LEPTON FLAVOR VIOLATING DECAY AND
THE $\tau \to \mu\mu\mu$ SEARCH AT THE LHC

MATT JAFFE

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Reviewed and approved* by the following:

Tony J. Huang
Associate Professor of Engineering Science and Mechanics
Thesis Supervisor

Christine B. Masters
Associate Professor of Engineering Science and Mechanics
Honors Adviser

Judith A. Todd
P. B. Breneman Department Head Chair
Professor of Department of Engineering Science and Mechanics

* Signatures are on file in the Schreyer Honors College and Engineering Science and Mechanics Office.
ABSTRACT

The Large Hadron Collider (LHC) is the largest, highest-energy particle accelerator ever constructed. It accelerates two counter-circulating proton beams around a 27 km ring, currently colliding them at center-of-mass energy $\sqrt{s} = 8$ TeV\(^{[1]}\). Many searches for new physics and tests of the Standard Model (SM) of particle physics are being performed at the four detectors of the LHC. One of these detectors is the LHCb experiment, which seeks to catch glimpses of new physics through indirect means as a method of probing even higher energy scales. One candidate to yield such a glimpse is the observation of lepton flavor violating decays, such as the $\tau \rightarrow \mu\mu\mu$ decay. This thesis presents an analysis of the $\tau \rightarrow \mu\mu\mu$ decay; in particular, the effort to select the vanishingly rare candidate events from the overwhelming background.
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Chapter 1

CERN, the LHC, and LHCb

CERN is the world’s largest particle physics laboratory, located in Geneva, Switzerland. Its name is a French acronym for Conseil Europeén pour la Recherche Nucleaire (European Council for Nuclear Research). The lab was established in 1954 by 12 European countries and has grown to include 20 member states and 7 observer states\cite{2}. Thousands of scientists from around the world contribute to the work at CERN.

1.1 The LHC\cite{1}

The flagship of the facility is the Large Hadron Collider. This multi-billion dollar venture is a proton acceleration system. A hadron is a composite particle constructed of quarks bound together by the strong force, such as the proton. Using older accelerators, protons are accelerated up to several hundred GeV before injection into the LHC accelerators. Once injected into the LHC, the proton beams are accelerated up to 8 TeV center of mass energy. These accelerations are accomplished using magnetic fields. Superconducting niobium-titanium wires (cooled by liquid helium to below 1.9 K) carrying approximately 15kA of current steer the beam around the ring, and focus the beam at interaction points.

The LHC utilizes the 27 km circular tunnel 100m underground that was constructed for the LEP experiment at CERN that ran from 1989-2000. Despite the same geometrical size, this experiment operated at significantly lower energy (maxing out at 209 GeV) because it utilized electron-positron collisions rather than hadron (i.e. - proton) collisions. The low mass of the electron in comparison to the proton ($m_p/m_e = \sim 2000$) limits the energy that can be achieved before energy loss associated with accelerating a charged particle (Bremsstrahlung radiation,
which is proportional to $m^4$) is too great to overcome with the accelerator. A proton collider can thus reach significantly higher energies.

Plans for the machine were developed throughout the 1990s and construction finished in 2008. In September 2008, a magnetic quench (loss of superconductivity, leading to massive resistance heating) caused a violent mechanical failure involving a leak of over 6 tons of cooling liquid helium. However, once repaired by November 2009, the machine has been running and steadily taking data ever since.

The purpose of the LHC is to search for physics beyond the Standard Model (SM) of particle physics. This model is an exceedingly accurate and predictive model that has been wildly successful in explaining a huge range of phenomena. However, there ultimately must be something more. There are several outstanding problems with the standard model such as (but not limited to):

1) Gravity is over 40 orders of magnitude weaker than the other fundamental forces. There is no current explanation for this.

2) Parameters. The SM has 19 free parameters that have no underlying basis and require extreme (unnatural) fine tuning to address the hierarchy problem. This is troubling.

3) Finite mass of neutrinos\[^9\]. This has been experimentally observed, but the Standard Model does not allow for this.

4) Dark matter and dark energy remain unexplained phenomena.

5) The abundance of matter over antimatter in the universe.

It is hoped that the LHC will help address some of these issues with the Standard Model, as well as point theoretical efforts in the right direction with experimental evidence.
Proton collisions occur at four interaction points along the ring. Each interaction point is home to a detector and experiment designed to hunt for different signs of new physics. Two general purpose experiments are ATLAS (A Toroidal Lhc ApparatuS) and CMS (Compact Muon Solenoid). These are both massive experiments involving over 2000 and over 3500 scientists worldwide, respectively. They are “general purpose” in that they are built to perform brute force searched for new physics, and are very versatile in the types of events that can be studied.

A third experiment is ALICE (A Large Ion Collider Experiment). One month out of the year, the proton beam is replaced by a beam of lead ions, Pb^{82+}, in an attempt to study a state of matter termed quark-gluon plasma. This exotic matter was present in the very early universe at very high energies, and motivates this study. ALICE is designed for this purpose.

