# Sensitivity to the Rare Decay $B^+ \to e^+ \nu_e$

Bachelor thesis at the faculty for physics
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submitted by
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# Sensitivtiät auf den seltenen Zerfall $B^+ \rightarrow e^+ \nu_e$

Bachelorarbeit an der Fakultät für Physik
der
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# Abstract

A comparison of two particle reconstruction methods, inclusive reconstruction and full event interpretation, for the decay mode $B^+ \to e^+ \nu_e$ is presented. The analysis is tested on simulated data of the Belle II detector at the SuperKEKB asymmetric-energy B factory. Inclusive reconstruction provides a signal detection efficiency of $\varepsilon_{Inc} = 10.46\%$ and would require a branhcing fraction of $\mathcal{B}_{Inc}(B^+ \to e^+ \nu_e) > 1.8 \cdot 10^{-6}$ to achieve a significance level of $3\sigma$ to be measured on the full Belle II data set. Full event interpretation provides a signal detection efficiency of $\varepsilon_{FEI} = 0.132\%$ and would require $\mathcal{B}_{FEI}(B^+ \to e^+ \nu_e) > 5.8 \cdot 10^{-5}$ to achieve the same significance.

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# Chapter 1

# Introduction

## 1.1 Motivation

The Standard Model (SM) is the current model with which matter is described. It categorises all known elementary particles into either fermions (particles with a half-integer spin) or bosons (particles with a an integer spin). Fermions include leptons and quarks, bosons particles such as photons and the recently discovered Higgs-boson. The SM doesn't just describe the particles themselves, but also the forces with which they interact with one another and that allow particle decay. The strong force, which binds quarks, is mediated via gluons, the weak force via $W$ and $Z$ bosons, and the electromagnetic force via photons. While the SM doesn't seem to have any incorrect predictions so far, it also isn't able to describe all the physical phenomena we know of today: Gravity has only been explainable with a hypothetical particle, the graviton, and discoveries such as dark matter can't be explained with the SM.

One phenomena that the SM is still being tested on is CP-symmetry violation (charged-conjugation-parity-symmetry violation). In 1964, James Cronin and Val Fitch discovered that not all physical laws behave the same way when a particle is swapped with it's antiparticle and it's spatial coordinates are mirrored [1].
In 1973, Makoto Kobayashi and Toshihide Maskawa calculated that there must be more quark families than previously established in the Standard Model to be able to explain the observed CP-symmetry violations [2]. They expanded on Nicola Cabibbo's previous work and created the Cabibbo-Kobayashi-Maskawa (CKM) matrix, which describes the likelihood of a quark changing it's flavour during an electroweak interaction [3]:

$$\begin{bmatrix} d\prime \\ s\prime \\ b\prime \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix} \tag{1.1}$$

On the right are the mass eigenstates of a quark coupled with the CKM matrix, which result in the weak eigenstates on the left. The CKM matrix contains complex entries and is unitary. This means $V^{\star}_{CKM} \cdot V_{CKM} = \mathbb{1}$, where $V^{\star}_{CKM}$ is the complex conjugate to $V_{CKM}$, which leads to the equations:

$$V^{\star}_{ub} \cdot V_{ud} + V^{\star}_{cb} \cdot V_{cd} + V^{\star}_{tb} \cdot V_{td} = 0 \tag{1.2}$$

$$\Leftrightarrow \frac{V^{\star}_{ub} \cdot V_{ud}}{V^{\star}_{cb} \cdot V_{cd}} + 1 + \frac{V^{\star}_{tb} \cdot V_{td}}{V^{\star}_{cb} \cdot V_{cd}} = 0 \tag{1.3}$$

Equation 1.3 can be plotted as a triangle in the complex plane (Fig. 1.1). In total, it is possible to derive six such unitary equations with their appropriate triangles from equation 1.1.

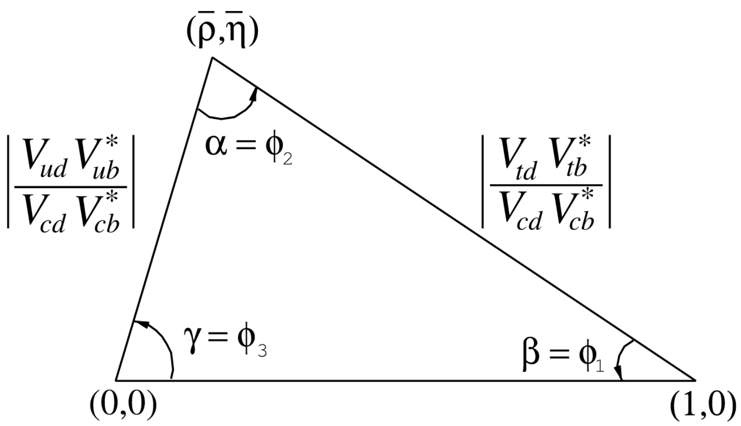


Figure 1.1: Unitary triangle in the complex plane [3]

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If the three vectors were to form a complete, closed triangle, then the Standard Model would describe flavour mixing perfectly and no additional causes or affects would be missing. If, on the other hand, they *weren't* to form a closed triangle, then that would be a signal for yet unknown physics. Therefore, it is of great interest to determine the entries of the CKM matrix with the highest possible precision.

The branching fraction of $B^+ \to e^+ \nu_e$ can be used to determine $V_{ub}$. In the Standard Model it is given as

$$\mathcal{B}\left(B^+ \to e^+ \nu_e\right) = \frac{G_F^2\, m_B\, m_e^2}{8\pi} \left(1 - \frac{m_e^2}{m_B^2}\right)^2 f_B^2\, |V_{ub}|^2\, \tau_B, \tag{1.4}$$

where $G_F$ is the Fermi coupling constant, the electron and $B$ meson masses are given with

$m_e$ and $m_B$, $f_B$ is the $B$ meson decay constant, and $\tau_B$ is the $B^+$ lifetime [4]. Assuming $|V_{ub}| = (4.39 \pm 0.33) \cdot 10^{-3}$ [5], the expected branching fraction is $(1.1 \pm 0.2) \cdot 10^{-11}$ [4]. It's extremely unlikely that this branching fraction will be measured with a significance of at least $3\sigma$, as the amount of expected $e^+e^- \to \Upsilon(4S)^1 \to B^+B^-$ events is only $2.6 \cdot 10^{10}$, which is one order of magnitude lower than required for an average of one $B^+ \to e^+ \nu_e$ event taking place. Therefore, if $B^+ \to e^+ \nu_e$ should be measured, then it would most likely have a different branching fraction as predicted and therefore contradict the Standard Model's prediction for $|V_{ub}|$, which would point to the existence of new physics.

