

Measurement of $D\bar{D}$ Decays from the $\psi(3770)$ Resonance

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Acknowledgements

This is where the Acknowledgements go!

Dedication

This is where the Dedications go!

Abstract

We measure the production cross section of $e^+e^- \rightarrow \psi(3770) \rightarrow D\bar{D}$ near the peak of the $\psi(3770)$ resonance. The $(69.80 \pm 0.03)\text{ pb}^{-1}$ of e^+e^- annihilation data used were collected in 2010 over a center-of-mass energy range of 3.735 GeV to 3.870 GeV. From previously observed $e^+e^- \rightarrow D\bar{D}$ cross section measurements, this shape cannot be explained by a single Breit-Wigner. Instead, this analysis fitted using interference effects from non-resonant $D\bar{D}$ production, and measured the mass and width of the $\psi(3770)$ more precisely than previous results.

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Chapter 1

Introduction

Since the discovery of the J/ψ particle in 1974, the charm energy range (3.0 GeV to 4.5 GeV) has been one of the most precisely studied regions in particle physics. This has led to the further discovery of many more resonances, as shown in Figure 1.1.

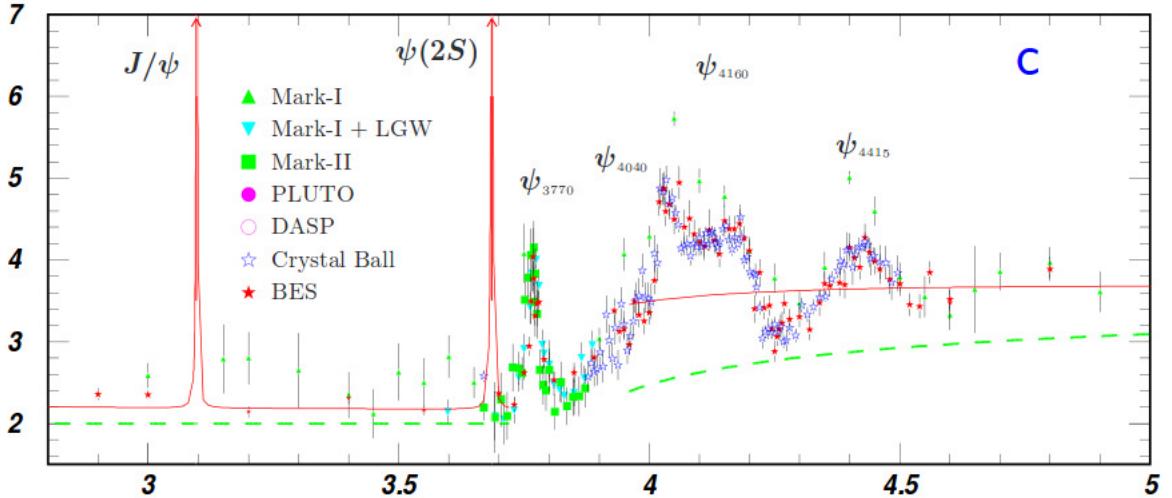


Figure 1.1: Measurements of $R = \sigma(e^+e^- \rightarrow \text{hadrons})/\sigma(e^+e^- \rightarrow \mu^+\mu^-)$.

Many of the lower mass resonances are predictable within the context of the quark model. However, there are a number of states which have been predicted, but not yet discovered. There are also states which were discovered experimentally without any corresponding predictions. A variety of these particles are shown in Figure 1.2.

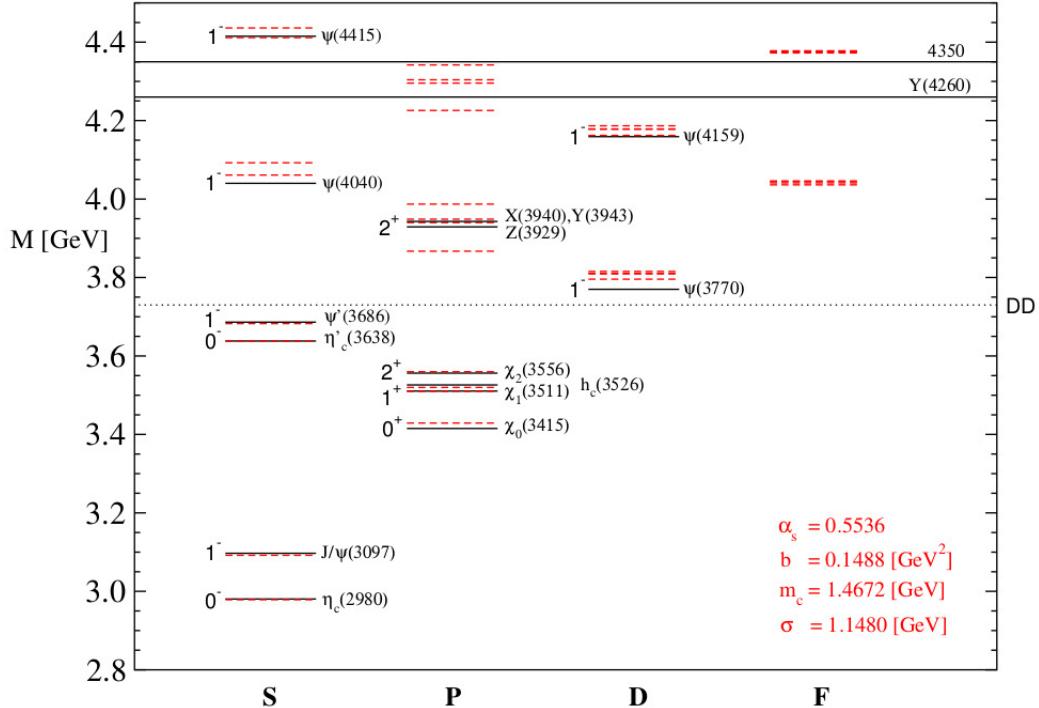


Figure 1.2: Measured and predicted charmonium resonances.
 Solid black lines represent measurements while the dashed red lines are predictions.

The resonances below the $D\bar{D}$ threshold, like the J/ψ and the $\psi(2S)$, show solid agreement with their theoretical predictions. However, many of the ones above, such as the $\psi(3770)$, still show some disagreement. This is likely due to the more complicated interactions introduced from $D\bar{D}$ decays. Several experiments have attempted to measure the shape of the $\psi(3770)$ based on different assumptions. The most prominent of these is the assumption of interference. This can have notable effects on the resultant parameters of the $\psi(3770)$, such as the mass, shown in Table 1.1.

| $M^{\psi(3770)}$ [MeV] (No Interference) | $M^{\psi(3770)}$ [MeV] (With Interference) |
|--|---|
| BES-II [1] 3772.0 ± 1.9 | BaBar [4] $3778.8 \pm 1.9 \pm 0.9$ |
| Belle [2] $3776.0 \pm 5.0 \pm 4.0$ | KEDR [5] $3779.2^{+1.8+0.5+0.3}_{-1.7-0.7-0.3}$ |
| BaBar [3] $3775.5 \pm 2.4 \pm 0.5$ | |

Table 1.1: Previous experimental results for the mass of the $\psi(3770)$. Where applicable, the first errors are statistical, the second are systematic, and the third are model-dependent.

Both BaBar [4] and KEDR [5] found it necessary to include interference effects for fitting the $D\bar{D}$ spectrum. However, the statistics of the KEDR sample were insufficient to fully resolve the discrepancies seen with other experiments that ignored interference. **Using the larger data sample available at BESIII, we have precisely measured and analyzed the shape of the $D\bar{D}$ spectrum around the $\psi(3770)$ resonance.** We have also used this measurement to probe the branching fraction of non- $D\bar{D}$ decays in this region.

To begin this analysis, we provide background on relevant theoretical concepts and derivations. Next, we detail specifications for the collider and detector which collected the data used for these measurements along with their related analysis software and reconstruction methods. From here, we describe the procedure for determining the $\psi(3770) \rightarrow D\bar{D}$ cross section and show the results with systematic uncertainties. Finally, we examine the current progress of measuring the non- $D\bar{D}$ branching fraction.

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 not included in the Standard Model. It 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 the forces between objects with electric charge, most notably binding together electrons and protons to form atoms and the structures they comprise. The theory of electromagnetic interactions is known as Quantum Electrodynamics (QED). Within this theory, 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 calculable through perturbation theory, where corrections are applied in terms of higher order factors of the coupling constant, α . This is possible due to its relatively small value ($\alpha \approx 1/137$), as the terms are convergent below very high orders of α .

2.1.2 Weak Force

The weak force is responsible for radioactive decay and other subatomic phenomena. 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 their masses non-zero, they are extremely heavy particles at 80.4 GeV and 90.2 GeV , respectively [6]. These large masses not only limit the interaction distance of the weak force, but also minimize the interaction strength (which is inversely proportion to mass). Furthermore, the large W and Z masses also lead 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 [8] 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 [9]. The resolution to this symmetry conservation involves yet a third symmetry, time reversal (T), in which time is replaced with its negative ($t \rightarrow -t$). While the weak force violates these symmetries individually, the application of all three (CPT) is conserved across all known processes, and is known as the CPT Theorem.

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. As a result of 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 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, known as quarks (see Section 2.1.4), from existing as isolated entities in a process known as confinement. The typical interaction range is on the order of the proton radius, around 10^{-15} m. QCD calculations face serious 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 the color charge. Despite its name, however, the term 'color' has no association with light, which is a purely electromagnetic phenomena. 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. Because particles with different color values are distinct, this effectively triples the number of possible particle combinations, due to combinatorics.

Unlike the photon, which does not carry an electric charge, gluons do possess a 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 non-zero charge of 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 bosons. This division is based on the Spin Statistics theorem, where fermions (bosons) have half-integer (integer) spins. As described by the Pauli Exclusion principle, nature restricts fermions from occupying the same quantum state. Bosons, however, do not have this restriction, and can have any number occupying the same state.

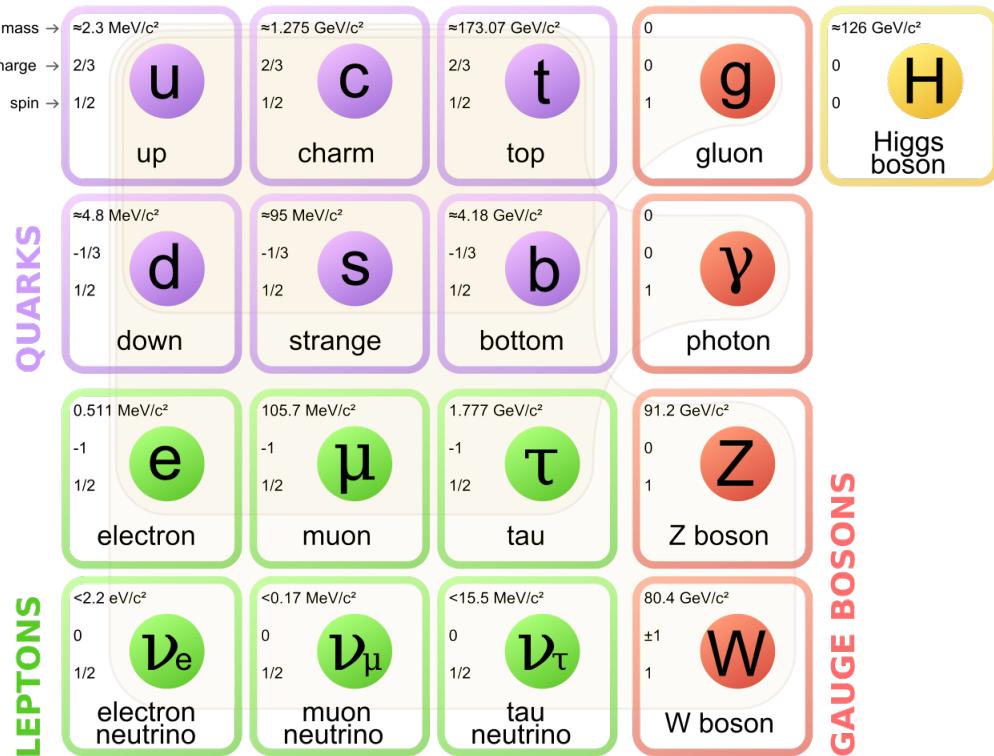


Figure 2.1: The standard model of particle physics.

It is comprised of two main groups: fermions, which includes the quarks and leptons, and bosons, which includes the gauge bosons and the Higgs boson. Image reproduced courtesy of [7].

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 antiparticles. These can be grouped into three generations, which aligns particles with the same electric charges, but greatly differing masses. As an example, the up (u), charm (c), and top (t) quarks all have an electric charge of $+2/3$ (in terms of the electron charge, e), but t is approximately five orders of magnitude more massive than u . For the quarks and fermions in Figure 2.1, rows indicate particles with the same electric charge, while 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 [10, 11, 12].

While the negatively charged quarks (d , s , and b) are labeled as definite states, the quarks are actually mixed states. Through weak interactions, each of these quarks can transform into other quarks. The probabilities for these transformations are expressed by the Cabibbo-Kobayashi-Maskawa (CKM) Matrix [13], shown in Figure 2.2. From the experimentally measured values [6], it is evident the matrix is nearly diagonal. It is also clear that correlations are strongest within each generation, as the off-diagonal terms are generally smaller than the diagonal ones. Additionally, though 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 equivalent.

$$\begin{bmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{bmatrix} = \begin{bmatrix} 0.97427 \pm 0.00014 & 0.22536 \pm 0.00061 & 0.00355 \pm 0.00015 \\ 0.22522 \pm 0.00061 & 0.97343 \pm 0.00015 & 0.0414 \pm 0.0012 \\ 0.00886^{+0.00033}_{-0.00032} & 0.0405^{+0.0011}_{-0.0012} & 0.99914 \pm 0.00005 \end{bmatrix}$$

Figure 2.2: The Cabibbo-Kobayashi-Maskawa (CKM) Matrix.

The values of the CKM matrix are typically parameterized using three Euler angles

$(\theta_{12}, \theta_{23}, \theta_{13})$ and a CP-violating phase parameter (δ_{13}) , where the indices represent the three generations of quarks. This formulation allows the matrix to be cast in the “standard” parametrization, shown in Figure 2.3. The form with three separated matrices clearly shows the connections between each generation of quarks. Namely, the third shows the original formulation in terms of a single rotation, the Cabibbo angle (θ_{12}) . This theory is known as the Glashow-Iliopoulos-Maiani (GIM) mechanism [[14] and was used to explain the suppression of flavor-changing neutral currents (FCNC) before the discovery of the charm quark.

$$\begin{aligned} & \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \\ &= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{bmatrix} \end{aligned}$$

Figure 2.3: The standard form of the Cabibbo-Kobayashi-Maskawa (CKM) Matrix. The parameterization is in terms of three angles $(\theta_{12}, \theta_{23}, \theta_{13})$ and a phase angle (δ_{13}) .

Here, $c_{ij} = \cos \theta_{ij}$ and $s_{ij} = \sin \theta_{ij}$.

The leptons are also organized into generations consisting of particles with two distinct charges. The electron (e^-), muon (μ^-), and tau (τ^-) are all negatively charged particles. There is also a neutral particle, a neutrino (ν), corresponding to each of the charged leptons (ν_e, ν_μ, ν_τ). These are very small mass (< 1 eV) particles with extremely low interactions. 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.

The Standard Model assumes 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. As with the quarks, 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 called the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix [15, 16]. Its formulation is 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 are the photon (γ) for electromagnetic force, the W^\pm and Z for the weak force, and the gluon (g) for the strong force. Each of the gauge bosons is 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 and dark energy, remain major obstacles to 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 much current and 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 analogously to the hydrogen atom. Namely, there is a spectrum of various excited states in the Charmonium region, just as the spectrum of states associated with the emission lines of hydrogen. The first three charmonium states to be discovered were the J/ψ , ψ' , 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 $\psi(3686)$ and the ψ'' is denoted $\psi(3770)$. The numbers in parentheses represent the mass of the particle in MeV.

An alternative labeling scheme 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 angular momentum of the particle, L refers to the orbital angular momentum, and J refers to the total angular momentum. Here, the values of L are in spectroscopic notation, where $L = 1, 2, 3, 4 \dots$ is denoted $S, P, D, F \dots$, and higher values follow alphabetically (excluding J). As each of these states is 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/ψ , $\psi(3686)$, and $\psi(3770)$ can be denoted 1^3S_1 , 2^3S_1 , and 1^3D_1 . The values of n and L are used for the alternate notation of $\psi(2S)$ representing $\psi(3686)$. However, the notation of $\psi(1D)$ is not often used for $\psi(3770)$. This is due to evidence of mixing in $\psi(3770)$ between the 2^3S_1 and 1^3D_1 states that suggests more complicated underlying interactions [17, 18].

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 $D\bar{D}$ 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 are drastically different, even while the available phase space is similar. Example Feynman diagrams for these two particles can be seen in Figures 2.4 and 2.5.

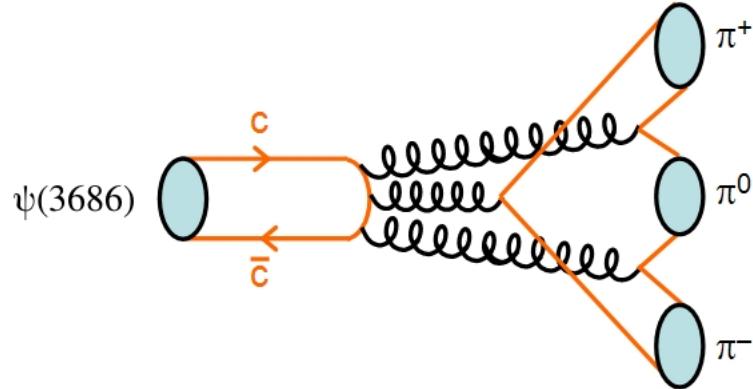


Figure 2.4: An example Feynman diagram for the decay of $\psi(3686)$. Without sufficient energy to produce D mesons, the decays of $\psi(3686)$ must be mediated by three hard gluons and are suppressed, as described by the OZI rule.

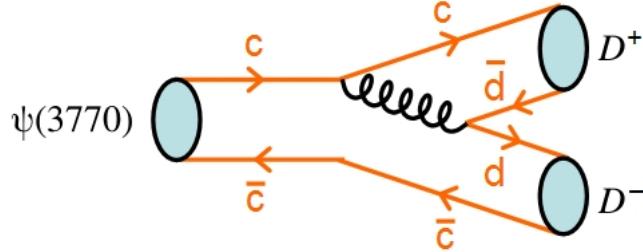


Figure 2.5: An example Feynman diagram for the decay of $\psi(3770)$. With sufficient energy to produce D mesons, the open-charm decays of $\psi(3770)$ are allowed to proceed, greatly increasing the total decay width.

The difference is also clearly seen in the total decay widths, where the most recent experimental averages [6] 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 [19], Zweig [20], and Iizuka [21], and is named the OZI rule. This states that any Feynman Diagram where the initial and final particles are separated at some point by only gluons represents a suppressed decay. Such 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 $D\bar{D}$ threshold, the allowed open-charm decays dominate, and the total width is greatly increased. This dominance points to a high branching fraction expected for decays of the type $\psi(3770) \rightarrow D\bar{D}$.

2.3 Derivation of $\sigma_{\psi(3770) \rightarrow D\bar{D}}$

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 [22] applied by the KEDR collaboration [5]. This method also corrects for Initial State Radiation

(ISR), affecting particles accelerated in a collider, and is given by the following:

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

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:

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

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

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

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

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

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 $z_{D\bar{D}}$ and $\sigma_{D\bar{D}}$ over sufficiently small intervals. By splitting the full W range into such intervals and integrating over each, this becomes

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

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

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

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

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

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

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

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:

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

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

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

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

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

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 [23] for a vector resonance:

$$d_{D\bar{D}} = \frac{\rho_{D\bar{D}}^3}{\rho_{D\bar{D}}^2 + 1}, \quad \rho_{D\bar{D}} = q_D R_0 = \left(\frac{\beta_D W}{2} \right) R_0. \quad (2.12)$$

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

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

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

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 center-of-mass energy range for this facility was selected to concentrate on $\tau^-\tau^+$ and $c\bar{c}$ production, from 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. Their operation was terminated 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. This creates many groups of electrons and positrons which are tightly packed in each ring during run time. 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 $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$, two orders of magnitude larger than the previous installation. This luminosity is optimized for energies near the $\psi(3770)$ resonance, as BESIII conducts many precision measurements and rare decay searches around this region. A detailed description of the BESIII detector can be found in Ref. [24].

3.1 BEPCII Accelerator

The setup for collisions in BEPCII begins with bombarding a fixed target with electrons in a linear accelerator. 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. 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 in the linear accelerator 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 of length 1.5 cm separated by 8 ns (2.4 m). These provide a maximum 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 introduces a net momentum in the radial direction to help prevent against tracks which may continue in the direction of the beam pipe, thereby avoiding detection.

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 residual 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 e^-e^+ collisions. Each collision occurs

within the beam-pipe of the detector, which has an inner and outer radii of 31.5 mm and 57.0 mm, and is evacuated to 5×10^{-10} Torr. Most of the apparatus is a region of uniform 1.0 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 allow measurement of the momenta of charged particles based on the curvature of their trajectories. It allows typical charged particles to sufficiently interact with much of the tracking volume, while minimizing those which curl too much to reach all layers of the detector.

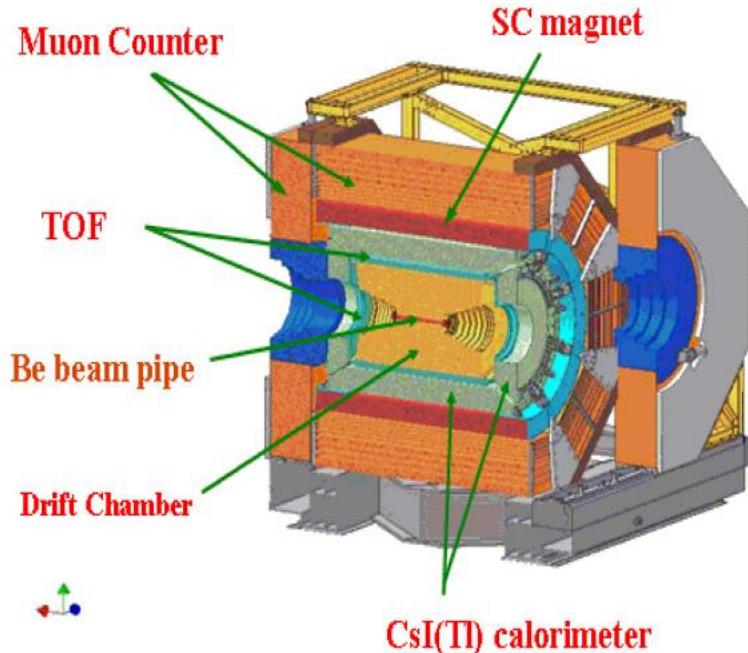


Figure 3.1: A schematic of the BESIII detector.

There are four main layers surrounding the beam-pipe: the Main Drift Chamber (MDC), the Time-of-Flight (ToF), the Electromagnetic Calorimeter (EMC), and the Muon Chamber (MUC). All but the MUC are surrounded by a uniform 1.0 T magnetic field produced by the super conducting solenoidal magnet.

The BESIII detector, shown in Figure 3.1, consists of four main components which address different aspects of measuring and 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 (MUC). Using the information provided by each of these, the tracks seen in the detector are given a particle hypothesis for their most likely identity. Only charged particles stable enough to traverse the detector volume are identifiable in this way. The charged particles identified at BESIII are electrons (e), muons (μ), pions (π), kaons (K), and protons (p). Short-lived particles, such as D^0 and D^+ , must be reconstructed from their decays into these constituents, as well as neutral shower energy from photons (γ).

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, charged particles travel in helical trajectories. The direction of curvature is used to determine the charge, while the radius of curvature of the track is used to determine the momentum.

The MDC is comprised of many layers of tungsten sense wires to detect the ionization of particles which pass through its gas-filled volume. The sense and field wires create an electric field which causes ionization electrons to drift towards the sense wires. This field is tuned to a strength which minimizes secondary ionization, except in the immediate vicinity of the sense wire. This produces an avalanche of secondary ionizations which creates a measurable current pulse in the sense wire. The amount of energy deposited by this process is proportional to the primary ionization produced by the track. Tracing the path of energy depositions over time allows for the reconstruction of each charged particle trajectory.

The main design of the MDC focuses on cylindrical layers of drift cells comprised of sense wires running coaxial to the beam pipe. The inner and outer radii of the MDC are 59 mm and 810 mm, respectively. There are 43 layers of sense wires which cover 93% of the 4π solid angle in the detector. These include 8 layers in the inner chamber, and 35 in the outer chamber. Each of the layers in the inner chamber are stereo layers (for measuring along the z -axis), while the 16 stereo layers and 19 axial layers (for measuring along the $x-y$ plane) are interleaved in the outer chamber. This arrangement provides position resolutions of 130 μm and 2 mm in the $r-\phi$ plane and beam direction, respectively, for each hit. The uncertainty in the transverse plane measurements is

dominated by electron diffusion and the readout time uncertainty for the electronics. For the transverse momentum, the resolution is about 0.5 % for tracks with momenta of 1 GeV, with uncertainties coming mainly from wire position measurements, and multiple scattering from material in the MDC.

The gas used for ionization is a mixture of 60% helium (He) and 40% methane (C_3H_8). Helium, because of its low atomic number, and thus, long radiation length, also minimizes multiple scattering which degrades the momentum resolution. Methane, with extra rotational and vibrational degrees of freedom not accessible to helium, quenches the ionization energy. Without this effect, electrons would be accelerated by the electric field, produced secondary ionization energy, and lead to electric breakdown.

In addition to trajectory, the MDC also measures the rate of energy loss over distance for a particle traveling through a material [25], as described by the Bethe-Bloch equation,

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

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. The resolution of dE/dx in the MDC is about 6 % for particles incident 90° to the beam-axis. The uncertainty is due to fluctuations in the number of primary ionizations along the flight path, fluctuations in the avalanche process, as well as from edge effects on each cell.

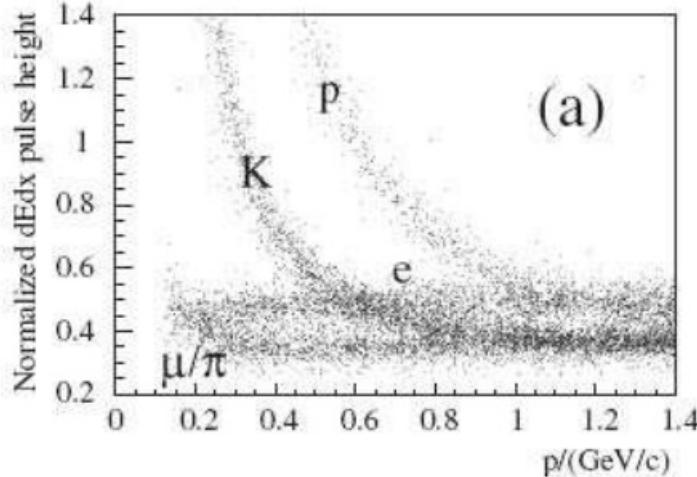


Figure 3.2: MDC energy deposition for various particles as a function of momenta. Distinction between K and π tracks is easier for low momenta, but becomes very difficult for higher values.

The energy deposition provides a method of determining particle identity, as this quantity depends on the velocity of the particle. An example of this behavior for multiple types of particles can be seen in Figure 3.2. To identify a particle from the various candidates, the measured energy deposition (dE/dx_{meas}) is compared against the expected value (dE/dx_{exp}) of each hit used to reconstruct the particle's trajectory (i):

$$\chi^2 = \sum_i \chi_i^2 = \left(\frac{dE/dx_{\text{meas}} - dE/dx_{\text{exp}}}{\sigma} \right)_i^2, \quad (3.2)$$

where σ represents the uncertainty on the measured energy deposition. This process provides a separation of 3σ between K and π tracks with momenta up to 770 MeV.

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, as shown in Figure 3.3. 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 process provides a separation of 3σ between K and π tracks with momenta up to 900 MeV.

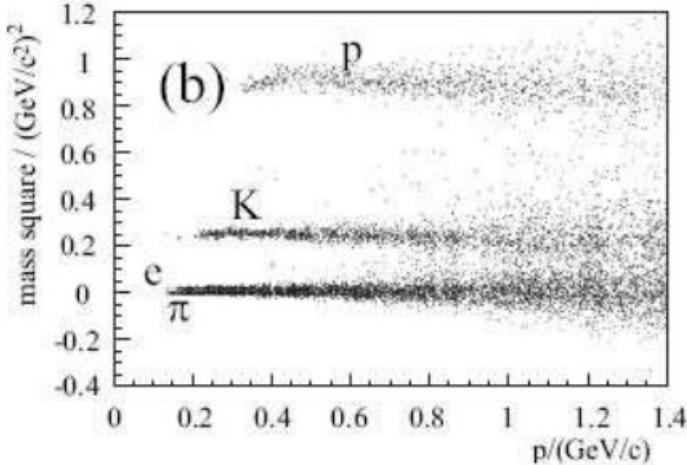


Figure 3.3: ToF measurements for various particles as a function of momenta. Distinction between K and π tracks is very easy for low momenta, but becomes more difficult for higher values.

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 measure the energy deposited by photons and electrons. Since most of the candidates identified in the detector are

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 and subsequent secondary e^+e^- pair production. This provides a clear distinction in the detector between electron and muon tracks above 200 MeV, as seen in Figure 3.4. Energy measurements from the EMC are also useful for identifying neutral particles which decay only to photons, such as π^0 .

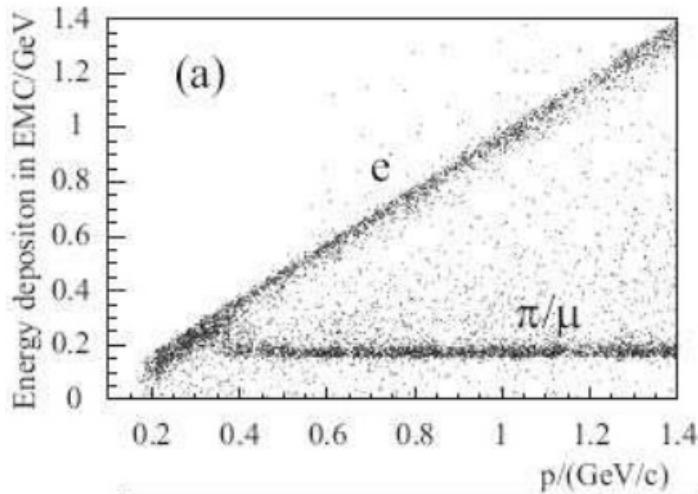


Figure 3.4: EMC energy deposition for various particles as a function of momentum. As the mass of e^- is so small, it deposits virtually all of its energy in the EMC. Both μ^- and π are generally minimum ionizing particles in this momenta range, and their similar masses make them difficult to distinguish with the EMC measurements alone.

The EMC is comprised of tellurium-doped cesium iodide ($\text{CsI}(\text{Tl})$) crystals with square front faces attached to a photodiode. Each of the 6240 crystals is 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 gaps between crystals, and by non-uniform light production. Additionally, only measurements of energy above 20 MeV are considered, because of the irreducible noise level in the detector. The position resolution is $\sigma = 0.6 \text{ cm}/\sqrt{E \text{ [GeV]}}$, and is primarily limited by the crystal segmentation. The

EMC 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), with a gap in between that does not provide reliable energy measurements.

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 penetrates the MUC. However, due to the magnetic field, only muons with $p > 0.4 \text{ GeV}$ can traverse deep enough to be identifiable.

The MUC is comprised of resistive plate counters (RPC) which are interspersed between the steel plates of the super-conducting solenoid's flux-return iron. Each of the steel layers increase in thickness working outwards from the center: 3 cm, 3 cm, 3 cm, 4 cm, 4 cm, 8 cm, 8 cm, 8 cm, and 15 cm. Like the other components, the MUC is split into a barrel and an endcap region. The barrel has nine RPC layers of 4 cm thickness. In the endcap, the first RPC layer is after the first steel layer, leaving only eight RPC layers. Each of these layers has RPC strips oriented along only one direction. For the barrel, the z (ϕ) orientation is read out for only the odd (even) layers. Conversely, the endcap only reads out the x (y) orientation in the odd (even) 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: a hardware trigger (L1) and a software event filter (L3). This process is illustrated in Figure 3.5. 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 ($e^+e^- \rightarrow e^+e^-$), which are used for calibration and luminosity measurements, this rate is 800 Hz within the detector acceptance.

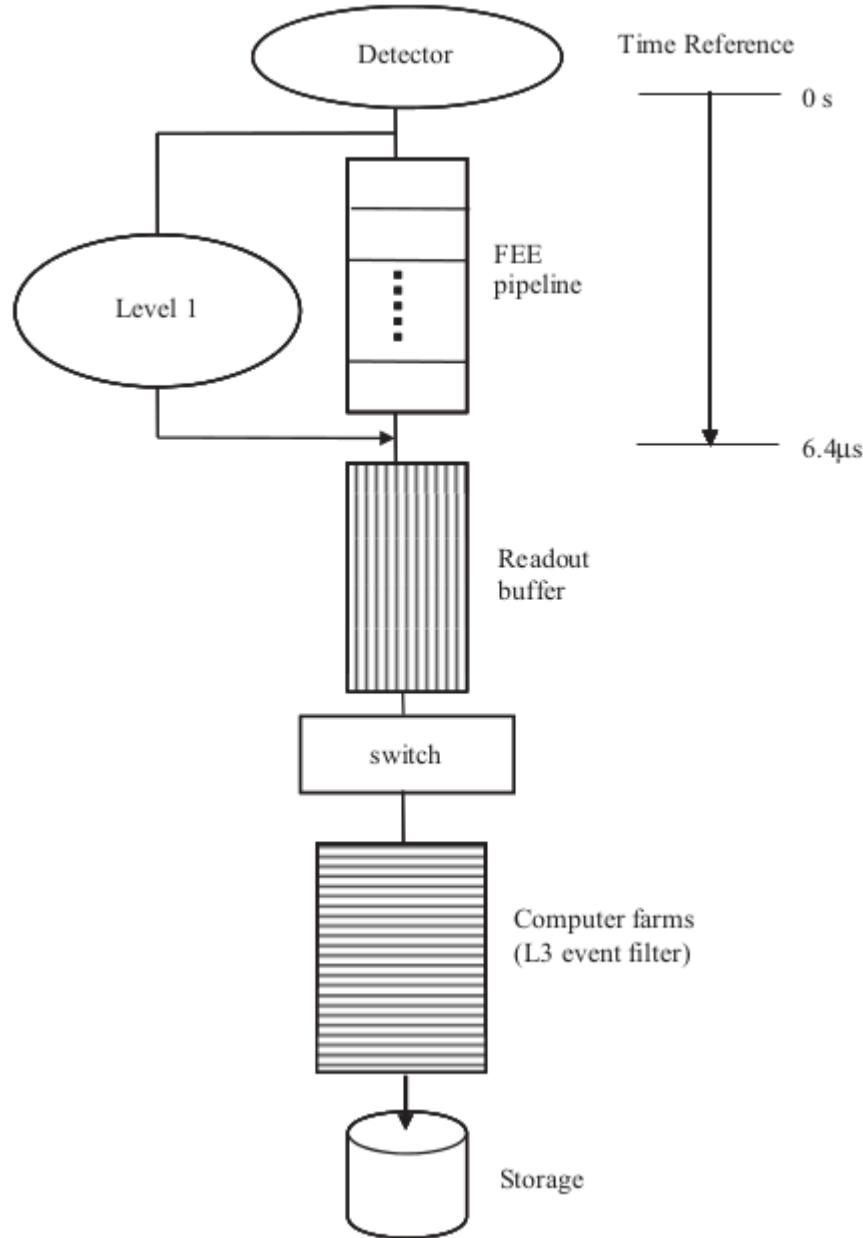


Figure 3.5: Triggering systems for event filtering at BESIII.