The final experiment is LHCb (LHC beauty), designed for precision measurements for indirect signs of new physics. The work for this thesis was performed for the LHCb collaboration, which will now be discussed further.

1.2 LHCb

As stated above, the LHCb experiment is designed to search for indirect signs of new physics using precision measurements. The “b” in its name stands for either “beauty” or “bottom”, both of which are terms used to name the b quark. Study of B physics (physics involving hadrons containing a b quark) is used to study CP violation.

CP violation is the breaking of CP symmetry. CP symmetry is the combination of C-symmetry and P-symmetry; Charge conjugation- and Parity- symmetry respectively. The combination into CP symmetry means that physics respecting this symmetry is identical in the case of charge conjugation (a particle is swapped with its antiparticle) and a parity flip (left and right are swapped). While CP symmetry is largely obeyed, this symmetry is broken in rare cases
as was first discovered in 1964\textsuperscript{(4)}. A study of CP violation hopes to shed light on fundamental physics as well as explain the predominance of matter over antimatter in our universe (the so-called “matter-antimatter asymmetry”).

A schematic of the LHCb detector is shown below in figure 1\textsuperscript{(5)}.

**Fig. 1.1 – Schematic of the LHCb Detector**

Particles collide in the beam pipe near the Vertex Locator (VELO). Heavy flavor physics, such as the B physics studied here, involves mainly forward particles, meaning that daughter particles fly from the interaction point with only a small angular deviation from the beam pipe. It is therefore not necessary to have an enclosed detector.

Tracking information is obtained through the VELO and tracking stations. The tracking stations are the TT and T1-T3 (silicon strip detectors), and the outer tracker (not shown, straw tube detectors). This system registers hits as the decay product relativistic particles move through them resulting in a chain of points that can be reconstructed into a track.
The powerful dipole magnet weighs over 1500 tons, and produces a magnetic field of over 2 T. This magnetic field causes deflection of charged particles, allowing for both identification of charge (positive, negative, or neutral) as well as momentum. Momentum can be determined from track curvature: a particle with high momentum has a smaller deflection and is referred to as “stiff” or “hard”, while a particle of lower momentum is “soft” and is curved more strongly. Analysis of the track curvature leads to a quantitative determination of particle momentum.

Particle identification (PID) is an important part of the data collection process. It is vital to know which types of particles are involved in a given decay. The first link in the PID chain is the RICH (Ring Imaging CHERenkov) detection system. Cherenkov radiation is a “sonic boom” of light that occurs when a rapidly moving particle passes through a medium at a speed higher than the speed of light in that medium. The shape of the resulting light cone can be used for PID.

Next in the chain are the ECAL and HCAL (Electromagnetic and Hadronic CALorimeters). These sections allow for precise measurements of the energies of electrons and photons, and hadrons, respectively. The ECAL is positioned such that the electromagnetic particles deposit their energy in showers inside of the device. This indicates that the energy shower registered by the ECAL was an electromagnetic particle. Hadrons survive a bit longer to decay in and lose their energy to the HCAL. The same principle applies, supplying more PID. Types of hadrons can be distinguished using other information such as momentum, and amount of energy deposited, and further daughter particles.

The muon detection system (M1-M5) is furthest downstream of the PID system. Muons fly through the detector without noticing material until they are far enough removed from the decay point. The muon detectors are located surrounding this critical point. Tracking hits in the
muon system are very nearly assured to be a muon, as any other particle is highly likely to have decayed long before the muon system. The additional track reconstruction provided by the muon system allows not only for muon identification, but also for more precise determination of momentum. This extra information is extremely useful, as muons are a critical component of many decay analyses, including the $\tau \rightarrow \mu \mu \mu$ of this thesis.
Chapter 2

The \( \tau \to \mu\mu\mu \) Decay

2.1 Lepton Flavor Violation

Leptons are particles that come in three flavors: electron, muon, and tau. The family of leptons consists of each of the particles for which the flavor is named, their corresponding neutrinos, and all of the corresponding antiparticles. With each of the three flavors is associated a corresponding flavor number. Any particle of a given flavor has +1 as that flavor number, and 0 for the other two flavors. An antiparticle of a given flavor has -1 as that flavor number. A representative table outlining this protocol is shown below:

<table>
<thead>
<tr>
<th></th>
<th>Electron #</th>
<th>Muon #</th>
<th>Tau #</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muon</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Electron Neutrino</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Anti-Tau</td>
<td>0</td>
<td>0</td>
<td>-1</td>
</tr>
</tbody>
</table>

In nearly all phenomena, lepton flavor is conserved. That is, in any decay, the mother and daughter particles have the same sum of all lepton numbers. An example of this is the most common decay path for a muon: \( \mu \to e^- \bar{\nu}_e \nu_\mu \). Here the muon decays to an electron, and anti-electron neutrino, and a muon neutrino. It is easy to see that tau number is conserved at zero. Muon number is conserved at +1 due to the muon and muon neutrino and the left and right hand side, respectively. Electron number is zero on both sides, as on the right the electron (+1) and anti-electron neutrino (-1) sum to zero.

