Thesis Title

A DISSERTATION
SUBMITTED TO THE FACULTY OF THE GRADUATE SCHOOL
OF THE UNIVERSITY OF MINNESOTA
BY

Andy Jarod Julin

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

Prof. Ron Poling

March, 2017

Acknowledgements

This is where the Acknowledgements go!

Dedication

This is where the Dedications go!

Abstract

This is where the Abstract goes!

Contents

List of Tables

List of Figures

Chapter 1

Introduction

Chapter 2

Theoretical Background

2.1 Standard Model

Developed throughout the 1960s and 1970s, the Standard Model provides the most complete description of observable matter in the universe to date. It is a classification of all confirmed subatomic particles currently known, and predicts the most accurate results of any scientific theory ever measured. Each of the electromagnetic, weak, and strong fundamental forces are well described by this formulation. These three are described by an $SU(3) \times SU(2) \times U(1)$ group, where the $SU(3)$ corresponds to the strong force, the $SU(2)$ corresponds to the weak force, and the $U(1)$ corresponds to the electromagnetic force. The remaining fundamental force, gravity, is negligible on the scale of the masses of fundamental particles, and will be ignored in the discussions that follow.

2.1.1 Electromagnetic Force

The electromagnetic force is responsible for attracting and repelling objects, most notably binding together electrons and protons to form atomic structures. The most prominent theory of electromagnetic interactions is known as Quantum Electrodynamics (QED). The mediator of this force is the photon, a massless vector boson. As there is only a single mediator, and a single conserved quantity (electric charge), the formulation of QED is relatively simple compared to the other forces. Still, the predictions it makes show astounding consistency with experiment, such as correctly calculating the anomalous magnetic dipole moment of the electron to more than 10 significant figures.

Much of this success is due to QED being expandable through perturbation theory, where corrections are applied in terms of higher order factors of the coupling constant, α. This is possible due to a relatively small coupling constant ($\alpha \approx 1/137$), as higher order terms are convergent.

2.1.2 Weak Force

The weak force is responsible for the decays of various particles into other forms. This is distinct from the electromagnetic and strong interactions, where the constituent particles cannot change their types (or flavors). The mediators of this force are the W and Z, which are massive vector bosons. Not only are each of these masses non-zero, they are considerably heavy particles at 80.4 GeV and 90.2 GeV, respectively. These large masses not only inhibit the interaction distance of the weak force, but also minimize the interaction strength (which is inversely proportion to mass). Furthermore, this mass excess also leads to much slower interaction times, further reducing the effects of the weak force in comparison to the strong and electromagnetic forces.

In addition to transforming particle flavor, the weak force is also unique in its violation of various symmetries. The first discovery of symmetry violation came in 1957, when Wu and others discovered the weak force did not behave identically under parity (P) transformations (i.e., mirror reflection). To account for this, a new theory conserving a compound symmetry was proposed. This combined charge conjugation (C), the swapping of particles with their antiparticles, with parity to form CP parity. However, in 1964, evidence of CP violation was also discovered by Cronin and Fitch. The resolution to this symmetry conservation involves yet a third symmetry, time reversal (T), in which time is replaced with its negative ($t \to -t$). While the weak force violates these symmetries individually, the application of all three (CPT) is conserved across all known processes.

At higher energy scales, the electromagnetic and weak forces unify into the electroweak force. In this theory, there are initially four massless gauge bosons mediating the interactions. Due to the Higgs mechanism, the initial gauge symmetry is broken at lower energies, and three of these bosons acquire a mass. These three bosons are the $W^{\pm}$ and Z, while the remaining massless boson is the γ. The energies scales required for this unification were only present in the early universe. Before this, it is also believed there was an epoch of even higher energy, in which the electroweak force merged with the strong force.

2.1.3 Strong Force

The strong force is responsible for binding together particles known as hadrons. The most prominent theory of strong interactions is known as Quantum Chromodynamics (QCD). Like the electromagnetic force, the mediator of the strong force is also a massless vector boson, the gluon. However, while massless particles typically correspond to an infinite interaction range, the strong potential becomes very large at higher separations. This prevents particles which interact through the strong force from existing as isolated entities, and is known as confinement. The typical interaction range is on the order of the proton radius, around 10^{-15} m. QCD provides additional challenges, however, as the coupling constant is not small ($\alpha_S \gtrsim 1$). This excludes the use of perturbation theory for most cases, as the higher order terms do not converge.

