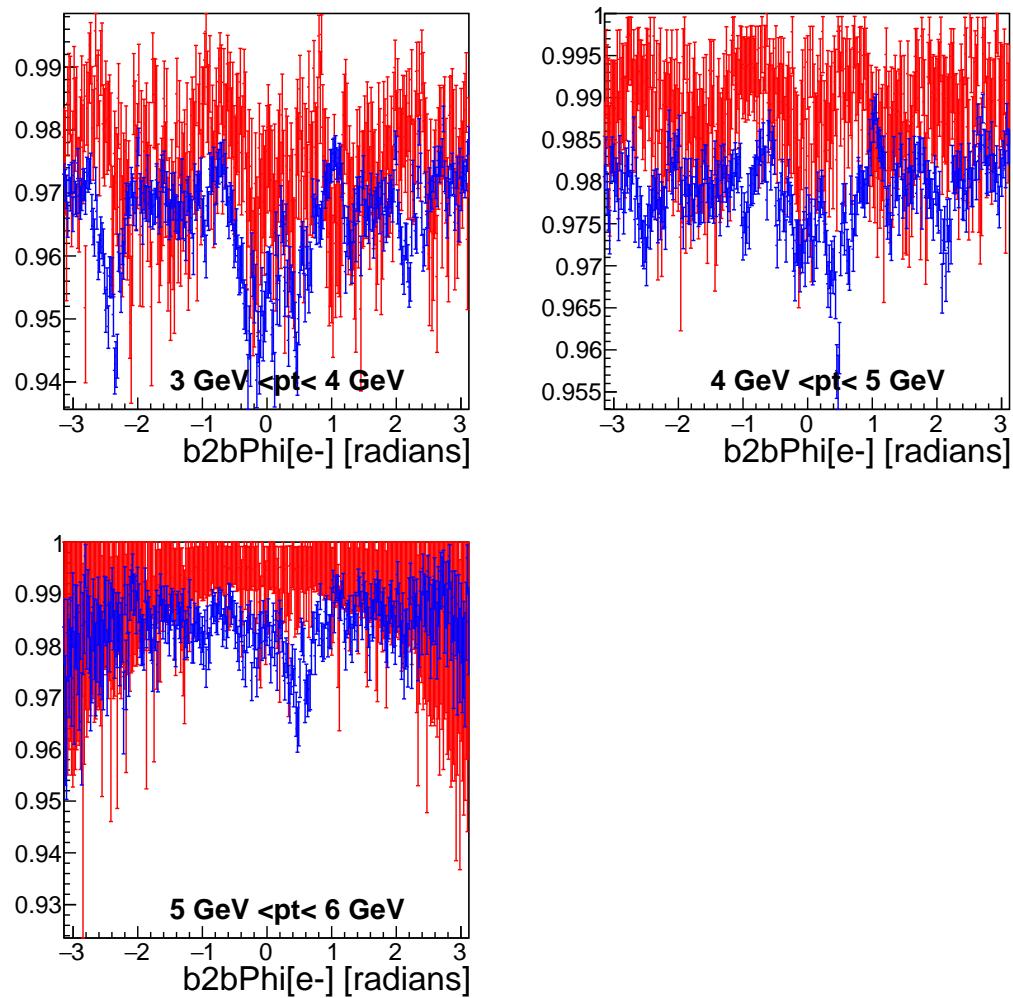


Figure 7.9.: Positron ϕ transverse momentum tracking efficiency plots in the barrel.
The tracking efficiency for phase2 data is shown in blue and phase2 MC in red.

7.2. Transverse Momentum Efficiencies

7.2.3. Backward End-Cap

Figure 7.10 shows the calculated positron tracking efficiencies for different transverse momenta in the backward end-cap. For transverse momenta between 1 GeV and 2 GeV, the tracking efficiency of phase2 MC and phase2 data are very close together. You can see some sort of plateau at $\text{abs}(\phi) \lesssim 1.5$. Here, the tracking efficiency is very high compared to the efficiency of the remaining ϕ angles. One half of the backward end-cap appears to have a significantly better efficiency. It is also worth noting, that for $\phi < 1.5$, phase2 data appears to have a higher efficiency compared to phase2 MC and for $\phi > 1.5$ it is the other way around. For transverse momenta between 2 GeV and 3 GeV, the tracking efficiency for $\text{abs}(\phi) > 1.5$ is again very low with just about 0.6. The plateau we saw before is also way more narrow and it only appears on phase2 MC. For phase2 data the tracking efficiency oscillates heavily at $\phi \approx 0$. It starts with a drop of the efficiency down to 0.4 at $\phi \approx -0.5$ followed by a local maximum of ~ 0.9 at $\phi \lesssim 0$. At $\phi \approx 0$ the efficiency falls down to 0.6 and goes back up to ~ 0.9 at $\phi \gtrsim 0$. Finally, it falls back down to around 0.4 at $\phi \approx 0.5$. The last efficiency drop for phase2 data appears at $\phi \approx 2$. Here the efficiency falls down to ~ 0.3 . For transverse momenta between 3 GeV and 4 GeV, the calculated tracking efficiency for phase2 MC is above 0.98 for all values of ϕ . For phase2 data, the tracking efficiency is above 0.95 for $\text{abs}(\phi) > 1$, but you can see the structure in the efficiency we saw in the previous transverse momenta range again. This time, the drops of the efficiency is not as dominant and it never falls below 0.87.

7. Phase2 Tracking Efficiency

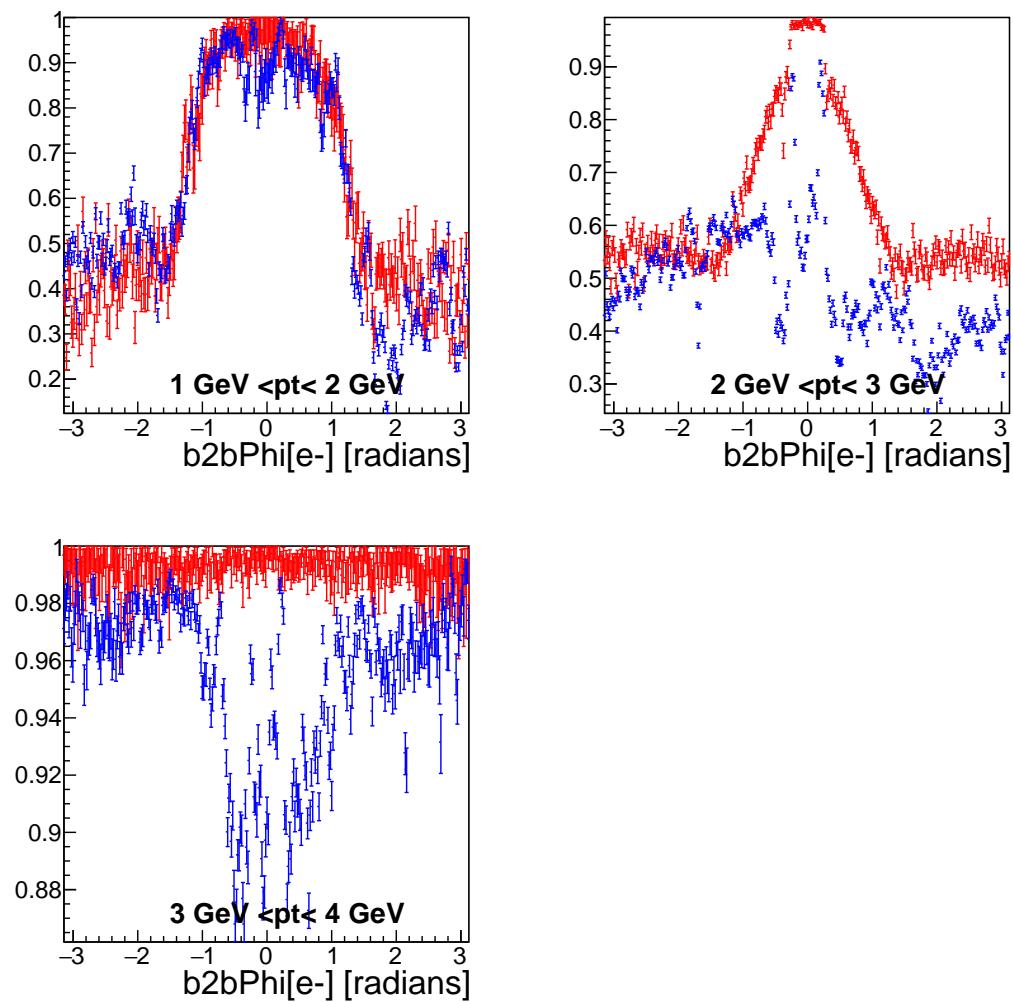


Figure 7.10.: Positron ϕ transverse momentum tracking efficiency plots in the backward end-cap. The tracking efficiency for phase2 data is shown in blue and phase2 MC in red.

7.2. Transverse Momentum Efficiencies

7.2.4. θ Efficiencies

Figure 7.11 shows the calculated electron tracking efficiencies for different transverse momenta as a function of the polar angle θ . For transverse momenta between 1 GeV and 2 GeV, almost all electrons are detected in the forward end-cap. The tracking efficiency for phase2 data is very low with only about 0.3 at $\theta \approx 0.25$. Then it jumps up to 0.75 at $\theta \approx 0.3$. After this it increases further until it reaches its maximum of about 0.9 at $\theta \approx 0.5$. The tracking efficiency for phase2 MC starts high with 0.9 at $\theta \approx 0.25$ but it first falls down to 0.7 at $\theta \approx 0.3$. After this it immediately jumps back up to 0.9. Then, it falls back to 0.8 at $\theta \approx 0.4$ and after this it rises back up to over 0.9 at $\theta \approx 0.5$. For transverse momenta between 2 GeV and 3 GeV, the tracking efficiency of phase2 data starts with 0.7 at $\theta \approx 0.25$. It reaches its local minimum of 0.4 at $\theta \approx 0.3$. After this the efficiency increases and has a maximum of over 0.9 at $\theta \approx 0.5$. With increasing values of θ the efficiency falls down. First rapidly in the forward end-cap then slowly in the barrel. It reaches a local minimum of 0.6 at $\theta \approx 1.0$. The tracking efficiency of phase2 MC starts with 0.85 and reaches a local maximum of 0.95 at $\theta \approx 0.5$. Similar to phase2 data, it falls down after this and reaches a local minimum of 0.6 at $\theta \approx 1.0$. In the backward end-cap, the tracking efficiency of phase2 MC starts with 0.9 and falls down rapidly to 0 at $\theta \approx 2.6$. The tracking efficiency of phase2 data has a similar structure but it is lower by about 0.4. Therefore, it reaches 0 earlier. For transverse momenta between 3 GeV and 4 GeV, the tracking efficiency for both phase2 MC and phase2 data start with almost 1 in the forward end-cap. They are close together and they decrease a little with increasing θ . Starting at $\theta \approx 0.7$, both tracking efficiencies fall down rapidly and they both reach a local minimum of 0.7 at $\theta \approx 1.0$. After this, the phase2 data tracking efficiency gets back up slowly reaching a local maximum at $\theta \approx 2.0$. After this maximum, the efficiency of phase2 data falls down and even has a dip at the transition between the barrel and the backward end-cap. Phase2 MC on the other hand, stays more or less the same in the middle region of the barrel. But it also has a local maximum starting at $\theta \approx 2.0$. The tracking efficiency starts to fall down at $\theta \approx 2.3$. For transverse momenta between 4 GeV and 5 GeV, most electron only hit the barrel and the forward end-cap. the tracking efficiency of phase2 data in the forward end-cap is always above 0.9. The efficiency for phase2 MC is worse for some values of θ due to the large errors. In the barrel, both tracking efficiencies stay above 0.95 with the exception of a wide local minimum of 0.9 at $\theta \approx 1.3$. Also, the tracking efficiency for phase2 data is almost always a little worse than the tracking efficiency of phase2 MC. For transverse momenta between 5 GeV and 6 GeV, almost all electrons are detected in the barrel. Except for some θ angles, the tracking efficiency for phase2 MC and phase2 data stays above 0.96. The tracking efficiency of phase2 data is always a little lower than the phase2 MC tracking efficiency.

Figure 7.12 shows the calculated positron tracking efficiency for different transverse momenta as a function of the polar angle θ . For transverse momenta between 1 GeV and 2 GeV, most of the positrons are detected in the backward end-cap. The tracking efficiency of phase2 data is about 0.85 before it falls down at the end of the backward

7. Phase2 Tracking Efficiency

end-cap. The tracking efficiency for phase2 MC has a similar structure but is also a little higher. For transverse momenta between 2 GeV and 3 GeV, the tracking efficiency for phase2 data starts low but it increases rapidly until it reaches a local maximum of about 0.85 at $\theta \approx 0.5$. After this, the tracking efficiency falls back down. It has a local minimum of about 0.6 at $\theta \approx 1.0$. For $\theta \approx 2.0$ the tracking efficiency is over 0.9 but it falls down with increasing θ and it has a significant dip at the barrel and backward end-cap transition. Then it goes back up until it finally falls down to 0 at the end of the backward end-cap. The phase2 MC tracking efficiency has a similar structure. But the calculated tracking efficiency of phase2 MC is higher compared to phase2 data for almost all values of θ . Also, the dip of the efficiency at the transition between barrel and backward end-cap is not as dominant in phase2 MC. For transverse momenta between 3 GeV and 4 GeV, the tracking efficiency for phase2 data starts with 0.9 at $\theta \approx 0.5$ and rises to a local maximum of 0.95 at the forward end-cap and barrel transition. After this, the tracking efficiency falls down and reaches a local minimum at $\theta \approx 1.0$. Then, it slowly increases until it reaches an efficiency of over 0.95 at $\theta \approx 2.1$. The efficiency stays at this value until the transition between the barrel and the backward end-cap. Here, it falls down a little and the efficiency reaches a local minimum of 0.88 in the backward end-cap at $\theta \approx 2.4$. Finally, the efficiency goes back up to over 0.99. The tracking efficiency for phase2 MC follows a similar path. With the exception that it starts in the forward end-cap at a higher value of over 0.95. Also, there is no local minimum for phase2 MC in the backward end-cap. But it appears to fall down at the end of the backward end-cap. For transverse momenta between 4 GeV and 5 GeV, the tracking efficiency for phase2 MC and phase2 data are close together. In the barrel, both are constantly above 0.92 with a wide minimum at $\theta \approx 1.0$. At $\theta \approx 2.0$, the tracking efficiency even reaches above 0.98 for both phase2 data and phase2 MC. In the backward end-cap, the tracking efficiency of phase2 MC appears to fall down earlier than the phase2 data tracking efficiency. For transverse momenta between 5 GeV and 6 GeV, almost all positrons hit the barrel. The tracking efficiency for both phase2 data and phase2 MC stays above 0.95 for all values with high statistic.

7.2. Transverse Momentum Efficiencies

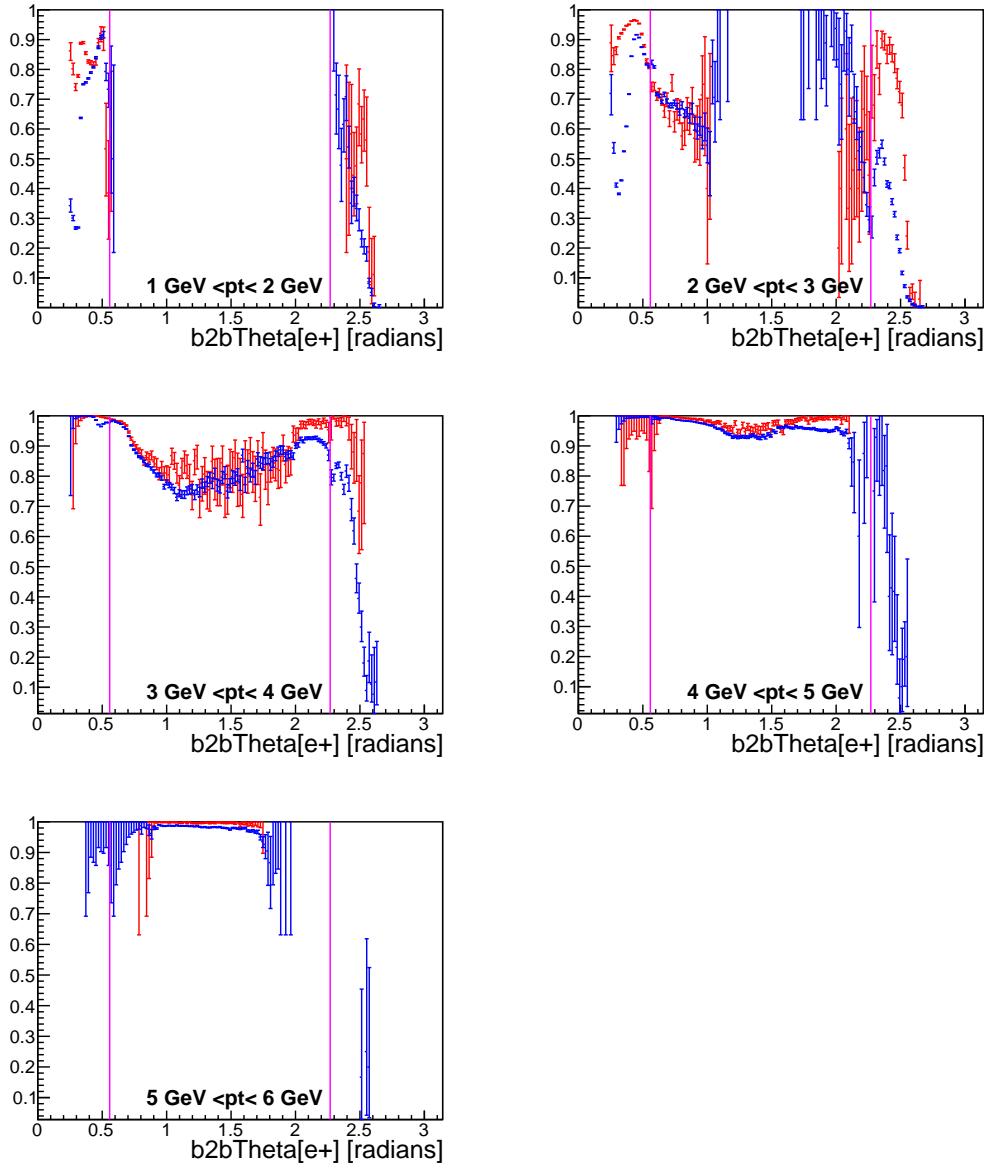


Figure 7.11.: Electron θ transverse momentum tracking efficiency plots. The tracking efficiency for phase2 data is shown in blue and phase2 MC in red. The pink line indicates the different sectors of the ECL.

7. Phase2 Tracking Efficiency

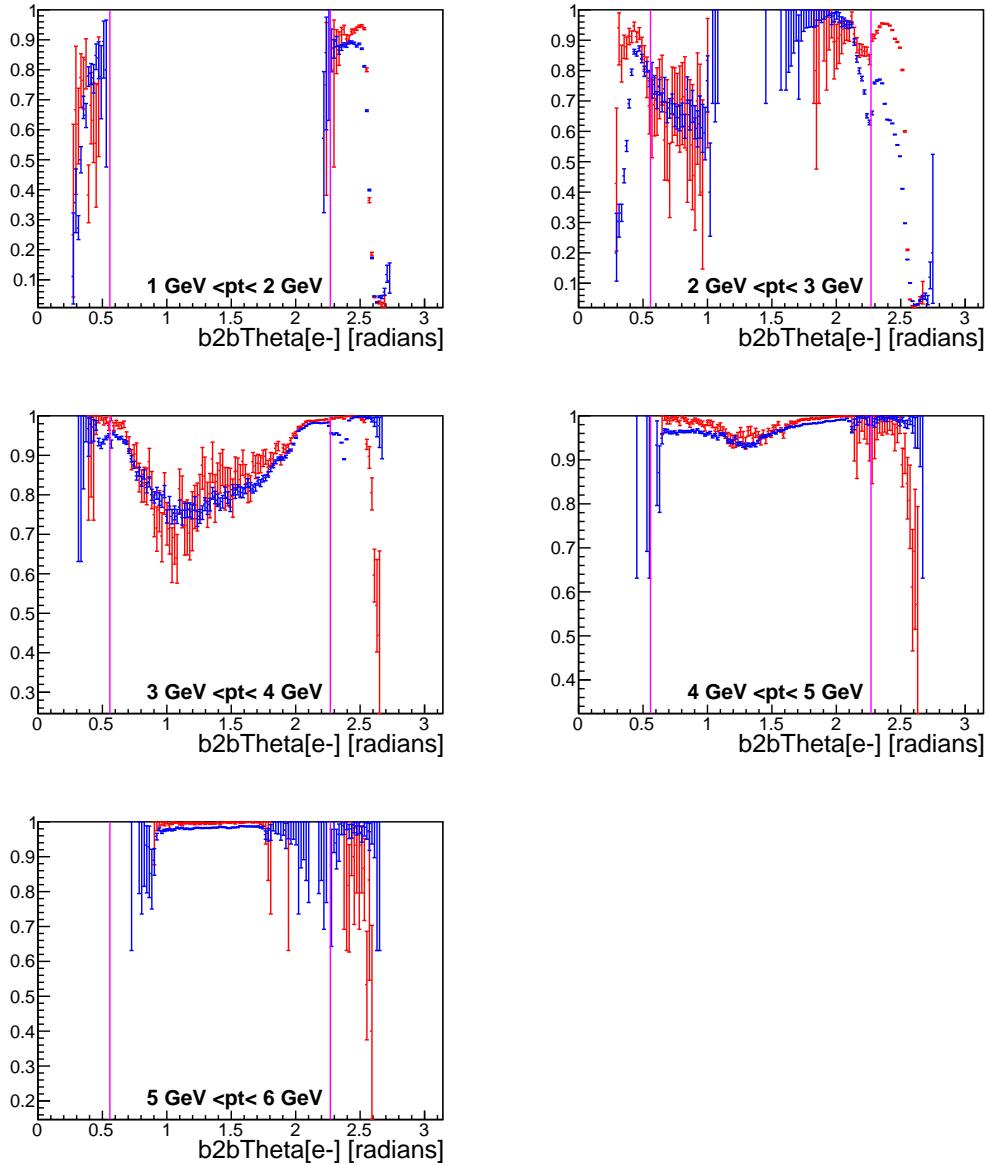


Figure 7.12.: Positron θ transverse momentum tracking efficiency plots. The tracking efficiency for phase2 data is shown in blue and phase2 MC in red. The pink line indicates the different sectors of the ECL.

7.3. θ - ϕ Efficiencies

7.3. θ - ϕ Efficiencies

In figure 7.13 you can see the θ - ϕ efficiencies for phase2 MC on the left and phase2 data on the right. The efficiencies for electrons are shown in the first line and positrons in the second line. These plots combine all momenta of the particles. For electrons, there is a difference between phase2 MC and phase2 data in the forward end-cap. For phase2 MC, there is almost no drop of the efficiency in the forward end-cap in contrast to phase2 data. For positrons the differences occur in the backward end-cap. The transition between high and low tracking efficiency is way more sharp on phase2 MC compared to phase2 data. Also, at around $\phi \approx 0$ and $\theta \approx 2.4$ there is something like a *horn* structure in phase2 data. This structure we already saw in section 7.1.3 for positrons with momenta between 3 GeV and 5 GeV.

7. Phase2 Tracking Efficiency

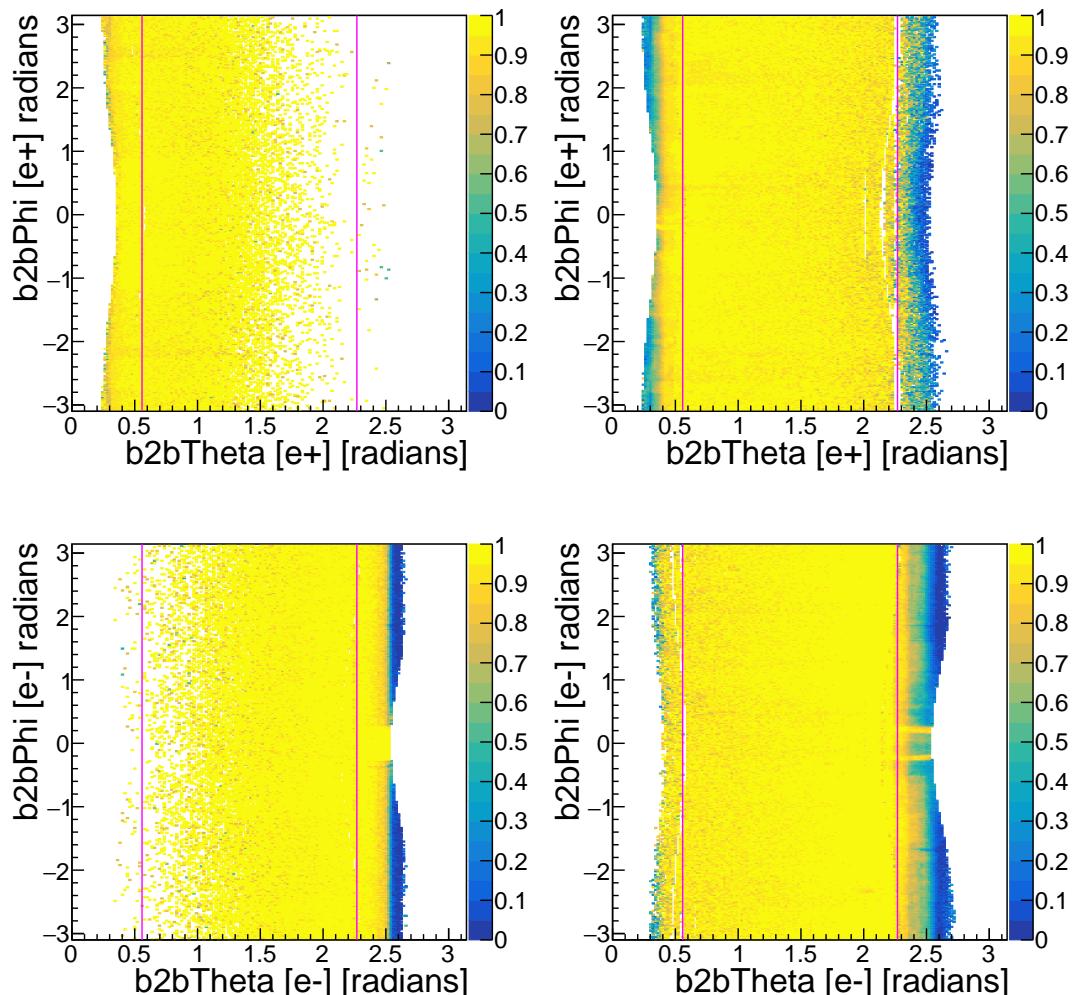


Figure 7.13.: θ - ϕ efficiencies for phase2. Left: Phase2 MC. Right: Phase2 data. First line: electron efficiencies. Second line: positron efficiencies. The 2D plots with the corresponding error can be found in the appendix B.26. The pink line indicates the different sectors of the ECL.

This chapter will start with a short description of phase3. Then the location of the files taken into account will be provided. Finally, the calculated tracking efficiency of electrons and positrons will be presented.

8.1. Phase3

Phase3 started successfully on March 11th, 2019. In contrast to phase2 the whole SVD and all ladders of the innermost in addition to two ladders of the outermost layer of the PXD were installed during phase3. A sketch of the PXD arrangement is shown in the appendix figure C.1. Phase3 is the first physics run of the Belle II project, in which the Belle II experiment will take data in a mostly fully equipped detector.[33]

8.2. Location

To have as much events as possible, all phase3 data files are taken into account. They contain Experiment 7 located on KEKCC at:

```
/group/belle2/dataprod/Data/release-03-02-02/DB00000654/proc9/e0007/4S/  
r0*/all/mdst/sub00/*.root
```

and Experiment 8 located on KEKCC at:

```
/group/belle2/dataprod/Data/release-03-02-02/DB00000654/proc9/e0008/4S/  
r0*/all/mdst/sub00/*.root
```

For Monte Carlo we will consider all files located on KEKCC at:

```
/belle/MC/release-01-00-02/DB00000294/MC10/prod00004664/s00/e0000/4S/  
r00000/3600520000/mdst/sub00
```

The selection described in chapter 6 will be used to select Bhabha events.

In figure 8.1 you can see the number of selected virtual photon candidates per event. You can see that in both phase3 MC and phase3 data only one candidate is selected per event.

8. Phase3 Tracking Efficiency

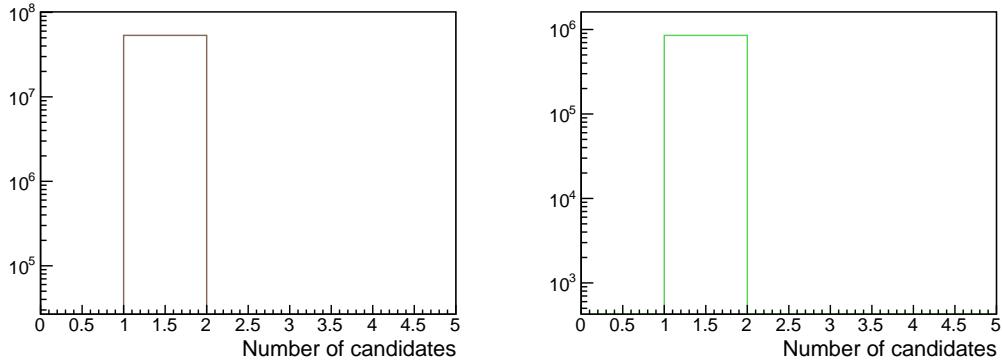


Figure 8.1.: The number of candidates per event after the selection is shown. Left: Phase3 Data. Right: Phase3 MC. A total of 852093 candidates are selected for phase3 data and $5.344275 \cdot 10^7$ candidates are selected for phase2 MC.

8.3. Tracking Efficiency

In this section the calculated tracking efficiencies for phase3 will be presented. Phase3 data will be shown in brown together with phase3 MC in green. The individual tracking efficiencies can be found in the appendix chapter C. Just like chapter 7, only efficiencies with $\Delta\epsilon < 0.4$ are plotted.

8.3.1. Momentum Efficiencies

8.3.1.1. Forward End-Cap

Figure 8.2 shows the calculated electron tracking efficiency for different momenta in the forward end-cap. For momenta between 4 GeV and 5 GeV, the tracking efficiency for phase3 data starts at 0.85 and falls down until it reaches a minimum of 0.7 at $\phi \approx 0$. After this it goes back up to 0.85. At the minimum something strange is happening to the phase3 data tracking efficiency. It seems like the tracking efficiency drops by ~ 0.1 every other value of ϕ . The result are two *ribbons* of efficiency in this region. The tracking efficiency of phase3 MC has a similar structure but due to the lower statistics the error bars are way bigger. For momenta between 5 GeV and 6 GeV, the structure of the tracking efficiencies are similar to the ones of the previous momentum range. But this time, the tracking efficiency starts at 0.9 for phase3 data and an efficiency of about 0.82 is reached in the minimum at $\phi \approx 0$. Also, for this momentum range, there are no *ribbons* of efficiency in the minimum. For momenta between 6 GeV and 7 GeV, the tracking efficiency for phase3 MC stays above 0.95 for almost all values of ϕ . The tracking efficiency for phase3 data ranges between 0.89 and 0.98. Some efficiencies appear to be scattered more or less random in this range. For momenta between 7 GeV and 8 GeV, the tracking efficiency for phase3 data is

8.3. Tracking Efficiency

almost 1 for $\text{abs}(\phi) > 1.5$. For $\text{abs}(\phi) < 1.5$, the tracking efficiency varies between 0.99 and 1. The phase3 MC tracking efficiency ranges between 0.975 and 1 for most values of ϕ . The error bars are significantly larger for $\text{abs}(\phi) > 1.5$. The best electron tracking efficiency for phase3 in the forward end-cap is obtained for electrons with a momentum between 7 GeV and 8 GeV.

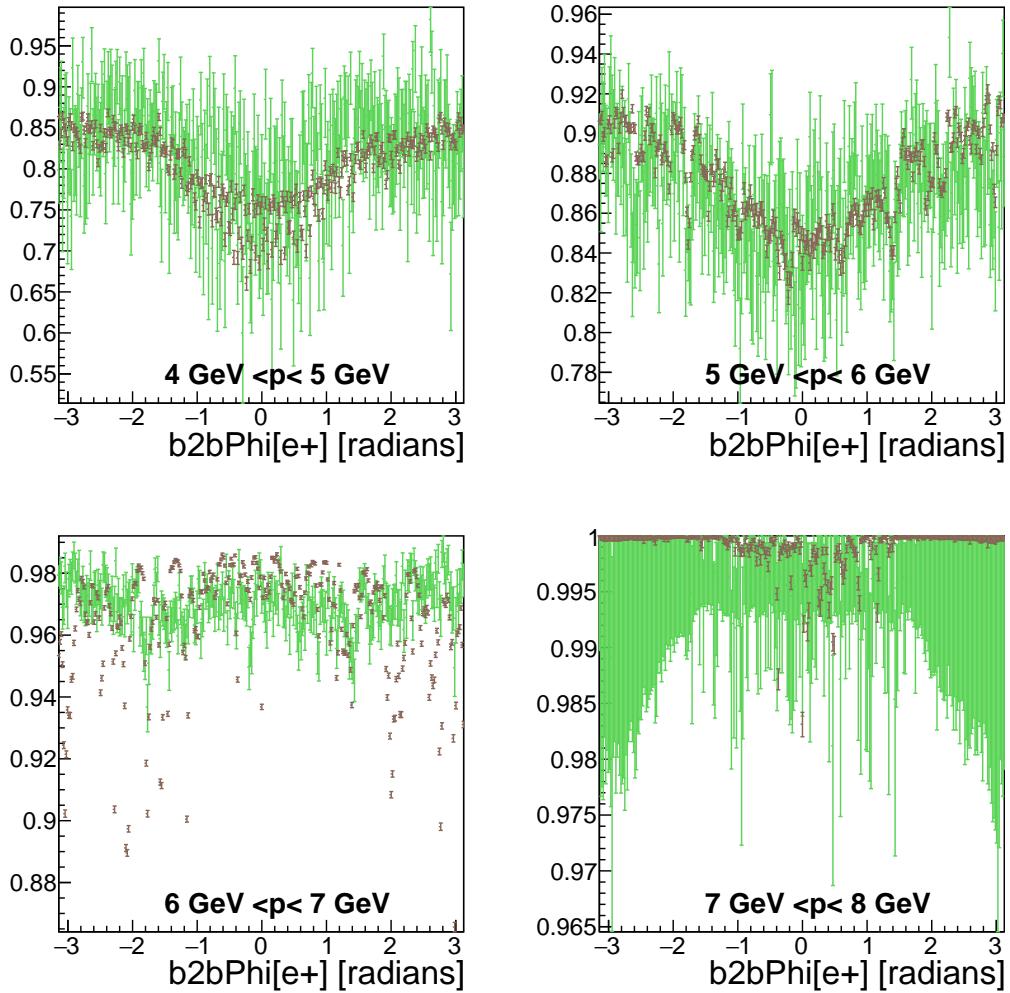


Figure 8.2.: Electron ϕ tracking efficiency plots in the forward end-cap. The tracking efficiency for phase3 data is shown in brown and phase3 MC in green.

8. Phase3 Tracking Efficiency

8.3.1.2. Barrel

Figure 8.3 shows the electron tracking efficiencies in the barrel. For momenta between 4 GeV and 5 GeV, the phase3 MC tracking efficiency is between 0.75 and 0.95. For phase3 data the tracking efficiency is between ~ 0.80 and 0.92. The lowest efficiencies occurs at $\phi \approx 0$, the highest efficiencies at $\text{abs}(\phi) \approx \pi$. The tracking efficiencies for higher momenta have a similar structure. For momenta between 5 GeV and 6 GeV the tracking efficiency is between ~ 0.90 and ~ 0.99 for phase3 MC and between ~ 0.93 and 0.98. The best tracking efficiency appears at momenta between 6 GeV and 7 GeV. Here, the calculated tracking efficiency is between ~ 0.98 and 1 for phase3 MC and between 0.990 and 0.997 for phase3 data.

Figure 8.4 shows the positron tracking efficiency in the barrel. For momenta between 3 GeV and 4 GeV, the calculated tracking efficiency for phase3 MC is between ~ 0.7 and ~ 0.97 . The lowest efficiency occurs at $\phi \approx 0$ and the highest at $\text{abs}(\phi) \approx \pi$. The phase3 data has a similar structure but the efficiency is between ~ 0.8 and ~ 0.9 . For momenta between 4 GeV and 5 GeV, the tracking efficiency is between ~ 0.965 and 0.998 for phase3 MC and between 0.98 and 0.990. The structure of the efficiencies is similar to the previous momenta but not as dominant. For momenta between 5 GeV and 6 GeV, the tracking efficiency is between ~ 0.94 and 1 for phase3 MC and between ~ 0.97 and ~ 0.99 for phase3 data. The structure of the efficiency of phase3 data is different to the structure of the efficiency for lower momenta. Now, the highest efficiency occurs at $\phi \approx 0$ and the lowest efficiency at $\text{abs}(\phi) \approx \pi$. For momenta between 6 GeV and 7 GeV, the calculated positron tracking efficiency is between ~ 0.8 and 1 for phase3 MC and between ~ 0.95 and 0.98 for phase3 data. The efficiency distribution is rather flat in both cases.

8.3. Tracking Efficiency

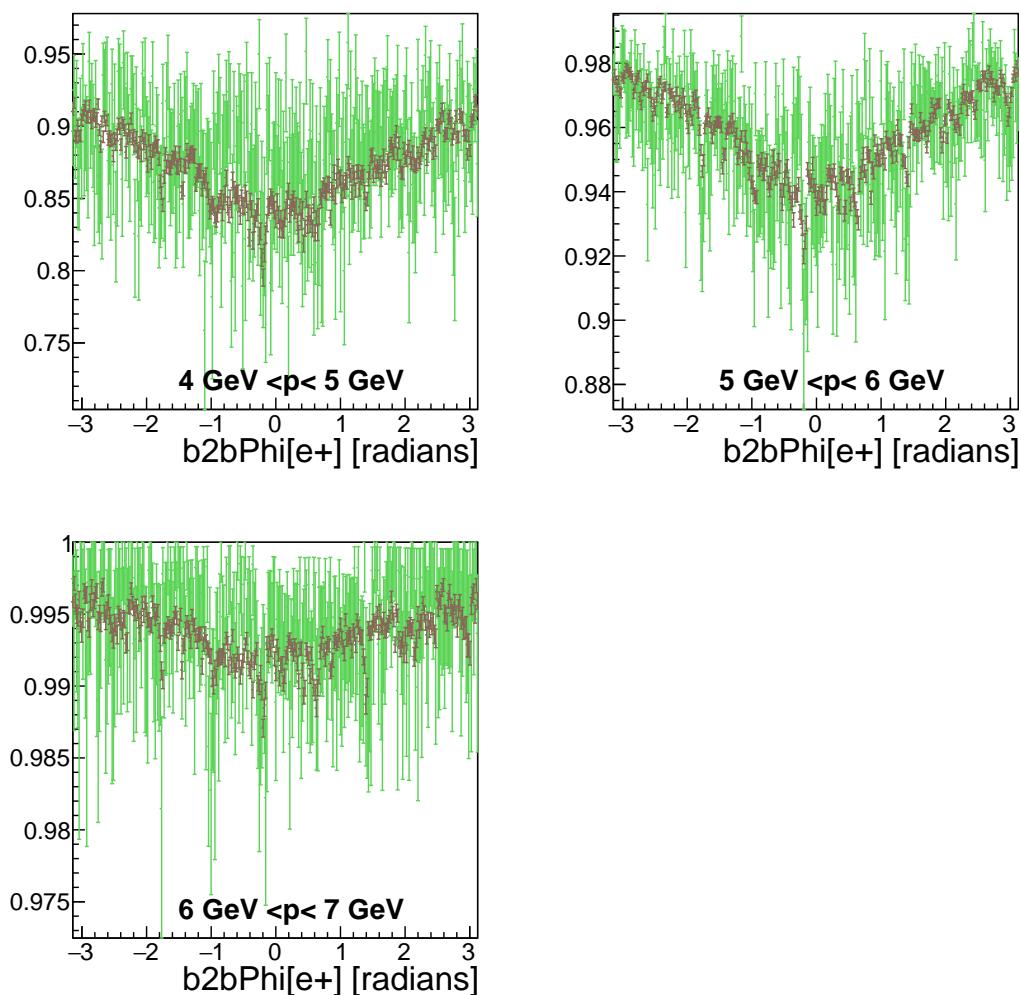


Figure 8.3.: Electron ϕ tracking efficiency plots in the barrel. The tracking efficiency for phase3 data is shown in brown and phase3 MC in green.

8. Phase3 Tracking Efficiency

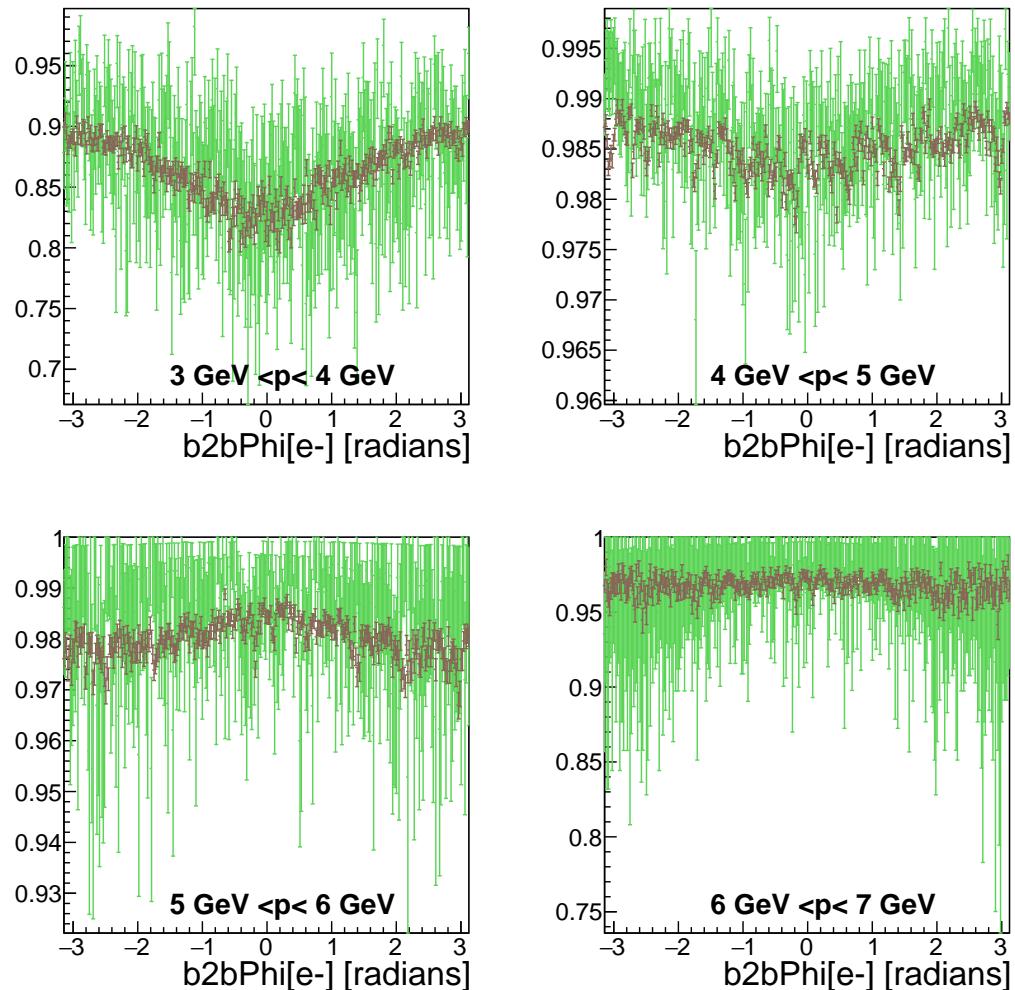


Figure 8.4.: Positron ϕ tracking efficiency plots in the barrel. The tracking efficiency for phase3 data is shown in brown and phase3 MC in green.