To be able to make observations of the nature of any particular decay mode, an entire decay has to be reconstructed using the data gathered by the detector. By doing so, information can be gained such as the mass, momentum, etc. of the reconstructed particles. This information can then be used to search for specific decay modes. The objective of this thesis is to compare two different reconstruction methods to find out which one would be more likely to be able to detect the $B^+ \to e^+ \nu_e$ decay mode. The two reconstruction methods that will be compared are "inclusive reconstruction" and "full event interpretation".

It should be noted that throughout this thesis charge conjugate states (for both decay modes and for particles) are implied. This means that the decay mode $B^- \to e^- \overline{\nu}_e$ is also searched for. Since the names of the variables and functions of the Belle II software refer to both electrons and positrons as "electrons", both charged states will be referred to as electrons in this thesis.

## 1.2 Belle II detector

The Belle II detector at the SuperKEKB collider is an upgraded version of the Belle detector, which ran at the previous KEKB collider. It's located in Tsukuba, Ibaraki Prefecture, Japan. SuperKEKB has asymmetric beam energies: the $e^+$ is accelerated to 4 GeV, the $e^-$ to 7 GeV [6] and, it's target luminosity is $8 \cdot 10^{35}\text{cm}^{-2}\ \text{s}^{-1}$. The detector itself is a combination of layers of subdetectors. The tracking of charged particles and the measurement of their momenta are done by the first three layers: a silicon **P**i**X**el **D**etector (PXD), a double-sided **S**ilicon **V**ertex **D**etector (SVD) and a **C**entral **D**rift **C**hamber (CDC), the last of which measures a particle's energy loss dE/dx, which also helps identify particles. Particle identification is implemented with the the **T**ime-**O**f-**F**light (TOP) and the **A**erogel **R**ing-**I**maging **CH**erenkov (ARICH) detectors, which use time measurements and Cherenkov angle measurements to determine the velocity of a particle. Photons are detected by the **E**lectromagnetic **C**a**L**orimeter (ECL), which can also be used to identify

[1] An $\Upsilon(4S)$ is an Upsilon meson (which consists of a bottom and antibottom quark) that has been excited to the 4S energy state.

electrons. Finally, **K**-**L**ongs and **M**uons are detected via the KLM detector [7].

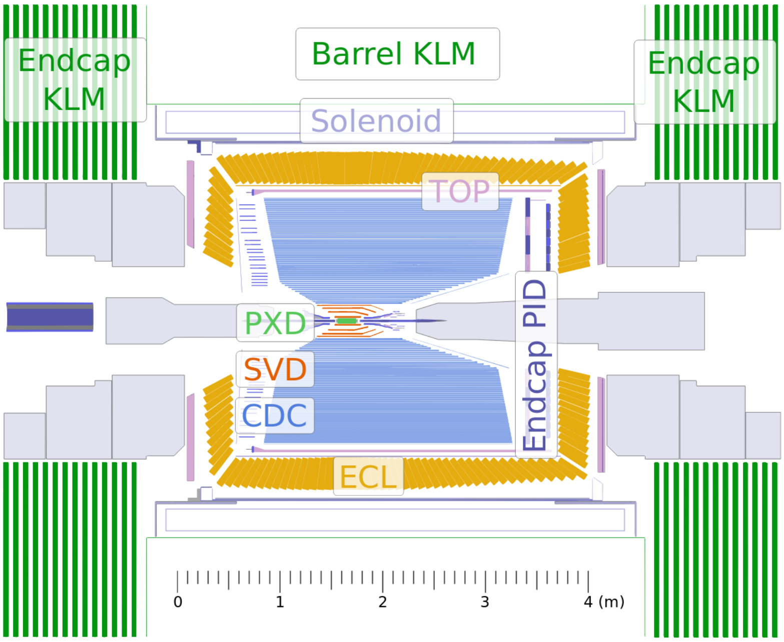



Figure 1.2: Side view of the Belle II detector [7].

# Chapter 2

# Analysis

## 2.1 Simulated data

Throughout this thesis, a "signal" $B$ meson refers to a $B^+$ meson that decays to $B^+ \to e^+ \nu_e$. A "tag" $B$ meson refers to the $B^-$ meson from the $\Upsilon(4S) \to B^+B^-$ decay mode, which itself doesn't decay via a specific mode.

Before an analysis can be run on real data, it must first be tested on simulated Monte Carlo data where every event is guaranteed to include the to-be-analysed signal decay mode. Simulated data is necessary for testing purposes, as every detail about every particle is known, which makes it possible to compare the results of an analysis with the data, unlike with real data. For this thesis, that means fixing the decay mode of the signal $B$ meson to $B^+ \to e^+\nu$ and generating 50,000 signal events.
The analysis has to be tested on 4,189,742 simulated background events as well. The objective is to reconstruct as few signal or tag $B$ mesons as possible from the background data, as they would all be incorrect. If too many are falsely reconstructed, then an increase in measurements, that would represent the signal events, won't be distinguishable from a statistical fluctuation of falsely reconstructed $B$ mesons and the signal decay mode won't be detectable.

All events are generated with EvtGen [8] and the detector response is simulated by GEANT4 [9].

## 2.2 Continuum background and continuum suppression

Not all $e^+$ $e^-$ collisions follow the decay mode $e^+e^- \to \Upsilon(4S) \to B\overline{B}$. Table 2.1 gives a basic overview of the cross sections for $e^+$ $e^-$ collisions.

| | cross section (nb) |
|---|---|
| $B\overline{B}$ | 1 |
| $q\overline{q}$ | 3 |
| $\tau^+\tau^-$ | 1 |

Table 2.1: Cross section for each physics event [10].

