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# Monte Carlo Study of Lepton Flavor Universality Violation in B Decays with Belle II Simulation

Sakul Mahat

# MONTE CARLO STUDY OF LEPTON FLAVOR UNIVERSALITY VIOLATION IN B DECAYS WITH BELLE II SIMULATION

by
Sakul Mahat

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Advisor: Dr. Jake Bennett

Reader: Dr. Thomas Browder

Reader: Dr. Breese Quinn

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# Abstract

Belle II, the first super B-Factory experiment, is designed to make precise measurements of weak interaction parameters and search for New Physics beyond the Standard Model of particle physics. The Standard Model of particle physics is a theory that classifies all known elementary particles and describes three of the four known fundamental forces in the universe. Physics beyond the Standard Model that addresses the theoretical developments needed to explain the deficiencies in the Standard Model is often referred to as New Physics. One of the assumptions of the Standard Model is that the couplings of particles that mediate the weak force (known as 'W' or 'Z' electroweak gauge bosons) to leptons are independent of lepton flavor. This thesis describes a study of the decay of $B^- \to D^0\,\tau^-\,\overline{\nu}_\tau$ in Belle II simulation. This decay is important to gather more information about the fundamental assumption of Lepton Flavor Universality. This thesis is organized as follows. The first sections include an introduction to the Standard Model and Lepton Universality, along with an introduction to the Belle II experiment. The following sections introduce the R(D$^{(*)}$) anomaly. The final sections explain the analysis technique and give the results of the study with Belle II simulations, along with a discussion of potential future work.

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# 1 Introduction

## 1.1 The Standard Model

The theories and discoveries of thousands of physicists since the early days of the twentieth century have resulted in a remarkable insight into the fundamental structure of matter. One guiding principle is that everything in the universe can be described as being made from a few basic building blocks called fundamental particles, whose interactions are governed by four fundamental forces. Our best understanding of how these particles and three of the forces are related to each other is encapsulated in the Standard Model (SM) of particle physics, which is summarized in Figure 1. Developed in the early 1970s, the SM has successfully explained almost all experimental results and precisely predicted a wide variety of phenomena. Over time and through many experiments, the SM has become established as a well-tested physics theory.

The Standard Model is made up of matter particles called quarks and leptons, along with force mediating bosons. Quarks are one type of elementary particle and are fundamental constituents of composite particles called hadrons, the most stable of which are protons and neutrons, the components of atomic nuclei. All commonly observable matter is composed of up quarks, down quarks and electrons, which are part of the first generation of matter.

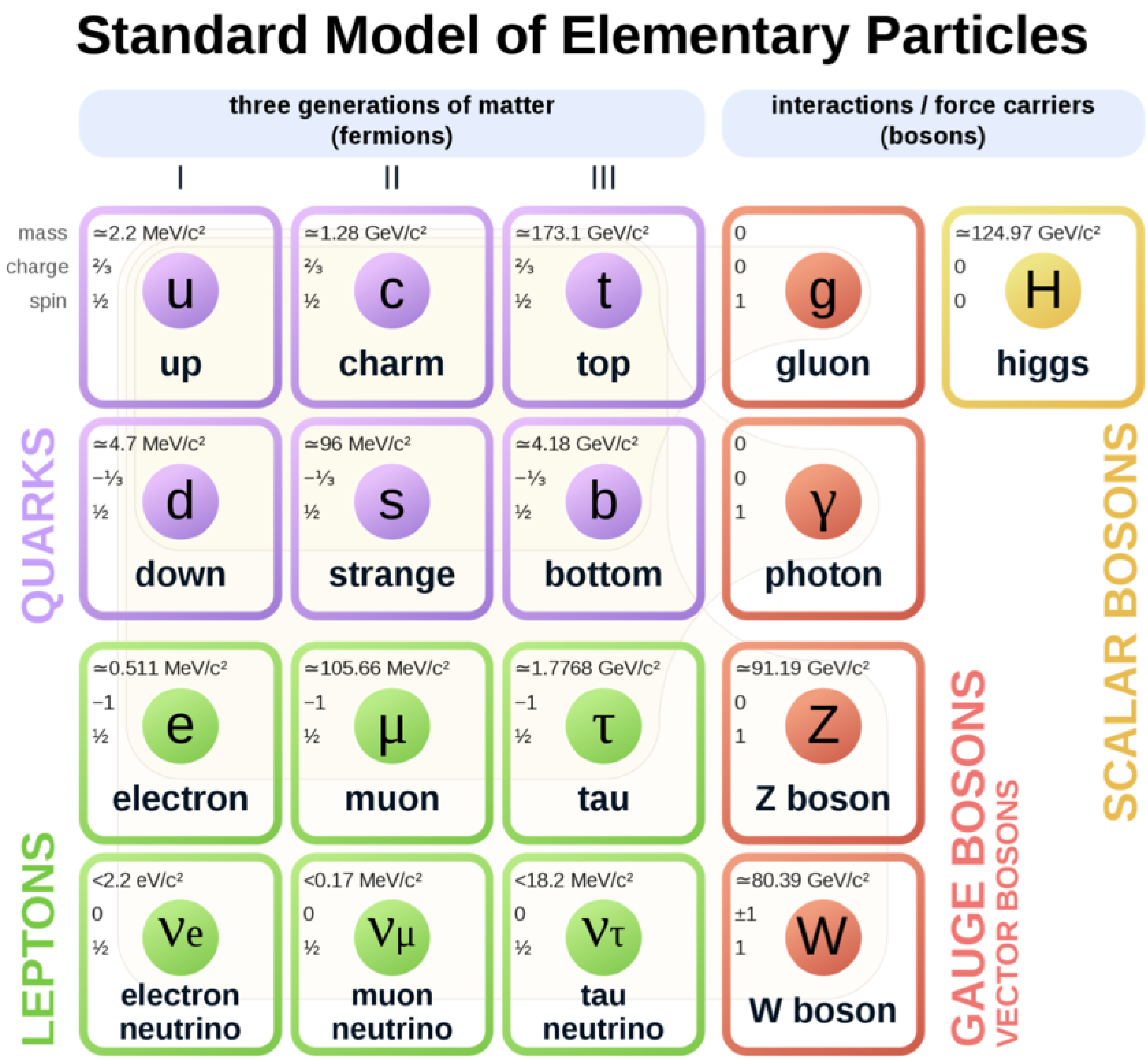


Figure 1: The Standard Model of particle physics

Leptons like electrons are a class of subatomic particles that respond only to the electromagnetic force, weak force, and gravitational force. However, leptons are not affected by the strong force. Leptons are said to be elementary particles (i.e they do not appear to be made up of smaller units of matter). Furthermore, leptons are defined as having one or zero units of electric charge, which quarks carry a fractional charge relative to the leptons. Charged leptons include electrons, muons, and taus and their antimatter partners, which carry an opposite charge. Electrons, the lightest charged leptons, have a mass only 1/1,840 that of a proton.

Particles can also be classified according to a property called spin. Bosons are particles that obey the rules of Bose-Einstein statistics. They have a quantum spin with an integer value, such as 0, 1, -1, 2, -2, etc. In contrast, fermions like quarks and leptons have a half-integer spin, such as 1/2, -1/2, -3/2, and so on. Since bosons control the interaction of physical forces (such as electromagnetism and possibly even gravity), they are often called force carriers.