8.3. Tracking Efficiency

8.3.1.3. Backward End-Cap

Figure 8.5 shows the positron tracking efficiency in the backward end-cap. For momenta between 2 GeV and 3 GeV, the phase3 MC tracking efficiency is above 0.9 for most values of ϕ . The biggest error bars appear at $\phi \approx 0$. For phase3 data, the tracking efficiency is above 0.99 for all values of ϕ . For momenta between 3 GeV and 4 GeV, the tracking efficiency of phase3 MC is between ~ 0.9 and 1. Again, the lowest efficiency occurs at $\phi \approx 0$ and the highest efficiency at $\text{abs}(\phi) \approx \pi$. The tracking efficiency of phase3 data has a strange structure. It is scattered between 0.75 and 0.97 but the error bars are rather small. Most of the time, the efficiency is above 0.9 but the efficiency drops by over 0.1 every other value of ϕ . For momenta between 4 GeV and 5 GeV, the tracking efficiency for phase3 MC is between 0.96 and 1. Similar to the previous momenta range, the lowest tracking efficiency occurs at $\phi \approx 0$ and the highest efficiency at $\text{abs}(\phi) \approx \pi$. The tracking efficiency structure for phase3 data is also similar to the previous momenta range. But for this momenta range, the tracking efficiency is between 0.9 and ~ 0.99 and without the scattered tracking efficiency values, the efficiency would be around 0.98. Also for this momenta range, the number of efficiency drops is smaller compared to the previous momenta range. For momenta between 5 GeV and 6 GeV, the tracking efficiency for phase3 MC is between 0.6 and 1. But the error bars are very large and therefore a structure in the efficiency can not be determined. For phase3 data, the tracking efficiency is above 0.9 for almost all values of ϕ .

8. Phase3 Tracking Efficiency

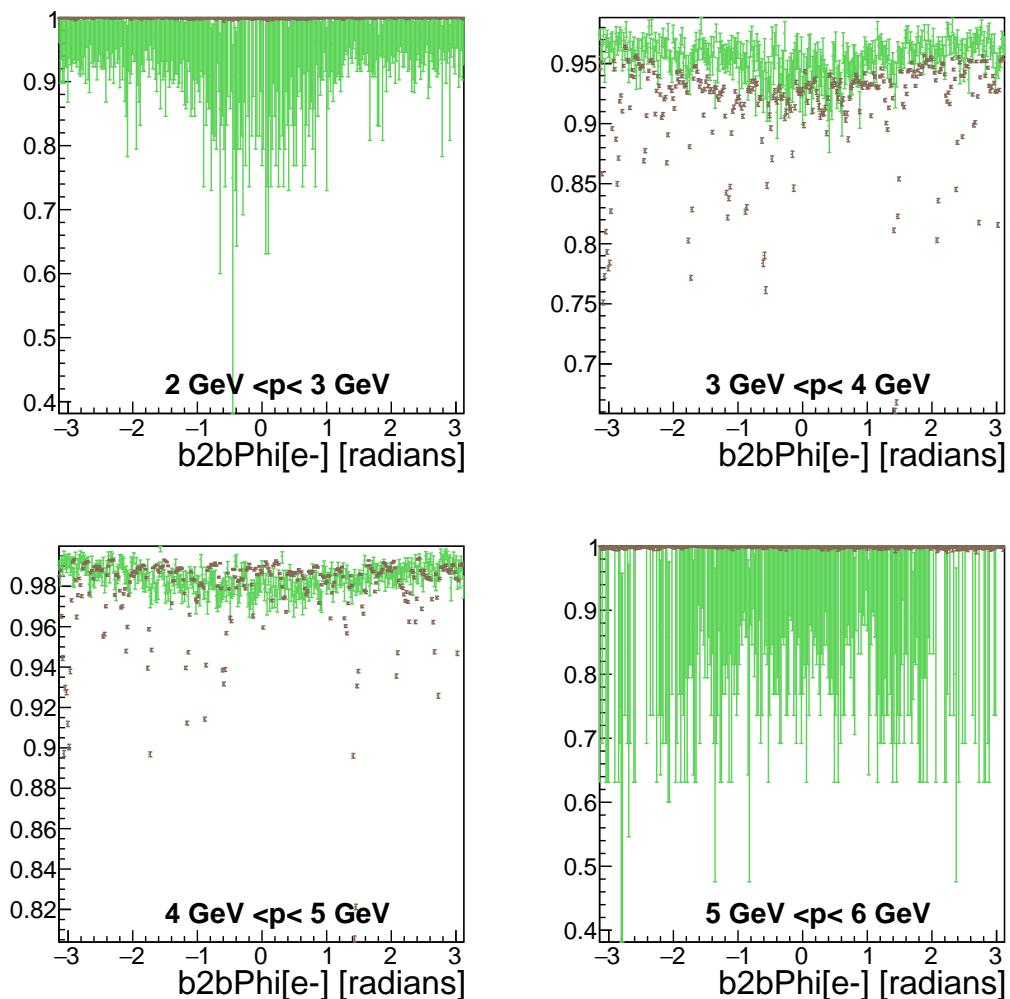


Figure 8.5.: Positron ϕ tracking efficiency plots in the backward end-cap. The tracking efficiency for phase3 data is shown in brown and phase3 MC in green.

8.3. Tracking Efficiency

8.3.1.4. θ Efficiencies

In figure 8.6 you can see the calculated electron tracking efficiency as a function of the polar angle θ . For momenta between 3 GeV and 4 GeV the tracking efficiency for phase3 MC starts in the forward end-cap with over 0.95 for most ϕ values. At the forward end-cap and barrel transition the efficiency drops down to 0 and goes back up to 0.6 at $\theta \approx 0.7$. After this, the tracking efficiency slowly increases to between ~ 0.80 and ~ 0.95 at $\theta \approx 0.4$. Then the efficiency drops drastically down to 0. The tracking efficiency of phase3 data starts even higher with almost 1 in the forward end-cap. Similar to the tracking efficiency of phase3 MC, the phase3 data efficiency drops at the forward end-cap and barrel transition. After this, the efficiency follows the phase3 MC efficiency until $\theta \approx 2.2$. At the barrel and backward end-cap transition, the phase3 data tracking efficiency drops down to around 0.55. In the backward end-cap the efficiency goes back up 0.7 before it finally falls down to 0. For momenta between 4 GeV and 5 GeV, both the phase3 MC and phase3 tracking efficiency starts at around 0.95 and decline with increasing θ . A local minimum of $\epsilon \approx 0.6$ appears at the forward end-cap transition. After the transition the efficiency jumps back to around 0.75 and then increases slowly until $\theta \approx 1.5$. Here the tracking efficiency stops for phase3 MC and it stays at the same height for the rest of the barrel. The tracking efficiency for phase3 MC finally drops down to 0 in the backward end-cap. In contrast, the phase3 data tracking efficiency already starts to fall down slowly at $\theta \approx 1.5$. At the barrel and backward end-cap transition, the phase3 data tracking efficiency drops down to ~ 0.8 . After this it goes back up to ~ 0.85 and it processed to decline, until it reaches 0 at the end of the backward end-cap. For momenta between 5 GeV and 6 GeV, the tracking efficiency for both phase3 MC and phase3 data starts at around 0.95. They then decrease very fast until the transition between forward end-cap and barrel with a tracking efficiency of about 0.85. At this transition a peak in the tracking efficiency occurs. The tracking efficiency jumps up to about 0.95 and falls back down to ~ 0.9 after the transition. Then, the efficiency goes up and reaches a plateau at $\theta \approx 1.3$ with an tracking efficiency of over 0.97. For momenta between 6 GeV and 7 GeV, the phase3 MC and phase3 data tracking efficiency starts at around 0.95 and directly falls down to 0.9 at $\theta \approx 0.3$. After this, the tracking efficiency goes back up to almost 1 and it stays this high until $\theta \approx 1.3$. For momenta between 7 GeV and 8 GeV, almost all electrons hit the forward end-cap. For phase3 data the tracking efficiency starts at almost 1 and stays that high for the whole forward end-cap. The tracking efficiency for phase3 MC also starts at almost 1 but the error bars become very large very fast with increasing θ .

Figure 8.7 shows the positron tracking efficiency in the backward end-cap as a function of the polar angle θ . For momenta between 2 GeV and 3 GeV, most of the positrons are detected in the backward end-cap. For phase3 MC the tracking efficiency is above 0.97 for almost all values of θ in the backward end-cap. For phase3 data, the tracking efficiency is even higher with over 0.99. For momenta between 3 GeV and 4 GeV, the tracking efficiency for phase3 data starts in the forward end-cap with over 0.9 but it decreases with increasing θ . In the barrel, the tracking efficiency for phase3 data starts

8. Phase3 Tracking Efficiency

very low. Probably due to the transition between forward end-cap and barrel. The efficiency jumps up to around 0.6 at $\theta \approx 0.7$. After this the tracking efficiency slowly increases. A difference between the tracking efficiency of phase3 MC and phase3 data occurs in at the transition between the barrel and the backward end-cap and in the backward end-cap itself. Around the transition the phase3 data efficiency has a small dip while the phase3 tracking efficiency has a small peak. In the backward end-cap, the phase3 MC tracking efficiency gets higher faster than the phase3 data tracking efficiency. A cap between the two of them is created. Also, there is another small dip in the phase3 data tracking efficiency at $\theta \approx 2.6$. For momenta between 4 GeV and 5 GeV, the tracking efficiency of phase3 MC and phase3 data starts at around 0.9 and it falls down with increasing θ . It reaches a minimum at the forward end-cap and barrel transition. After this transition, the tracking efficiency gets higher until $\theta \approx 1.6$. After this, the tracking efficiency continues to get bigger starting with over 0.95 and ending with almost 1 at the transition between barrel and backward end-cap. In the backward end-cap, the efficiency decreases slowly before it peaks at the very end of the backward end-cap. For phase3 data, there is even a small dip before that very last peak. For momenta between 5 GeV and 6 GeV, the tracking efficiency starts rather low in the forward end-cap, but in the barrel the tracking efficiency begins to rise. It reaches its plateau of $\epsilon \gtrsim 0.97$ at around $\theta \approx 1.3$. In the backward end-cap, the phase3 data tracking efficiency is noticeably higher than the phase3 tracking efficiency. Also, there is a small dip in the phase3 tracking efficiency at $\theta \approx 1.9$. For momenta between 6 GeV and 7 GeV, the tracking efficiency increases in the forward end-cap from about 0.8 to 0.95 for phase3 data and to over 0.97 for phase3 MC. In the barrel, the tracking efficiency continues to increase for phase3 data until it reaches 0.99. There is a dip in the tracking efficiency at $\theta \approx 1.1$ for phase3 data. At $\theta \approx 1.2$, the efficiency drops by over 5 %. The phase3 MC tracking efficiency stays in the barrel above 0.97. In the backward end-cap, phase3 data has a tracking efficiency of over 0.98.

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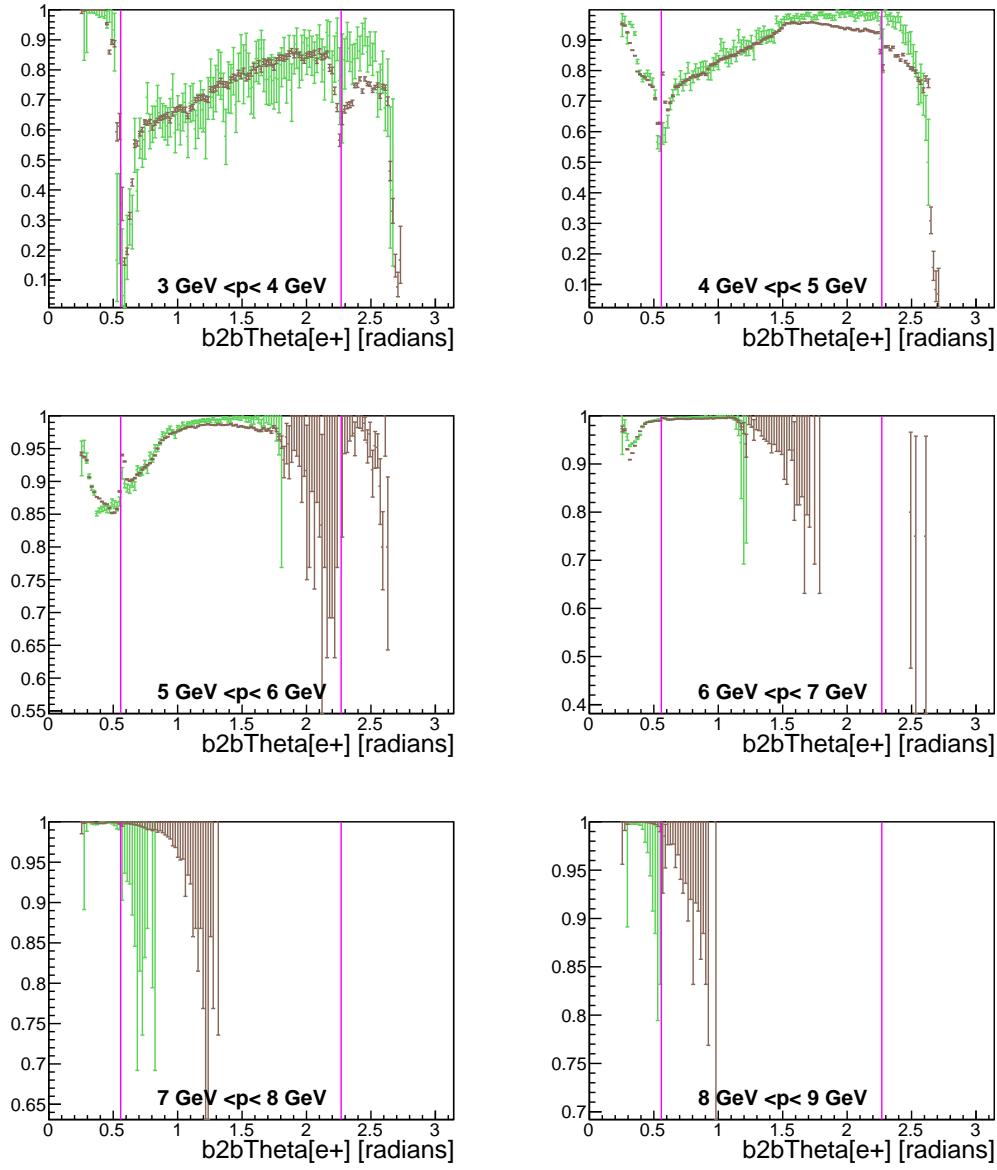


Figure 8.6.: Electron θ momentum tracking efficiency plots. The tracking efficiency for phase3 data is shown in brown and phase3 MC in green. The pink line indicates the different sectors of the ECL.

8. Phase3 Tracking Efficiency

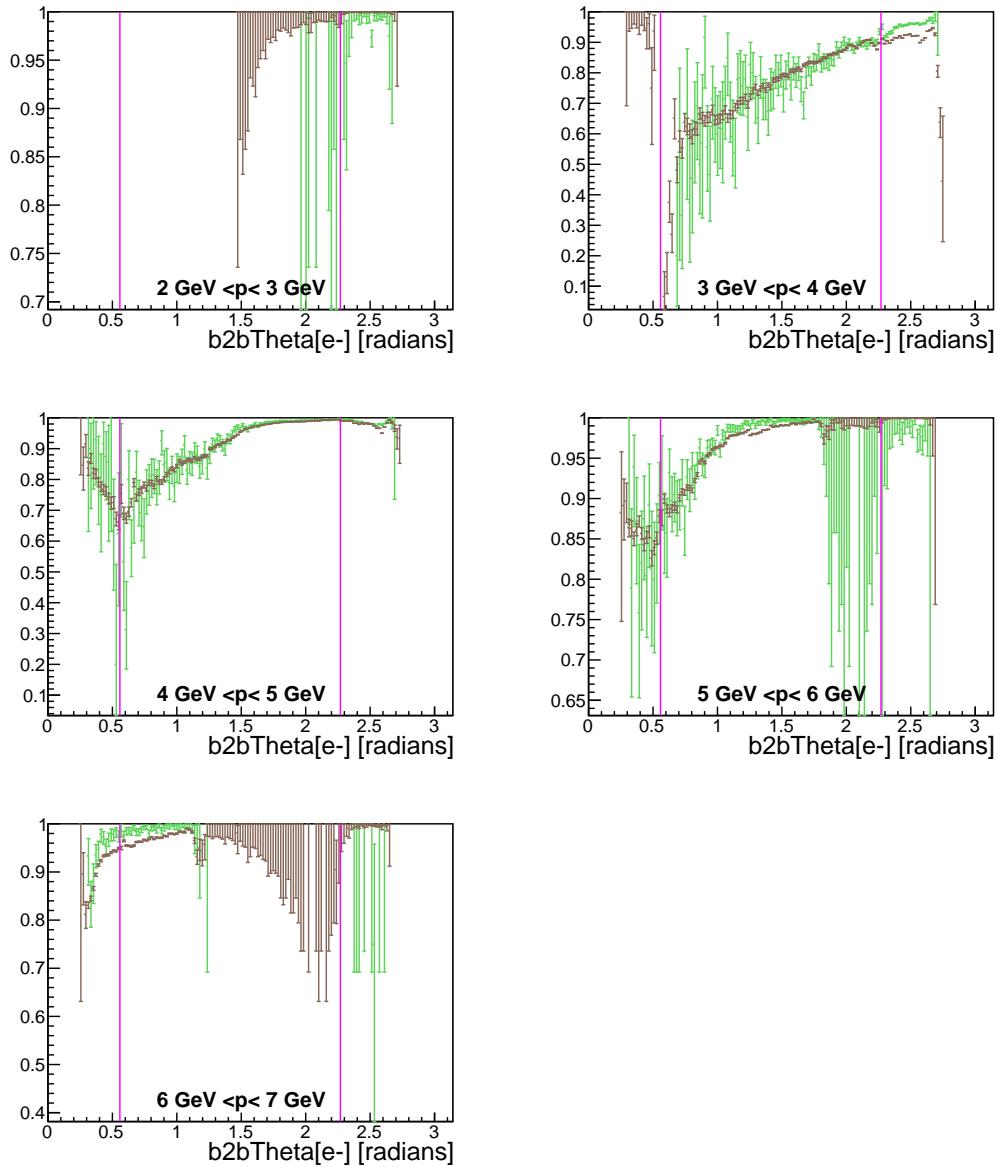


Figure 8.7.: Positron θ momentum tracking efficiency plots. The tracking efficiency for phase3 data is shown in brown and phase3 MC in green. The pink line indicates the different sectors of the ECL.

8.3. Tracking Efficiency

8.3.2. Transverse Momentum Efficiencies

8.3.2.1. Forward End-Cap

In figure 8.8 you can see the calculated tracking efficiency for electrons in the forward end-cap for different transverse momenta. For transverse momenta between 1 GeV and 2 GeV, the tracking efficiency for phase3 data and phase3 MC is above ~ 0.85 for $\text{abs}(\phi) > 1.5$. For decreasing $\text{abs}(\phi)$, the efficiency also decreases with a minimum at $\phi \approx 0$. Similar to the first momentum plot of figure 7.1¹, there is a *ribbon* structure in the phase3 data tracking efficiency at $\phi \approx 0$. For transverse momenta between 2 GeV and 3 GeV, the phase3 MC tracking efficiency is above 0.9 for all values of ϕ . It has a minimum at $\phi \approx 0$ and the highest efficiencies are reached at $\phi \approx \pi$. The tracking efficiency for phase3 data is between 0.88 and 0.98. Again, some efficiencies appear to be scattered more or less random at this range. For transverse momenta between 3 GeV and 4 GeV, the tracking efficiency for phase3 MC is above 0.96 for all values of ϕ . For phase3 data, the tracking efficiency is even above 0.985 for almost all values of ϕ . There are some exceptions which again, appears to be scattered.

¹This figure shows the phase3 electron tracking efficiencies for different momenta in the forward end-cap

8. Phase3 Tracking Efficiency

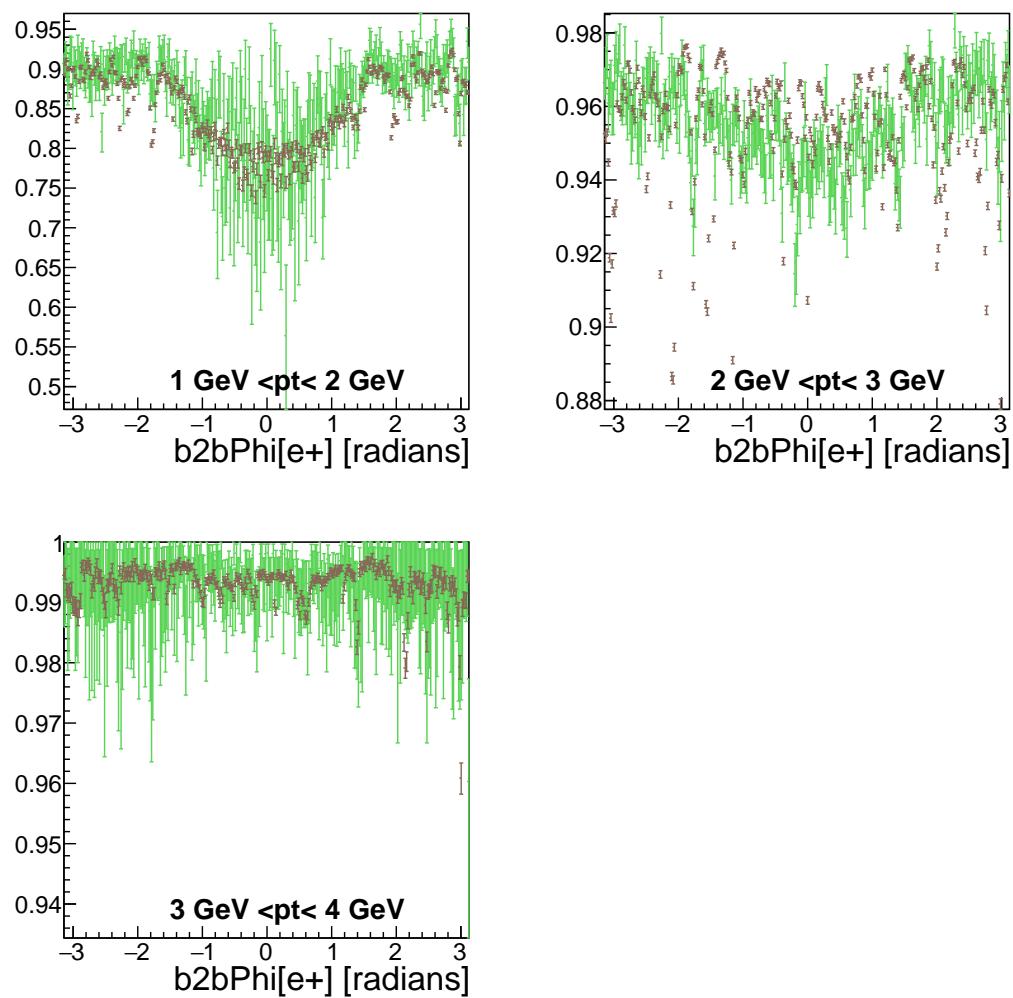


Figure 8.8.: Electron ϕ transverse momentum tracking efficiency plots in the forward end-cap. The tracking efficiency for phase3 data is shown in brown and phase3 MC in green.

8.3. Tracking Efficiency

8.3.2.2. Barrel

Figure 8.9 shows the calculated electron tracking efficiency in the barrel for different transverse momenta. For transverse momenta between 2 GeV and 3 GeV, the tracking efficiency for phase3 MC the errors are rather large but you can still see that the minimum of the tracking efficiency is at $\phi \approx 0$. The tracking efficiency for phase3 data, seems to oscillate between ~ 0.6 and ~ 0.8 . The two maximums appear at $\text{abs}(\phi) \approx 2.0$ and the two minimums at $\phi \approx 0$ and $\text{abs}(\phi) \approx \pi$. For transverse momenta between 3 GeV and 4 GeV, the oscillation is still visible for phase3 data and phase3 MC. But it is not as dominant. The tracking efficiency oscillates between ~ 0.93 and ~ 0.97 for phase3 data and between ~ 0.90 and ~ 0.99 for phase3 MC. For transverse momenta between 4 GeV and 5 GeV, the tracking efficiency stays rather flat for both phase3 data and phase3 MC. The efficiency is between 0.97 and 0.99 for phase3 data and between ~ 0.95 and 1 for phase3 MC. For transverse momenta between 5 GeV and 6 GeV, the calculated tracking efficiency is between 0.98 and almost 1 for phase3 data and between ~ 0.95 and 1 for phase3 MC. Phase3 data has the best tracking efficiency at $\text{abs}(\phi) \approx \pi$ in contrast to phase3 MC which has the best tracking efficiency at $\phi \approx 0$ due to the large errors at $\text{abs}(\phi) \approx \pi$.

In figure 8.10, you can see the calculated positron tracking efficiency in the barrel for different transverse momenta. For transverse momenta between 3 GeV and 4 GeV, the calculated tracking efficiency is between ~ 0.93 and ~ 0.99 for phase3 MC and between ~ 0.96 and ~ 0.98 for phase3 data. Again, the lowest efficiencies occurs at $\phi \approx 0$. For transverse momenta between 4 GeV and 5 GeV, the calculated tracking efficiency for phase3 MC is between 0.96 and 1 and between ~ 0.975 and ~ 0.988 for phase3 data. For transverse momenta between 5 GeV and 6 GeV, the tracking efficiency is between ~ 0.985 and ~ 0.995 for phase3 data and between ~ 0.94 and 1 for phase3 MC. The error bars for phase3 MC are decreasing in length with increasing $\text{abs}(\phi)$.

8. Phase3 Tracking Efficiency

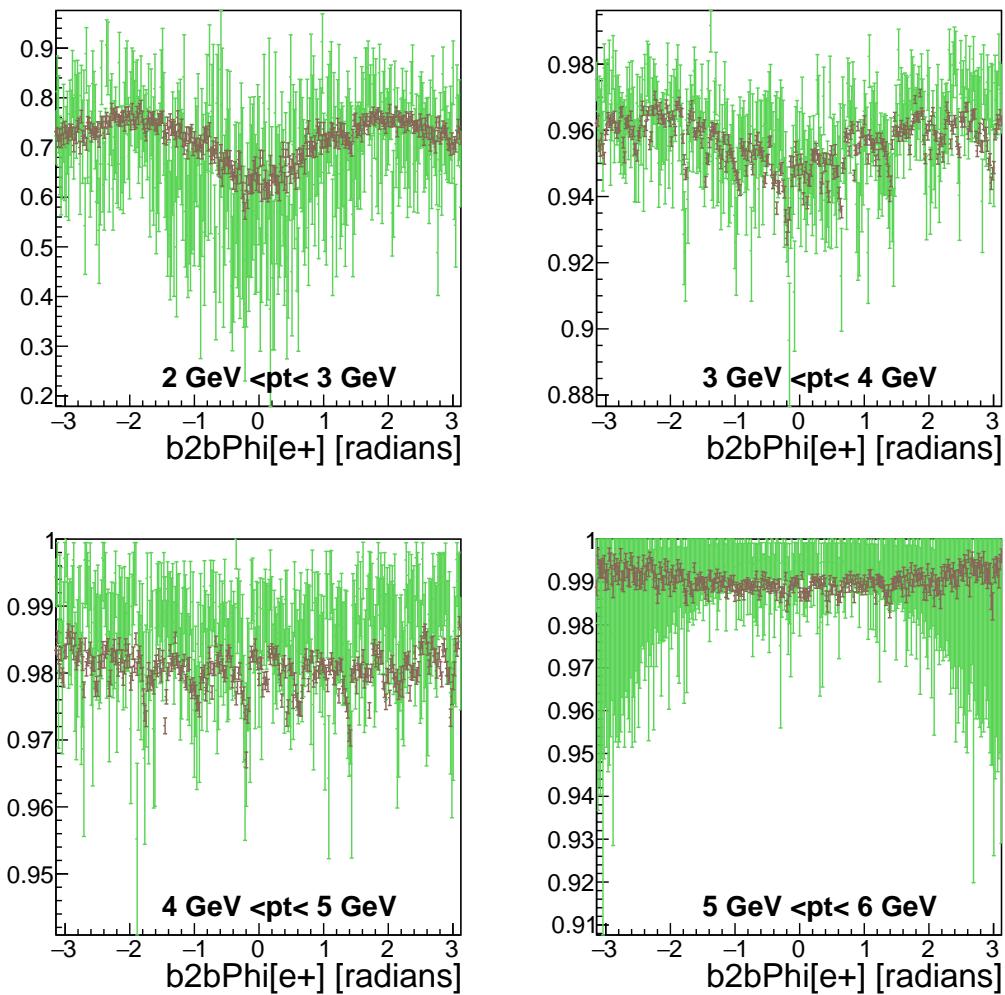


Figure 8.9.: Electron ϕ transverse momentum tracking efficiency plots in the barrel.
The tracking efficiency for phase3 data is shown in brown and phase3 MC
in green.

8.3. Tracking Efficiency

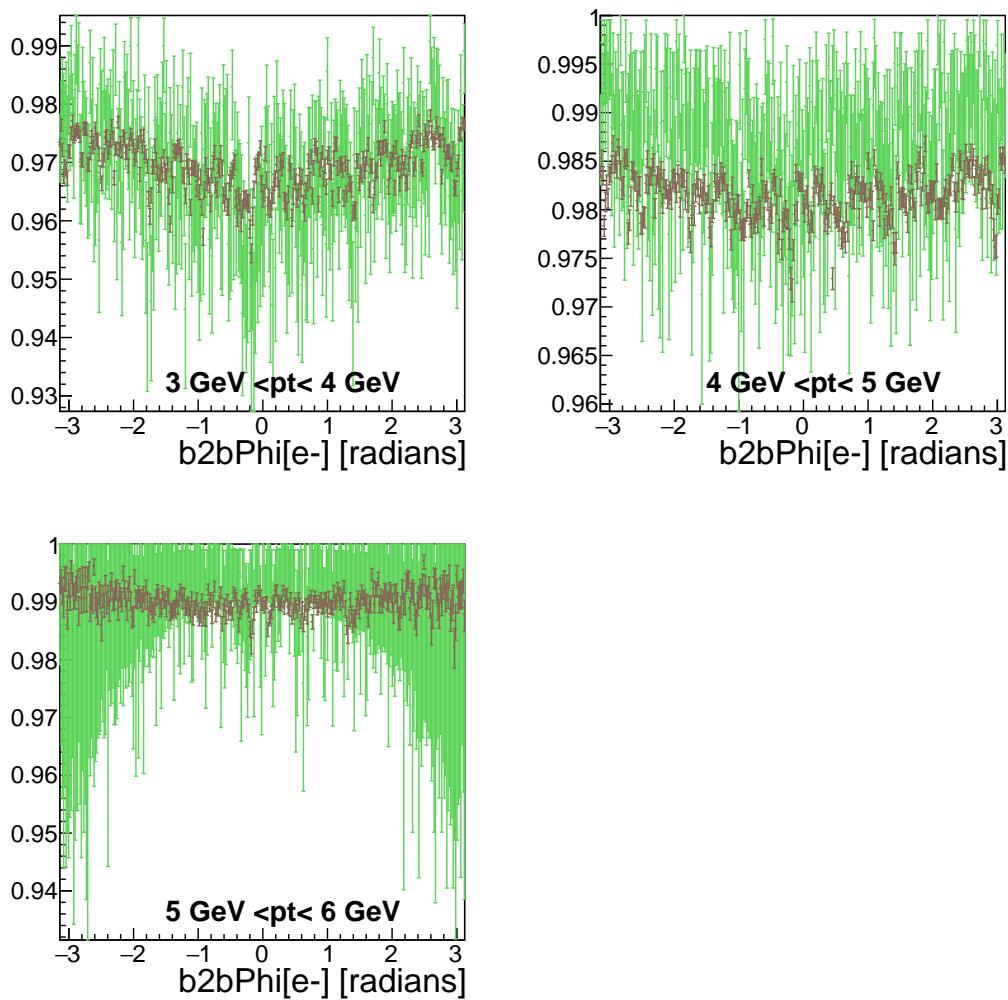


Figure 8.10.: Positron ϕ transverse momentum tracking efficiency plots in the barrel.
The tracking efficiency for phase3 data is shown in brown and phase3
MC in green.

8. Phase3 Tracking Efficiency

8.3.2.3. Backward End-Cap

Figure 8.11 shows the calculated positron tracking efficiency in the backward end-cap for different momenta. For transverse momenta between 1 GeV and 2 GeV, the calculated phase3 MC tracking efficiency is above 0.92 for $\text{abs}(\phi) > 1$. For $\text{abs}(\phi) < 1$ the error bars are noticeably larger and the efficiency is between 0.75 and 1. For phase3 data a strange structure occurs. For phase3 data the highest tracking efficiency appears at $\text{abs}(\phi) < 0.5$. Here the efficiency is between ~ 0.96 and ~ 0.99 . For $\text{abs}(\phi) > 0.5$ the highest efficiency is ~ 0.97 . And the tracking efficiencies seem to be scattered between 0.75 and 0.96. For transverse momenta between 2 GeV and 3 GeV, the calculated tracking efficiency is between ~ 0.95 and ~ 0.99 for phase3 MC and between ~ 0.72 and ~ 0.98 for phase3 data. Again, the tracking efficiency for phase3 data appears to be scattered randomly. For transverse momenta between 3 GeV and 4 GeV, the tracking efficiency for phase3 MC is between ~ 0.96 and 1. The efficiency range is mostly determined by the error bars. The tracking efficiency for phase3 data is above 0.99 most of the time. There are some rather smaller dips at $\phi \approx -\pi, -1.8, -1.2, -0.8, 1.2$ and 2.1 .

8.3. Tracking Efficiency

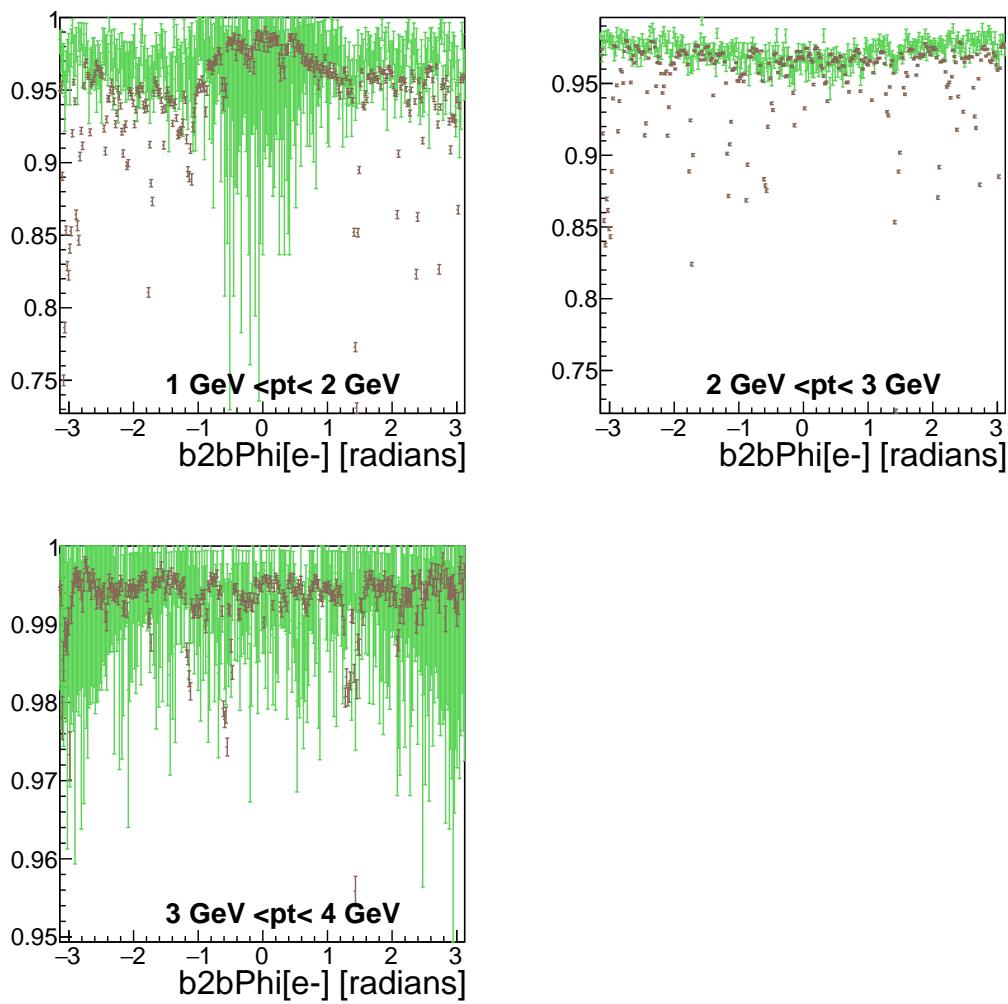


Figure 8.11.: Positron ϕ transverse momentum tracking efficiency plots in the backward end-cap. The tracking efficiency for phase3 data is shown in brown and phase3 MC in green.

8. Phase3 Tracking Efficiency

8.3.2.4. θ Efficiencies

Figure 8.12 shows the calculated electron tracking efficiency as a function of the polar angle θ for different transverse momenta. For transverse momenta between 1 GeV and 2 GeV, almost all electrons hit one of the end-caps. In the forward end-cap, both the phase3 MC and phase3 data tracking efficiency start at 0.95 but both fall down to ~ 0.78 at $\theta \approx 0.4$. After this, both efficiencies rise back up to over 0.9 at $\theta \approx 0.5$. At the forward end-cap and barrel transition, the efficiency falls down again. In the backward end-cap, the phase3 data tracking efficiency rises at first. It reaches a local maximum of about 0.8 at $\theta \approx 2.5$. For increasing θ the tracking efficiency falls down until it finally reaches 0 at the end of the backward end-cap. For transverse momenta between 2 GeV and 3 GeV, the calculated tracking efficiency for phase3 MC starts very high with almost 1 at the beginning of the forward end-cap. But it also falls down to ~ 0.95 quickly. At $\theta \approx 0.45$, the phase3 MC tracking efficiency falls down drastically to ~ 0.7 at the forward end-cap barrel transition. After this it slowly decreases further. The phase3 data tracking efficiency also starts very high at the beginning of the forward end-cap. But it also has a small dip at $\theta \approx 0.3$. The phase3 data tracking efficiency also falls drastically at $\theta \approx 0.45$ until it reaches the barrel. In the barrel it continues to fall slowly. After the barrel and backward end-cap transition both the phase3 MC and the phase3 data tracking efficiency first rise to a maximum of ~ 0.95 for phase3 MC and ~ 0.8 for phase3 data at $\theta \approx 2.45$. After this maximum, both efficiencies drop. For transverse momenta between 3 GeV and 4 GeV, the calculated tracking efficiency in the forward end-cap is above 0.99 for both phase3 data and phase3 MC for almost all values of θ . In the barrel, the phase3 data tracking efficiency starts to fall down and reaches a local minimum of about 0.72 at $\theta \approx 1.2$. After this the tracking efficiency rises slowly up to ~ 0.85 at $\theta \approx 2.0$. The tracking efficiency of phase3 MC also falls down in the barrel but due to the large errors the minimum is somewhere between $1.0 < \theta < 2.0$. After $\theta \approx 2.0$ both tracking efficiencies jump up and stay at roughly the same height until $\theta \approx 2.4$. The phase3 data tracking efficiency goes up to ~ 0.9 and the phase3 MC efficiency goes up to over 0.95. The last maximum appears at $\theta \approx 2.45$. Here, the tracking efficiency for phase3 data goes up to over 0.96 before it falls down at the end of the backward end-cap. For transverse momenta between 4 GeV and 5 GeV, the calculated phase3 data tracking efficiency is above 0.98 for almost all values of θ in the forward end-cap. At the forward end-cap and barrel transition, the tracking efficiency drops down to ~ 0.95 . But it jumps back to almost 1 for both phase3 data and phase3 MC afterwards. Then, with increasing θ , the tracking efficiency slowly falls down until it reaches its local minimum of ~ 0.92 at $\theta \approx 1.4$. After this minimum, the tracking efficiencies go back up. Phase3 data already reaches its efficiency plateau of $\epsilon \approx 0.95$ at $\theta \approx 1.6$. Phase3 MC on the other hand rises up to almost 1 at $\theta \approx 1.9$. This results in a difference of the efficiencies between phase3 data and phase3 MC. For transverse momenta between 5 GeV and 6 GeV, almost all electrons hit the barrel. The tracking efficiency starts with over 0.99 for both phase3 data and phase3 MC at $\theta \approx 0.9$. The phase3 tracking efficiency stays

8.3. Tracking Efficiency

more or less the same with increasing θ but the phase3 data tracking efficiency slowly decreases until it reaches its minimum of ~ 0.96 at $\theta \approx 1.8$.

Figure 8.13 shows the calculated positron tracking efficiency as a function of the polar angle θ for different transverse momenta. For transverse momenta between 1 GeV and 2 GeV, the tracking efficiency for phase3 data and phase3 MC have a drop in the forward end-cap. Phase3 data is going from about 0.9 down to about 0.78. On phase3 MC you can see a similar structure. In the backward end-cap, the tracking efficiency stays above 0.95 for both phase3 data and phase3 MC with the exception of a drop at $\theta \approx 2.6$. For transverse momenta between 2 GeV and 3 GeV, the tracking efficiency for phase3 data starts above 0.9, falls down and has a minimum at $\theta \approx 0.3$. The tracking efficiency of phase3 MC also appears to fall down first with a minimum at the same θ angle. With increasing θ both tracking efficiencies rise to a local maximum of ~ 0.94 for phase3 data and ~ 0.95 for phase3 MC at $\theta \approx 0.35$. At the end of the backward end-cap, the efficiency falls down again and it continues to fall in the barrel. At the end of the barrel, the tracking efficiency is above 0.95 at $\theta \approx 1.9$. It slowly decreases with increasing θ and at $\theta \approx 2.1$ it drops down to ~ 0.85 . The error bars of the phase3 MC tracking efficiency are too large in the barrel to describe the structure. At $\theta \approx 2.1$ the phase3 tracking efficiency is below 0.9. With increasing θ both efficiencies rise until they reach a plateau of ~ 0.95 for phase3 data and ~ 0.96 for phase3 MC in the backward end-cap. Phase3 data has an additional minimum of ~ 0.92 in the backward end-cap at $\theta \approx 2.6$. Both phase3 MC and phase3 data have a maximum of ~ 0.98 at $\theta \approx 2.7$. For transverse momenta between 3 GeV and 4 GeV, the phase3 MC tracking efficiency starts in the forward end-cap with over 0.97 but it decreases until it reaches its minimum at $0.9 < \theta < 1.4$ with efficiencies below ~ 0.65 . After the minimum the efficiency goes back up. In the backward end-cap the phase3 MC tracking efficiency has a maximum of over 0.99. The tracking efficiency of phase3 data follows a similar path. But it starts a little lower in the forward end-cap with ~ 0.95 and it reaches its minimum of ~ 0.73 at $\theta \approx 0.1$. For transverse momenta between 4 GeV and 5 GeV, almost all positrons hit the barrel or the backward end-cap. In the barrel the tracking efficiency starts at ~ 0.95 for phase3 data and at ~ 0.98 for phase3 MC at $\theta \approx 0.7$. With increasing θ both efficiencies fall down and have a minimum of ~ 0.92 at $\theta \approx 1.4$. Then both efficiencies rise back up again and they stay high with over 0.98. Note that there is a small dip in both efficiencies at $\theta \approx 2.15$. For transverse momenta between 5 GeV and 6 GeV, most of the positrons hit the barrel. The tracking efficiency for phase3 MC and phase3 data stays above ~ 0.98 . On phase3 data, the tracking efficiency has a small dip at $\theta \approx 1.7$. The efficiency drops down by $\sim 5\%$.