Strong interactions are associated with a corresponding conserved quantity known as color charge. There are three colors associated with this charge, red (r), green (g), and blue (b). For anti-particles, there are oppositely charged values ($\bar{r}, \bar{g}$, and $\bar{b}$). In order for hadrons to be formed, the total color values of the constituents must be colorless. This means the total sum must involve all three colors (rgb or $\bar{r}\bar{g}\bar{b}$) or pairs of opposite colors ($r\bar{r}, g\bar{g}$, or $b\bar{b}$). However, these individual colors are not observable in nature. This effectively triples the number of possible particle combinations, due to combinatorics.

Unlike the photon, which is neutral to the electromagnetic force, the gluon also carries color charge. There are eight possible color combinations which a gluon may possess, which are typically expressed using the Gell-Mann representation of $SU(3)$. With this basis, each gluon is linearly independent, and no combination of gluons can be used to form a color singlet state. This inclusion of color by the force carrier makes QCD significantly more complex than QED. In fact, carrying color charge means gluons can also interact with each other directly, leading to certain theoretical states such as glueballs.

2.1.4 Elementary Particles

There are two primary groups contained in the Standard Model, fermions and boson. This division is based off the Spin Statistics theorem, where fermions have half-integer spins, and bosons have integer values. Because of these values, the Pauli Exclusion principle restricts fermions from occupying the same spatial state, and thus there are restrictions on their spatial density. Bosons, however, do not have this restriction, and can have any number occupying the same space. Thus, fermions are typically more tangible matter (such as electrons), while bosons typically represent the forces interacting between them (such as photons).

Fermions

The fermions are divided by their interaction types into two major groups, quarks (q) and leptons (l). Each of these groups contains six particles with their corresponding antiparticle. These can also be categorized into three generations, which aligns particles with the same electric charges, but greatly differing masses. For example, the up (u), charm (c), and top (t) quarks all have an electric charge of $+2/3$, but t is approximately five orders of magnitude more massive than u. In **??**, the rows indicate particles with the same electric charge, while the columns represent each generation of particles.

Although all fermions interact both electromagnetically and weakly, only the quarks interact strongly. Because of confinement, quarks cannot exist as isolated particles, and are only found in nature as groups of particles called hadrons. The most common types of hadrons exist as quark-antiquark pairs, known as mesons, or as groups of three quarks (or antiquarks), known as baryons. There are, however, indications of more exotic combinations of quarks, such as tetra- ($qq\bar{q}\bar{q}$) or penta-quark ($qqqq\bar{q}$) states seen by recent experiments.

While the negatively charged quarks (d, s, and b) are labeled as definite states, each of the quarks are actually mixed states. Through weak interactions, each of these quarks can transform into other states. The probabilities for these transformations are given by the Cabibbo-Kobayashi-Maskawa (CKM) Matrix, shown in Fig. **??**. Note that while the convention splits the negatively charged quarks into mixed states (leaving the positively charged quarks fixed), this choice has no physical basis. The reverse choice of having mixed positively charged quarks is also valid.

The leptons are also divided into two major distinctions based on their charge. The electron (e^-), muon (μ^-), and tau (τ^-) are all negatively charged particles. With the exception of mass, the interaction properties of each flavor is very similar. However, the three flavors themselves are treated as separate conserved quantities. There is also a neutral particle, a neutrino (ν), corresponding to each one (ν_e, ν_μ, ν_τ). These are very small mass ($< 1\,\mathrm{eV}$) particles with extremely low interactions.

The original formulation of the Standard Model assumed these neutrinos to be massless particles. However, this was violated by the discovery of neutrino oscillations, where transformations occur between neutrino flavor states due to differences in their masses. Additionally, the flavor states, ν_e, ν_μ, and ν_τ, are not the states observed in nature. Rather, the states with definite mass, labeled ν_1, ν_2, and ν_3, are linear combinations of the three flavor states. This can be expressed in a rotation of bases analogous to the CKM Matrix for quarks.

Bosons

For each of the three forces included in the Standard Model, there are accompanying gauge bosons. These include the photon (γ) for electromagnetic force, the W and Z for the weak force, and the gluon (g) for the strong force. Each of the gauge bosons are a spin-1 vector boson, which means there are three available polarization states (-1, 0, +1). However, since the photon and gluon are both massive, gauge invariance requires these to have transverse polarizations. This means the spin-0 state is eliminated, and there are only two polarization states for each. There is also the Higgs boson (H), which unifies the electromagnetic and weak forces, and whose interactions with other particles is responsible for their mass. This is the only known fundamental spin-0 particle, which means it has only one polarization state.