Fermions are divided into three generations of matter. Each member of a higher generation has greater mass than the corresponding particle of the lower generation, with the possible exception of the neutrinos (whose small but non-zero masses have not been accurately determined). For example, the first-generation electron has a mass of only 0.511 MeV/$c^2$, the second-generation muon has a mass of 106 MeV/$c^2$, and the third-generation tau has a mass of 1777 MeV/$c^2$ (almost twice as much as a proton) [6]. This mass hierarchy causes particles of higher generations to decay to the first generation particles, which explains why everyday matter (atoms) is made of particles from only the first generation. Furthermore, to study and analyze the decays that include particles of higher generations, accelerators are used to produce very high energy environments from which particles can be created. This allows experimental physicists to study such high generation particles.

## 1.2 Lepton Flavor Universality

Although the SM is believed to be theoretically self-consistent and has demonstrated great success in providing experimental predictions, it leaves some phenomena unexplained and falls short of being a complete theory of fundamental interactions. It does not fully explain the baryon asymmetry of the universe, incorporate the full theory of gravitation as described by general relativity, nor account for the accelerating expansion of the universe, as possibly described by dark energy. The SM does not contain any viable dark matter particle that possesses all of the required properties deduced from observational cosmology. It also does not incorporate neutrino oscillations and their non-zero masses [6]. Furthermore, high energy physicists are also on a quest to test a fundamental theory of the SM called lepton flavor universality. Lepton flavor universality is the idea that all three types of charged leptons, electrons, muons and taus, interact in the same way with other particles. As a result, the different lepton types should be created equally often in particle transformations, or "decays", after accounting for differences in their masses. However, some measurements of particle decays made by the LHCb collaboration and other experiments over the past few years have indicated a possible difference in their behaviour. Taken separately, these measurements are not statistically significant enough to claim a violation of lepton flavor universality and hence a crack in the Standard Model, but it is intriguing that hints of a difference have been popping up in different particle decays and experiments.

An example of lepton flavor universality is depicted in Figure 2 [4], which shows two decays. The top diagram shows a transition from a bottom quark to a charm quark and the bottom diagram shows the decay of a bottom quark to a strange quark. In each of these decays, a weak boson is emitted and decays into additional final state particles. If lepton flavor is conserved, the rate of such decays should be independent of the lepton flavor (type), after accounting for differences in lepton mass.

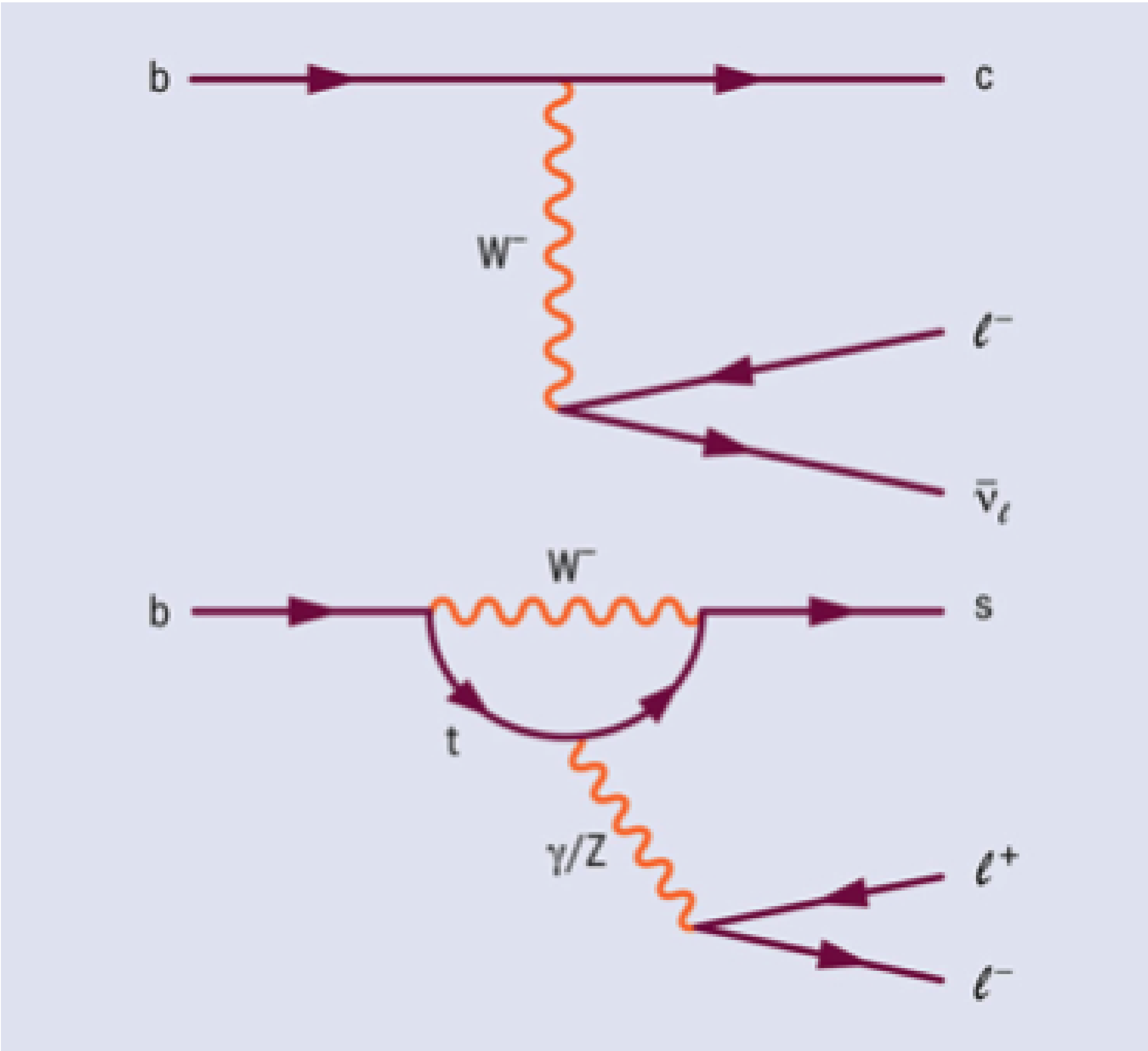

Figure 2: Feynman diagram in the Standard Model for two classes of processes relevant to the study of Lepton Flavor Universality

# 2 The Belle II Experiment

A common explanation of the big bang suggests that matter and antimatter should have been created in equal amounts. If this is true, why is the universe today filled almost entirely with matter and not antimatter? Physicists attribute this to the difference in the behaviour of matter and antimatter due to the violation of the so-called CP symmetry. This fundamental symmetry of nature states that the laws of physics should not change when a particle is interchanged with its antiparticle (charge conjugation) and the signs of all its spatial coordinates are flipped (parity). While the SM allows for violation of CP symmetry, it is not sufficient to explain the observed excess of matter in the universe.

The Belle II experiment is a general-purpose particle physics experiment designed to study the properties of B mesons (heavy particles containing a beauty quark) and many other topics. The successor to the Belle experiment, Belle II was commissioned at the SuperKEKB accelerator complex at KEK in Tsukuba, Ibaraki prefecture, Japan [1, 2].