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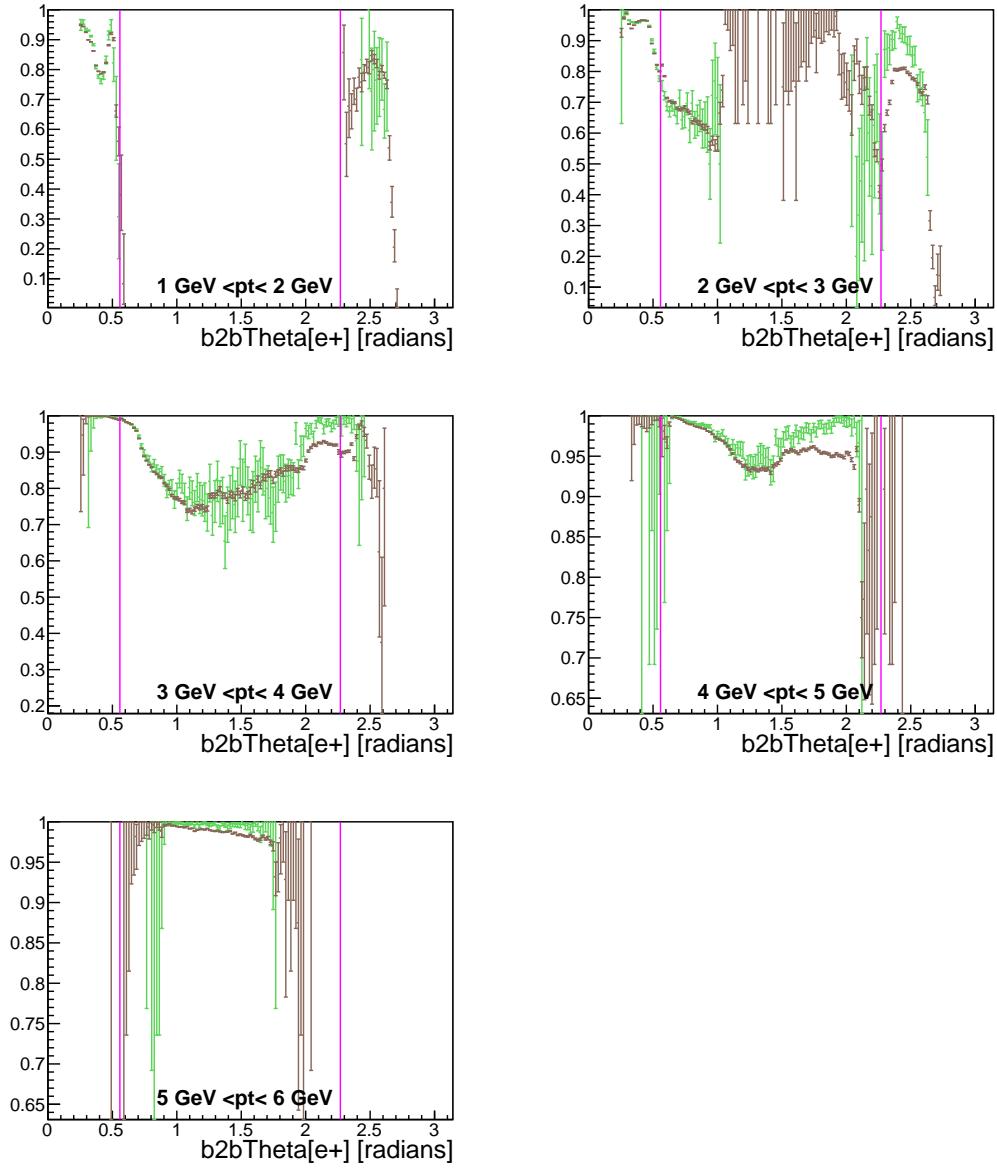


Figure 8.12.: Electron θ transverse momentum tracking efficiency plots. The tracking efficiency for phase3 data is shown in brown and phase3 MC in green. The pink line indicates the different sectors of the ECL.

8.3. Tracking Efficiency

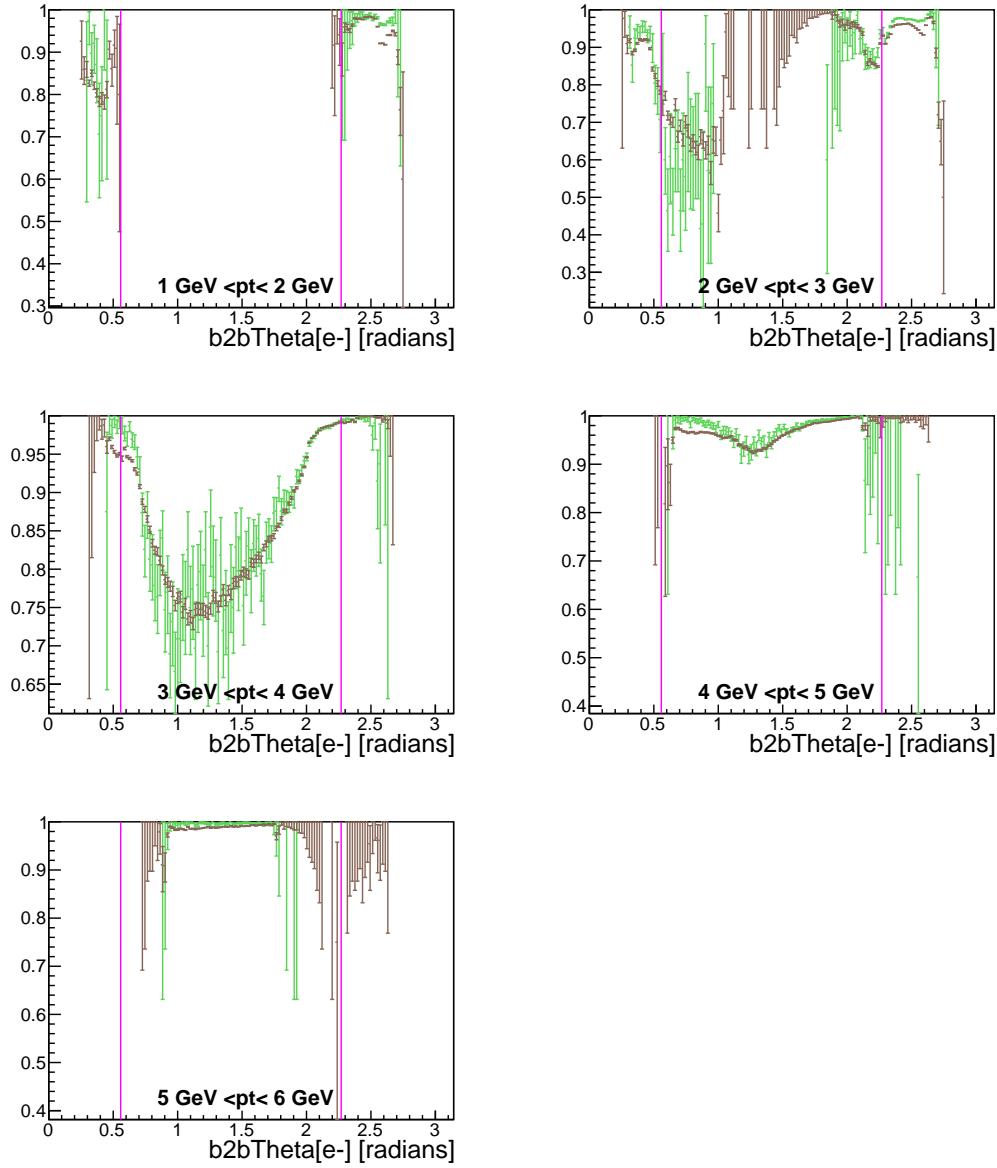


Figure 8.13.: Positron θ transverse momentum tracking efficiency plots. The tracking efficiency for phase3 data is shown in brown and phase3 MC in green. The pink line indicates the different sectors of the ECL.

8. Phase3 Tracking Efficiency

8.3.3. θ - ϕ Efficiencies

In figure 8.14 you can see the θ - ϕ efficiencies.² Similar to section 7.3, the phase3 MC efficiency is shown on the left and phase3 data on the right. The electron efficiencies are presented in the first line and the positron in the second line. Again, these plots combine all momenta. For phase3 data you can see horizontal efficiency drops in the forward end-cap and in the barrel at $\phi \approx -1.8, -1.0, -0.2, 0.6, 0.1$ and 3.0 . This efficiency losses are also kind of visible for phase3 MC but only in the forward end-cap, since the statistics in the barrel is too low. Also, they don't appear to be as dominant as the drops on phase3 data. You can also see that there are horizontal efficiency losses for the positron phase3 data tracking efficiency. But they only appear in the backward end-cap at $\phi \approx -3.0, -1.7, -0.5, 1.4$ and 2.6 . On phase3 MC there are no horizontal efficiency drops in the backward end-cap. These horizontal efficiency drops can also be seen in the electron phase3 data tracking efficiency plots but unfortunately the statistics on phase3 MC is too low to see efficiencies in the backward end-cap at all.

²I highly recommend to look at these plots from a digital device because the differences are very small and difficult to spot on paper

8.3. Tracking Efficiency

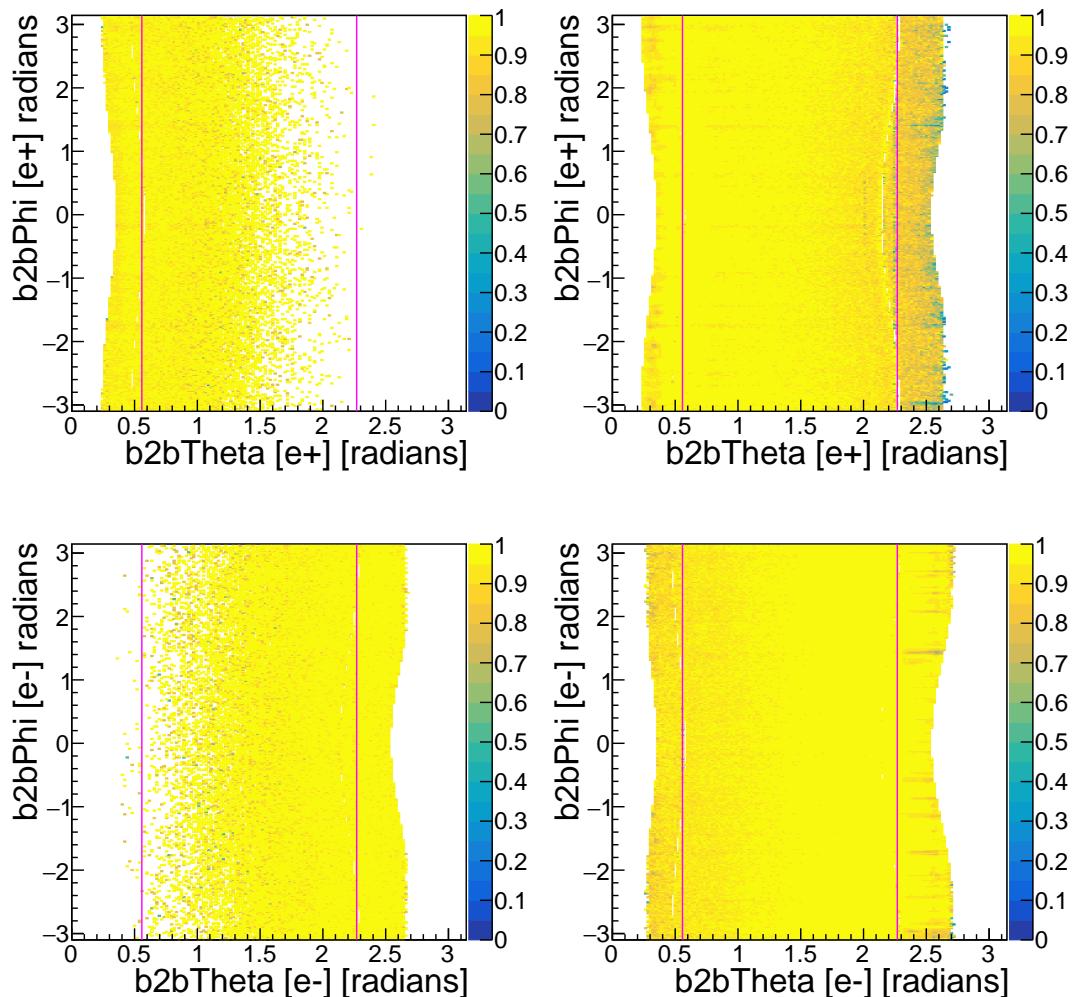


Figure 8.14.: $\theta\text{-}\phi$ efficiencies for phase3. Left: Phase3 MC. Right: Phase3 data. First line: electron efficiencies. Second line: positron efficiencies. The 2D plots with the corresponding error can be found in the appendix C.26. The pink line indicates the different sectors of the ECL.

THIS chapter will provide a comparison between the tracking efficiencies of phase2 and phase3. I will only present some plots and only the differences in the efficiencies will be described because the efficiencies very already discussed in the previous chapters. Also, only momenta plots for phase2 data and phase3 data will be shown.

The biggest difference between phase2 and phase3 is the presence of the SVD and approximately half of the PXD detector in phase3. Since the PXD is also able to detect charged particle, we expect to have a higher tracking efficiency on phase3 compared to phase2.

9.1. θ -Efficiencies

In figure 9.1 you can see the electron tracking efficiency of phase2 data and phase3 data as a function of the polar angle θ for different momenta ranges. In the barrel, there is no difference between the two tracking efficiencies. The biggest discrepancy occurs in the end-caps. Here, we see a drastically improvement across all momenta. For momenta between 3 GeV and 6 GeV, the phase3 data tracking efficiency drops down at a higher θ angle in the backward end-cap. And for momenta between 4 GeV and 8 GeV, the tracking efficiency starts with a local maximum in the forward end-cap and it is overall higher than the phase2 data tracking efficiency. Since more electrons are hitting the forward end-cap compared to the backward end-cap, we will compare the electron tracking efficiency in the forward end-cap of phase2 data and phase3 data in the next section.

Figure 9.2 shows the electron tracking efficiency of phase2 data and phase3 data as a function of the polar angle θ for different momenta ranges. Again, there is basically no difference between the efficiencies in the barrel. For momenta between 3 GeV and 5 GeV, the tracking efficiency is improved drastically in the backward end-cap. The phase3 data tracking efficiency either stays at the same height coming from the barrel or it even rises higher. For momenta between 4 GeV and 7 GeV, the tracking efficiency in the forward end-cap is also improved. In the next section we will also discuss the differences in the positron tracking efficiency in the backward end-cap.

9. Comparing Phase2 With Phase3

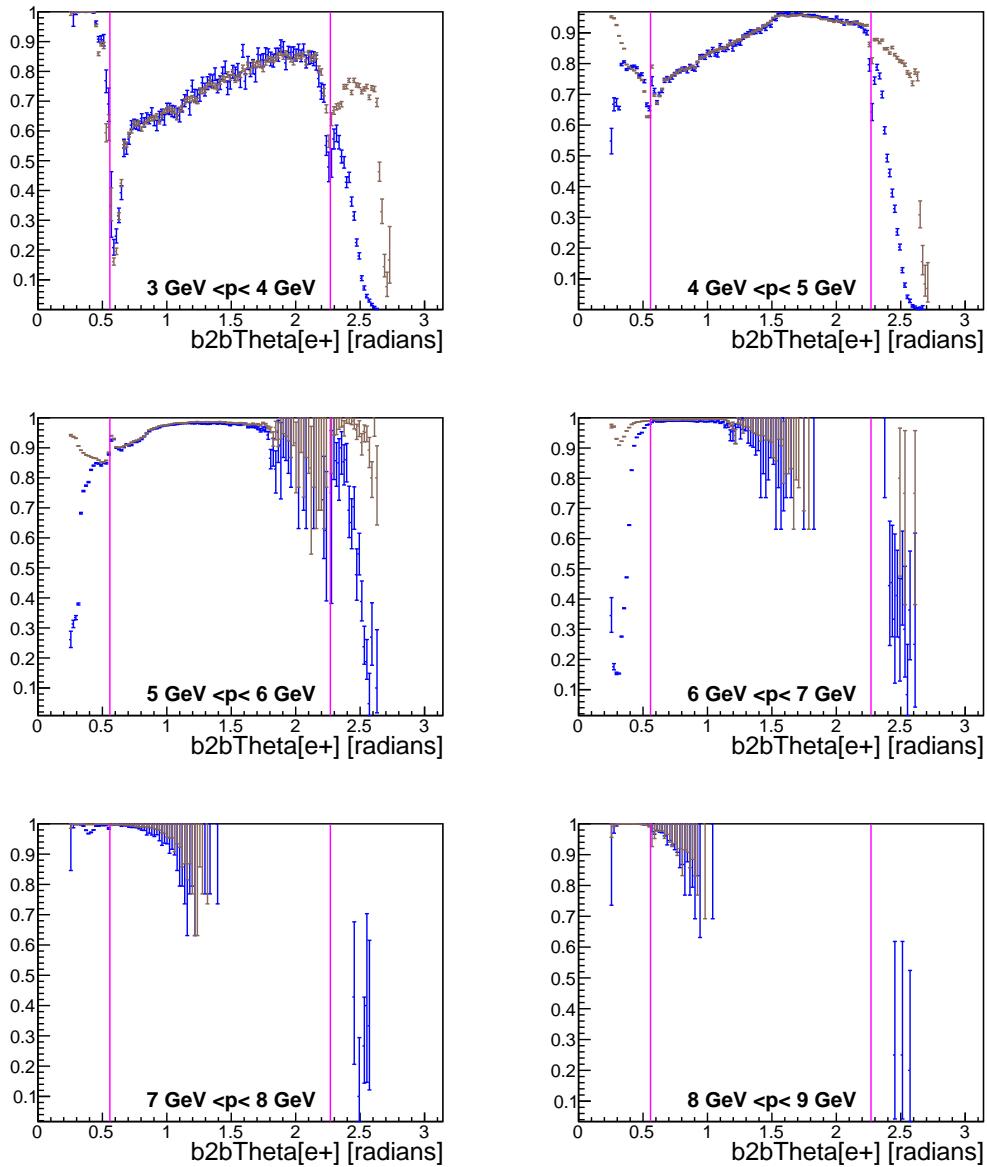


Figure 9.1.: Electron θ momentum tracking efficiency plots. The tracking efficiency of phase2 data is shown in blue and phase3 data in brown. The pink line indicates the different sectors of the ECL.

9.1. θ -Efficiencies

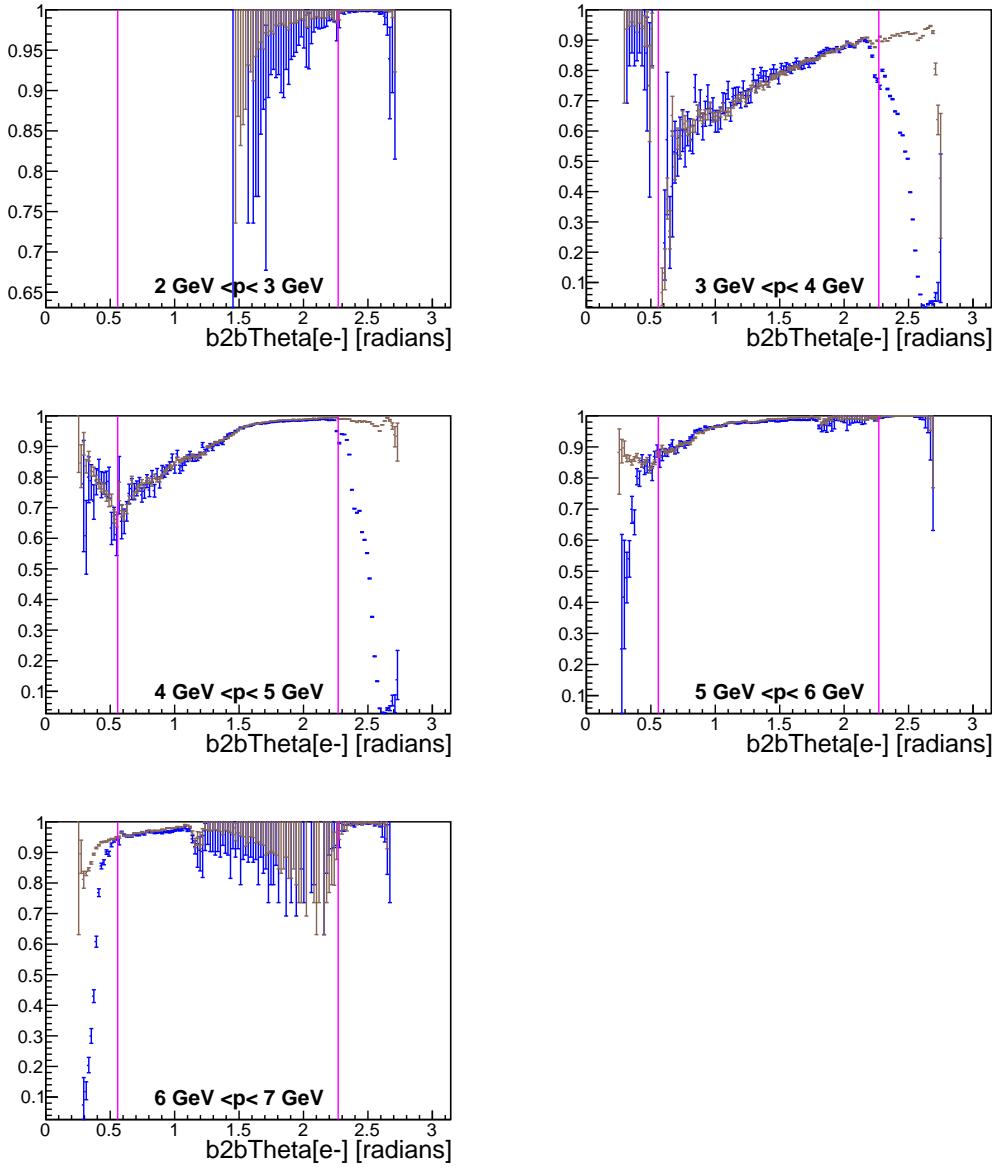


Figure 9.2.: Positron θ momentum tracking efficiency plots. The tracking efficiency of phase2 data is shown in blue and phase3 data in brown. The pink line indicates the different sectors of the ECL.

9. Comparing Phase2 With Phase3

9.2. ϕ -Efficiencies

In figure 9.3 you can see the phase2 data and phase3 data electron tracking efficiency in the forward end-cap for different momenta. For momenta between 4 GeV and 6 GeV, the phase3 data tracking efficiency is noticeably higher for $\text{abs}(\phi) > 1$. Both phase2 data and phase3 data tracking efficiency have a local minimum at $\phi \approx 0$. For momenta between 6 GeV and 8 GeV, the phase3 data tracking efficiency is overall higher than the phase2 data tracking efficiency and for momenta over 7 GeV the phase3 data tracking efficiency is above 0.99 for all values of ϕ .

Figure 9.4 shows the phase2 data and phase3 data positron tracking efficiency in the backward end-cap for different momenta.

9.2. ϕ -Efficiencies

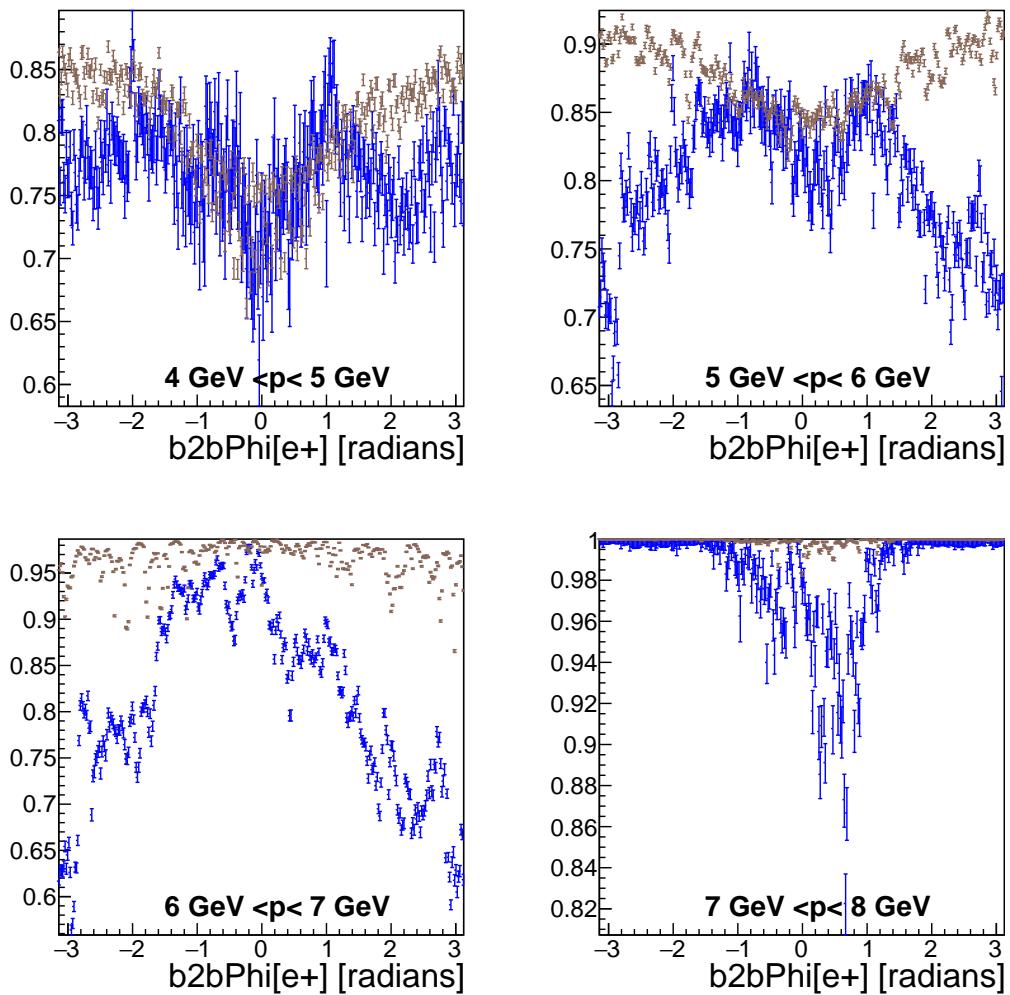


Figure 9.3.: Electron ϕ momentum tracking efficiency in the forward end-cap. The tracking efficiency of phase2 data is shown in blue and phase3 data in brown. The pink line indicates the different sectors of the ECL.

9. Comparing Phase2 With Phase3

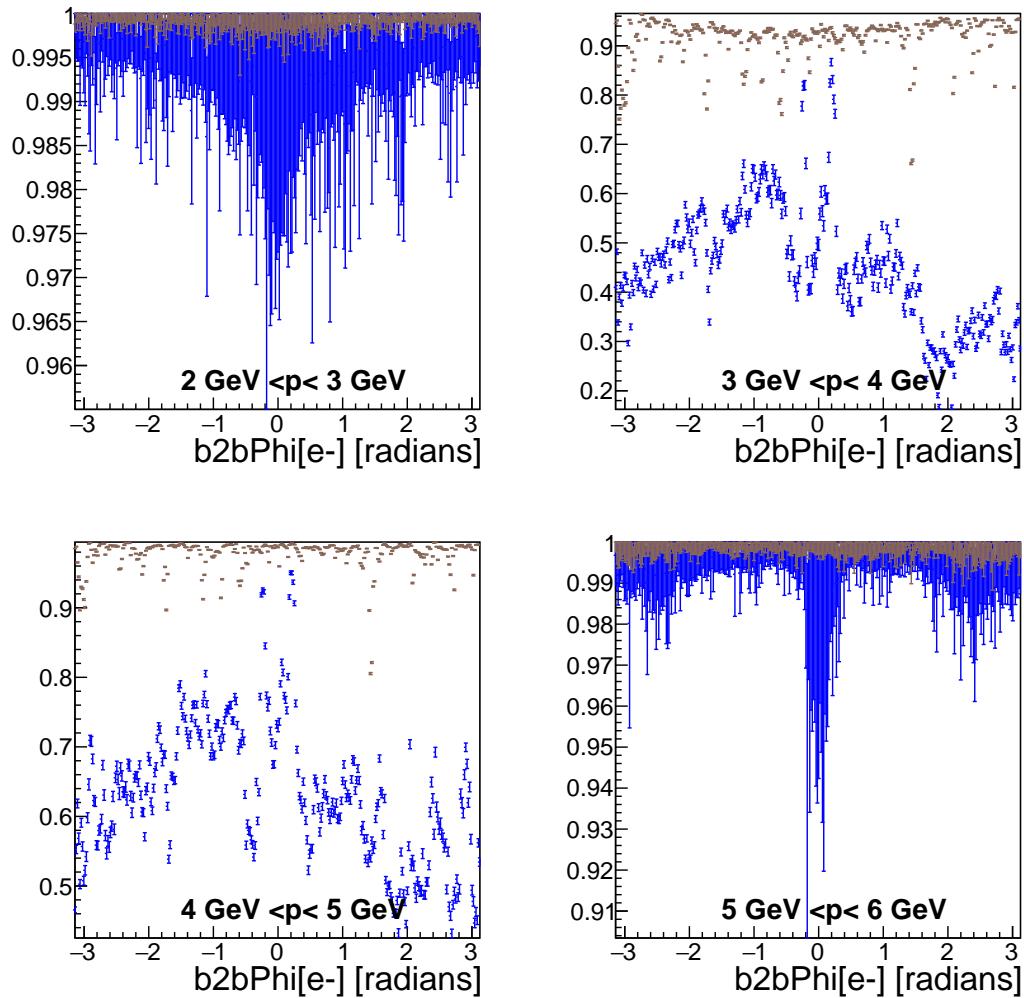


Figure 9.4.: Positron ϕ momentum tracking efficiency in the forward end-cap. The tracking efficiency of phase2 data is shown in blue and phase3 data in brown. The pink line indicates the different sectors of the ECL.

In this work the tracking efficiency of the innermost detectors of Belle II was presented. Using Monte Carlo-Truth information, these are the informations of the generated MC particle and therefore the true properties of these particles, I tried to show that it is possible to select outgoing electron/positron events, also known as Bhabha events, with informations solely coming from the electromagnetic calorimeter (ECL), a sub-detector of Belle II. This selection is rather basic because it is mostly based on just the kinematics of these Bhabha events. Then, using this selection, I managed to reconstruct these Bhabha events even without the MC-Truth information. Therefore, it was possible to apply this selection on real data and tracking efficiencies could be calculated. This was done for phase2 MC, phase2 data, phase3 MC and phase3 data. The calculated tracking efficiencies for phase2 MC and phase2 data were compared in detail and differences were highlighted. The same was done with the tracking efficiencies of phase3 MC and phase3 data.

Phase2 was a test run to study the background at Belle II. For this phase only a small fraction of the vertex detectors (VXD) were installed.

For the phase2 tracking efficiency, we saw that most of the time, the tracking efficiencies of phase2 MC are higher than the tracking efficiencies of phase2 data. But this was expected, because on MC, there are no dead times of the detector, the detector is always performing at its best and some structures of the detector, like cabling or screws, which may interfere with the outgoing particles, are maybe not implemented in the simulation, ultimately leading to a higher efficiency. This is also true for phase3. Unfortunately, the phase2 and phase3 MC has noticeably larger error bars compared to phase2 and phase3 data due to the lower statistics.

The tracking efficiencies, especially in the end-caps, of phase2 MC and phase2 data have remarkable differences in structure and in the height. The biggest differences occur at $\phi \approx 0$. For these angles even the structure of the tracking efficiencies vary often times. Also, both tracking efficiencies fall drastically down to 0 at the end of both end-caps. In the barrel, phase2 MC and phase2 data are closer together, most of the time.

10. Summary And Conclusion

For phase3, the first physics run for Belle II, more parts of the VXD were installed. This includes the silicon vertex detector (SVD) and most of the pixel detector (PXD). Overall, the tracking efficiencies in both end-caps got way better for electrons and positrons and for all momenta. One has to mention, that there are drops in the phase3 data tracking efficiency for some ϕ values. In the barrel, unfortunately, no noticeable improved of the tracking efficiency could be observed.

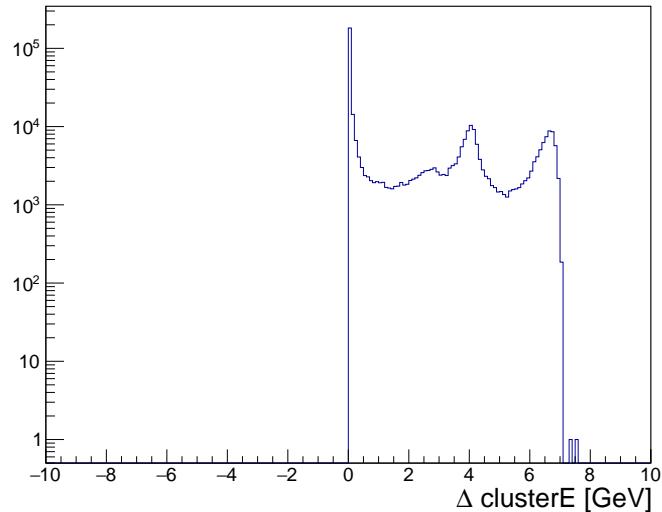
A Additional Preparation Plots

Figure A.1.: $\text{clusterE}(\text{HclE}) - \text{clusterE}(\text{LclE})$ of the reconstructed candidates. This shows that the HclE daughters has always a higher cluster energy than the LclE daughter.

A. Additional Preparation Plots

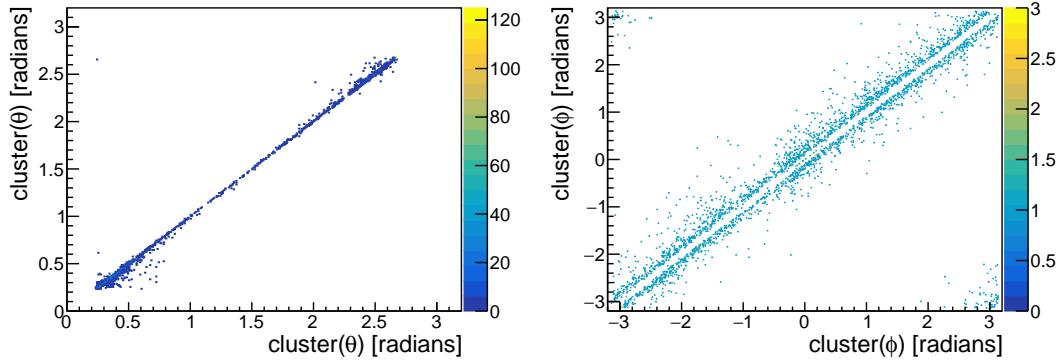


Figure A.2.: Left: The θ angle of the clusters after the *cluster splitting*. Almost all the time, both clusters have the same θ angle. Right: The ϕ angle of the clusters after the *cluster splitting*. The ϕ angle of both clusters are always slightly different. Therefore, *cluster splitting* always occurs along the polar angle.

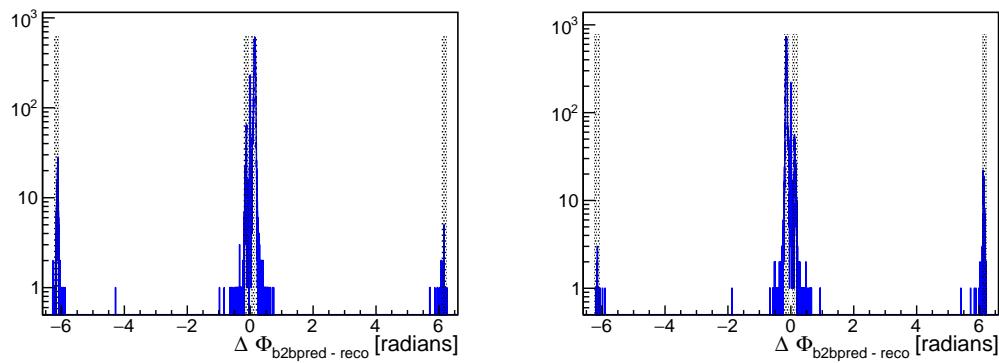


Figure A.3.: Left: Predicted $\text{clusterPhi}(\text{HclE})$ - Reconstructed $\text{clusterPhi}(\text{LclE})$. Right: Predicted $\text{clusterPhi}(\text{LclE})$ - Reconstructed $\text{clusterPhi}(\text{HclE})$. Only particles within the gray area are taken into account. Both plots are created with phase2 data. Note the logarithmic scale.

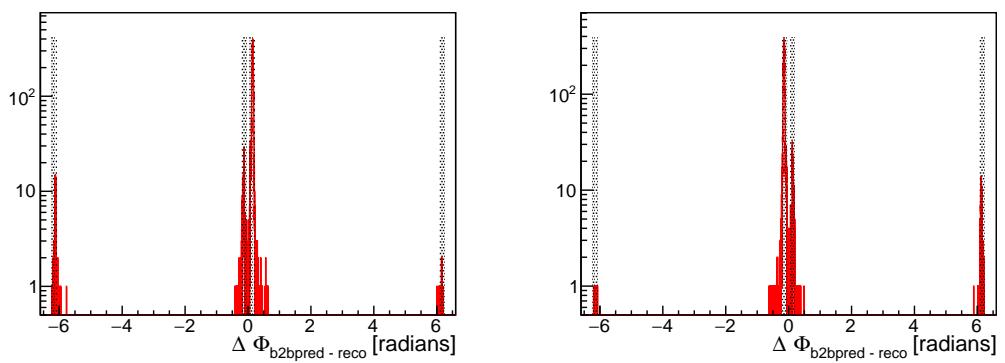


Figure A.4.: Left: Predicted clusterPhi(HclE) - Reconstructed clusterPhi(LclE).
 Right: Predicted clusterPhi(LclE) - Reconstructed clusterPhi(HclE).
 Only particles within the gray area are taken into account. Both plots
 are created with phase2 MC data. Note the logarithmic scale.

A. Additional Preparation Plots

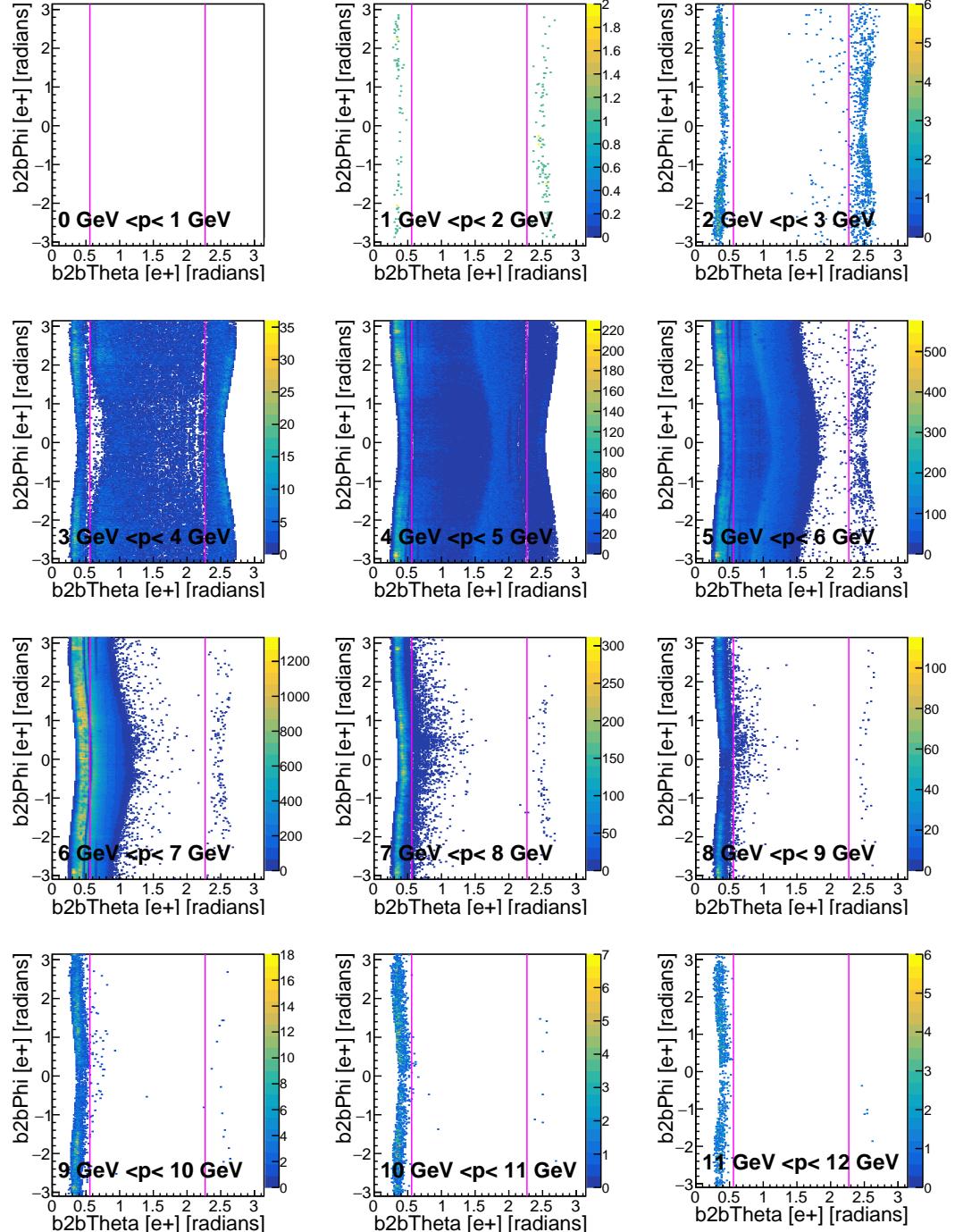


Figure A.5.: Predicted θ and ϕ denominator histograms of the *probe* particle for different momenta for electrons for phase2 Data are shown. The different areas of interest are indicated by the pink line.

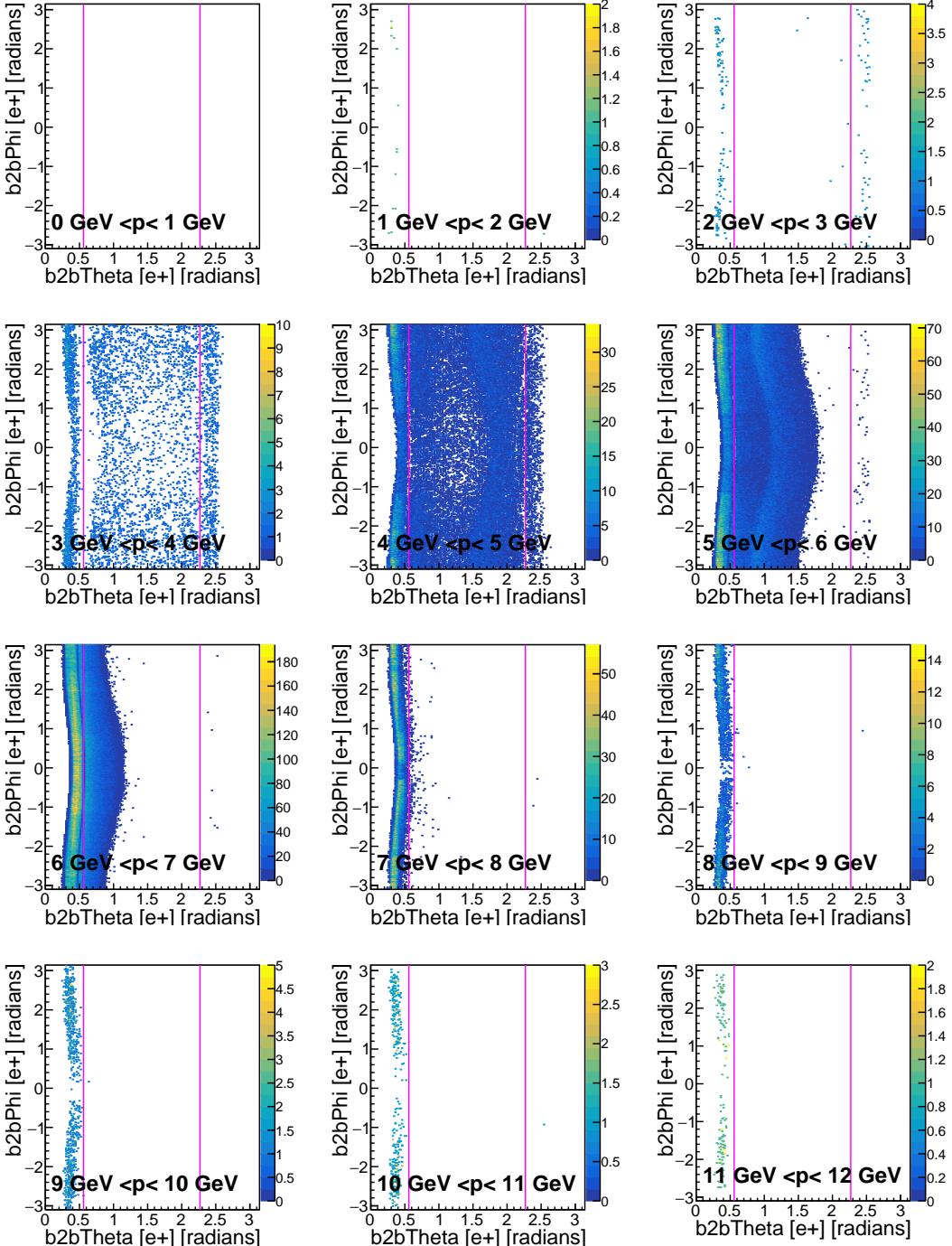


Figure A.6.: Predicted θ and ϕ enumerator histograms of the *probe* particle for different momenta for electrons for phase2 MC are shown. The different areas of interest are indicated by the pink line.