Here, $q\bar{q}$ stands for quark-antiquark combinations. Specifically: charm $c\bar{c}$, strange $s\bar{s}$, up $u\bar{u}$ and down $d\bar{d}$. Bottom and top quarks are excluded, as bottom quarks form the aforementioned $\Upsilon(4S)$ and the top quarks would require more energy to be produced, thus they aren't measured. The $e^+e^- \to q\overline{q}$ decay modes are known as "continuum background" in the Belle II software and separating them from $B\overline{B}$ events is known as "continuum suppression". Belle II has software dedicated to implementing continuum suppression, as machine learning has to be used on sample data to be able to tell the difference between the products of a $B\overline{B}$ decay mode and continuum background.

Continuum suppression is mostly based on the decay topologies of a $B\overline{B}$ decay mode and the trajectories of the final state particles of a continuum decay mode. The mass of a $B$ meson is $M_B \approx 5.28\ \frac{\text{GeV}}{\text{c}^2}$, so the combined mass of $B$ and $\overline{B}$ is $M_{B\overline{B}} \approx 10.56\ \frac{\text{GeV}}{\text{c}^2}$ [3], which is very close to the mass of a $\Upsilon(4S)$ ($M_{\Upsilon(4S)} \approx 10.58\ \frac{\text{GeV}}{\text{c}^2}$) [3]. This means that the $B$ and $\overline{B}$ have very little momentum in the $\Upsilon(4S)$ frame.

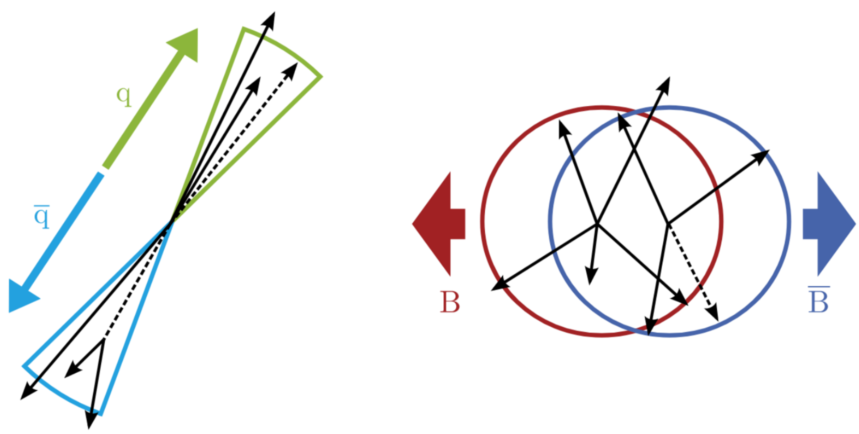



Figure 2.1: Topologies of a $B\overline{B}$ decay and a continuum decay [11].

A $B$ meson decays isotropically in it's own center of mass frame, meaning the trajectories of the daughter particles point in all directions. Therefore, a $B$ meson with very little momentum will decay isotropically in the $\Upsilon(4S)$ frame. Continuum events, on the other hand, do not share this property. Quarks have a small mass compared to the center-of-mass energy of the $e^+e^-$ system, which leads them to having high momenta. Also, the trajectories of a quark pair are opposite to one another, and the jets, into which they decay, have similar trajectories to the appropriate quarks [12]. Jets are formed through the hadronisation of quarks, since they have colour charges and aren't able to exist on their own [13]. This characteristical topology can be used to separate the signal and tag events from the continuum, as seen in Fig. 2.1).

A "Fast Boosted Decision Tree" (FastBDT) is used to separate most of the continuum background from the signal events by outputting a probability how likely an event *isn't* a continuum event. An example can be seen in Fig. 2.2. A decision tree is a system of boolean comparisons that lead to the classification of an object. In this case, a decision tree would compare the many continuum variables of a particle with the trained data to decide whether or not the given particle is a part of the continuum background. A boosted decision tree is a more complex form of decision tree built out of many smaller decision trees. The reason this implementation of a BDT is called "Fast" is that it's better optimised compared to other available implementations. A detailed description of FastBDT can be found in [14].

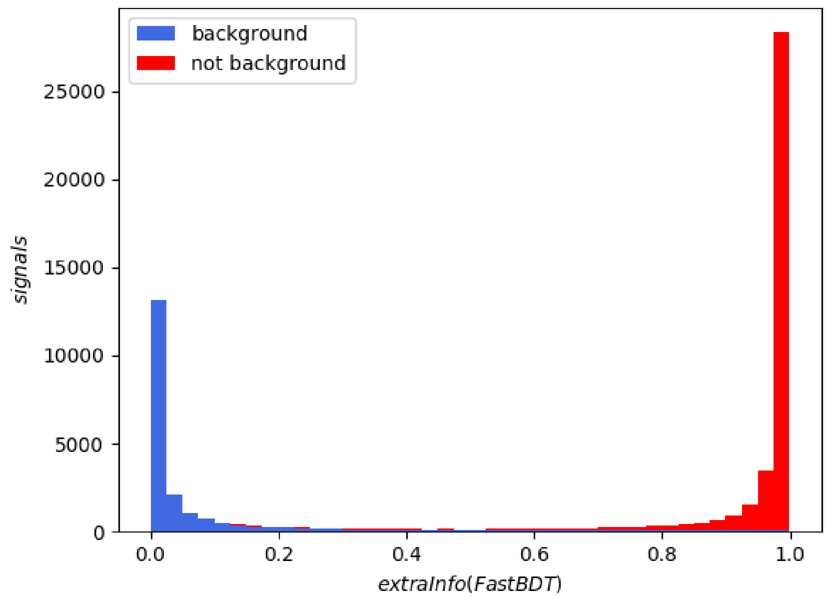



Figure 2.2: *extraInfo(FastBTD)* of the reconstructed signal $B$ meson for full event interpretation.