Even with the amazing success of the Standard Model, the theory is not complete. Along with neutrino oscillations, other effects, such as dark matter or dark energy, remain major hindrances in constructing a unified theory. Such a theory must also include gravity, but there remain significant difficulties in explaining its effects through a quantum field theory. There also remains no conclusive explanation for various constants, such as the masses of each fundamental particle. Still, the Standard Model remains the most precise description of the universe to date, and continues to provide the basis for future experimental and theoretical work.

2.2 Charmonium

The majority of this analysis focuses on a specific group of particles known as Charmonium. These particles are resonances formed by a $c\bar{c}$ pair, and can be treated analogous to the hydrogen atom. Namely, there is a spectrum of various excited states in the Charmonium region, just as with the emission lines of hydrogen. The three states which are focused on include the $J/\psi, \psi'$, and ψ''. The ' and " marks indicate these are the first and second excited states of the J/ψ, respectively. More commonly, the ψ' is denoted as either $\psi(3686)$ or $\psi(2S)$ and the ψ'' is denoted $\psi(3770)$. The numbers in parentheses represent the mass of the particle in MeV.

An alternative label for these states uses the quantum numbers for each particle. This is written in the form $N^{2s+1}L_J$, where N refers to the principal quantum number, s refers to the total spin of the particle, L refers to the angular momentum, and J refers to the total angular momentum. Here, the values of L are in spectroscopic notation, where $L = 1, 2, 3, 4 \ldots$ is denoted $S, P, D, F \ldots$, and higher values follow alphabetically (excluding J). As each of these states are comprised of two spin-$\frac{1}{2}$ particles, the value of s in this case can only be 0 (opposite) or 1 (aligned). With this, the $J/\psi, \psi(3686)$, and $\psi(3770)$ are typically denoted 1^3S_1, 2^3S_1, and 1^3D_1. The values of n and L are used for the alternate notation in $\psi(2S)$, however the form of $\psi(1D)$ is not often used for $\psi(3770)$. This is due to evidence of mixing between the 2^3S_1 and 1^3D_1 states that suggests more complicated underlying interactions.

In fact, while the comparisons from this model work well for states less massive than the $\psi(3770)$, the predictions made above this often break down. This is likely based on the energy required to produce open-charm D mesons, such as $D^+(c\bar{u})$ and $D^0(c\bar{d})$. The $D\overline{D}$ threshold (twice the mass of the D^0) is just above the $\psi(2S)$ mass, and just slightly below the $\psi(3770)$ mass. Therefore, the decay products of the two particles end up being drastically different, even while the available phase space is relatively similar.

The difference is most clearly seen in the total decay widths, where the most recent experimental averages are $\Gamma^{\psi(2S)} = 286\,\text{keV}$ and $\Gamma^{\psi(3770)} = 27.5\,\text{MeV}$. An explanation for this discrepancy was proposed independently in the 1960s by Okubo, Zweig, and Iizuka, and is named the OZI rule. Effectively, any Feynman Diagram where the initial and final particles are separated at some point by only gluons represents a suppressed decay. This behavior requires that the momentum transfer from the initial particles must occur entirely through these gluons. Because of the decreasing strength of the strong interaction with higher momentum transfer, the rate of these decays is thereby inhibited. This is further compounded by the need for three gluons in such an interaction, as one gluon could not conserve color charge, and two could not converse C-parity. Once above the $D\overline{D}$ threshold, the allowed open-charm decays dominate, and the total width is massively increased. Such dominance points to a high branching fraction expected for decays of the type $\psi(3770) \to D\overline{D}$.

2.3 $\psi(3770) \to D\overline{D}$ Cross Section

The production rate for a pair of D mesons coming from $\psi(3770)$ at a given center-of-mass energy can be calculated following an approach of Kuraev and Fadin applied by the KEDR collaboration. This method also corrects for Initial State Radiation (ISR), affecting particles accelerated in a collider, and is given by the following:

$$\sigma^{RC}_{D\overline{D}}(W) = \int z_{D\overline{D}}(W\sqrt{1-x})\,\sigma_{D\overline{D}}(W\sqrt{1-x})\,\mathcal{F}(x,W^2)\,dx. \tag{2.1}$$