A. Additional Preparation Plots

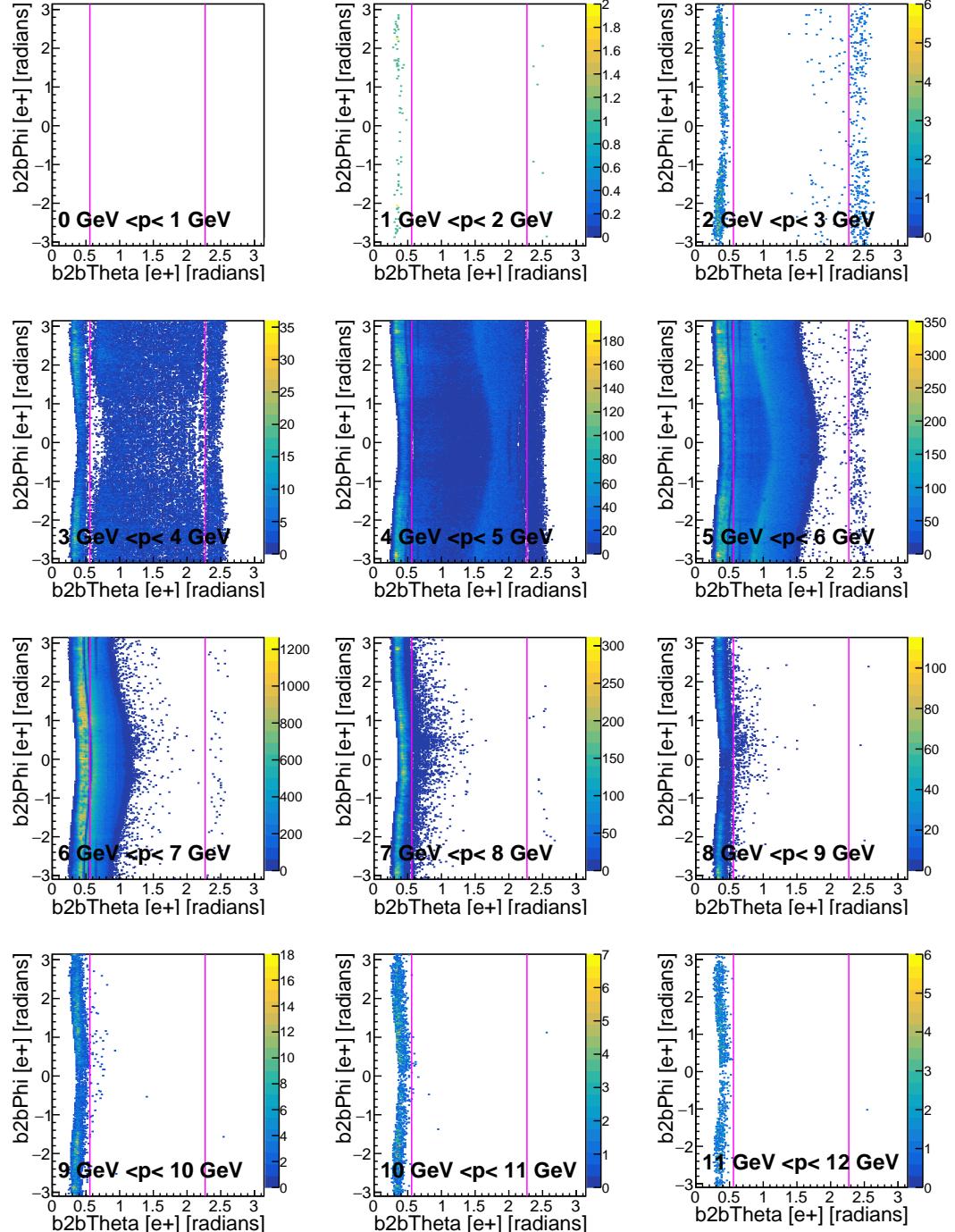


Figure A.7.: Predicted θ and ϕ enumerator histograms of the *probe* particle for different momenta for electrons for phase2 data are shown. The different areas of interest are indicated by the pink line.

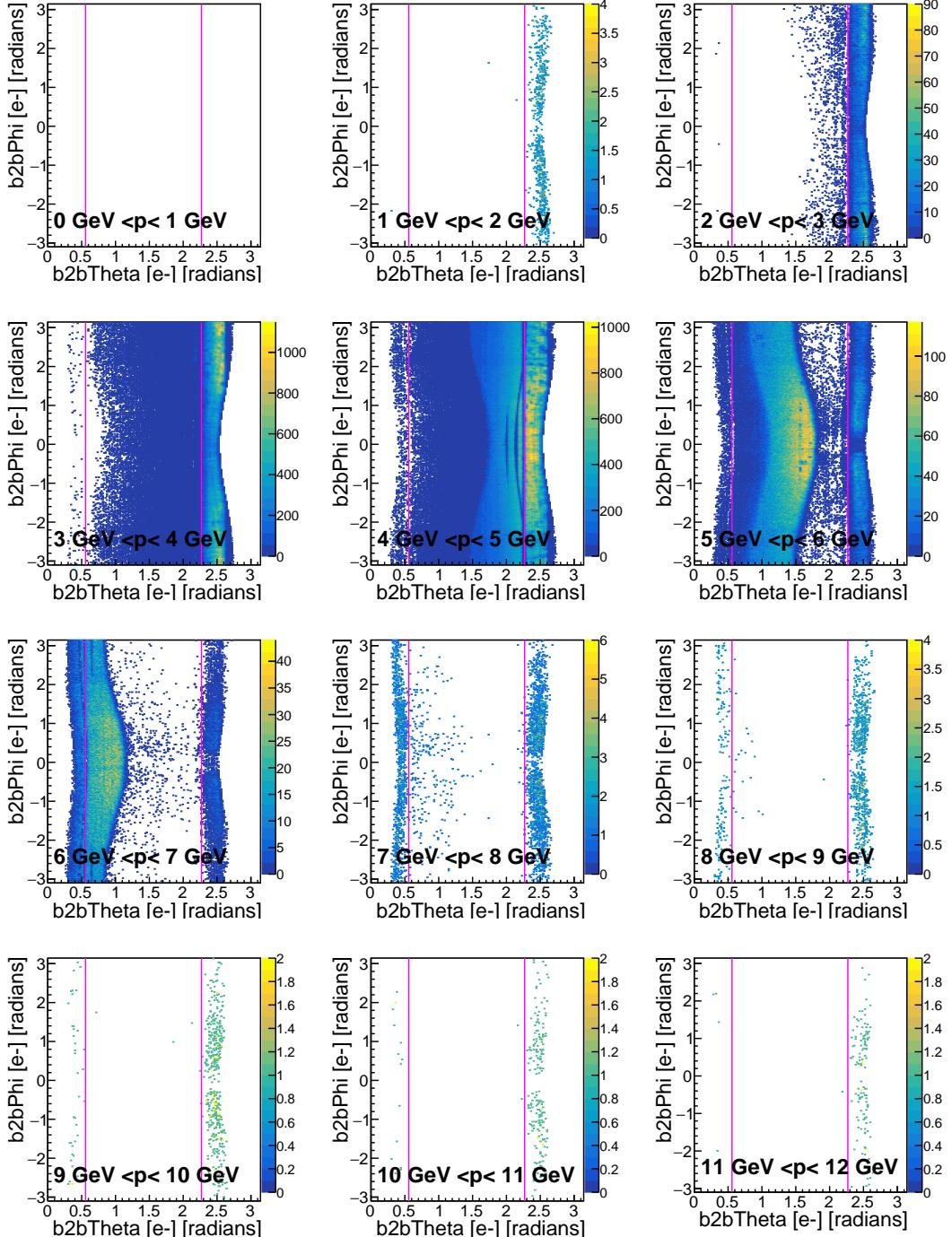


Figure A.8.: Predicted θ and ϕ denominator histograms of the *probe* particle for different momenta for positrons for phase2 Data are shown. The different areas of interest are indicated by the pink line.

A. Additional Preparation Plots

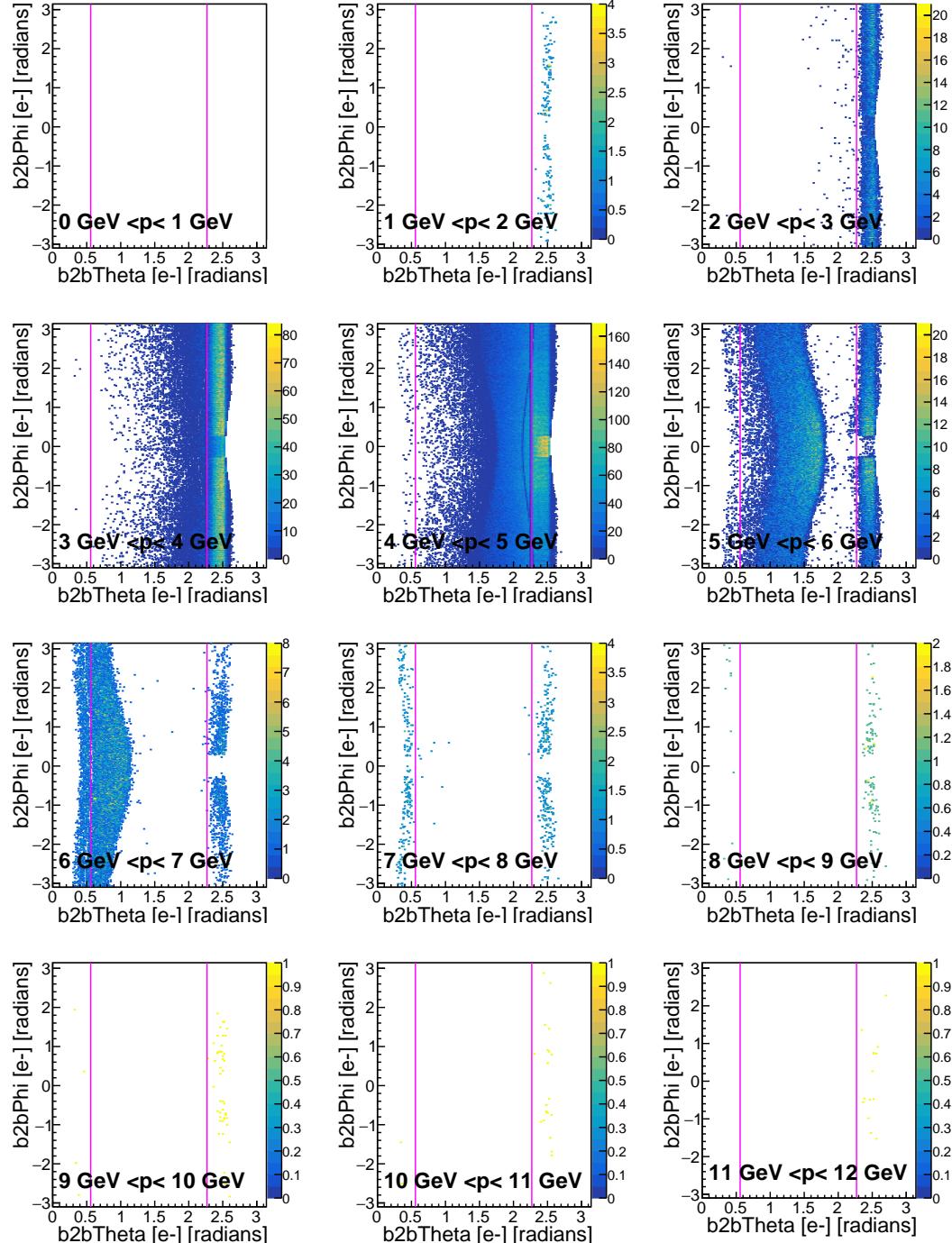


Figure A.9.: Predicted θ and ϕ denominator histograms of the *probe* particle for different momenta for positrons for phase2 MC are shown. The different areas of interest are indicated by the pink line.

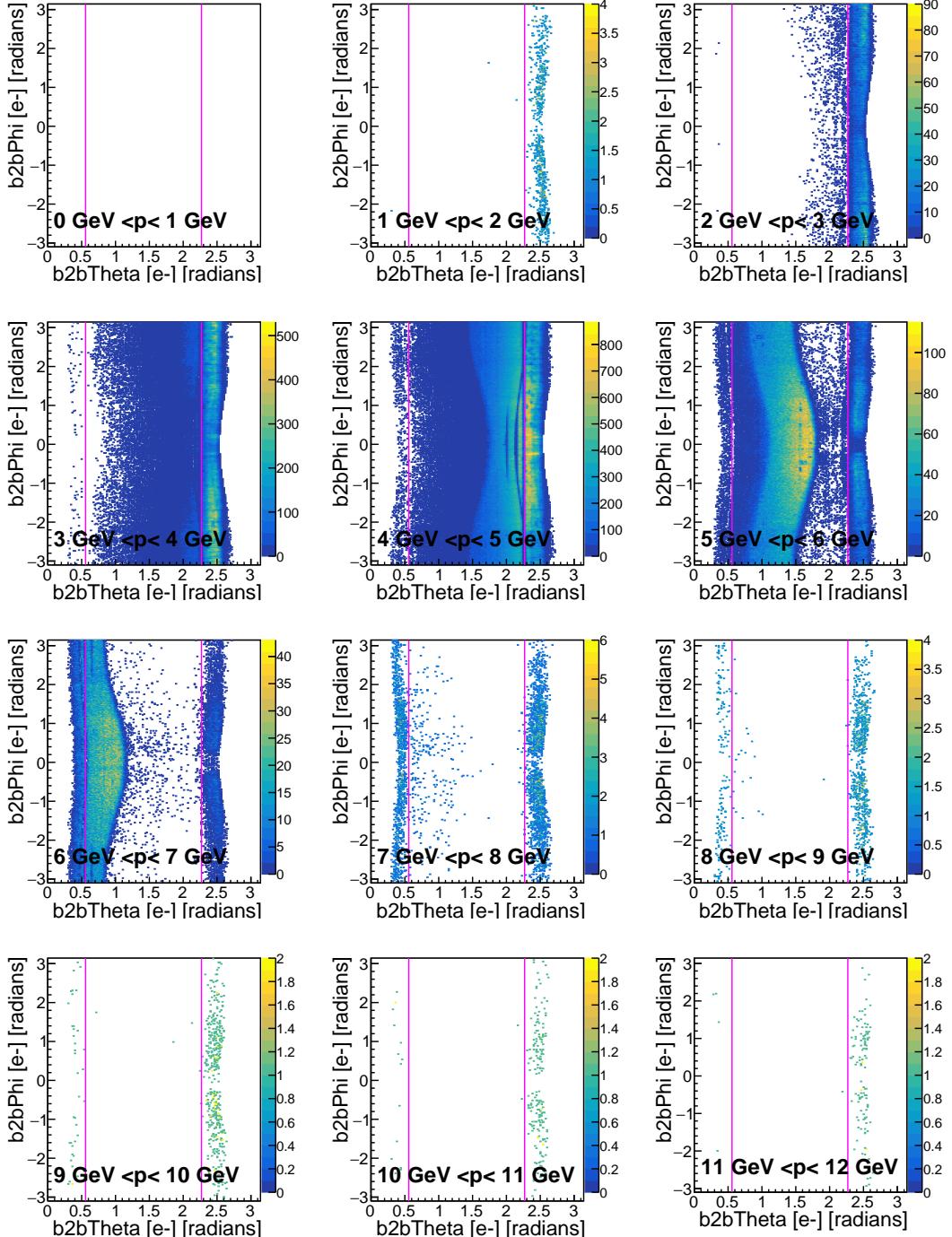


Figure A.10.: Predicted θ and ϕ denominator histograms of the *probe* particle for different momenta for positrons for phase2 Data are shown. The different areas of interest are indicated by the pink line.

A. Additional Preparation Plots

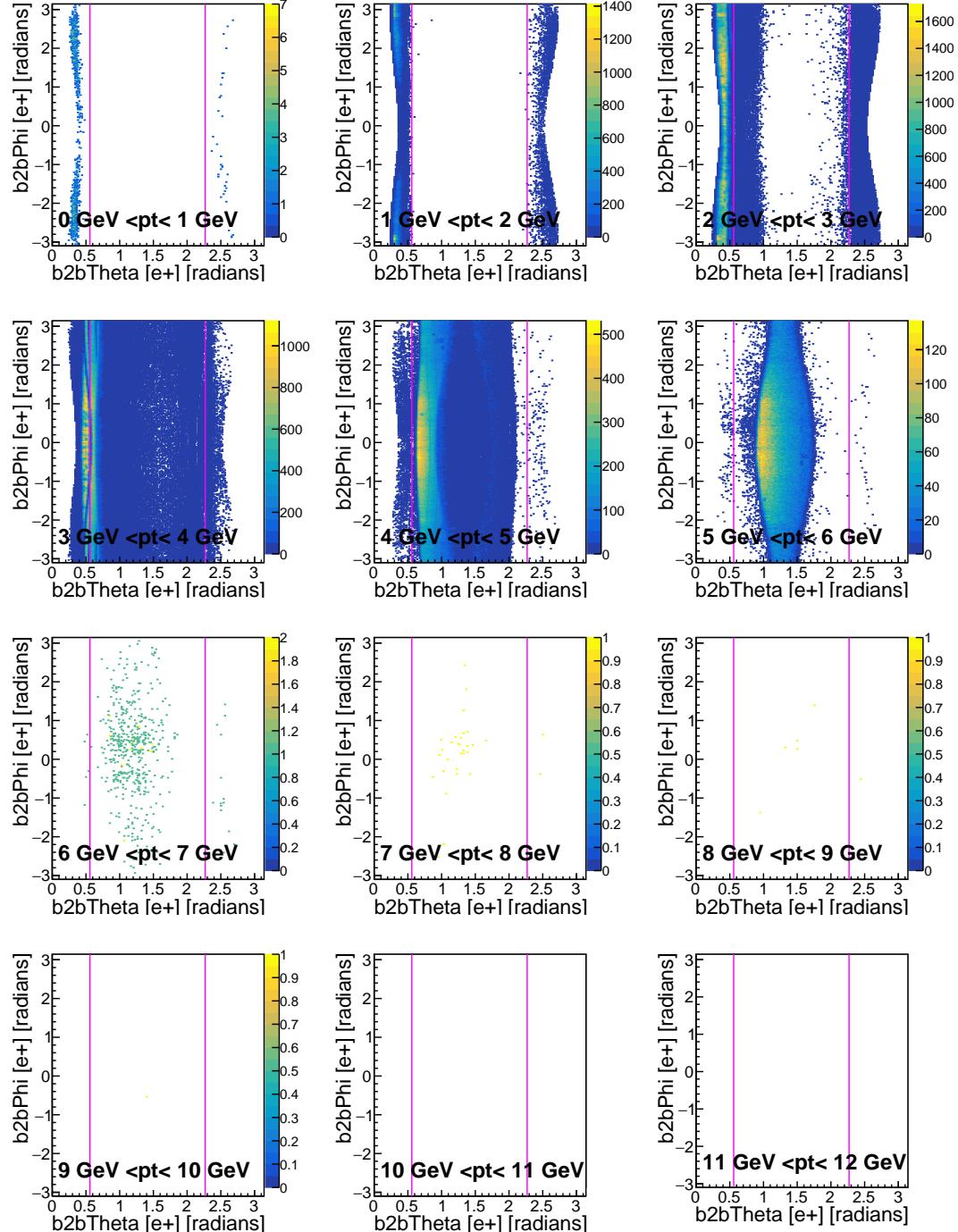


Figure A.11.: Predicted θ and ϕ denominator histograms of the *probe* particle for different transverse momenta for electrons for phase2 Data are shown. The different areas of interest are indicated by the pink line.

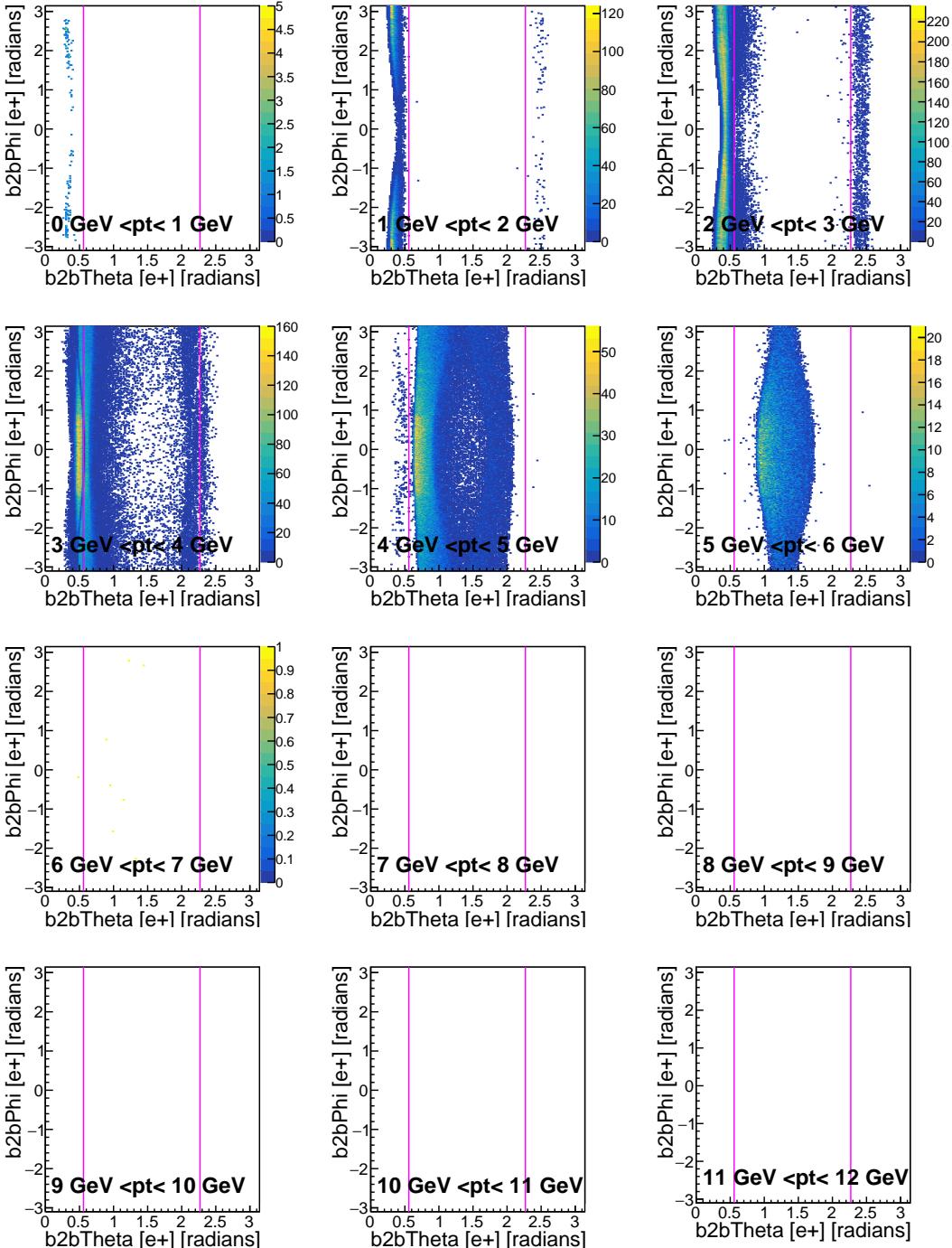


Figure A.12.: Predicted θ and ϕ denominator histograms of the *probe* particle for different transverse momenta for electrons for phase2 MC are shown. The different areas of interest are indicated by the pink line.

A. Additional Preparation Plots

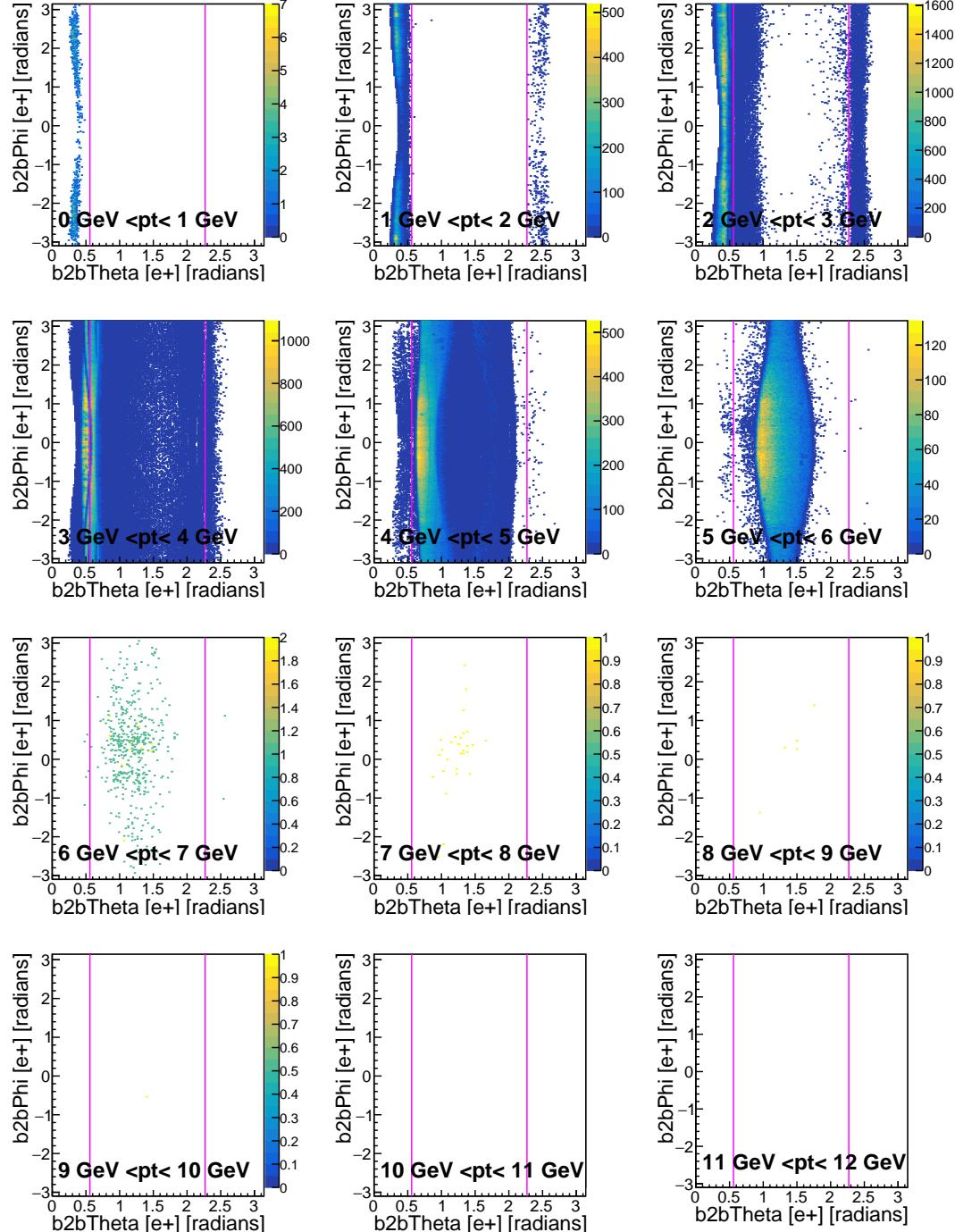


Figure A.13.: Predicted θ and ϕ denominator histograms of the *probe* particle for different transverse momenta for electrons for phase2 data are shown. The different areas of interest are indicated by the pink line.

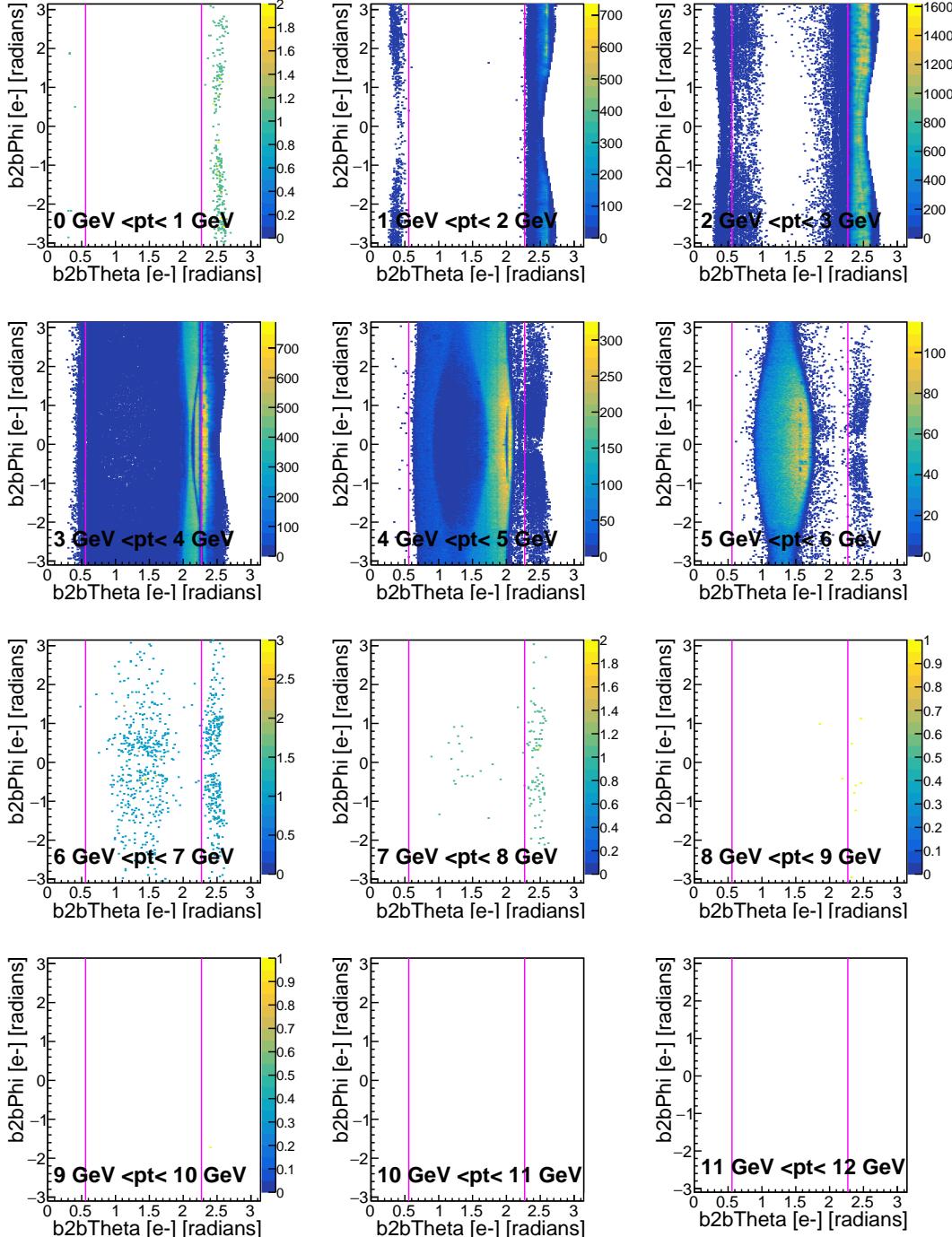


Figure A.14.: Predicted θ and ϕ denominator histograms of the *probe* particle for different transverse momenta for positrons for phase2 Data are shown. The different areas of interest are indicated by the pink line.

A. Additional Preparation Plots

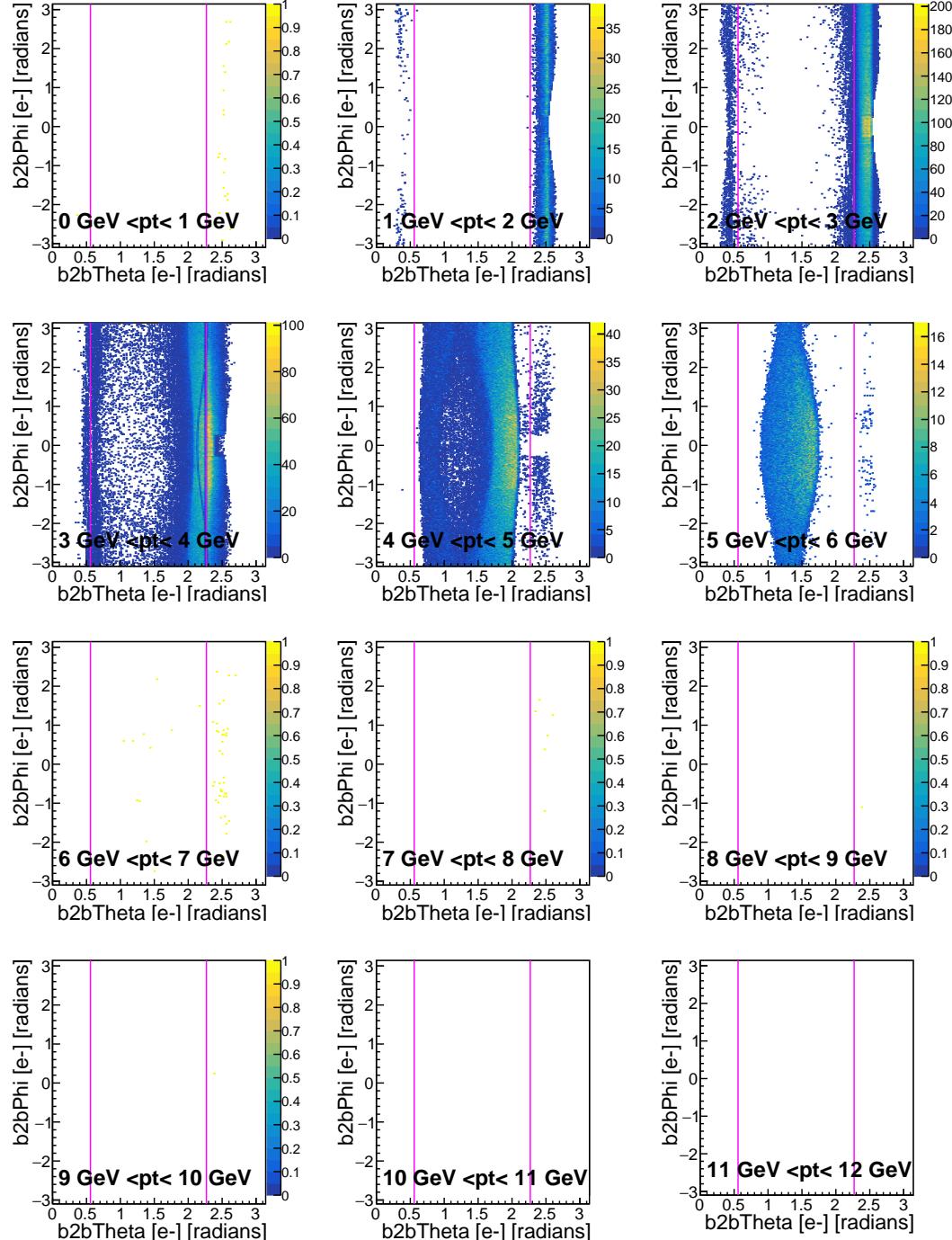


Figure A.15.: Predicted θ and ϕ denominator histograms of the *probe* particle for different transverse momenta for positrons for phase2 MC are shown. The different areas of interest are indicated by the pink line.

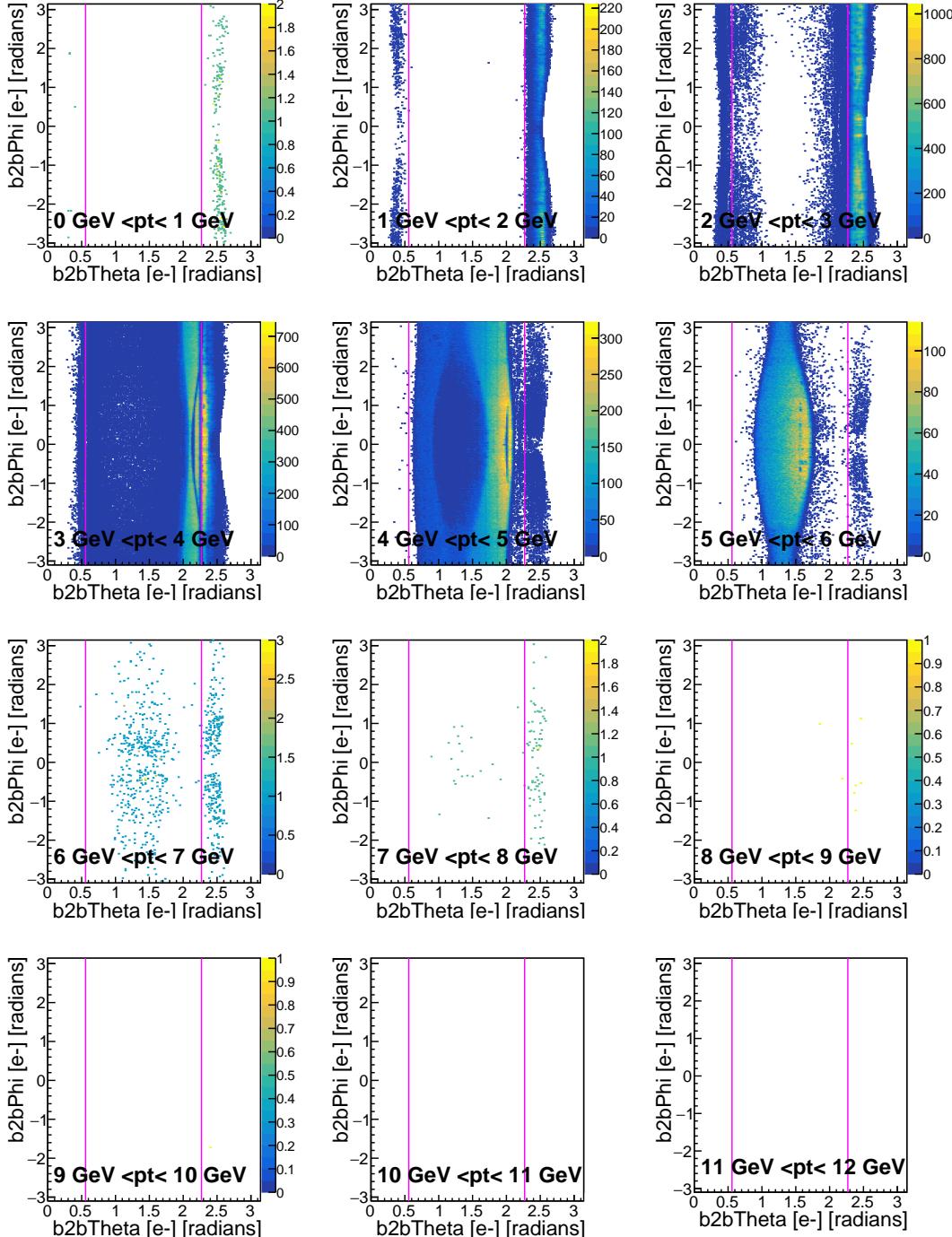


Figure A.16.: Predicted θ and ϕ denominator histograms of the *probe* particle for different transverse momenta for positrons for phase2 data are shown. The different areas of interest are indicated by the pink line.

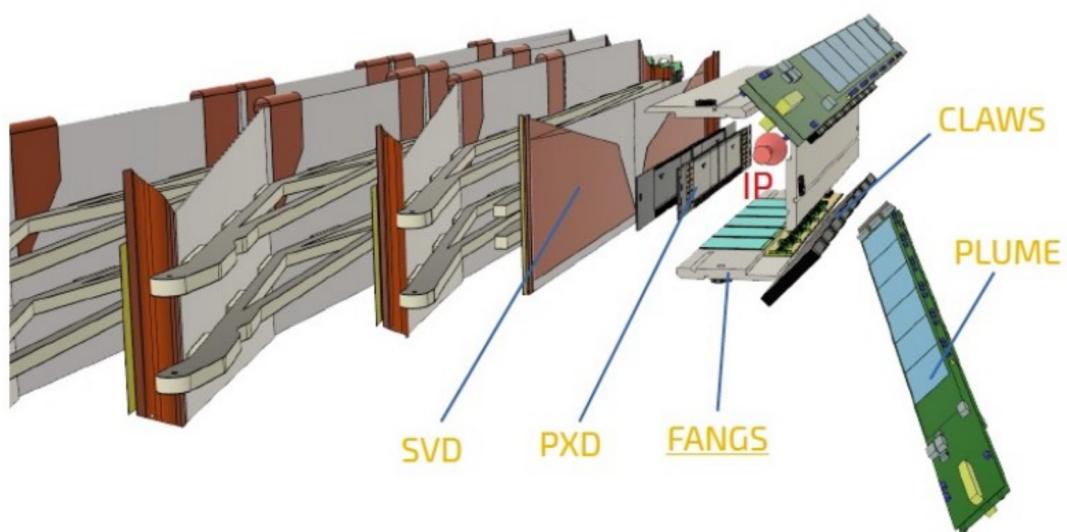


Figure B.1.: The status of the VXD detector during phase2.[34]

B. Additional Phase2 Plots

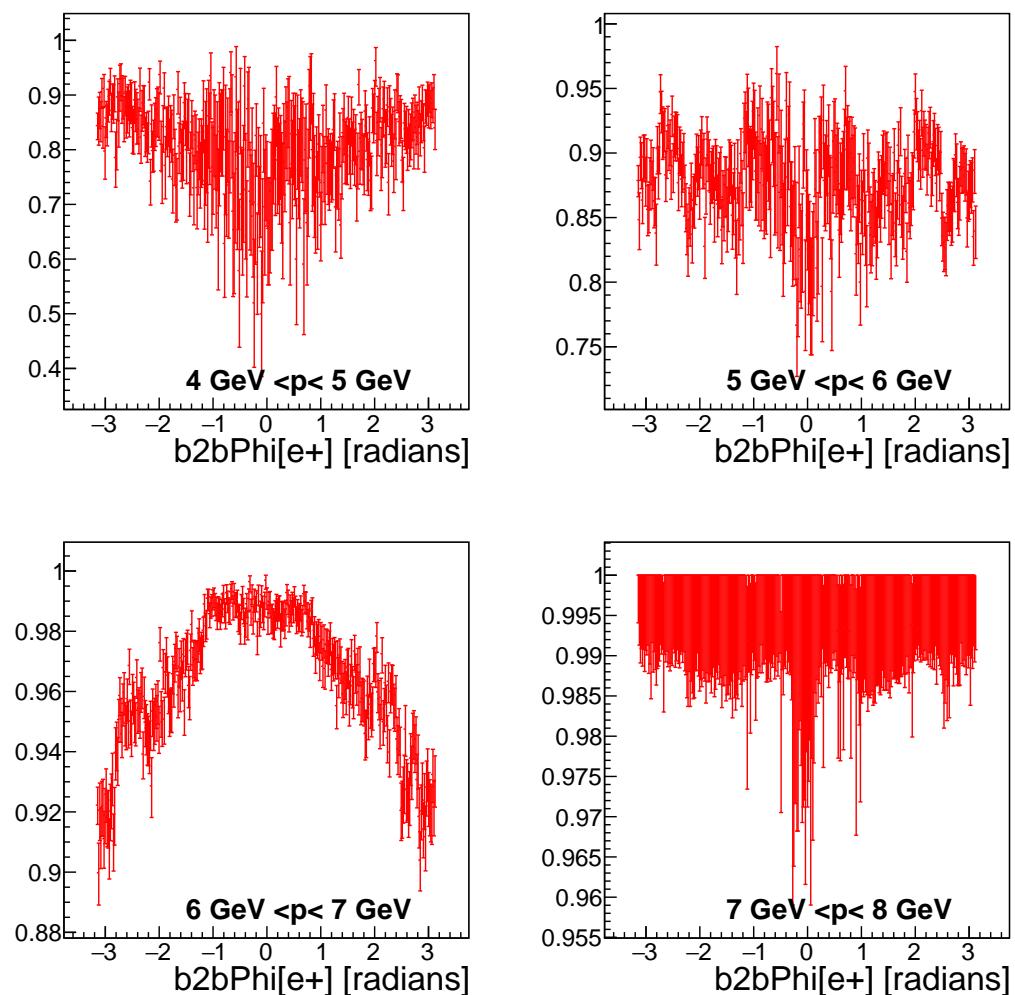


Figure B.2.: Electron ϕ tracking efficiency plots in the forward end-cap for phase2 MC.