There are, however, events both observed and predicted that violate lepton flavor conservation. These events are particularly rare and/or difficult to study. However, precise
measurements of lepton flavor violation (LFV) can lead to a better understanding of new physics beyond the Standard Model. The $\tau \to \mu\mu\mu$ decay is one such lepton flavor violating decay.

### 2.2 Motivation for Study

The $\tau \to \mu\mu\mu$ ("tau to three mu") decay violates conservation of lepton flavor in both the tau and muon sectors. Under the standard model, it is forbidden to occur directly and has a vanishingly small branching ratio\(^5\) (BR = $10^{-54}$). This means that one out of every $10^{54}$ $\tau$ particles that decays will decay in this way. In practice, this means that this decay will never be observed. This rarity is due to the weak and complicated coupling mechanisms required for the decay to occur, the details of which are shown in the figure below.

![Figure 2-1: Feynman Diagram of the SM $\tau \to \mu\mu\mu$ decay](image)

However, several new physics models predict much higher BRs for this decay, some approaching experimentally accessible ranges (BR = $10^{-9}$ to $10^{-10}$). The goal is that the LHCb detector will enable a search to significantly improve the current world best limit on this decay (BR < $2.1 \times 10^{-8}$ as set by the Belle experiment\(^6\)). This search will either: (a) lower the leading limit on the decay and thus test/place restrictions on extensions of the standard model or (b) find new physics.
The (a) scenario, although less exciting, is more likely and still very important. There are thousands of models extending the Standard Model that are ostensibly mathematically consistent, but provide no as yet testable results. A lowering of the branching ratio limit of this decay would rule out a significant class of extensions {including minimal supersymmetric extensions (MSSM)\cite{7} and Littlest Higgs Models\cite{8}}, thus clarifying the path to a Standard Model extension.
Chapter 3

The $\tau \rightarrow \mu\mu\mu$ Data Analysis Strategy

Any modern accelerator physics study necessitates a significant data analysis component. A simple presentation of statistics demonstrates this need. The LHC beams consist of bunches of protons separated by 25ns. This means that proton collisions, occurring in each detector during bunch crossings, occur $1 / 25\text{ns} = 40$ million times/sec. Add in the fact that each bunch crossing results in a handful of proton-proton collisions, and these events occur at a rate on the order of $10^8$ Hz. At about 1MB/event, this equates to nearly $1 \text{PB/s} = 6000$ iPods worth of storage/second. Clearly, this is infeasible.

The huge majority of these events are uninteresting, in that since they are so common, they have been extensively studied already. Current studies focus on rarer events. A huge effort is thus devoted to developing criteria for interesting events. In effect, different stages of data cuts develop a “fingerprint” of a decay (or class of decays) of varying resolution. The numbers that follow will are specific to the LHCb detector, which operates at much lower luminosity (i.e. – fewer events per second) than the heavy hitters ATLAS and CMS.

The raw events seen by the detector occur at $\sim 40$ MHz. As mentioned, the huge majority of these events are uninteresting. The first filter these events pass through are known as the trigger. In LHCb, the trigger system consists of a level 0 trigger (L0) and the high level trigger (HLT). The L0 reduces the 40 MHz to $\sim 1$ MHz, which the HLT then cuts down to 3 kHz. This process happens in real time, a tremendous achievement of hardware/software interplay. These real time cuts are known as “online analysis”. The events that are cut by the trigger are lost forever, and the remaining 3 kHz of events are saved to the LHCb data bank$^{[3]}$. 
From here, “offline analysis” of the data can be performed at the experimenter’s leisure, compared to the nanosecond timescale, at least. Procedures are in place that delete unused data after on the order of a year. When performing a very particular study of a single decay, such as $\tau \rightarrow \mu\mu\mu$, several stages of cuts are required.

### 3.1 The Signal

The difficulty in analyzing a decay like $\tau \rightarrow \mu\mu\mu$ is that we seek to quantify a phenomenon which we expect not to occur. We thus need a way to quantify “how much” we don’t see it. That is, not seeing the decay in $100\, \tau$ decays is less significant that not seeing the decay in $10^6\, \tau$ decays. In practice it is more complicated to keep track of than in this simple example, so we will outline our strategy here.