## 2.3 Particle reconstruction

### 2.3.1 Overview: Inclusive reconstruction

Once the signal $B$ meson has been reconstructed, the tag $B$ meson is reconstructed with the rest of the particles that were measured in the event (after certain cuts have been applied to reduce the chance of background particles being included in the reconstruction). What characterises the inclusive reconstruction is that the tag $B$ meson isn't reconstructed via a specific decay mode. Instead, the remaining particles are combined via their four-momenta without regarding whether or not the identified end-state particles are a possible result of a $B$ meson decay. Since particles measured by the detectors aren't always identified well enough to be given a definitive classification, there can be multiple possible combinations for a tag $B$ meson for any given event, of which only one can possibly be correct. For example, kaons and pions can be hard to differentiate, therefore a kaon might be identified as both, which would result it two different reconstruction combination possibilities. Strict cuts for the missing energy are implemented to reduce the possibility of false combinations and to sort out events with semi-leptonic decays (since neutrinos can't be measured) [12]. This approach has a high efficiency for correctly reconstructing events with signal decays, but it's disadvantage is a low purity $\left(\frac{signal}{signal+background}\right)$.

Unfortunately, at the time of writing, the advanced tool "inclusiveBtagReconstruction" of the Belle II software hasn't yet been fully implemented. This means that it isn't currently possible to reconstruct the tag $B$ meson and therefore not possible to reconstruct the $\Upsilon(4S)$, which makes the inclusive reconstruction as described above out of scope of this thesis. Instead, a simpler form shall be used, where all particles remaining in the detector after the signal reconstruction are collected into a "rest-of-event" object, which allows the application of "masks" (filters).

### 2.3.2 Overview: Full event interpretation

The main difference between full event interpretation (FEI) and inclusive reconstruction is that FEI checks if the combination of particles to be reconstructed to the tag $B$ meson follows a legitimate decay mode, including semi-leptonic decays (although, in this analysis semi-leptonic decays shall be ignored) [12]. If not, then the combination is ignored. As a result, the efficiency of FEI is lower than using inclusive reconstruction, but it's prutiy is higher. Once the tag $B$ meson has been reconstructed, it's combined with the signal $B$ meson to from a $\Upsilon(4S)$ candidate.

The reconstruction of a decay mode is done in hierarchically. First, all the end state particles are reconstructed. Then, the different possible intermediate state particles are reconstructed via every legitimate decay mode, which are inturn used to reconstruct the

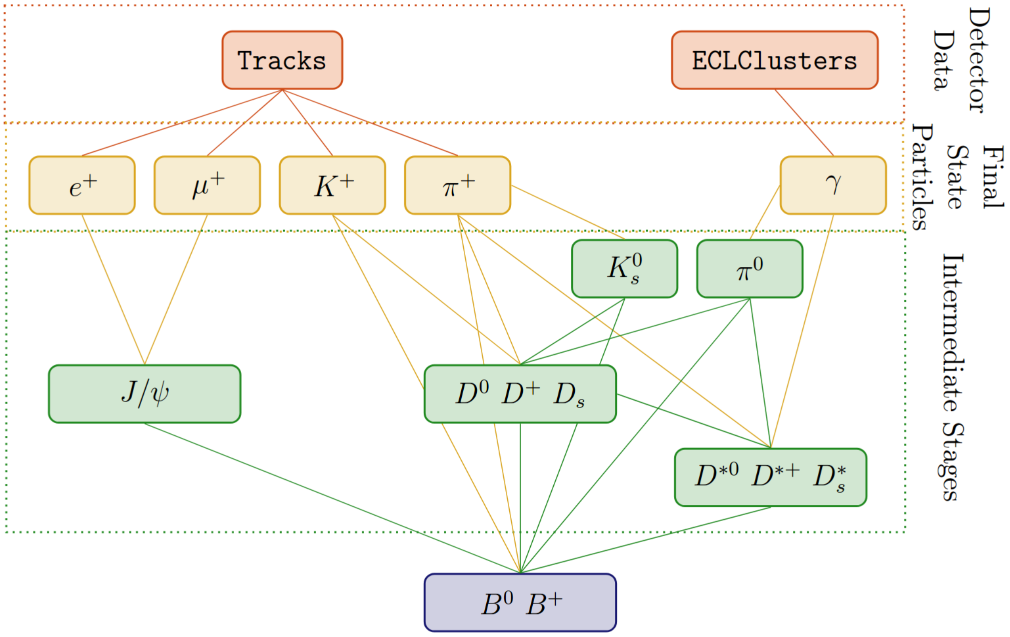



Figure 2.3: An example of the structure of a hierarchic reconstruction [15].

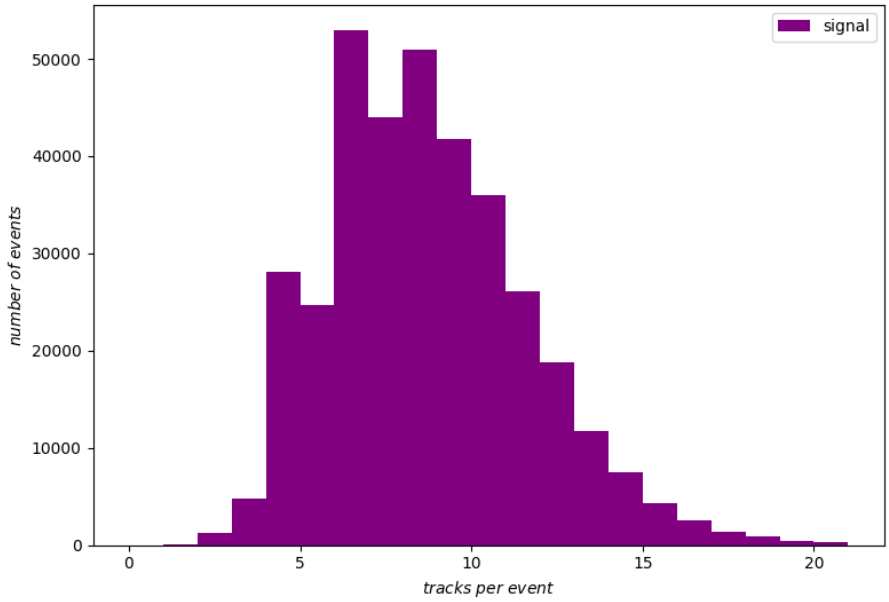
original particle [15].