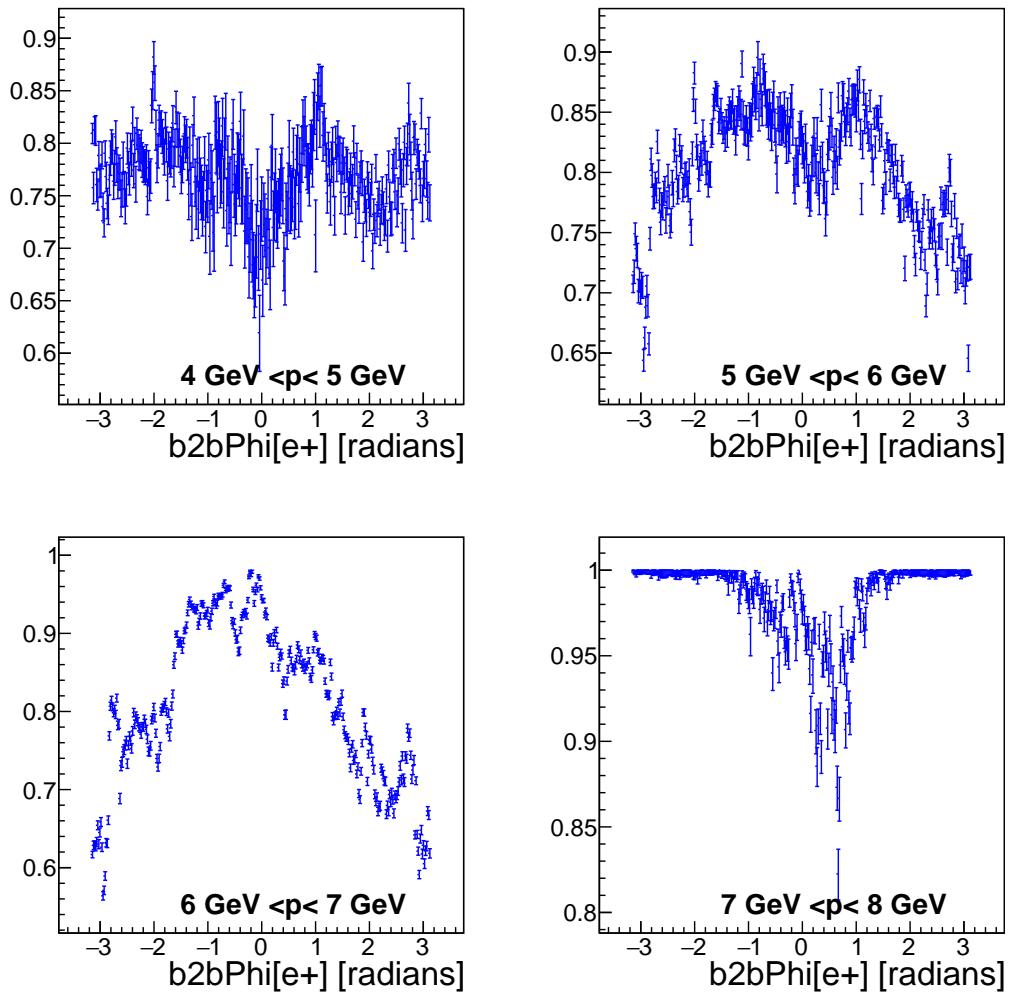


Figure B.3.: Electron ϕ tracking efficiency plots in the forward end-cap for phase2 Data.

B. Additional Phase2 Plots

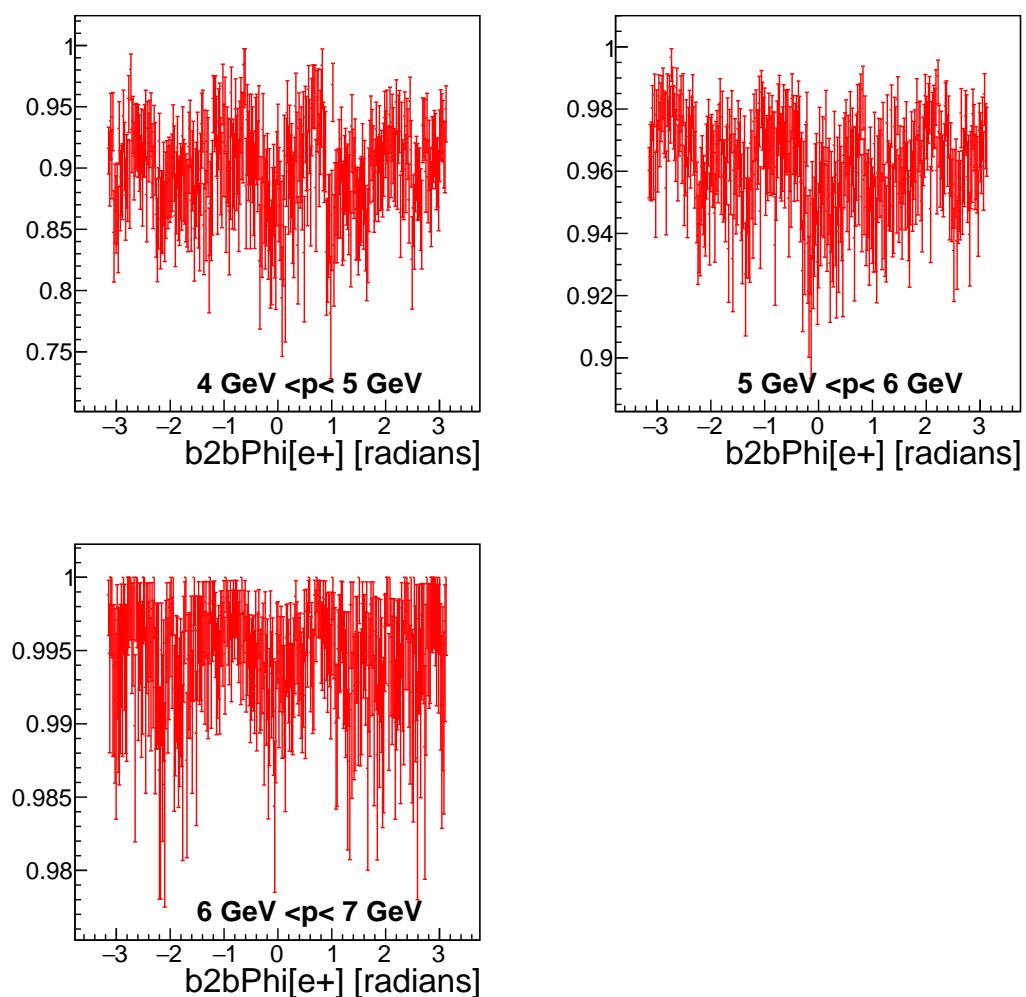


Figure B.4.: Electron ϕ tracking efficiency plots in the barrel for phase2 MC.

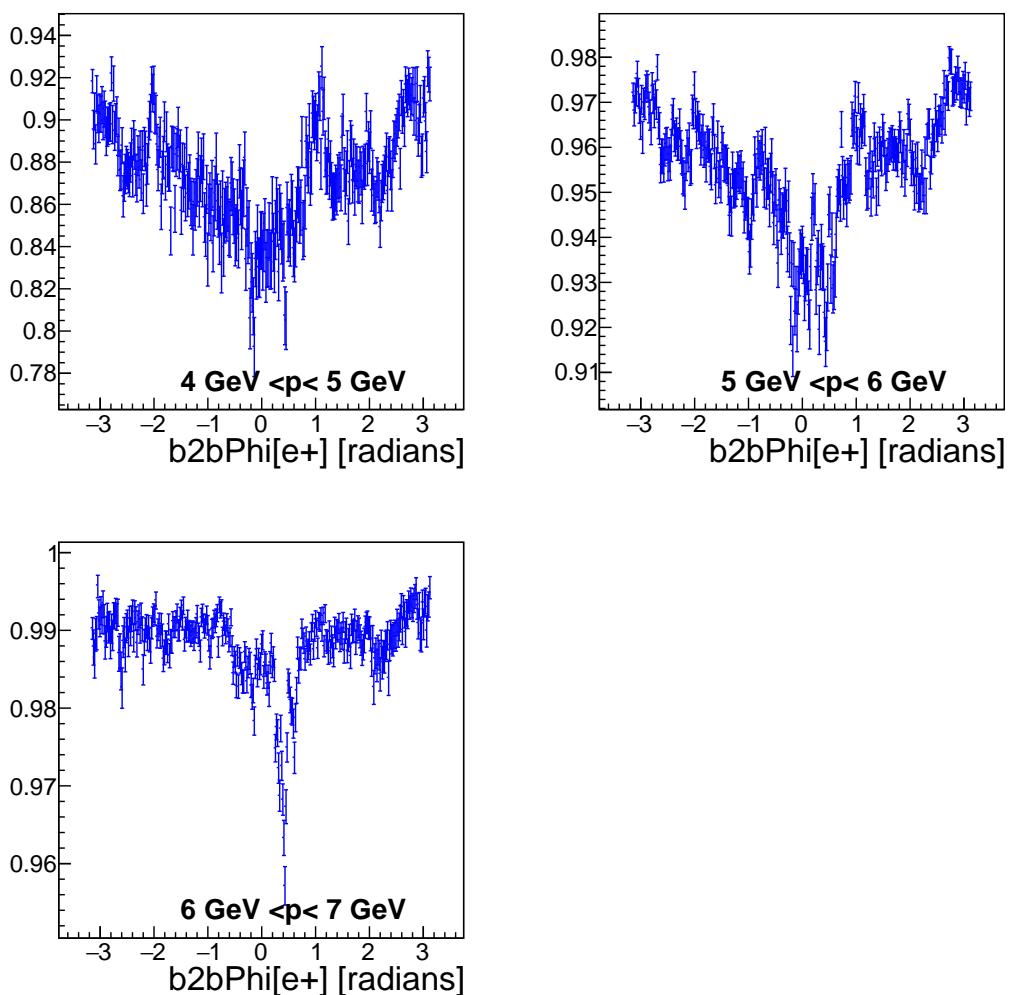


Figure B.5.: Electron ϕ tracking efficiency plots in the barrel for phase2 Data.

B. Additional Phase2 Plots

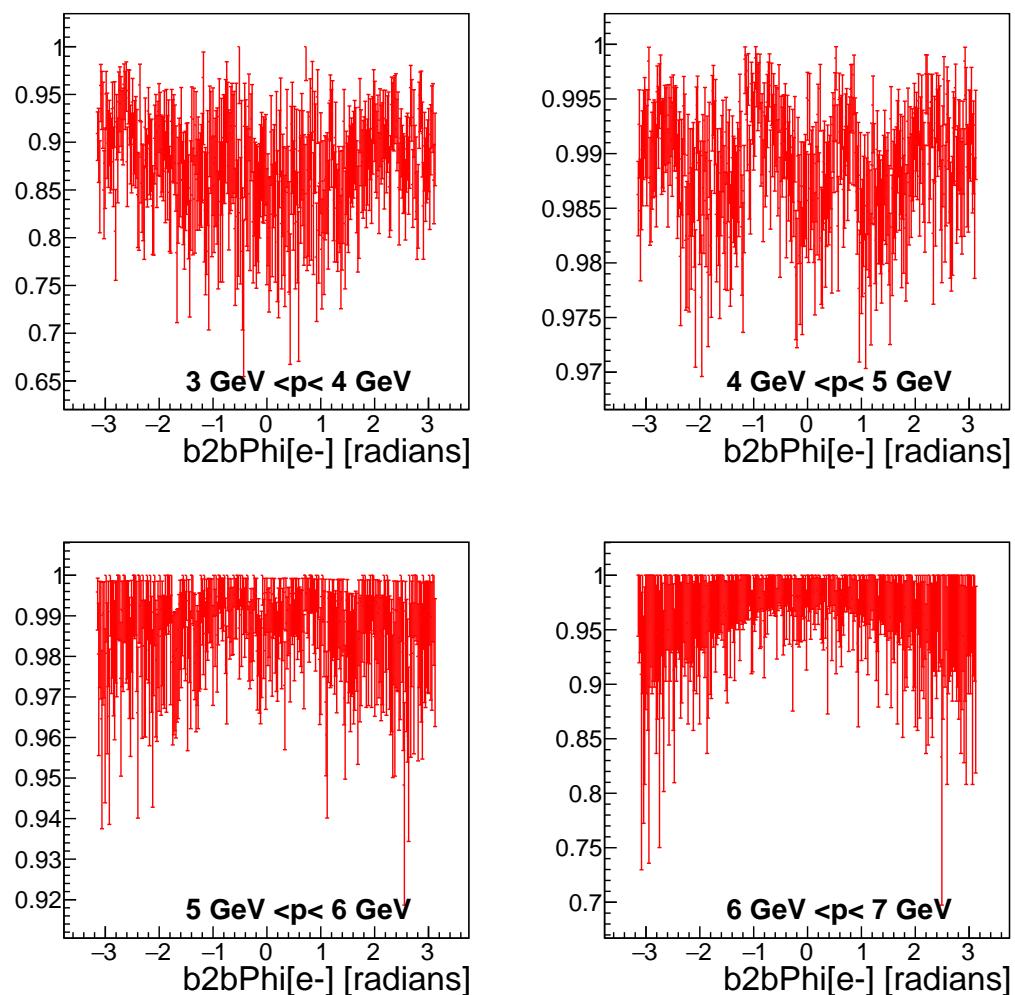


Figure B.6.: Positron ϕ tracking efficiency plots in the barrel for phase2 MC.

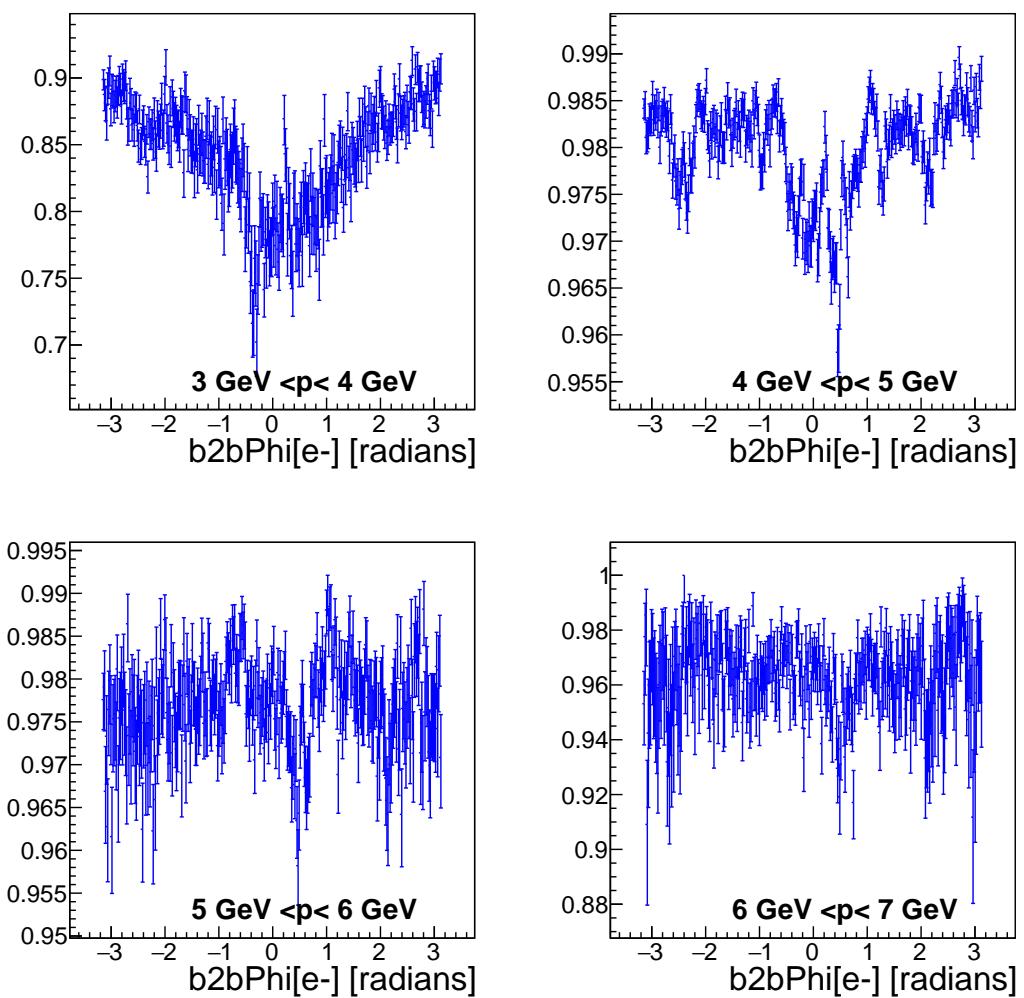


Figure B.7.: Positron ϕ tracking efficiency plots in the barrel for phase2 Data.

B. Additional Phase2 Plots

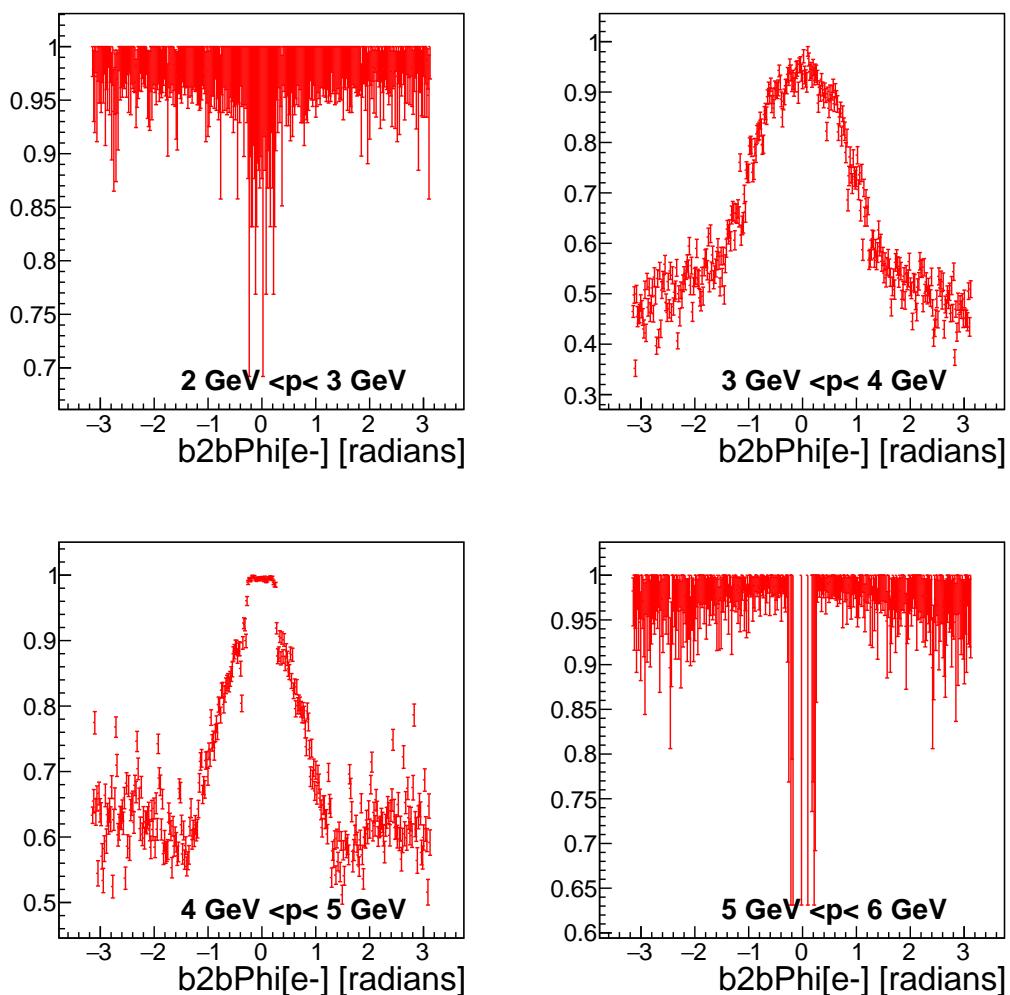


Figure B.8.: Positron ϕ tracking efficiency plots in the backward end-cap for phase2 MC.

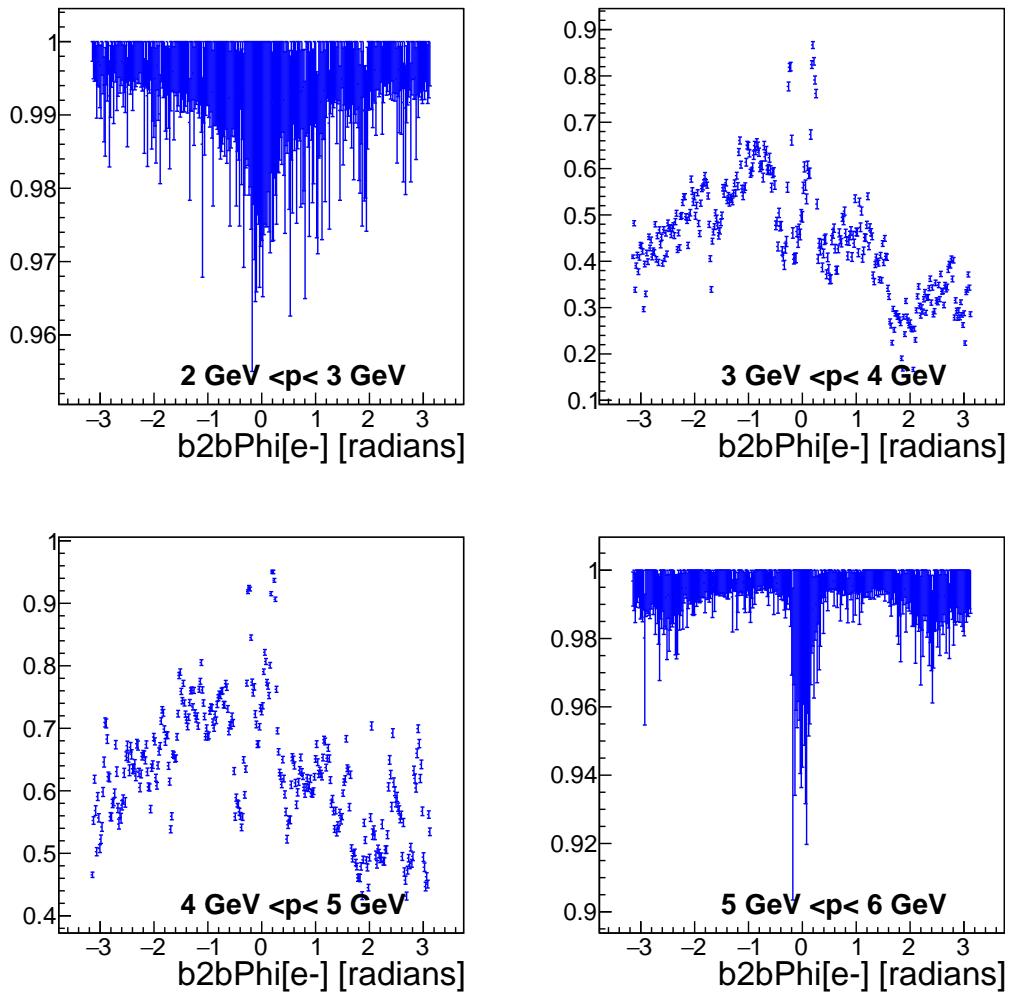


Figure B.9.: Positron ϕ tracking efficiency plots in the backward end-cap for phase2 Data.

B. Additional Phase2 Plots

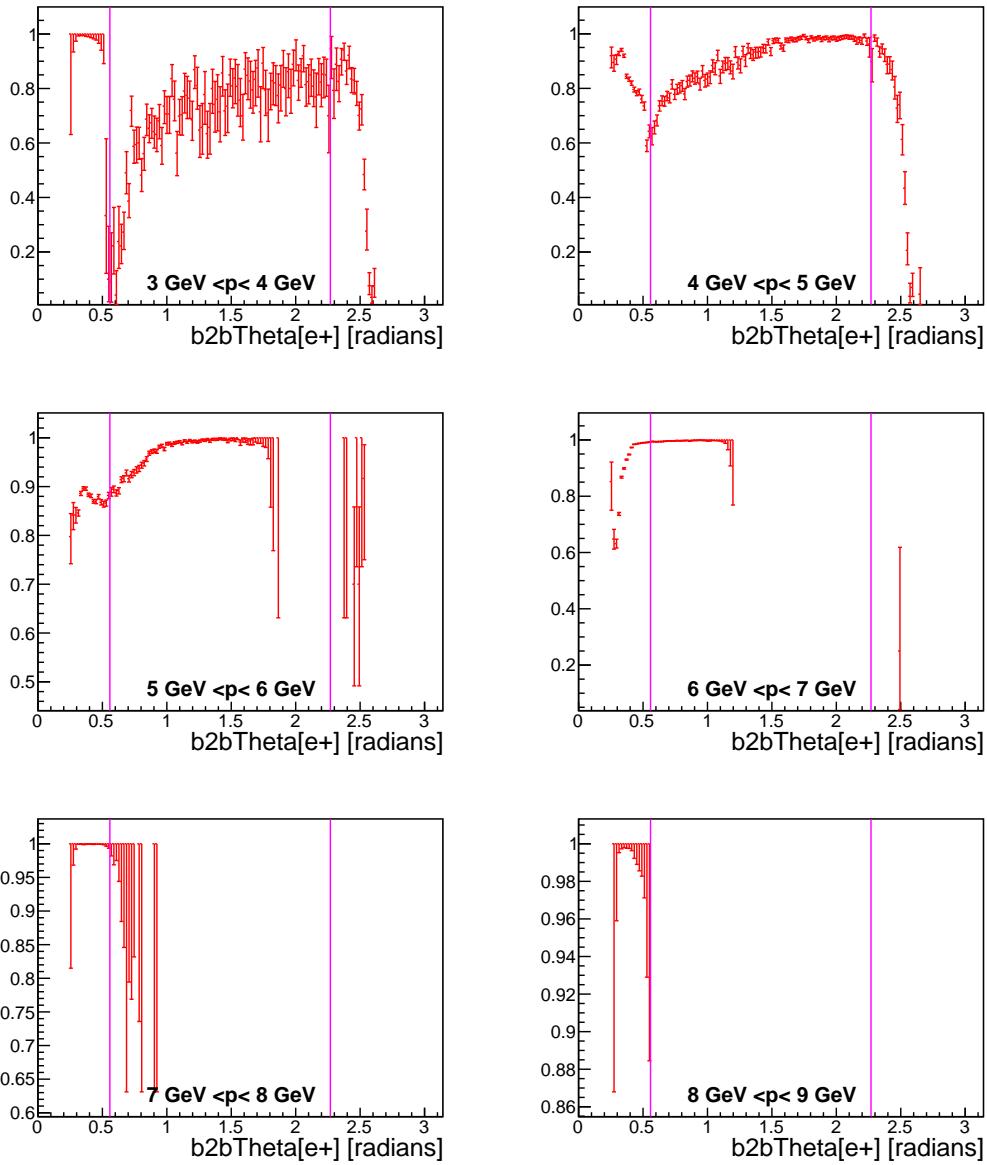


Figure B.10.: Electron ϕ tracking efficiency plots for phase2 MC. The pink line indicates the different sectors of the ECL.

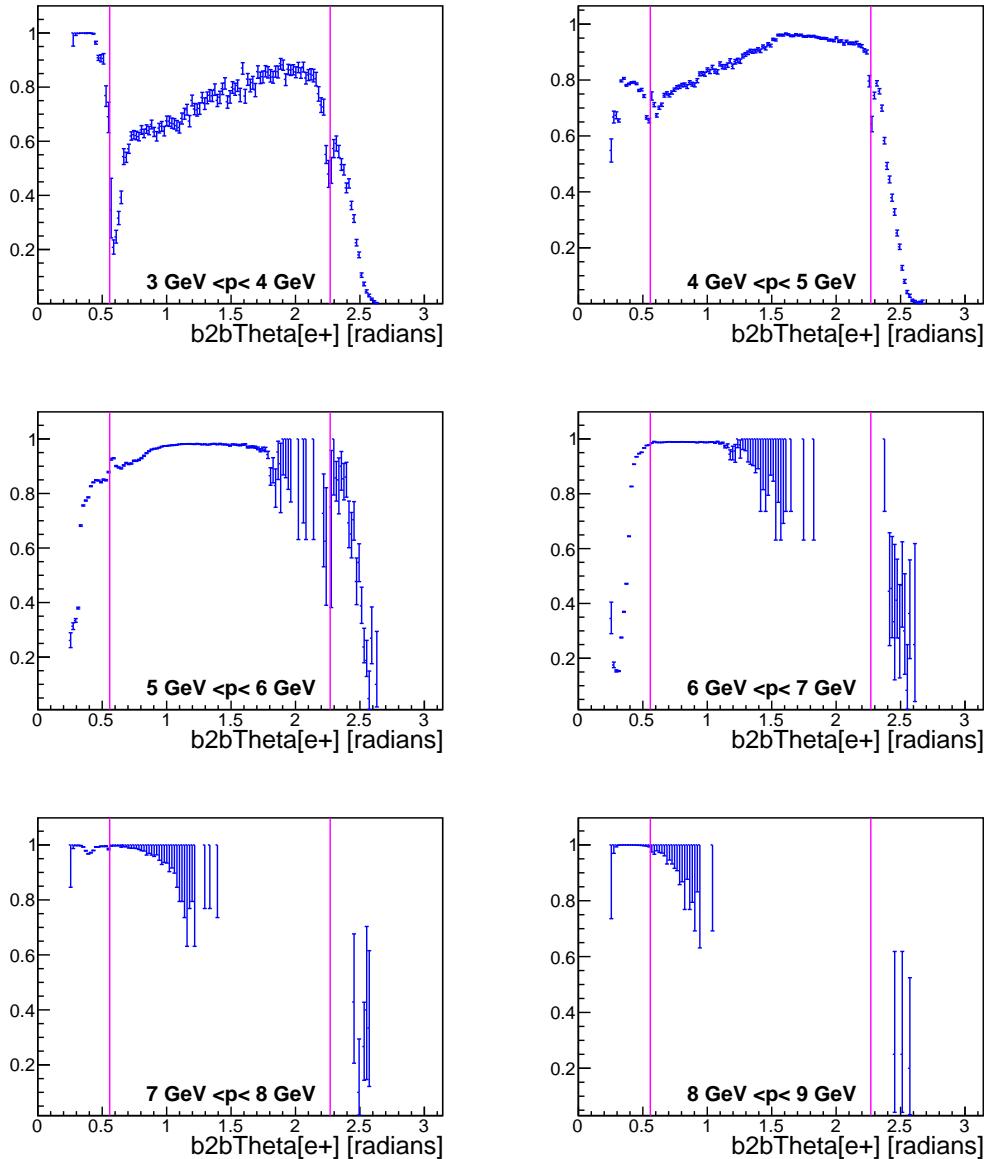


Figure B.11.: Electron ϕ tracking efficiency plots for phase2 Data. The pink line indicates the different sectors of the ECL.

B. Additional Phase2 Plots

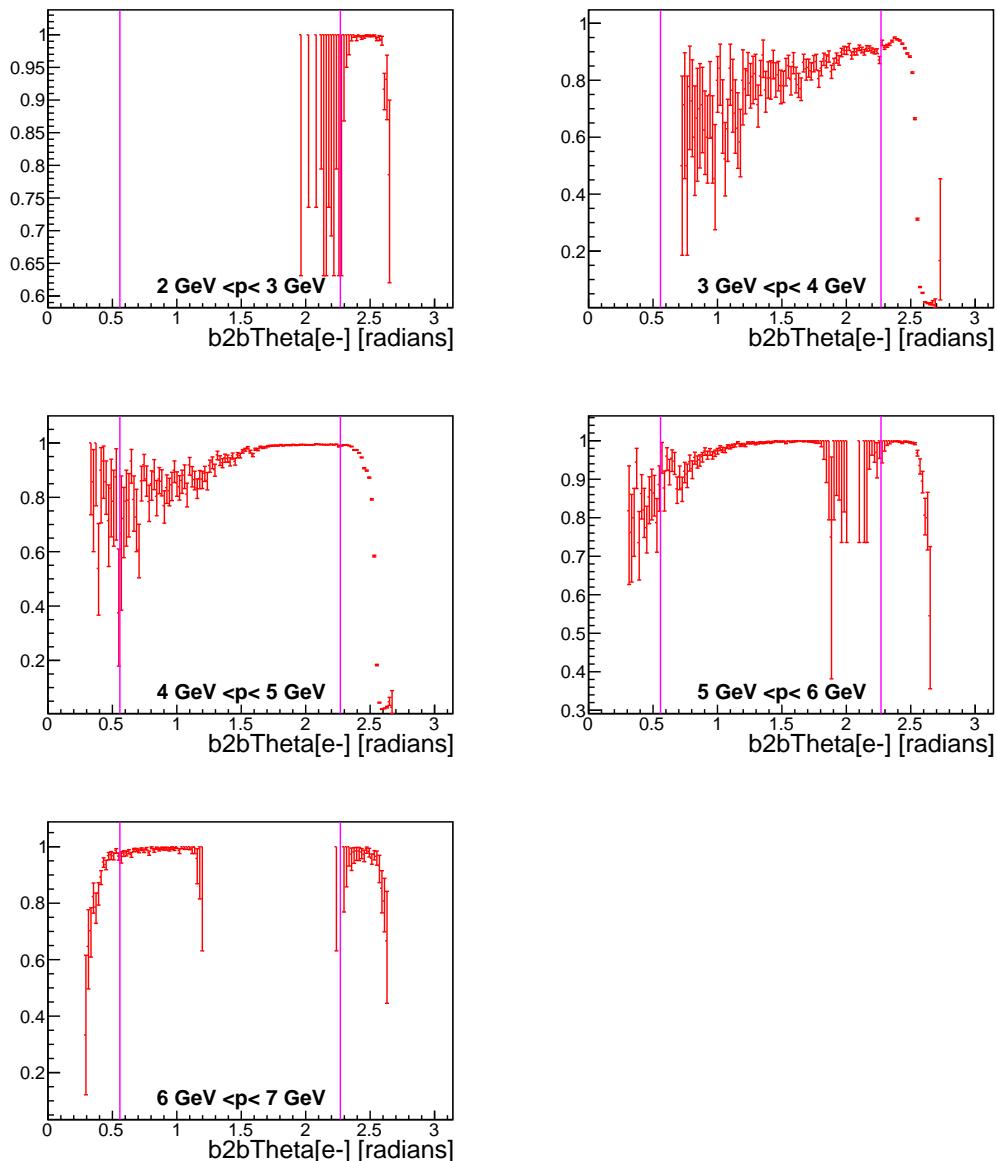


Figure B.12.: Positron ϕ tracking efficiency plots for phase2 MC. The pink line indicates the different sectors of the ECL.

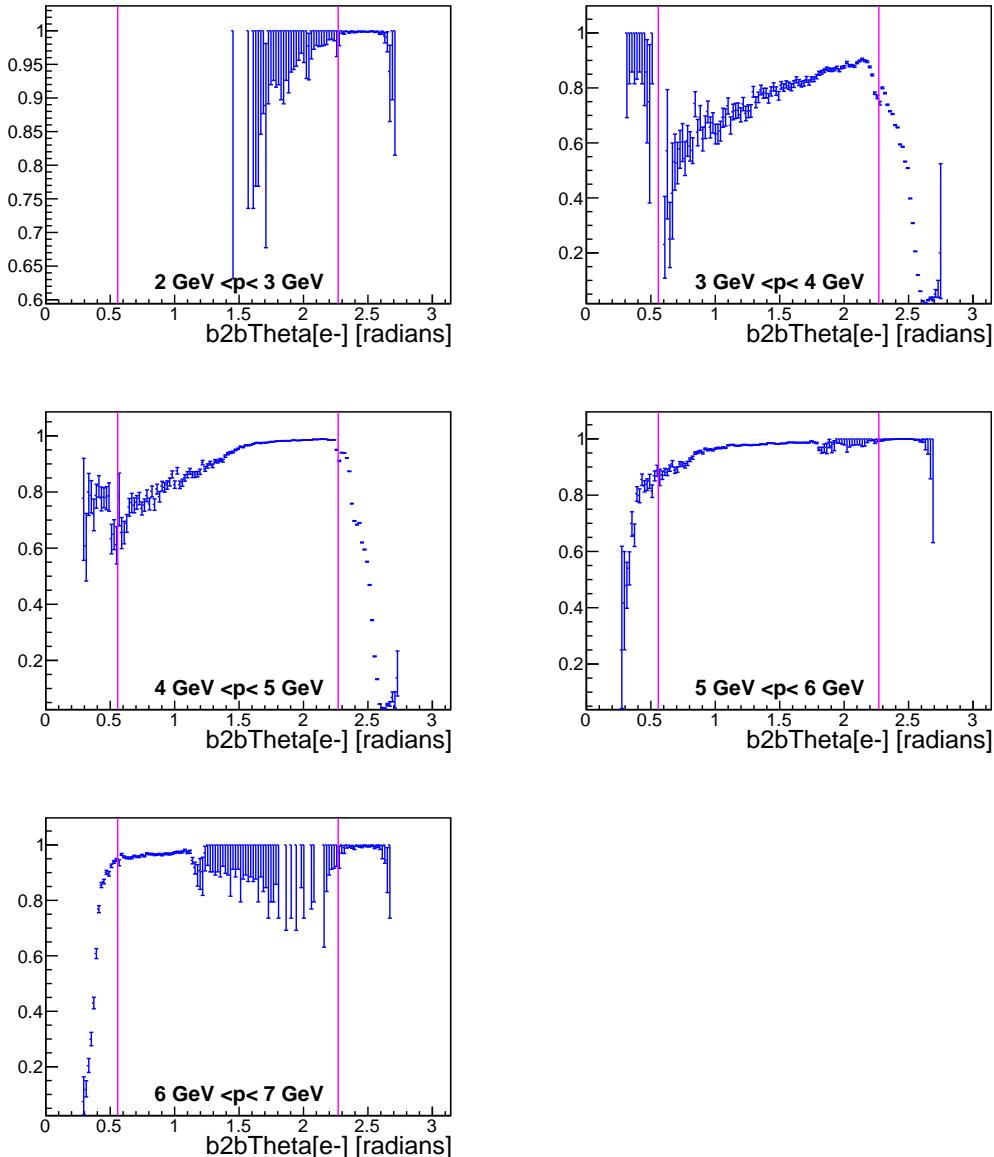


Figure B.13.: Positron ϕ tracking efficiency plots for phase2 Data. The pink line indicates the different sectors of the ECL.

B. Additional Phase2 Plots

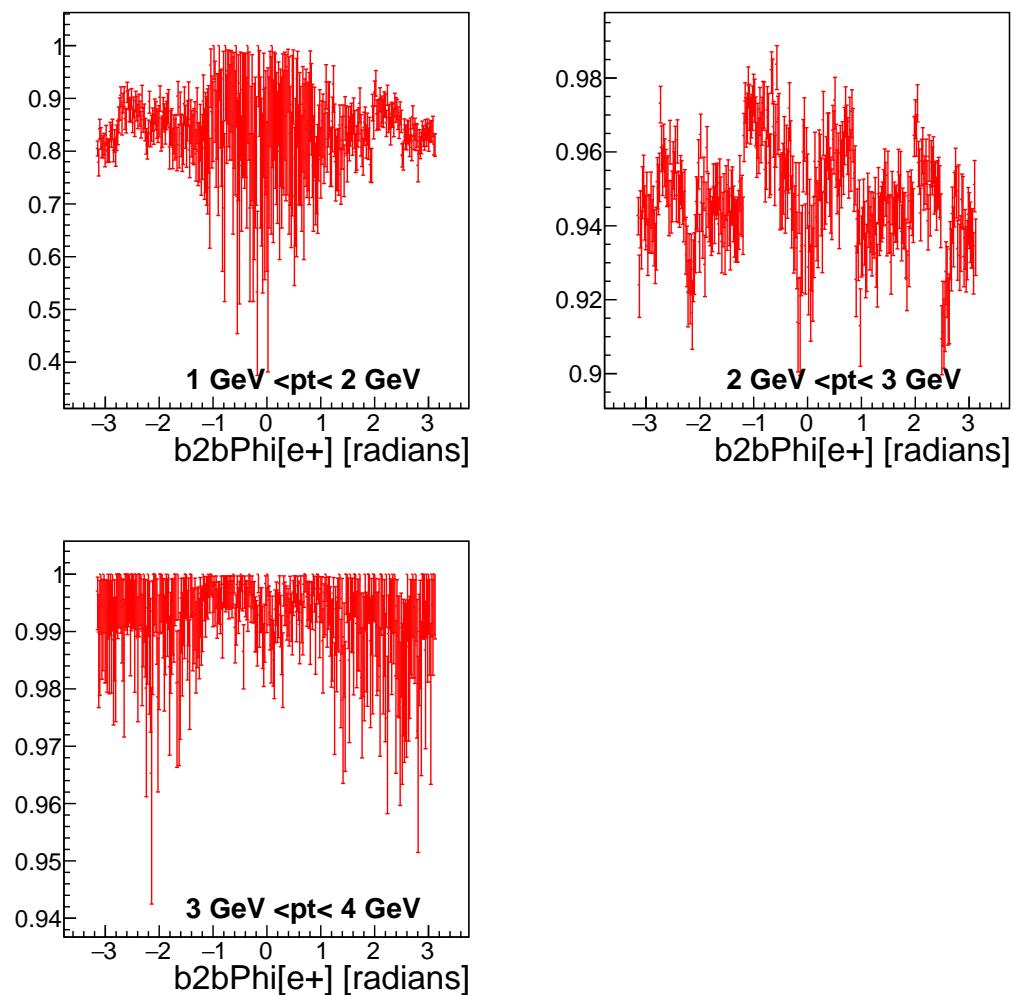


Figure B.14.: Electron ϕ transverse momentum tracking efficiency plots in the forward end-cap for phase2 MC.