Here, W is the given center-of-mass energy, x is an approximation for the fraction of radiated energy, and $\mathcal{F}(x,W^2)$ is the probability of losing this energy from ISR:

$$\begin{gathered}\mathcal{F}(x,W^2) = \beta\,x^{\beta-1}\left[1+\frac{\alpha}{\pi}\left(\frac{\pi^2}{3}-\frac{1}{2}\right)+\frac{3}{4}\beta+\beta^2\left(\frac{37}{96}-\frac{\pi^2}{12}-\frac{L}{72}\right)\right] = \beta\,x^{\beta-1}F(W^2),\\ \beta = \frac{2\alpha}{\pi}(L-1), \qquad L = \log\left(\frac{W^2}{m_e^2}\right).\end{gathered} \tag{2.2}$$

The factor $z_{D\overline{D}}$ includes the expected Coulomb interaction between the mesons in of the charged mode (D^+D^-),

$$z_{D^+D^-} = \frac{\pi\alpha/\beta_{D^+}}{1-\exp(-\pi\alpha/\beta_{D^+})} \times \theta(W-2m_{D^+}), \tag{2.3}$$

but only accounts for the $D\overline{D}$ energy threshold in the neutral mode ($D^0\bar{D}^0$),

$$z_{D^0\bar{D}^0} = \theta(W - 2m_{D^0}). \tag{2.4}$$

The theta function imposes the step in the cross section at the production threshold.

The integral in Eq. 2.1 can be simplified by taking advantage of the relatively constant values of $z_{D\overline{D}}$ and $\sigma_{D\overline{D}}$ over sufficiently small intervals. By splitting the full W range into such intervals and integrating over each, this becomes

$$\int \mathcal{F}(x, W^2)\ dx \approx \sum_{n=0}^{N} F(W^2) \int_{\frac{n}{N}}^{\frac{n+1}{N}} \beta x^{\beta-1}\ dx = \sum_{n}^{N} F(W^2) \left[x_{\text{upper}}^{\beta} - x_{\text{lower}}^{\beta}\right]. \tag{2.5}$$

The upper, lower, and mid-point values are given by

$$x_i = \left[1 - \left(\frac{2m_D}{W}\right)^2\right] \left(\frac{n_i}{N}\right), \qquad n_i : \begin{cases} n_{\text{lower}} &= n \\ n_{\text{mid}} &= n + \frac{1}{2} \\ n_{\text{upper}} &= n + 1 \end{cases}. \tag{2.6}$$

The bracketed expression in Eq. 2.6 represents the maximum value of x determined by the theta functions of Eqs. 2.3 and 2.4. To maintain sufficient precision with this interval approximation, the value of $N = 1024$ is used. Combining this with the other factors in Eq. 2.1, the cross section including the effect of ISR becomes

$$\sigma_{D\overline{D}}^{RC}(W) = \sum_{n=0}^{N} z_{D\overline{D}}(W')\, \sigma_{D\overline{D}}(W')\, F(W^2) \left[1 - \left(\frac{2m_D}{W}\right)^2\right]^{\beta} \left[\frac{[(n+1)^{\beta} - n^{\beta}]}{N^{\beta}}\right], \tag{2.7}$$

where $W' = W\sqrt{1 - x_{\text{mid}}}$. The Born level $D\overline{D}$ cross section is given theoretically by

$$\sigma_{D\overline{D}} = \frac{\pi\alpha^2}{3W^2}\beta_D^3 |F_D(W)|^2, \qquad \beta_D = \sqrt{1 - \frac{4m_D^2}{W^2}}. \tag{2.8}$$

Here, β_D is the velocity of the D meson in the center-of-mass system. The form factor F_D represents the contribution of each individual resonant (R) component and the total non-resonant (NR) component. Each resonant piece is parametrized with a phase angle relative to the non-resonant contribution:

$$F_D(W) = F_D^{\mathrm{NR}}(W) + \sum_r F_D^{R_r}(W)\, e^{i\phi_r}. \tag{2.9}$$

Each resonant contribution to the form factor is modeled by a Breit-Wigner amplitude,

$$F_D^R(W) = \frac{6\,W\sqrt{(\Gamma_{ee}/\alpha^2)(\Gamma_{D\overline{D}}(W)/\beta_D^3)}}{M^2 - W^2 - iM\Gamma(W)}, \tag{2.10}$$

where Γ_{ee} is the electron partial width, and $\Gamma(W)$ represents the total width of the resonance with mass M:

$$\Gamma(W) = \left(\frac{M}{W}\right)\left[\frac{z_{D\overline{D}}(W)\, d_{D\overline{D}}(W)}{z_{D^0\bar{D}^0}(M)\, d_{D^0\bar{D}^0}(M) + z_{D^+D^-}(M)\, d_{D^+D^-}(M)}\right]\Gamma(M). \tag{2.11}$$