To prevent overloading the event recording system, non-physics background events must be eliminated from the data stream. This processing uses simple read-out information from each of the layer of the detector to quickly and efficiently determine whether or not events should be further considered for analysis.

The first 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, L1 has a maximum rate of about 4 kHz. Because of this, when the buffer holding the subdetector data is around 80 % full, L1 triggering is halted until the buffer drops below 10 % full.

From the MDC, L1 gathers information about each charged track. The main parameter examined is the number of superlayers a track passed through. Here, a superlayer is the collection of wires at the same radial distance away from the center of the detector. Tracks are defined as ‘short’ if they deposit energy in segments of superlayers 3–5, or ‘long’ for superlayers 3–5 and 10. To ensure a sufficient momentum to reach the outer superlayers while originating at 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, 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, 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 maximum event rate of 3 kHz, or a tape write speed of 40 MB/s.

Chapter 4

Analysis Software

4.1 BESIII Offline Software System

Reconstructing and processing event data gathered by the BESIII detector is done using the BESIII Offline Software System (BOSS) [26]. This is an analysis software distribution written using the C++ language and running primarily on the Scientific Linux CERN operating system [27]. There are five main parts to BOSS: framework, simulation, reconstruction, calibration, and analysis.

4.1.1 Framework

The framework is built on the Gaudi software architecture [28], which provides a standard interface and utilities for things such as event simulation, data processing, and physics analysis. The software is managed using the Configuration Management Tool [29], which provides a method for creating packages, handling package dependencies, and producing executables from source code. There are three main filetypes for data stored by the framework: raw data (`.raw`), reconstructed data (`.rec`), and Data-Summary-Tape (`.dst`). The latter two of these file types are derived from the ROOT [30] format (`.root`) for easy management and usage in various analyses.

4.1.2 Simulation

There are four main parts to the simulation process: event generation, detector description, particle tracking, and detector response. Event generation is primarily handled by the Monte Carlo (MC) generators KKMC, BesEvtGen, and Babayaga, which are described below. To model its geometry and materials, a unique description of the detector has been created using a format based on XML. This allows both simulation and reconstruction packages to appropriately model the behavior of events within the specific environment of BESIII. For particle tracking, interactions with detector materials are handled by GEANT4 [31]. Lastly, detector responses are modeled by the so-called ‘digitization code’. This takes into account each detector component, as well as readout electronics, and realistic situations such as noise or dead channels. There is also a simulation of the triggering system implemented.

KKMC

Originally developed for the LEP and SLC colliders, KKMC [32] is a generator used to model electroweak interactions. Namely, the processes generated are of the form $e^+e^- \rightarrow f\bar{f} + (n)\gamma$, where $f = \{\mu, \tau, u, d, s, c, b\}$, and $(n)\gamma$ represents any number of additional photons. These are modeled taking into account second-order sub-leading corrections, as well as initial-state radiation (ISR), and interference between initial- and final-state radiation (FSR). The effects of beam energy spread, typically on the order of 1 MeV near the $\psi(3770)$, can also be included.

After generation, the $f\bar{f}$ pair is decayed by models depending on the fermions involved. The TAUOLA library [33] is used to decay $\tau^-\tau^+$ pairs, and takes into account spin-polarization effects. The PYTHIA model [34] is used to hadronize final-state $q\bar{q}$ continuum production using the parton shower model. For resonances like the $\psi(3770)$, the only action performed by KKMC is the generation of ISR. After this, the virtual photon produced is handed off to BesEvtGen.

BesEvtGen

Originally developed for the CLEO and BaBar collaborations, EvtGen [35] is another widely used generator. It is the basis for BesEvtGen [36], which incorporates many

different decay models into a single utility. Over 30 exclusive decay models are available in BesEvtGen, as well as the capability to incorporate user-created models.

The simulation process occurs sequentially using dynamic information from decay amplitude probabilities and forward / backward spin-density matrices. From this, final state radiation is handled by the PHOTOS model [37]. To generate unknown decays of charmonium resonances, the LundCharm model [38] is used, while other unknown hadronic decays are handled by PYTHIA. For radiative processes, such as radiative return to J/ψ or $\psi(2S)$, the VECTORISR model [39] is used. This occurs when one particle in the initial e^+e^- pair radiates a photon of high enough energy that only lower mass resonances can be produced from the reduced center-of-mass energy. When the radiation is less intense, the $\psi(3770)$ resonance is directly produced through the combination of KKMC and BesEvtGen.

Babayaga

Production of QED processes is done using the Babayaga generator [40]. This includes $e^+e^- \rightarrow \{e^+e^-, \mu^+\mu^-, \gamma\gamma\}$. The results are of very high precision, with an estimated theoretical accuracy of 0.1 %. It also matches exact next-leading-order corrections from the parton shower algorithm. The high precision also helps determine the efficiencies and acceptances required to precisely measure the integrated luminosities of each data sample.

4.1.3 Reconstruction

Reconstruction primarily involves information about specific types of particles from each of the four main detector layers. These sources of information are as follows:

- a charged track finding algorithm and a Kalman-filter-based track-fitter
- a particle identifying algorithm based on dE/dx and time-of-flight measurements
- a shower- and cluster-finding algorithm for EMC energy and position
- a muon track finding algorithm

Further descriptions about each of these processes can be found in Sec. 4.2. Additionally, algorithms for determining the corresponding beam bunch crossing, as well as for secondary vertex and track refitting, are also utilized.

4.1.4 Calibration

To maintain consistent production and analysis of datasets, a centralized source of run-dependent information is maintained by BOSS. This includes algorithms which determine the calibration constants for each sub-detector, as well as a centralized database to store the results. Each of the calibration outputs are stored in a ROOT file along with other details such as the beam energy, luminosity, magnetic field information, trigger conditions, and hardware / software versions. While all of this information is stored by a central MySQL [41] server at IHEP, databases for other institutions in BESIII regularly synchronize with this server to create a mirrored copy of these values.

4.2 Detector Simulation

The following sections detail the simulation, calibration, and reconstruction processes for each layer. Each of these relies on a geometry description created using GEANT4.

4.2.1 Multi-Layer Drift Chamber

Simulating events in the MDC accounts for the axial layers and endplates, the stereo layers, and the stereo cells. The simulation also heavily relies on the calibration parameters to determine things such as wire efficiency and resolution as a function of drift distance for each wire, noise in each layer, and other misalignment issues.

Calibration of the MDC uses $J/\psi \rightarrow \mu^+ \mu^-$ events to determine position and dE/dx measurements. Using J/ψ events allows for quickly obtaining sufficient statistics due to the very large production cross section at the peak. The information determined includes constants such as $x - t$ relations, timing, alignment, and absolute wire efficiency. Each of these values are stored in the database for each run. Additionally, turning off the magnetic field could allow for precise determination of wire positions.

Reconstructing MDC events starts by finding axial track segments using raw hits. Each of these are found by searching for pre-calculated patterns. Next, these segments

are linked to circular tracks by a circular fit using the least-squares method. Stereo segments are then added using an iterative helix fit. Lastly, additional hits which were possibly missed from the initial reconstruction are applied using a Kalman-filter process. This process also examines the tracks over multiple particle hypotheses. The reconstruction is remarkably efficient, with over 98 % of tracks with $p_T > 150 \text{ MeV}$ being reconstructed, even amidst high backgrounds. From this, the charge, momentum, and trajectory can be determined for each track.

In addition to tracking, the MDC also analyzes dE/dx for each particle. This calculates the energy deposition of each track as it passes through the chamber, and corrects the measured charge amplitudes to determine a probability for each particle hypothesis. Corrections applied account for things such as multiple scatterings, magnetic deflections, and ionization. This likelihood from dE/dx is used in conjunction with information from the ToF to identify the actual type of particle for each track.

4.2.2 Time-of-Flight System

Simulating events in the ToF accounts for the scintillator, wrapping materials, and photomultiplier tubes (PMTs). The process converts the energy deposited in the scintillator into photons, then propagates the shape of a photon pulse (rather than individual photons) to the PMTs in order to generate an electronic signal. A discriminator is applied to each pulse to determine the analog-to-digital conversion (ADC) and time-to-digital conversion (TDC) outputs. The algorithm is tested using the results of beam tests, however, subsequently gathered data sets require updated tuning. A full simulation tracing each optical photon can also be used for further details on the timing measurement.

Calibration of the ToF also uses J/ψ decays to leptons to determine both timing and energy measurements. The information determined includes effective velocity, attenuation length, and muon energy loss. The status and performance of the ToF are also regularly monitored by a laser-fiberoptics pulsing system.

Reconstructing ToF events starts by using tracks with trajectories extrapolated from the MDC. Each track is then matched with a particular ToF module; either the two layers of the barrel, or the single-layer endcap. The travel time for each hypothesis is then calculated using a weighted average of results from PMTs at both ends of the scintillator. Corrections are also applied to account for aspects like the effective light

velocity in the scintillator and the light attenuation length. Measurements of dE/dx are obtained for both charged and neutral particles, and are added back into the EMC in order to improve the shower energy resolution.

4.2.3 Electromagnetic Calorimeter

Simulating events in the EMC accounts for the crystals, casing, silicon photodiodes, preamplifier boxes, cables, and the support system. For each of the crystals and photodiodes, hit information is recorded, and the deposited energy is summed. From this, photon statistics are computed, and the resulting photodiode response is converted into electronic signals. To obtain the waveform in the time domain, an inverse Laplace transform is applied. Then, a sampling and peak searching process is simulated to yield energy and time information. For each bin, Gaussian-type electronic noise is added, and the background is produced by summing over the waveforms.

Calibration of the EMC uses Bhabha electrons with $E > 1.55 \text{ GeV}$ for the high energy response, and $\pi^0 \rightarrow \gamma\gamma$ decays for the low energy response. The responses for individual crystals must be analyzed separately, due to their potential intrinsic variations. As a result, they are monitored frequently by a LED light pulser, and periodically recalibrated. Corrections due to temperature variations can also be applied.

Reconstructing EMC events starts by converting the ADC value of each crystal into energy based on the calibration constants. After this, clusters in both the barrel and endcaps are formed by analyzing local maximum energy deposits, called seeds. A clustering algorithm then relates hits around these seeds and sums the values for a particular shower. The positions of each shower is then calculated using energy-weighted first moments. If multiple seeds are found in one cluster, a splitting algorithm is invoked to split the cluster into multiple showers. Additionally, matching energy deposits from the ToF are also added back into the total shower energy. This improves the energy resolution, particularly for low energy photons.

4.2.4 Muon Identifier

Simulating events in the MUC accounts for forming each RPC, creating sets of strips to form each read-out plane, combining each of these with aluminum boxes to form a

muon counter module, and placing the modules alongside iron slabs. The digitization from the read-out planes is selected to fire based off the distance away of each track. Noise is simulated using Poisson distributions initially determined from measurements made during the construction of the chamber, and updated with the taking of actual data.

Calibration of the MUC analyzes RPC detection efficiencies over a function of area. The cluster size and noise levels are also studied.

Reconstructing MUC events starts by searching for collected hits in each of the barrel and endcap orientations. The two collections are then combined with reconstructed tracks from the MDC. Since low momentum muons may cause only a few layers to fire, a subsequent search is performed over unused hits based on the extrapolated trajectories of MDC tracks. The reconstruction process primarily analyzes the depth of the track in the MUC, the maximum number of hits in the layers fired by a track, and the matching between a MDC track with the MUC stand-alone track. These parameters, along with the track momentum and MDC exit angle, are input into an Artificial Neural Network in order to distinguish between hadron and muon tracks. The distinction process is quite effective, generally removing $\sim 96\%$ of pions and keeping around $\sim 90\%$ of muons.

4.3 *D*-Tagging

From the decay of the $\psi(3770)$, the most commonly produced particles are $D^0\overline{D}^0$ or D^+D^- pairs. Since the $D\overline{D}$ pairs produced are two-body decays, the energy available to each D is half of the center-of-mass energy (in the center-of-mass reference frame). Each of these D mesons then quickly decays to certain sets of particles. Reconstructing one of these decays requires assembling the right combination of such particles. From energy and momentum conservation, the total 4-momentum of the constituents must match the total energy of the D meson.

This reconstruction technique is known as ‘*D*-Tagging’, and was pioneered by the MARK-III collaboration [42, 43]. For our analysis, the particles analyzed in the detector include π^\pm , K^\pm , π^0 , and K_S^0 , and the decay modes used are shown in Table 4.1. There are three D^0 modes and six D^+ modes, where charge conjugation (converting all particles to their anti-particles) is implied throughout the analysis. The modes used are chosen for

their effectiveness of reconstruction in the detector; they generally have higher branching fractions and minimize multiplicity (the number of tracks used). Additionally, for the neutral modes, the doubly-Cabbibo suppressed decays (DCSD), such as $D^0 \rightarrow K^+ \pi^-$, are also included by this procedure.

| | | |
|---|---|---|
| (0) $D^0 \rightarrow K^- \pi^+$ | (200) $D^+ \rightarrow K^- \pi^+ \pi^+$ | (203) $D^+ \rightarrow K_S^0 \pi^+ \pi^0$ |
| (1) $D^0 \rightarrow K^- \pi^+ \pi^0$ | (201) $D^+ \rightarrow K^- \pi^+ \pi^+ \pi^0$ | (204) $D^+ \rightarrow K_S^0 \pi^+ \pi^+ \pi^-$ |
| (3) $D^0 \rightarrow K^- \pi^+ \pi^+ \pi^-$ | (202) $D^+ \rightarrow K_S^0 \pi^+$ | (205) $D^+ \rightarrow K^+ K^- \pi^+$ |

Table 4.1: The reconstructed D -tag modes used in this analysis.

This process occurs for each event and searches over each decay mode for each charm (i.e., both D^+ and D^-). The combinations chosen for reconstruction are those with the smallest energy difference from the expected value. More than one D combination can be extracted from a given event, as long as it satisfies all other requirements (see Section 4.3.1). While this may sound like it overestimates the number of actual D particles found, the process is also used to calculate reconstruction efficiency, thereby cancelling out this effect.

4.3.1 Selection Cuts

Before being considered as potential reconstruction candidates, each track in the detector must also pass other cuts specific to its identified particle type. The following describes the necessary criteria required for the particles in the decay modes we are using.

π^\pm/K^\pm Selection

Each of the reconstructed charged tracks must pass vertex cuts in both the transverse ($x - y$) and beam (z) directions relative to the interaction point. This requires tracks originate sufficiently close to the interaction point to ensure they are not other backgrounds, such as cosmic rays, or other tracks which have decayed in flight. There is also a cut on the angle measured within the MDC (θ) to ensure the track has not disappeared down the beam-line (where detection cannot occur). Lastly, from the particle identification process, the probability of being a pion (kaon) must be more likely than being a kaon (pion). The values for each of these requirements can be found in Table 4.2.

| | |
|------------------|-----------------------------|
| Vertex (xy) | $V_{xy} < 1 \text{ cm}$ |
| Vertex (z) | $ Vz < 10 \text{ cm}$ |
| MDC Angle | $ \cos \theta < 0.93$ |
| Pion Probability | $P(\pi) > 0, P(\pi) > P(K)$ |
| Kaon Probability | $P(K) > 0, P(K) > P(\pi)$ |

Table 4.2: The required cuts to identify charged tracks as π^\pm or K^\pm .

γ Selection

To distinguish photon energy from noise, each shower in the EMC is required to have a certain amount of deposited energy. These cuts are different for the barrel ($|\cos \theta| < 0.80$) and endcap ($0.84 < |\cos \theta| < 0.92$) regions. Each photon must also pass a TDC timing cut to ensure they are consistent with actual physics events, and not originating at other times. The values for each of these requirements can be found in Table 4.3.

| | | |
|-------------------------|---|---------------------------------|
| Minimum Energy (Barrel) | $E_{\text{EMC}} > 25 \text{ MeV}$ | $(\cos \theta < 0.80)$ |
| Minimum Energy (Endcap) | $E_{\text{EMC}} > 50 \text{ MeV}$ | $(0.84 < \cos \theta < 0.92)$ |
| TDC Timing | $(0 \leq t \leq 14) \times 50 \text{ ns}$ | |

Table 4.3: The required cuts to identify neutral showers as a γ .

π^0 Selection

Reconstructing π^0 mesons involves finding $\gamma\gamma$ pairs, as this is its most dominant decay ($\sim 99\%$). Each of the γ showers used must pass the cuts described above. Additionally, at least one photon in the pair must be found in the barrel region. Each of the two photons are then kinematically fit to compare with the invariant mass of the π^0 , and must also pass a proper fit cut. The resulting momentum from this fit is used for reconstructing D -tag candidates. The values used for each of these requirements are shown in Table 4.4.

| | |
|--------------|---|
| Nominal Mass | $115 \text{ MeV} < m_{\pi^0} < 150 \text{ MeV}$ |
| Fit Quality | $\chi^2 < 200, \text{Converged}$ |

Table 4.4: The required cuts to reconstruct $\gamma\gamma$ pairs as a π^0 .

K_S^0 Selection

Reconstructing K_S^0 mesons involves finding $\pi^+\pi^-$ pairs, as this is its most common decay ($\sim 70\%$). While $\pi^0\pi^0$ pairs are also a substantial decay mode ($\sim 30\%$), these are not considered for reconstruction due to the increased difficulty of finding correct 4γ sets. To account for the K_S^0 decaying in flight, each of the charged pions considered are not subjected to the vertex or probability cuts in Table 4.2. Instead, the two found pions are kinematically constrained to a common vertex. The results must pass a nominal mass cut ($\sim 3\sigma$) and a proper fit cut to be deemed a K_S^0 . From this, the resulting momentum from the vertex fit is used for reconstructing D -tag candidates. The values used for each of these requirements are shown in Table 4.5.

| | |
|--------------|---|
| Nominal Mass | $487 \text{ MeV} < m_{K_S^0} < 511 \text{ MeV}$ |
| Fit Quality | $\chi^2 < 100$, Converged |

Table 4.5: The required cuts to reconstruct $\pi^+\pi^-$ pairs as a K_S^0 .

Cosmic Ray and Lepton Veto

Lastly, when reconstructing the mode $D^0 \rightarrow K^-\pi^+$, an additional veto is used. Since the mode has only two charged tracks, it is common to misidentify particles which come from cosmic ray and two-lepton backgrounds. To prevent this, cuts on the timing difference between the tracks, as well as on the particle identification process, are enacted. The values used for each of these requirements are shown in Table 4.6.

| | |
|-------------------------|--|
| Timing (TDC) | $ t_1 - t_2 < 5 \times 50 \text{ ns}$ |
| Particle Identification | $(\chi_{e^-}^2 + \chi_{e^+}^2) - (\chi_{K^-}^2 + \chi_{\pi^+}^2) > 10$ |

Table 4.6: Cuts to prevent cosmic ray and lepton backgrounds in $D^0 \rightarrow K^-\pi^+$.

4.3.2 Reconstruction

After each of the constituent particles are identified, a reconstructed D candidate can be characterized by two main properties:

$$\Delta E = |E_{\text{beam}} - E_{\text{tag}}|, \quad m_{\text{BC}} = \sqrt{E_{\text{beam}}^2 - |\vec{p}_{\text{tag}}|^2}. \quad (4.1)$$

These are the energy difference (ΔE) and the beam-constrained mass (m_{BC}), and effectively represent the energy and momentum of the D -tag, respectively. As the candidate with the smallest ΔE for each decay mode in each event is selected, the values will typically peak near 0 MeV. Distributions of m_{BC} , meanwhile, typically peak near $m_{D^0} = 1.865 \text{ GeV}$ or $m_{D^+} = 1.870 \text{ GeV}$. Additionally, while invariant mass ($m_{\text{inv}} = \sqrt{E_{\text{tag}}^2 - |\vec{p}_{\text{tag}}|^2}$) can also be examined, m_{BC} is generally preferred due to a higher precision for the beam energy than of the individual particles comprising the D candidate.

Chapter 5

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

The main objective of this analysis is to measure the $\sigma_{\psi(3770) \rightarrow D\bar{D}}$ cross section at center-of-mass energies around the $\psi(3770)$. While the cross section very near the $\psi(3770)$ mass has been measured with excellent precision [44], the shape over a wider energy range has not been measured to a precise degree. This has left open the possibility of multiple functional shapes which could describe the cross section, and asks the question of whether or not to include interference effects. Fits to this region with a single Breit-Wigner shape (i.e., no interference) have provided an unsatisfactory description of the $\psi(3770)$, and further necessitate the need for interference. The most prominent candidate for shapes with interference assume a contribution from the lower mass $\psi(2S)$ state, and is the form considered here.

5.1 Form Factors

The procedure for this analysis largely follows the methodology of the KEDR collaboration [5]. With the larger statistics available at BESIII, however, an inclusive cross section measurement (such as performed by KEDR) is not required. Instead, the goal is to measure the production rate of $D\bar{D}$ events decaying from $\psi(3770)$ directly. The derivation for this cross section is given in Section 2.3. However, the description of the form factor contribution (Equation (2.9)) must still be determined. Since we assume

the $\psi(2S)$ resonant contribution is negligible in the energy range of our measurements, the only major resonant contribution is from the $\psi(3770)$:

$$F_D(W) = F_D^{\text{NR}}(W) + F_D^{\psi(3770)}(W) e^{i\phi^{\psi(3770)}}. \quad (5.1)$$

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

$$F_D^{\text{NR}} = F_{\text{NR}} \exp(-q_D^2/a_{\text{NR}}^2), \quad (5.2)$$

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 $D\bar{D}$ production above threshold,

$$F_D^{\text{NR}}(W) = F_D^{\psi(2S)}(W) + F_0, \quad (5.3)$$

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 Equation (2.10), but with a modification to the total width:

$$\Gamma^{\psi(2S)}(W) = \left(\frac{M^{\psi(2S)}}{W} \right) \left[\frac{z_{D^0\bar{D}^0}(W) d_{D^0\bar{D}^0}(W) + z_{D^+D^-}(W) d_{D^+D^-}(W)}{z_{D^0\bar{D}^0}(M^{\psi''}) d_{D^0\bar{D}^0}(M^{\psi''}) + z_{D^+D^-}(M^{\psi''}) d_{D^+D^-}(M^{\psi''})} \right] \Gamma^{\psi(2S)}(M). \quad (5.4)$$

Without this modification, the mass of the $\psi(2S)$ would be below the $D\bar{D}$ threshold, and thus, the vanishing $z_{D\bar{D}}$ 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 Equation (5.4), the true physical meaning of the parameter $\Gamma^{\psi(2S)}(W)$ is uncertain. For the radii in Equation (2.12), however, the values used are distinct for each meson: $R_{\psi(2S)} = 0.75$ fm and $R_{\psi(3770)} = 1.00$ fm.

5.2 Data and Monte Carlo Samples

5.2.1 Data Samples

This analysis primarily uses scan data produced by BEPCII and collected by BESIII in 2010 over an energy range of 3.643 GeV to 3.890 GeV. These data are partitioned into 34 center-of-mass energy (E_{cm}) bins of variable size over a range of 3.735 GeV to 3.870 GeV. The bin partitioning was determined from measurements of center-of-mass energies (Section 5.2.2). The total range was chosen to be above the $D^0\bar{D}^0$ threshold (3.730 GeV) and below the $D^{*0}\bar{D}^0$ threshold (3.872 GeV). This range includes bins which are below the threshold for D^+D^- (3.739 GeV), with production beginning in the third bin.

Additionally, there are three higher statistics points used for comparison. These include an ‘On-Peak $\psi(3770)$ ’ sample of 2.93 fb^{-1} at $E_{\text{cm}} = 3.7732 \text{ GeV}$, an ‘XYZ-scan’ sample of 50.54 pb^{-1} at $E_{\text{cm}} = 3.810 \text{ GeV}$, and an ‘R-scan’ sample of 7.95 pb^{-1} at $E_{\text{cm}} = 3.850 \text{ GeV}$. The first of these is the high statistics measurement very near the $\psi(3770)$ mass using double-tag reconstruction (both D and \bar{D} in a single event) performed by Derrick Toth. The other two samples were analyzed using the same procedure as for the scan data (See Sections 5.3 to 5.5). None of these points are used to determine the final results, as the differences between samples introduce additional systematics which overshadow any statistical improvement. However, these provide useful comparisons at important energy points along the cross section shape.

5.2.2 Center-of-Mass Energy Measurement

To precisely determine the values of center-of-mass energy along the scan data region, events of $e^+e^- \rightarrow \mu^+\mu^-$ collisions were analyzed to determine their invariant mass (m_{inv}). Assuming minimal radiating energy from the muons, this value is effectively equal to the energy produced by the collider. The selection process for such events is shown in Table 5.1. The statistics of the scan data are too small to precisely determine the energy for individual runs. Therefore, multiple runs were combined together into bins based off the assumption each was taken at nearly identical energies. A comparison of the measured values to the online beam energies is shown in Figure 5.1.

| | |
|-----------------------|--|
| Vertex (xy) | $V_{xy} < 1 \text{ cm}$ |
| Vertex (z) | $ Vz < 10 \text{ cm}$ |
| MDC Angle | $ \cos \theta ^{\mu^\pm} < 0.80$ |
| Muon Opening Angle | $\cos(179.64^\circ) < \cos \theta_{\mu\mu} < \cos(178.60^\circ)$ |
| Energy-Momentum Ratio | $0.05 \leq (E/p)^{\mu^\pm} < 0.15$ |
| Shower Energy | $0.0 \text{ GeV} < E_{EMC}^{\mu^\pm} < 0.3 \text{ GeV}$ |

Table 5.1: Selection cuts on muon tracks used to determine the center-of-mass energy.

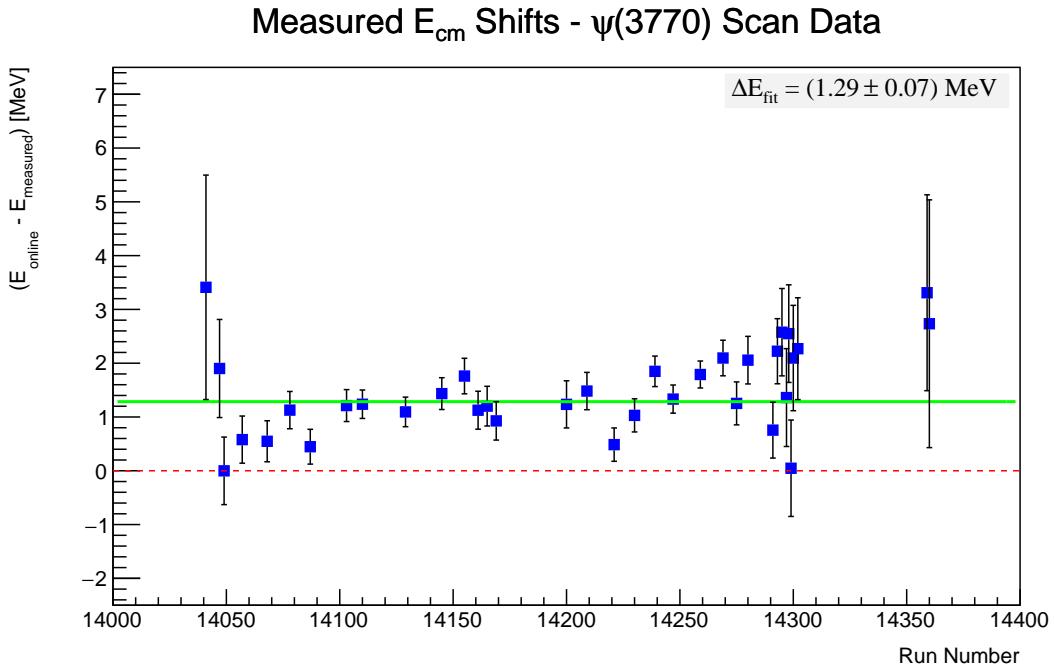


Figure 5.1: The differences measured for scan data center-of-mass energies. The average difference (green) is about 1.29 MeV higher than the recorded energy values provided by the collider at run time (red).

The use of muons to determine energy is subject to an overall scale shift due to potentially miscalibrated magnetic field effects. This requires a point of reference in order to ensure the measured values are correctly determined. We use the first round of the on-peak $\psi(3770)$ sample for this comparison, as its center-of-mass energy has been alternatively measured to a very precise degree [45]. The results of this method compared to our own for the on-peak data are shown in Figure 5.2. It is evident the

official procedure using $D\bar{D}$ events provides more stability over the run range than using muons. Still, the difference between average values of each measurement is taken as the offset for shifting the measured scan data points. From this, the measured center-of-mass energies for the scan data are increased by 1.86 MeV to determine the final values. Compared to the initial measurements of scan data energy, this indicates the values were lower by ~ 0.7 MeV on average. The final center-of-mass energies of the scan data, along with the luminosity of each bin, are shown in Table 5.3.

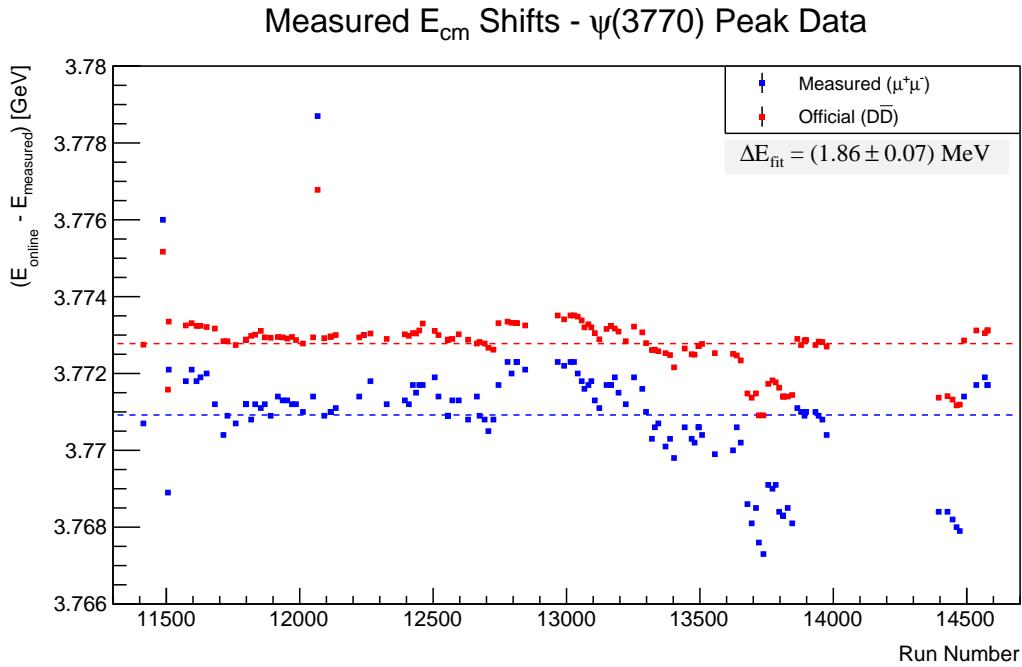


Figure 5.2: The values measured for on-peak data center-of-mass energies. The difference between our measured values (blue) and the official values (red) is used to shift the results of the measured scan data energy values.

5.2.3 Luminosity Measurement

To precisely determine the values of luminosity for each bin, radiative Bhabha events ($e^+e^- \rightarrow e^+e^-(\gamma)$) were analyzed to determine the total number of collisions produced. The procedure used is described in Ref. [46]. For each run, 1.4×10^6 events were generated using Babayaga 3.5. We select events with only two (oppositely) charged tracks, satisfying the event selection criteria shown in Table 5.2.

| | |
|--|--|
| Vertex (xy) | $V_{xy} < 1 \text{ cm}$ |
| Vertex (z) | $ Vz < 10 \text{ cm}$ |
| MDC Angle | $ \cos \theta < 0.80$ |
| Exclude $e^+e^- \rightarrow \mu^+\mu^-(\gamma)$ Events | $E_{\text{EMC}} > 0.73 \times E_{\text{beam}}$ |
| Exclude $e^+e^- \rightarrow \gamma J/\psi, J/\psi \rightarrow e^+e^-$ Events | $p > 0.93 \times E_{\text{beam}}$ |

Table 5.2: Selection cuts on electron tracks used to determine the luminosity.

Applying these cuts to both data and MC identically, we use the resulting number of events found in the MC divided by the number of total generated events to determine the efficiency (ϵ_{MC}). From this, and using the cross section provided by the generator (σ_{Bhabha}), we can take the events found in data (N_{data}) to determine the integrated luminosity (\mathcal{L}) of each run:

$$\mathcal{L} = \frac{N_{\text{data}}}{\sigma_{\text{Bhabha}} \epsilon_{MC}} \quad (5.5)$$

The integrated luminosity for each bin is shown in Table 5.3. The total luminosity for the scan data used is $(69.80 \pm 0.03) \text{ pb}^{-1}$, where the error listed is statistical.

| Bin | Run Range | E_{cm} Range [GeV] | \mathcal{L} [pb $^{-1}$] |
|-----|---------------|-----------------------------|-----------------------------|
| 0 | 14041 - 14046 | 3.734 - 3.736 | 0.8293(30) |
| 1 | 14360 - 14360 | 3.736 - 3.744 | 0.3287(19) |
| 2 | 14047 - 14048 | 3.744 - 3.748 | 0.9524(32) |
| 3 | 14049 - 14053 | 3.748 - 3.750 | 1.4055(39) |
| 4 | 14057 - 14067 | 3.750 - 3.751 | 2.2717(50) |
| 5 | 14068 - 14077 | 3.751 - 3.753 | 2.9702(57) |
| 6 | 14078 - 14086 | 3.753 - 3.755 | 3.3080(60) |
| 7 | 14087 - 14101 | 3.755 - 3.756 | 3.4162(61) |
| 8 | 14103 - 14109 | 3.756 - 3.759 | 3.8712(65) |
| 9 | 14110 - 14123 | 3.759 - 3.762 | 4.4382(70) |
| 10 | 14129 - 14144 | 3.762 - 3.765 | 4.4896(70) |
| 11 | 14145 - 14154 | 3.765 - 3.767 | 3.2828(60) |
| 12 | 14155 - 14160 | 3.767 - 3.771 | 2.4418(52) |
| 13 | 14161 - 14164 | 3.771 - 3.774 | 2.0151(47) |
| 14 | 14165 - 14168 | 3.774 - 3.777 | 1.8261(45) |
| 15 | 14169 - 14174 | 3.777 - 3.780 | 1.8237(45) |
| 16 | 14200 - 14203 | 3.780 - 3.782 | 1.9505(46) |
| 17 | 14209 - 14217 | 3.782 - 3.787 | 2.1500(49) |
| 18 | 14221 - 14226 | 3.787 - 3.789 | 2.5488(53) |
| 19 | 14230 - 14238 | 3.789 - 3.792 | 2.8320(56) |
| 20 | 14239 - 14246 | 3.792 - 3.797 | 3.5310(63) |
| 21 | 14247 - 14258 | 3.797 - 3.800 | 4.0479(67) |
| 22 | 14259 - 14268 | 3.800 - 3.802 | 3.9284(66) |
| 23 | 14269 - 14274 | 3.802 - 3.807 | 2.6929(55) |
| 24 | 14275 - 14279 | 3.807 - 3.809 | 1.7604(44) |
| 25 | 14280 - 14290 | 3.809 - 3.813 | 1.2539(38) |
| 26 | 14291 - 14292 | 3.813 - 3.815 | 0.8969(32) |
| 27 | 14293 - 14294 | 3.815 - 3.823 | 0.6803(28) |
| 28 | 14295 - 14296 | 3.823 - 3.832 | 0.3997(21) |
| 29 | 14297 - 14297 | 3.832 - 3.839 | 0.2846(18) |
| 30 | 14298 - 14298 | 3.839 - 3.849 | 0.2802(18) |
| 31 | 14299 - 14299 | 3.849 - 3.855 | 0.2764(18) |
| 32 | 14300 - 14301 | 3.855 - 3.863 | 0.3188(19) |
| 33 | 14302 - 14303 | 3.863 - 3.870 | 0.3002(19) |

Table 5.3: Measured luminosities for each energy bin.
The uncertainties listed are statistical errors from the data selection, as uncertainties from the MC statistics are negligible.