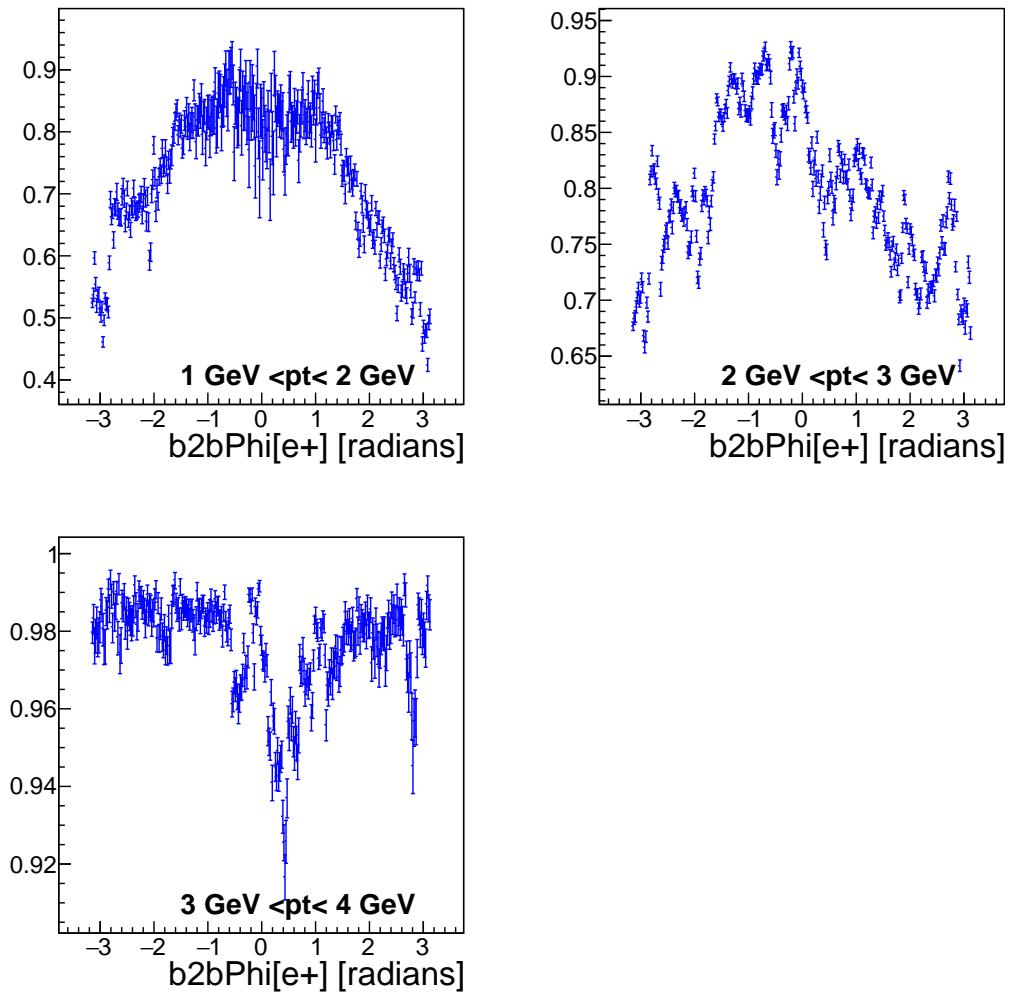


Figure B.15.: Electron ϕ transverse momentum tracking efficiency plots in the forward end-cap for phase2 Data.

B. Additional Phase2 Plots

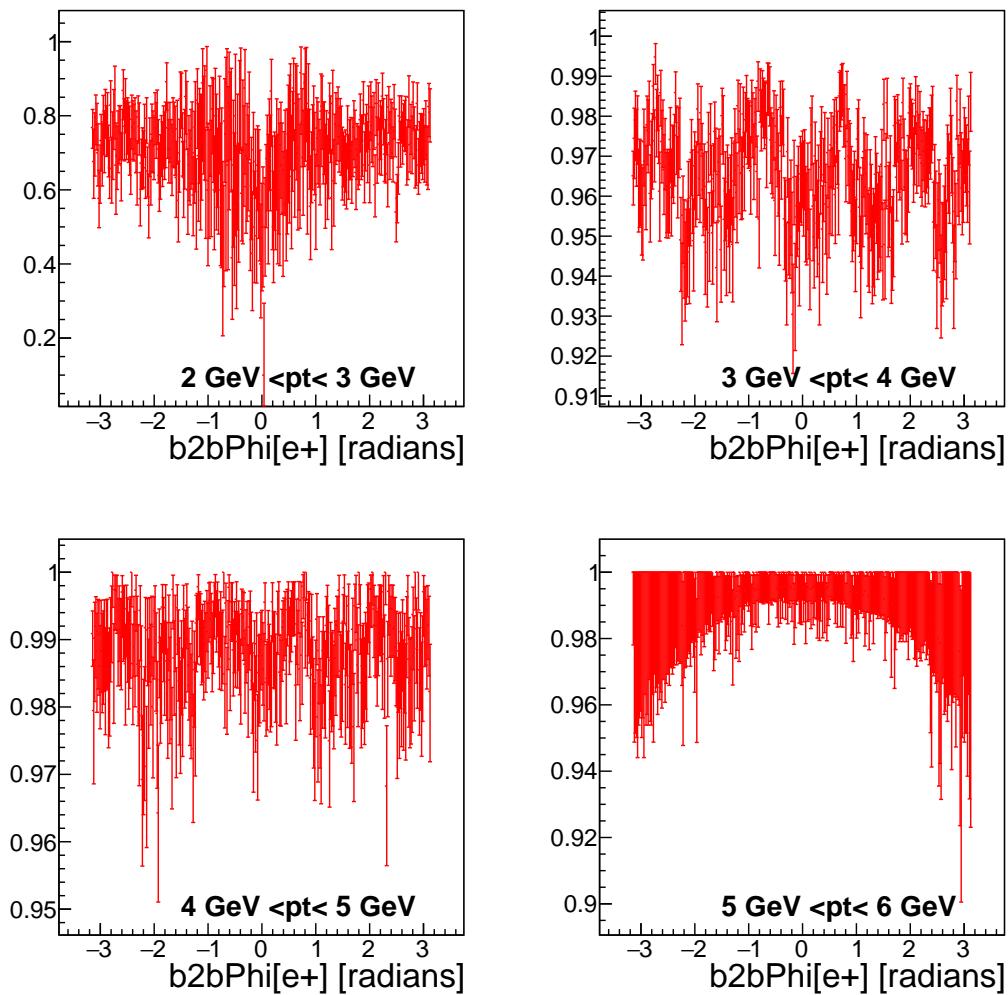


Figure B.16.: Electron ϕ transverse momentum tracking efficiency plots in the barrel for phase2 MC.

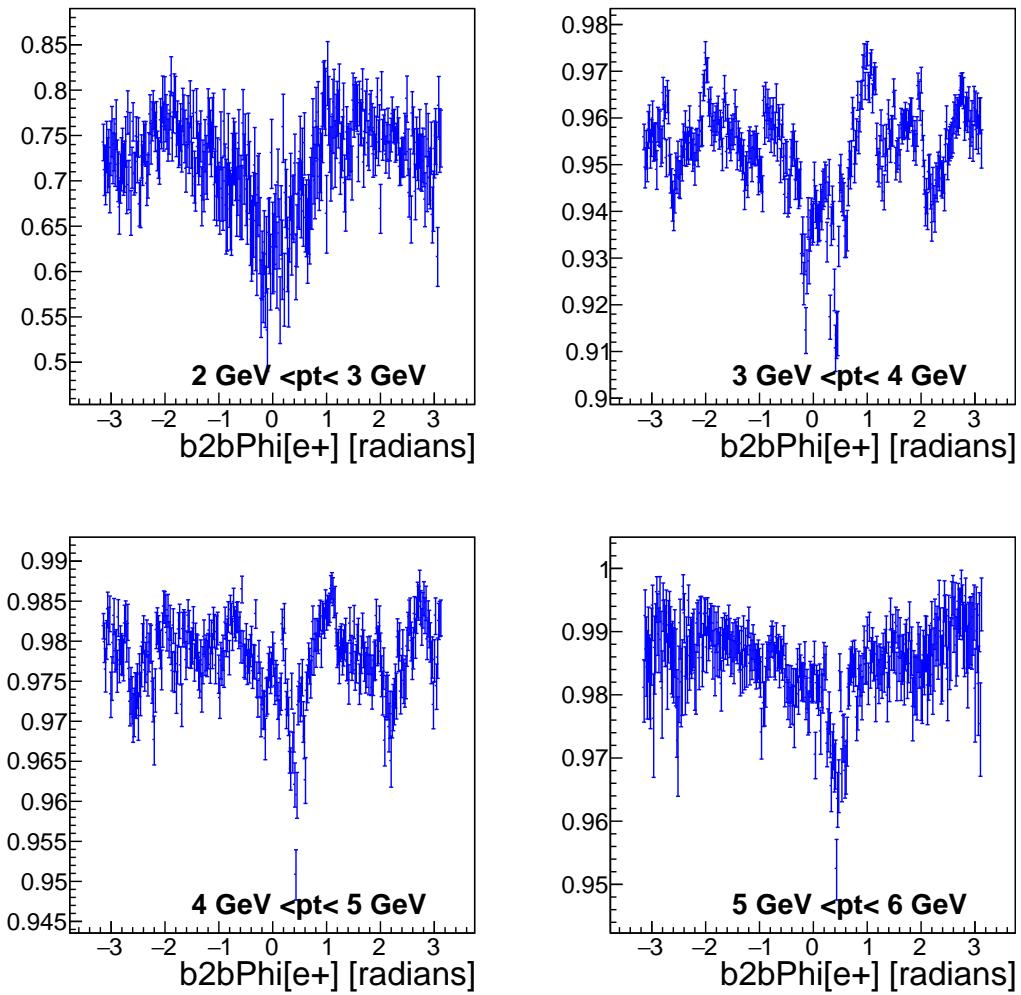


Figure B.17.: Electron ϕ transverse momentum tracking efficiency plots in the barrel for phase2 Data.

B. Additional Phase2 Plots

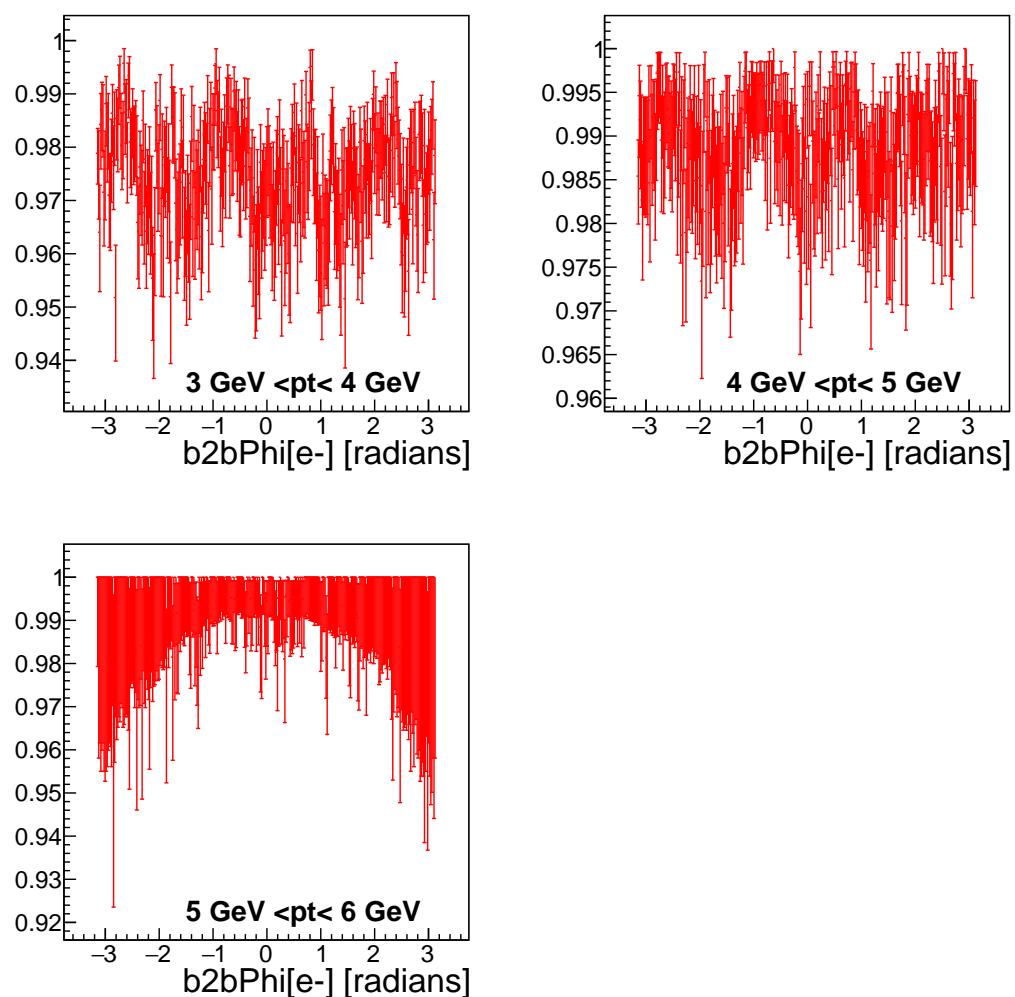


Figure B.18.: Positron ϕ transverse momentum tracking efficiency plots in the barrel for phase2 MC.

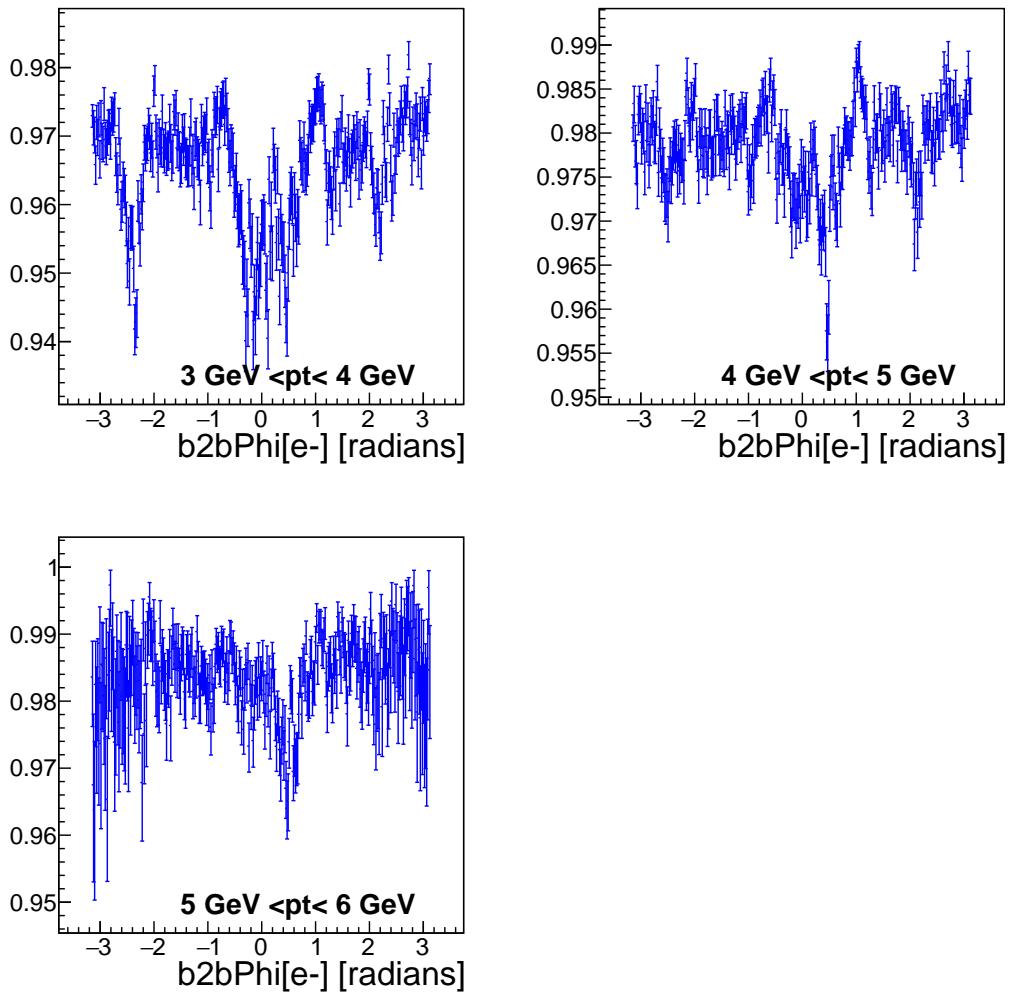


Figure B.19.: Positron ϕ transverse momentum tracking efficiency plots in the barrel for phase2 Data.

B. Additional Phase2 Plots

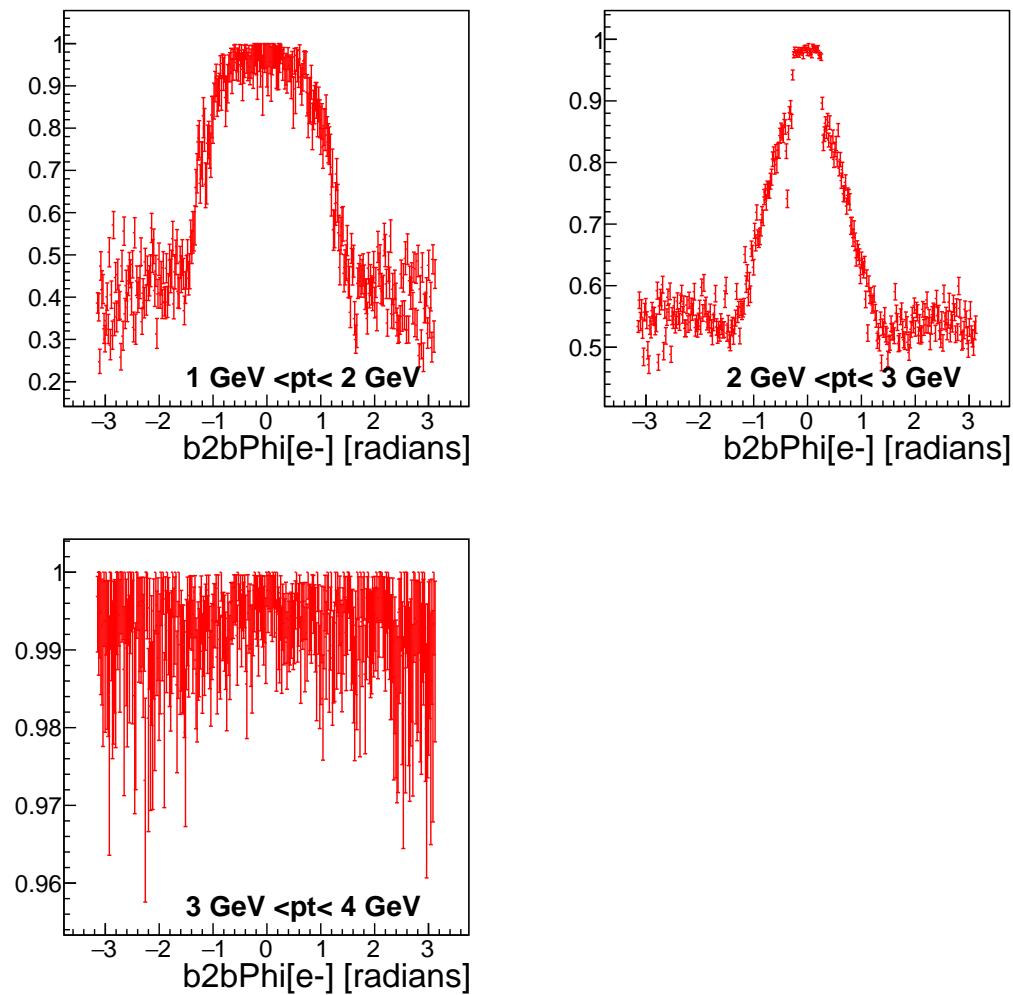


Figure B.20.: Positron ϕ transverse momentum tracking efficiency plots in the backward end-cap for phase2 MC.

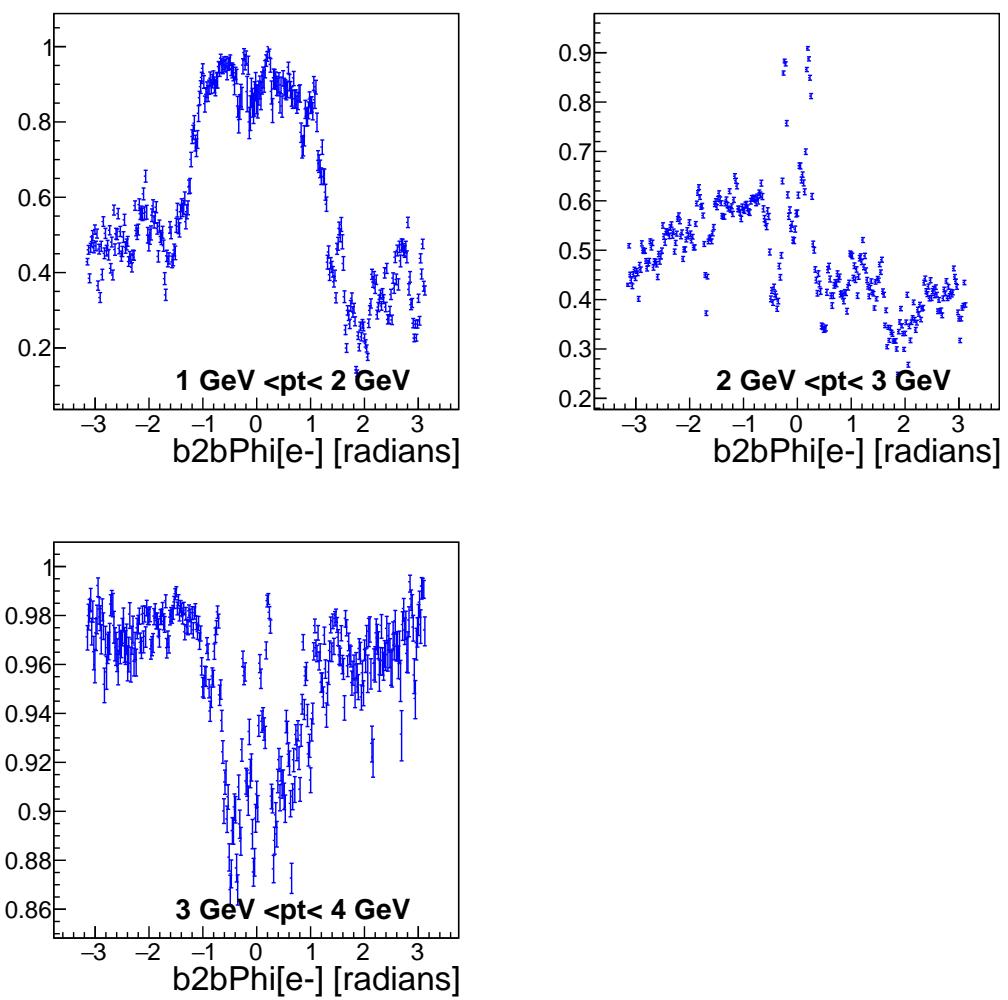


Figure B.21.: Positron ϕ transverse momentum tracking efficiency plots in the backward end-cap for phase2 Data.

B. Additional Phase2 Plots

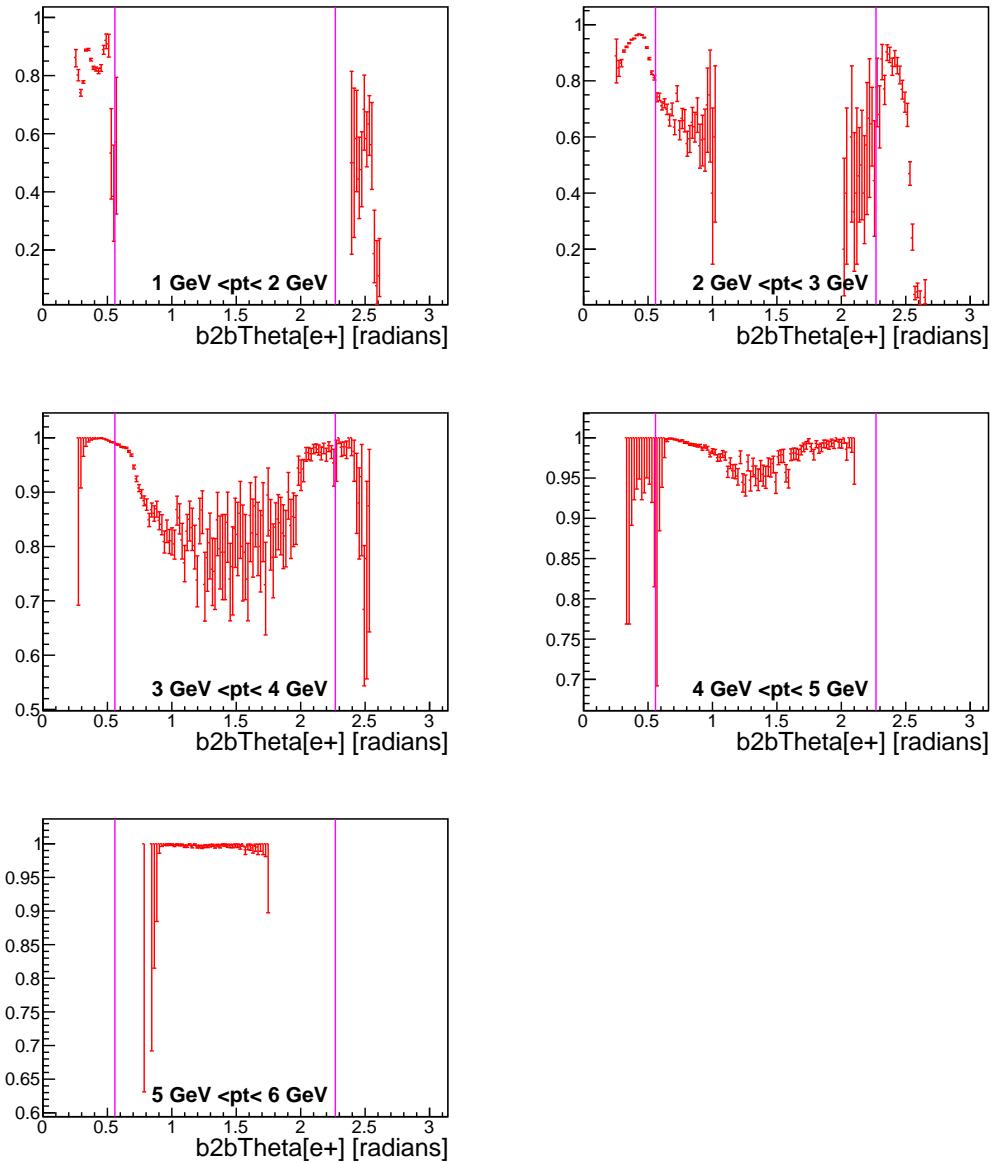


Figure B.22.: Electron ϕ transverse momentum tracking efficiency plots for phase2 MC. The pink line indicates the different sectors of the ECL.

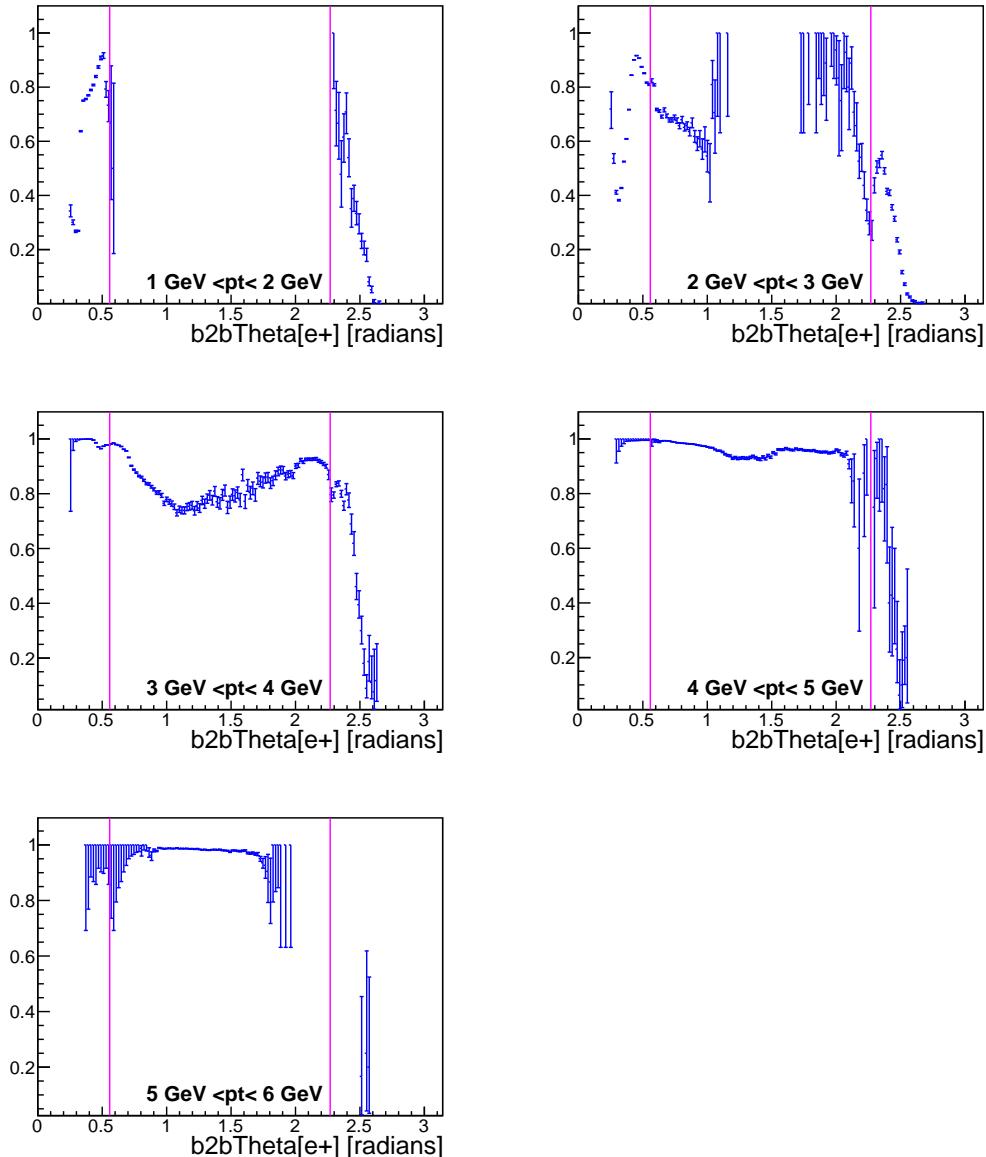


Figure B.23.: Electron ϕ transverse momentum tracking efficiency plots for phase2 Data. The pink line indicates the different sectors of the ECL.

B. Additional Phase2 Plots

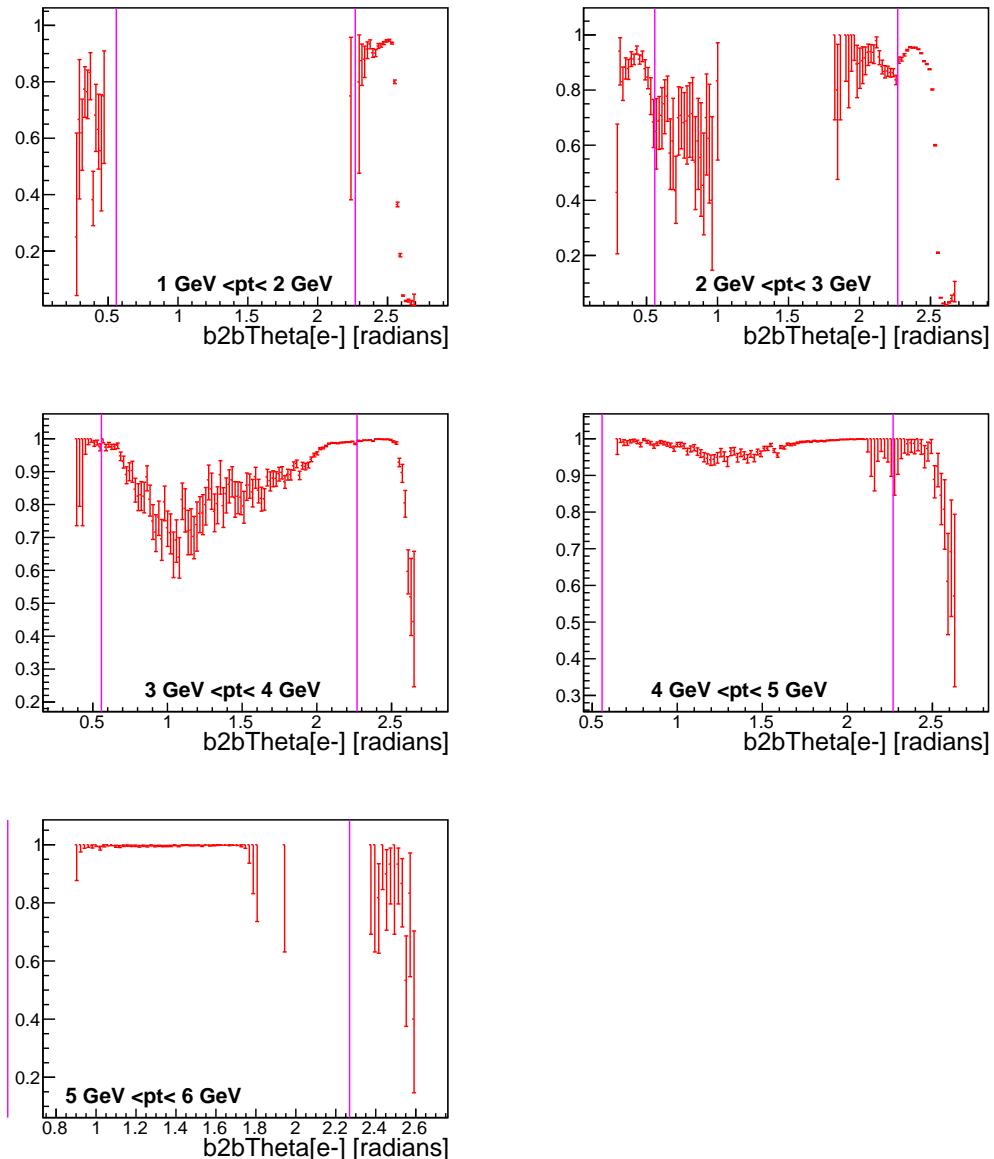


Figure B.24.: Positron ϕ transverse momentum tracking efficiency plots for phase2 MC. The pink line indicates the different sectors of the ECL.

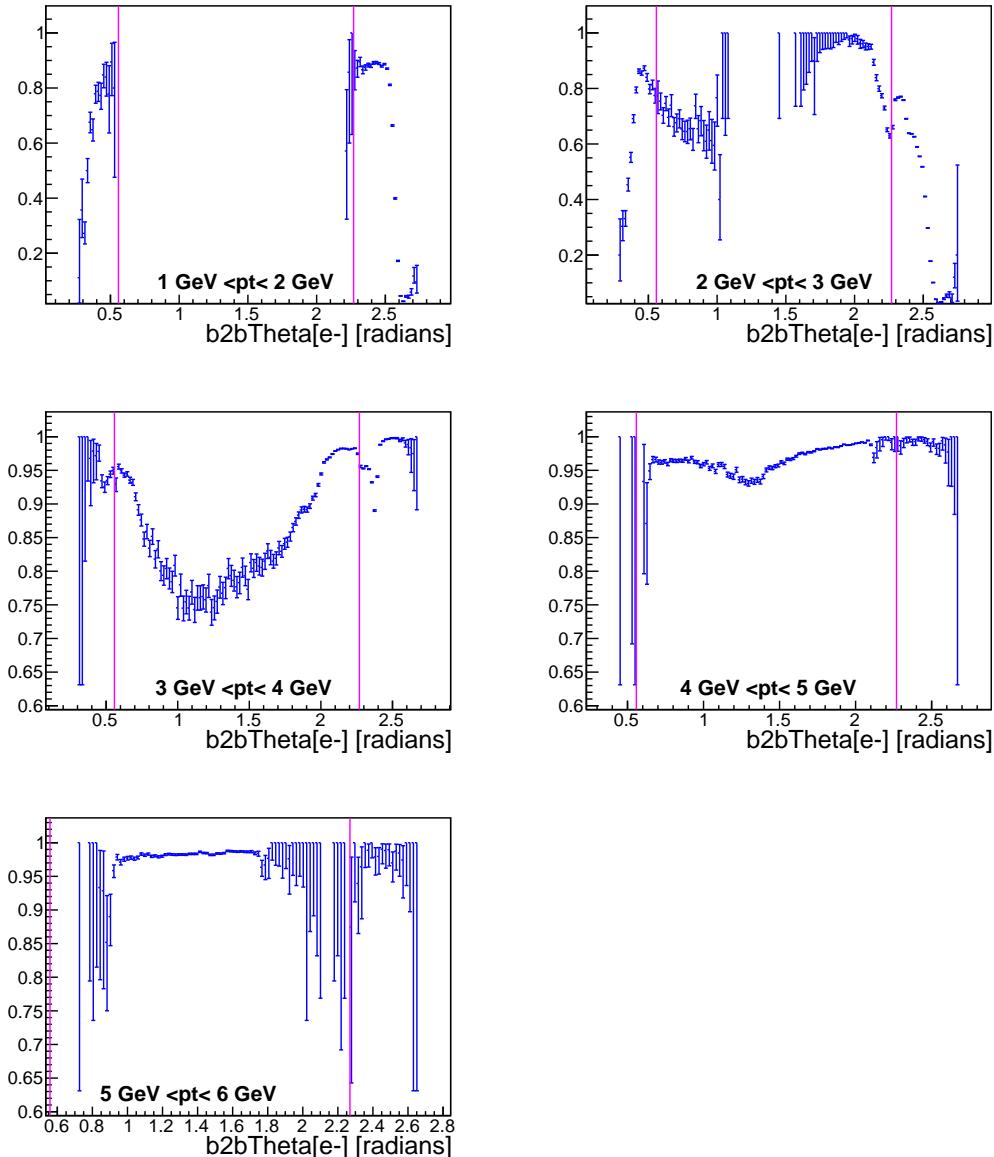


Figure B.25.: Positron transverse momentum ϕ tracking efficiency plots for phase2 Data. The pink line indicates the different sectors of the ECL.

B. Additional Phase2 Plots

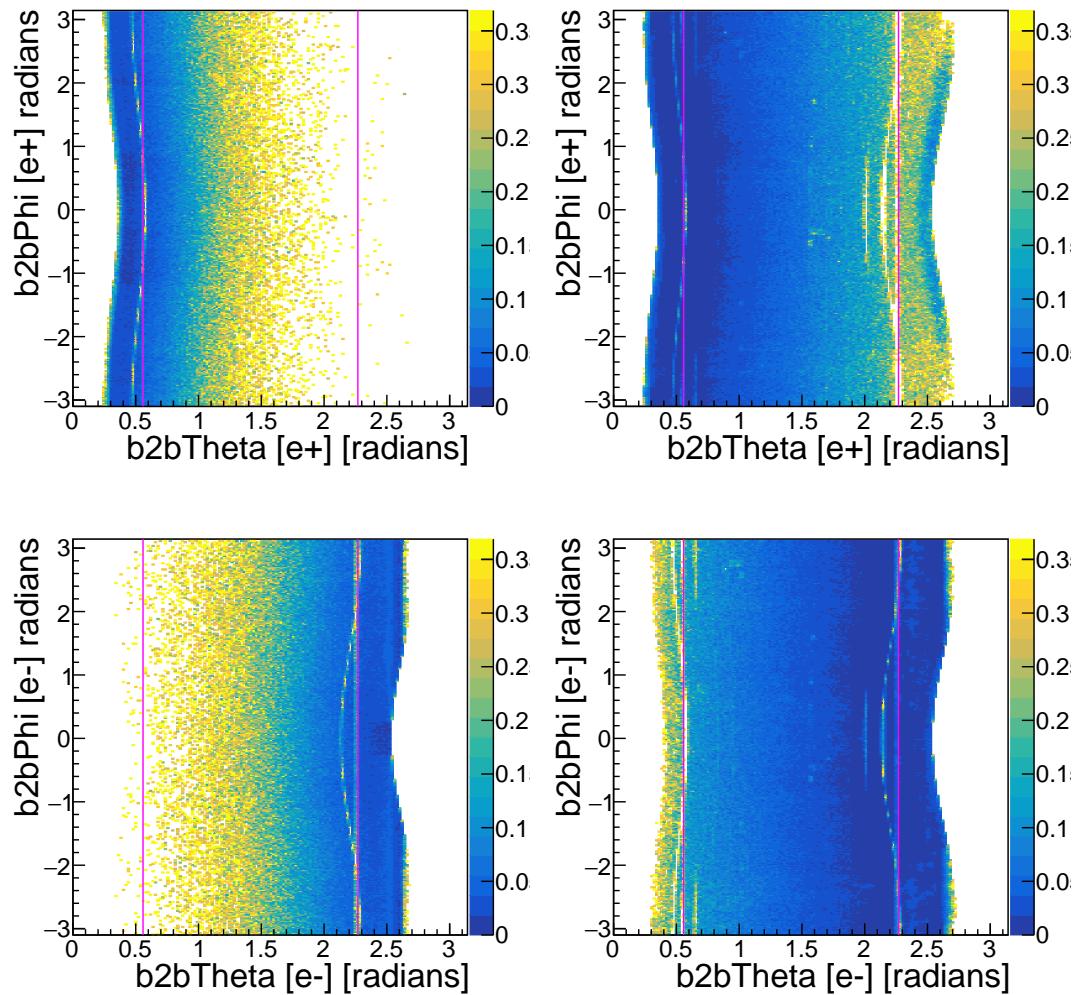


Figure B.26.: θ - ϕ efficiency errors for phase2. Left: Phase2 MC. Right: Phase2 data.
First line: electron efficiency errors. Second line: positron efficiency errors.