The value of $\Gamma(M)$ represents the total width at the nominal mass of the resonance. The factors $d_{D^+D^-}$ and $d_{D^0\bar{D}^0}$ are the Blatt-Weisskopf damping factors for a vector resonance [**?**]:

$$d_{D\overline{D}} = \frac{\rho^3_{D\overline{D}}}{\rho^2_{D\overline{D}} + 1}, \qquad \rho_{D\overline{D}} = q_D R_0 = \left(\frac{\beta_D\, W}{2}\right) R_0. \tag{2.12}$$

Here, q_D is the D momentum in the center-of-mass frame, while R_0 represents the radius of the parent particle. The $D\overline{D}$ partial width listed in Eq. 2.10 is simply the total width rescaled according to $\mathcal{B}_{nD\overline{D}}$, the sum of all non-$D\overline{D}$ decay modes of $\psi(3770)$:

$$\Gamma_{D\overline{D}}(W) = \Gamma(W) \times (1 - \mathcal{B}_{nD\overline{D}}). \tag{2.13}$$

Chapter 3

Detector and Related Systems

All data used for this analysis were collected at the third Beijing Spectrometer (BESIII), located in Beijing, China, at the Institute of High Energy Physics (IHEP) campus. This detector records e^+e^- collision events provided by the second Beijing Electron-Positron Collider (BEPCII). The target energies for these collisions focus on τ^- and c production in the range of about 2.0 GeV to 4.6 GeV. Both of these machines are upgrades from previous versions built on the same sites. The first BEPC and BES were originally constructed in 1989, while the upgrade to BESII occurred in 1996. These two sites were closed in 2004 to prepare for the upgrades to the current systems.

In 2009, BEPCII and BESIII began operation with the goal of utilizing greatly increased luminosity. For example, instead of the single-bunch electron collisions of BEPC, the new design utilized multiple bunch collisions. BEPCII also utilizes a dual-storage ring for the electrons and positrons, compared to the single-ring available at BEPC. The improvements provide BEPCII with a design luminosity of $10^{33}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, two orders of magnitude larger than the previous installation. This luminosity is optimized for energies just above the $D\overline{D}$ threshold, as BESIII conducts many precision measurements and rare decay searches around this region.

3.1 BEPCII Accelerator

The setup for collisions in BEPCII begins with bombarding a fixed target with electrons. This generates high energy photons which interact with the target material to form e^+e^-

pairs. The positrons from these pairs are then separated magnetically. Using a linear accelerator, these positrons are then injected into the desired storage ring until they reach the desired beam current. As electrons do not need to be created in this manner, they are instead directly accelerated and injected into the opposite storage ring. These injections occur at a rate of 50 mA/ min for positrons and 200 mA/ min for electrons.

To achieve the necessary high beam currents, many bunches of electrons and positrons are packed into the evacuated rings. During operation, each ring contains 93 bunches spaced 8 ns (2.4 m) with a length of 1.5 cm. These provide a beam current of 0.91 A while operating in collision mode. At the interaction point, each beam is focused using super-conducting quadrupole magnets to compress the beam size to about 5.7 µm vertically, while the horizontal beam size is about 380 µm. For collisions, each beam is also angled towards the center of the storage rings with an angle of 11 mrad. This crossing angle provides better resolution for determining particle momenta in the detector.

For a normal run, collisions continue occurring until the instantaneous luminosity falls below useful levels. While this is typically depleted due to the collisions between the e^+e^- particles, other unwanted interactions (such as those with beam-gas in the storage rings) also reduce these currents. When this happens, BEPCII can replenish the beams using top-off injections. This allows the collider to continue utilizing the remaining particles within the storage rings without dumping the beams completely. Recycling these leftover electrons and positrons saves considerable time, and allows for more efficient data taking.

3.2 BESIII Detector

Centered around the interaction point of BEPCII, the BESIII detector records information about the particles produced by the resulting collisions. Each collision occurs within the beam-pipe of the detector, which is used to minimize multiple-scatterings and secondary interactions. Its inner and outer radii are 31.5 mm and 57.0 mm, and is pressurized to 5×10^{-10} Torr. Surrounding the entire apparatus is a uniform, 1 T magnetic field provided by a super-conducting solenoid with a mean radius of 1.482 m and a length of 3.53 m. The field points in the z-direction, which is along the direction of the e^+ beam. The x-direction points towards the center of the storage rings, while the

y-direction is vertically upwards. This magnetic field is used to provide better precision on momenta measurements. An appropriate field strength curves the tracks of charged particles sufficiently to interact with more of the tracking volume, while minimizing those which curl too much to reach all layers of the detector.