## 2.4 Implementation: Inclusive reconstruction

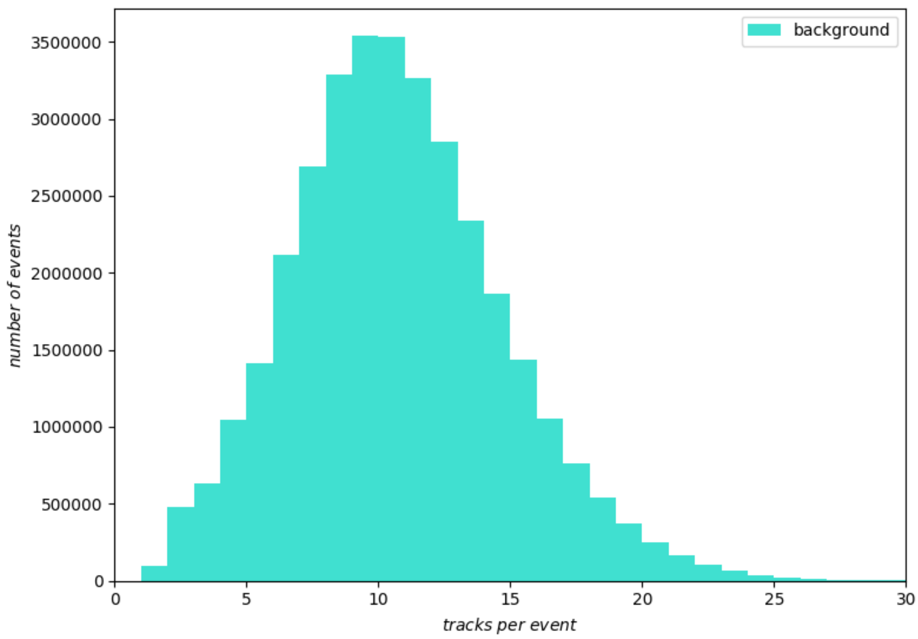
For this method, only events that have eleven tracks (i.e. eleven charged end-state-particles) or less shall be analysed. The simulated background events tend to have more tracks per event compared to the signal events (see Fig. 2.4). Therefore, by cutting all events with twelve or more tracks, a large percentage ($\approx 35\%$) of background events are removed, whereas a smaller percentage ($\approx 13\%$) of signal events are removed, which improves the signal to background ratio.

Before a $B$ meson can be reconstructed, the particles in an event are allocated to lists for the separate type of particles, e.g. a list for the electrons, another for the charged pions, and so on. It is possible to create cuts for each list; this allows the separation of particles of the same type, but with different properties.

First, the electrons are reconstructed with a correct reconstruction efficiency of 0.95. Charged pions, kaons, and muons are reconstructed with with analysis-provided tools




(a) Tracks per event for simulated signal events.




(b) Tracks per event for simulated background events.

Figure 2.4

benchmarked at a correct reconstruction efficiency of 0.95, where as neutral pions and photons, that aren't daughters of a decayed neutral pion, have a lower efficiency of 0.40 [16]. Neutral pions are harder to identify, since they are both without charge and have to be reconstructed out of two photons (which is done automatically by the software). Therefore, they have lower identification probabilities, so only the ones with a high identification value are used.

The signal $B$ meson is then reconstructed with the restriction of only using electrons with $2.3\ \frac{\text{GeV}}{\text{c}} < p_e < 2.9\ \frac{\text{GeV}}{\text{c}}$, where $p_e$ is the electron's four-momentum in the $\Upsilon(4S)$ rest frame [4]. Neutrinos can't be used for the reconstruction, as they can't be detected; the resulting missing energy is taken into account throughout the analysis. The decay of a $B$ meson to an electron and a neutrino is a two-body decay. Since their masses are much smaller than that of a $B$ meson and also similar to one another, the four-momentum of the $B$ is split relatively evenly among them, with $p_e \approx p_\nu \approx \frac{M_B}{2c} \approx 2.64\ \frac{\text{GeV}}{\text{c}}$.

The reconstructed $B$ meson is then compared to the simulated data to see whether or not it was reconstructed correctly, which is noted for later analysis. Next, a rest-of-event "mask" is created and all particle lists are added to it (except for the electrons that have already been used to reconstruct a $B$ meson). The mask allows cuts to be implemented on the rest-of-event as a whole. It uses cuts on the minimum energy of a photon, depending on the position of the detector where the photon was measured. A photon in the boost direction should have a higher energy, one in the opposite direction a lower energy. Afterwards, continuum suppression is implemented on the signal $B$ mesons and the rest-of-event mask. Photons that were used to reconstruct a neutral pion are removed (neutral pion's are already accounted for in the rest-of-event). All signal $B$ mesons whose rest-of-event's have a missing energy of $-0.5\ \text{GeV} < \Delta E < 0.5\ \text{GeV}$ are also cut, where $\Delta E = \frac{E_{beam}}{2} - E_{measured}$. Finally, cuts of $5.260\ \frac{\text{GeV}}{\text{c}^2} < M_{bc,\ ROE} < 5.295\ \frac{\text{GeV}}{\text{c}^2}$ and $extraInfo(FastBDT) > 0.8$ are implemented. $M_{bc,\ ROE} = \sqrt{E_{beam}^2 - p^2}$ is the beam-constrained mass of the rest-of-event, where $E_{beam}$ is the beam energy. Since the energy of a $B$ meson is well known, using the exact energy (the beam energy) instead of the measured energy (which can be inaccurate) gives a more accurate calculation for the mass of a $B$ meson.