APPENDIX

C

Additional Phase3 Plots

C. Additional Phase3 Plots

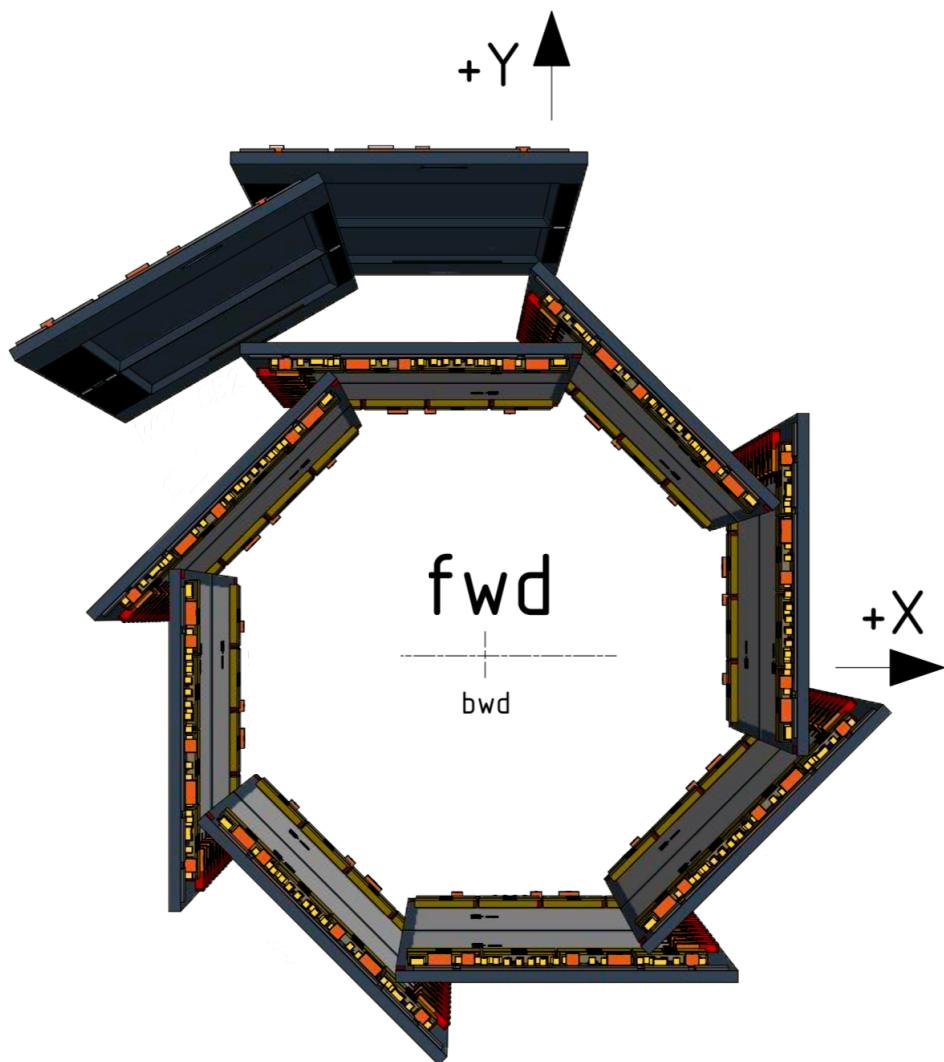


Figure C.1.: The status of the PXD during phase3. You can see that the innermost layer is completely installed and only 2 out 12 from the outer layer are installed. This sketch was modified to make it easier to look at.[35]

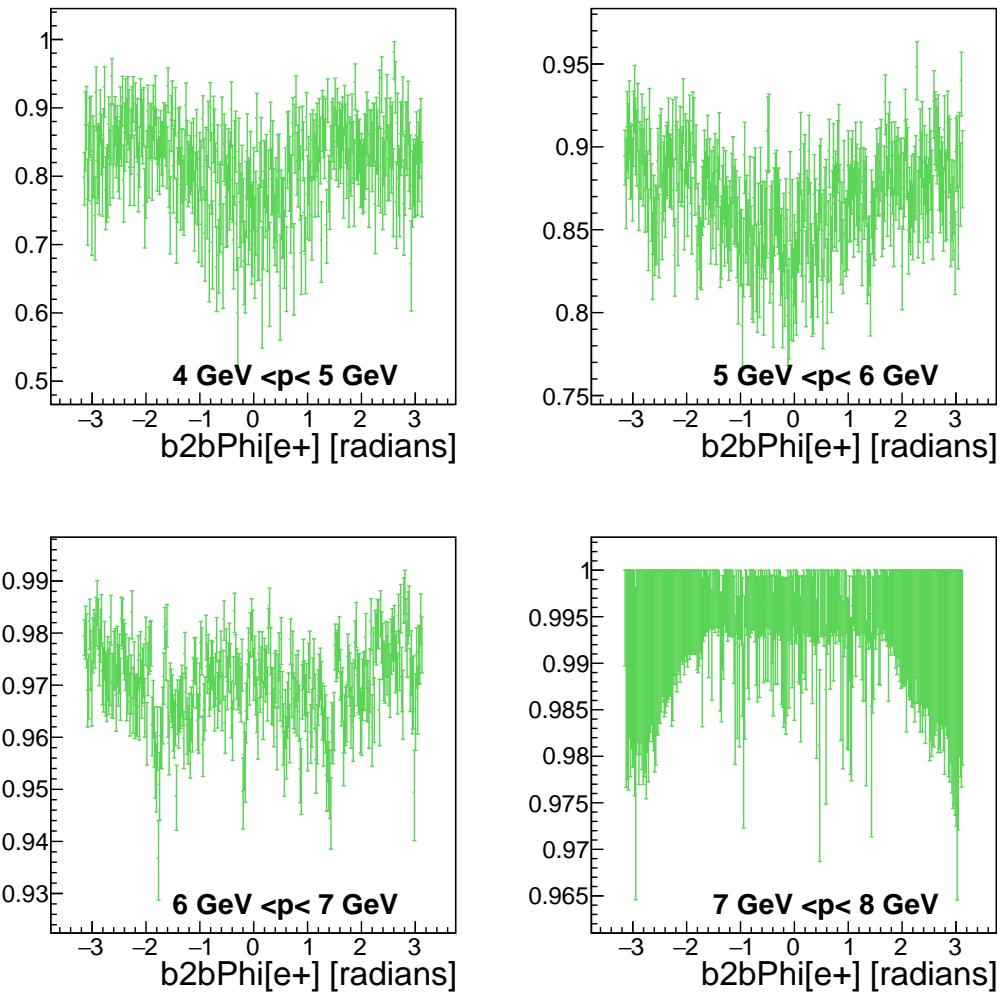


Figure C.2.: Electron ϕ tracking efficiency plots in the forward end-cap for phase3 MC.

C. Additional Phase3 Plots

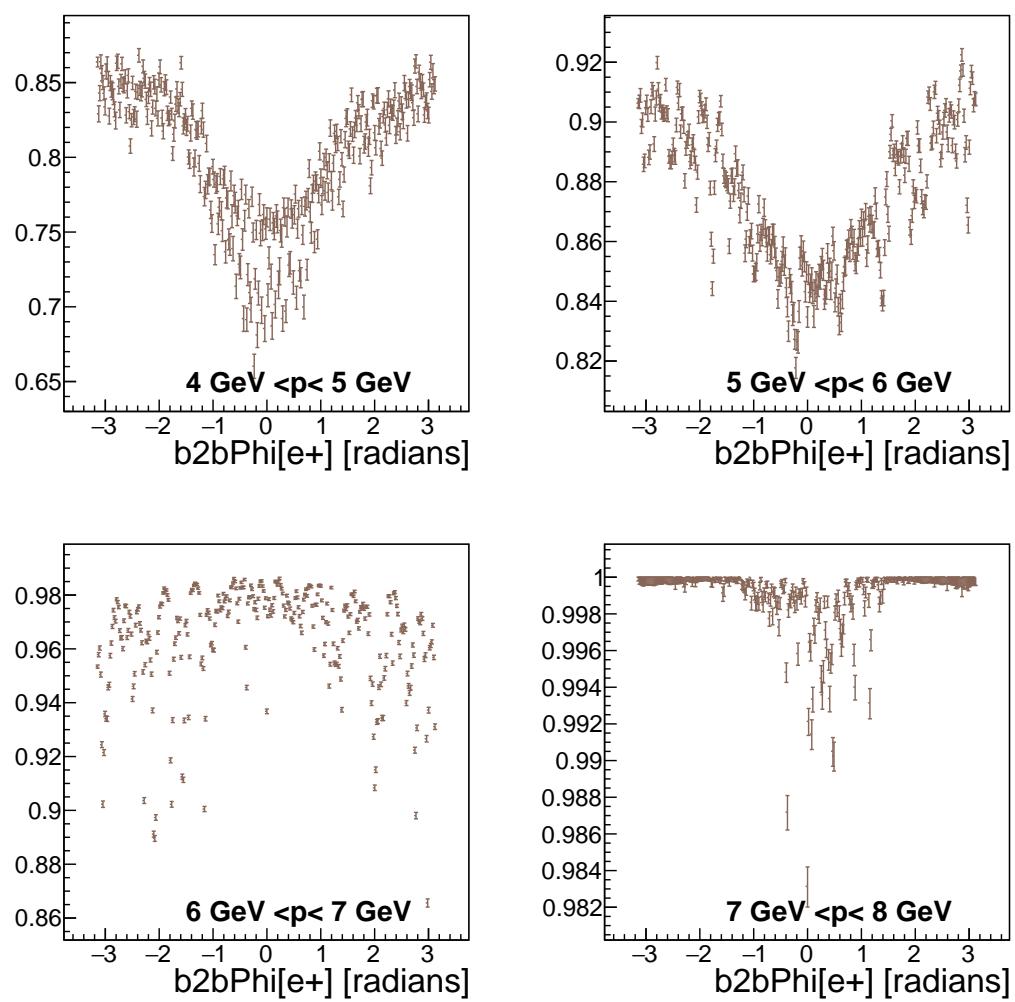


Figure C.3.: Electron ϕ tracking efficiency plots in the forward end-cap for phase3 Data.

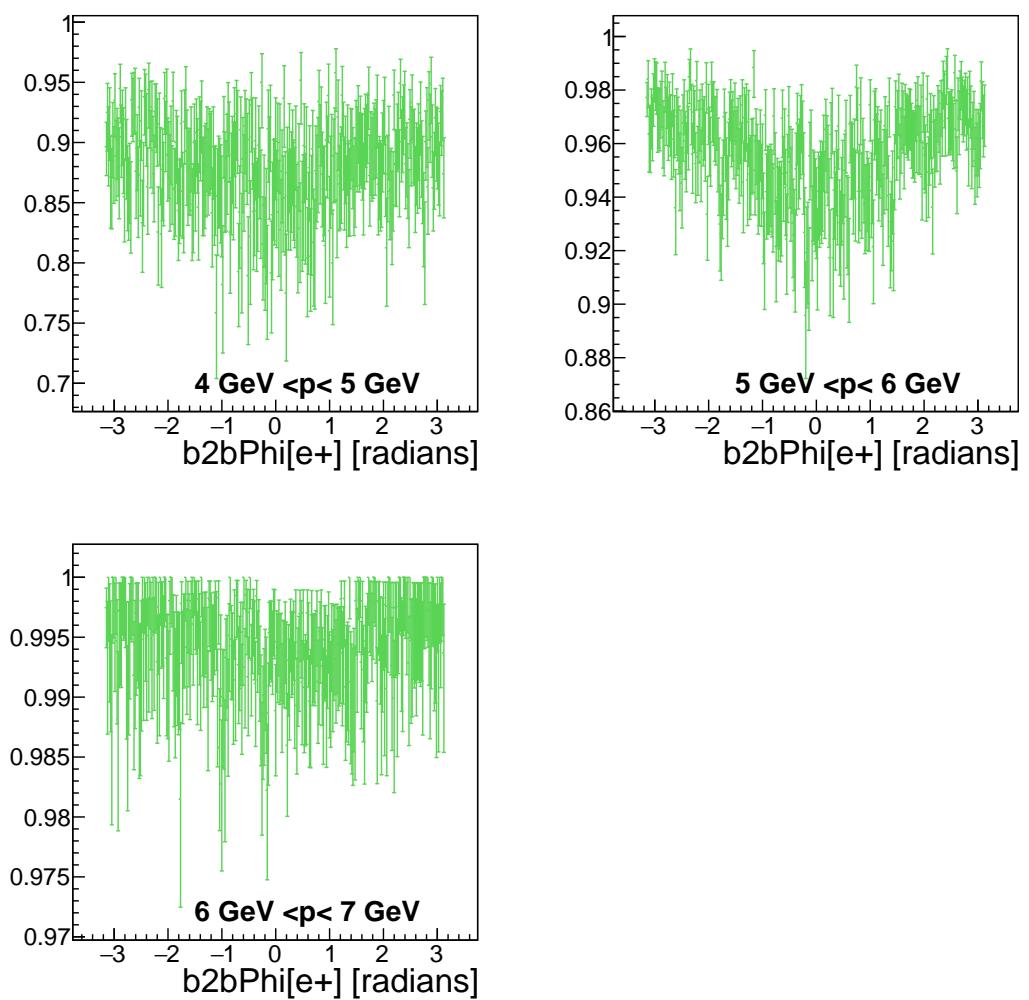


Figure C.4.: Electron ϕ tracking efficiency plots in the barrel for phase3 MC.

C. Additional Phase3 Plots

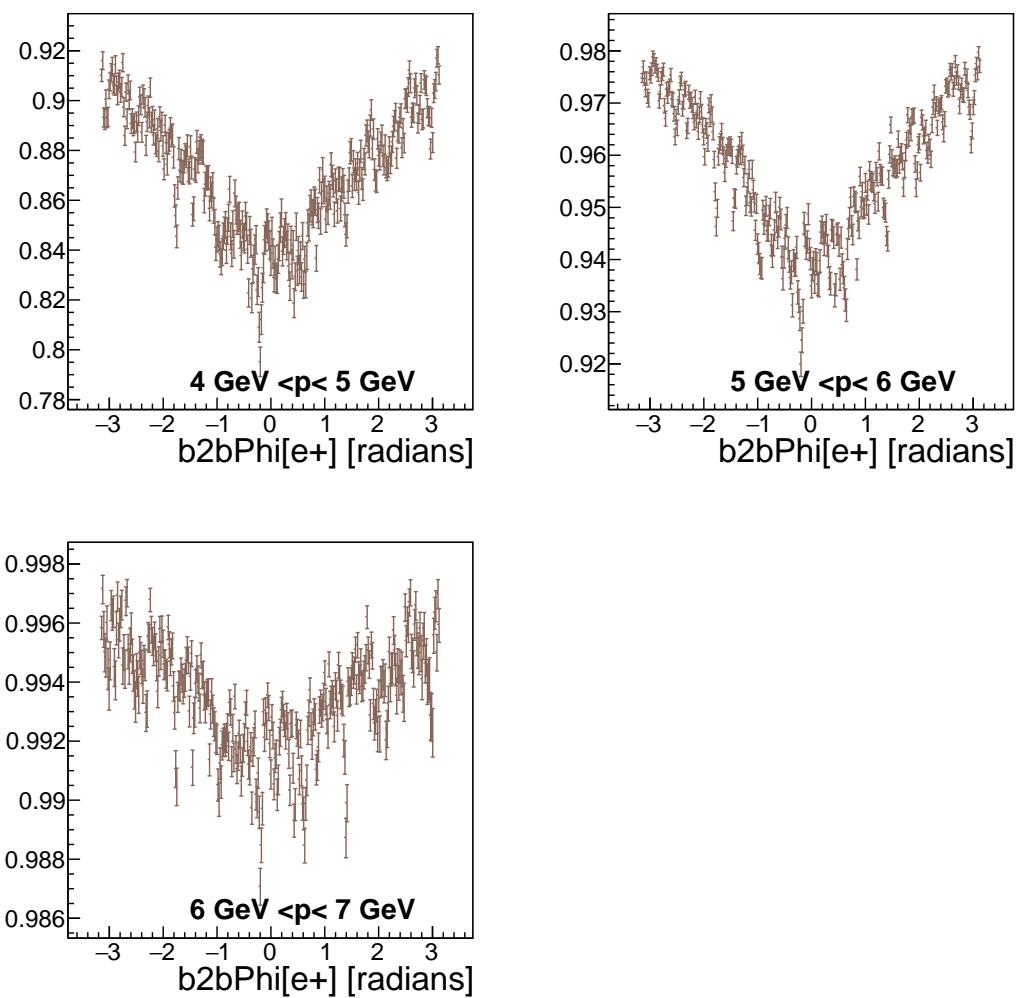


Figure C.5.: Electron ϕ tracking efficiency plots in the barrel for phase3 Data.

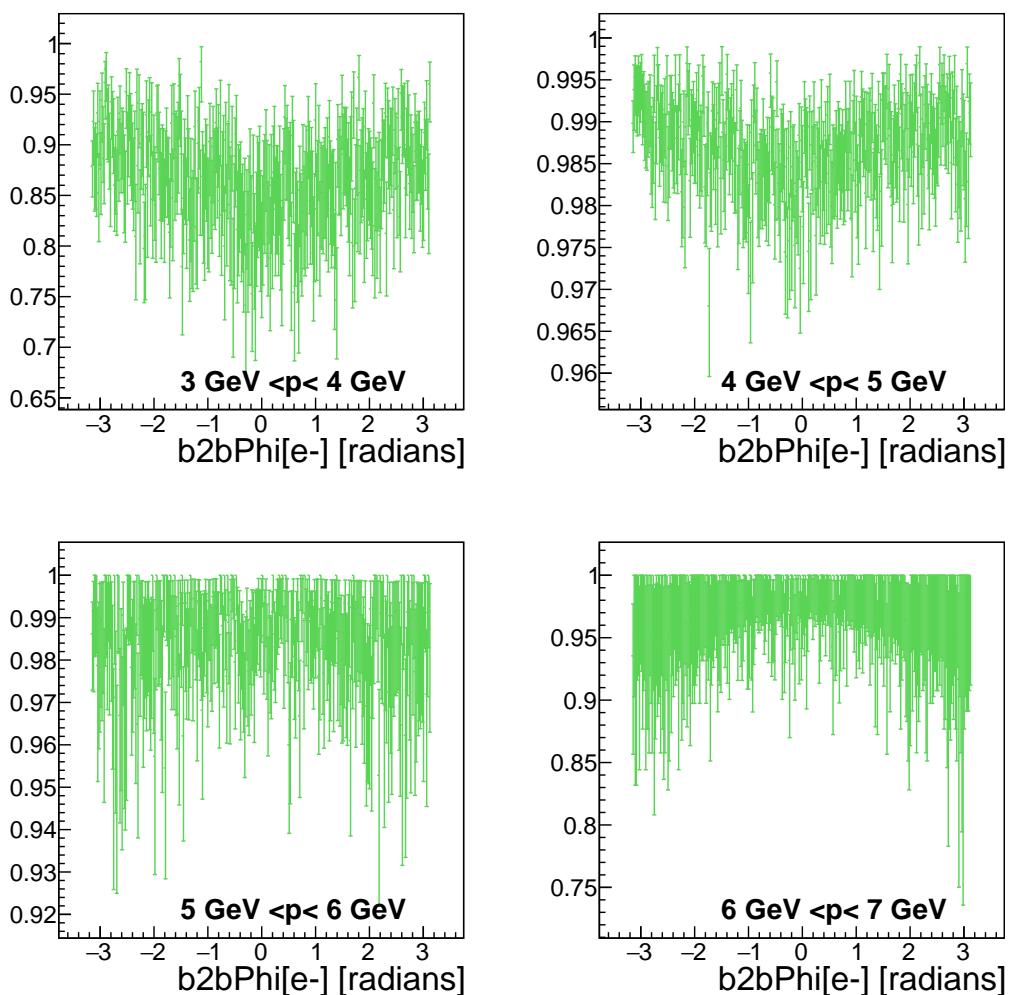


Figure C.6.: Positron ϕ tracking efficiency plots in the barrel for phase3 MC.

C. Additional Phase3 Plots

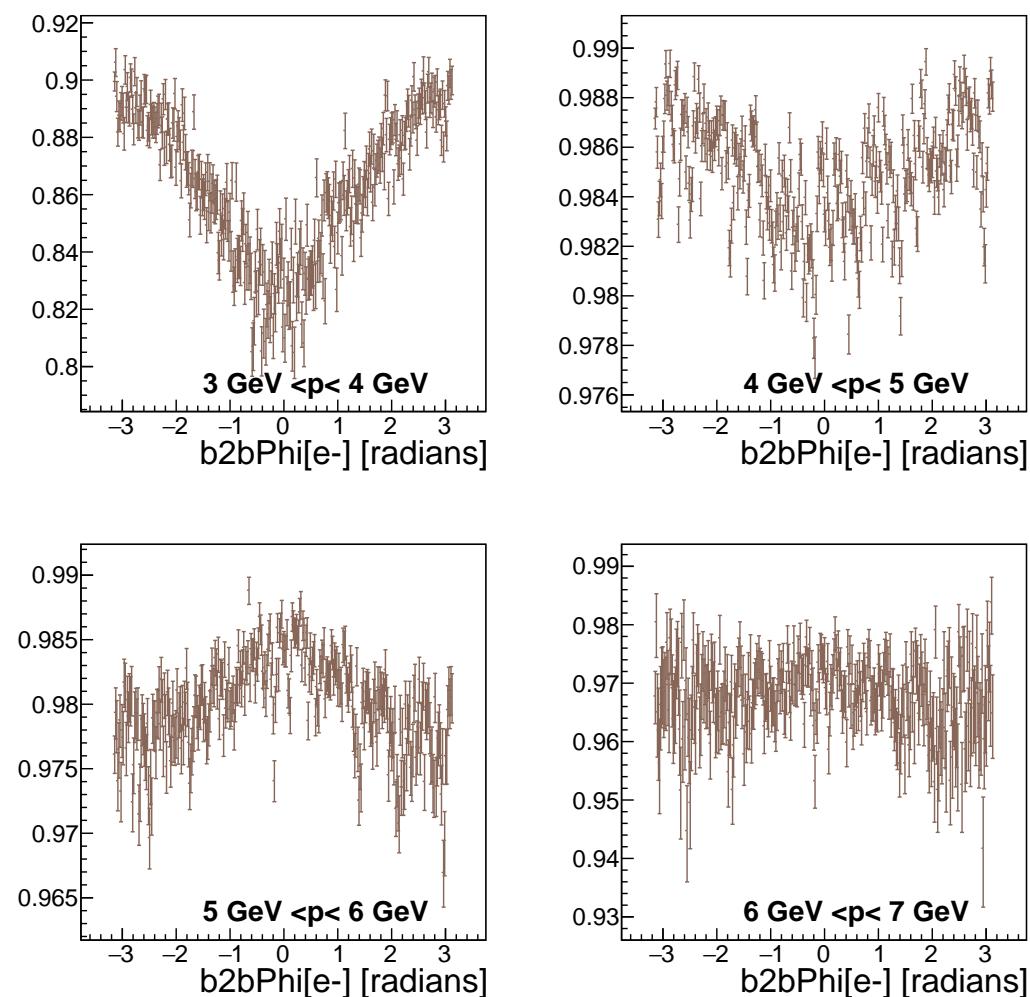


Figure C.7.: Positron ϕ tracking efficiency plots in the barrel for phase3 Data.

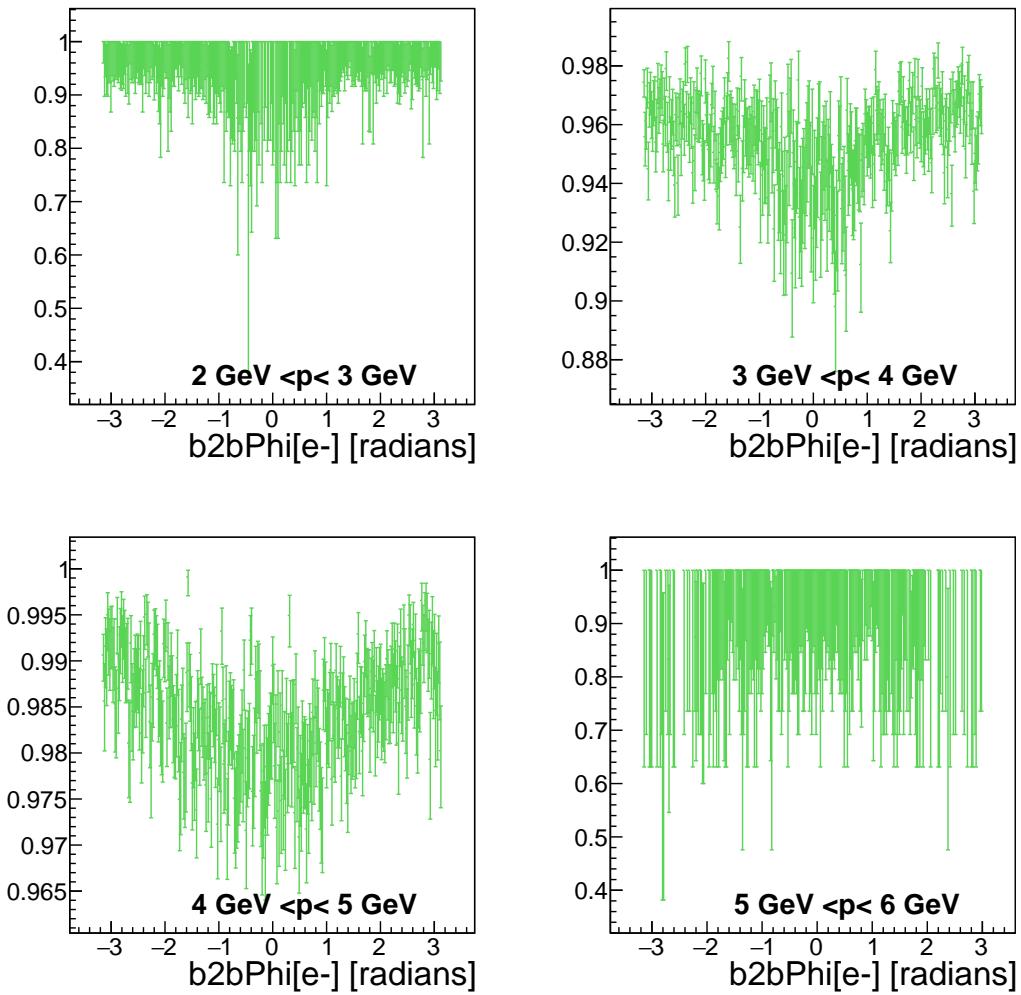


Figure C.8.: Positron ϕ tracking efficiency plots in the backward end-cap for phase3 MC.

C. Additional Phase3 Plots

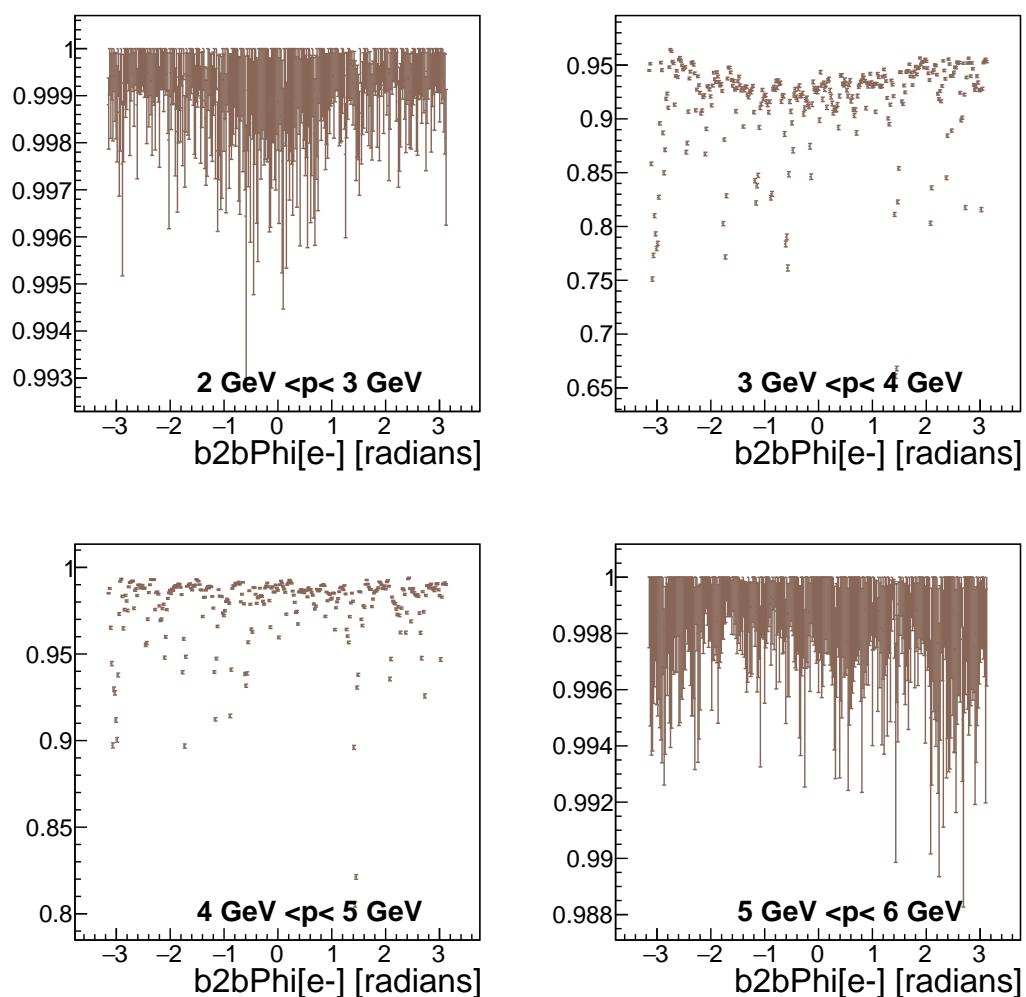


Figure C.9.: Positron ϕ tracking efficiency plots in the backward end-cap for phase3 Data.

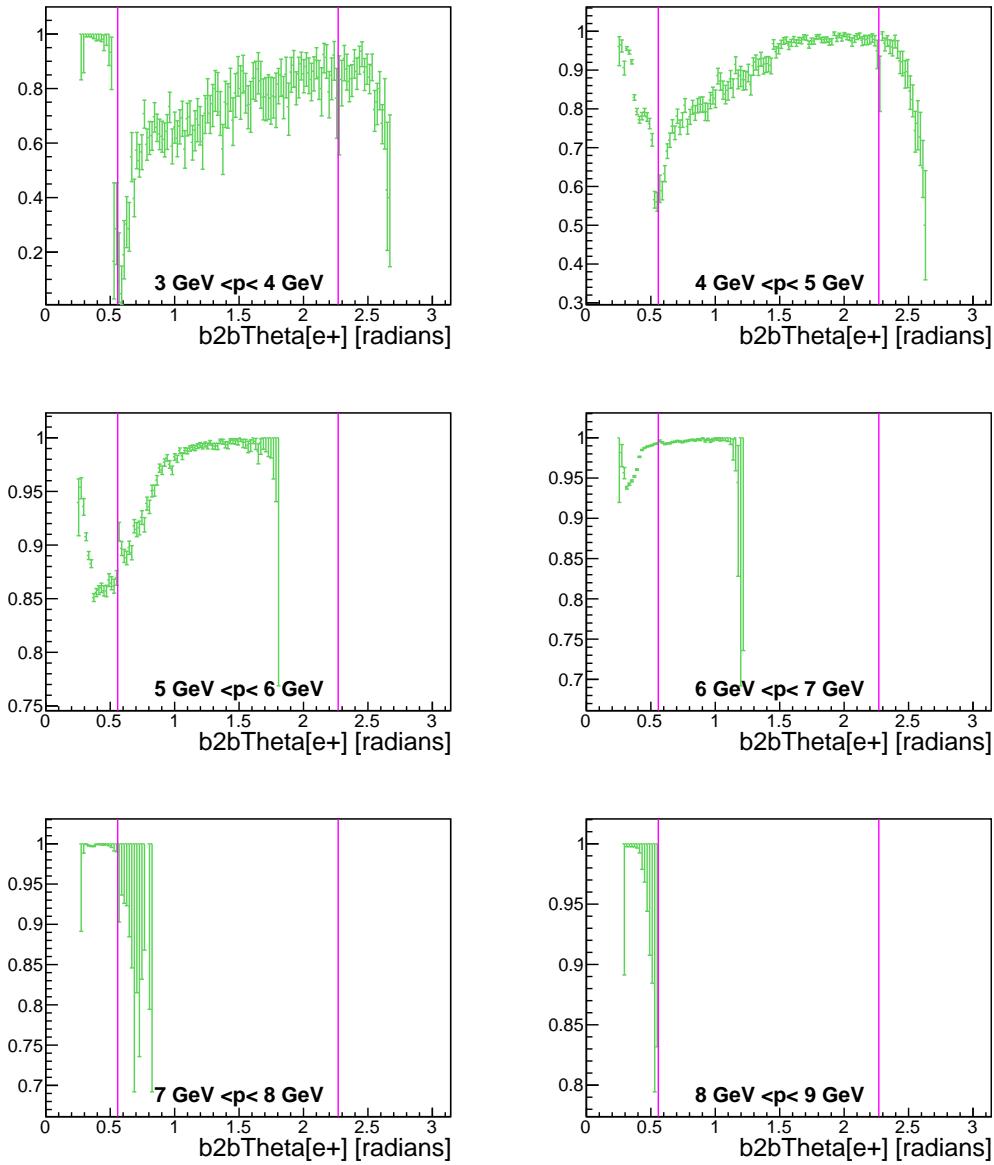


Figure C.10.: Electron ϕ tracking efficiency plots for phase3 MC. The pink line indicates the different sectors of the ECL.

C. Additional Phase3 Plots

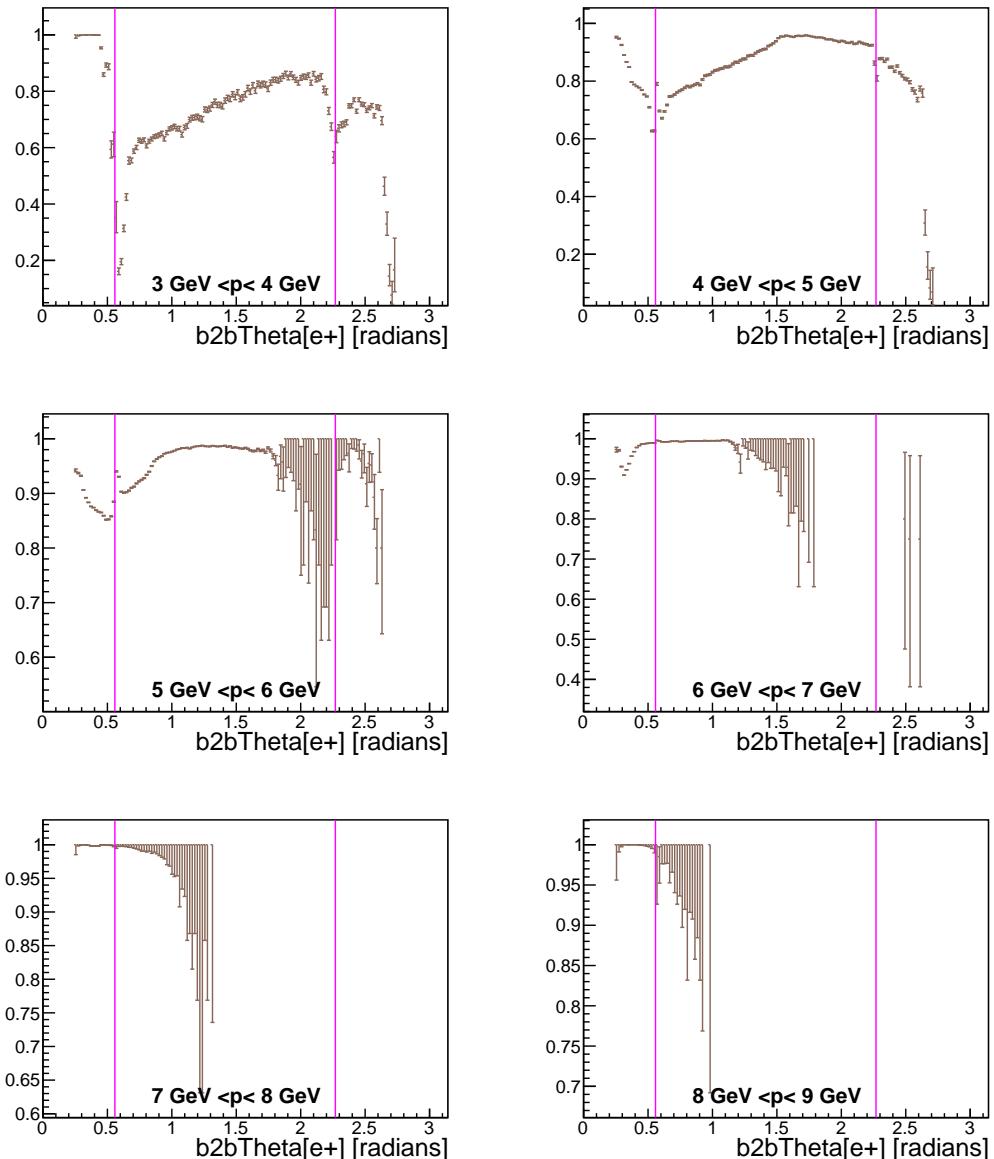


Figure C.11.: Electron ϕ tracking efficiency plots for phase3 Data. The pink line indicates the different sectors of the ECL.

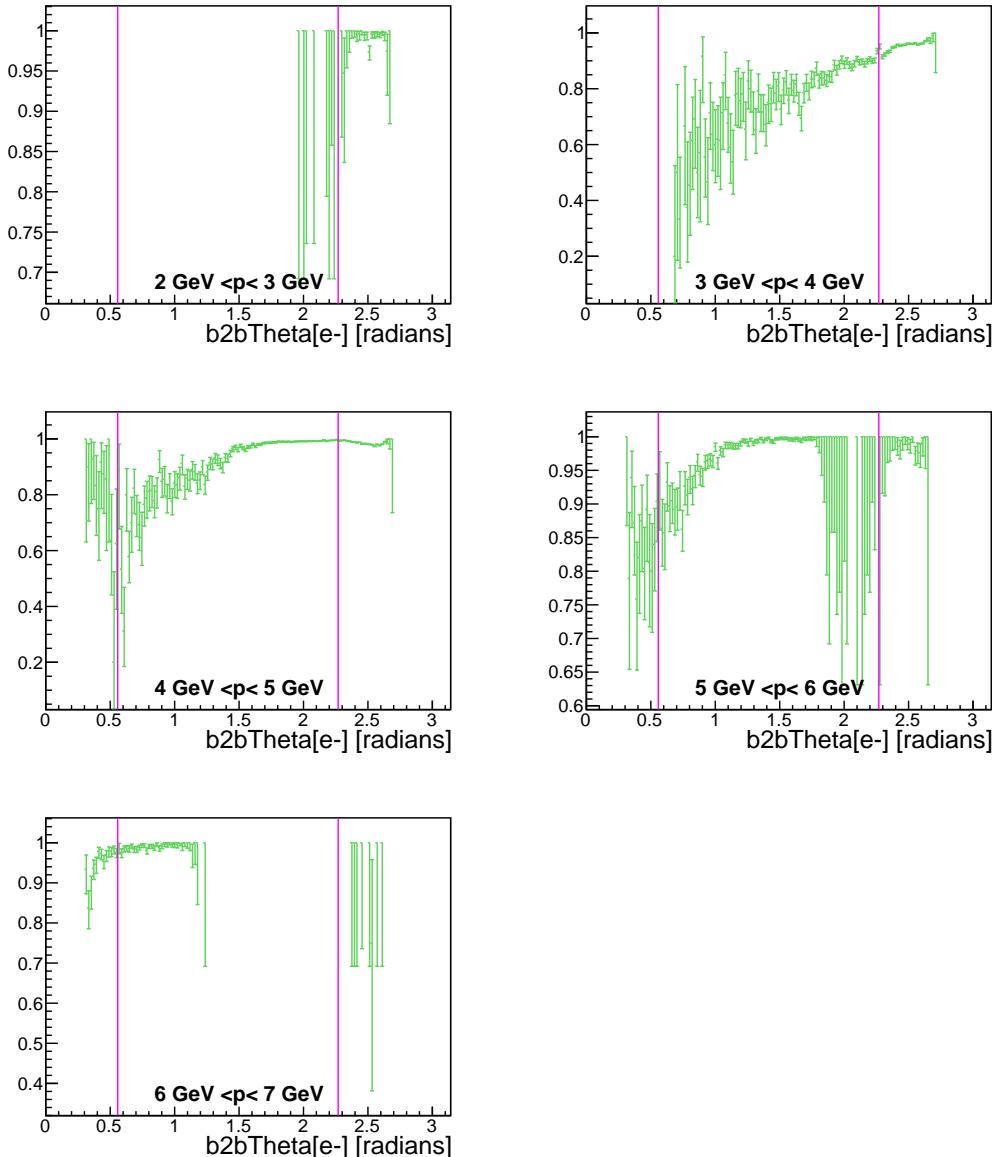


Figure C.12.: Positron ϕ tracking efficiency plots for phase3 MC. The pink line indicates the different sectors of the ECL.

C. Additional Phase3 Plots

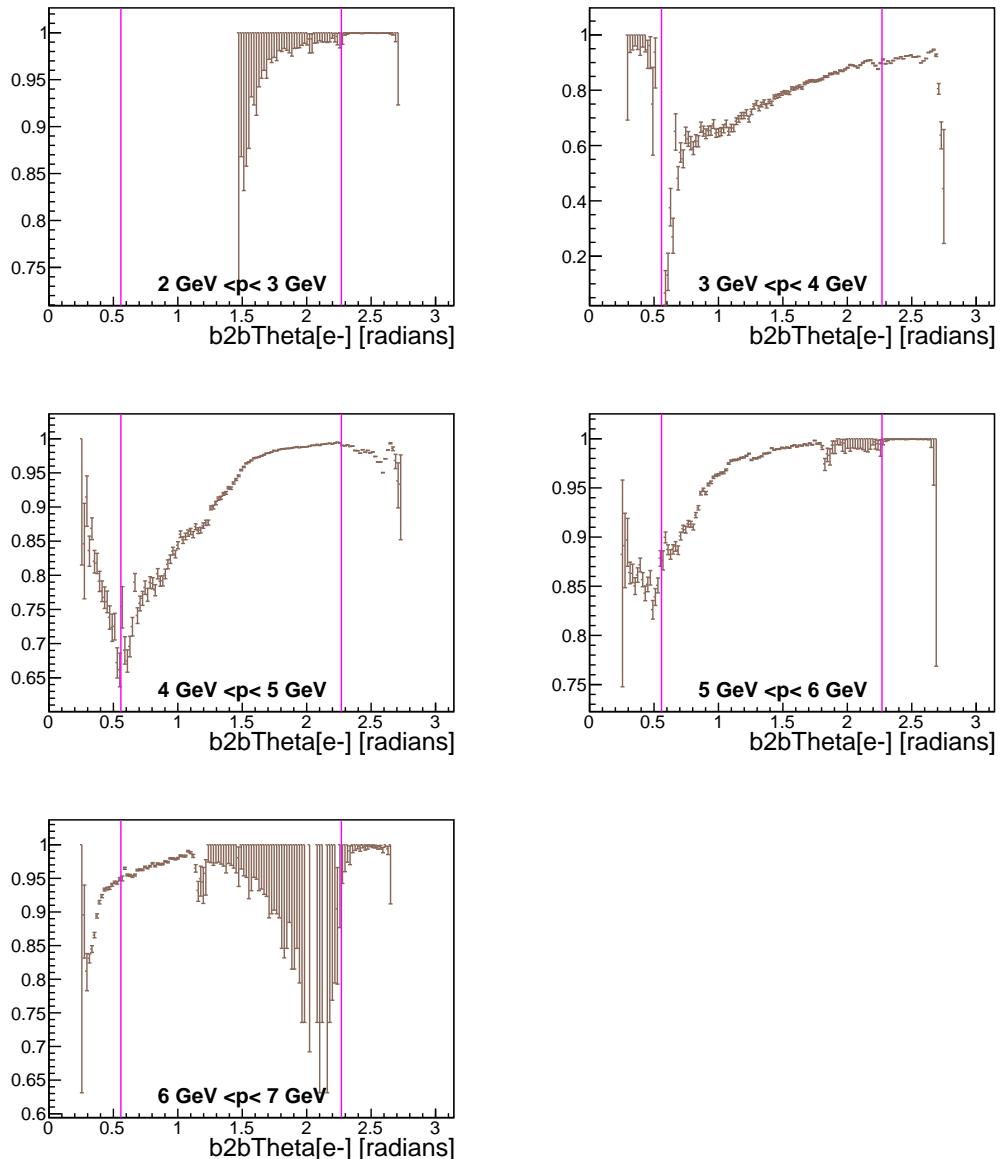


Figure C.13.: Positron ϕ tracking efficiency plots for phase3 Data. The pink line indicates the different sectors of the ECL.