Belle II is an asymmetric ($e^+$ $e^-$) accelerator. When beams of electrons and positrons collide, they annihilate into energy, which can produce different states. The electron and positron beam energies are 7 GeV/$c^2$ and 4 GeV/$c^2$, respectively. This asymmetry means that particles produced in the interaction are not at rest, but have a momentum along the direction of the electron beam. This is useful for studies of CP violation, which is outside the scope of this study. The beam energies are tuned such that the energy in the collision is sufficient to produce an $\Upsilon$(4S), which is a excited state of $\Upsilon$ meson and consists of a bottom quark and a bottom anti-quark. The $\Upsilon$(4S) has a modest cross-section compared to the other $\Upsilon(nS)$ states ($\approx$1.05 nb) but is the lowest-lying state above the threshold to produce a $B\bar{B}$ meson pair. The $\Upsilon$(4S) will later play an important role in the Missing Mass Squared Technique described in Section 4.2. Other possible production modes from the electron-positron interaction include quark pairs, as illustrated in Figure 3.

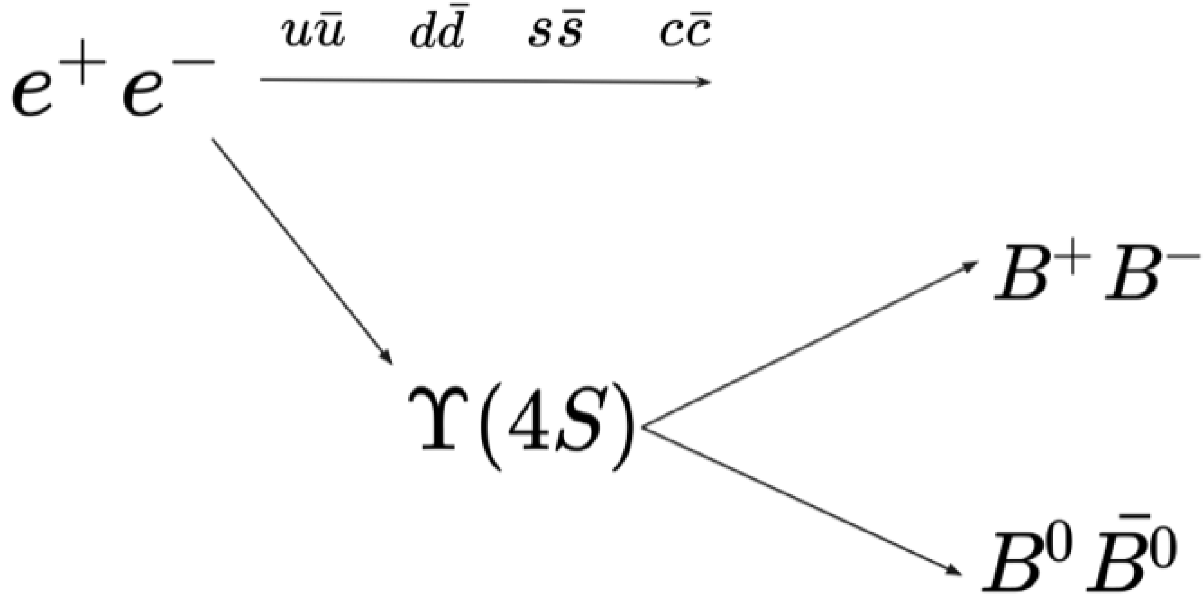


Figure 3: Possible states produced in the $e^+e^-$ collision

### 2.0.1 The Belle II Detector

In SuperKEKB, bunches of matter particles (electrons) and their anti-particles (positrons), with energies up to 8 giga electron volts, are brought to collision at rates almost 40 times that of the previous KEKB accelerator. Higher generation particles are produced from the energy in the collisions and their decay products are measured and analyzed in the Belle II detector, which is shown in Figure 4.

In the Belle II detector, various detector subsystems are arranged in cylindrical layers around the beam pipe and are optimized to detect the decay products from the beam collision. The decay products, such as electrons, muons, pions and other secondary particles, can be measured precisely with these devices. The whole Belle II detector is approximately 10 meters wide, 10 meters high and weighs about 1,500 tons [1].

The electron and positron beams collide in at the center of the Belle II detector, called the interaction region (IR). Surrounding the interaction region are subsystems of the Belle II detector, which will be discussed shortly, that gather information such as the energy, momenta, and mass of particles traversing the detector. However, the individual particles themselves are not detected. Rather, the interactions of those particles with the detector subsystems are used to infer the necessary information.

After the particles are produced at the IR, they travel the Vertex Detector (VXD), which itself is composed of two subsystems, the Pixel Detector (PXD) and the Silicon Vertex Detector(SVD). Together, these serve to provide precise measurements of vertices, which are where a particle decays into byproducts. Vertices are important to identify long-lived particles and are used as input to measurements like particle lifetimes.

After passing through the VXD, particles then enter the Central Drift Chamber (CDC), which is the primary tracking device in the detector. The CDC is a cylindrical chamber filled with a gas mixture containing ethane and helium. When a charged particle travels through this chamber, it ionizes the gas along its path. The electrons freed in this interaction drift toward sense wires that are held at a high potential. Hits on the sense wires can be used to determine the trajectory of the charged particle. A uniform magnetic field from a solenoid causes charged particles to curve while traversing the CDC. By measuring the curvature of the "track" of ionized particles, it is possible to measure the momentum of the particle.

The other major components of the Belle II detector, which is illustrated in Figure 4, include particle identification detectors, an electromagnetic calorimeter (ECL), and a $K_L$ and muon detector (KLM). The ECL is designed to measure the energy of particles coming from a collision. The KLM is important for identifying particles that interact with the tracking system only weakly. For example, pions will very likely be quickly absorbed in the iron flux return of the solenoid magnet that produces the uniform magnetic field within the Belle II detector. However, muons will penetrate many layers of iron and can therefore be uniquely identified by the KLM which is made up of layers of resistive plate capacitors, interleaved with the layers of iron.

The Belle II trigger and data acquisition systems, along with offline computing, have also been upgraded relative to those used in Belle. This helps the experiment to cope with the expected high background environment and very high rate of collisions at SuperKEKB.