## 2.5 Implementation: Full event interpretation

The signal reconstruction is the same for FEI as it was for the inclusive reconstruction method. The rest-of-event mask is also created, but it's only used to make the implementation of continuum suppression possible and to cut out all events where the mask still has too many particles left in it after the tag $B$ meson has been reconstructed (ideally, there shouldn't be any particles left). Then, the reconstruction of the tag $B$ meson itself is implemented with the full event toolkit [17]. As previously mentioned, only events with hadronic decays are reconstructed. The toolkit outputs a likelihood that the tag *B* meson has been correctly reconstructed.

If there seems to be multiple possibly correct combinations for the tag *B* meson, then only the one with the highest probability of being correct is kept and all others are thrown out. Tight cuts of -0.15 GeV < $E_{miss}$ < 0.1 GeV and 5.26 $\frac{\text{GeV}}{\text{c}^2}$ < $M_{bc,\ tag}$ < 5.295 $\frac{\text{GeV}}{\text{c}^2}$ are imposed on the remaining tag *B* mesons. The signal and tag *B* mesons are then matched to the simulated data.
The $\Upsilon(4S)$ are reconstructed out of the remaining tag *B* mesons and their allocated signal *B* mesons, with loose cuts of 7.5 $\frac{\text{GeV}}{\text{c}^2}$ < $M_{\Upsilon(4S)}$ < 10.5 $\frac{\text{GeV}}{\text{c}^2}$ and -2.0 $\frac{\text{GeV}}{\text{c}^2}$< $M_{miss}$ < 4.0 $\frac{\text{GeV}}{\text{c}^2}$, which take the missing mass and energy of the missing neutrino of the signal decay into account. There are multiple combinations for a $\Upsilon(4S)$ for each event, since the signal *B* mesons haven't been sorted via their probability of being correct reconstructions. Therefore, all the $\Upsilon(4S)$ of a single event are sorted via the probability that the combination of their daughter signal *B* meson is correct. Only the highest is kept; the rest are cut. A final cut $extraInfo(FastBDT) > 0.8$ is implemented.

## 2.6 Results

The momentum in the $\Upsilon(4S)$ frame of the electron from the signal decay is used as the fit variable for the signal decay mode, since it theoretically should be about 2.64 $\frac{\text{GeV}}{\text{c}}$. To be precise, the momentum of an electron that is the granddaughter of a correctly reconstructed $\Upsilon(4S)$ will be used, since just regarding the momentum of any electron within 2.3 $\frac{\text{GeV}}{\text{c}}$ < $p_e$ < 2.9 $\frac{\text{GeV}}{\text{c}}$ would have a much higher likelihood of including background events. Unfortunately, this will not be done for the inclusive reconstruction, since it currently isn't possible to reconstruct the $\Upsilon(4S)$ with that method. Instead, it will have to suffice to regard electrons where the rest-of-event survived the previously described cuts.

Both correctly reconstructed signal events and events where there was a signal decay, but the signal *B* meson was incorrectly reconstructed, are counted as signal events. In this case, an false reconstruction of a signal *B* meson would mean an electron that originates from the decay of the tag *B* meson being used to reconstruct the signal *B* meson. They are included, because there was still technically a signal decay, and the objective is to be able to detect signal events among all the background events.

### 2.6.1 Inclusive reconstruction

Since the inclusive reconstruction can't be properly implemented, the momentum of an electron in the $\Upsilon(4S)$ frame will be compared to it's momentum in the frame of the signal $B$ meson to see which frame generates a better peak (Fig. **??**). There are less events in the plot of the signal $B$ meson frame, as the momentum of some electrons exceeded the chosen interval. For a better comparison of the plot shapes, those electrons have been ignored.

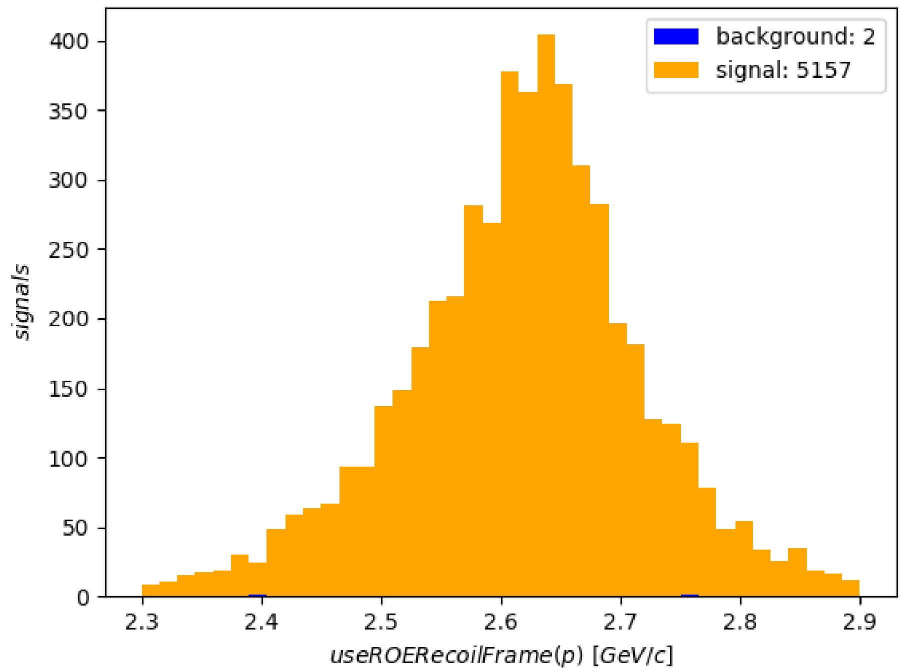



Figure 2.5: Electron momentum in the signal $B$ meson frame.

The momentum has a sharper peak in the signal $B$ meson frame, which would be better for detection, if both frames have a relatively flat background shape. But, with the only six background events, it isn't possible to tell what shape the background will take when the analysis is run on real data. For example, while the signal $B$ meson frame has a sharper peak, the background could also peak at the same momentum, making it impossible to see the signal, while the background in the $\Upsilon(4S)$ frame could have a flat shape. This would mean that the $\Upsilon(4S)$ frame would actually be better, even though the shape of the signal wouldn't be as good. More simulated background data is required to get a better idea of the form of the background.