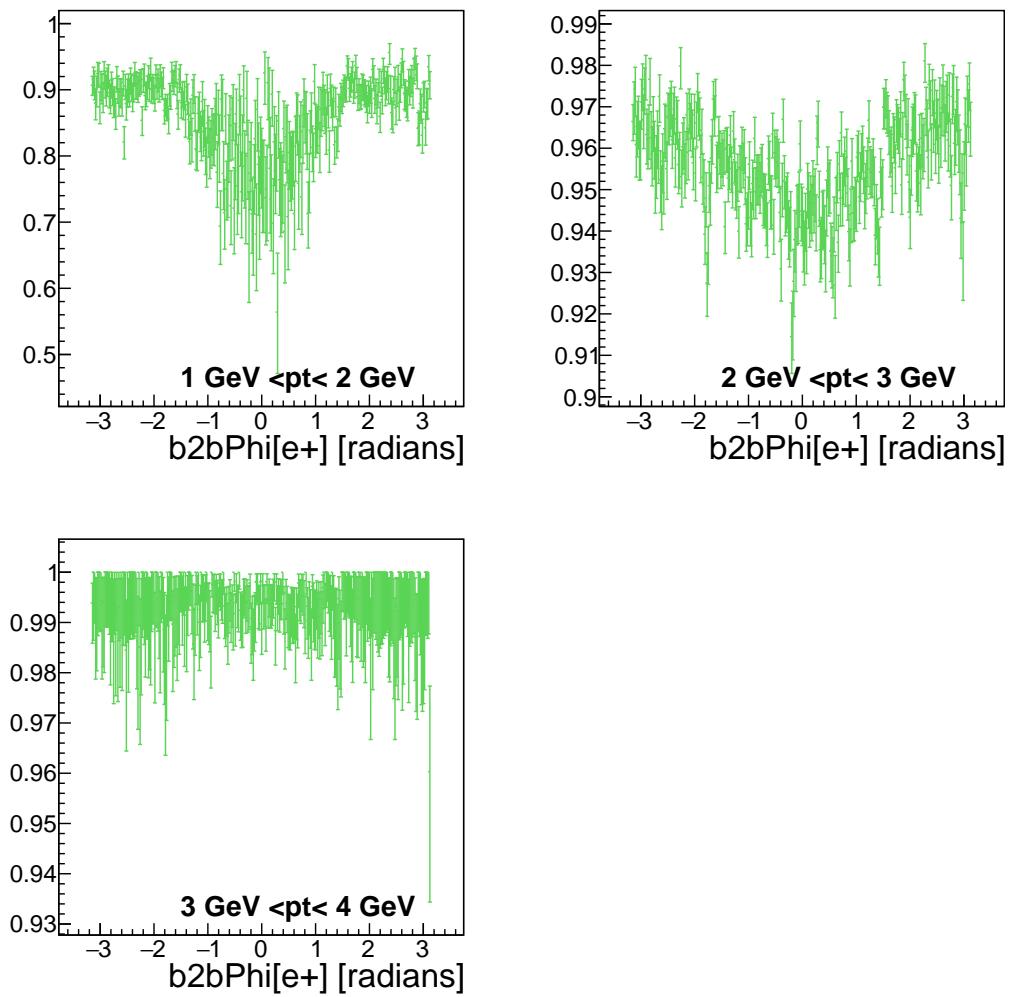


Figure C.14.: Electron ϕ transverse momentum tracking efficiency plots in the forward end-cap for phase3 MC.

C. Additional Phase3 Plots

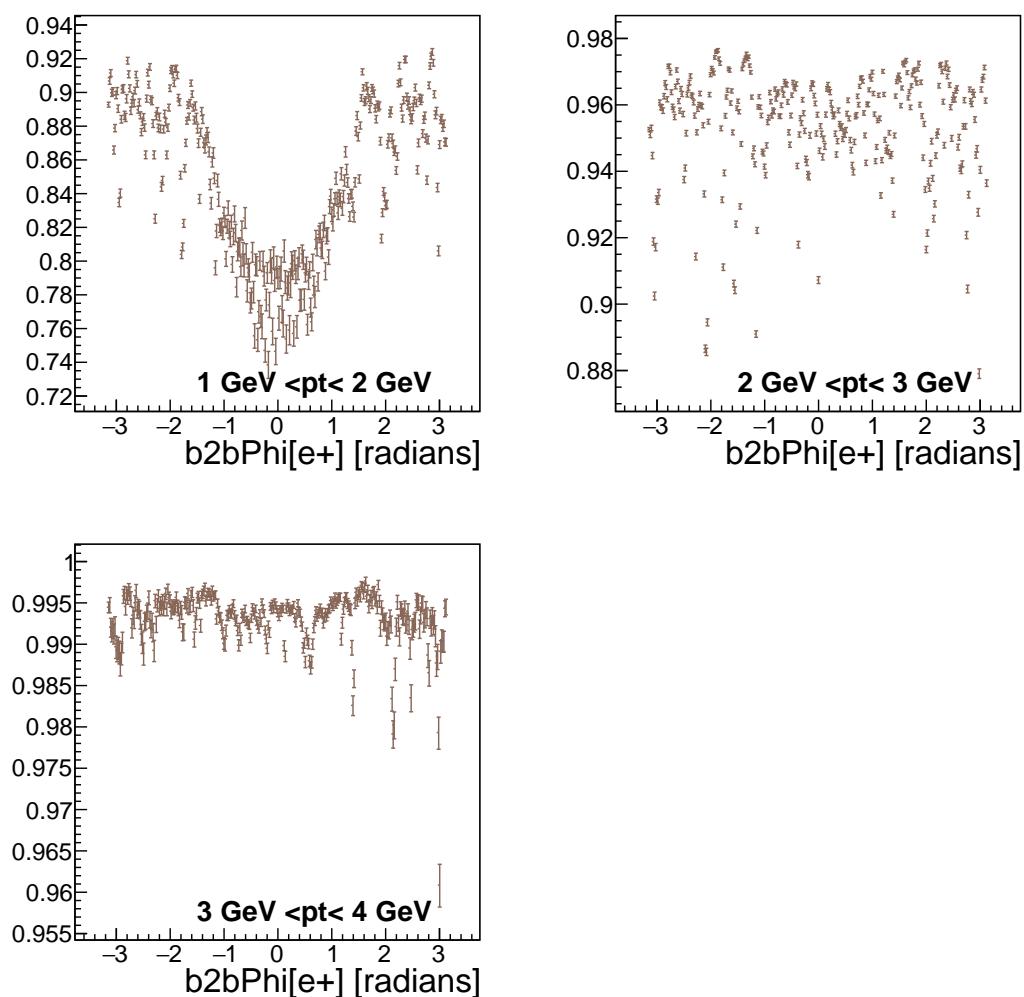


Figure C.15.: Electron ϕ transverse momentum tracking efficiency plots in the forward end-cap for phase3 Data.

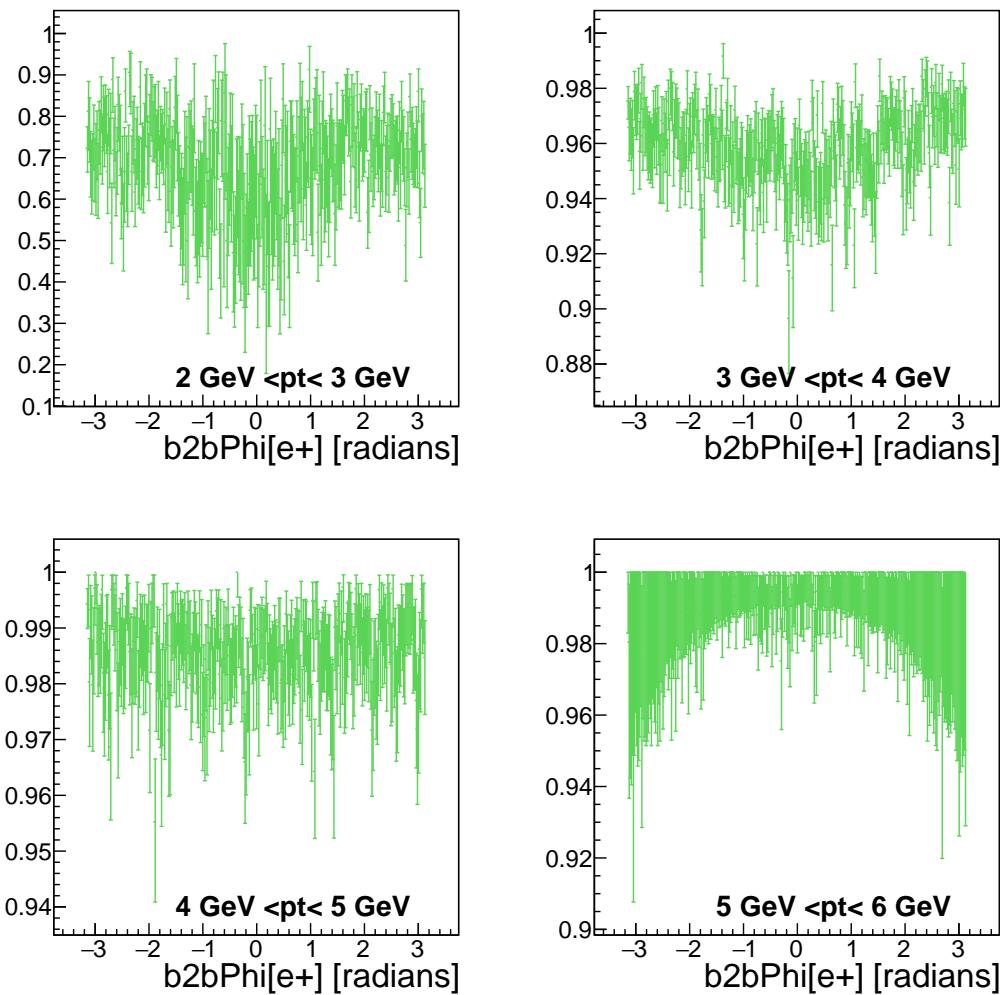


Figure C.16.: Electron ϕ transverse momentum tracking efficiency plots in the barrel for phase3 MC.

C. Additional Phase3 Plots

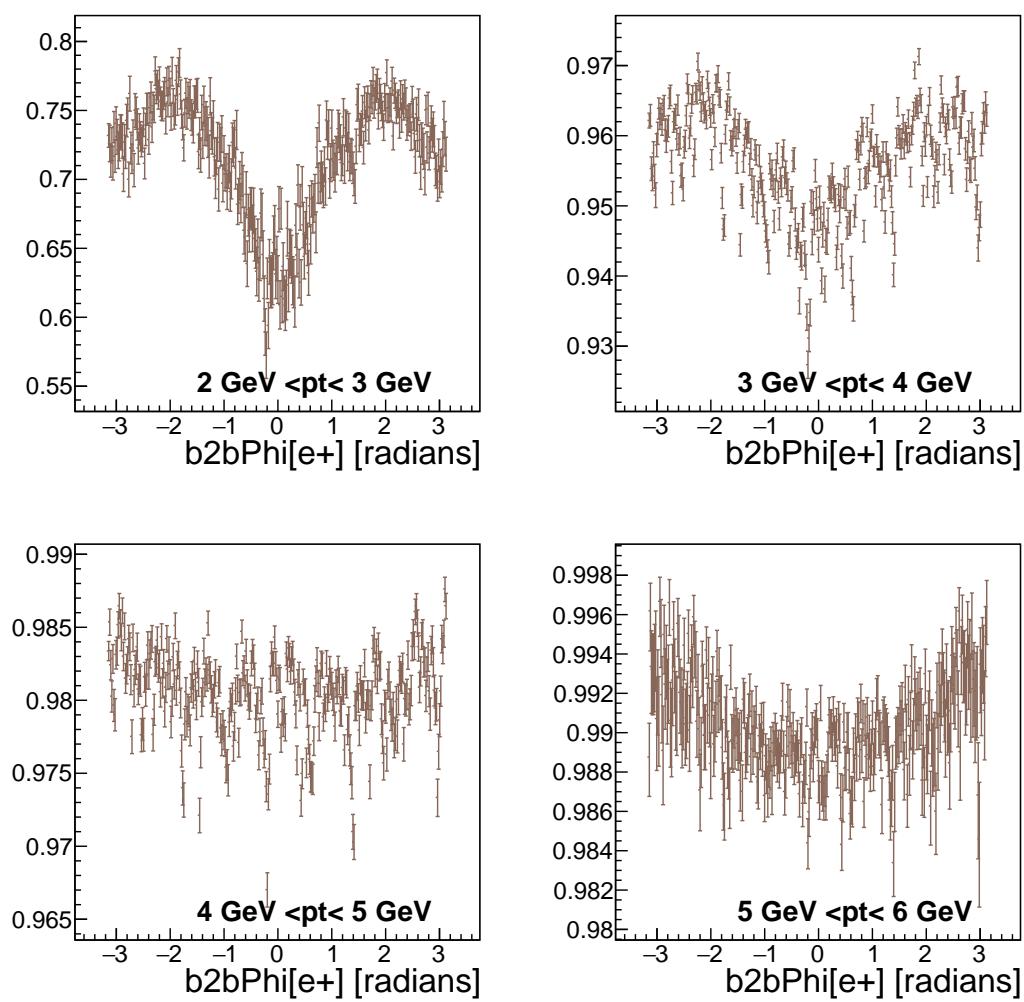


Figure C.17.: Electron ϕ transverse momentum tracking efficiency plots in the barrel for phase3 Data.

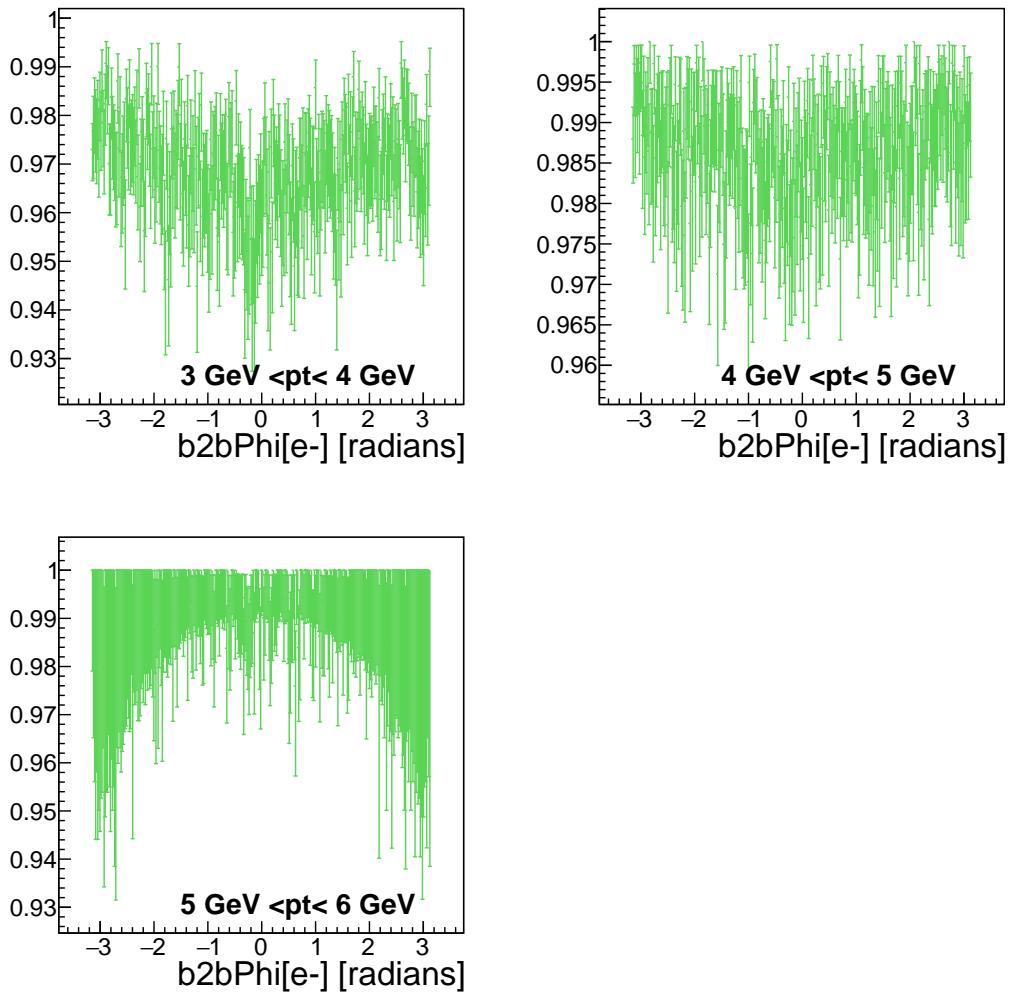


Figure C.18.: Positron ϕ transverse momentum tracking efficiency plots in the barrel for phase3 MC.

C. Additional Phase3 Plots

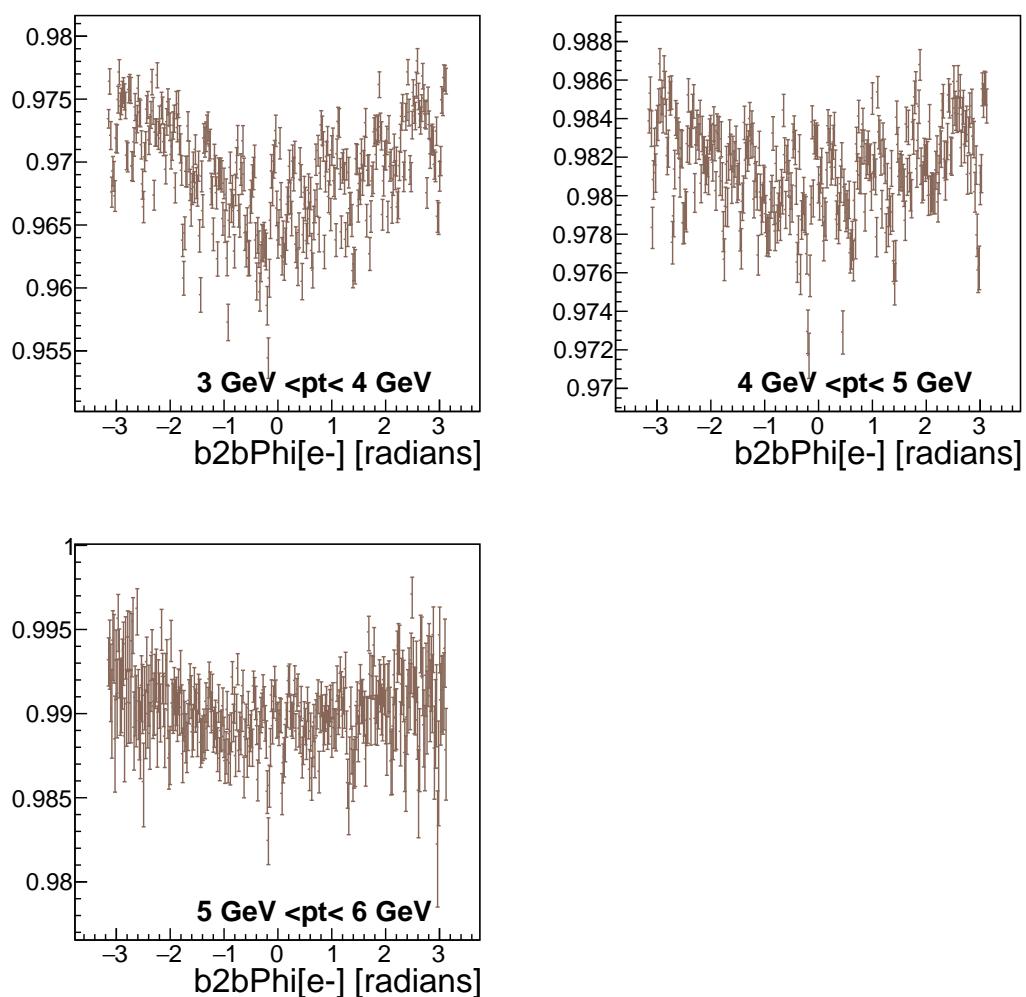


Figure C.19.: Positron ϕ transverse momentum tracking efficiency plots in the barrel for phase3 Data.

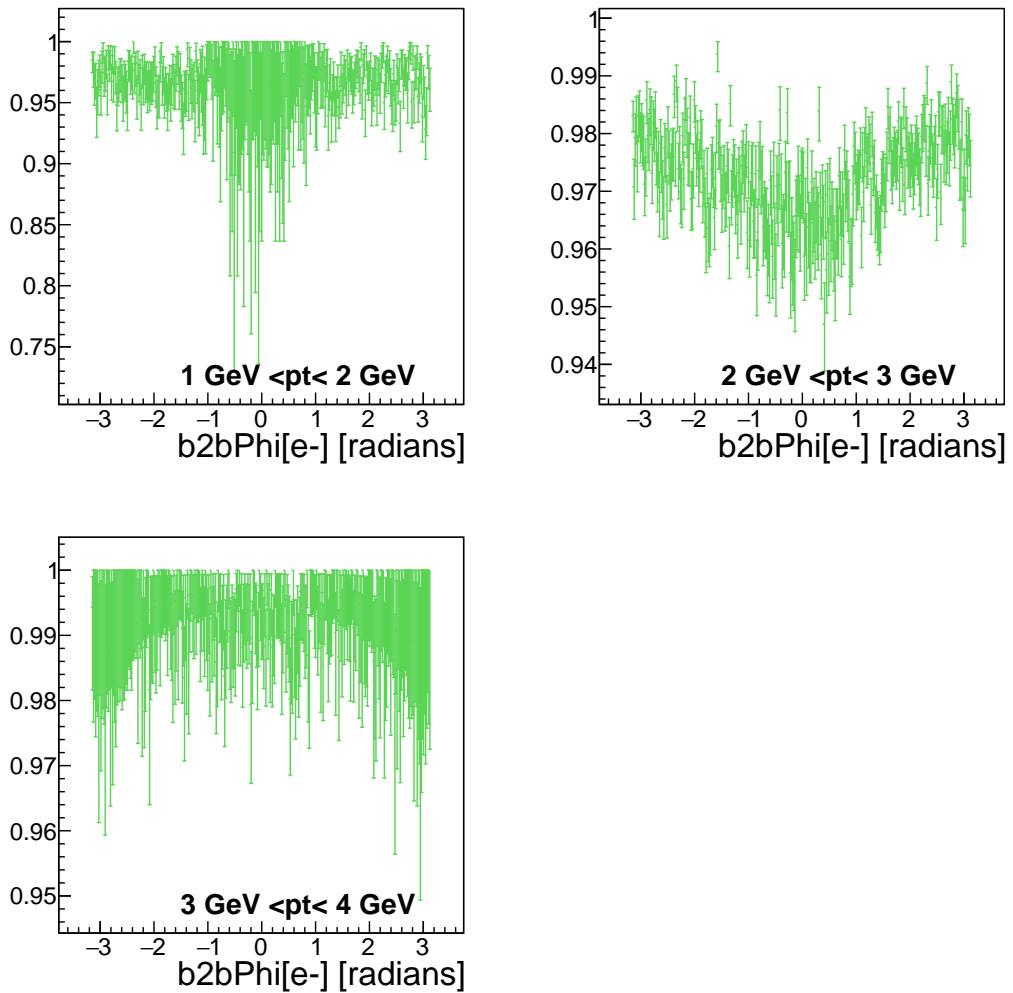


Figure C.20.: Positron ϕ transverse momentum tracking efficiency plots in the backward end-cap for phase3 MC.

C. Additional Phase3 Plots

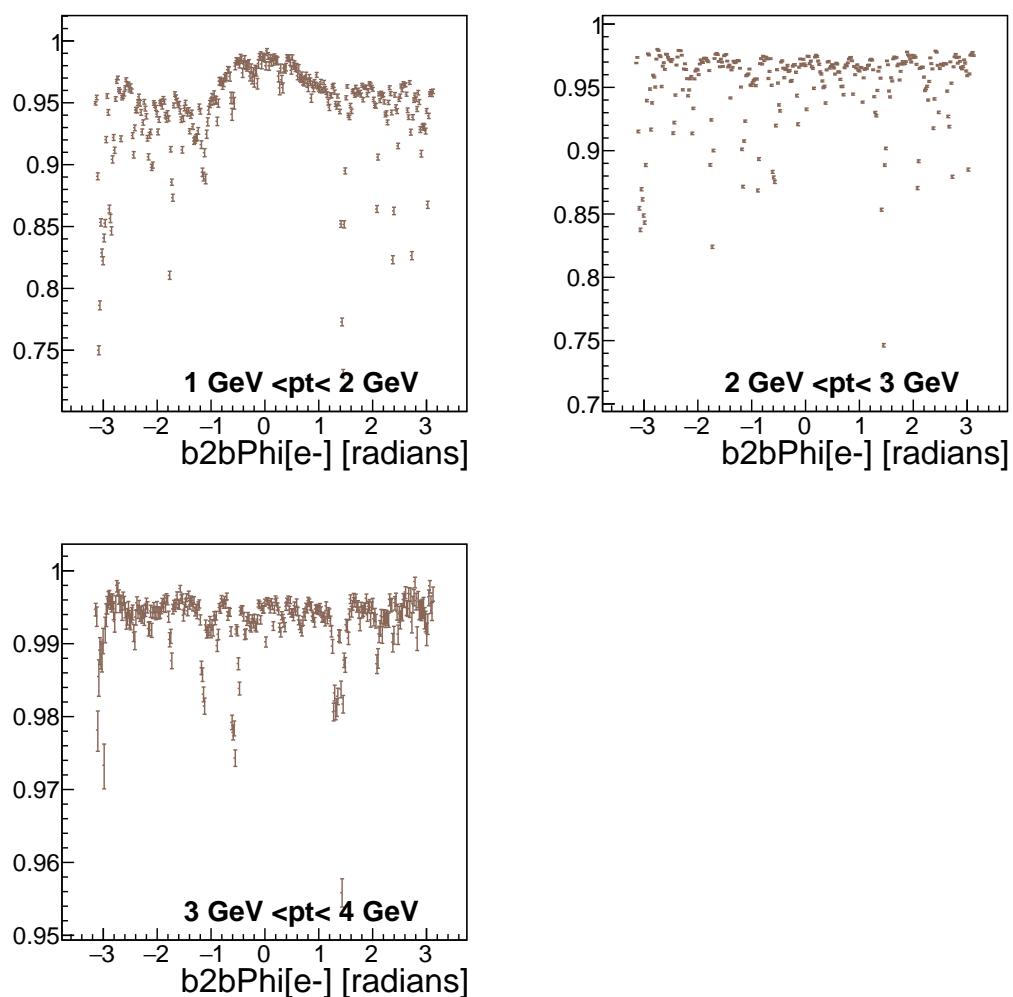


Figure C.21.: Positron ϕ transverse momentum tracking efficiency plots in the backward end-cap for phase3 Data.

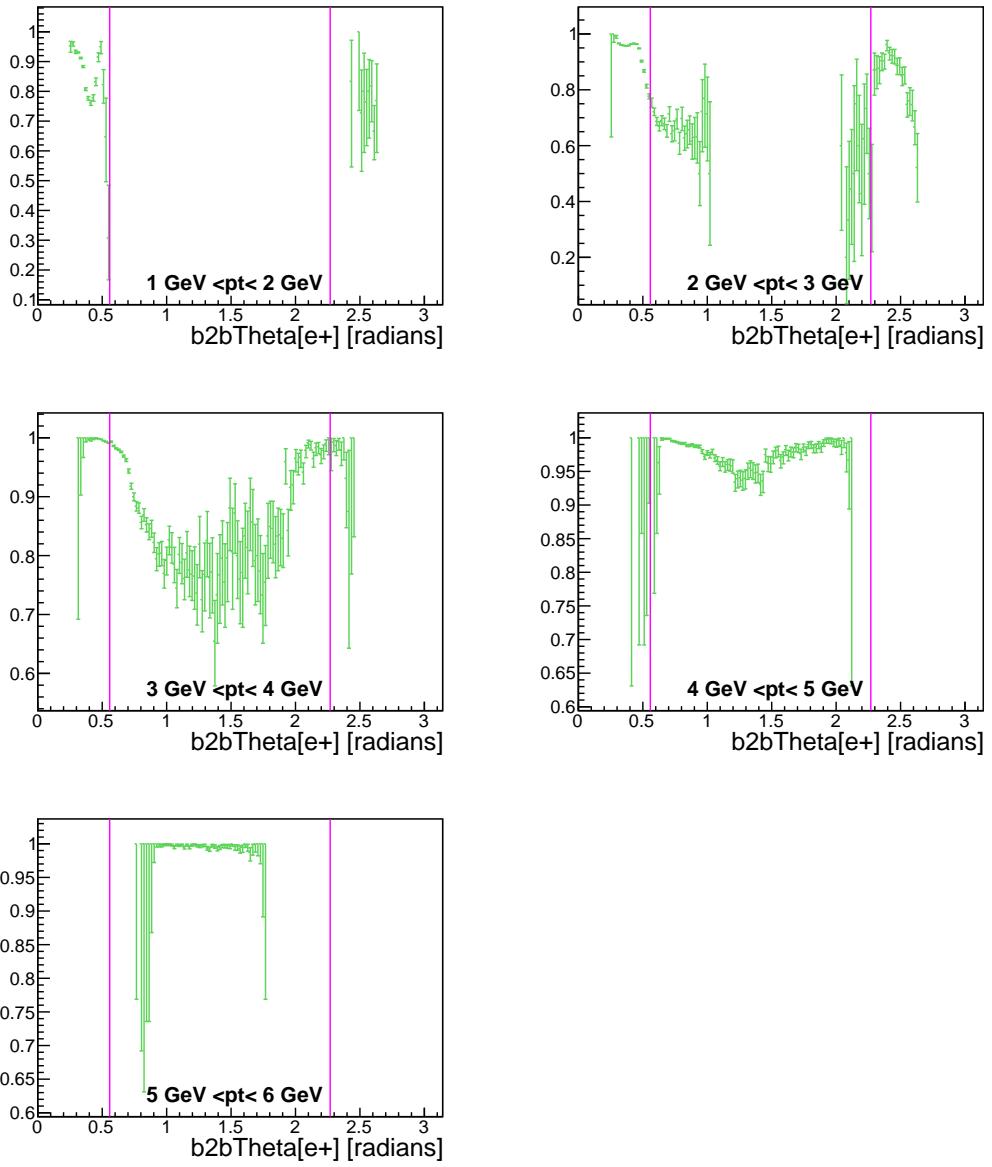


Figure C.22.: Electron ϕ transverse momentum tracking efficiency plots for phase3 MC. The pink line indicates the different sectors of the ECL.

C. Additional Phase3 Plots

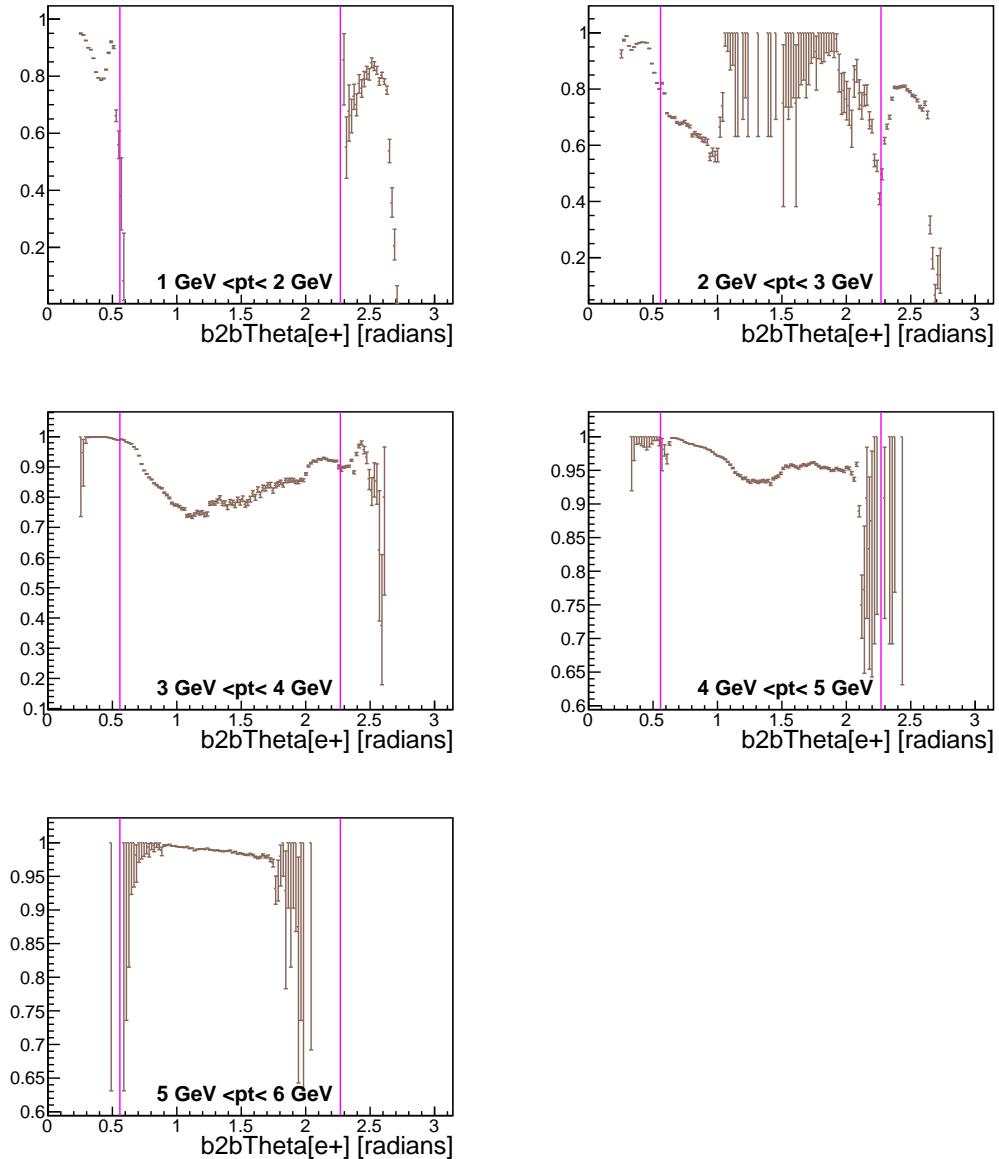


Figure C.23.: Electron ϕ transverse momentum tracking efficiency plots for phase3 Data. The pink line indicates the different sectors of the ECL.

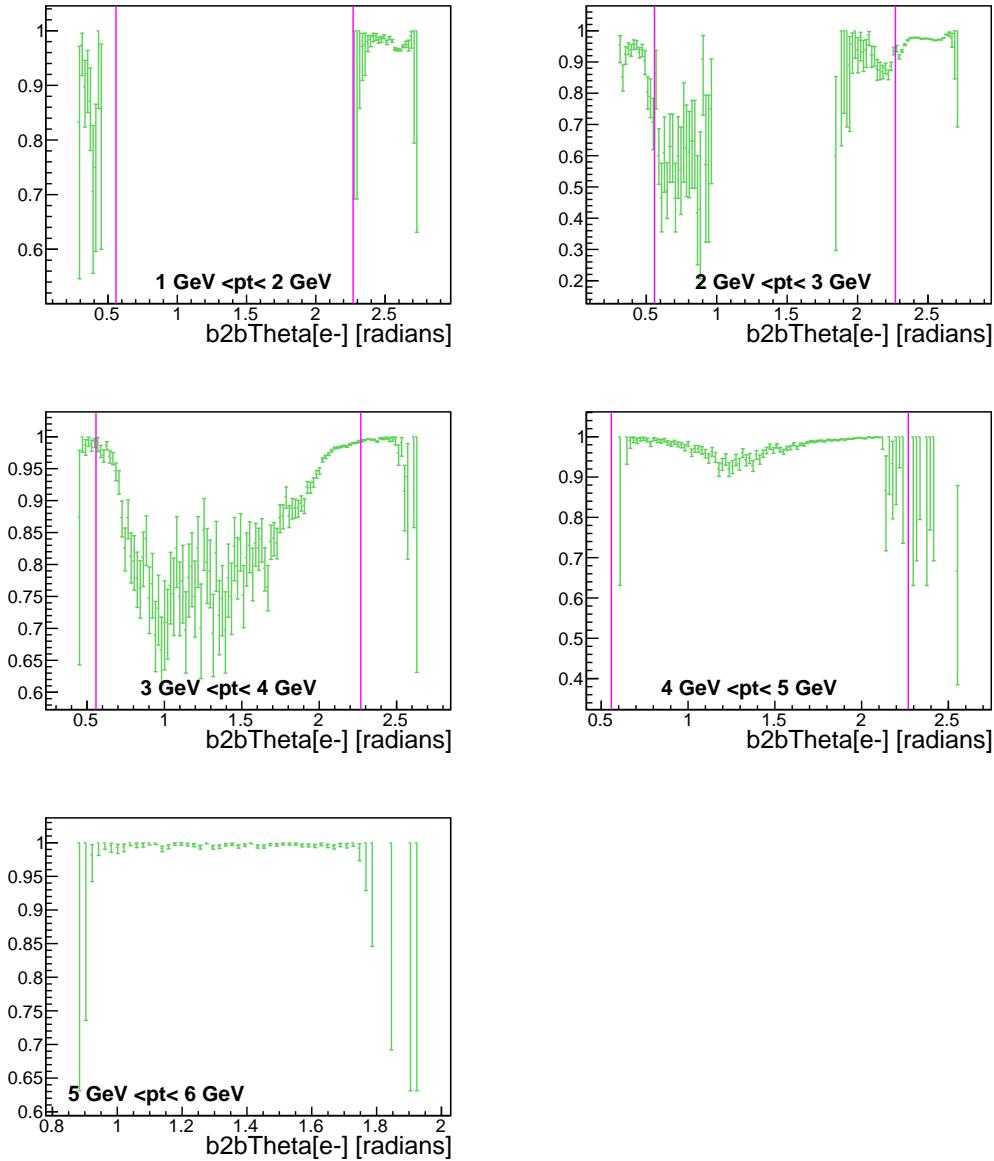


Figure C.24.: Positron ϕ transverse momentum tracking efficiency plots for phase3 MC. The pink line indicates the different sectors of the ECL.

C. Additional Phase3 Plots

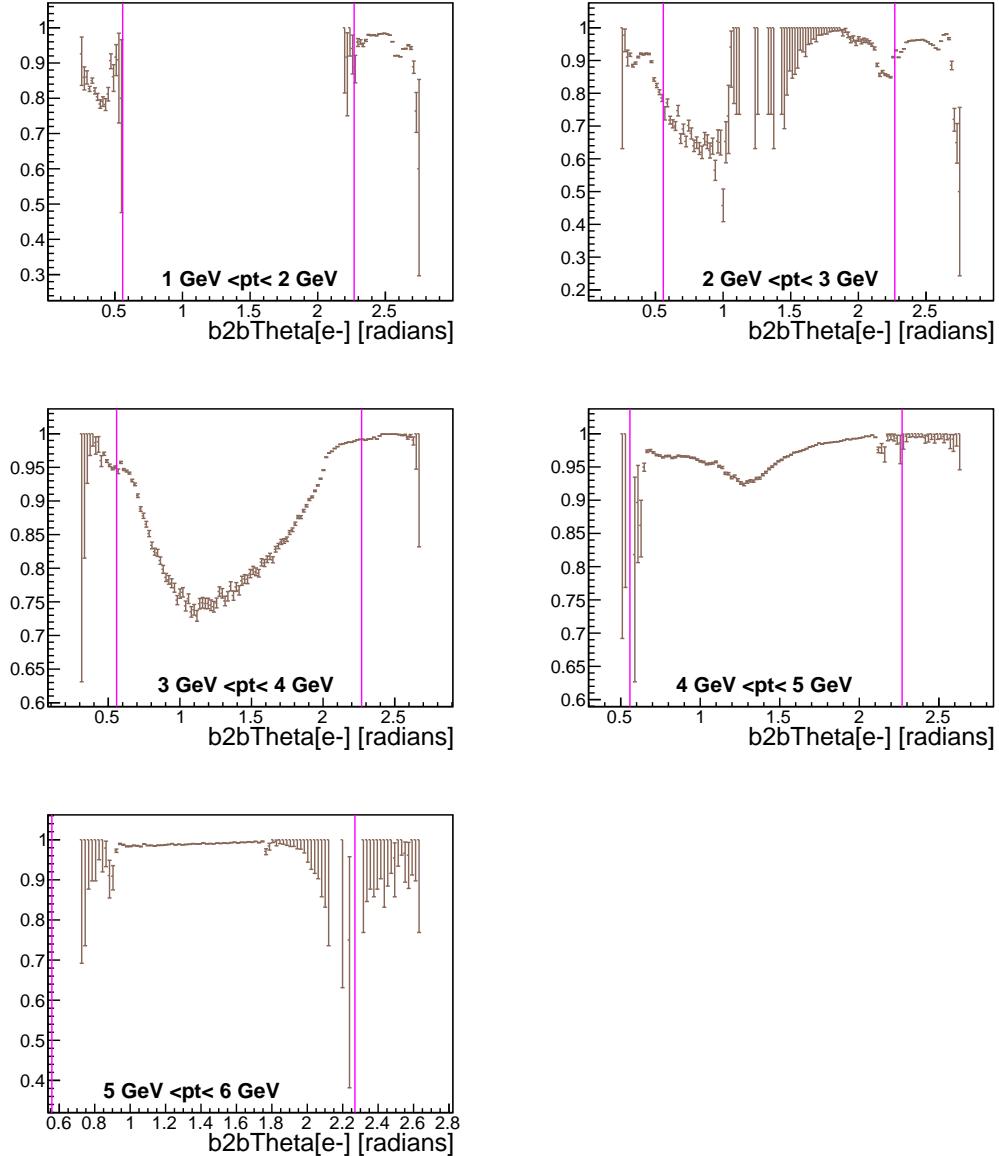


Figure C.25.: Positron transverse momentum ϕ tracking efficiency plots for phase3 Data. The pink line indicates the different sectors of the ECL.

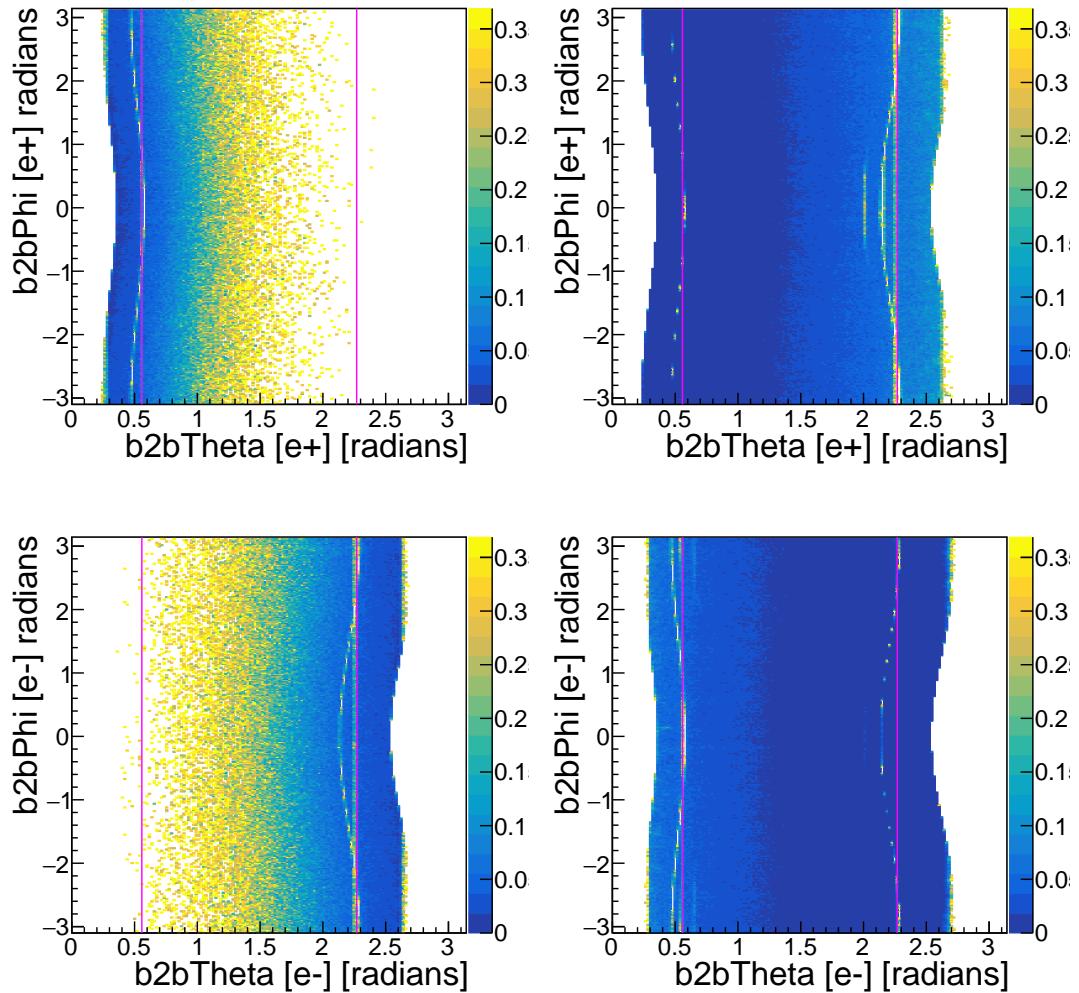


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