5.2.4 Monte Carlo Generation

To compare to the scan data sample, several Monte Carlo (MC) samples were produced. For the main signal determination, samples of generic $D^0\overline{D}^0$ from $\psi(3770)$ and generic D^+D^- from $\psi(3770)$ were generated with 2×10^5 events per bin. In addition, $100 \times$ data-size samples were produced for $q\bar{q}$, $\tau^-\tau^+$, radiative return to J/ψ (denoted $\gamma J/\psi$), and radiative return to $\psi(2S)$ (denoted $\gamma\psi'$). Each of these samples was generated at the University of Minnesota in July of 2014 using BOSS 6.6.4.p02. The $D^0\overline{D}^0$, D^+D^- , $q\bar{q}$, and $\tau^-\tau^+$ states were generated using KKMC, while the $\gamma J/\psi$ and $\gamma\psi'$ were generated with BesEvtGen. All except $q\bar{q}$ were then decayed with BesEvtGen. The total numbers of events in each sample can be found in Table 5.4.

| Sample | Number of Events |
|--|---------------------|
| $\psi(3770) \rightarrow D^0\overline{D}^0$ | 6.800×10^6 |
| $\psi(3770) \rightarrow D^+D^-$ | 6.400×10^6 |
| $q\bar{q}$ | 8.916×10^7 |
| $\gamma J/\psi$ | 7.307×10^6 |
| $\gamma\psi'$ | 2.457×10^7 |
| $\tau^-\tau^+$ | 2.164×10^7 |
| Data | 4.844×10^8 |

Table 5.4: Number of events contained in each generated sample and the scan data.

In general, all MC samples were generated based off communal decay card information used within BESIII. However, the $D\overline{D}$ samples were generated by implementing the Born-level cross section shape from the final fit into KKMC. This procedure was repeated over five iterations in order to provide a more data-driven basis for the ISR corrections. The effects of this process are examined in Section 5.6.

5.2.5 Software Packages

The main packages used for this analysis are shown in Table 5.5. The package `DtagRecAlg` is a custom package used to extract variables from `DTagAlg` relevant to the analysis.

| Package | Version |
|------------|-----------|
| KKMC | v00-00-51 |
| DTagAlg | v00-00-51 |
| DTagRecAlg | v00-00-01 |

Table 5.5: The software packages used in this analysis and their version numbers.

5.3 Signal Determination

We measure the yields of both $D^0\overline{D}^0$ and D^+D^- events with two-dimensional fits to ΔE and m_{BC} . MC samples are partitioned into the following four groups: proper D -tags ($N_{D\bar{D}}$), misreconstructed D -tags (N_{misrec}), continuum ($N_{q\bar{q}}$), and other (N_{other}). The first two groups are obtained using truth information from the $D\bar{D}$ samples, while the last group is a combination of the $\tau^-\tau^+$, $\gamma J/\psi$, and $\gamma\psi'$ samples. These groups are fitted to data using the RooFit package to perform a negative log-likelihood minimization for each energy bin (E_i) separately for both D^0 and D^+ . For each fit, the four MC sample groups are used to construct 2D (ΔE vs. m_{BC}) PDF functions that are fitted against the corresponding data histograms. The proper $D\bar{D}$ shape is treated as signal, and its integral after fitting (N_D) is used for determining the signal yields and cross sections. An example fit is shown in Fig. 5.3, while the complete set of these plots can be found in Appendices B and C.

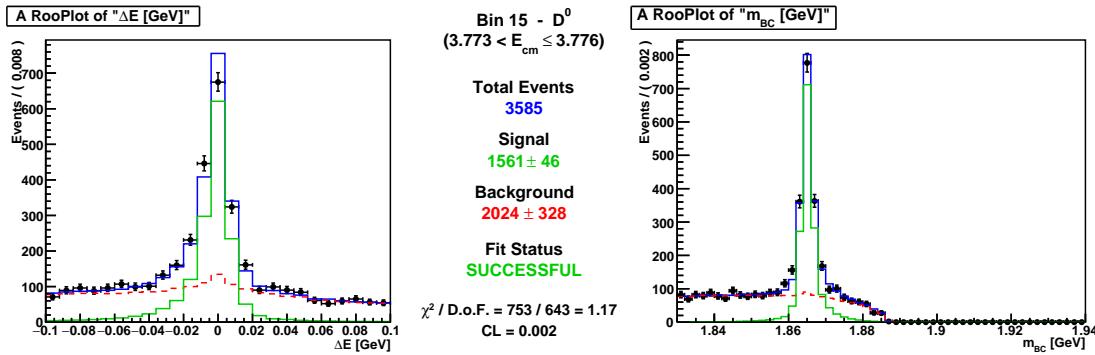


Figure 5.3: An example 2D (ΔE vs. m_{BC}) signal fit.

The covers D^0 events in the region $3.773 \text{ GeV} < E_{\text{cm}} \leq 3.776 \text{ GeV}$. The data points (black) are fitted by the total MC shape (blue), which is the sum of the signal (green) and background (red) components.

5.4 Efficiency Correction

In addition to the parameters gathered by `DTagAlg`, truth information was taken from the generic $D\bar{D}$ samples in order to determine the mode-by-mode reconstruction efficiency. To be deemed proper, a reconstruction must pass not only the standard D -tag cuts, but also match the generator information for the event. This process removes peaking backgrounds from modes with similar constituents. The total number of proper D -tag reconstructions is then divided by the number of D particles generated for each mode, and the mode-by-mode efficiencies are weighted by the PDG branching ratios [6] to determine the overall efficiency (ϵ_D) for each of D^0 and D^+ :

$$\epsilon_D = \sum_i \epsilon_i \text{ rec } \mathcal{B}_i = \sum_i \left(\frac{N_i \text{ prop}}{N_i \text{ gen}} \right) \mathcal{B}_i. \quad (5.6)$$

Each D^0 efficiency also includes the corresponding DCSD terms for its decay (See Section 4.3).

To determine the cross section at each point, this procedure was applied separately for each energy bin. The total number of proper and generated particles for each energy bin are shown in Table 5.6 for D^0 and Tables 5.7 and 5.8 for D^+ . The efficiencies for D^+ and D^0 were also calculated across the total sample, and are shown for each mode in Table 5.9 and Figure 5.4. Total efficiencies of each bin for both D^0 and D^+ are shown in Table 5.10.

5.4.1 CP Violation Correction

Due to CP violation in the $D^0\bar{D}^0$ system, each of the neutral decay modes must be corrected to account for quantum correlations. This is done by applying scaling factors to the efficiency for each of the three modes used in reconstruction. The corrections are parameterized for each mode (m) by the following form [47]:

$$\alpha_{D^0 \rightarrow m} = 1 + r_m^2 + 2 \times y \times r_m \times R_m \times \cos(\delta_m). \quad (5.7)$$

Here, r_m and δ_m represent the relative magnitudes and phases between the Cabibbo-favored and doubly-Cabibbo-suppressed modes, respectively, while the factor of R_m

| Bin | $D^0 \rightarrow K^- \pi^+$ | | | $D^0 \rightarrow K^- \pi^+ \pi^0$ | | | $D^0 \rightarrow K^- \pi^+ \pi^+ \pi^-$ | | |
|-----|-----------------------------|------------------|-------------------------|-----------------------------------|------------------|-------------------------|---|------------------|-------------------------|
| | N_{prop} | N_{gen} | ϵ_{rec} | N_{prop} | N_{gen} | ϵ_{rec} | N_{prop} | N_{gen} | ϵ_{rec} |
| 0 | 11197 | 15757 | 0.711 | 21600 | 55815 | 0.387 | 13592 | 33714 | 0.403 |
| 1 | 11266 | 15713 | 0.717 | 21735 | 56189 | 0.387 | 13651 | 33621 | 0.406 |
| 2 | 11065 | 15557 | 0.711 | 21683 | 55791 | 0.389 | 13984 | 33431 | 0.418 |
| 3 | 10748 | 15501 | 0.693 | 21114 | 55767 | 0.379 | 13168 | 33505 | 0.393 |
| 4 | 11176 | 15779 | 0.708 | 21922 | 55873 | 0.392 | 13613 | 33410 | 0.407 |
| 5 | 10984 | 15722 | 0.699 | 21366 | 56027 | 0.381 | 13483 | 33748 | 0.400 |
| 6 | 10837 | 15507 | 0.699 | 21144 | 55551 | 0.381 | 13738 | 33639 | 0.408 |
| 7 | 10707 | 15645 | 0.684 | 20889 | 56193 | 0.372 | 13074 | 33494 | 0.390 |
| 8 | 11031 | 15585 | 0.708 | 21788 | 55891 | 0.390 | 13967 | 33826 | 0.413 |
| 9 | 10994 | 15485 | 0.710 | 21978 | 56012 | 0.392 | 14020 | 33601 | 0.417 |
| 10 | 10952 | 15497 | 0.707 | 21400 | 56126 | 0.381 | 13727 | 33591 | 0.409 |
| 11 | 11025 | 15535 | 0.710 | 21700 | 55919 | 0.388 | 13980 | 33706 | 0.415 |
| 12 | 10909 | 15593 | 0.700 | 21713 | 55876 | 0.389 | 13787 | 33335 | 0.414 |
| 13 | 11088 | 15826 | 0.701 | 21696 | 55758 | 0.389 | 14013 | 33805 | 0.415 |
| 14 | 10975 | 15620 | 0.703 | 21576 | 55591 | 0.388 | 14039 | 33581 | 0.418 |
| 15 | 10965 | 15672 | 0.700 | 21501 | 55647 | 0.386 | 13777 | 33644 | 0.409 |
| 16 | 10803 | 15438 | 0.700 | 21505 | 55667 | 0.386 | 13832 | 33822 | 0.409 |
| 17 | 10913 | 15473 | 0.705 | 21574 | 56023 | 0.385 | 14163 | 34131 | 0.415 |
| 18 | 11156 | 15856 | 0.704 | 21461 | 55706 | 0.385 | 13725 | 33321 | 0.412 |
| 19 | 11124 | 15728 | 0.707 | 21775 | 56192 | 0.388 | 13930 | 33935 | 0.410 |
| 20 | 10837 | 15530 | 0.698 | 21149 | 55737 | 0.379 | 13883 | 33703 | 0.412 |
| 21 | 10756 | 15397 | 0.699 | 21212 | 55815 | 0.380 | 13577 | 33907 | 0.400 |
| 22 | 10986 | 15582 | 0.705 | 21178 | 56343 | 0.376 | 13352 | 33773 | 0.395 |
| 23 | 11147 | 15861 | 0.703 | 21088 | 56167 | 0.375 | 13200 | 33680 | 0.392 |
| 24 | 10785 | 15633 | 0.690 | 20763 | 55952 | 0.371 | 12651 | 33660 | 0.376 |
| 25 | 10972 | 15490 | 0.708 | 20687 | 55957 | 0.370 | 12841 | 33512 | 0.383 |
| 26 | 11016 | 15645 | 0.704 | 20707 | 55785 | 0.371 | 12563 | 33615 | 0.374 |
| 27 | 10800 | 15420 | 0.700 | 20244 | 55748 | 0.363 | 12362 | 33359 | 0.371 |
| 28 | 10939 | 15694 | 0.697 | 20077 | 55550 | 0.361 | 12507 | 33497 | 0.373 |
| 29 | 10839 | 15689 | 0.691 | 20685 | 56386 | 0.367 | 12575 | 33551 | 0.375 |
| 30 | 10798 | 15766 | 0.685 | 20238 | 55433 | 0.365 | 12526 | 33885 | 0.370 |
| 31 | 10568 | 15438 | 0.685 | 20533 | 55825 | 0.368 | 12901 | 33745 | 0.382 |
| 32 | 10820 | 15679 | 0.690 | 20706 | 55823 | 0.371 | 13155 | 33810 | 0.389 |
| 33 | 10643 | 15736 | 0.676 | 20488 | 55672 | 0.368 | 12875 | 33547 | 0.384 |

Table 5.6: Number of proper and generated particles for D^0 .
The mode-by-mode numbers of particles used in the efficiency calculations for
 $D^0 \rightarrow K^- \pi^+$, $D^0 \rightarrow K^- \pi^+ \pi^0$, and $D^0 \rightarrow K^- \pi^+ \pi^+ \pi^-$.

| Bin | $D^+ \rightarrow K^- \pi^+ \pi^+$ | | | $D^+ \rightarrow K^- \pi^+ \pi^+ \pi^0$ | | | $D^+ \rightarrow K_S^0 \pi^+$ | | |
|-----|-----------------------------------|------------------|-------------------------|---|------------------|-------------------------|-------------------------------|------------------|-------------------------|
| | N_{prop} | N_{gen} | ϵ_{rec} | N_{prop} | N_{gen} | ϵ_{rec} | N_{prop} | N_{gen} | ϵ_{rec} |
| 2 | 20643 | 37609 | 0.549 | 6853 | 24250 | 0.283 | 2302 | 5900 | 0.390 |
| 3 | 19935 | 37582 | 0.530 | 6569 | 24235 | 0.271 | 2335 | 6114 | 0.382 |
| 4 | 20859 | 37915 | 0.550 | 6653 | 24216 | 0.275 | 2291 | 5879 | 0.390 |
| 5 | 20193 | 37647 | 0.536 | 6611 | 24051 | 0.275 | 2292 | 5965 | 0.384 |
| 6 | 20484 | 37814 | 0.542 | 6616 | 24184 | 0.274 | 2292 | 5924 | 0.387 |
| 7 | 19635 | 37462 | 0.524 | 6411 | 24708 | 0.259 | 2127 | 5815 | 0.366 |
| 8 | 20876 | 37758 | 0.553 | 6867 | 24343 | 0.282 | 2328 | 5841 | 0.399 |
| 9 | 20873 | 37739 | 0.553 | 6754 | 24284 | 0.278 | 2377 | 5911 | 0.402 |
| 10 | 20571 | 37487 | 0.549 | 6604 | 24249 | 0.272 | 2360 | 6010 | 0.393 |
| 11 | 20669 | 37468 | 0.552 | 6818 | 24268 | 0.281 | 2296 | 5904 | 0.389 |
| 12 | 20843 | 37838 | 0.551 | 6783 | 24247 | 0.280 | 2401 | 6074 | 0.395 |
| 13 | 20486 | 37286 | 0.549 | 6942 | 24582 | 0.282 | 2335 | 6184 | 0.378 |
| 14 | 20935 | 37961 | 0.551 | 6836 | 24467 | 0.279 | 2282 | 5963 | 0.383 |
| 15 | 20543 | 37458 | 0.548 | 6769 | 24135 | 0.280 | 2295 | 5889 | 0.390 |
| 16 | 20713 | 37543 | 0.552 | 6758 | 24376 | 0.277 | 2356 | 5921 | 0.398 |
| 17 | 21016 | 37757 | 0.557 | 6949 | 24470 | 0.284 | 2302 | 5903 | 0.390 |
| 18 | 21123 | 38024 | 0.556 | 6635 | 24111 | 0.275 | 2320 | 5889 | 0.394 |
| 19 | 20708 | 37357 | 0.554 | 6662 | 24240 | 0.275 | 2204 | 5855 | 0.376 |
| 20 | 20760 | 37761 | 0.550 | 6768 | 24395 | 0.277 | 2263 | 5883 | 0.385 |
| 21 | 20860 | 37893 | 0.550 | 6668 | 24216 | 0.275 | 2296 | 5996 | 0.383 |
| 22 | 20827 | 37820 | 0.551 | 6673 | 24421 | 0.273 | 2353 | 5997 | 0.392 |
| 23 | 20796 | 37554 | 0.554 | 6723 | 24377 | 0.276 | 2290 | 5957 | 0.384 |
| 24 | 20058 | 37410 | 0.536 | 6415 | 24310 | 0.264 | 2341 | 5966 | 0.392 |
| 25 | 20677 | 37552 | 0.551 | 6462 | 24245 | 0.267 | 2364 | 5987 | 0.395 |
| 26 | 20300 | 37491 | 0.541 | 6539 | 24405 | 0.268 | 2356 | 5993 | 0.393 |
| 27 | 20754 | 37704 | 0.550 | 6530 | 24295 | 0.269 | 2288 | 5969 | 0.383 |
| 28 | 20213 | 37428 | 0.540 | 6362 | 24146 | 0.263 | 2341 | 5988 | 0.391 |
| 29 | 20565 | 37545 | 0.548 | 6495 | 24257 | 0.268 | 2262 | 5916 | 0.382 |
| 30 | 20313 | 37773 | 0.538 | 6535 | 24167 | 0.270 | 2323 | 6075 | 0.382 |
| 31 | 20322 | 37280 | 0.545 | 6566 | 24389 | 0.269 | 2378 | 5927 | 0.401 |
| 32 | 20883 | 37992 | 0.550 | 6594 | 24249 | 0.272 | 2306 | 5855 | 0.394 |
| 33 | 20645 | 37738 | 0.547 | 6560 | 24195 | 0.271 | 2269 | 5945 | 0.382 |

Table 5.7: Number of proper and generated particles for D^+ (part 1).
The mode-by-mode numbers of particles used in the efficiency calculations for
 $D^+ \rightarrow K^- \pi^+ \pi^+$, $D^+ \rightarrow K^- \pi^+ \pi^+ \pi^0$, and $D^+ \rightarrow K_S^0 \pi^+$.

| Bin | $D^+ \rightarrow K_S^0 \pi^+ \pi^0$ | | | $D^+ \rightarrow K_S^0 \pi^+ \pi^+ \pi^-$ | | | $D^+ \rightarrow K^+ K^- \pi^+$ | | |
|-----|-------------------------------------|------------------|-------------------------|---|------------------|-------------------------|---------------------------------|------------------|-------------------------|
| | N_{prop} | N_{gen} | ϵ_{rec} | N_{prop} | N_{gen} | ϵ_{rec} | N_{prop} | N_{gen} | ϵ_{rec} |
| 2 | 5742 | 27235 | 0.211 | 3562 | 15019 | 0.237 | 1720 | 4019 | 0.428 |
| 3 | 5668 | 27699 | 0.205 | 3169 | 14877 | 0.213 | 1637 | 3970 | 0.412 |
| 4 | 5710 | 27527 | 0.207 | 3358 | 14750 | 0.228 | 1791 | 4016 | 0.446 |
| 5 | 5614 | 27654 | 0.203 | 3282 | 14696 | 0.223 | 1748 | 3981 | 0.439 |
| 6 | 5656 | 27475 | 0.206 | 3392 | 14823 | 0.229 | 1771 | 4075 | 0.435 |
| 7 | 5481 | 27597 | 0.199 | 3293 | 14860 | 0.222 | 1593 | 3951 | 0.403 |
| 8 | 5827 | 27975 | 0.208 | 3462 | 15035 | 0.230 | 1736 | 4042 | 0.429 |
| 9 | 6003 | 27589 | 0.218 | 3427 | 14906 | 0.230 | 1716 | 3940 | 0.436 |
| 10 | 5722 | 27751 | 0.206 | 3327 | 14854 | 0.224 | 1690 | 3941 | 0.429 |
| 11 | 5888 | 27649 | 0.213 | 3385 | 14837 | 0.228 | 1672 | 3930 | 0.425 |
| 12 | 5731 | 27651 | 0.207 | 3370 | 14926 | 0.226 | 1718 | 3889 | 0.442 |
| 13 | 5792 | 27618 | 0.210 | 3336 | 14669 | 0.227 | 1696 | 3958 | 0.428 |
| 14 | 5745 | 27608 | 0.208 | 3288 | 14702 | 0.224 | 1712 | 3904 | 0.439 |
| 15 | 5832 | 27480 | 0.212 | 3384 | 14808 | 0.229 | 1649 | 3855 | 0.428 |
| 16 | 5891 | 27758 | 0.212 | 3443 | 14845 | 0.232 | 1783 | 3947 | 0.452 |
| 17 | 5954 | 27639 | 0.215 | 3484 | 14910 | 0.234 | 1804 | 3941 | 0.458 |
| 18 | 5875 | 27669 | 0.212 | 3366 | 14913 | 0.226 | 1700 | 3968 | 0.428 |
| 19 | 5773 | 27838 | 0.207 | 3371 | 14782 | 0.228 | 1766 | 4037 | 0.437 |
| 20 | 6024 | 28019 | 0.215 | 3367 | 14801 | 0.227 | 1709 | 3903 | 0.438 |
| 21 | 5804 | 27645 | 0.210 | 3306 | 14819 | 0.223 | 1688 | 3863 | 0.437 |
| 22 | 5893 | 27692 | 0.213 | 3304 | 14949 | 0.221 | 1741 | 3975 | 0.438 |
| 23 | 5780 | 27865 | 0.207 | 3313 | 14981 | 0.221 | 1670 | 3891 | 0.429 |
| 24 | 5623 | 27811 | 0.202 | 3161 | 14867 | 0.213 | 1667 | 3954 | 0.422 |
| 25 | 5684 | 27490 | 0.207 | 3250 | 14794 | 0.220 | 1711 | 3966 | 0.431 |
| 26 | 5704 | 27829 | 0.205 | 3137 | 14811 | 0.212 | 1641 | 3958 | 0.415 |
| 27 | 5630 | 27497 | 0.205 | 3132 | 14881 | 0.210 | 1678 | 3972 | 0.422 |
| 28 | 5724 | 28006 | 0.204 | 3271 | 14828 | 0.221 | 1690 | 3931 | 0.430 |
| 29 | 5693 | 27554 | 0.207 | 3272 | 15009 | 0.218 | 1772 | 3994 | 0.444 |
| 30 | 5574 | 27717 | 0.201 | 3308 | 14730 | 0.225 | 1673 | 4026 | 0.416 |
| 31 | 5556 | 27556 | 0.202 | 3288 | 15049 | 0.218 | 1746 | 3965 | 0.440 |
| 32 | 5785 | 27634 | 0.209 | 3259 | 14840 | 0.220 | 1680 | 3923 | 0.428 |
| 33 | 5653 | 27528 | 0.205 | 3287 | 14959 | 0.220 | 1734 | 4031 | 0.430 |

Table 5.8: Number of proper and generated particles for D^+ (part 2).
The mode-by-mode numbers of particles used in the efficiency calculations for
 $D^+ \rightarrow K_S^0 \pi^+ \pi^0$, $D^+ \rightarrow K_S^0 \pi^+ \pi^+ \pi^-$, and $D^+ \rightarrow K^+ K^- \pi^+$.

| Decay Mode (i) | PDG \mathcal{B}_i [%] | MC Efficiency ϵ_i |
|---|-------------------------|----------------------------|
| $D^0 \rightarrow K^- \pi^+$ | 3.89 ± 0.05 | 0.7002 ± 0.0011 |
| $D^0 \rightarrow K^- \pi^+ \pi^0$ | 13.93 ± 0.50 | 0.3794 ± 0.0004 |
| $D^0 \rightarrow K^- \pi^+ \pi^+ \pi^-$ | 8.11 ± 0.21 | 0.3988 ± 0.0006 |
| $\epsilon_{D^0} = (11.245 \pm 0.020)\%$ | | |
| $D^+ \rightarrow K^- \pi^+ \pi^+$ | 9.13 ± 0.19 | 0.5471 ± 0.0007 |
| $D^+ \rightarrow K^- \pi^+ \pi^+ \pi^0$ | 5.99 ± 0.18 | 0.2739 ± 0.0006 |
| $D^+ \rightarrow K_S^0 \pi^+$ | 1.47 ± 0.07 | 0.3883 ± 0.0014 |
| $D^+ \rightarrow K_S^0 \pi^+ \pi^0$ | 6.99 ± 0.27 | 0.2079 ± 0.0005 |
| $D^+ \rightarrow K_S^0 \pi^+ \pi^+ \pi^-$ | 3.12 ± 0.11 | 0.2237 ± 0.0007 |
| $D^+ \rightarrow K^+ K^- \pi^+$ | 0.95 ± 0.03 | 0.4317 ± 0.0018 |
| $\epsilon_{D^+} = (9.770 \pm 0.063)\%$ | | |

Table 5.9: Mode-by-mode reconstruction efficiencies for D^0 and D^+ .

The values shown are over the entire data sample, while calculations for the cross sections use the values of each energy point individually (see Table 5.10). The errors listed on the PDG branching fractions are shown for reference, and are not included in the efficiency errors (see Section 5.6.1).

represents a coherence factor characterizing the variation of δ_m over phase space. Note, there is no such variation for a two-body decay (like $D^0 \rightarrow K^- \pi^+$), so $R_{D^0 \rightarrow K^- \pi^+} = 1$. The value of y represents the difference in total width components of the $D^0 \bar{D}^0$ system, $y = (\Gamma_2 - \Gamma_1)/(\Gamma_2 + \Gamma_1)$, where 1 and 2 represent the CP-odd and CP-even states, respectively.

The mode-dependent values for these factors are listed in Table 5.11. These are taken from the *CPV*-allowed values in [48] for $D^0 \rightarrow K^- \pi^+$, and from [49] for $D^0 \rightarrow K^- \pi^+ \pi^0$ and $D^0 \rightarrow K^- \pi^+ \pi^+ \pi^-$. The value of $y = 0.0066^{+0.0007}_{-0.0010}$ is also from [48], and is the same for all modes. After applying each of the mode-dependent corrections, the efficiency for the full sample changes from $\epsilon_{D^0} = (11.320 \pm 0.213)\%$ to $\epsilon_{D^0} = (11.352 \pm 0.213)\%$, and similarly for the efficiencies of each E_{cm} bin.

| Mode | r_m | R_m | δ_m [°] | α_m |
|---|---------------------|------------------------|-----------------------|---------------------------------|
| $D^0 \rightarrow K^- \pi^+$ | 0.0591 ± 0.0063 | 1 | $11.8^{+9.5}_{-14.7}$ | 1.00426 ± 0.00083 |
| $D^0 \rightarrow K^- \pi^+ \pi^0$ | 0.0447 ± 0.0012 | 0.81 ± 0.06 | 18^{+14}_{-15} | 1.00248 ± 0.00014 |
| $D^0 \rightarrow K^- \pi^+ \pi^+ \pi^-$ | 0.0549 ± 0.0006 | $0.43^{+0.17}_{-0.13}$ | -52^{+28}_{-17} | $1.00270^{+0.00014}_{-0.00012}$ |

Table 5.11: The quantum correlated factors for the D^0 modes.

| E_{bin} | ϵ_{D^0} | ϵ_{D^+} |
|------------------|---------------------|---------------------|
| 0 | 0.1146 ± 0.0005 | - |
| 1 | 0.1151 ± 0.0005 | - |
| 2 | 0.1161 ± 0.0005 | 0.0990 ± 0.0005 |
| 3 | 0.1119 ± 0.0005 | 0.0952 ± 0.0005 |
| 4 | 0.1156 ± 0.0005 | 0.0983 ± 0.0005 |
| 5 | 0.1131 ± 0.0005 | 0.0964 ± 0.0005 |
| 6 | 0.1137 ± 0.0005 | 0.0972 ± 0.0005 |
| 7 | 0.1104 ± 0.0005 | 0.0934 ± 0.0005 |
| 8 | 0.1157 ± 0.0005 | 0.0991 ± 0.0005 |
| 9 | 0.1165 ± 0.0005 | 0.0996 ± 0.0005 |
| 10 | 0.1141 ± 0.0005 | 0.0977 ± 0.0005 |
| 11 | 0.1157 ± 0.0005 | 0.0990 ± 0.0005 |
| 12 | 0.1152 ± 0.0005 | 0.0986 ± 0.0005 |
| 13 | 0.1154 ± 0.0005 | 0.0985 ± 0.0005 |
| 14 | 0.1157 ± 0.0005 | 0.0984 ± 0.0005 |
| 15 | 0.1146 ± 0.0005 | 0.0986 ± 0.0005 |
| 16 | 0.1146 ± 0.0005 | 0.0992 ± 0.0005 |
| 17 | 0.1151 ± 0.0005 | 0.1003 ± 0.0005 |
| 18 | 0.1148 ± 0.0005 | 0.0990 ± 0.0005 |
| 19 | 0.1151 ± 0.0005 | 0.0984 ± 0.0005 |
| 20 | 0.1138 ± 0.0005 | 0.0988 ± 0.0005 |
| 21 | 0.1129 ± 0.0005 | 0.0982 ± 0.0005 |
| 22 | 0.1122 ± 0.0005 | 0.0984 ± 0.0005 |
| 23 | 0.1118 ± 0.0005 | 0.0982 ± 0.0005 |
| 24 | 0.1094 ± 0.0005 | 0.0953 ± 0.0005 |
| 25 | 0.1105 ± 0.0005 | 0.0975 ± 0.0005 |
| 26 | 0.1098 ± 0.0005 | 0.0962 ± 0.0005 |
| 27 | 0.1082 ± 0.0005 | 0.0969 ± 0.0005 |
| 28 | 0.1081 ± 0.0005 | 0.0961 ± 0.0005 |
| 29 | 0.1087 ± 0.0005 | 0.0971 ± 0.0005 |
| 30 | 0.1078 ± 0.0005 | 0.0959 ± 0.0005 |
| 31 | 0.1092 ± 0.0005 | 0.0969 ± 0.0005 |
| 32 | 0.1104 ± 0.0005 | 0.0978 ± 0.0005 |
| 33 | 0.1090 ± 0.0005 | 0.0971 ± 0.0005 |

Table 5.10: The overall reconstruction efficiency of D^0 and D^+ for each energy bin. These values are used to calculate the corresponding cross sections at each energy point. The listed errors are statistical only.

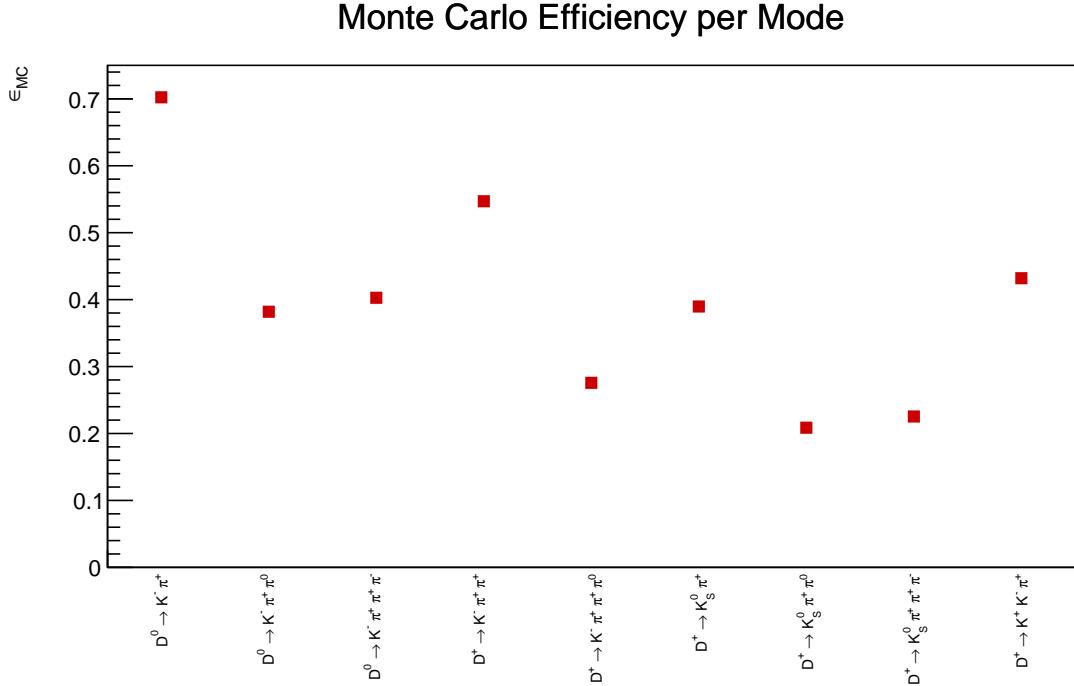


Figure 5.4: Mode-by-mode MC efficiencies for D^0 and D^+ .
The error bars are negligible on the scale shown.

5.5 Fitting Procedure

After applying the correction in Section 5.4.1, the efficiency values (Table 5.10) were combined with the luminosity (Table 5.3) and the signal values from each 2D fit (Table 5.12) to determine the cross section at each energy point. Since each $\psi(3770)$ produces a $D\bar{D}$ pair, a factor of 2 is included to avoid double counting:

$$\sigma_{D\bar{D}}^{RC}(E_i) = \frac{N_D(E_i)}{2 \epsilon_D(E_i) \mathcal{L}(E_i)}. \quad (5.8)$$

The resulting cross section values for D^0 and D^+ are also listed in Table 5.12, and shown in Figure 5.5.