The first step is to analyze what the decay *would* look like in the detector. This is done using Monte Carlo simulations in which a $\tau$ mother particle is forced to decay into 3 muons as daughter particles. In a large simulation, this is run many times. We can then analyze the statistical distribution of detector outputs to establish a “fingerprint” of how this decay should present itself in our detector. The simulation allows us to understand the statistical distribution of kinematic variables measured by the detector. Examples of these variables include daughter muon momentum, quality of track fit, and vertex matching. Some of these kinematic distributions are shown in Figure 3-1 on the following page. The $\tau \rightarrow \mu\mu\mu$ (signal) Monte Carlo distributions are shown in blue. A special background distribution is shown in red. This will be discussed later. The names and physical meaning of the variables plotted here will also be much more thoroughly discussed later in this thesis.
**Figure 3-1**: Sample kinematic distributions of the signal Monte Carlo
3.2 Control and Normalization Channels

Once we have a solid understanding of the behavior of the $\tau \rightarrow \mu \mu$ signal, we in principle know what to look for in the detector. However, suppose the decay does not behave the way we expect it to. In this scenario, we could easily miss an abundance of $\tau \rightarrow \mu \mu$ decays. We need a way to verify that the behavior of our signal in simulation behaves the same way in actual experiment. Enter the concept of a control channel.

A control channel for a decay is a kinematically similar, but far more common decay that can be used as a proxy. The idea is to choose a well-known decay that is very similar to the signal. We chose to use two decays $D_s \rightarrow \pi \pi \pi$ (“$D_s$ to three pi”) and $D_s \rightarrow \phi (\mu \mu) \pi$ (“$D_s$ to phi pi”; the $\phi$ meson immediately decays to two muons). The mother in each of these decays is a $D_s$ particle, consisting of a charm and anti-strange quark (or conjugate). This choice is suitable for the following reasons:

1) The decays are kinematically similar, seen below in the kinematics plots of fig. 3-2.

![Figure 3-2: Signal Monte Carlo and control channel kinematics](image-url)
2) These decays have much higher branching ratios\(^5\), meaning that they are much more common:

i. \(\text{BR}(D_s \to \pi\pi\pi) = 1.10 \times 10^{-2}\)

ii. \(\text{BR}(D_s \to \varphi\pi) = 1.36 \times 10^{-5}\)

3) \(D_s\) is the majority source of \(\tau\) leptons\(^5\). A high, known percentage of \(\tau\)'s originate from \(D_s\) mothers (78\%). This very useful for the decays’ function as a normalization channel, which will be discussed shortly.

This brings us to the concept of a normalization channel. A normalization channel is used to normalize your results against to gain a quantitative handle on the signal branching ratio. Consider a perfect experiment in which we detect exactly one signal event in a large data sample. We can then calculate the branching ratio by:

\[
\text{BR}(\tau \to \mu\mu\mu) = \frac{N(\tau \to \mu\mu\mu)}{N(D_s \to \pi\pi\pi)} \times \frac{\text{BR}(D_s \to \pi\pi\pi)}{\text{BR}(D_s \to \tau X)} \times f(\tau \text{ from } D_s) \times \frac{\varepsilon(D_s \to \pi\pi\pi)}{\varepsilon(\tau \to \mu\mu\mu)}
\]

The notation here means the following:

i. \(\text{BR}(X \to Y)\): Branching ratio of \(X\) decaying to \(Y\)

ii. \(N(X \to Y)\): The number of \(X\) decaying to \(Y\) events we detected in our experiment

iii. \(f(\tau \text{ from } D_s)\): The percentage of \(\tau\) leptons that come from \(D_s\) mothers

iv. \(\varepsilon(X \to Y)\): Our efficiency in capturing \(X\) decaying to \(Y\) events.

v. \(D_s \to \tau X\): \(D_s\) decaying to \(\tau\) plus anything.

The same equation holds for using the \(D_s \to \varphi\pi\) channel. Having two channels thus provides a nice consistency check.

This formula makes sense by reasoning through it. We take the ratio of observed signal events to observed normalization events. We then scale this by the branching ratio of the normalization channel to get “number of observed signal events / number of \(D_s\) produced”. Dividing by the branching ratio of \(D_s \to \tau X\) converts this to “number of observed signal events * number of
\( \tau \) produced (assuming that all \( \tau \)'s present came from \( D_s \) mothers, and 100% efficiencies). We remove these assumptions by scaling by the known percentage of \( \tau \)'s from \( D_s \) mothers, and the ratio of relevant efficiencies.

Using this formula, we can obtain a quantitative analysis of the decay. If we see signal events, we can calculate a branching ratio. If we (as expected) observe no signal events, we can use statistical analysis to set an upper limit on the branching ratio to a certain confidence level.
Chapter 4

Making Cuts

In principle, we have laid out our method for performing the analysis. However, to this point we have entirely omitted the hard, messy, complicated work involved in actually selecting our signal and control events from among millions of background events. Indeed, the huge majority of work behind this thesis lay in drafting and optimizing these selection methods. We will discuss here how these tasks are performed.

In a perfect world, we could define an exact set of specifications that would be present in all signal events (100% efficiency) and absent in all background events (100% rejection rate). However, this is not possible for several reasons. Some (far from all) are:

1) Due to the enormity of the background, there are bound to be events that purely by chance mimic very closely the characteristics of a signal event.