The BESIII detector is split into four main layers which analyze different aspects for identifying particles. Starting from the most interior, these layers are the Multi-Layer Drift Chamber (MDC), the Time-of-Flight System (ToF), the Electromagnetic Calorimeter (EMC), and the Muon Identifier (MU). Using the information provided by each layer, the particles seen in the detector are given a hypothesis for their most likely candidate. Only particles stable enough to sufficiently traverse the detector are identifiable. These include electrons (e), muons (μ), pions (π), kaons (K), and protons (p). Particles such as D^0 and D^+ must be reconstructed from their decays into these constituents.

3.2.1 Multi-Layer Drift Chamber

The purpose of the Multi-Layer Drift Chamber is to determine the momenta and trajectories of charged particles. Because of the magnetic field encasing the detector, charged particles will travel in helical trajectories. The direction of travel is used to determine their charge, while the curvature of the track is used to determine their momenta.

The MDC comprised of many layers of tungsten and sense wires to detect the ionization of particles which pass through its gas-filled volume. The tungsten wires create a constant electric field which causes ionized electrons to drift towards the sense wires. This field is tuned to a strength which minimizes secondary ionization. Conversely, the electric field near each of the sense wires is much larger than the rest of the volume. This forces an avalanche of secondary ionizations in order to create a current in the sense wires. The amount of energy deposited by this process is proportional to the original ionization levels. Tracing the path of energy depositions over time allows for the reconstruction of each charged particle trajectory.

The gas used for ionization is a mixture of 60% helium (He) and 40% methane (C_3H_8). Helium, being chemically inert, will not interact with the ionized electrons used to measure the position and deposited energy. Its low atomic number, and thus, long radiation length, also minimizes multiple scatterings which degrade the momentum resolution. Methane, with extra rotational and vibrational degrees of freedom not accessible to Helium, quenches the ionization energy. Without this effect, the ionization energy would not be diffused, and would degrade the measurements of deposited energy.

In addition to trajectory, the MDC also measures the rate of energy loss over distance for a particle traveling through a material,

$$-\frac{dE}{dx} = 4\pi N \frac{z^2 e^4}{m_e \beta^2} \left[\log\left(\frac{2 m_e \beta^2}{I(1-\beta^2)} \right) - \beta^2 \right], \tag{3.1}$$

where N is the electron number density of the material, z is the charge of the particle in terms of e, the charge of the electron, m_e is the mass of the electron, β is the velocity of the particle, and I is the mean excitation potential for electrons in the material being traversed. This provides a method of distinguishing particle candidates, as this quantity depends on the velocity of the particle.

There are 43 layers of sense wires within the MDC which cover 93% of the 4π solid angle in the detector. These wires create a constant electric field

3.2.2 Time-of-Flight System

The purpose of the Time-of-Flight System is to determine the velocity of charged particles. This is useful for distinguishing particles with similar momenta, but different masses. It uses information provided by the MDC to determine the probability for each charged track to match the possible particle hypotheses. Namely, this includes the measured momentum, the expected time interval based on its trajectory, and the mass for each particle hypothesis. This provides a separation of 3σ for K/π particles with momenta up to 900 MeV.

The ToF is comprised of two bands of staggered plastic scintillators attached to photomultiplier tubes (PMTs). These two bands, located at 0.81 m and 0.86 m from the beam-pipe, measure a time difference used to determine the speed of each charged particle. The resolution is about 100 ps, and is largely limited by the scintillation light rise time, as well as fluctuations associated with the PMTs. The layer is split into two regions, barrel and endcap, which cover the ranges $|\cos\theta| < 0.82$ and $0.85 < |\cos\theta| < 0.95$, respectively. The former is dual-layer with each containing 88 scintillators of 5 cm thickness arranged in a trapezoidal cross section, while the latter contains two single layers of 48 fan-shaped scintillators. Between the two are support structures for the MDC as well as other service lines.

3.2.3 Electromagnetic Calorimeter

The purpose of the Electromagnetic Calorimeter is to determine the energy deposited by photons. Since each of the candidates identified in the detector will be relativistic, they are minimum ionizing particles. This causes each to deposit a relatively constant value of energy, independent of the measured momenta. However, electrons, with their extremely small mass, will deposit significant amounts of energy due to Bremsstrahlung radiation. This provides a clear distinction in the detector between electron and muon tracks above 200 MeV. Energy measurements from the EMC are also useful for identifying neutral particles which decay only to photons, such as π^0.