Using the measured $D\bar{D}$ cross sections, we fit to Equation (2.7) using each of the form factor choices described in Section 5.1. In each case, there are four common fit parameters: $M^{\psi(3770)}$, $\Gamma^{\psi(3770)}$, $\Gamma_{ee}^{\psi(3770)}$, and $\phi^{\psi(3770)}$. These represent the mass, total

| E_{mid} | $N_{D^0\overline{D}^0}$ | $\sigma_{D^0\overline{D}^0}^{RC}$ [nb] | $N_{D^+D^-}$ | $\sigma_{D^+D^-}^{RC}$ [nb] |
|------------------|-------------------------|--|---------------|-----------------------------|
| 3.7342 | 31 ± 9 | 0.164 ± 0.046 | - | - |
| 3.7368 | 16 ± 5 | 0.218 ± 0.068 | - | - |
| 3.7447 | 169 ± 16 | 0.765 ± 0.070 | 28 ± 7 | 0.150 ± 0.038 |
| 3.7483 | 264 ± 20 | 0.838 ± 0.064 | 96 ± 13 | 0.360 ± 0.048 |
| 3.7501 | 509 ± 28 | 0.968 ± 0.053 | 196 ± 18 | 0.439 ± 0.040 |
| 3.7517 | 831 ± 34 | 1.237 ± 0.052 | 329 ± 23 | 0.574 ± 0.040 |
| 3.7534 | 1036 ± 38 | 1.377 ± 0.051 | 481 ± 27 | 0.748 ± 0.042 |
| 3.7556 | 1182 ± 41 | 1.566 ± 0.055 | 508 ± 28 | 0.797 ± 0.045 |
| 3.7562 | 1459 ± 45 | 1.629 ± 0.051 | 701 ± 32 | 0.914 ± 0.042 |
| 3.7592 | 2014 ± 52 | 1.948 ± 0.052 | 1054 ± 39 | 1.192 ± 0.045 |
| 3.7624 | 2444 ± 58 | 2.385 ± 0.058 | 1346 ± 44 | 1.534 ± 0.051 |
| 3.7650 | 2062 ± 53 | 2.715 ± 0.071 | 1223 ± 42 | 1.882 ± 0.066 |
| 3.7676 | 1746 ± 48 | 3.102 ± 0.087 | 1059 ± 39 | 2.200 ± 0.081 |
| 3.7713 | 1585 ± 46 | 3.406 ± 0.101 | 1045 ± 38 | 2.634 ± 0.098 |
| 3.7742 | 1569 ± 46 | 3.714 ± 0.111 | 1103 ± 40 | 3.067 ± 0.111 |
| 3.7775 | 1543 ± 46 | 3.692 ± 0.111 | 1108 ± 39 | 3.078 ± 0.111 |
| 3.7802 | 1539 ± 46 | 3.444 ± 0.104 | 1006 ± 38 | 2.599 ± 0.100 |
| 3.7829 | 1381 ± 44 | 2.791 ± 0.090 | 951 ± 38 | 2.206 ± 0.088 |
| 3.7869 | 1167 ± 42 | 1.995 ± 0.072 | 821 ± 36 | 1.627 ± 0.073 |
| 3.7891 | 888 ± 38 | 1.361 ± 0.058 | 656 ± 34 | 1.178 ± 0.062 |
| 3.7926 | 739 ± 36 | 0.920 ± 0.045 | 475 ± 32 | 0.680 ± 0.045 |
| 3.7970 | 514 ± 34 | 0.562 ± 0.037 | 329 ± 31 | 0.414 ± 0.039 |
| 3.8003 | 374 ± 31 | 0.424 ± 0.035 | 186 ± 28 | 0.241 ± 0.037 |
| 3.8024 | 196 ± 23 | 0.325 ± 0.038 | 125 ± 23 | 0.236 ± 0.043 |
| 3.8070 | 136 ± 19 | 0.352 ± 0.050 | 97 ± 17 | 0.289 ± 0.051 |
| 3.8093 | 65 ± 14 | 0.233 ± 0.050 | 32 ± 13 | 0.132 ± 0.055 |
| 3.8135 | 12 ± 10 | 0.060 ± 0.049 | 26 ± 11 | 0.153 ± 0.066 |
| 3.8153 | 8 ± 7 | 0.056 ± 0.051 | 12 ± 8 | 0.089 ± 0.063 |
| 3.8229 | 12 ± 7 | 0.140 ± 0.083 | 15 ± 8 | 0.197 ± 0.107 |
| 3.8320 | 4 ± 5 | 0.069 ± 0.086 | 3 ± 5 | 0.046 ± 0.099 |
| 3.8390 | 14 ± 6 | 0.237 ± 0.105 | 14 ± 7 | 0.254 ± 0.124 |
| 3.8494 | 11 ± 6 | 0.186 ± 0.104 | 10 ± 6 | 0.186 ± 0.118 |
| 3.8555 | 24 ± 8 | 0.337 ± 0.111 | 17 ± 6 | 0.273 ± 0.104 |
| 3.8632 | 22 ± 8 | 0.340 ± 0.127 | 6 ± 5 | 0.099 ± 0.091 |

Table 5.12: The $D\overline{D}$ cross section at each E_{cm} point.

The number of data events observed in each E_{cm} bin are also shown. The uncertainties on the cross sections are statistical only and come from the signal fitting (N_D), PDG values (Table 5.9), and MC reconstruction efficiency (Table 5.10). The values for $N_{D^0\overline{D}^0}$ and $N_{D^+D^-}$ are taken from the signal fits shown in Appendices B and C.

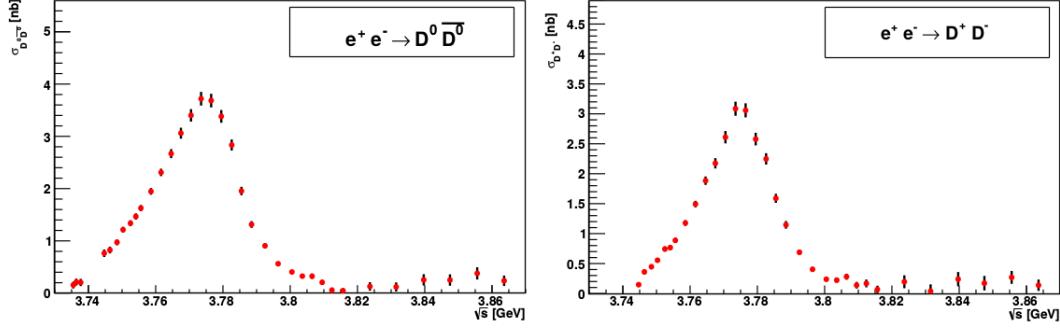


Figure 5.5: The measured $e^+e^- \rightarrow D\bar{D}$ cross sections.
The $D^0\bar{D}^0$ cross section is shown on the left and D^+D^- is shown on the right.

width, electron partial width, and relative phase to the non-resonant contribution for the $\psi(3770)$, respectively. This notation for the total width corresponds to $\Gamma(M)$ in Section 2.3. Two additional fitting parameters are dependent on which form factor is being used: F_{NR} and a_{NR} for the exponential, or $\Gamma^{\psi(2S)}$ and F_0 for the VDM. For the former, these represent the amplitude and exponent normalization for the non-resonant contribution. In the latter case, these represent the modified total width for the $\psi(2S)$ above resonance (see Section 5.1) and the constant contribution of resonances above the $\psi(3770)$. The fitting is done simultaneously for D^0 and D^+ with identical parameters using TMinuit with a χ^2 minimization. The value minimized is the sum of the χ^2 values from each of the D^0 and D^+ cross section functions. Results for the Exponential and VDM choices are shown in Figures 5.6 and 5.7, respectively.

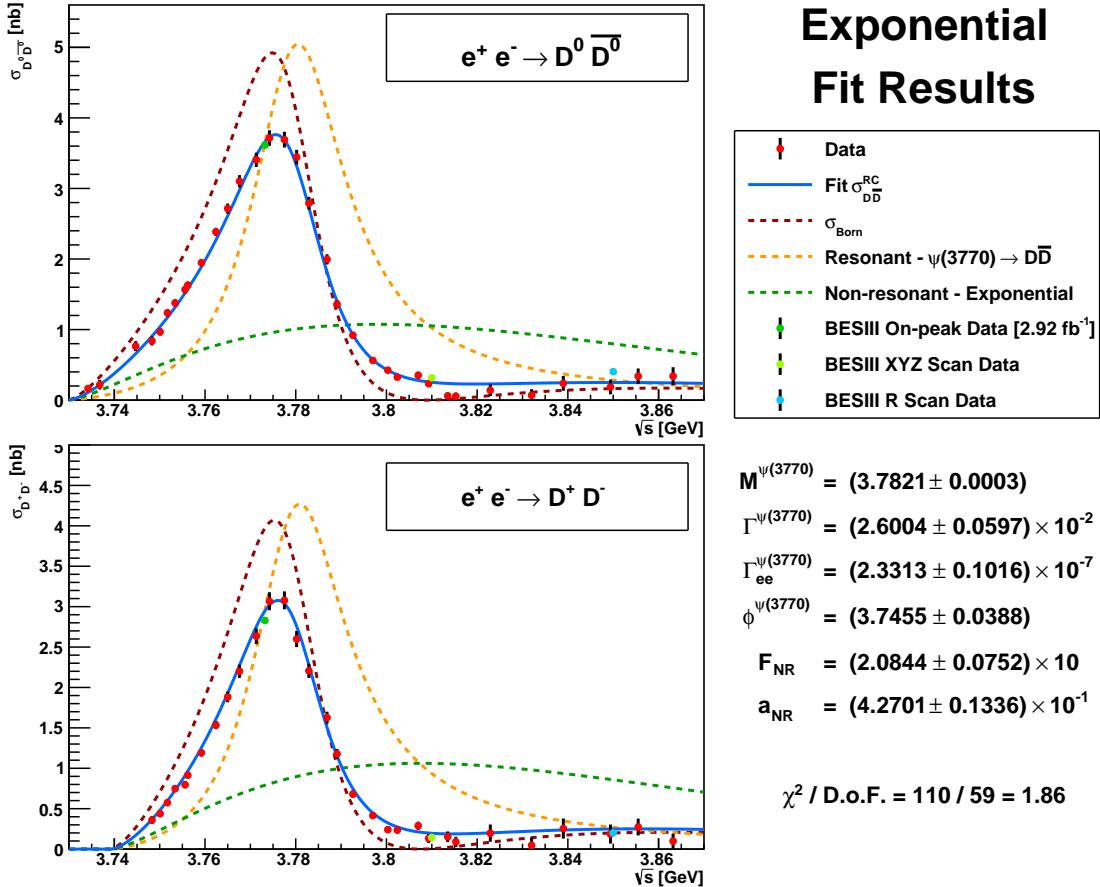


Figure 5.6: The Exponential Model fit results.

The results for D^0 are shown on the top and the results for D^+ are shown on the bottom. The fit shape (blue) is calculated from Equation (2.1) using the non-resonant component from Equation (5.2).

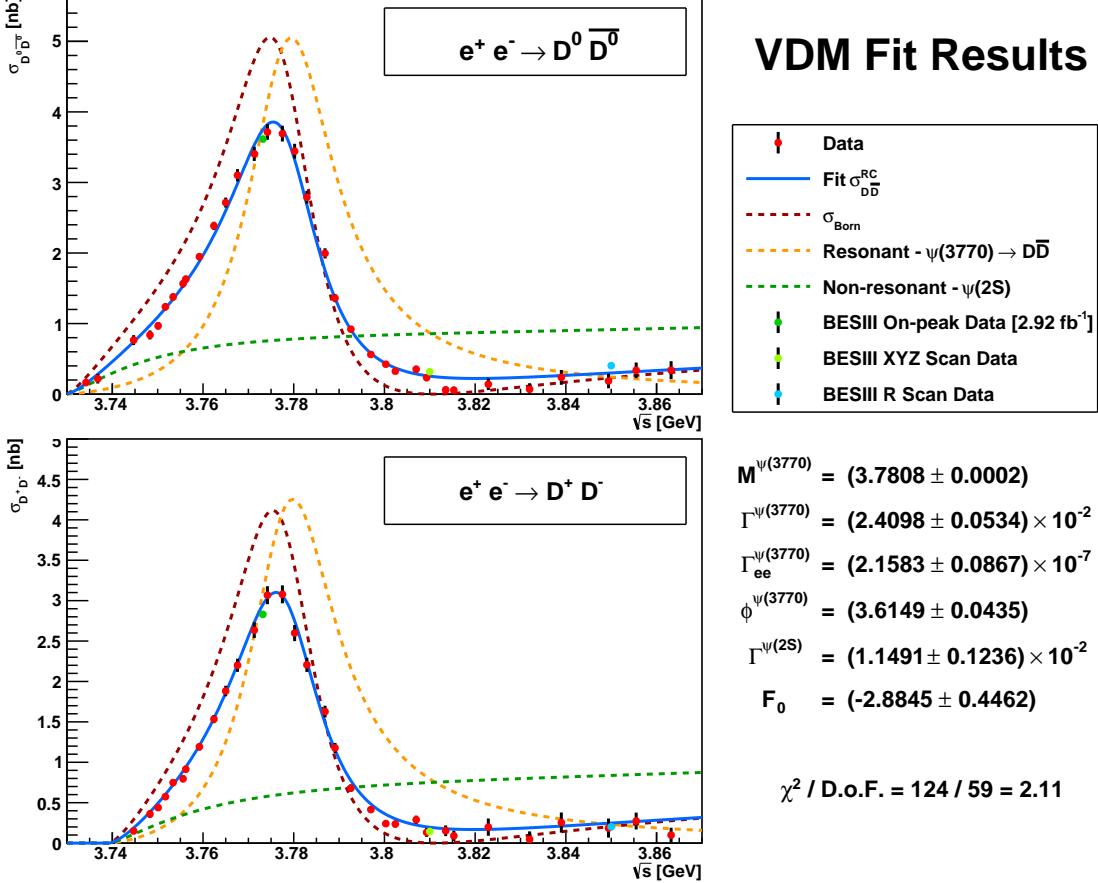


Figure 5.7: The Vector Dominance Model fit results.

The results for D^0 are shown on the top and the results for D^+ are shown on the bottom. The fit shape (blue) is calculated from Equation (2.1) using the non-resonant component from Equation (5.3).

5.5.1 Coulomb Correction

In the development of this analysis, it was discovered that the theoretical formulation in Section 2.3 did not lead to a successful fit of the $D\bar{D}$ cross sections, shown in Figure 5.8. Namely, including the Coulomb effect pulls the $D^0\bar{D}^0$ and D^+D^- cross sections in opposite directions. We found the best fits were achieved by altering Equation (2.3) to set the Coulomb factor to 1. While this disagrees with conventional theoretical wisdom, it is consistent with studies of $\Upsilon(4S) \rightarrow B\bar{B}$ where applying a Coulomb correction for the charged final state also leads to inconsistency with data.

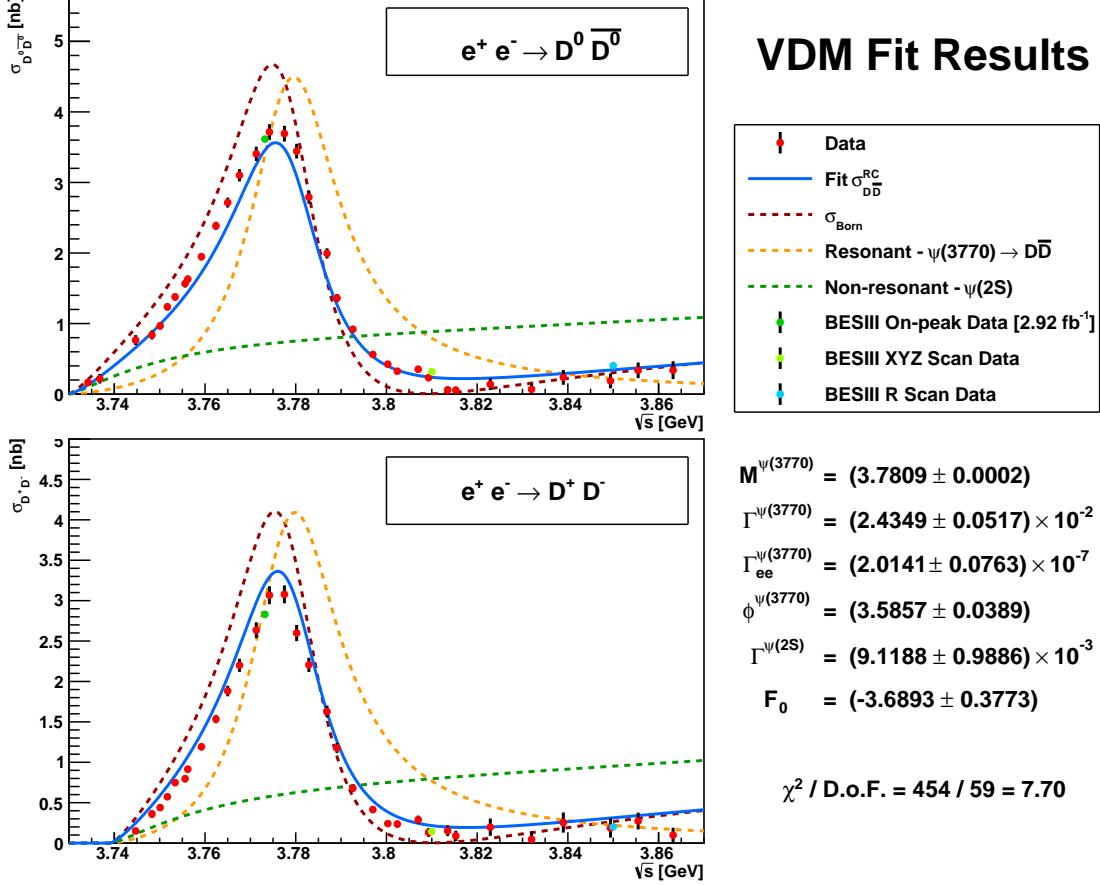


Figure 5.8: The Vector Dominance Model fit results with Coulomb interactions. The results for D^0 are shown on the top and the results for D^+ are shown on the bottom. Including this factor provides notably worse results than when excluding it (see Figure 5.7).

This is most clearly seen in the ratio of $D^+ D^-$ and $D^0 \bar{D}^0$ cross sections, shown in Figure 5.9, where the ‘No Coulomb’ method sets $z_{D^+ D^-}$ in Equations (2.7) and (2.11) to unity, the ‘Partial Coulomb’ sets this factor to unity only for Equation (2.7), and the ‘Full Coulomb’ is the default assumption. Agreement of the measured cross section ratio with the ‘No Coulomb’ calculation is substantially better. This is also true for the high statistics points measured at the $\psi(3770)$ peak by Derrick Toth [44] (light blue). As the data tend to follow the ‘No Coulomb’ method, we choose this as our nominal method for the results, presented in Section 5.7. However, the interpretation for this

behavior is still undetermined.

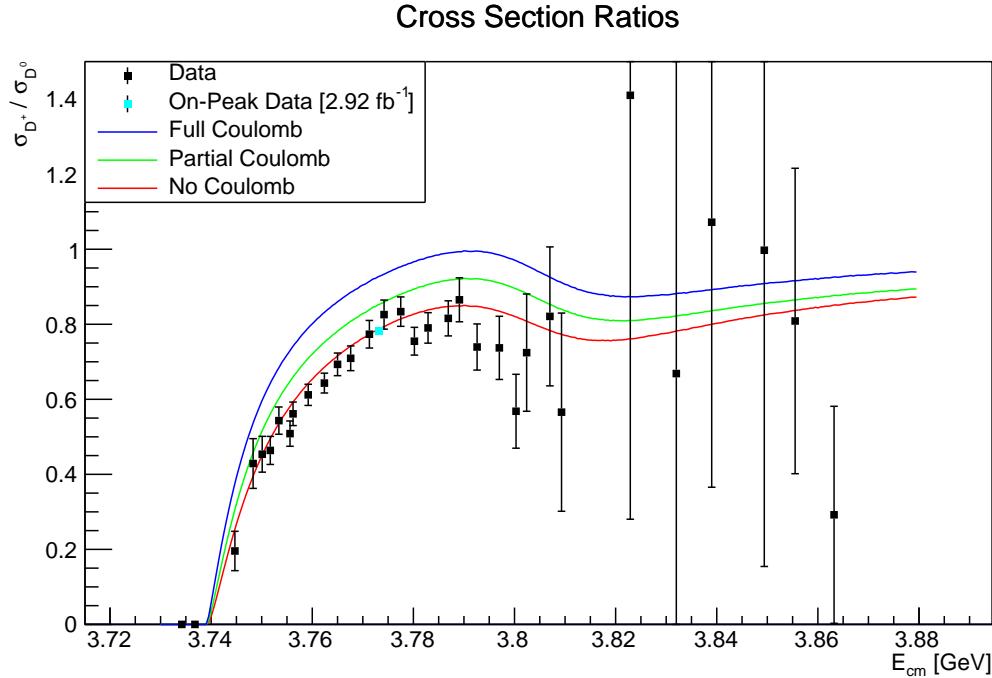


Figure 5.9: The ratio of measured D^+ to D^0 cross sections.
Several levels of Coulomb interactions are examined.

5.6 Systematics

To assess the systematic uncertainties in our results, we look at a variety of factors. Many of these affect all BESIII analyses, such as luminosity and tracking. Others, like the modification to KKMC generation (see Section 5.2.4), are specific to this analysis. The remaining systematics are typically due to less well-known parameters, like the radii used to describe the $\psi(2S)$ and $\psi(3770)$ (see Section 5.1). Each of these contributions, as well as their total, can be found in Table 5.16.

5.6.1 $\psi(3770)$ Parameter Systematics

Each systematic is obtained by changing a specific aspect, and re-fitting to the altered values using the VDM method. The uncertainties for each parameter are obtained by

taking the difference between this result and the nominal fit (Figure 5.7). Generally, each change was done both positively and negatively, and the values used are the largest differences seen between the two changes. The systematics examined in this analysis are summarized below, where a * denotes aspects which were deemed negligible.

Luminosity

A 1 % change [50] was applied to \mathcal{L} in Equation (5.8). As this is an overall scale change, the only variable significantly affected is $\Gamma_{ee}^{\psi(3770) \rightarrow D\bar{D}}$.

π^\pm / K^\pm Tracking

A 1.0 % change [51] was applied for each π^\pm or K^\pm in a given decay mode. The summed contribution for each mode is applied to ϵ_m in Equation (5.6). As this is an overall scale change, the only variable significantly affected is $\Gamma_{ee}^{\psi(3770) \rightarrow D\bar{D}}$.

π^0 Tracking

A 2.0 % change [52] was applied for each π^0 in a given decay mode. The summed contribution for each mode is applied to ϵ_m in Equation (5.6). As this is an overall scale change, the only variable significantly affected is $\Gamma_{ee}^{\psi(3770) \rightarrow D\bar{D}}$.

K_S^0 Tracking

A 1.5 % change [53] was applied for each K_S^0 in a given decay mode. The summed contribution for each mode is applied to ϵ_m in Equation (5.6). As this is an overall scale change, the only variable significantly affected is $\Gamma_{ee}^{\psi(3770) \rightarrow D\bar{D}}$.

Single Tag Fitting

A mode-dependent change [44] was applied to N in Equation (5.8). Differences from fitting were obtained by Derrick Toth after examining the use of single-Gaussian convolved signal shapes, and are shown in Table 5.13. The changes applied were obtained from the sums of the mode-dependent values averaged over their efficiencies. As this is an overall scale change, the only variable significantly affected is $\Gamma_{ee}^{\psi(3770) \rightarrow D\bar{D}}$.

| Tag Mode | Difference (%) |
|---|----------------|
| $D^0 \rightarrow K^- \pi^+$ | 0.27 |
| $D^0 \rightarrow K^- \pi^+ \pi^0$ | 0.10 |
| $D^0 \rightarrow K^- \pi^+ \pi^+ \pi^-$ | 0.47 |
| D^0 Average: | 0.25 % |
| $D^+ \rightarrow K^- \pi^+ \pi^+$ | 0.20 |
| $D^+ \rightarrow K^- \pi^+ \pi^+ \pi^0$ | 0.00 |
| $D^+ \rightarrow K_S^0 \pi^+$ | 0.17 |
| $D^+ \rightarrow K_S^0 \pi^+ \pi^0$ | 0.29 |
| $D^+ \rightarrow K_S^0 \pi^+ \pi^+ \pi^-$ | 0.17 |
| $D^+ \rightarrow K^+ K^- \pi^+$ | 0.74 |
| D^+ Average: | 0.20 % |

Table 5.13: Single-tag fitting differences by mode.

The total D^0 and D^+ values are averaged over the efficiencies for each mode.

PDG Branching Fractions

A mode-dependent change based on the PDG branching fraction errors (Table 5.9) was applied to ϵ_m in Equation (5.6). The branching fraction for each mode was changed by its uncertainty. As this is an overall scale change, the only variable significantly affected is $\Gamma_{ee}^{\psi(3770) \rightarrow D\bar{D}}$.

Meson Radii

The most uncertain parameters used in the analysis are the radii of the mesons $\psi(2S)$ and $\psi(3770)$. We take the same values as used by KEDR, however, each of these is quoted to have an $\sim 25\%$ uncertainty. With this, we adjust the two radii values up or down by 25% over the four possible combinations (both up, both down, and each opposite). The maximum deviations from the nominal method seen across all four cases is used as the systematic uncertainty. Due to the high level of uncertainty on these parameters, this effect provides one of the largest systematic sources in the analysis.

MC Iteration*

In generating MC for this analysis, the $D\bar{D}$ samples used a modified form of KKMC which generates events based off an input Born cross-section shape for the $\psi(3770)$.

However, as this shape is also the final output of the procedure, only an estimation of the results can be used for generation. To assess the variation from the input shape, we compared the output fit parameters to those used in the generation process. This process used the Exponential method, and the results are shown in Table 5.14. The numbers listed are from an earlier iteration of the MC than shown in Section 5.5, but the consistency seen is representative of all iterations. Very little difference is seen in the primary fitting parameters of the $\psi(3770)$. These similarities show the fit result values converging, even after only a single iteration. From this, we treat variations due to MC iteration as negligible.

| Parameter | | KKMC Input | Fit Results | Difference |
|---|-------|----------------------|----------------------|------------|
| $M^{\psi(3770)}$ | [GeV] | 3.7815 ± 0.0003 | 3.7814 ± 0.0003 | 0.0001 |
| $\Gamma^{\psi(3770)}$ | [MeV] | 24.887 ± 0.686 | 24.839 ± 0.681 | 0.048 |
| $\Gamma_{ee}^{\psi(3770) \rightarrow D\bar{D}}$ | [eV] | 217.55 ± 11.18 | 214.65 ± 11.10 | 2.90 |
| $\phi^{\psi(3770)}$ | | 3.6374 ± 0.0513 | 3.6375 ± 0.0518 | 0.0001 |
| F_{NR} | | 21.394 ± 1.866 | 20.147 ± 1.765 | 0.992 |
| a_{NR} | | -1.6202 ± 0.5271 | -1.5265 ± 0.5119 | 0.0937 |

Table 5.14: Comparison of input and output fit parameters.

The MC generation is done using the Exponential form factor model as an input Born cross section to generate $D\bar{D}$ events using KKMC.

MC ISR Generation*

To compare to the generation process of KKMC, we also generated alternative MC samples of $D\bar{D}$ using the ConExc ISR generator. This process used an input Born level shape identical to a previous iteration produced with KKMC. Each of the background samples used (such as $q\bar{q}$ and $\tau^-\tau^+$) were the same as in the nominal procedure. The cross section results using the VDM model are shown in Table 5.15, and provide $\psi(3770)$ fit parameters within the statistical errors of the nominal method. From this, we treat variations due to the MC ISR generator as negligible.

| Parameter | | ConExc Fit Results | KKMC Fit Results |
|---|-------|----------------------|----------------------|
| $M^{\psi(3770)}$ | [GeV] | 3.7803 ± 0.0003 | 3.7804 ± 0.0003 |
| $\Gamma^{\psi(3770)}$ | [MeV] | 23.784 ± 0.616 | 23.732 ± 0.612 |
| $\Gamma_{ee}^{\psi(3770) \rightarrow D\bar{D}}$ | [eV] | 204.68 ± 10.28 | 207.35 ± 10.02 |
| $\phi^{\psi(3770)}$ | | 3.5954 ± 0.0559 | 3.5952 ± 0.0525 |
| $\Gamma_{ee}^{\psi(2S)}$ | [MeV] | 12.229 ± 1.336 | 14.070 ± 1.431 |
| F_0 | | -2.3415 ± 0.4898 | -2.0768 ± 0.4924 |

Table 5.15: Comparison of output fit parameters between ISR generators.

The MC generation is done using both the ConExc and KKMC generators and the final VDM fit results are shown. The values shown are from a previous iteration than the final results, but the output from each method remains very similar.

Intermediate Resonances*

In looking at the mode $D^+ \rightarrow K^- \pi^+ \pi^+$, we also analyzed the contribution of intermediate resonances, like the ρ^0 . Using the 2.93 fb^{-1} data sample of $\psi(3770)$ events at $E_{\text{cm}} = 3.773 \text{ GeV}$, we split the signal region of this mode based on a 1.0 (GeV)^2 cut in both the invariant masses of $K\pi$ and $\pi\pi$ separately. These cuts were chosen to separate the sample into distinctly different regions, as can be seen in Figure 5.10. Fitting the signal distributions for each of these subsamples, we found no statistically significant deviations in the measured yields. From this, we treat variations due to intermediate resonances as negligible.

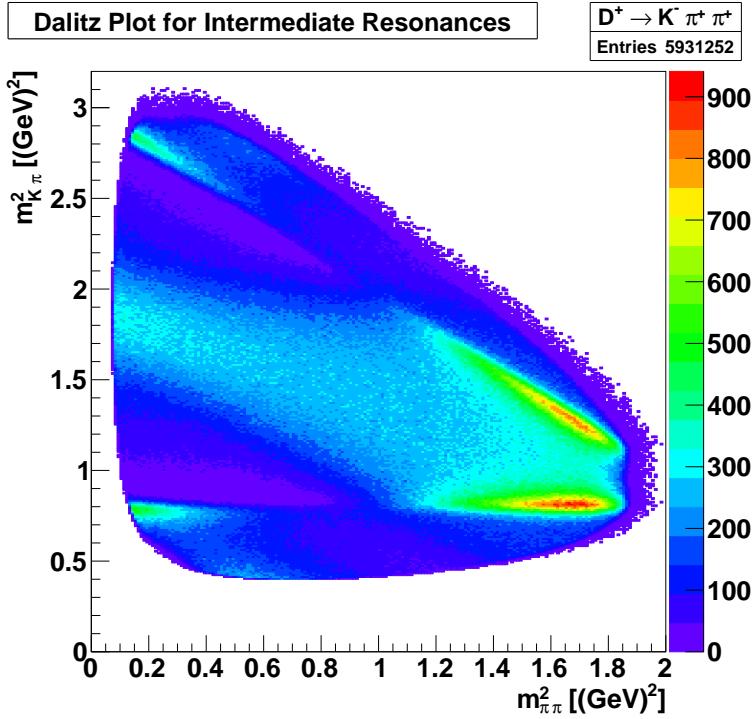


Figure 5.10: The $K\pi$ vs. $\pi\pi$ invariant masses for the mode $D^+ \rightarrow K^- \pi^+ \pi^+$. The data used are from the on-peak $\psi(3770)$ sample, as the statistics are significantly higher than for the scan data.

Non-Resonant Form Factor

In addition to the systematics described above, there is a significant source of uncertainty coming from the non-resonant form factor used. Each of the models examined, Exponential and VDM, provided quality fit results for the cross section shapes. From this, we conservatively assign an uncertainty equal to the differences in fit parameters provided by these two methods. Following the example of KEDR, we treat this as separate from the other systematics, and list it as a model uncertainty.

| Systematic | $M^{\psi(3770)}$ [%] | $\Gamma^{\psi(3770)}$ [%] | $\Gamma_{ee}^{\psi(3770) \rightarrow D\bar{D}}$ [%] | $\phi^{\psi(3770)}$ [%] |
|-----------------------------------|----------------------|---------------------------|---|-------------------------|
| Luminosity | 0.000 | 0.004 | 1.005 | 0.014 |
| K^\pm/π^\pm Tracking | 0.000 | 0.008 | 2.646 | 0.033 |
| π^0 Tracking | 0.000 | 0.012 | 0.746 | 0.028 |
| K_S^0 Tracking | 0.000 | 0.004 | 0.260 | 0.019 |
| Single Tag Fits | 0.000 | 0.012 | 0.213 | 0.008 |
| PDG Errors | 0.000 | 0.017 | 2.840 | 0.036 |
| Meson Radii | 0.016 | 2.411 | 3.512 | 1.477 |
| Form Factor [†] | 0.034 | 7.909 | 8.016 | 3.613 |
| Total [%] | 0.016 | 2.411 | 5.389 | 1.479 |
| Relative Stat. Error [σ] | 3.000 | 1.088 | 1.342 | 1.229 |

Table 5.16: Systematic uncertainties relative to the measured parameters of the $\psi(3770)$.

[†]The Form Factor is treated as an uncertainty on the model, and is not included in the total systematic error.

5.6.2 Cross Section Systematics

In addition to the statistical uncertainties provided in Table 5.12, we also provide systematic uncertainties on the cross section measurements. These are calculated from the systematic shifts (ΔS) which affect Equation (5.8): Luminosity, K^\pm/π^\pm Tracking, π^0 Tracking, K_S^0 Tracking, and Single Tag Fits. For the luminosity, this value is the same 1% shift used previously. The others are calculated by weighting the efficiency from each decay mode:

$$\Delta S = \frac{\sum_m \epsilon_m \Delta S_m}{\sum_m \epsilon_m} \quad (5.9)$$

The value of ΔS_m for K^\pm/π^\pm Tracking is 1.0% per K^\pm or π^\pm in each decay mode, and defined similarly for the other systematics using the previously listed values. The calculated shifts are listed in Table 5.17, and the resulting cross section values are listed in Table 5.18.

| Systematic | $\Delta S(D^0) [\%]$ | $\Delta S(D^+) [\%]$ |
|--------------------------|----------------------|----------------------|
| Luminosity | 1.00 | 1.00 |
| K^\pm/π^\pm Tracking | 2.58 | 2.59 |
| π^0 Tracking | 0.94 | 0.63 |
| K_S^0 Tracking | 0.00 | 0.42 |
| Single Tag Fits | 0.25 | 0.20 |
| PDG Error | 0.31 | 0.18 |
| Total | 2.95 | 2.89 |

Table 5.17: Systematics shifts affecting the cross section measurements.
The total shifts are used to calculate the systematic uncertainties of the D^0 and D^+ cross sections.

| E_{mid} [GeV] | $\sigma_{D^0\bar{D}^0}^{RC}$ [nb] | $\sigma_{D^+\bar{D}^-}^{RC}$ [nb] |
|------------------------|-----------------------------------|-----------------------------------|
| 3.7342 | $0.164 \pm 0.046 \pm 0.005$ | - |
| 3.7368 | $0.218 \pm 0.068 \pm 0.006$ | - |
| 3.7447 | $0.765 \pm 0.070 \pm 0.023$ | $0.150 \pm 0.038 \pm 0.004$ |
| 3.7483 | $0.838 \pm 0.064 \pm 0.025$ | $0.360 \pm 0.048 \pm 0.010$ |
| 3.7501 | $0.968 \pm 0.053 \pm 0.029$ | $0.439 \pm 0.040 \pm 0.013$ |
| 3.7517 | $1.237 \pm 0.052 \pm 0.036$ | $0.574 \pm 0.040 \pm 0.017$ |
| 3.7534 | $1.377 \pm 0.051 \pm 0.041$ | $0.748 \pm 0.042 \pm 0.022$ |
| 3.7556 | $1.566 \pm 0.055 \pm 0.046$ | $0.797 \pm 0.045 \pm 0.023$ |
| 3.7562 | $1.629 \pm 0.051 \pm 0.048$ | $0.914 \pm 0.042 \pm 0.026$ |
| 3.7592 | $1.948 \pm 0.052 \pm 0.057$ | $1.192 \pm 0.045 \pm 0.034$ |
| 3.7624 | $2.385 \pm 0.058 \pm 0.070$ | $1.534 \pm 0.051 \pm 0.044$ |
| 3.7650 | $2.715 \pm 0.071 \pm 0.080$ | $1.882 \pm 0.066 \pm 0.054$ |
| 3.7676 | $3.102 \pm 0.087 \pm 0.092$ | $2.200 \pm 0.081 \pm 0.064$ |
| 3.7713 | $3.406 \pm 0.101 \pm 0.100$ | $2.634 \pm 0.098 \pm 0.076$ |
| 3.7742 | $3.714 \pm 0.111 \pm 0.110$ | $3.067 \pm 0.111 \pm 0.089$ |
| 3.7775 | $3.692 \pm 0.111 \pm 0.109$ | $3.078 \pm 0.111 \pm 0.089$ |
| 3.7802 | $3.444 \pm 0.104 \pm 0.102$ | $2.599 \pm 0.100 \pm 0.075$ |
| 3.7829 | $2.791 \pm 0.090 \pm 0.082$ | $2.206 \pm 0.088 \pm 0.064$ |
| 3.7869 | $1.995 \pm 0.072 \pm 0.059$ | $1.627 \pm 0.073 \pm 0.047$ |
| 3.7891 | $1.361 \pm 0.058 \pm 0.040$ | $1.178 \pm 0.062 \pm 0.034$ |
| 3.7926 | $0.920 \pm 0.045 \pm 0.027$ | $0.680 \pm 0.045 \pm 0.020$ |
| 3.7970 | $0.562 \pm 0.037 \pm 0.017$ | $0.414 \pm 0.039 \pm 0.012$ |
| 3.8003 | $0.424 \pm 0.035 \pm 0.013$ | $0.241 \pm 0.037 \pm 0.007$ |
| 3.8024 | $0.325 \pm 0.038 \pm 0.010$ | $0.236 \pm 0.043 \pm 0.007$ |
| 3.8070 | $0.352 \pm 0.050 \pm 0.010$ | $0.289 \pm 0.051 \pm 0.008$ |
| 3.8093 | $0.233 \pm 0.050 \pm 0.007$ | $0.132 \pm 0.055 \pm 0.004$ |
| 3.8135 | $0.060 \pm 0.049 \pm 0.002$ | $0.153 \pm 0.066 \pm 0.004$ |
| 3.8153 | $0.056 \pm 0.051 \pm 0.002$ | $0.089 \pm 0.063 \pm 0.003$ |
| 3.8229 | $0.140 \pm 0.083 \pm 0.004$ | $0.197 \pm 0.107 \pm 0.006$ |
| 3.8320 | $0.069 \pm 0.086 \pm 0.002$ | $0.046 \pm 0.099 \pm 0.001$ |
| 3.8390 | $0.237 \pm 0.105 \pm 0.007$ | $0.254 \pm 0.124 \pm 0.007$ |
| 3.8494 | $0.186 \pm 0.104 \pm 0.005$ | $0.186 \pm 0.118 \pm 0.005$ |
| 3.8555 | $0.337 \pm 0.111 \pm 0.010$ | $0.273 \pm 0.104 \pm 0.008$ |
| 3.8632 | $0.340 \pm 0.127 \pm 0.010$ | $0.099 \pm 0.091 \pm 0.003$ |

Table 5.18: Measurements of the D^0 / D^+ cross sections.
The first errors are statistical and the second are systematic.