2) Any information characteristic of a decay presents itself in a statistical distribution. For example, the daughter momentum of a particle is not pinned to a specific value for a $\tau \to \mu\mu\mu$ decay, but rather obeys a certain distribution law. This distribution carries an intrinsic spread, which overlaps with background fakes.

3) Finite limitations of the detector hardware.

To overcome these problems, we must sacrifice signal efficiency in order to ensure total background rejection. The end result of an analysis like this typically requires a signal efficiency of about 1% to attain the necessary background rejection. This comes from the requisite strict cuts that must unfortunately slice away some of the intrinsic spread of the signal variables’ spreads. However, there are several intermediate stages before this final result.
4.1 Methods

We employed a huge variety of tools in the quest to optimize our set of cuts. Some were already in existence, and some were created along the way. To perform our analysis, we used code written in ROOT (“the” language of high energy physics analysis), Python, and C++ to perform various tasks. This was all performed on the LHCb software framework. A few of the more general tools/methods will be outlined below.

N-1 Cuts

One way to visualize the utility of a single cut amongst a set is to make a so-called (n-1) plot. For each element of the set, a histogram is generated applying all the cuts except that element. We then can see if this cut helps, hurts, or has little to no effect on our cause. An example of an (n-1) canvas is seen below in figure 4.1.

![Figure 4-1: N-1 canvas for signal vs. background](image)

The red in each histogram indicates the proposed location of the cut in question. Note for example that the bottom left histogram shows an advantageous cut, while the bottom right
histogram shows a cut that seems to have already been applied to this data set. This technique is useful in drafting full sets of cuts for these reasons.

**Quantitative Efficiency: Simple Tools**

An example of the interplay of different coding languages can be seen in the following application. We used a script written in Python, referencing ROOT objects, and run through LHCb software. This particular script (“Simple Tools”) allowed us to get quantitative information about sets of cuts. An example of the output (which has been cleaned up visually from the text output) is seen below in figure 4.2.

<table>
<thead>
<tr>
<th>Table 4-1: Useful Simple Tools output</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cut</strong></td>
</tr>
<tr>
<td>Bilp &lt; 1.8</td>
</tr>
<tr>
<td>Vchi2 &lt; 6</td>
</tr>
<tr>
<td>Max(muPIDp)&lt;0</td>
</tr>
<tr>
<td>Max(muPIDp)&lt;5</td>
</tr>
<tr>
<td>Max(muTrkch2)&lt;1.4</td>
</tr>
<tr>
<td>Cos(angle) &gt;0.999975</td>
</tr>
<tr>
<td>Max(muTrack&lt;40000)</td>
</tr>
</tbody>
</table>

We can compare the efficiencies of each cut alone with the (N-1) efficiency of the cut. In this way, we can see for example see that the Max(muPIDp) cut is fairly useless and that the Cos(angle) cut is vital.

**Signal Blinding**

In the later stages of cuts, it is common practice to blind the signal region and try to eliminate all background outside. This prevents experimenter bias from choosing cuts that happen to create a peak where it is expected to be. The later stages are conducted “blinded” until a satisfying set of cuts has been drafted. The signal can then be unblended to see the effect of these cuts on the expected signal peak.
Bi-variate Optimization

Two cuts can often have drastic effects on each other if the variables in question represent physically correlated properties (e.g. – max(daughter momentum) and cos(angle)). We can use a 3D histogram to analyze the efficiencies of these cuts over a range of values for each. We can then choose the best pair of cuts.

These are only a handful of the instruments, often written on the fly, that were used throughout the course of this work. However, they present a representative sample of the methods and tools suited to this type of work. We now present a more in-depth look at the stages of cut drafting.

4.2 Stripping Cuts

Stripping refers to the first set of cuts we use in our analysis. It is the first stage in our offline analysis. The stripping objectives are to:

1) Maintain high signal efficiency for all three channels

2) Provide sufficient background rejection to reduce the data to an acceptable amount.

It is useful to keep the stripping cuts as similar as possible across all three channels. The more similar these cuts are, the more accurately the controls can serve as a proxy for the signal. We verify signal efficiency by testing on Monte Carlo simulations of all three channels.

It is also favorable to keep cuts loose at this stage, and tighten them later if necessary. The primary focus of the stripping is signal retention, with background rejection being pursued only to the necessary degree. Maintaining background is useful here because it allows for later study of events that closely mimic the true signal. LHCb stripping lines are required to pass \( \leq 0.05\% \) of events, so we seek stripping performance just under this threshold.
Developing a set of stripping cuts for the $\tau \to \mu \mu$ decay was the first objective of this thesis. This was accomplished by exploiting differences between the distributions of our desired channels (using signal Monte Carlo simulations) and the distributions of the background (either Monte Carlo or real data). As an example, Fig 4-1 shows distributions of these data in the $\chi^2$ value of the vertex fit of the three daughter particles. In this example, we can define a threshold value, and simply throw out any event with a vertex $\chi^2$ greater than this threshold. This is how a cut works. By capitalizing on distribution differences, we can achieve the stripping goals.