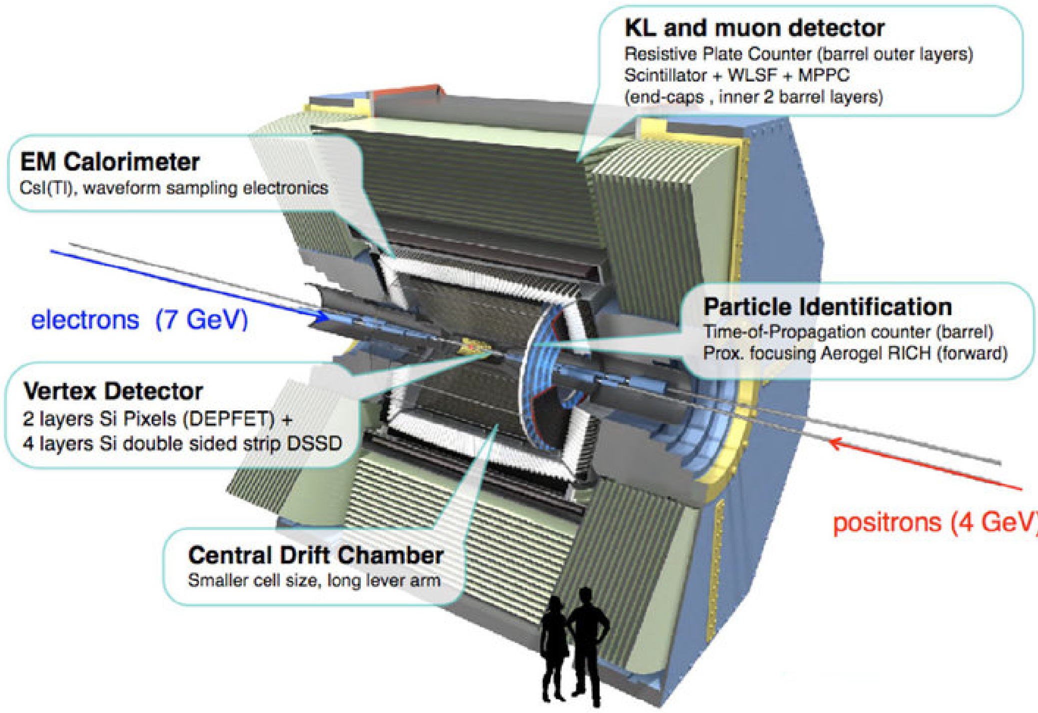


Figure 4: Overview of the Belle II detector

### 2.0.2 The Belle II analysis software framework

The Belle II Analysis Software Framework (basf2) is used in every step of the analysis. The framework consists of 41 packages that provide almost all software needs of the experiment, from interpretation of signals from the detector to high-level validation of the detector performance [5]. It is written primarily in C++ with a Python user interface.

Figure 5 gives a schematic overview of basf2 from the perspective of an analysis of simulated data. First, events of interest are generated. The response of the detector is then simulated and the detector information is reconstructed as though the true particle information were not available. Finally the information obtained from detector reconstruction, such as the momentum and mass of particles, is recorded and used for additional analysis.

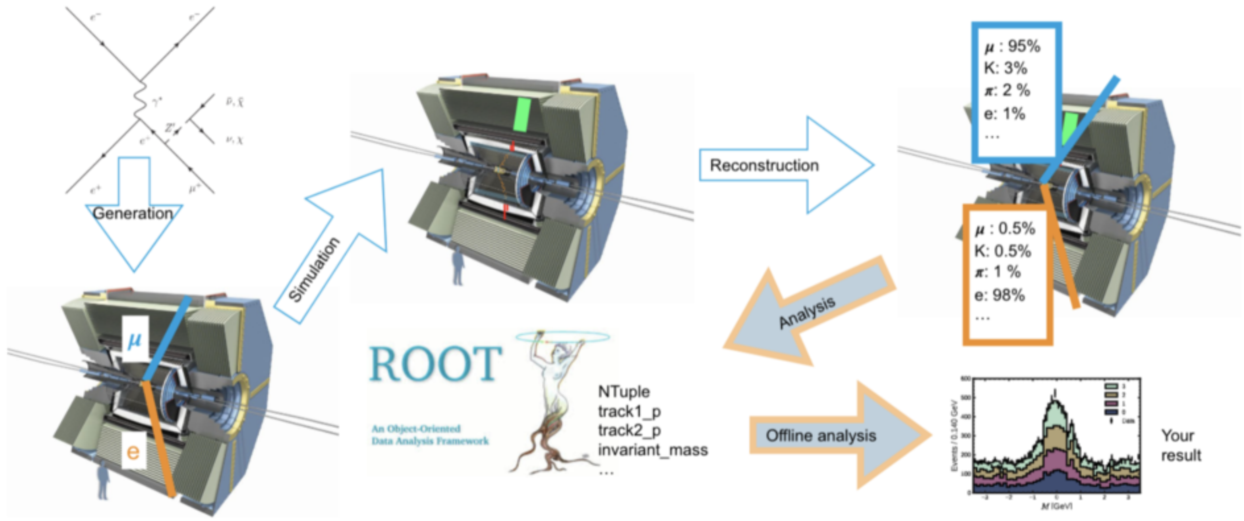


Figure 5: Overview of the BASF2 Framework

# 3 R(D) and R(D*)

The branching fraction (BF) for a decay is the relative number of particles that decay to a particular final state with respect to the total number of particle decays. For example, the BF for a $B$ meson decaying to a $D$ meson, a lepton, and an anti-neutrino is given by $\frac{N_{rec}^{(B\to Dl\nu)}}{\epsilon \times N(B)}$, where $N_{rec}^{(B\to Dl\nu)}$ is the total number of reconstructed events of this type, $\epsilon$ is the reconstruction efficiency, and $N(B)$ is the total number of $B$ decays in the dataset under study. Branching fractions can be predicted by theory, with or without new physics contributions. By comparing theoretical and experimentally measured branching fractions, it is possible to expose potential contributions from new physics.

The SM assumes that the couplings of particles that mediate the weak force to leptons are independent of lepton flavor. As a consequence of this assumption, the SM can be used to make a prediction for the value of $R(D^{(*)}) = \frac{B(B^- \to D^{(*)}\,\tau^-\,\overline{\nu}_\tau)}{B(B^- \to D^{(*)}\,l^-\,\overline{\nu}_l)}$, which is the ratio of the branching fraction for semileptonic $B$ decays that include a tauon to those that include an electron muon. However, measurements from experiments including BaBar, Belle, and LHCb have shown discrepancies between the theoretical and experimental results, currently at the level of $3.3\sigma$ for the combination of $R(D)$ and $R(D^*)$, as shown in Figure 6 [3]. The discrepancy is calculated as the difference in the measured and predicted values, divided by the combined uncertainty. By improving the experimental measurements of these quantities, this discrepancy can be further clarified. In particle physics, a discrepancy of $5\sigma$ is typically required in order to claim a "discovery". In this case, such a discovery would suggest the presence of new physics.