5.7 Results

After incorporating the systematic and model uncertainties, the total results for the main $\psi(3770)$ parameters are shown in Table 5.19. The results shown are from the VDM model, as we treat this as the nominal results. The Exponential model is used as a measure of uncertainty, however, the quality of fits found by this approach means it cannot be excluded as a viable option.

| | | |
|---|----------------------------------|--------------|
| $M^{\psi(3770)}$ | $3780.8 \pm 0.2 \pm 0.6 \pm 1.3$ | [MeV] |
| $\Gamma^{\psi(3770)}$ | $24.1 \pm 0.5 \pm 0.6 \pm 1.9$ | [MeV] |
| $\Gamma_{ee}^{\psi(3770) \rightarrow D\bar{D}}$ | $216 \pm 9 \pm 11 \pm 17$ | [eV] |
| $\phi^{\psi(3770)}$ | $207 \pm 3 \pm 3 \pm 7$ | [$^\circ$] |

Table 5.19: Final results for the $\psi(3770)$ parameters.

The first error listed is statistical, the second is systematic, and the third is from the form factor model.

Additionally, since this analysis is based on an approach developed by the KEDR collaboration, a comparison to their results is also shown in table 5.20. For their measurement of $\Gamma_{ee}^{\psi(3770)}$, two solutions were found with very close χ^2 values, so both are quoted in their final results. With the larger statistics available at BESIII, no alternate solution was found during searches over the parameter space.

| Method | $M^{\psi(3770)}$ [MeV] | $\Gamma^{\psi(3770)}$ [MeV] | $\Gamma_{ee}^{\psi(3770) \rightarrow D\bar{D}}$ [eV] |
|-------------|--|--------------------------------------|--|
| Exponential | $3782.1 \pm 0.3 \pm 0.6$ | $26.0 \pm 0.6 \pm 0.7$ | $233 \pm 10 \pm 13$ |
| VDM | $3780.8 \pm 0.2 \pm 0.6$ | $24.1 \pm 0.6 \pm 0.6$ | $216 \pm 9 \pm 12$ |
| KEDR | $3779.2^{+1.8+0.5+0.3}_{-1.7-0.7-0.3}$ | $24.9^{+4.6+0.5+0.2}_{-4.0-0.6-0.9}$ | $154^{+79+17+13}_{-58-9-25},$ $414^{+72+24+90}_{-80-26-10}$ |
| PDG | 3773.15 ± 0.33 | 27.2 ± 0.9 | $[262 \pm 18] \times \mathcal{B}_{D\bar{D}}$ |

Table 5.20: Fit results compared to the KEDR results and the PDG.

The first errors listed are statistical, while the second are systematic. In the case of KEDR, the third error is from the model.

We can also compare our results to the cross section values found in the previous analysis of BESIII's on-peak $\psi(3770)$ data sample of 2.93 fb^{-1} by Derrick Toth [44]. The values displayed on Figures 5.6 and 5.7 are his double-tag (DT) values. Each of these cross sections are shown in Table 5.21. Further analysis to better understand

the differences seen is still in progress, however both methods used in this analysis are within $\sim 1\sigma$ of the high statistics method.

| Model | $\sigma_{D^0 \bar{D}^0}$ [nb] | $\sigma_{D^+ D^-}$ [nb] |
|--------------|-------------------------------|-----------------------------|
| Derrick (DT) | $3.615 \pm 0.010 \pm 0.035$ | $2.830 \pm 0.011 \pm 0.026$ |
| Exponential | $3.662 \pm 0.131 \pm 0.108$ | $2.947 \pm 0.118 \pm 0.085$ |
| VDM | $3.748 \pm 0.131 \pm 0.111$ | $2.951 \pm 0.118 \pm 0.085$ |

Table 5.21: Comparison of cross section calculations at $E_{\text{cm}} = 3.7732 \text{ GeV}$. The values measured previously used a 2.93 fb^{-1} data sample of $\psi(3770)$ events to reconstruct double-tag (DT) decays. The first errors listed are statistical, while the second is systematic.

Chapter 6

Measurement of Hadronic Production and $\Gamma(\psi(3770) \rightarrow \text{non-}D\bar{D})$

The second half of this analysis concerns the measurement of hadronic production. Namely, we are examining hadronic events in the regions above the $D\bar{D}$ threshold (scan data) and below the $\psi(2S)$ peak (continuum data). After identifying the total number of hadronic events in data, we can determine $\sigma_{\psi(3770) \rightarrow \text{non-}D\bar{D}}$ in the scan region by subtracting off all other known decay processes. Using this, along with the previous values of $\sigma_{\psi(3770) \rightarrow D\bar{D}}$, we can measure the non- $D\bar{D}$ branching fraction:

$$\Gamma(\psi(3770) \rightarrow \text{non-}D\bar{D}) = \frac{\sigma_{\psi(3770) \rightarrow \text{non-}D\bar{D}}}{\sigma_{\psi(3770) \rightarrow D\bar{D}} + \sigma_{\psi(3770) \rightarrow \text{non-}D\bar{D}}}. \quad (6.1)$$

6.1 Data and Monte Carlo Samples

6.1.1 Data Samples

The data used for this analysis was also produced by BEPCII and collected by BESIII. The samples used include continuum data taken at 3.650 GeV in 2009 (old continuum), as well as multiple other continuum points taken around this energy in 2013 (new continuum). We also use Round 1 (R1) and Round 2 (R2) of the high-statistics $\psi(3770)$

data taken in 2010 and 2011, respectively. Each of these samples, and their measured luminosities, can be seen in Table 6.1. The values of luminosity were measured during a previous version of this analysis using the procedure described in Section 5.2.3. The labels given to each continuum point are the intended energy targets, but generally differ from their true values. In addition to these datasets, the scan data described previously (Section 5.2.1) is also used.

6.1.2 Center-of-Mass Energy Measurement

As before, a precise measurement of each energy point is vital to the accuracy of the final results. Most notably, due to the rapidly increasing shape of the $\psi(2S)$ cross section near the high end of the continuum points, the value of the 3671 (New) point is highly susceptible to the assumed cross section of the $\psi(2S)$. Following the procedure of Section 5.2.2, we measured the E_{cm} value of each continuum point. This resulted in a 4 MeV to 6 MeV shift downwards for each of the new continuum points, but virtually no shift for the old continuum point. The measured energies and luminosities of each sample are shown in Table 6.1.

| Sample Name | E_{cm} [GeV] | Luminosity pb $^{-1}$ |
|-------------------|-----------------------|-----------------------|
| 3500 (New) | 3.496 | 3.680 ± 0.009 |
| 3542 (New) | 3.538 | 3.481 ± 0.009 |
| 3600 (New) | 3.596 | 0.395 ± 0.019 |
| 3650 (New) | 3.644 | 5.420 ± 0.009 |
| 3671 (New) | 3.665 | 4.669 ± 0.009 |
| 3650 (Old) | 3.650 | 44.334 ± 0.009 |
| $\psi(3770)$ (R1) | 3.773 | 926.922 ± 0.092 |
| $\psi(3770)$ (R2) | 3.773 | 1978.920 ± 0.091 |

Table 6.1: Data samples used for the inclusive measurement.

While the 3600 (New) sample was intended to be similar in luminosity to the other continuum points, accelerator issues inhibited the data collection procedure. The new continuum points also have a much smaller luminosity compared to the other datasets used in this analysis.

6.2 Event Selection

In order to select the number of hadronic events in each sample, we apply a variety of cuts. For charged tracks in the MDC, these include the cuts shown in Table 6.2.

| | |
|-----------------|-------------------------|
| Vertex (xy) | $V_{xy} < 1 \text{ cm}$ |
| Vertex (z) | $ Vz < 10 \text{ cm}$ |
| MDC Angle | $ \cos \theta < 0.93$ |

Table 6.2: Selection cuts on charged tracks used to count hadronic events.

For neutral tracks in the EMC, these include the cuts shown in Table 6.3.

| | | |
|-------------------------|---|---------------------------------|
| Minimum Energy (Barrel) | $E_{\text{EMC}} > 25 \text{ MeV}$ | $(\cos \theta < 0.80)$ |
| Minimum Energy (Endcap) | $E_{\text{EMC}} > 50 \text{ MeV}$ | $(0.86 < \cos \theta < 0.92)$ |
| TDC Timing | $(0 \leq t \leq 14) \times 50 \text{ ns}$ | |

Table 6.3: Selection cuts on neutral tracks used to count hadronic events.

To reject background events of $e^+e^- \rightarrow e^+e^-$ or $e^+e^- \rightarrow \gamma\gamma$, we also employ cuts related to the highest energy and highest momentum tracks in the event. These are listed in Table 6.4.

| | | |
|------------------|---|------------------------------|
| Highest Energy | $\cos \theta_+^{\max} < 0.8$ | $(N_{\text{tracks}} = 2)$ |
| | $\cos \theta_-^{\max} > -0.8$ | |
| Highest Momentum | $\cos \theta_+^{\max} < 0.8 \text{ or } (p/E_{\text{cm}})_+^{\max} \leq 0.3$ | $(N_{\text{tracks}} = 3, 4)$ |
| | $\cos \theta_-^{\max} > -0.8 \text{ or } (p/E_{\text{cm}})_-^{\max} \leq 0.3$ | |
| Highest Momentum | $0.8 \leq (E_{\text{EMC}}/p)_+^{\max} \leq 1.1$ | |
| | $0.8 \leq (E_{\text{EMC}}/p)_-^{\max} \leq 1.1$ | |

Table 6.4: Selection cuts to remove Bhabha and two-photon backgrounds.

The $+$ and $-$ denote positively and negatively charged tracks, respectively. The $^{\max}$ notation indicates the highest energy or momenta track for the corresponding charge. The energy cuts depend on the total number of charged tracks in the event, N_{tracks} .

After applying these sets of cuts, there are three groups of cuts which are considered: Standard (SHAD), Loose (LHAD), and Tight (THAD). For the nominal procedure, SHAD is used, while LHAD and THAD are for future systematic considerations. The cuts included in each of these sets are shown in Tables 6.5 to 6.7. These apply to the number of charged tracks (N_{tracks}), the visible energy (E_{vis}), the total visible momentum

in the z -direction ($p_{z\text{vis}}$), the maximum shower energy ($E_{\text{EMC}}^{\text{max}}$), and the total shower energy ($E_{\text{EMC}}^{\text{tot}}$). Here, ‘visible’ refers to the sum over charged and neutral tracks.

| | | |
|-----------------------|---|------------------------------|
| Number of Tracks | $N_{\text{tracks}} > 2$ | |
| Visible Energy | $(E_{\text{vis}}/E_{\text{cm}}) > 0.3$ | |
| Visible Momentum | $(p_{z\text{vis}}/E_{\text{vis}}) < 0.6$ | $(N_{\text{tracks}} = 3, 4)$ |
| Maximum Shower Energy | $(E_{\text{EMC}}^{\text{max}}/E_{\text{beam}}) < 0.75$ | $(N_{\text{tracks}} = 3, 4)$ |
| Total Shower Energy | $0.25 < (E_{\text{EMC}}^{\text{tot}}/E_{\text{cm}}) < 0.75$ | $(N_{\text{tracks}} = 3)$ |
| | $0.15 < (E_{\text{EMC}}^{\text{tot}}/E_{\text{cm}}) < 0.75$ | $(N_{\text{tracks}} = 4)$ |

Table 6.5: Standard selection cuts (SHAD) for counting hadronic events.

| | | |
|-----------------------|---|------------------------------|
| Number of Tracks | $N_{\text{tracks}} > 1$ | |
| Visible Energy | $(E_{\text{vis}}/E_{\text{cm}}) > 0.4$ | $(N_{\text{tracks}} = 2)$ |
| | $(E_{\text{vis}}/E_{\text{cm}}) > 0.3$ | $(N_{\text{tracks}} \geq 3)$ |
| Visible Momentum | $(p_{z\text{vis}}/E_{\text{vis}}) < 0.3$ | $(N_{\text{tracks}} = 2)$ |
| | $(p_{z\text{vis}}/E_{\text{vis}}) < 0.6$ | $(N_{\text{tracks}} = 3, 4)$ |
| Maximum Shower Energy | $(E_{\text{EMC}}^{\text{max}}/E_{\text{beam}}) < 0.50$ | $(N_{\text{tracks}} = 2)$ |
| | $(E_{\text{EMC}}^{\text{max}}/E_{\text{beam}}) < 0.75$ | $(N_{\text{tracks}} = 3, 4)$ |
| Total Shower Energy | $0.25 < (E_{\text{EMC}}^{\text{tot}}/E_{\text{cm}}) < 0.75$ | $(N_{\text{tracks}} = 2, 3)$ |
| | $0.15 < (E_{\text{EMC}}^{\text{tot}}/E_{\text{cm}}) < 0.75$ | $(N_{\text{tracks}} = 4)$ |

Table 6.6: Loose selection cuts (LHAD) for counting hadronic events.

| | | |
|-----------------------|---|------------------------------|
| Number of Tracks | $N_{\text{tracks}} > 3$ | |
| Visible Energy | $(E_{\text{vis}}/E_{\text{cm}}) > 0.4$ | |
| Visible Momentum | $(p_{z\text{vis}}/E_{\text{vis}}) < 0.6$ | $(N_{\text{tracks}} = 4)$ |
| Maximum Shower Energy | $(E_{\text{EMC}}^{\text{max}}/E_{\text{beam}}) < 0.75$ | $(N_{\text{tracks}} = 4, 5)$ |
| Total Shower Energy | $0.15 < (E_{\text{EMC}}^{\text{tot}}/E_{\text{cm}}) < 0.75$ | $(N_{\text{tracks}} = 4)$ |
| | $0.00 < (E_{\text{EMC}}^{\text{tot}}/E_{\text{cm}}) < 0.75$ | $(N_{\text{tracks}} = 5)$ |

Table 6.7: Tight selection cuts (THAD) for counting hadronic events.

6.3 Hadron Counting

In order to determine the total number of hadronic events in each data sample, we use the average velocity in the z -direction. Signal events should have tracks which average to zero around the collision point, while background events will have randomly oriented

momenta. The fits are done using a double Gaussian shape for the signal and a 2nd order polynomial for the background.

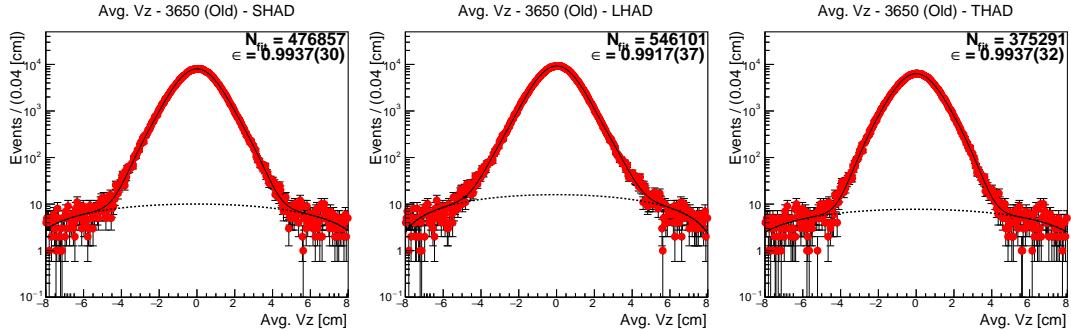


Figure 6.1: The number of hadrons found in the 3650 (Old) data sample. This includes results for SHAD (left), LHAD (middle), and THAD (right).

6.4 Background Subtraction

To precisely determine the number of hadronic events in the old continuum sample, we must subtract off a variety of backgrounds. The samples considered for this measurement include two-track QED processes (e^+e^- , $\mu^+\mu^-$, $\tau^-\tau^+$, $\gamma\gamma$), radiative J/ψ ($\gamma J/\psi$), two photon fusion (2γ), and events coming from $\psi(2S)$. Initially, we assume the $\psi(2S)$ has a standard Breit-Wigner shape.

Each background contributes to the total number of reconstructed events based on their cross section (σ) and reconstruction efficiency (ϵ_{MC}):

$$N_{\text{had}} = \mathcal{L} \times \sigma \times \epsilon_{\text{MC}}. \quad (6.2)$$

The efficiency is simply the fraction of reconstructed tracks compared to the total generated in a given MC sample:

$$\epsilon_{\text{MC}} = \left(\frac{N_{\text{rec}}}{N_{\text{gen}}} \right) \quad (6.3)$$

The MC samples were generated with 2.5×10^3 events for each of the 79 runs in the old continuum data for each of the included backgrounds. Each sample was analyzed with all three cut selection groups (see Section 6.2). The reconstruction efficiencies for each, along with their cross sections at 3.650 GeV are shown in Table 6.8.

| 3650 (Old) Reconstruction | | | | |
|---------------------------|---------------|-----------------------------------|-----------------------------------|-----------------------------------|
| Sample | σ [nb] | ϵ_{MC} (SHAD) [%] | ϵ_{MC} (LHAD) [%] | ϵ_{MC} (THAD) [%] |
| e^+e^- | 554.562 | 0.0006 ± 0.0002 | 0.0008 ± 0.0002 | 0.0001 ± 0.0001 |
| $\mu^+\mu^-$ | 5.560 | 0.0033 ± 0.0004 | 0.0044 ± 0.0005 | 0.0029 ± 0.0004 |
| $\tau^-\tau^+$ | 1.844 | 12.8351 ± 0.0255 | 28.7692 ± 0.0382 | 9.9371 ± 0.0224 |
| $\gamma J/\psi$ | 1.260 | 45.9222 ± 0.0482 | 55.1722 ± 0.0529 | 34.1250 ± 0.0416 |
| $\gamma\gamma$ | 21.530 | 0.0009 ± 0.0002 | 0.0010 ± 0.0002 | 0.0005 ± 0.0002 |
| 2γ | 1.257 | 2.4109 ± 0.0110 | 4.6297 ± 0.0153 | 1.6468 ± 0.0091 |
| $\psi(2S)^{\dagger}$ | 0.150 | 62.9891 ± 0.0078 | 69.2882 ± 0.0082 | 51.6942 ± 0.0071 |

Table 6.8: Reconstruction of background samples for the old continuum data. These include standard QED two-track processes (e^+e^- , $\mu^+\mu^-$, $\tau^-\tau^+$, $\gamma\gamma$), radiative J/ψ ($\gamma J/\psi$) and two photon fusion (2γ) events, and a contribution coming from $\psi(2S)$.

\dagger The $\psi(2S)$ is assumed to have a standard Breit-Wigner shape.

Using each of these values, we can determine the total number of hadronic events in the data. This is done by subtracting the expected amount of background from the measured number of events passing each selection method in data. The results for the old continuum data are shown in Table 6.9. Given that the e^+e^- , $\mu^+\mu^-$, and $\gamma\gamma$ samples have contributions which are much smaller than the uncertainty on the total result, we exclude these from the final calculation.

| 3650 (Old) Results | | | |
|----------------------|-------------------------|-------------------------|-------------------------|
| Sample | N_{had} (SHAD) | N_{had} (LHAD) | N_{had} (THAD) |
| Data | 477001 ± 691 | 546546 ± 739 | 375380 ± 613 |
| e^+e^-* | 149 ± 43 | 187 ± 48 | 12 ± 12 |
| $\mu^+\mu^-*$ | 8 ± 1 | 11 ± 1 | 7 ± 1 |
| $\tau^-\tau^+$ | 10490 ± 30 | 23514 ± 59 | 8122 ± 25 |
| $\gamma J/\psi$ | 25658 ± 60 | 30826 ± 71 | 19067 ± 46 |
| $\gamma\gamma^*$ | 9 ± 2 | 10 ± 2 | 4 ± 1 |
| 2γ | 1443 ± 7 | 2771 ± 11 | 986 ± 6 |
| $\psi(2S)^{\dagger}$ | 4175 ± 9 | 4593 ± 10 | 3427 ± 7 |
| Hadrons | 435234 ± 694 | 484842 ± 745 | 343779 ± 615 |

Table 6.9: Hadronic events selected in the old continuum data. As expected, SHAD finds less events than LHAD and more than THAD.

* The contribution is neglected for the total results.

\dagger The $\psi(2S)$ is assumed to have a standard Breit-Wigner shape.

6.5 Efficiency Extrapolation

Due to complicated interactions above the $D\bar{D}$ threshold, $q\bar{q}$ events not coming from $\psi(3770)$ are currently not well modeled by our MC generators. In order to accurately count these events, we utilize the continuum data, as below the $\psi(2S)$ the process is more reliable. Assuming the production of these events remains consistent over energy, we can use the measurements at lower energies to extrapolate to higher energies:

Measuring the hadronic events for the new continuum data follows exactly as for the old continuum data, but with the negligible backgrounds excluded. The number of hadrons found in each data sample can be seen in Figures 6.2 to 6.6. Reconstruction efficiencies are shown in Table 6.10 with the total results shown in Table 6.11.

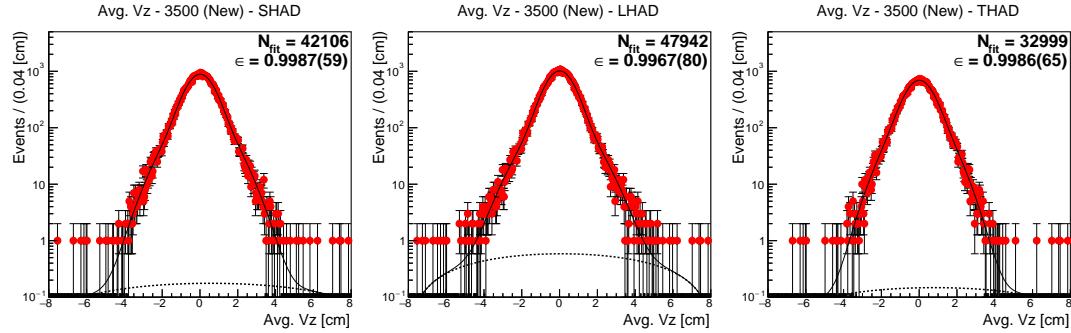


Figure 6.2: The number of hadrons found in the 3500 (New) data sample. This includes results for SHAD (left), LHAD (middle), and THAD (right).

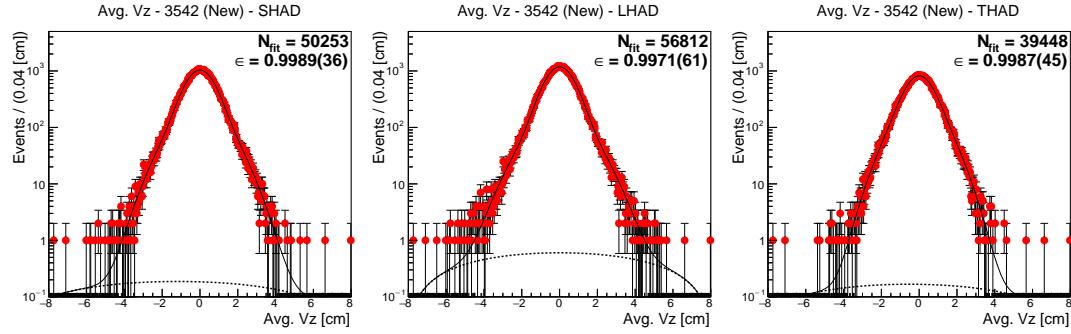


Figure 6.3: The number of hadrons found in the 3542 (New) data sample. This includes results for SHAD (left), LHAD (middle), and THAD (right).

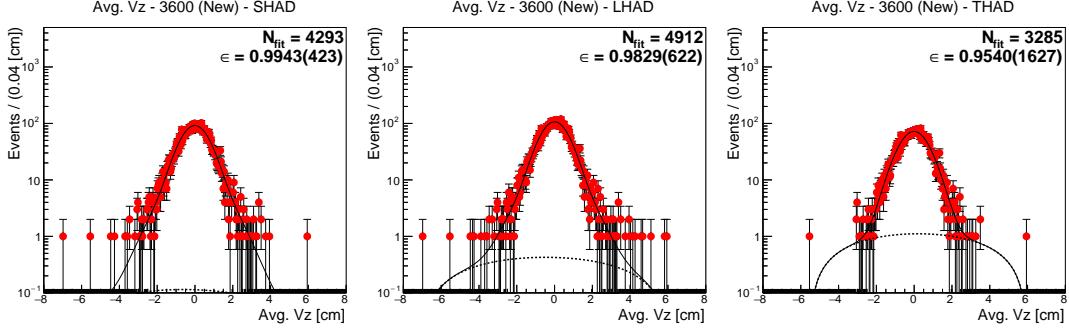


Figure 6.4: The number of hadrons found in the 3600 (New) data sample. This includes results for SHAD (left), LHAD (middle), and THAD (right).

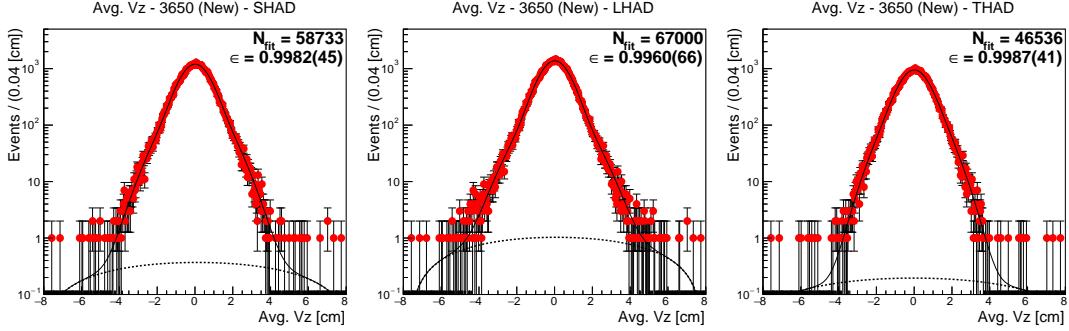


Figure 6.5: The number of hadrons found in the 3650 (New) data sample. This includes results for SHAD (left), LHAD (middle), and THAD (right).

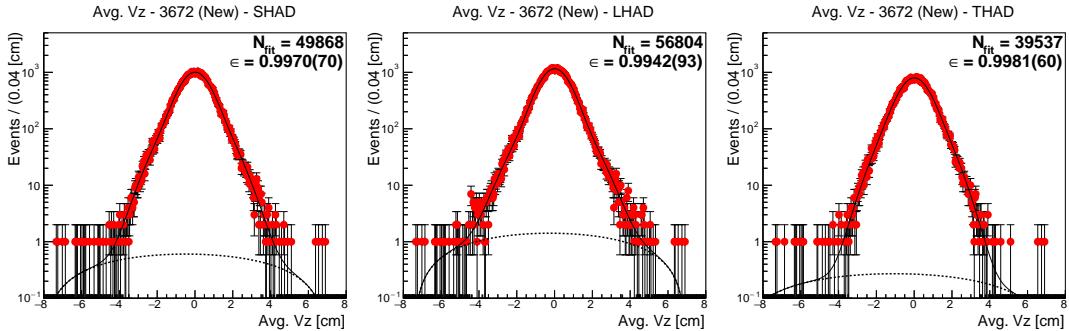


Figure 6.6: The number of hadrons found in the 3671 (New) data sample. This includes results for SHAD (left), LHAD (middle), and THAD (right).

| 3500 (New) Reconstruction | | | | |
|---------------------------|---------------|-----------------------------------|-----------------------------------|-----------------------------------|
| Sample | σ [nb] | ϵ_{MC} (SHAD) [%] | ϵ_{MC} (LHAD) [%] | ϵ_{MC} (THAD) [%] |
| $\tau^-\tau^+$ | 0.000 | - | - | - |
| $\gamma J/\psi$ | 1.831 | 47.079 ± 0.077 | 56.117 ± 0.084 | 35.320 ± 0.066 |
| 2γ | 1.240 | 2.380 ± 0.017 | 4.924 ± 0.025 | 1.644 ± 0.014 |
| $\psi(2S)^{\dagger}$ | 0.006 | 62.989 ± 0.008 | 69.288 ± 0.008 | 51.694 ± 0.007 |

| 3542 (New) Reconstruction | | | | |
|---------------------------|---------------|-----------------------------------|-----------------------------------|-----------------------------------|
| Sample | σ [nb] | ϵ_{MC} (SHAD) [%] | ϵ_{MC} (LHAD) [%] | ϵ_{MC} (THAD) [%] |
| $\tau^-\tau^+$ | 0.000 | - | - | - |
| $\gamma J/\psi$ | 1.632 | 47.188 ± 0.072 | 56.430 ± 0.079 | 35.355 ± 0.063 |
| 2γ | 1.270 | 2.386 ± 0.016 | 5.046 ± 0.024 | 1.633 ± 0.013 |
| $\psi(2S)^{\dagger}$ | 0.009 | 62.989 ± 0.008 | 69.288 ± 0.008 | 51.694 ± 0.007 |

| 3600 (New) Reconstruction | | | | |
|---------------------------|---------------|-----------------------------------|-----------------------------------|-----------------------------------|
| Sample | σ [nb] | ϵ_{MC} (SHAD) [%] | ϵ_{MC} (LHAD) [%] | ϵ_{MC} (THAD) [%] |
| $\tau^-\tau^+$ | 1.262 | 12.851 ± 0.080 | 29.096 ± 0.121 | 10.040 ± 0.071 |
| $\gamma J/\psi$ | 1.412 | 47.524 ± 0.154 | 56.902 ± 0.169 | 35.703 ± 0.134 |
| 2γ | 1.311 | 2.651 ± 0.036 | 5.089 ± 0.050 | 1.897 ± 0.031 |
| $\psi(2S)^{\dagger}$ | 0.024 | 62.989 ± 0.008 | 69.288 ± 0.008 | 51.694 ± 0.007 |

| 3650 (New) Reconstruction | | | | |
|---------------------------|---------------|-----------------------------------|-----------------------------------|-----------------------------------|
| Sample | σ [nb] | ϵ_{MC} (SHAD) [%] | ϵ_{MC} (LHAD) [%] | ϵ_{MC} (THAD) [%] |
| $\tau^-\tau^+$ | 1.844 | 12.964 ± 0.033 | 28.939 ± 0.049 | 10.154 ± 0.029 |
| $\gamma J/\psi$ | 1.260 | 47.414 ± 0.063 | 57.043 ± 0.069 | 35.701 ± 0.055 |
| 2γ | 1.346 | 2.410 ± 0.014 | 4.675 ± 0.020 | 1.682 ± 0.012 |
| $\psi(2S)^{\dagger}$ | 0.110 | 62.989 ± 0.008 | 69.288 ± 0.008 | 51.694 ± 0.007 |

| 3671 (New) Reconstruction | | | | |
|---------------------------|---------------|-----------------------------------|-----------------------------------|-----------------------------------|
| Sample | σ [nb] | ϵ_{MC} (SHAD) [%] | ϵ_{MC} (LHAD) [%] | ϵ_{MC} (THAD) [%] |
| $\tau^-\tau^+$ | 2.026 | 12.997 ± 0.047 | 28.851 ± 0.069 | 10.169 ± 0.041 |
| $\gamma J/\psi$ | 1.205 | 47.496 ± 0.089 | 57.237 ± 0.098 | 35.745 ± 0.077 |
| 2γ | 1.361 | 2.473 ± 0.020 | 4.787 ± 0.028 | 1.698 ± 0.017 |
| $\psi(2S)^{\dagger}$ | 0.436 | 62.989 ± 0.008 | 69.288 ± 0.008 | 51.694 ± 0.007 |

Table 6.10: Reconstruction of background samples for the new continuum data.