The final set of cuts developed is presented in Table 4.2. The efficiencies on the various channels are shown below in Table 4.3.

**Table 4.2** – Stripping cuts for each channel

<table>
<thead>
<tr>
<th>Cut</th>
<th>Tau23Mu</th>
<th>Ds23Pi</th>
<th>Ds2PhiPi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass Window (MeV)</td>
<td>400</td>
<td>250</td>
<td>80</td>
</tr>
<tr>
<td>Mother IPS &lt;</td>
<td>15</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>$Vchi2 &lt;$</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>$c^* \tau$ (um) &gt;</td>
<td>100</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>Daughter Pt (MeV) &gt;</td>
<td>300</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td>Daughter Track $X^2$/DoF &lt;</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Daughter IPS &gt;</td>
<td>9</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>TIS cut applied?</td>
<td>no</td>
<td>yes</td>
<td>no</td>
</tr>
</tbody>
</table>

**Table 4.3** – Stripping efficiencies for each channel

<table>
<thead>
<tr>
<th>Channel</th>
<th>Signal Efficiency</th>
<th>Background Rejection</th>
<th>Background Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tau23Mu</td>
<td>0.683</td>
<td>0.99960</td>
<td>0.00040</td>
</tr>
<tr>
<td>Ds23Pi</td>
<td>0.501</td>
<td>0.99790</td>
<td>0.00210</td>
</tr>
<tr>
<td>Ds2PhiPi</td>
<td>0.563</td>
<td>0.99956</td>
<td>0.00044</td>
</tr>
</tbody>
</table>

We will now present a brief description of the logic behind each of the stripping cuts.
i. **Mass Window** – We take a wide mass window to include background events for further study.

ii. **Mother IPS** – The Impact Parameter Significance is a measure of how far from the primary vertex the mother particle was created. This ensures that the mother particle originates from the primary vertex.

iii. **Vertex $\chi^2$** – This is a variable which measures the fit quality of the common vertex of the three daughter particles. Cutting on this variable thus helps to eliminate fakes in which 3 decay products did not actually come from the same mother.

iv. $c*\tau$ – This variable is the flight length of the mother particle (the speed of light, at which the particle is very nearly traveling, times the particles lifetime). The mother particles we are looking for have characteristic lifetimes, thus characteristic flight lengths. We cut on this variable in order to exclude more rapid decays.

v. **Daughter $P_t$** – $P_t$ is transverse momentum, or momentum in the plane perpendicular to the direction of the beam pipe. This cut eliminates a huge amount of background at only a modest cost to our signal. This makes sense because we expect random background to be more likely to have low $P_t$ decay products.

vi. **Daughter Track $\chi^2$** – This variable measures the fit quality of the reconstructed daughter track. If there is a very poor fit, it is more likely that the track reconstruction was inaccurate, and that the event is a fake.

vii. **Daughter IPS** – This cuts on the same variable as in the case of the mother. However, since the mother has a finite flight length, a true signal event would have a high IPS (particle originates a significant distance from the primary vertex). This cut helps ensure this quality is present.

viii. **TIS** – This cut is added to reduce the number of (comparatively) much more common $D_s \to \pi\pi\pi$ events. It requires that the event be Triggered Independent of Signal; that is,
something in the event other than the $D_s \rightarrow \pi\pi\pi$ decay passes the trigger. If there is a true $D_s$ event, other signs of charmed or strange physics will be present in the decay (as a $D_s$ consists of a charmed and strange quark-antiquark pair) which should also trigger.

We see that we obtain good signal efficiencies and sufficiently reject the background to the $0.05\%$ LHCb limit. The exception is the background rejection of the $D_s \rightarrow \pi\pi\pi$ channel. It passes ~4 times too many events. For now, we simply pre-scale this by 4 (i.e. – only take 1 out of every 4 events), but it is an aspect which certainly requires further study to optimize the stripping. Note also that we maintained high similarity in cuts across all three channels.

We were satisfied with the performance of these stripping cuts, and committed them to the LHCb software framework where they then began operation in real data collection.