The EMC is comprised of tellurium-doped cesium iodide (CsI(Tl)) crystals with square front faces attached to a photodiode. Each of the 6240 crystals are 5.2 cm long on the square edges and 28 cm (15 radiation lengths) deep. To prevent photons from aligning with the gaps between each crystal, each one is offset with a tilt of 1.5° in the ϕ-direction and 1.5° to 3° in the θ-direction. These crystals provide an energy resolution (σ/E) of 2.5% at 1 GeV and 4% down to 100 MeV. This is limited by energy not deposited over the length of the crystal, the areas between crystals, and by non-uniform light production. Additionally, only measurements of energy above 20 MeV are considered, as below this value is indistinguishable from noise. The position resolution is $\sigma = 0.6\,\mathrm{cm}/\sqrt{E\ [\mathrm{GeV}]}$, and is primarily limited by the crystal segmentation. The layer has an inner radius of 94 cm and a total weight of approximately 24 tons. It covers the regions $|\cos\theta| < 0.83$ (barrel) and $0.85 < |\cos\theta| < 0.93$ (endcap), but does not well capture the region between the two.

3.2.4 Muon Identifier

The purpose of the Muon Identifier is to determine the likelihood of a charged particle being a muon. Since electrons are significantly lower mass, they deposit virtually all of their remaining energy in the EMC. Additionally, since muons do not interact strongly, they will penetrate notably further than will pions, kaons, or protons. This provides a clear indication of a muon when a particle traverses much of the MU layer. However, due to the magnetic field, only muons with $p > 0.4\,\mathrm{GeV}$ will be able to traverse deep enough to be identifiable.

The MU is comprised of resistive plate counters (RPC) which are interspersed between the steel plates of the super-conducting solenoid. Like the other layers, it is split into a barrel and an endcap region. The barrel has a total thickness of 41 cm including nine RPC layers. In the endcap, the first RPC layer is after a 4 cm layer of steel, and thus, has only eight RPC layers.

3.3 Triggering Systems

In order to maintain a high efficiency for selecting physics events, many backgrounds must be filtered out. At BESIII, this is done through a triggering system with two-tiers, level 1 (L1) and level 3 (L3), illustrated in Fig. **??**. The filtered background events are primarily from beam-related sources, such as beam-gas or beam-wall interactions, and occur at a rate of about 13 MHz. To assist with this process, collimators and masks are used to prevent lost electrons from interacting with the detector. However, there are also other sources of backgrounds, such as cosmic rays, which occur at a rate of about 1.5 kHz. The total backgrounds must be suppressed to a rate which does not overwhelm the recording of events by the readout systems. This rate is roughly 2 kHz at the J/ψ peak, and 600 Hz for the $\psi(2S)$ when running near peak luminosity. For Bhabha events ($e^+e^- \to e^+e^-$), which are used for calibration and luminosity measurements, this rate is 800 Hz within detector acceptance.

The first triggering step (L1) reads out every clock cycle (24 ns) at a rate of 41.65 MHz. It uses information from the MDC, ToF, and EMC collectively to reduce the rates of beam-related backgrounds to 1.84 kHz and cosmic rays to about 200 Hz. However, the L1 has a maximum rate of about 4 kHz. Because of this, when the buffer holding the subdetector data is around 80 % full, L1 triggers are halted until the buffer drops below 10 % full. The efficiency of the L1 process is summarized in Table **??**.

From the MDC, the L1 gathers information about each charged track. The main parameter examined is the number of superlayers a track passed through. These are defined as 'short' tracks if they deposit energy in segments of superlayers 3-5, or 'long' tracks for superlayers 3-5 and 10. To ensure a sufficient momentum to reach the outer superlayers while originating the interaction point, a minimum transverse momentum cut is applied to each track. This cut is 90 MeV and 120 MeV for short and long tracks, respectively. In addition to the numbers of short and long tracks for an event, the information about back-to-back tracks is also used.

From the ToF, the L1 gathers information about the number of hits in the barrel and end-cap regions. It also examines the number of back-to-back hits in each of the two regions. Here, 'back-to-back' is defined as having hits within a range of 9 counters on the opposite side of the detector.

From the EMC, the L1 gathers information about the clustering of energies around a local maximum-energy crystal. This includes the number of isolated clusters, as well as the information about back-to-back hits in the barrel and end-cap. Additionally, the balance of energy in the ϕ-direction (barrel) and in the z-direction (endcap) is also used.