[†] The $\psi(2S)$ is assumed to have a standard Breit-Wigner shape.

| 3500 (New) Results | | | |
|----------------------|-------------------------|-------------------------|-------------------------|
| Sample | N_{had} (SHAD) | N_{had} (LHAD) | N_{had} (THAD) |
| Data | 42106 ± 205 | 47942 ± 219 | 32999 ± 182 |
| $\gamma J/\psi$ | 3173 ± 10 | 3782 ± 11 | 2380 ± 8 |
| 2γ | 109 ± 1 | 225 ± 1 | 75 ± 1 |
| $\psi(2S)^{\dagger}$ | 13 ± 1 | 14 ± 1 | 14 ± 1 |
| Hadrons | 38812 ± 205 | 43921 ± 219 | 30533 ± 182 |
| 3542 (New) Results | | | |
| Sample | N_{had} (SHAD) | N_{had} (LHAD) | N_{had} (THAD) |
| Data | 50253 ± 224 | 56812 ± 238 | 39448 ± 199 |
| $\gamma J/\psi$ | 3450 ± 9 | 4126 ± 10 | 2585 ± 7 |
| 2γ | 136 ± 1 | 287 ± 1 | 93 ± 1 |
| $\psi(2S)^{\dagger}$ | 26 ± 1 | 28 ± 1 | 21 ± 1 |
| Hadrons | 46641 ± 224 | 52371 ± 239 | 36749 ± 199 |
| 3600 (New) Results | | | |
| Sample | N_{had} (SHAD) | N_{had} (LHAD) | N_{had} (THAD) |
| Data | 4293 ± 66 | 4912 ± 70 | 3285 ± 57 |
| $\tau^-\tau^+$ | 64 ± 3 | 145 ± 7 | 50 ± 2 |
| $\gamma J/\psi$ | 265 ± 13 | 317 ± 16 | 199 ± 10 |
| 2γ | 14 ± 1 | 26 ± 1 | 10 ± 1 |
| $\psi(2S)^{\dagger}$ | 6 ± 1 | 7 ± 1 | 5 ± 1 |
| Hadrons | 3944 ± 67 | 4417 ± 72 | 3023 ± 58 |
| 3650 (New) Results | | | |
| Sample | N_{had} (SHAD) | N_{had} (LHAD) | N_{had} (THAD) |
| Data | 58733 ± 242 | 67000 ± 259 | 46536 ± 216 |
| $\tau^-\tau^+$ | 1295 ± 4 | 2892 ± 7 | 1015 ± 3 |
| $\gamma J/\psi$ | 3239 ± 7 | 3896 ± 8 | 2439 ± 6 |
| 2γ | 176 ± 1 | 341 ± 2 | 123 ± 1 |
| $\psi(2S)^{\dagger}$ | 376 ± 1 | 414 ± 1 | 309 ± 1 |
| Hadrons | 53647 ± 242 | 59458 ± 259 | 42652 ± 216 |
| 3671 (New) Results | | | |
| Sample | N_{had} (SHAD) | N_{had} (LHAD) | N_{had} (THAD) |
| Data | 49868 ± 223 | 56804 ± 238 | 39537 ± 199 |
| $\tau^-\tau^+$ | 1229 ± 5 | 2729 ± 8 | 962 ± 4 |
| $\gamma J/\psi$ | 2671 ± 7 | 3219 ± 8 | 2010 ± 6 |
| 2γ | 157 ± 1 | 304 ± 2 | 108 ± 1 |
| $\psi(2S)^{\dagger}$ | 1282 ± 3 | 1410 ± 3 | 1052 ± 2 |
| Hadrons | 44528 ± 224 | 49141 ± 239 | 35405 ± 199 |

Table 6.11: Hadronic events selected in the new continuum data.

[†] The $\psi(2S)$ is assumed to have a standard Breit-Wigner shape.

Since the rate of $q\bar{q}$ production varies smoothly with energy, the reconstruction efficiency (relative to the old continuum data) for a given E_{cm} point (in MeV) can be calculated as follows:

$$\frac{\epsilon(E_{\text{cm}})}{\epsilon(3650)} = \left[\frac{N_{\text{had}}(E_{\text{cm}})}{N_{\text{had}}(3650)} \right] \left[\frac{\mathcal{L}(3650)}{\mathcal{L}(E_{\text{cm}})} \right] \left[\frac{E_{\text{cm}}}{3650} \right]^2. \quad (6.4)$$

This efficiency ratio is calculated for each of the new continuum points, and a linear fit is performed for each of the selection cut methods. From this slope, we can extrapolate to find the expected number of hadronic events for the scan data. As the old continuum data was taken at a relatively similar time as the scan data, we use it as a normalization point for the efficiency extrapolation. The results for each cut are shown in Figures 6.7 to 6.9, where the dashed black line is the fit to the new continuum, and the solid green line is the extrapolation to higher energies.

From these extrapolations, it is evident the highest energy point (3.665 GeV) is generally lower than the other new continuum points. This is most likely due to the assumption of a standard Breit-Wigner shape for the $\psi(2S)$. Recent experimental evidence indicates this resonance may be susceptible to interference effects which distort the shape away from its peak. If the actual shape is lower than expected for the higher energy continuum points, it would decrease the background contribution thereby raising the efficiency ratio. This behavior is explored in Section 6.7, as BESIII plans to take considerably more data across this region in the near future. For now, we continue with the default Breit-Wigner assumption, and apply the procedure for the $\psi(3770)$ data. While the final results may not be indicative of the true values, it will provide limits for measuring various important other parameters of the $\psi(3770)$.

Efficiency Extrapolation - SHAD

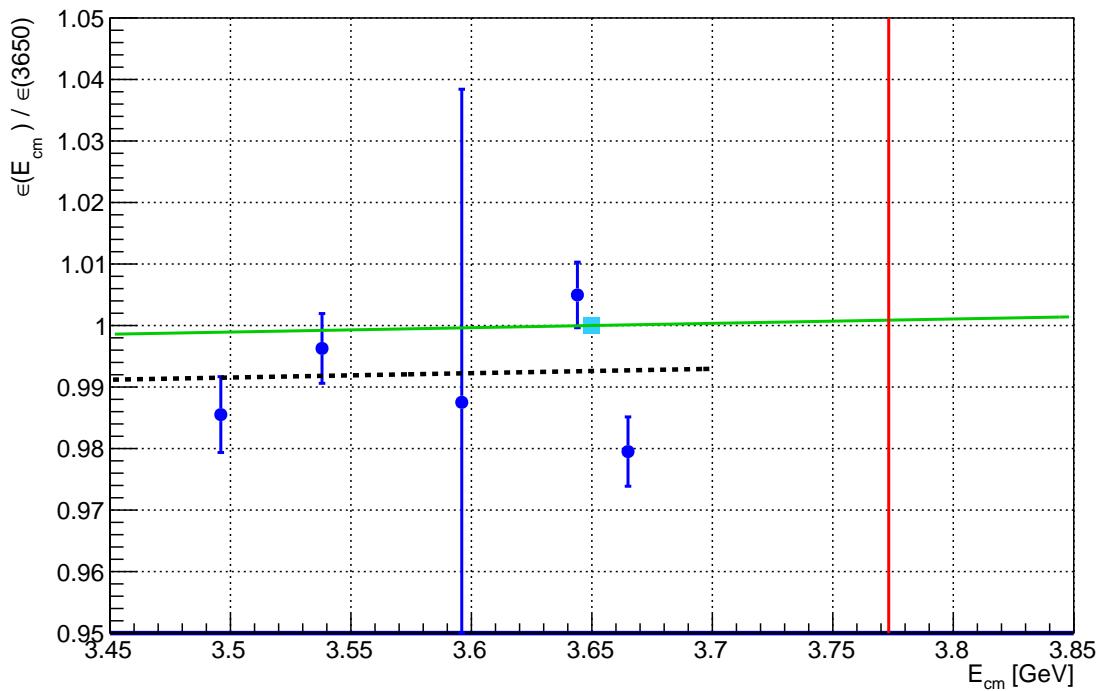


Figure 6.7: The extrapolation for SHAD events using the new continuum data. The new continuum points (blue) are fit using a linear slope (dashed black), then extrapolated to higher energies (solid green) based on the old continuum energy point at 3.650 GeV (cyan). The energy point for the $\psi(3770)$ samples at 3.773 GeV is also shown (solid red).

Efficiency Extrapolation - LHAD

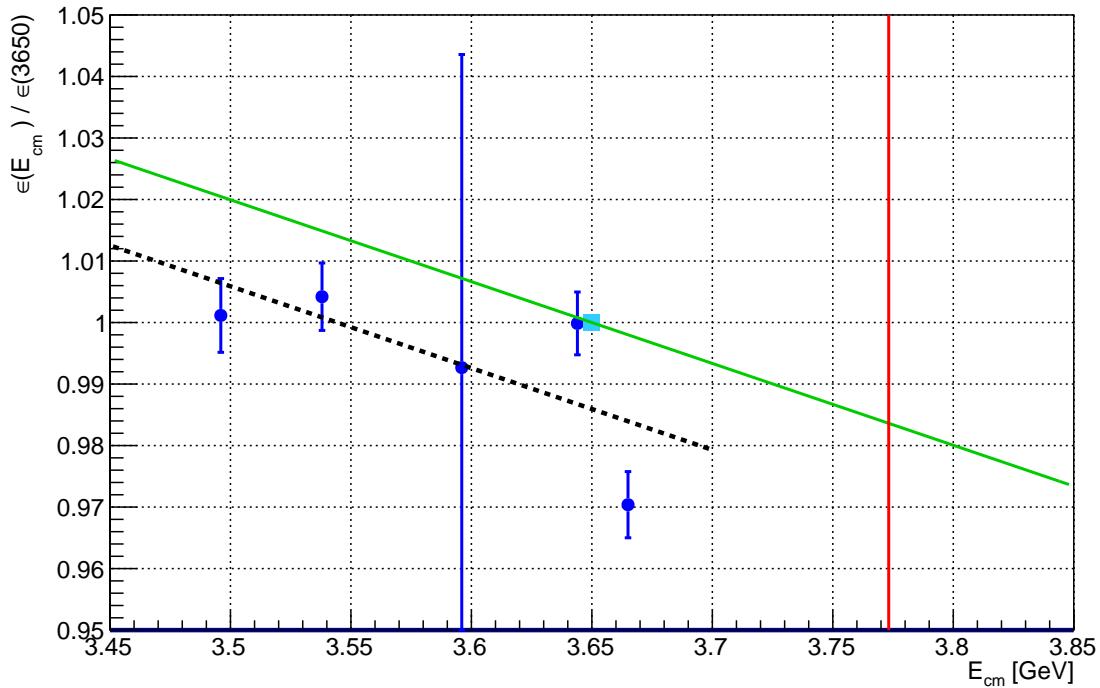


Figure 6.8: The extrapolation for LHAD events using the new continuum data. The new continuum points (blue) are fit using a linear slope (dashed black), then extrapolated to higher energies (solid green) based on the old continuum energy point at 3.650 GeV (cyan). The energy point for the $\psi(3770)$ samples at 3.773 GeV is also shown (solid red).

Efficiency Extrapolation - THAD

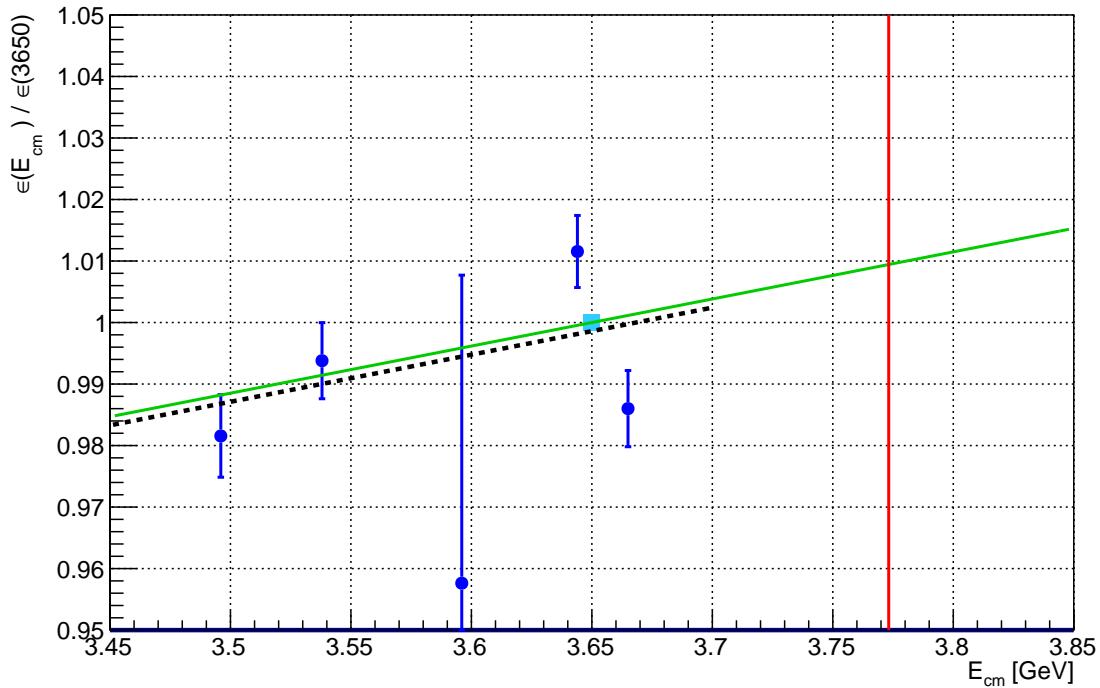


Figure 6.9: The extrapolation for THAD events using the new continuum data. The new continuum points (blue) are fit using a linear slope (dashed black), then extrapolated to higher energies (solid green) based on the old continuum energy point at 3.650 GeV (cyan). The energy point for the $\psi(3770)$ samples at 3.773 GeV is also shown (solid red).

6.6 Results for $\psi(3770)$ Data

The procedure for determining the hadronic events in the $\psi(3770)$ data is similar to the continuum region, but with certain modifications introduced due to the different relevant backgrounds. Namely, above the $D\bar{D}$ peak, contributions from $D^0\bar{D}^0$ and D^+D^- events must be accounted for. Also, instead of the $\psi(2S)$ component, there is now a background from radiative $\psi(2S)$ production ($\gamma\psi(2S)$). Lastly, due to the minimal contribution of two photon fusion events (2γ) in this region, this component is neglected for the $\psi(3770)$ samples. The counting of total hadronic events, however, functions identically to the continuum data, and the results are shown in Figures 6.10 and 6.11.

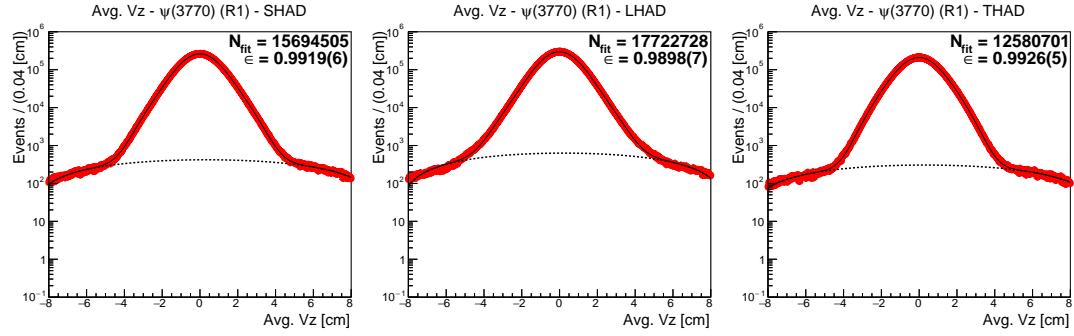


Figure 6.10: The number of hadrons found in the $\psi(3770)$ (R1) data sample. This includes results for SHAD (left), LHAD (middle), and THAD (right).

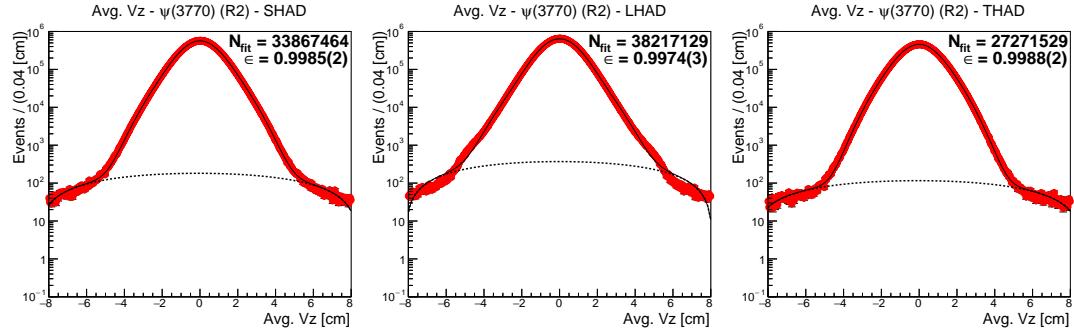


Figure 6.11: The number of hadrons found in the $\psi(3770)$ (R2) data sample. This includes results for SHAD (left), LHAD (middle), and THAD (right).

6.6.1 $D\bar{D}$ Correction

Since the $D\bar{D}$ cross section is not a smooth scaling of energy (like $q\bar{q}$), we must precisely determine its reconstruction efficiency using data. Instead of using the standard definition of ϵ_{MC} for $D\bar{D}$, we apply a correction based on the multiplicity of $D\bar{D}$ events in both data and MC. This is done by finding single-tagged D candidates and counting the number of tracks not used for reconstruction. By randomly sampling pairs of points from this distribution, and assuming the decays are uncorrelated, we can produce an average representation of multiplicity in $D\bar{D}$ events. From this new distribution, selections methods for SHAD, LHAD, and THAD are performed based off number of tracks selected by the simplified cut criteria shown in Table 6.12 relative to the total. The corrections applied to each efficiency are the ratio of these selections in data and MC. As the $\psi(3770)$ samples for R1 and R2 were taken at different times, they are treated separately for this process. The results for each are shown in Table 6.13 with the corresponding distributions shown in Figures 6.12 to 6.15.

| Selection Method | Number of Tracks |
|------------------|-------------------------|
| SHAD | $N_{\text{tracks}} > 2$ |
| LHAD | $N_{\text{tracks}} > 1$ |
| THAD | $N_{\text{tracks}} > 3$ |

Table 6.12: Selection methods for the $D\bar{D}$ efficiency correction.

| Selection | $\psi(3770)$ R1 | | $\psi(3770)$ R2 | |
|-----------|--|--|--|--|
| | $(\epsilon_{\text{Data}}/\epsilon_{\text{MC}})(D^0)$ | $(\epsilon_{\text{Data}}/\epsilon_{\text{MC}})(D^+)$ | $(\epsilon_{\text{Data}}/\epsilon_{\text{MC}})(D^0)$ | $(\epsilon_{\text{Data}}/\epsilon_{\text{MC}})(D^+)$ |
| SHAD | 0.9751 | 0.9992 | 0.9759 | 0.9999 |
| LHAD | 0.9930 | 1.0018 | 0.9935 | 1.0024 |
| THAD | 0.9662 | 1.0064 | 0.9684 | 1.0108 |

Table 6.13: Efficiency corrections for the $\psi(3770)$ samples.

The corrections are impactful for D^0 , but minimal for D^+ . This is due to the differences in their low-side other D multiplicities, as seen in Figures 6.12 to 6.15.

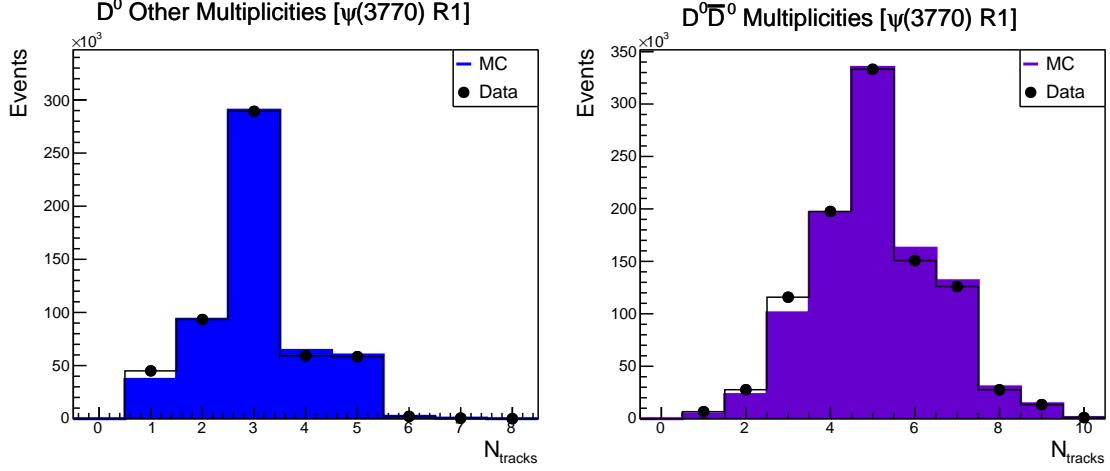


Figure 6.12: The other-side D^0 tracks and corresponding $D^0\overline{D}^0$ multiplicities for R1. The distribution of good tracks not used for reconstruction of single-tagged D^0 particles (left) is randomly sampled for pairs of points which comprise the total multiplicity distribution (right). The tracks in the $D^0\overline{D}^0$ multiplicity distribution are used to determine the efficiency correction based off the cuts in Table 6.12.

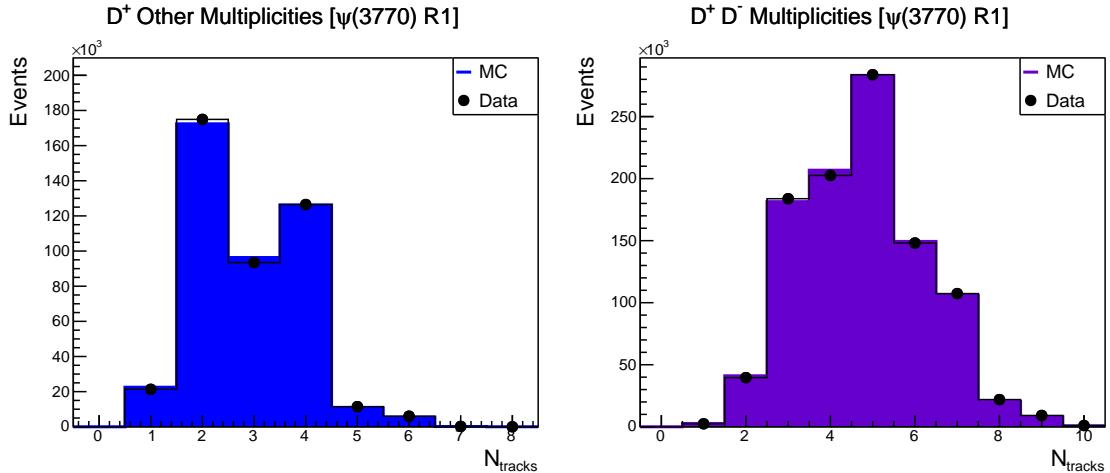


Figure 6.13: The other-side D^+ tracks and corresponding D^+D^- multiplicities for R1. The distribution of good tracks not used for reconstruction of single-tagged D^+ particles (left) is randomly sampled for pairs of points which comprise the total multiplicity distribution (right). The tracks in the D^+D^- multiplicity distribution are used to determine the efficiency correction based off the cuts in Table 6.12.

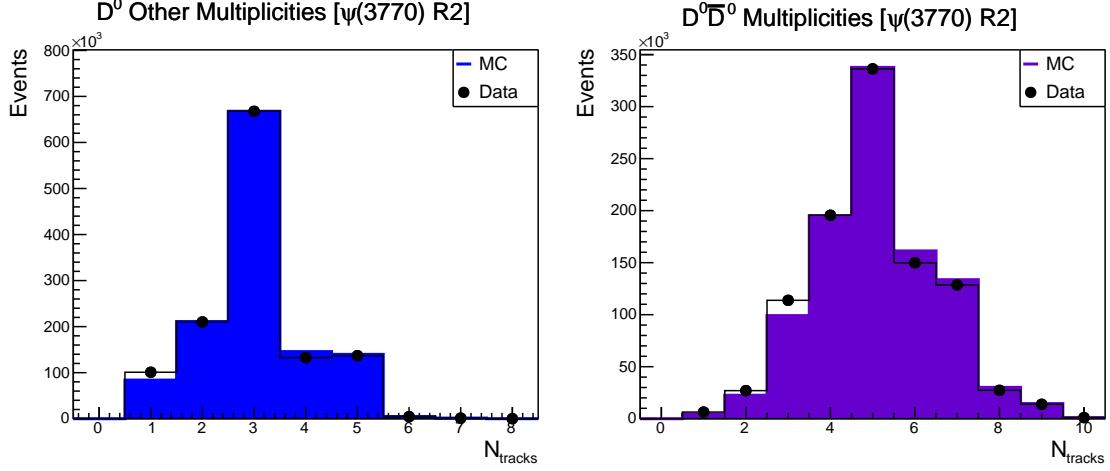


Figure 6.14: The other-side D^0 tracks and corresponding $D^0\overline{D}^0$ multiplicities for R2. The distribution of good tracks not used for reconstruction of single-tagged D^0 particles (left) is randomly sampled for pairs of points which comprise the total multiplicity distribution (right). The tracks in the $D^0\overline{D}^0$ multiplicity distribution are used to determine the efficiency correction based off the cuts in Table 6.12.

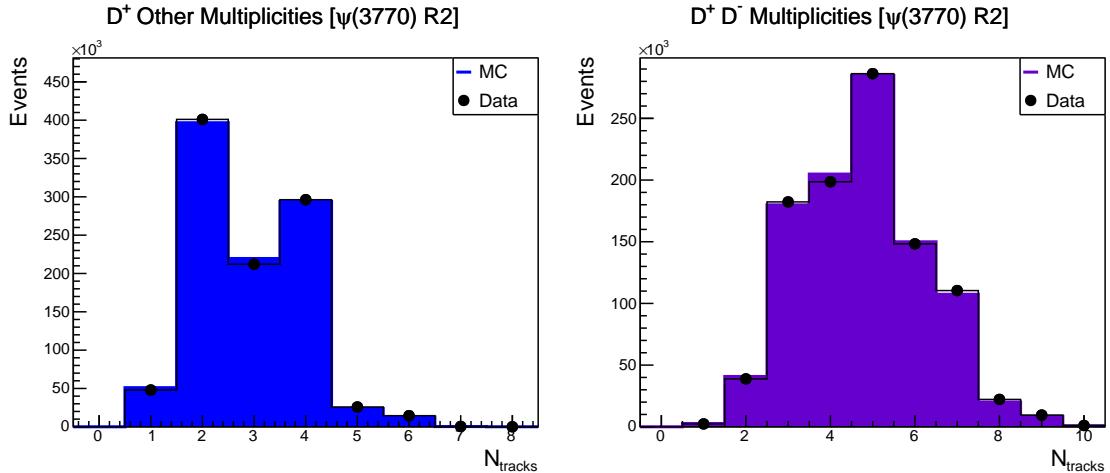


Figure 6.15: The other-side D^+ tracks and corresponding D^+D^- multiplicities for R2. The distribution of good tracks not used for reconstruction of single-tagged D^+ particles (left) is randomly sampled for pairs of points which comprise the convolved distribution (right). The number of tracks in the D^+D^- multiplicity distribution is used to determine the efficiency correction based off the cuts in Table 6.12.

6.6.2 Reconstruction Efficiencies

MC samples for each of the new backgrounds introduced above the $D\bar{D}$ threshold were generated in the same way as for the continuum data. The reconstruction efficiencies for each are shown in Table 6.14. Values for the $D^0\bar{D}^0$ and D^+D^- samples have already been multiplied by the correction factors discussed in Section 6.6.1.

For the cross section of $\gamma\psi(2S)$, rather than the radiative return formula (as used with $\gamma J/\psi$), we use results from CLEO-c and BESIII to determine the value. These values are $\sigma(e^+e^- \rightarrow \gamma\psi(2S), \psi(2S) \rightarrow \pi^+\pi^-J/\psi) = (1036 \pm 13 \pm 23) \text{ pb}$ from the CLEO-c measurement, and $\Gamma(\psi(2S) \rightarrow \pi^+\pi^-J/\psi) = (34.43 \pm 0.30) \%$ after averaging the BESIII measurement with the value from the PDG. From this, we determine

$$\sigma(e^+e^- \rightarrow \gamma\psi') = \frac{\sigma(e^+e^- \rightarrow \gamma\psi', \psi' \rightarrow \pi^+\pi^-J/\psi)}{\Gamma(\psi' \rightarrow \pi^+\pi^-J/\psi)} = (3009 \pm 81) \text{ pb}. \quad (6.5)$$

Additionally, the $D^0\bar{D}^0$ and D^+D^- cross sections are taken from the on-peak $\psi(3770)$ measurement performed by Derrick Toth [44].

| $\psi(3770)$ (R1) Reconstruction | | | | |
|----------------------------------|---------------|-----------------------------------|-----------------------------------|-----------------------------------|
| Sample | σ [nb] | ϵ_{MC} (SHAD) [%] | ϵ_{MC} (LHAD) [%] | ϵ_{MC} (THAD) [%] |
| $D^0\bar{D}^0$ | 3.615 | 73.9324 ± 0.0142 | 79.8496 ± 0.0147 | 60.3601 ± 0.0128 |
| D^+D^- | 2.830 | 61.4048 ± 0.0146 | 68.8212 ± 0.0154 | 49.4007 ± 0.0131 |
| $\tau^-\tau^+$ | 2.652 | 12.7566 ± 0.0253 | 28.0142 ± 0.0374 | 9.8776 ± 0.0222 |
| $\gamma J/\psi$ | 0.986 | 46.6185 ± 0.0206 | 56.2494 ± 0.0227 | 34.7544 ± 0.0178 |
| $\gamma\psi(2S)$ | 3.009 | 63.2551 ± 0.0137 | 69.9696 ± 0.0144 | 51.5643 ± 0.0123 |

| $\psi(3770)$ (R2) Reconstruction | | | | |
|----------------------------------|---------------|-----------------------------------|-----------------------------------|-----------------------------------|
| Sample | σ [nb] | ϵ_{MC} (SHAD) [%] | ϵ_{MC} (LHAD) [%] | ϵ_{MC} (THAD) [%] |
| $D^0\bar{D}^0$ | 3.615 | 74.5111 ± 0.0097 | 80.3399 ± 0.0101 | 61.0386 ± 0.0088 |
| D^+D^- | 2.830 | 61.8444 ± 0.0100 | 69.1974 ± 0.0106 | 49.9163 ± 0.0090 |
| $\tau^-\tau^+$ | 2.652 | 12.8646 ± 0.0254 | 28.2140 ± 0.0376 | 10.0198 ± 0.0224 |
| $\gamma J/\psi$ | 0.986 | 47.0066 ± 0.0146 | 56.6679 ± 0.0161 | 35.1951 ± 0.0127 |
| $\gamma\psi(2S)$ | 3.009 | 63.7345 ± 0.0097 | 70.4050 ± 0.0102 | 52.1189 ± 0.0088 |

Table 6.14: Reconstruction of background samples for the $\psi(3770)$ data.

6.6.3 Signal Amounts

Using the reconstruction efficiencies from Section 6.6.2, we can compute the contribution of background events for each sample. For the $q\bar{q}$ component, we scale the number of hadronic events found in the 3650 (Old) sample based on equation (6.4) for both R1 and R2 separately. Due to the uncertainty on the extrapolation procedure, this becomes the dominant source of error on the resulting hadronic events. This is also highly susceptible to the assumption of the $\psi(2S)$ shape for calculating the continuum points in the extrapolation fit. The resulting number of hadronic events is shown in Table 6.15.

| $\psi(3770)$ (R1) Results | | | |
|---------------------------|-------------------------|-------------------------|-------------------------|
| Sample | N_{had} (SHAD) | N_{had} (LHAD) | N_{had} (THAD) |
| Data | 15694505 ± 3962 | 17722728 ± 4210 | 12580701 ± 3547 |
| $q\bar{q}^\dagger$ | 8522688 ± 71353 | 9330411 ± 76320 | 6789405 ± 61599 |
| $D^0\bar{D}^0$ | 2477345 ± 534 | 2675620 ± 560 | 2022561 ± 473 |
| D^+D^- | 1610764 ± 414 | 1805311 ± 442 | 1295875 ± 366 |
| $\tau^-\tau^+$ | 313542 ± 622 | 688559 ± 922 | 242781 ± 547 |
| $\gamma J/\psi$ | 425891 ± 193 | 513875 ± 213 | 317504 ± 166 |
| $\gamma\psi(2S)$ | 1764254 ± 419 | 1951528 ± 445 | 1438185 ± 372 |
| Hadrons | 490569 ± 71795 | 658730 ± 76807 | 401064 ± 61995 |

| $\psi(3770)$ (R2) Results | | | |
|---------------------------|-------------------------|-------------------------|-------------------------|
| Sample | N_{had} (SHAD) | N_{had} (LHAD) | N_{had} (THAD) |
| Data | 33867464 ± 5820 | 38217129 ± 6182 | 27271529 ± 5222 |
| $q\bar{q}^\dagger$ | 18314683 ± 154300 | 20015495 ± 164688 | 14644571 ± 133785 |
| $D^0\bar{D}^0$ | 5330375 ± 738 | 5747352 ± 770 | 4366577 ± 662 |
| D^+D^- | 3463499 ± 583 | 3875291 ± 620 | 2795485 ± 520 |
| $\tau^-\tau^+$ | 675063 ± 1331 | 1480514 ± 1972 | 525781 ± 1175 |
| $\gamma J/\psi$ | 916819 ± 288 | 1105253 ± 317 | 686446 ± 249 |
| $\gamma\psi(2S)$ | 3795113 ± 603 | 4192317 ± 636 | 3103459 ± 541 |
| Hadrons | 1179686 ± 155135 | 1589187 ± 165610 | 991049 ± 134532 |

Table 6.15: Hadronic events selected in the $\psi(3770)$ data.

[†] The $q\bar{q}$ contribution is obtained using an extrapolation from the continuum region in which the $\psi(2S)$ is assumed to have a standard Breit-Wigner shape.

6.6.4 Non- $D\bar{D}$ Branching Fraction (Breit-Wigner)

The resulting hadronic production is assumed to result from non- $D\bar{D}$ decays of the $\psi(3770)$. We can convert this into a cross section as follows:

$$\sigma(\psi(3770) \rightarrow \text{non-}D\bar{D}) = \frac{N_{\text{non-}D\bar{D}}}{\epsilon_{\text{non-}D\bar{D}} \times \mathcal{L}}. \quad (6.6)$$

For the efficiency of non- $D\bar{D}$ events, the value of ϵ_{MC} for $\gamma\psi(2S)$ is used due to the assumption of similar behavior in their decays. Using the standard Breit-Wigner assumption for the $\psi(2S)$, the results for the cross section and branching fraction of non- $D\bar{D}$ decays from $\psi(3770)$ are shown in Tables 6.16 and 6.17.

| Sample | $\sigma_{\text{non-}D\bar{D}}$ [nb] (SHAD) | $\sigma_{\text{non-}D\bar{D}}$ [nb] (LHAD) | $\sigma_{\text{non-}D\bar{D}}$ [nb] (THAD) |
|-------------------|--|--|--|
| $\psi(3770)$ (R1) | 0.9892 ± 0.1219 | 1.1679 ± 0.1179 | 0.9925 ± 0.1291 |
| $\psi(3770)$ (R2) | 1.0877 ± 0.1224 | 1.2926 ± 0.1183 | 1.1142 ± 0.1298 |
| Lum. Weighted | 1.0563 ± 0.1223 | 1.2528 ± 0.1182 | 1.0754 ± 0.1296 |

Table 6.16: Cross sections for $\psi(3770) \rightarrow \text{non-}D\bar{D}$ found using the $\psi(3770)$ data. The $q\bar{q}$ contributions were calculated using the Breit-Wigner formulation for the $\psi(2S)$ component in the continuum extrapolation.

| Sample | $\Gamma_{\text{non-}D\bar{D}}$ (SHAD) | $\Gamma_{\text{non-}D\bar{D}}$ (LHAD) | $\Gamma_{\text{non-}D\bar{D}}$ (THAD) |
|-------------------|---------------------------------------|---------------------------------------|---------------------------------------|
| $\psi(3770)$ (R1) | 0.1331 ± 0.0183 | 0.1534 ± 0.0185 | 0.1334 ± 0.0190 |
| $\psi(3770)$ (R2) | 0.1444 ± 0.0186 | 0.1671 ± 0.0189 | 0.1474 ± 0.0193 |
| Lum. Weighted | 0.1408 ± 0.0185 | 0.1627 ± 0.0187 | 0.1430 ± 0.0192 |

Table 6.17: Branching fractions for $\psi(3770) \rightarrow \text{non-}D\bar{D}$ found using the $\psi(3770)$ data. The $q\bar{q}$ contributions were calculated using the Breit-Wigner formulation for the $\psi(2S)$ component in the continuum extrapolation.