### 4.3 Selection Cuts

Once having passed through the stripping lines, the next step is selection. These cuts are tighter, and designed to more fully extract the signal from the background. The goals of the selection are to:

1) Reject background extremely efficiently

2) Maintain as high signal efficiency as possible for all channels

We have currently only developed selection cuts for the control channels. The most recent version is presented in Table 4.4, along with the relevant efficiencies in Table 4.5.
Table 4.4 – Developed selection cuts for each control channel

<table>
<thead>
<tr>
<th>Cut</th>
<th>Ds23Pi</th>
<th>Ds2PhiPi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass Window (MeV)</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Mother IPS</td>
<td>1.8</td>
<td>1.8</td>
</tr>
<tr>
<td>Vchi2</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>DLL (K - π)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>DLL (p - π)</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Daughter Track $\chi^2$/DoF&lt;</td>
<td>1.4</td>
<td>1.4</td>
</tr>
<tr>
<td>Cos (angle)</td>
<td>0.999875</td>
<td>0.999875</td>
</tr>
<tr>
<td>Daughter $P_{tot}$</td>
<td>40,000</td>
<td>40,000</td>
</tr>
</tbody>
</table>

Table 4.5 – Selection efficiencies for each channel (relative to stripping)

<table>
<thead>
<tr>
<th>Channel</th>
<th>Signal Efficiency</th>
<th>Background Rejection</th>
<th>Background Rejection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ds23Pi</td>
<td>0.177</td>
<td>0.999538</td>
<td>0.000462</td>
</tr>
<tr>
<td>Ds2PhiPi</td>
<td>0.190</td>
<td>0.999538</td>
<td>0.000462</td>
</tr>
</tbody>
</table>

Again, we present a brief discussion of the physical reasoning behind each cut. As a preface, we note that the cuts are generally tighter because we are more willing at this stage than in the stripping to sacrifice signal efficiency to maximize background rejection.

i. **Mass Window** – We now narrow the mass window to about 3σ to include mostly signal

ii. **Mother IPS** – Simply a more stringent restraint on the same idea as in the stripping description.

iii. **Mother Vertex $\chi^2$** – Same type of tightening.

iv. **DLL (K - π)** – Selects pions as daughters by cutting on the Delta Log Likelihood of the daughters being pions against kaons.

v. **DLL (p - π)** – Same as above, but against protons

vi. **Daughter Track $\chi^2$** – Another tightening

vii. **Cos (angle)** – Ensures that the reconstructed τ track points in very close to the same direction as the line between the primary vertex and the τ decay vertex. This helps rule out intermediate decays and partially reconstructed tracks.
viii. *Daughter* $P_{tot}$ – Capitalizes on a significant difference in distributions of total momentum $\sqrt{p_T^2 + \vec{p}_T^2}$ between background and control channel Monte Carlo simulations.

While we did make significant progress on the selection cuts, this job is still far from completion. This will be discussed further in the future work section.
Chapter 5

Summary of Results

While the final efficiencies of these cuts are presented above, it should be noted that this is far from a complete history of the development. Information concerning individual cut efficiencies and the time evolution of our cuts has been omitted here for simplicity.

A visual summary of this body of work is presented below in Figures 5-1 and 5-2. The histograms shown were obtained by passing LHCb data through our committed stripping lines and most current selection cuts. First is a histogram showing a $D_s$ mass peak extracted from among $>26M$ background events. The clear peak of the histogram at the mass of the $D_s$ shows that our cuts have indeed selected decay events with $D_s$ mothers. It contains a sum fit of a linear fit to the background and a Gaussian fit to the $D_s$ peak. Although work remains to be done, this peak demonstrates our cuts’ capability to reconstruct a clean signal in our control channels.

Figure 5.2 shows the splitting of this mass peak into the two control channels ($\beta$), and compares them to peaks obtained from simulated data (no background). Note here that the spread of the peak is not due to limited detector resolution, etc. The $D_s$ is such a short lived particle (lifetime on the order of $10^{-13}$ s) that the Heisenberg uncertainty relation between energy and time comes into play\textsuperscript{[5]}. This fundamental fuzziness in energy (mass) presents itself with a finite, intrinsic spread of the $D_s$ mass peak. These figures can be seen on the following page.
Figure 5-1: Extracted $D_s$ mass

![Graph showing extracted $D_s$ mass](image)

Figure 5-2: $D_s$ channel splitting

![Graphs showing $D_s$ channel splitting](images)
To summarize, we have:

1) Developed, characterized and committed a set of stripping lines for the $\tau \to \mu\mu$ decay and its control channels $D_s \to \pi\pi\pi$ and $D_s \to \varphi(\mu\mu)\pi$.

2) Begun the development of selection cuts for our three channels.

The details of the composition and efficiencies of these cuts have been outlined in the thesis above. However, it is very clear that this analysis is not complete, and we will now discuss some steps that must be performed to carry this analysis to completion.
Chapter 6

Future Work

Many tasks remain in order to finish this measurement. We will list a few of them in order to convey a sense of what lies in the future for this analysis.

a) Re-optimize the stripping lines in the $D_s \to \pi\pi\pi$ channel to eliminate the need for pre-scaling (while maintaining as much similarity as possible between channels).

b) Introduce PID cuts to the control channels to split the $D_s$ mass peak into the two distinct decays.

c) Analyze selection cuts on the $\tau \to \mu\mu\mu$ signal Monte Carlo. We imagine using an earlier, looser version of the $D_s$ cuts as a starting point then optimizing to the $\tau \to \mu\mu\mu$ channel.

d) Once finalized, a rigorous documentation and statistical analysis of cut effects must be performed at all stages (i.e. – stripping and selection for all three channels). This will make possible calculation of a branching ratio/upper limit.

e) Look at a lot of real data.