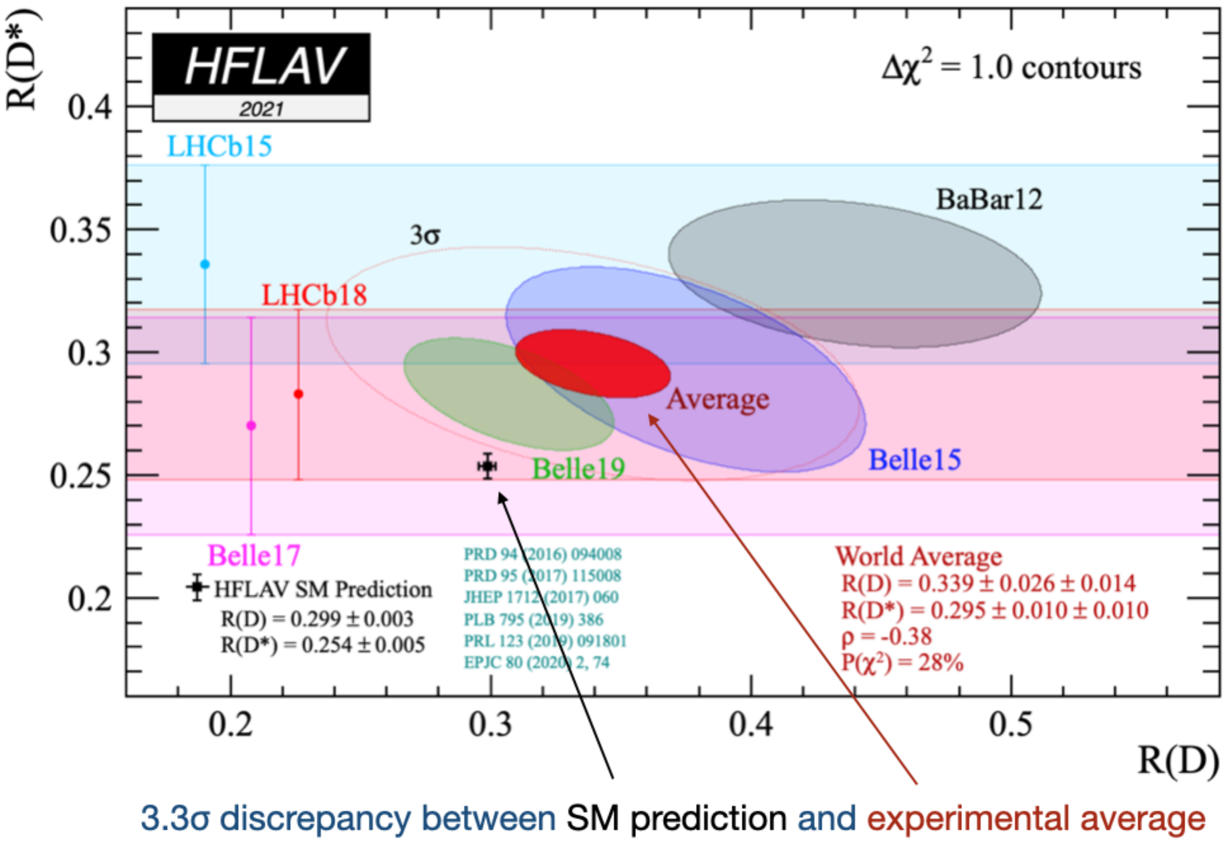


Figure 6: $R(D^*)$ and $R(D)$ measurements by different experiments

# 4 Study of $B^- \to D^0 \, \tau^- \, \overline{\nu}_\tau$

This study includes an investigation of simulated Belle II Monte Carlo (MC), with a goal of preparing the first steps of a measurement of R(D). Such a measurement requires the reconstruction of what is called the signal mode, $B^- \to D^0 \, \tau^- \, \overline{\nu}_\tau$ (Figure 7), and what is called the calibration mode, $B^- \to D^0 \, \mu^- \, \overline{\nu}_\mu$. In the signal mode, the $\tau$ decays into a $\mu$ and two additional neutrinos, in order to conserve lepton flavor. Therefore, both modes include a muon in the final state, but have a different number of final state neutrinos. Events of this type are generated, reconstructed, and analyzed with basf2.

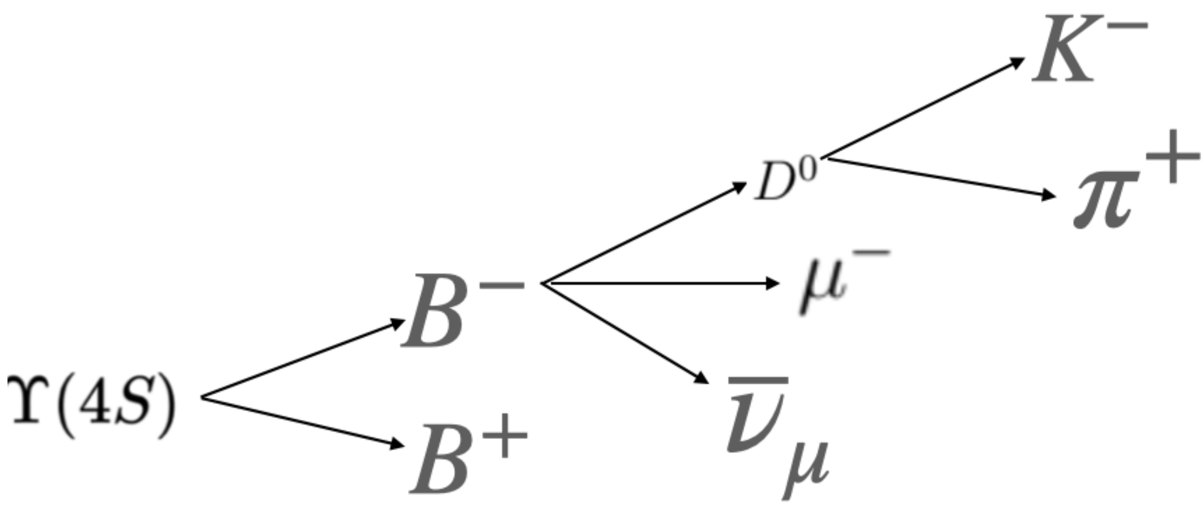


Figure 7: Schematic diagram calibration mode: $B^- \to D^0\,\tau^-\,\overline{\nu}_\tau$

## 4.1 Selection Criteria

It is not possible to perfectly identify events that come from the signal and control modes. Instead, reconstructed properties that are characteristic of the signal are used to select only events that are likely to be of interest and reject “background” events that come from other types of particle decays. Such backgrounds skew the results of the measurement. Therefore, it is important to study a series of different analysis variables to determine an effective set of selection criteria in order to reduce the background and isolate the signal events.

At the reconstruction level, tracks are required to have distance of closest approach to the IR within 2 cm in the direction transverse to the beam and within 0.5 cm in the longitudinal direction.

The $D$ meson is the only intermediate particle in the interaction of interest and most often decays into a kaon and a pion. To increase the likelihood that the final state particles, one kaon and pion, actually come from a $D$ meson decay, its invariant mass can be studied. As is evident from Figure 8, signal events lie in a peak near the expected mass of the $D$ meason (1.865 $GeV/c^2$). However, background events may or may not include a real $D$ meson decay. That is, a fake $D$ may be created from any two particle tracks, but a real $D$ that decays to a kaon and a pion may have been created from other interactions than the signal. Therefore, additional selection criteria are required to isolate the signal events for further analysis.

Muons and pions are often indistinguishable in the Belle II tracking system, since both create very similar ionization patterns. However, particle identification information from the KLM can effectively isolate a muon as discussed above. The muon identification (ID), which gives the probability that a charged track was created by a muon, can be used to select tracks with a high likelihood to have come from a muon and not another particle type (Figure 9). We require that the muon ID be greater than 0.9 to be certain of choosing the muons in alignment with our mode of interest.