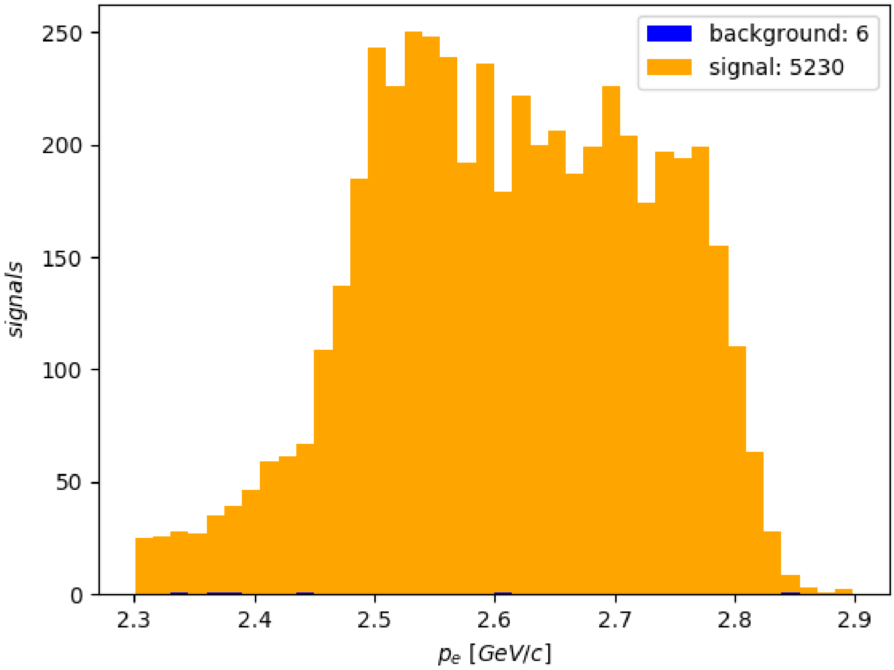



Figure 2.6: Electron momentum in the $\Upsilon(4S)$ frame for inclusive reconstruction.

5230 of the 50,000 generated signals events were correctly detected and reconstructed. This gives the inclusive tag reconstruction a signal efficiency of $\varepsilon_{Inc} = 10.46\%$. The background is discussed in 2.6.3.

### 2.6.2 Full event interpretation

The proper shape of Fig. 2.7 is unidentifiable due to the low amount of reconstructed $\Upsilon(4S)$.It's important to note that there are no background events remaining. This means that it isn't possible to precisely calculate how well the analysis filters background events. Instead, an upper limit for the maximum amount of expected background events will be calculated.
66 of the 50,000 generated signals events were correctly detected and reconstructed. This gives the inclusive tag reconstruction a signal efficiency of $\varepsilon_{FEI} = 0.132\%$. The background is discussed in 2.6.3.

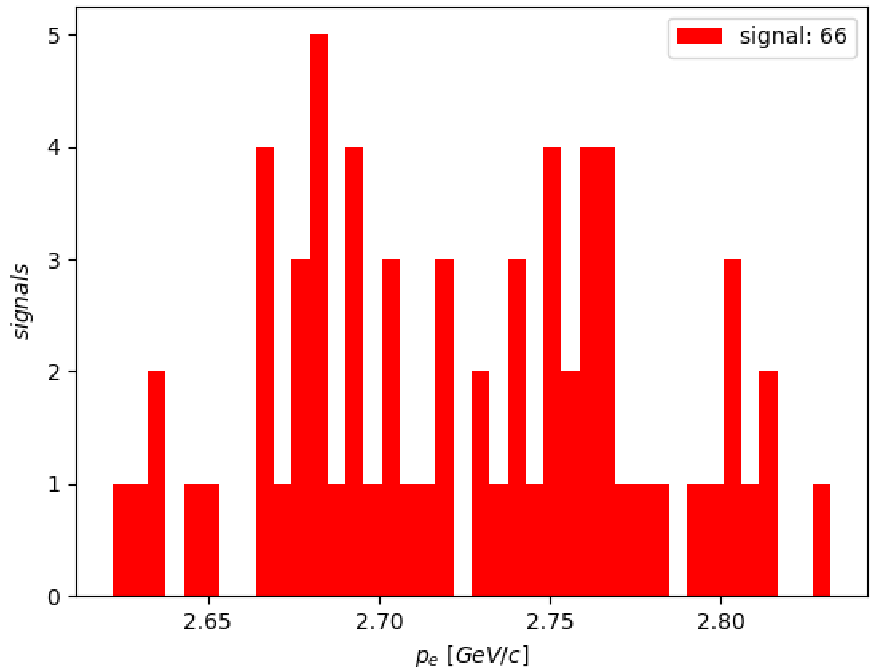



Figure 2.7: Electron momentum in the $\Upsilon(4S)$ frame for FEI.

### 2.6.3 Total expected background and required branching fraction for detection

Since FEI removed all the simulated background data, an upper limit for how many background events can be expected when analysing real data will be calculated, for which the simulated data will be scaled.
Each simulated background decay channel contains a different amount of events (see Table 2.2).

| | $c\bar{c}$ | $d\bar{d}$ | $s\bar{s}$ | $u\bar{u}$ | *charged* | *mixed* | $\tau^+\tau^-$ |
|---|---|---|---|---|---|---|---|
| sim. events | 586,783 | 711,636 | 681,313 | 830,010 | 480,000 | 480,000 | 420,000 |

Table 2.2: Simulated events per decay channel. *charged* stands for non-signal decay mode events that come from $B^+B^-$, *mixed* for events with decay modes that come from $B^0\overline{B^0}$.