The subdetector information gathered during L1 is then passed off to an online computer farm (L3) where the event is assembled. This step reduces backgrounds from a rate of about 2 kHz to about 1 kHz. Combined with the signal rate at the J/ψ peak (2 kHz), this corresponds to a total event rate of 3 kHz, or a tape write speed of 40 MB/s.

Chapter 4

Analysis Software

4.1 Simulation

4.2 Monte Carlo Generators

4.3 Reconstruction

4.3.1 Multi-Layer Drift Chamber

4.3.2 Time-of-Flight System

4.3.3 Electromagnetic Calorimeter

4.3.4 Muon Identifier

4.4 Database

Chapter 5

Analysis Tools

5.1 D-Tagging

5.2 Selection Cuts

5.3 Software Packages

Chapter 6

Measurement of $\sigma_{D\overline{D}}$ near $\psi(3770)$

As a simplifying assumption, we use $\mathcal{B}_{nD\overline{D}} = 0$ throughout the analysis.

6.1 Form Factors

In Eq. 2.9, we assume the $\psi(2S)$ resonant contribution is negligible in the energy range of our measurements, so the only major resonant contribution is from the $\psi(3770)$:

$$F_D(W) = F_D^{\mathrm{NR}}(W) + F_D^{\psi(3770)}(W)\, e^{i\phi^{\psi(3770)}}. \tag{6.1}$$

Currently, there is no definitive model for the non-resonant term, so we use two alternative parameterizations for this. The first is a simple exponential model:

$$F_D^{NR} = F_{NR}\, \exp(-q_D^2/a_{NR}^2), \tag{6.2}$$

where both F_{NR} and a_{NR} are parameters determined through fitting. The second treatment implements a Vector Dominance Model (VDM). This assumes the interference effects are due to the $\psi(2S)$ mediating $D\overline{D}$ production above threshold,

$$F_D^{NR}(W) = F_D^{\psi(2S)}(W) + F_0, \tag{6.3}$$

and that the effective properties of the $\psi(2S)$ are similar to those of the $\psi(3770)$. The real constant F_0 represents the potential effect of higher resonances, like the $\psi(4040)$.

The first term is similar to Eq. 2.10, but with a modification to the total width:

$$\Gamma^{\psi(2S)}(W) = \left(\frac{M^{\psi(2S)}}{W}\right) \left[\frac{z_{D^0\bar{D}^0}(W)\, d_{D^0\bar{D}^0}(W) + z_{D^+D^-}(W)\, d_{D^+D^-}(W)}{z_{D^0\bar{D}^0}(M^{\psi''})\, d_{D^0\bar{D}^0}(M^{\psi''}) + z_{D^+D^-}(M^{\psi''})\, d_{D^+D^-}(M^{\psi''})}\right] \Gamma^{\psi(2S)}(M). \tag{6.4}$$

Without this modification, the mass of the $\psi(2S)$ would be below the $D\overline{D}$ threshold, and thus, the vanishing $z_{D\overline{D}}$ terms would cause a singularity in the width. Therefore, we use the mass of the $\psi(3770)$ in its place to estimate the effects in this region. While it may behave like the total width in Eq. 6.4, the true the physical meaning of the parameter $\Gamma^{\psi(2S)}(W)$ is uncertain. For the radii in Eq. 2.12, however, the values used are distinct for each meson: $R_{\psi(2S)} = 0.75\,\mathrm{fm}$ and $R_{\psi(3770)} = 1.00\,\mathrm{fm}$.

6.2 Data and Monte Carlo Samples

6.2.1 Luminosity Calculation

6.2.2 Monte Carlo Generation

6.3 Signal Determination

6.4 Efficiency Correction

6.4.1 CP Violation Correction

6.5 Fitting Procedure

6.5.1 Coulomb Correction

6.6 Systematics

Chapter 7

Conclusion

This is where the Conclusions go!

References

Appendix A

Glossary and Acronyms

Care has been taken in this thesis to minimize the use of jargon and acronyms, but this cannot always be achieved. This appendix defines jargon terms in a glossary, and contains a table of acronyms and their meaning.

A.1 Glossary

- **Cosmic-Ray Muon** (**CR** μ) – A muon coming from the abundant energetic particles originating outside of the Earth's atmosphere.

A.2 Acronyms

Table A.1: Acronyms

Acronym	Meaning
CRμ	Cosmic-Ray Muon