6.7 $\psi(2S)$ Background Investigation

The most impactful assumption for the measurement of the branching fraction is the cross section shape of $\psi(2S)$ in the continuum region. For the procedure thus far, we have assumed this shape to be a standard Breit-Wigner. Given the drop in relative efficiency for the 3671 (New) data point (see Figure 6.7), it is likely this overestimates the branching fraction (see Table 6.17) by subtracting off too large of a background component for the $\psi(2S)$.

As an alternative comparison, we use the ratio of cross section productions for the resonance peak and continuum values,

$$\frac{\sigma_{\text{res}}}{\sigma_{\text{cont}}(E_{\text{cm}})} = \frac{\sqrt{2\pi} (M_{\text{res}} - E_{\text{cm}})^2}{\Gamma_{\text{res}} \times \sigma_{E_{\text{cm}}}}, \quad (6.7)$$

where M_{res} and Γ_{res} are the mass and total width of the resonance, respectively, and $\sigma_{E_{\text{cm}}}$ is the center-of-mass energy spread during collection of the data. For the $\psi(2S)$, with $M_{\psi(2S)} = 3686.1 \text{ MeV}$ and $\Gamma_{\psi(2S)} = 0.299 \text{ MeV}$, assuming an energy spread of $\sigma_{E_{\text{cm}}} = 1.5 \text{ MeV}$ gives $\sigma_{\psi(2S)} \sim 2500 \times \sigma_{\text{cont}}(E_{\text{cm}})$ at $E_{\text{cm}} = 3.665 \text{ GeV}$.

In 2009, BESIII collected 166.25 pb^{-1} of data at $E_{\text{cm}} = 3.686 \text{ GeV}$ and found $(106.41 \pm 0.86) \times 10^6$ events of $\psi(2S)$ decays [54], corresponding to $\sigma_{\psi(2S)} \sim 640 \text{ nb}$. Using Equation (6.7) for each of the continuum points, we obtain the cross section values shown in Table 6.18, where each generally is notably smaller than from the Breit-Wigner assumption.

| Sample | E_{cm} [GeV] | $\sigma_{\psi(2S)}$ [nb] (Ratio) | $\sigma_{\psi(2S)}$ [nb] (BW) |
|------------|-----------------------|----------------------------------|-------------------------------|
| 3500 (New) | 3.496 | 0.0032 | 0.0056 |
| 3542 (New) | 3.538 | 0.0052 | 0.0092 |
| 3600 (New) | 3.596 | 0.0141 | 0.0244 |
| 3650 (New) | 3.644 | 0.0646 | 0.1101 |
| 3671 (New) | 3.665 | 0.2572 | 0.4359 |
| 3650 (Old) | 3.650 | 0.0879 | 0.1495 |

Table 6.18: Cross sections of $\psi(2S)$ calculated using two different methods.

6.7.1 Non- $D\bar{D}$ Branching Fraction ($\psi(2S)$ from Data)

We repeat the procedure using the cross sections calculated based off Equation (6.7) in place of the Breit-Wigner values (see Table 6.18). This leads to the continuum extrapolations shown in Figures 6.16 to 6.18. The non- $D\bar{D}$ results are shown in Tables 6.19 and 6.20, where the branching fractions are lower on average by around 1.6% compared to the original method.

| Sample | $\sigma_{\text{non-}D\bar{D}}$ [nb] (SHAD) | $\sigma_{\text{non-}D\bar{D}}$ [nb] (LHAD) | $\sigma_{\text{non-}D\bar{D}}$ [nb] (THAD) |
|-------------------|--|--|--|
| $\psi(3770)$ (R1) | 0.8367 ± 0.1224 | 1.0157 ± 0.1184 | 0.8391 ± 0.1297 |
| $\psi(3770)$ (R2) | 0.9353 ± 0.1230 | 1.1406 ± 0.1189 | 0.9609 ± 0.1304 |
| Lum. Weighted | 0.9039 ± 0.1228 | 1.1008 ± 0.1187 | 0.9220 ± 0.1302 |

Table 6.19: Cross sections for $\psi(3770) \rightarrow \text{non-}D\bar{D}$ found using the $\psi(3770)$ data. The $q\bar{q}$ contributions were calculated using $\psi(2S)$ data for the $\psi(2S)$ components in the continuum extrapolation.

| Sample | $\Gamma_{\text{non-}D\bar{D}}$ (SHAD) | $\Gamma_{\text{non-}D\bar{D}}$ (LHAD) | $\Gamma_{\text{non-}D\bar{D}}$ (THAD) |
|-------------------|---------------------------------------|---------------------------------------|---------------------------------------|
| $\psi(3770)$ (R1) | 0.1149 ± 0.0180 | 0.1361 ± 0.0181 | 0.1152 ± 0.0188 |
| $\psi(3770)$ (R2) | 0.1267 ± 0.0183 | 0.1504 ± 0.0185 | 0.1297 ± 0.0190 |
| Lum. Weighted | 0.1230 ± 0.0182 | 0.1458 ± 0.0183 | 0.1251 ± 0.0190 |

Table 6.20: Branching fractions for $\psi(3770) \rightarrow \text{non-}D\bar{D}$ found using the $\psi(3770)$ data. The $q\bar{q}$ contributions were calculated using $\psi(2S)$ data for the $\psi(2S)$ components in the continuum extrapolation.

Efficiency Extrapolation - SHAD

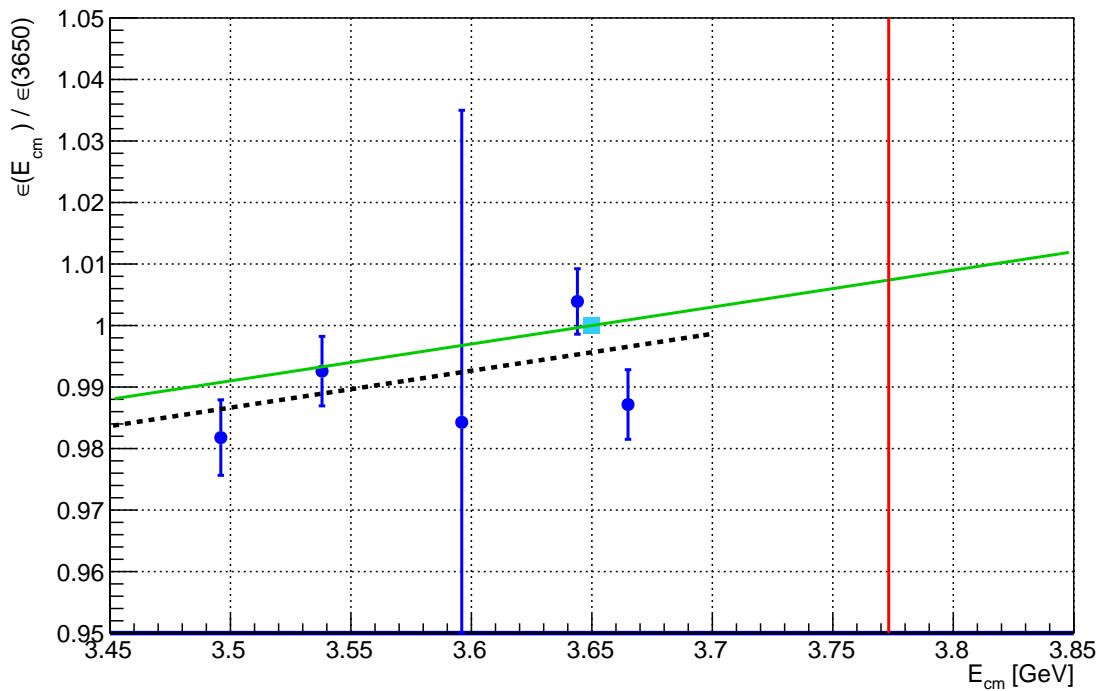


Figure 6.16: The extrapolation for SHAD events using $\psi(2S)$ data.

The new continuum points (blue) are fit using a linear slope (dashed black), then extrapolated to higher energies (solid green) based on the old continuum energy point at 3.650 GeV (cyan). The energy point for the $\psi(3770)$ samples at 3.773 GeV is also shown (solid red).

Efficiency Extrapolation - LHAD

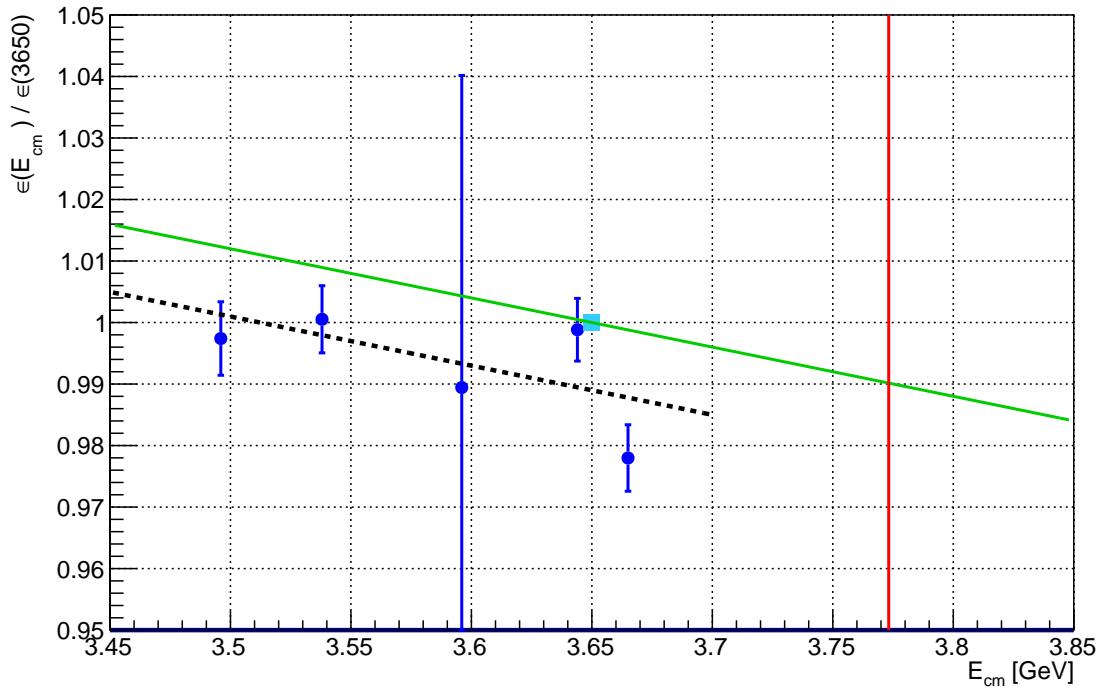


Figure 6.17: The extrapolation for LHAD events using $\psi(2S)$ data.

The new continuum points (blue) are fit using a linear slope (dashed black), then extrapolated to higher energies (solid green) based on the old continuum energy point at 3.650 GeV (cyan). The energy point for the $\psi(3770)$ samples at 3.773 GeV is also shown (solid red).

Efficiency Extrapolation - THAD

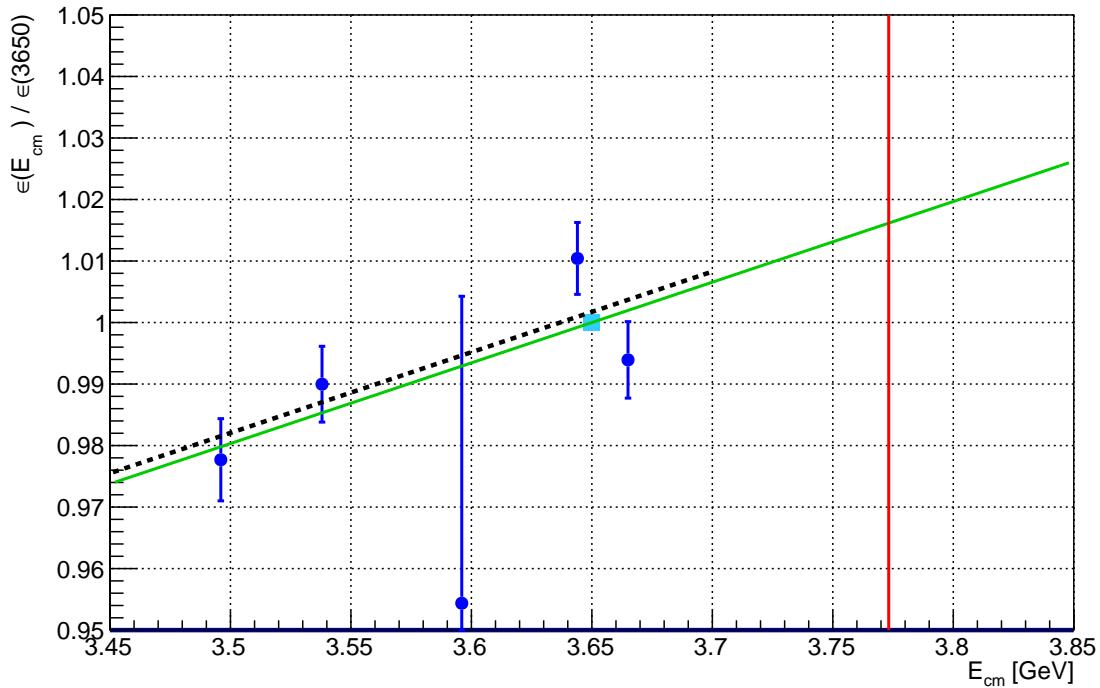


Figure 6.18: The extrapolation for THAD events using $\psi(2S)$ data.

The new continuum points (blue) are fit using a linear slope (dashed black), then extrapolated to higher energies (solid green) based on the old continuum energy point at 3.650 GeV (cyan). The energy point for the $\psi(3770)$ samples at 3.773 GeV is also shown (solid red).

6.7.2 Non- $D\bar{D}$ Branching Fraction ($\psi(2S)$ Excluded)

While the Breit-Wigner formulation likely provides an upper bound to the non- $D\bar{D}$ branching fractions, it is unclear how much lower the true values are. The modification detailed in Section 6.7 provides a likely estimation of the actual value, but previous experiments have measured wildly fluctuating values. In fact, some results have shown no evidence of a non- $D\bar{D}$ branching fraction at all. To obtain a potential lower bound from our procedure, we can repeat the measurement without including any contribution from $\psi(2S)$ events. This will increase the extrapolated reconstruction efficiency fits, which subtracts off a larger amount of hadrons from the $\psi(3770)$ data, and corresponds to a lower branching fraction. The results for this procedure are shown in Tables 6.21 and 6.22.

| Sample | $\sigma_{\text{non-}D\bar{D}}$ [nb] (SHAD) | $\sigma_{\text{non-}D\bar{D}}$ [nb] (LHAD) | $\sigma_{\text{non-}D\bar{D}}$ [nb] (THAD) |
|-------------------|--|--|--|
| $\psi(3770)$ (R1) | 0.6190 ± 0.1232 | 0.7986 ± 0.1192 | 0.6203 ± 0.1305 |
| $\psi(3770)$ (R2) | 0.7179 ± 0.1238 | 0.9239 ± 0.1197 | 0.7421 ± 0.1313 |
| Lum. Weighted | 0.6864 ± 0.1236 | 0.8839 ± 0.1195 | 0.7033 ± 0.1311 |

Table 6.21: Cross sections for $\psi(3770) \rightarrow \text{non-}D\bar{D}$ found using the $\psi(3770)$ data. The $q\bar{q}$ contributions were calculated after excluding the $\psi(2S)$ components in the continuum extrapolation.

| Sample | $\Gamma_{\text{non-}D\bar{D}}$ (SHAD) | $\Gamma_{\text{non-}D\bar{D}}$ (LHAD) | $\Gamma_{\text{non-}D\bar{D}}$ (THAD) |
|-------------------|---------------------------------------|---------------------------------------|---------------------------------------|
| $\psi(3770)$ (R1) | 0.0876 ± 0.0178 | 0.1102 ± 0.0176 | 0.0878 ± 0.0187 |
| $\psi(3770)$ (R2) | 0.1002 ± 0.0180 | 0.1254 ± 0.0179 | 0.1033 ± 0.0188 |
| Lum. Weighted | 0.0962 ± 0.0179 | 0.1205 ± 0.0178 | 0.0983 ± 0.0188 |

Table 6.22: Branching fractions for $\psi(3770) \rightarrow \text{non-}D\bar{D}$ found using the $\psi(3770)$ data. The $q\bar{q}$ contributions were calculated after excluding the $\psi(2S)$ components in the continuum extrapolation.

Efficiency Extrapolation - SHAD

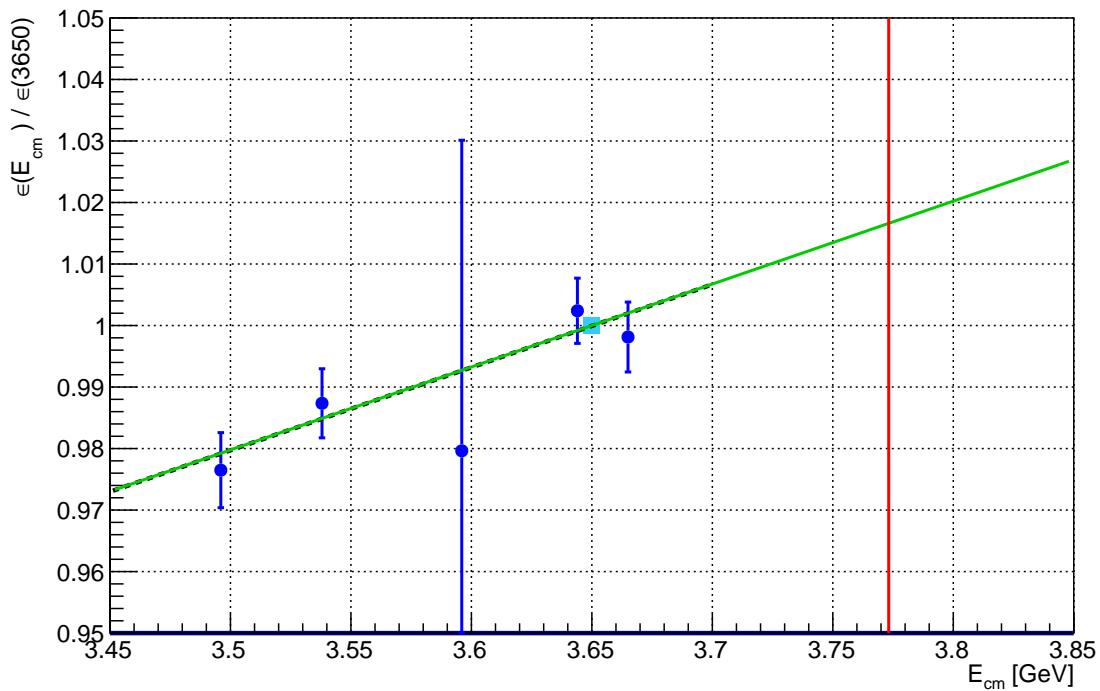


Figure 6.19: The extrapolation for SHAD events without including $\psi(2S)$ events. The new continuum points (blue) are fit using a linear slope (dashed black), then extrapolated to higher energies (solid green) based on the old continuum energy point at 3.650 GeV (cyan). The energy point for the $\psi(3770)$ samples at 3.773 GeV is also shown (solid red).

Efficiency Extrapolation - LHAD

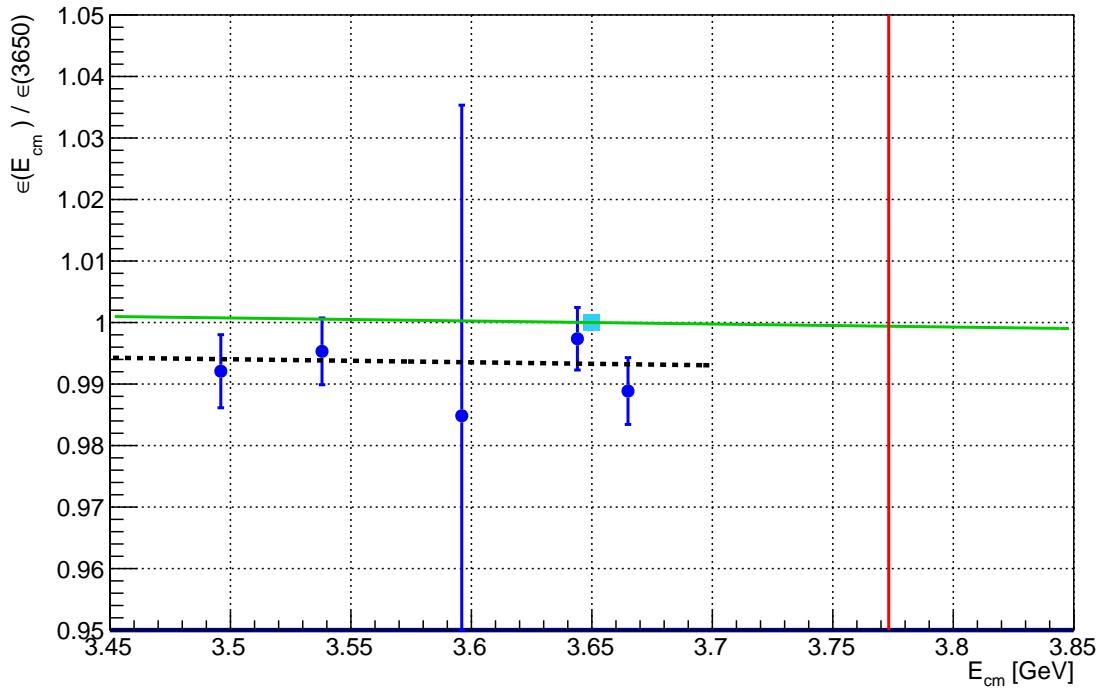


Figure 6.20: The extrapolation for LHAD events without including $\psi(2S)$ events. The new continuum points (blue) are fit using a linear slope (dashed black), then extrapolated to higher energies (solid green) based on the old continuum energy point at 3.650 GeV (cyan). The energy point for the $\psi(3770)$ samples at 3.773 GeV is also shown (solid red).

Efficiency Extrapolation - THAD

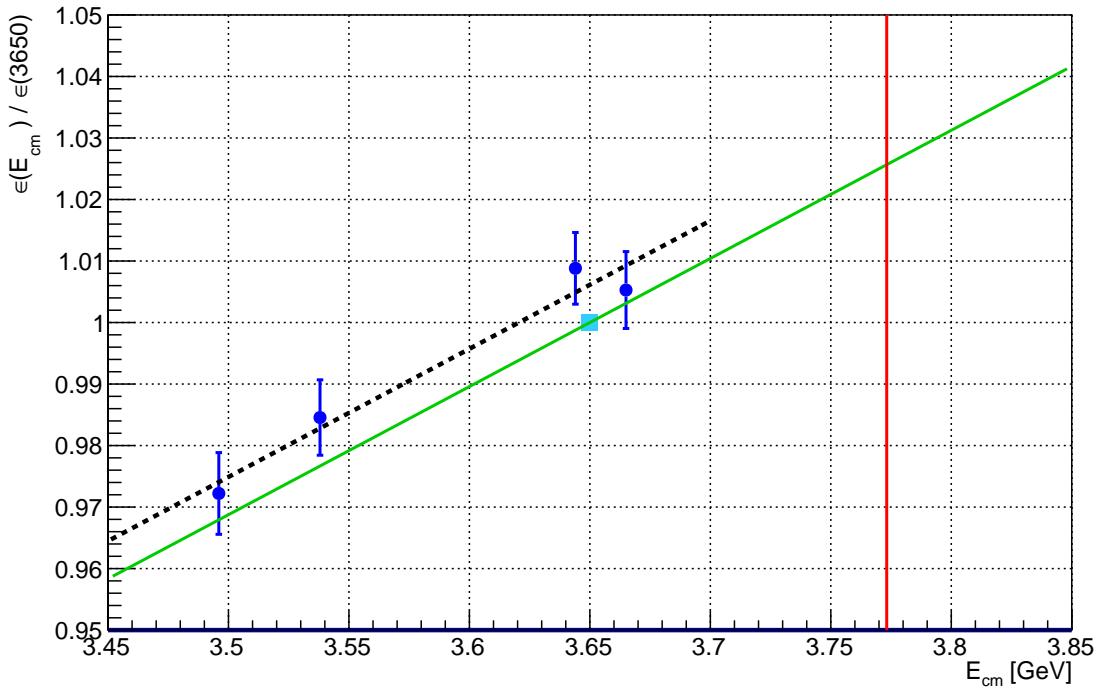


Figure 6.21: The extrapolation for THAD events without including $\psi(2S)$ events. The new continuum points (blue) are fit using a linear slope (dashed black), then extrapolated to higher energies (solid green) based on the old continuum energy point at 3.650 GeV (cyan). The energy point for the $\psi(3770)$ samples at 3.773 GeV is also shown (solid red).

6.8 Results for Scan Data

In addition to the $\psi(3770)$ data, we also examine the energy points of the scan data. While the statistics for these points are far lower, it will provide insight for the behavior of hadronic production with changing center-of-mass energy. We use $\psi(2S)$ data in order to extrapolate the $q\bar{q}$ events throughout this region (see Section 6.7.1).

Each scan data point used will be referred to by its name listed in Table 6.23. The cross sections for each background sample are also listed, where the $D\bar{D}$ values are taken from the results in Table 5.18. To determine the cross sections of $\gamma\psi(2S)$ at each point, the values were calculated using the standard radiative formula (as for $\gamma J/\psi$), then scaled by the ratio of the data-driven value from Equation (6.5) to the value of this formula at 3.773 GeV.

The total hadronic counting fits for the scan data can be found in Appendix D. As the $\psi(3770)$ R1 data was taken at a similar time as the scan data, we use the same $D\bar{D}$ corrections from R1 for all of the scan data sample points. The reconstruction efficiencies and signal amounts can be found in Appendices E and F, respectively.

In addition to the non- $D\bar{D}$ branching fraction, we can also examine the inclusive hadronic cross section as a function of center-of-mass energy: Dividing the fit counts for each selection method from Appendix D by the luminosities from Table 5.3, we find the inclusive cross sections shown in Figure 6.22. As these values are independent of the extrapolation procedure, they are immediately ready for use in future analyses.

The non- $D\bar{D}$ cross sections and branching ratios calculated for each scan point are shown in Figures 6.23 and 6.24, respectively. For comparison, the same calculation for the $\psi(3770)$ data is also shown on each of these plots. Due to the uncertain cross section shape of the $\psi(2S)$ required to properly extrapolate to the scan data region, these values are not representative of a true measurement for the branching fraction. For now, we have done our best to ensure the accuracy of all other background components analyzed. This means, with an improved understanding of the $\psi(2S)$ cross section in the continuum region (likely to be analyzed in the very near future, as BESIII has data taking planned for this region), the branching fraction value can easily be updated for a final result. From our analysis of the $\psi(2S)$ background (see Section 6.7), we expect this value to be in the range 9.6 % to 14.1 % with our current estimate being 12.3 %.

| Sample | E_{cm} [GeV] | $D^0\bar{D}^0$ [nb] | D^+D^- [nb] | $\tau^-\tau^+$ [nb] | $\gamma J/\psi$ [nb] | $\gamma\psi(2S)$ [nb] |
|-------------|-----------------------|---------------------|---------------|---------------------|----------------------|-----------------------|
| 3734 (Scan) | 3.7342 | 0.164 | 0.000 | 2.467 | 1.060 | 5.359 |
| 3736 (Scan) | 3.7368 | 0.218 | 0.000 | 2.475 | 1.055 | 5.094 |
| 3744 (Scan) | 3.7447 | 0.765 | 0.150 | 2.514 | 1.039 | 4.428 |
| 3748 (Scan) | 3.7483 | 0.838 | 0.360 | 2.522 | 1.032 | 4.180 |
| 3750 (Scan) | 3.7501 | 0.968 | 0.439 | 2.533 | 1.029 | 4.065 |
| 3751 (Scan) | 3.7517 | 1.237 | 0.574 | 2.542 | 1.025 | 3.969 |
| 3753 (Scan) | 3.7534 | 1.377 | 0.748 | 2.553 | 1.022 | 3.871 |
| 3755 (Scan) | 3.7556 | 1.566 | 0.797 | 2.562 | 1.018 | 3.752 |
| 3756 (Scan) | 3.7562 | 1.629 | 0.914 | 2.573 | 1.017 | 3.721 |
| 3759 (Scan) | 3.7592 | 1.948 | 1.192 | 2.584 | 1.011 | 3.572 |
| 3762 (Scan) | 3.7624 | 2.385 | 1.534 | 2.598 | 1.005 | 3.426 |
| 3765 (Scan) | 3.7650 | 2.715 | 1.882 | 2.613 | 1.000 | 3.315 |
| 3767 (Scan) | 3.7676 | 3.102 | 2.200 | 2.627 | 0.995 | 3.212 |
| 3771 (Scan) | 3.7713 | 3.406 | 2.634 | 2.641 | 0.989 | 3.075 |
| 3774 (Scan) | 3.7742 | 3.714 | 3.067 | 2.656 | 0.983 | 2.975 |
| 3777 (Scan) | 3.7775 | 3.692 | 3.078 | 2.669 | 0.978 | 2.870 |
| 3780 (Scan) | 3.7802 | 3.444 | 2.599 | 2.683 | 0.973 | 2.788 |
| 3782 (Scan) | 3.7829 | 2.791 | 2.206 | 2.696 | 0.968 | 2.712 |
| 3786 (Scan) | 3.7869 | 1.995 | 1.627 | 2.709 | 0.961 | 2.605 |
| 3789 (Scan) | 3.7891 | 1.361 | 1.178 | 2.722 | 0.957 | 2.550 |
| 3792 (Scan) | 3.7926 | 0.920 | 0.680 | 2.739 | 0.951 | 2.467 |
| 3797 (Scan) | 3.7970 | 0.562 | 0.414 | 2.755 | 0.944 | 2.370 |
| 3800 (Scan) | 3.8003 | 0.424 | 0.241 | 2.771 | 0.938 | 2.301 |
| 3802 (Scan) | 3.8024 | 0.325 | 0.236 | 2.784 | 0.935 | 2.260 |
| 3807 (Scan) | 3.8070 | 0.352 | 0.289 | 2.795 | 0.927 | 2.174 |
| 3809 (Scan) | 3.8093 | 0.233 | 0.132 | 2.807 | 0.923 | 2.133 |
| 3813 (Scan) | 3.8135 | 0.060 | 0.153 | 2.819 | 0.917 | 2.063 |
| 3815 (Scan) | 3.8153 | 0.056 | 0.089 | 2.829 | 0.914 | 2.034 |
| 3822 (Scan) | 3.8229 | 0.140 | 0.197 | 2.859 | 0.902 | 1.920 |
| 3832 (Scan) | 3.8320 | 0.069 | 0.046 | 2.887 | 0.888 | 1.799 |
| 3839 (Scan) | 3.8390 | 0.237 | 0.254 | 2.914 | 0.877 | 1.716 |
| 3849 (Scan) | 3.8494 | 0.186 | 0.186 | 2.939 | 0.862 | 1.604 |
| 3855 (Scan) | 3.8555 | 0.337 | 0.273 | 2.967 | 0.853 | 1.545 |
| 3863 (Scan) | 3.8632 | 0.340 | 0.099 | 2.988 | 0.843 | 1.476 |

Table 6.23: Energy values and background cross sections for the scan data.

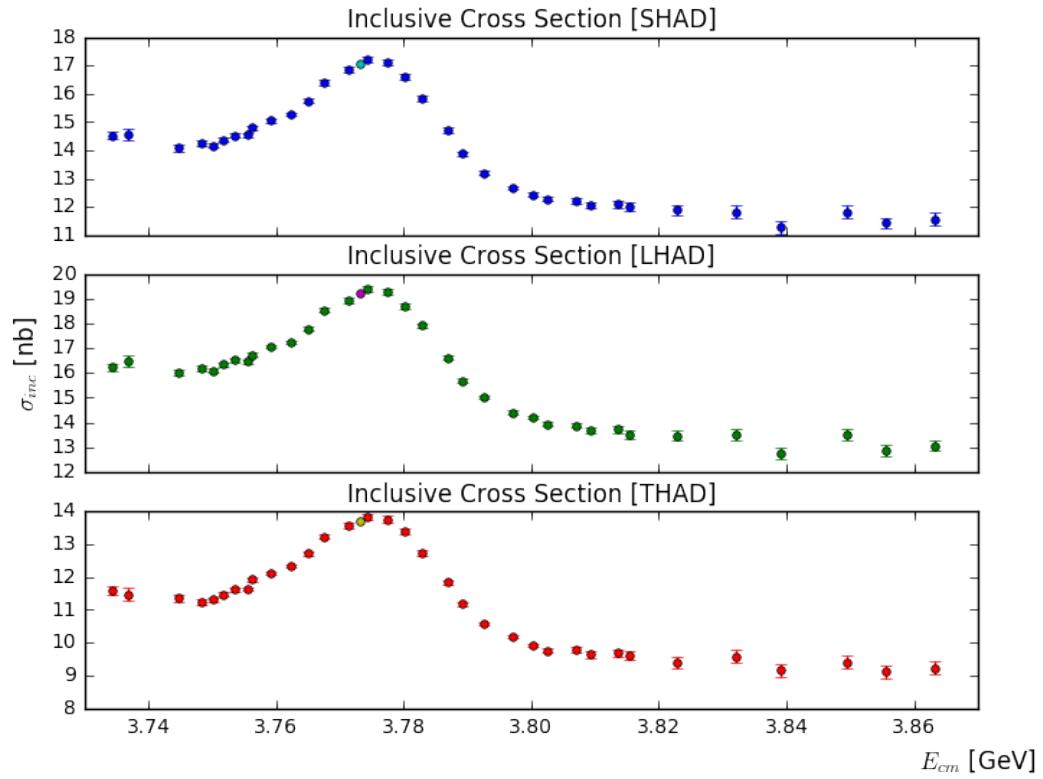


Figure 6.22: The inclusive cross sections measured for the scan data region. The cyan, purple, and yellow points correspond to the luminosity-averaged inclusive cross sections measured for the $\psi(3770)$ data.