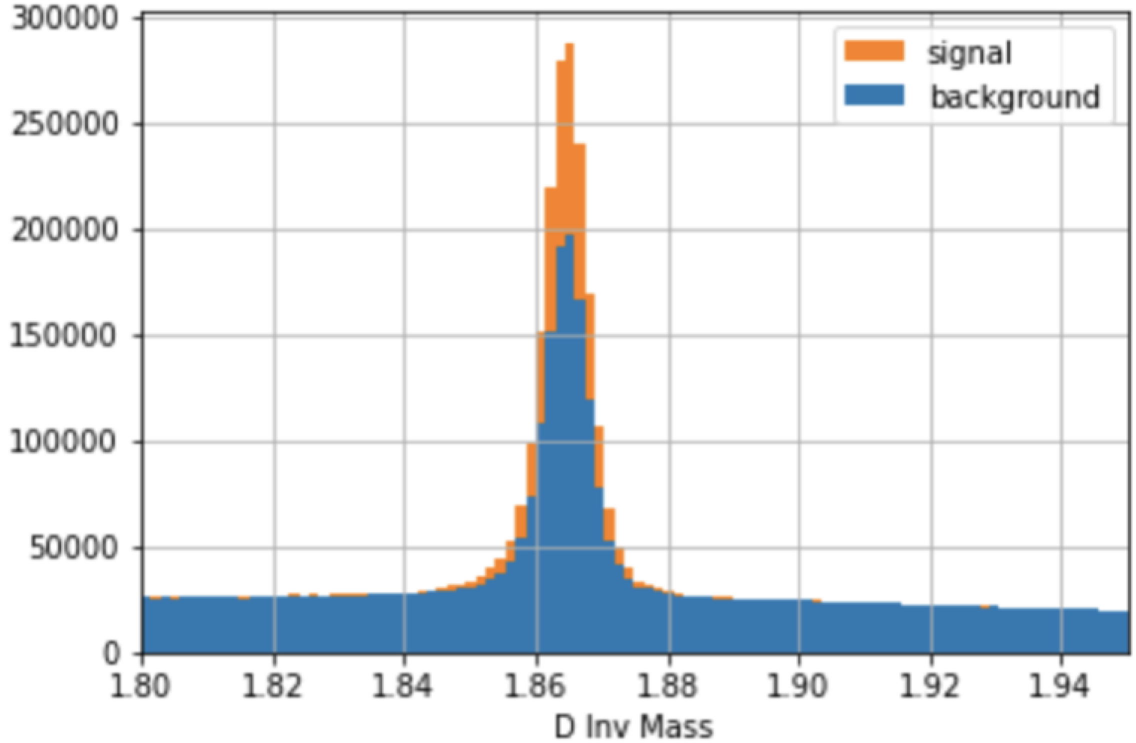


Figure 8: The $D$ meson candidate mass in units of GeV/$c^2$.

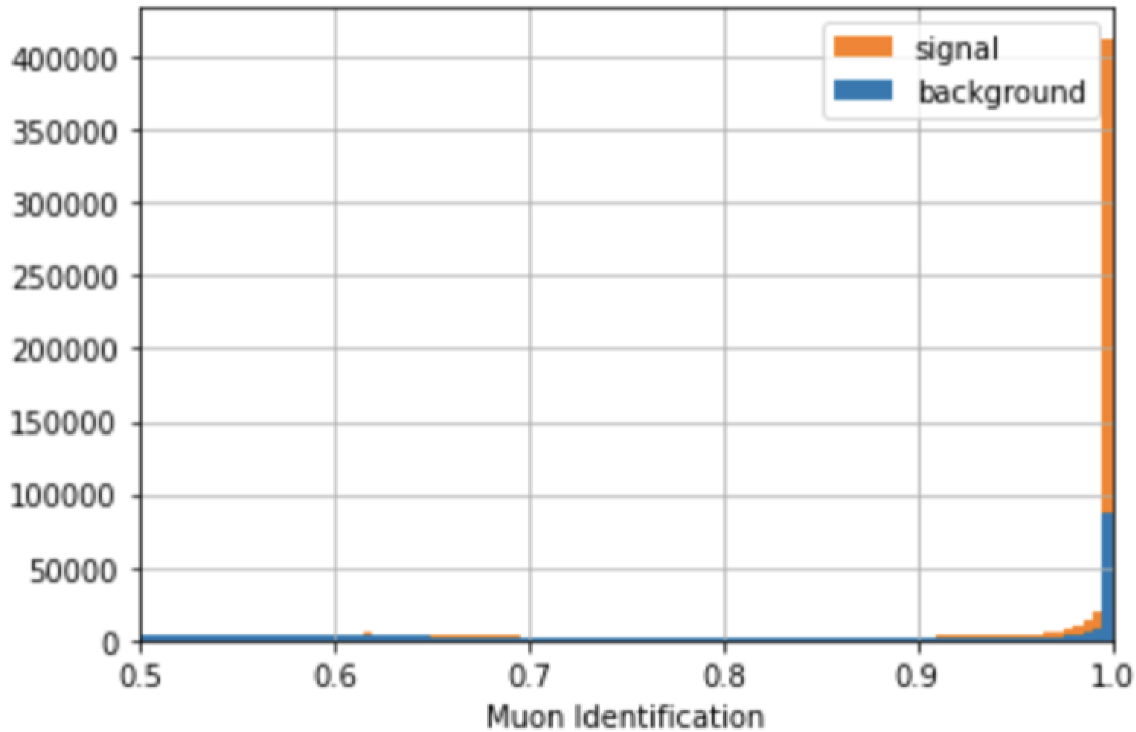


Figure 9: The muon ID for the sample under study.

Two powerful variables to distinguish signal and background in $B$ meson decays have to do with conservation of energy and momentum. For example, the energy of one $B$ meson, when produced as a $B$ meson pair, must be half of the total available energy. The beam constrained mass is therefore defined as, $M_{bc} = \sqrt{E_{beam}^2/c^4 - p_B^2/c^2}$, where $p_B$ is the three momentum of reconstructed $B$ meson candidate and $E_{beam}$ is half of the center-of-energy of the colliding electron-positron pair. Then the difference between the reconstructed and predicted energies, $\Delta E = E_{beam} - E_B$, provides another means by which to identify signal events. These distributions are shown in Figure 10. For this analysis, events are required to have $M_{bc} > 5.24$ and $\Delta E < 0.5$ to reduce backgrounds from events that do not come from $B\bar{B}$ decays.