For the simulated data, a maximum of one event per decay channel can be expected to be seen: $\frac{1}{\text{sim. events}}$. By scaling each channel to the size expected for 1 ab$^{-1}$ of data (see [18]), the amount of background events, that can be expected to be seen when this analysis is used on 1 ab$^{-1}$ of real data, is received (see Table 2.3).

| | $c\bar{c}$ | $d\bar{d}$ | $s\bar{s}$ | $u\bar{u}$ | *charged* | *mixed* | $\tau^+\tau^-$ | *sum* |
|---|---|---|---|---|---|---|---|---|
| exp. events | 2340 | 563 | 562 | 1934 | 1178 | 1178 | 2188 | 8765 |

Table 2.3: Expected events per 1 ab$^{-1}$ per decay channel. *sum* is the total amount of expected background events per 1 ab$^{-1}$.

Belle II is expecting to acquire 50 ab$^{-1}$ of data, therefore the upper limit for the total amount of expected background events for FEI is $b_{FEI} = 50 \cdot sum = 438,250$. Since the inclusive reconstruction had six background events left, the amount of expected background is $b_{Inc} = 6 \cdot 50 \cdot sum = 2,629,500$.
A significance level of $3\sigma$ is standard to claim evidence of a decay mode. A rough estimate for the significance level is $S = \frac{s}{\sqrt{b}}$, where $S$ is the significance level, $s$ the amount of remaining signal events after the analysis and $b$ the amount of remaining background events. Therefore, the necessary number of signal events needed for a significance level of $3\sigma$ is $s_{FEI} = 3 \cdot \sqrt{438,250} \approx 1986$ for FEI and $s_{Inc} = 3 \cdot \sqrt{2,629,500} \approx 4865$ for inclusive reconstruction, assuming perfect signal detection efficiencies.

From this the branching ratios necessary for a significance level of $3\sigma$ can be calculated. As previously stated, $e^+e^- \to \Upsilon(4S) \to B\overline{B}$ events have a cross section of about 1 nb (see Table 2.1), and $\mathcal{B}(\Upsilon(4S) \to B^+B^-) = (51.4 \pm 0.6)\,\%$ [3], so for an integrated luminosity of 50 ab$^{-1}$ we can expect about $2.6 \cdot 10^{10}$ $B^+B^-$ events. Taking the signal efficiencies into account, the resulting branching fractions are:

$$\mathcal{B}_{FEI}(B^+ \to e^+ \nu_e) = \frac{s_{FEI}}{2.6 \cdot 10^{10}} \cdot \frac{1}{\varepsilon_{FEI}} \approx 5.8 \cdot 10^{-5} \quad (2.1)$$

$$\mathcal{B}_{Inc}(B^+ \to e^+ \nu_e) = \frac{s_{Inc}}{2.6 \cdot 10^{10}} \cdot \frac{1}{\varepsilon_{Inc}} \approx 1.8 \cdot 10^{-6} \quad (2.2)$$

While the required branching fraction for FEI is a magnitude bigger than that of inclusive reconstruction, it should be emphasized that this is an upper limit, since no background data made it through the analysis. A better result can be achieved by testing the analysis on a larger data sample.

# Chapter 3

# Conclusion

## 3.1 Summary

Two methodes, inclusive reconstruction and full event interpretation, are compared for the search for the decay $B^+ \to e^+ \nu_e$ . They both select electrons whose momenta are within a specified interval and reconstruct the signal $B$ meson the same way. The inclusive reconstruction currently isn't able to reconstruct the tag $B$ meson, therefore it combines the remaining particles into a rest-of-event "mask", upon which further cuts are implemented. FEI reconstructs the tag $B$ meson while implementing cuts, and then uses both $B$ mesons to reconstruct the $\Upsilon(4S)$. The momentum of the remaining electrons is used as the identifier for the decay mode. Inclusive reconstruction has a much higher efficiency for detecting signal decays, but has more background compared to FEI. An upper limit has been calculated for FEI's expected background, since none of the simulated background events made it through the analysis. To be classified as a detection, a signal with a significance level of $3\sigma$ would have to be detected. To be able to do so, the inclusive reconstruction method is sensitive to a branching ratio of $\mathcal{B}_{Inc}(B \to e\,\nu_e) \approx 1.8 \cdot 10^{-6}$ for a significance level of $3\sigma$ and FEI is sensitive to $\mathcal{B}_{FEI}(B \to e\,\nu_e) \approx 5.8 \cdot 10^{-5}$ for a significance level of $3\sigma$. These are much larger than the theoretical branching fraction of $(1.1 \pm 0.2) \cdot 10^{-11}$.

## 3.2 Outlook

A problem that occurred during the analysis is that the full event interpretation removed all of the background events from the sample. This means that it wasn't possible to calculate exactly how efficient FEI is and how likely it is to see a signal event should one occur. If there were background events remaining, then that amount could be scaled to calculate how many background events can be expected from the real data of 50 ab$^{-1}$. As a result, it is only possible to calculate a maximum number of expected background events, which might be much greater than this analysis could actually achieve.

A large amount of data was ignored during the FEI by excluding all events with semi-leptonic decays. A more in depth analysis should have more and stricter cuts to be able to include semi-leptonic events without worsening the purity of FEI.

It would have also been beneficial to have been able to develope fits for the shapes of the signal and background data. The fits would have then been usable on real data to be able to calculate the number of signal and background events after an analysis.

What also isn't taken into account is beam background due to lost beam particles, beam-gas, synchrotron radiation and infra-beam effects [10]. These effects would create a larger background, which means that there would have to be a higher amount of detected signal events to get a significance level of $3\sigma$.

The biggest hinderance for this analysis is that the function "*inclusiveBtagReconstruction*" currently doesn't work, which means that isn't possible to accurately compare inclusive reconstruction to FEI, and the background of inclusive reconstruction is larger than it would otherwise be. Although inclusive reconstruction should in theory have a bigger background than FEI, it should also result in a higher amount of signal detections. Therefore, it could be that the signal decay mode would be more likely to be detected via this method when implemented properly, even when FEI is tested on a larger sample size.

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# Erklärung

Hiermit erkläre ich, die vorliegende Arbeit selbständig verfasst zu haben und keine anderen als die in der Arbeit angegebenen Quellen und Hilfsmittel benutzt zu haben.

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