The unmatched luminosity of the LHC presents an opportunity to set the world-best limit on the $\tau \to \mu\mu\mu$ decay, lowering the upper limit on the branching ratio. This would allow for exclusion of several classes of models for physics beyond the Standard Model. Once the support behind this analysis is completed, all that is needed is for the LHC to continue running, gather more data, and keep pushing that limit down.
References


[4]: *Violation of CP Invariance and the Possibility of Very Weak Interactions*, L Wolfenstein (1964), Physical Review Letters 13 p. 562


[10]: *Flavour Physics and CP Violation*, Robert Fleischer (2006), Constraints (May) p. 82
Academic Vita

EDUCATION

The Pennsylvania State University, Schreyer Honors College, Class of 2012
Intended Triple Major in
Physics  Mathematics  Engineering Science
Minor: Nanotechnology

RESEARCH AND WORK EXPERIENCE

Penn State Physics Department – Undergraduate Research Assistant  2011 - present
Primary Investigator: Dr. Martin Bojowald
Study nonlinear discrete difference equations arising from loop quantum cosmology to describe cosmological inhomogeneity. Find and analyze solutions of these equations (including the special case of soliton solutions) to see what cosmological implications arise.

European Center for Nuclear Research (CERN) - Summer Student  2011
Supervisor: Dr. Johannes Albrecht
REU through University of Michigan (headed by Dr. Homer Neal) and CERN Summer Student Program. Studied lepton flavor violating decay $\tau \rightarrow \mu \mu \mu$ for LHCb collaboration. Developed stripping and selection cuts for signal and normalization channels.

Penn State Physics Department – Undergraduate Research Assistant  2010
Primary Investigator: Dr. Jun Zhu
Developed and characterized graphene transfer techniques for use in field effect biosensing devices. Grew graphene via CVD, transferred onto $\text{Si}/\text{SiO}_2$ and used optical lithography to pattern devices. Tested and characterized graphene and device quality.

Turbo Research, Inc./TRI Transmission and Bearing) - Summer Intern  2009
Lionville PA, http://www.turboresearch.com/
Supervisors: Andy Follett, Dr. Mel Giberson
Manufactured high precision, heavy duty bearings for use in power plants. Used metal machining equipment to fabricate parts. Implemented a full ISO 9001:2008 Quality Management System (including ~300 pages of rigorous, expansive documentation).

LAB/COMPUTER SKILLS

Proficient in Mathematica, ROOT, C++ and Python
Experience using AFM, photolithography equipment, metal machining tools, Raman spectroscopy, electrical probe station, and standard lab bench

REFERENCE LIST

Dr. Homer Neal
Samuel A. Goudsmit Professor of Physics;
Director, ATLAS project at University of Michigan
haneal@umich.edu

Dr. Martin Bojowald
Associate Professor of Physics, Penn State University
bojowald @ gravity.psu.edu

Dr. Johannes Albrecht
CERN Research Fellow
johannes.albrecht@cern.ch

Dr. Jun Zhu
Assistant Professor of Physics, Penn State University
jzhu @ phys.psu.edu
AWARDS

- Department of Engineering Science and Mechanics Student Marshall 2012
- Department of Physics Student Marshall 2012
- Euler Memorial Scholarship (PSU Math Dept.) 2012
- Marin Joseph Memorial Scholarship 2011-2012
- William J and Lois Kesterton Leight Memorial Scholarship 2011-2012
- Morrow Endowed Scholarship 2008-2012
- Pentz Memorial Academic Excellence Scholarship (SHC) 2008-2012
- President’s Senior Award 2011
- Vivek Robert & Myrtle Scholarship 2010-2011
- Teas Research Assistant Scholarship 2010
- President’s Freshman Award 2008

EXTRACURRICULAR

- Penn State Mens Club Ultimate Frisbee 2008 - present
  - Captain (2011-2012)
  - 2011 - 2nd Place Ohio Valley Region finish
  - Our team is a club sport dedicated to competing at the highest level. We train hard year round, and compete against other colleges near and far throughout the spring season.

- Springfield THON 2009 - present
  - THON is the largest student-run philanthropy organization in the world. It is run at Penn State and benefits the Four Diamonds Fund at the Hershey Medical Center, which pays for pediatric cancer treatment and research. THON 2012 raised over $10.6 million. The fundraising year culminates in a 46 hour no-sleeping, no-sitting dance marathon.
  - Springfield is an independent organization that raises money for THON. Our organization raised over $170,000 for THON 2012. I had the honor and privilege of dancing for Springfield in THON 2012.