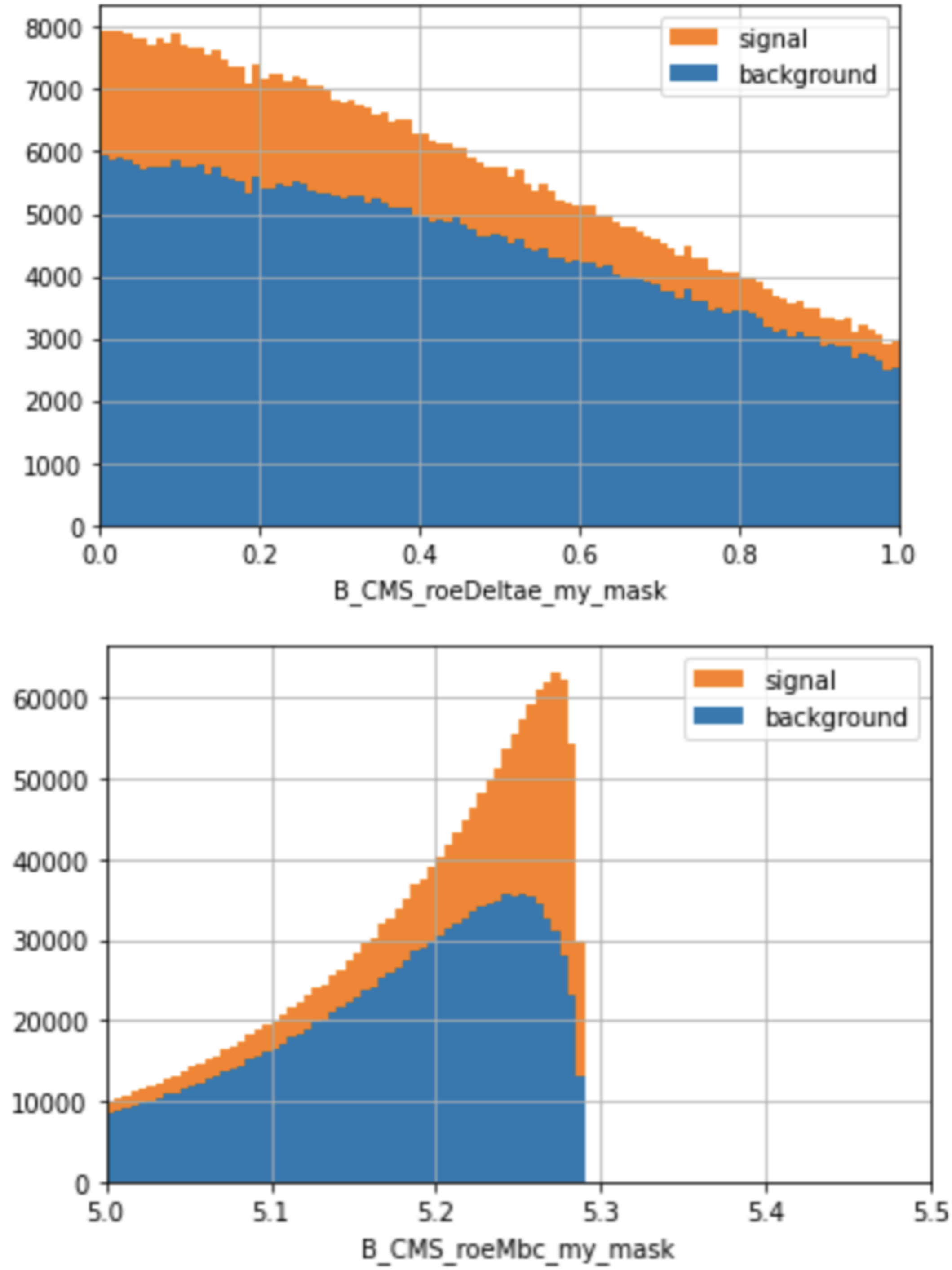


Figure 10: $M_{bc}$ (top) and $\Delta E$ (bottom) distributions in units of GeV/$c^2$.

## 4.2 Missing Mass Squared Technique

The biggest challenge for this measurement is to measure decays that include neutrinos, which do not interact with the detector and therefore cannot be measured at Belle II. The signal mode has three missing neutrinos, which complicates the measurement even further. To construct a distribution that can discriminate these events, a missing mass technique is used, wherein the quantity $MM^2 = P[B\overline{B} - (D^0 + l^-) - ROE]^2$ is determined. In the center of mass frame, the energy and momentum of the initial state is well known. Therefore the energy and momentum of the initial $\Upsilon$(4S) can be compared to that of the final state $D^0$ and lepton ($l^-$), along with the energy and momentum for all of the particles in the event, which are together referred to as the Rest of Event (ROE) particles. This can be visually represented in the schematic diagram in Figure 11.

Figure 12 shows the missing mass squared, $MM^2 = P[B\overline{B} - (D^0 + \mu^-) - ROE]^2$, which corresponds to the mass of the missing neutrino, for the calibration mode. As the neutrino has a very small (though non-zero) mass, the signal peak is close to zero, as expected.

Figure 13 shows the missing mass squared for the signal mode, which includes a $\tau$ decay. In this case, the missing mass squared represents the sum of three neutrinos. The signal peak is therefore not consistent with zero, since the momentum of the three neutrinos cannot be as precisely constrained. The top plot in the figure shows the missing mass squared before the selection criteria are applied and the bottom plot after they are applied. It is clear that the background has been significantly reduced.

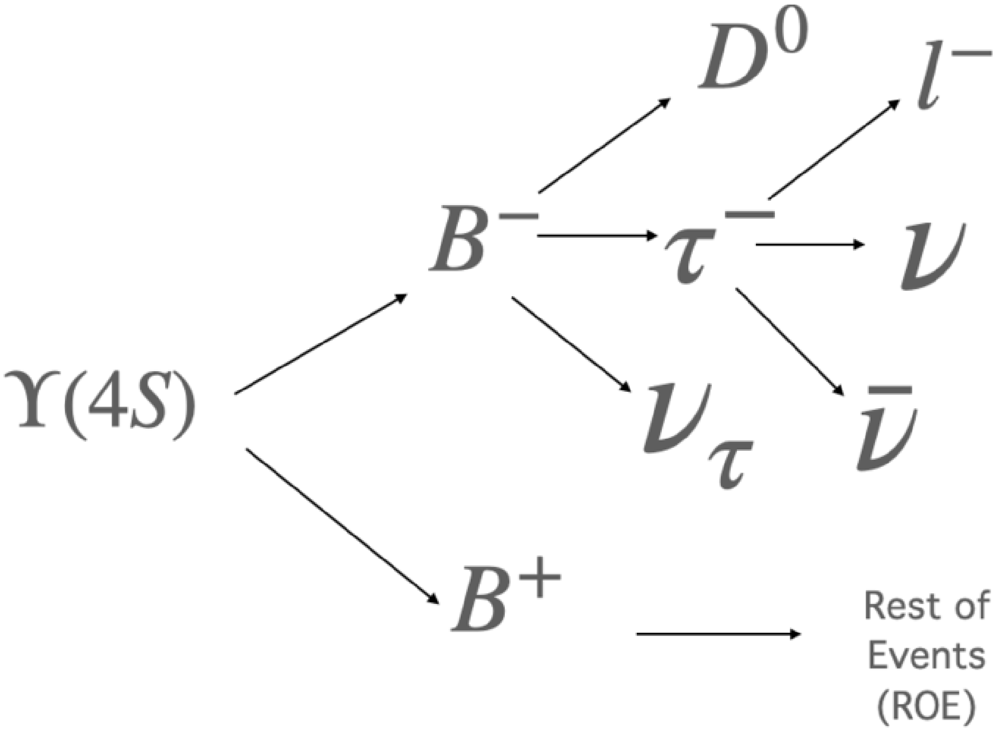


Figure 11: Schematic diagram of missing neutrions in $B^- \to D^0\,\tau^-\,\overline{\nu}_\tau$

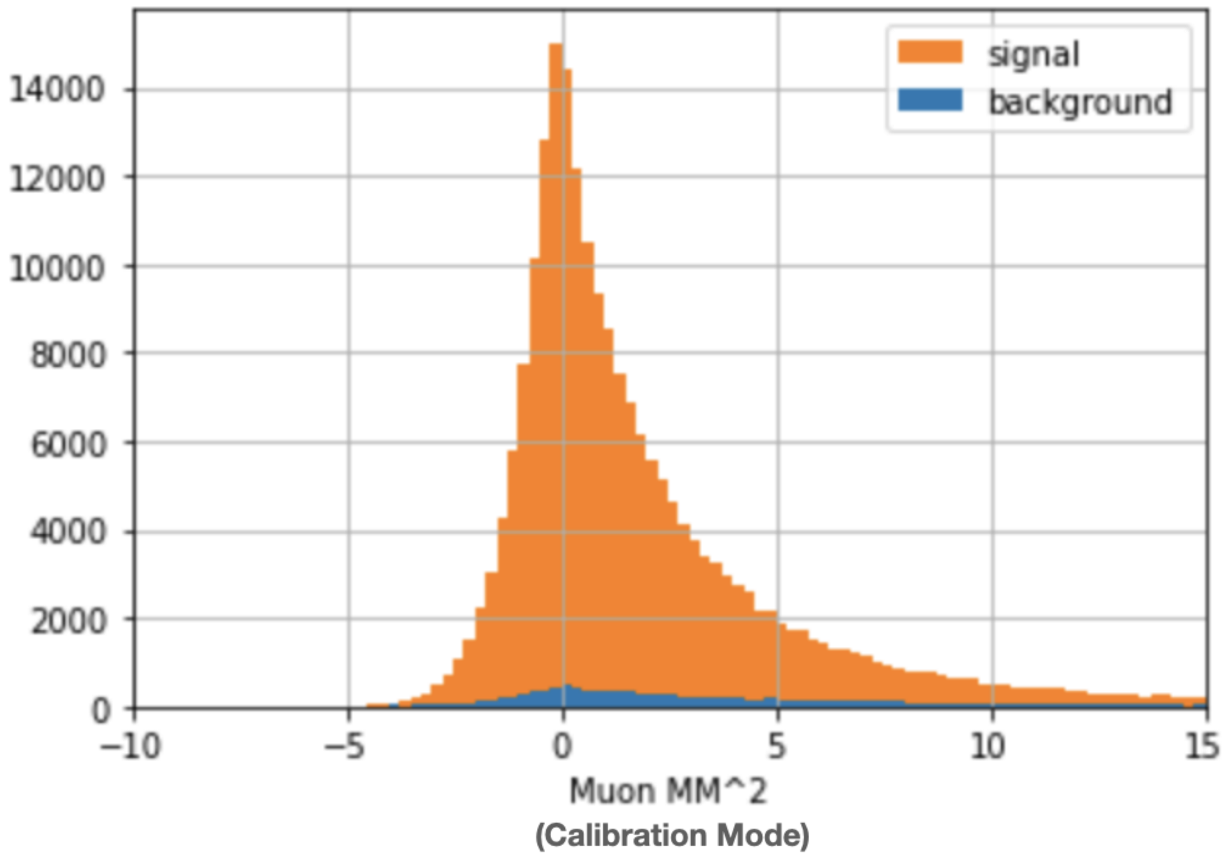


Figure 12: The missing mass (in units of $\mathrm{GeV}^2/c^4$) for the calibration mode, $B^- \to D^0\,\mu^-\,\overline{\nu}_\mu$.

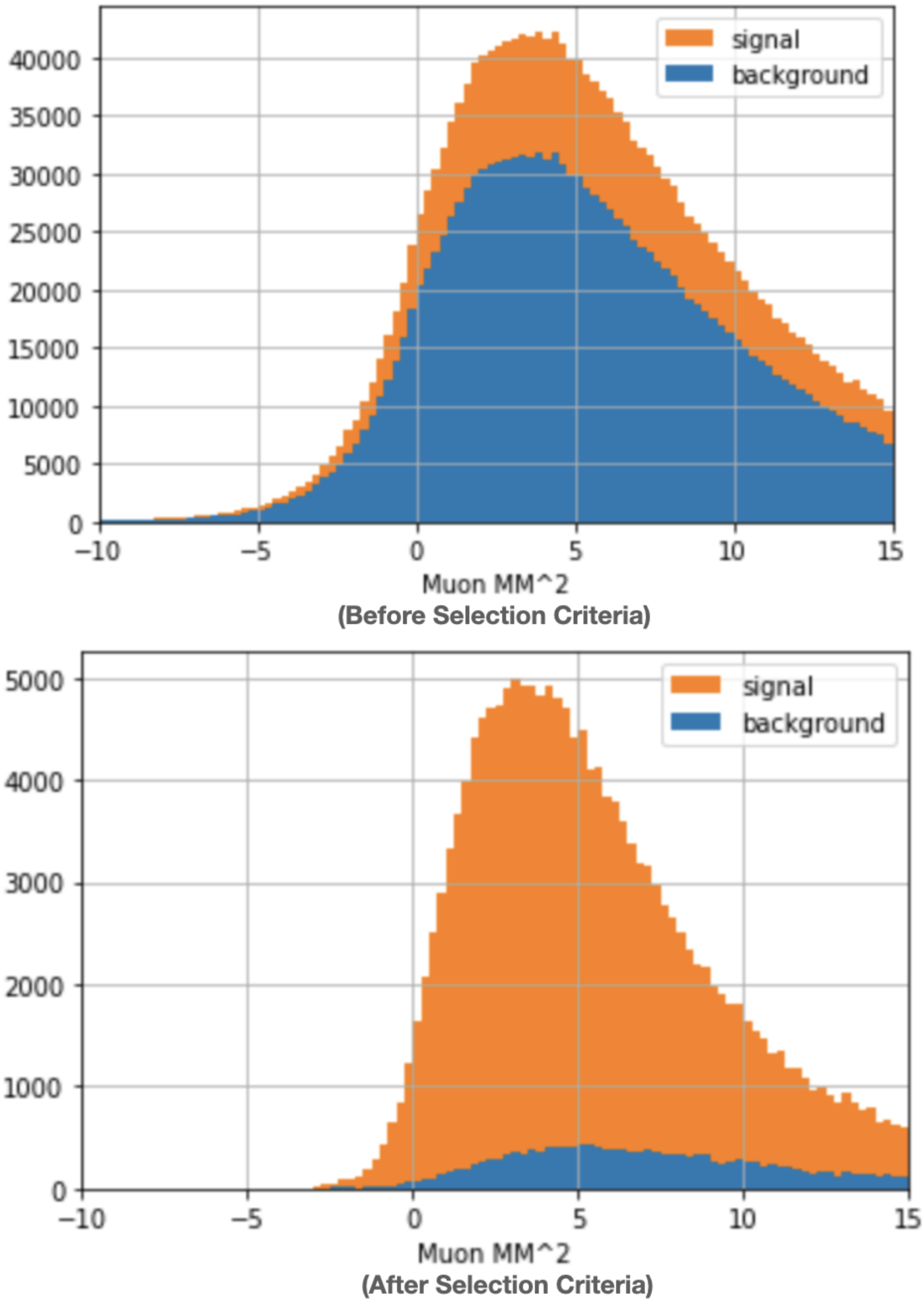


Figure 13: The missing mass (in units of $\mathrm{GeV}^2/c^4$) for the signal mode, $B^- \rightarrow D^0\,\tau^-\,\overline{\nu}_\tau$, before (top) and after (bottom) selection criteria are applied.

From the plots above, it can be seen that the peak location of the calibration mode ($B^- \rightarrow D^0\,\mu^-\,\overline{\nu}_\mu$) and that of the signal mode ($B^- \rightarrow D^0\,\tau^-\,\overline{\nu}_\tau$) are different. The peak of the calibration mode is at zero mass, where as that of the signal mode is further to the right of zero. This is due to the fact that the calibration mode has only one missing neutrino and our signal mode has three. This difference in the nature of the peak between the two modes was predicted by the theory and was consistent with the plots that we saw.

# 5 Conclusion

This research represents a study of simulated data from Belle II, working towards an analysis of real data. Decays of simulated $B$ mesons are used to investigate R(D), which is a useful quantity to test the SM prediction of Lepton Flavor Universality. With the precise knowledge of the initial state at Belle II, the missing mass squared of particles reconstructed in the detector can be used to isolate events with missing neutrinos. The next step in this analysis is to fit the missing mass distributions to determine the number of events in the signal and calibration modes and calculate the ratio, R(D). In addition, additional backgrounds must also be investigated, to ensure that a clean signal can be identified.

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