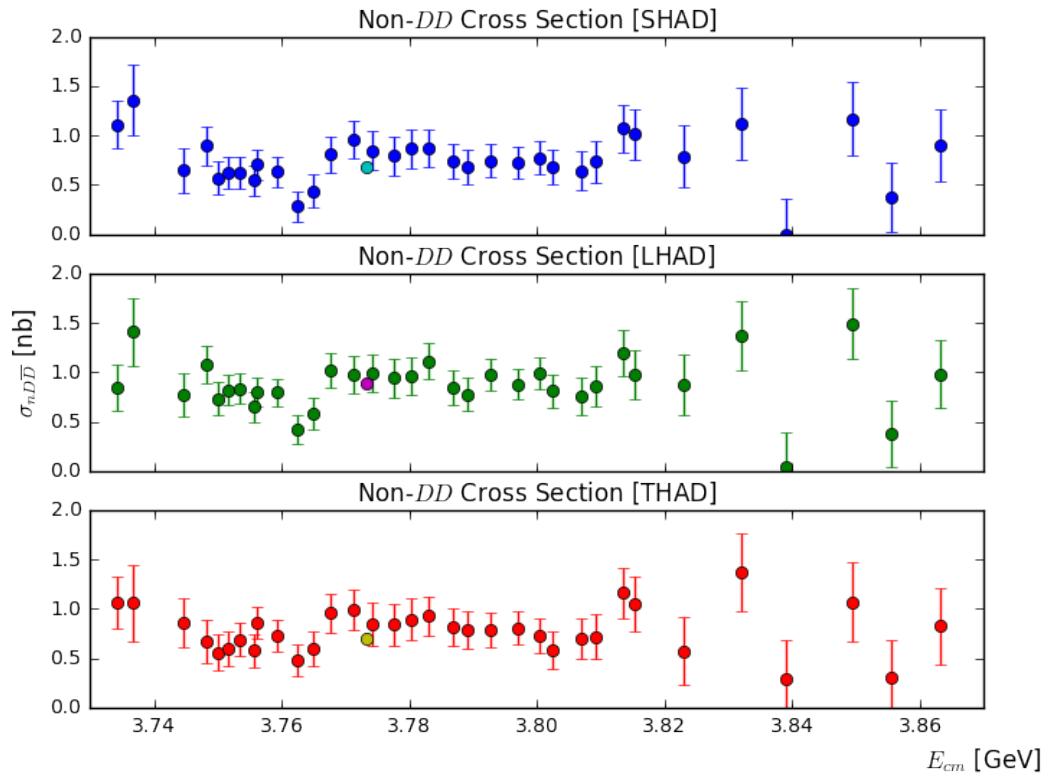


Figure 6.23: The non- $D\bar{D}$ cross sections measured for the scan data region. The cyan, purple, and yellow points correspond to the luminosity-averaged non- $D\bar{D}$ cross sections measured for the $\psi(3770)$ data.

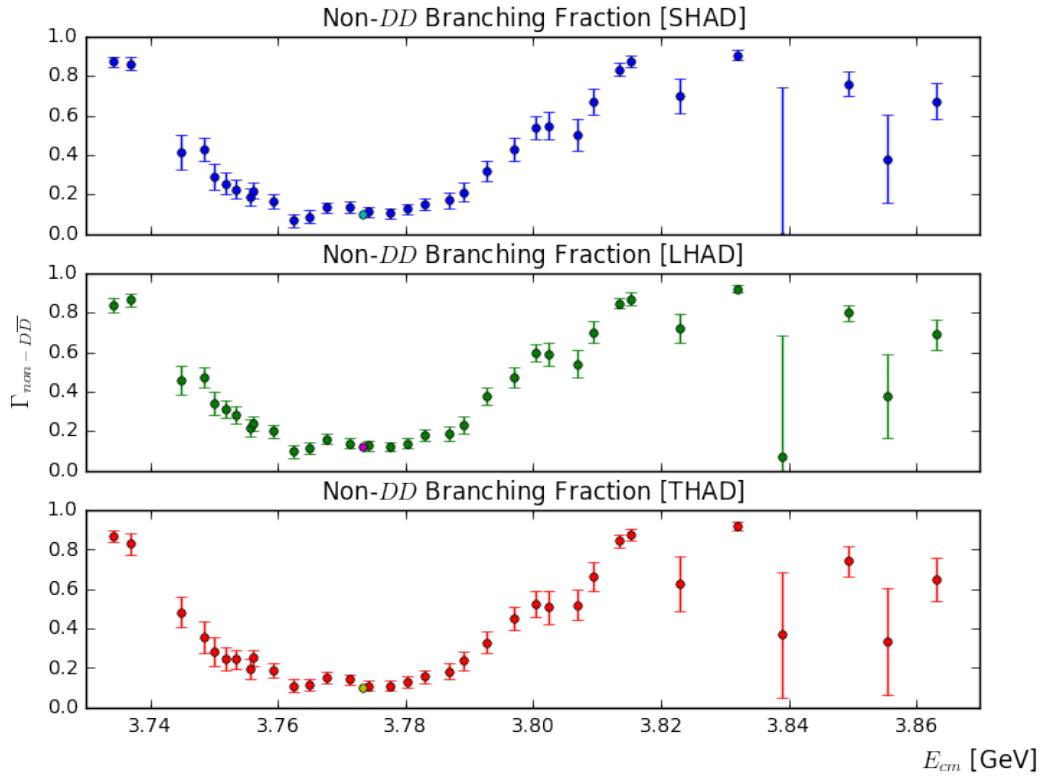


Figure 6.24: The non- $D\bar{D}$ branching fractions measured for the scan data region. The cyan, purple, and yellow points correspond to the luminosity-averaged non- $D\bar{D}$ branching fractions measured for the $\psi(3770)$ data.

Chapter 7

Conclusion

This is where the Conclusions go!

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Appendix A

Glossary and Acronyms

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

A.1 Glossary

A.2 Acronyms / Initialisms

Table A.1: Acronyms and Initialisms

| Name | Meaning |
|--------|---|
| BESIII | The third Beijing Spectrometer |
| IHEP | Institute of High Energy Physics |
| BEPCII | The second Beijing Electron-Position Collider |
| MDC | Multi-Layer Drift Chamber |
| ToF | Time-of-Flight System |
| EMC | Electromagnetic Calorimeter |
| MUC | Muon Identifier |
| PMTs | Photomultipler Tubes |

Continued on next page

Table A.1 – Continued from previous page

| Acronym | Meaning |
|---------|--------------------------------|
| RPC | Resistive Plate Counter |
| ISR | Initial State Radiation |
| FSR | Final State Radiation |
| BOSS | BESIII Offline Software System |
| MC | Monte Carlo |
| ADC | Analog-to-Digital Conversion |
| TDC | Time-to-Digital Conversion |

Appendix B

D^0 Signal Fits

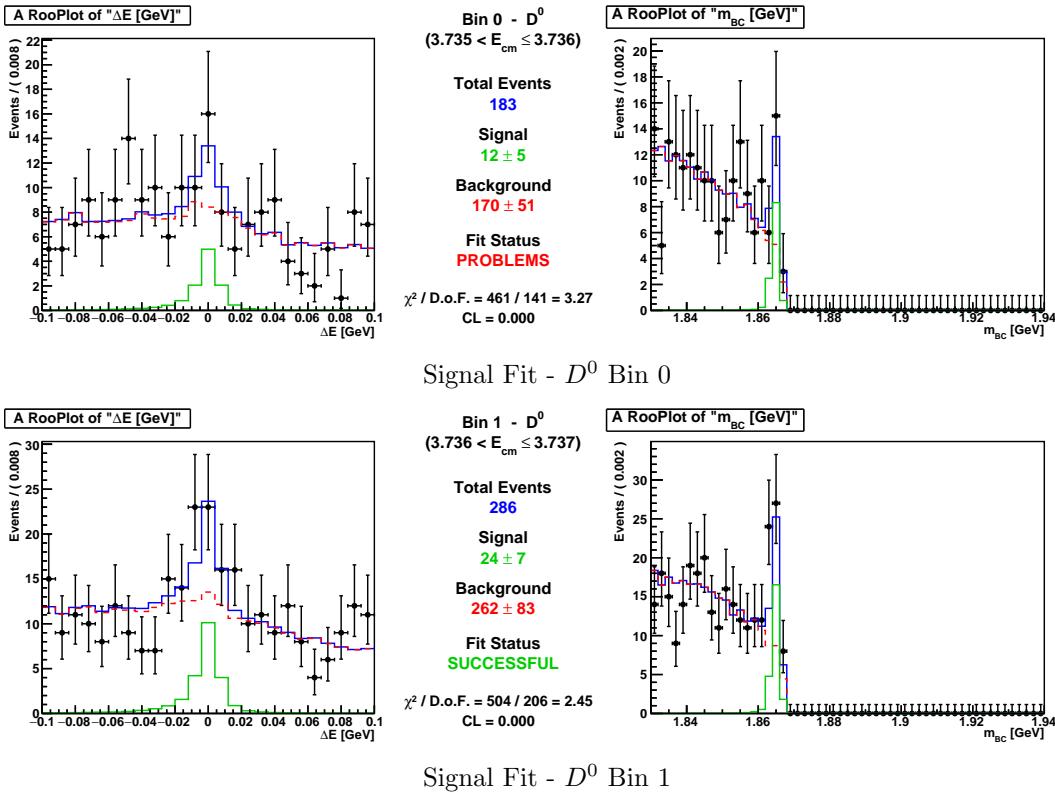
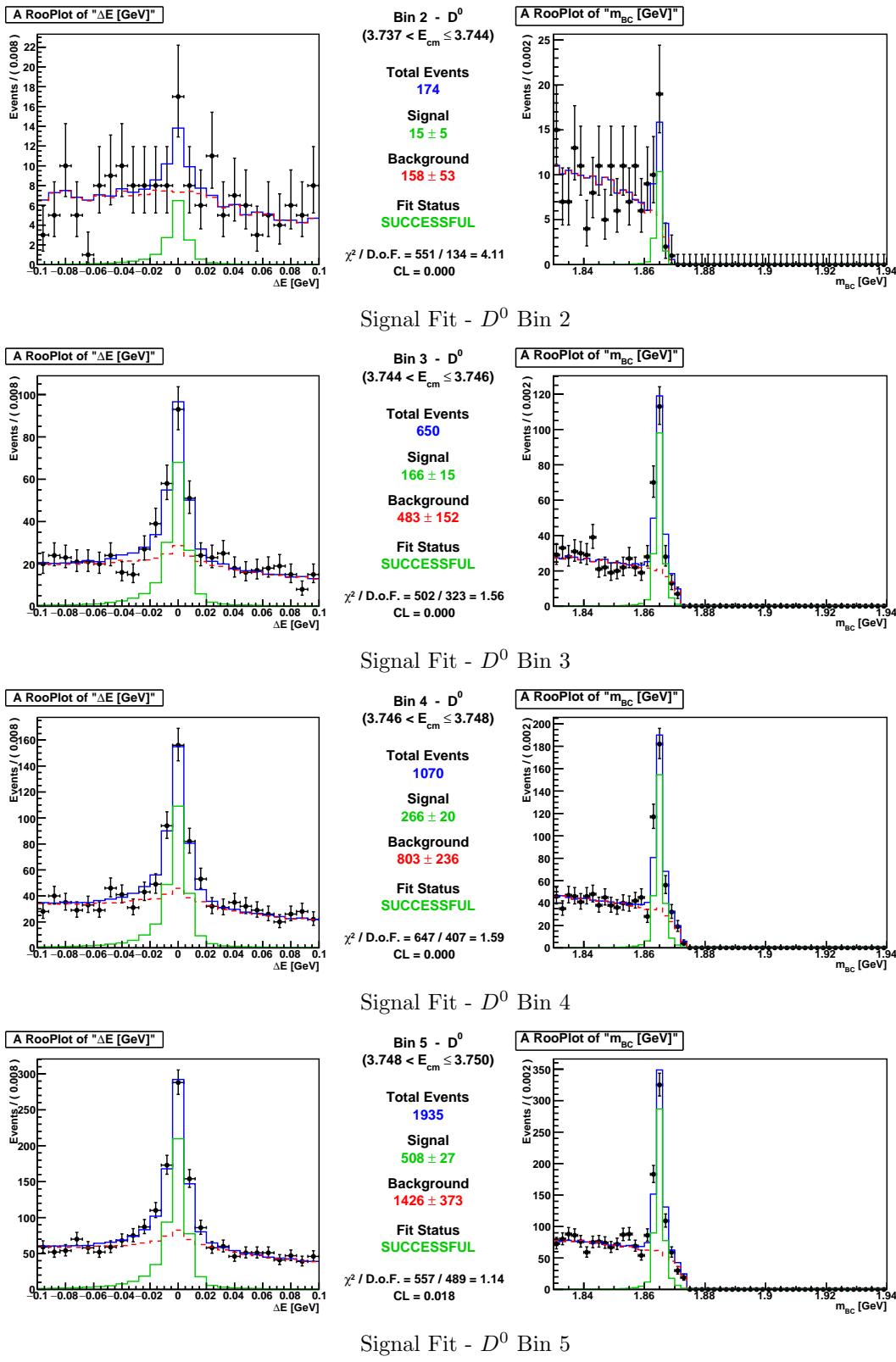
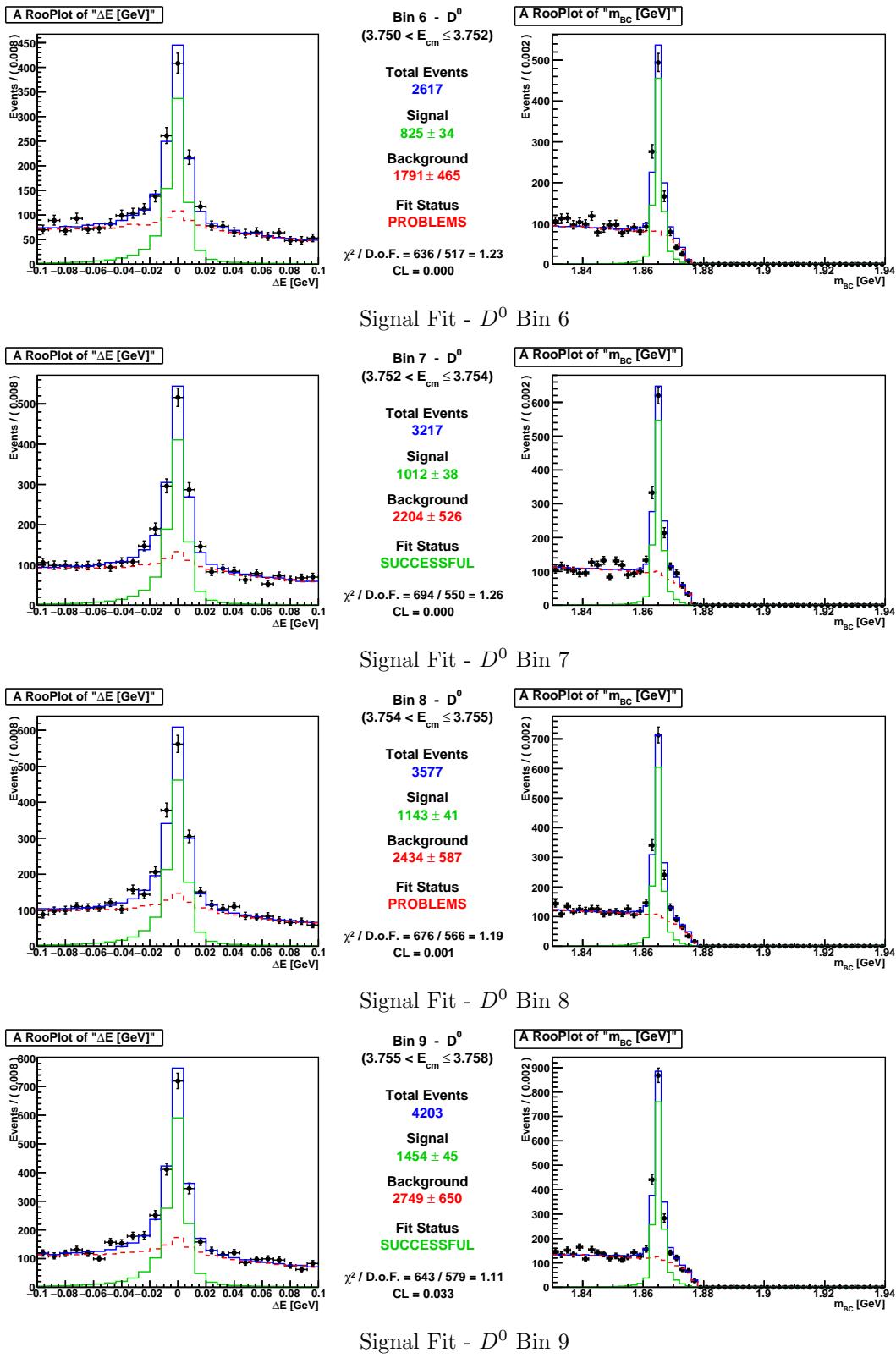
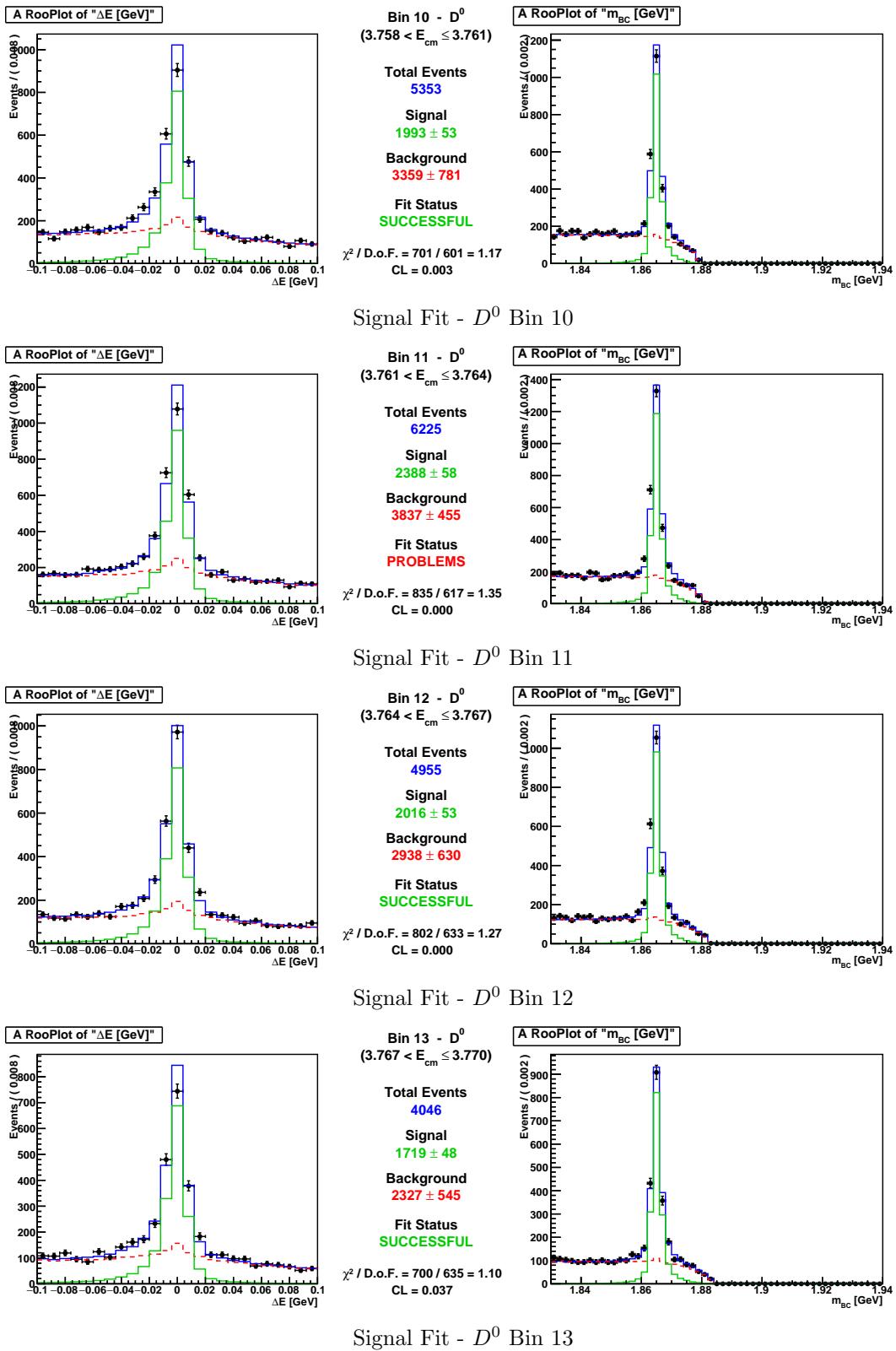
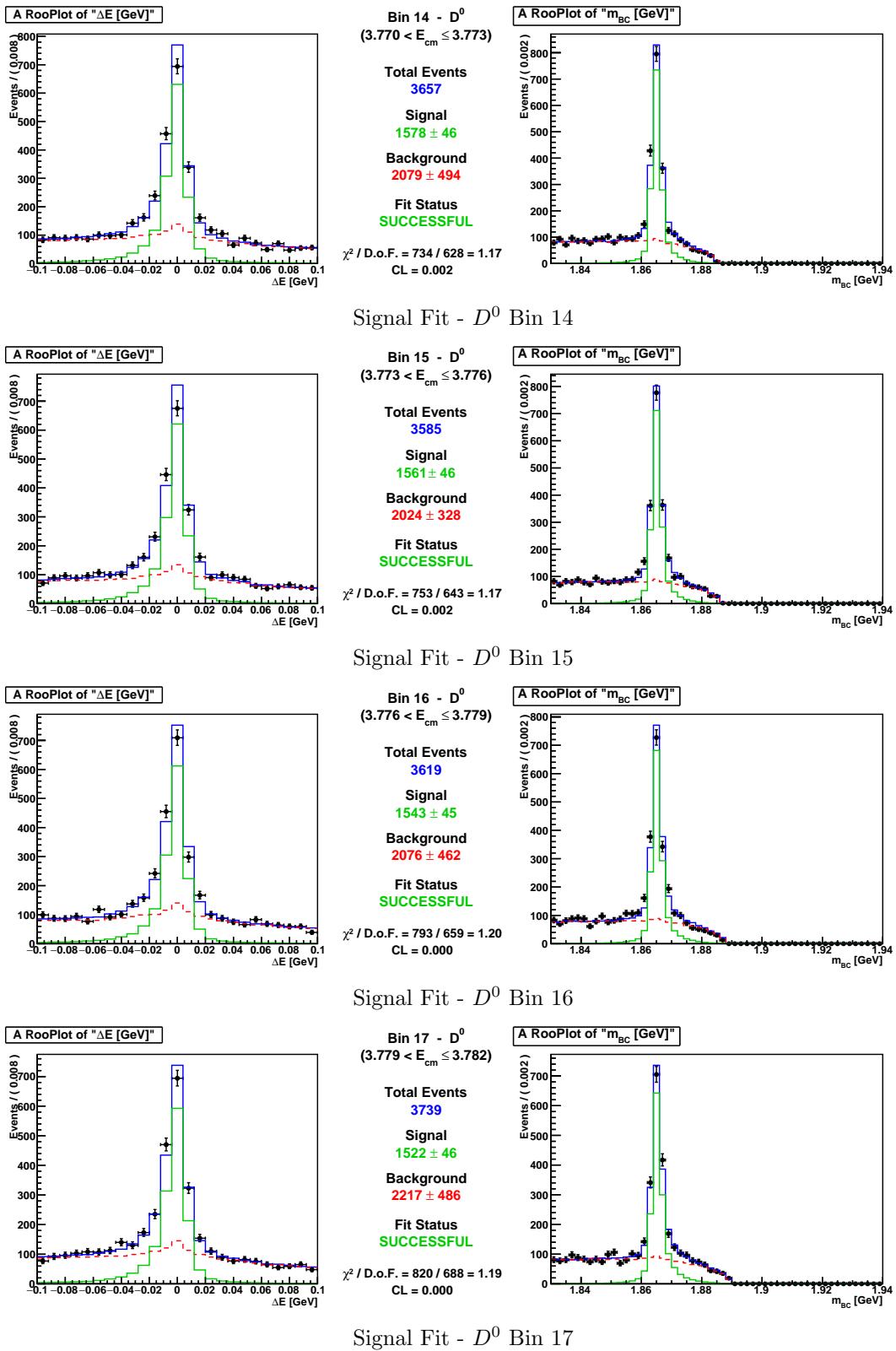


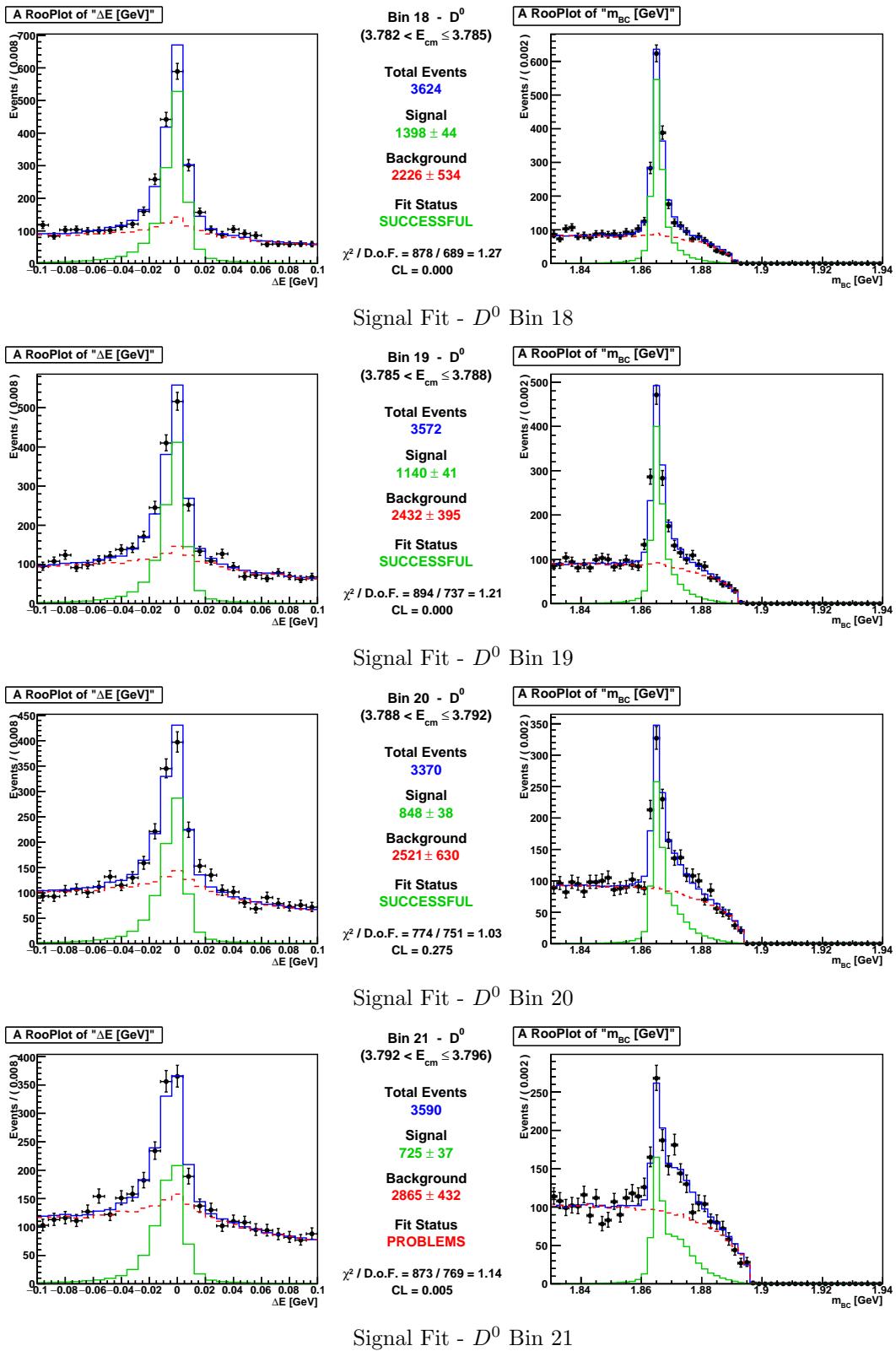
Figure B.1: Signal Fitting Plots for D^0 Bins 0 - 1.

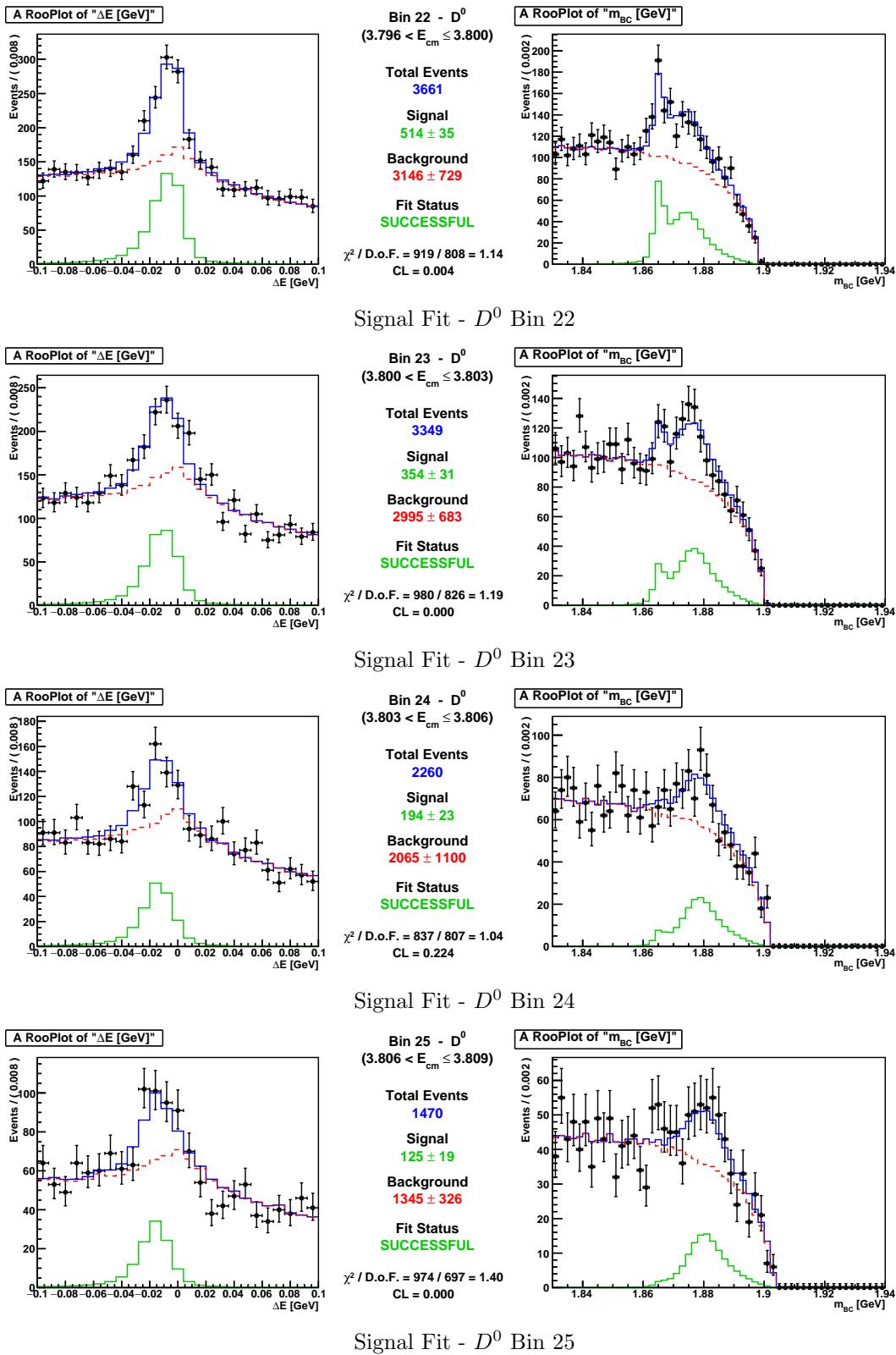
Figure B.2: Signal Fitting Plots for D^0 Bins 2 - 5.

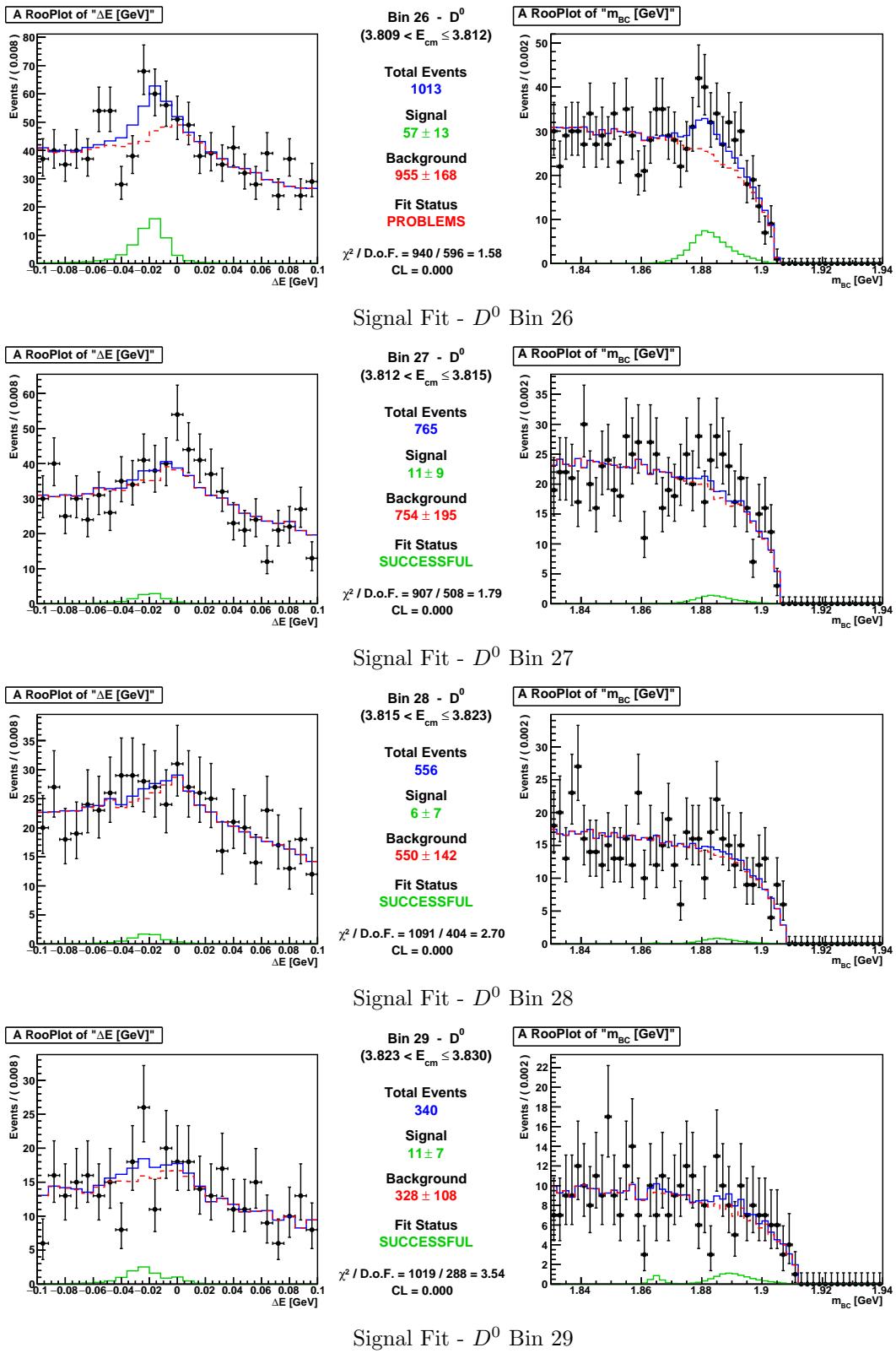
Figure B.3: Signal Fitting Plots for D^0 Bins 6 - 9.

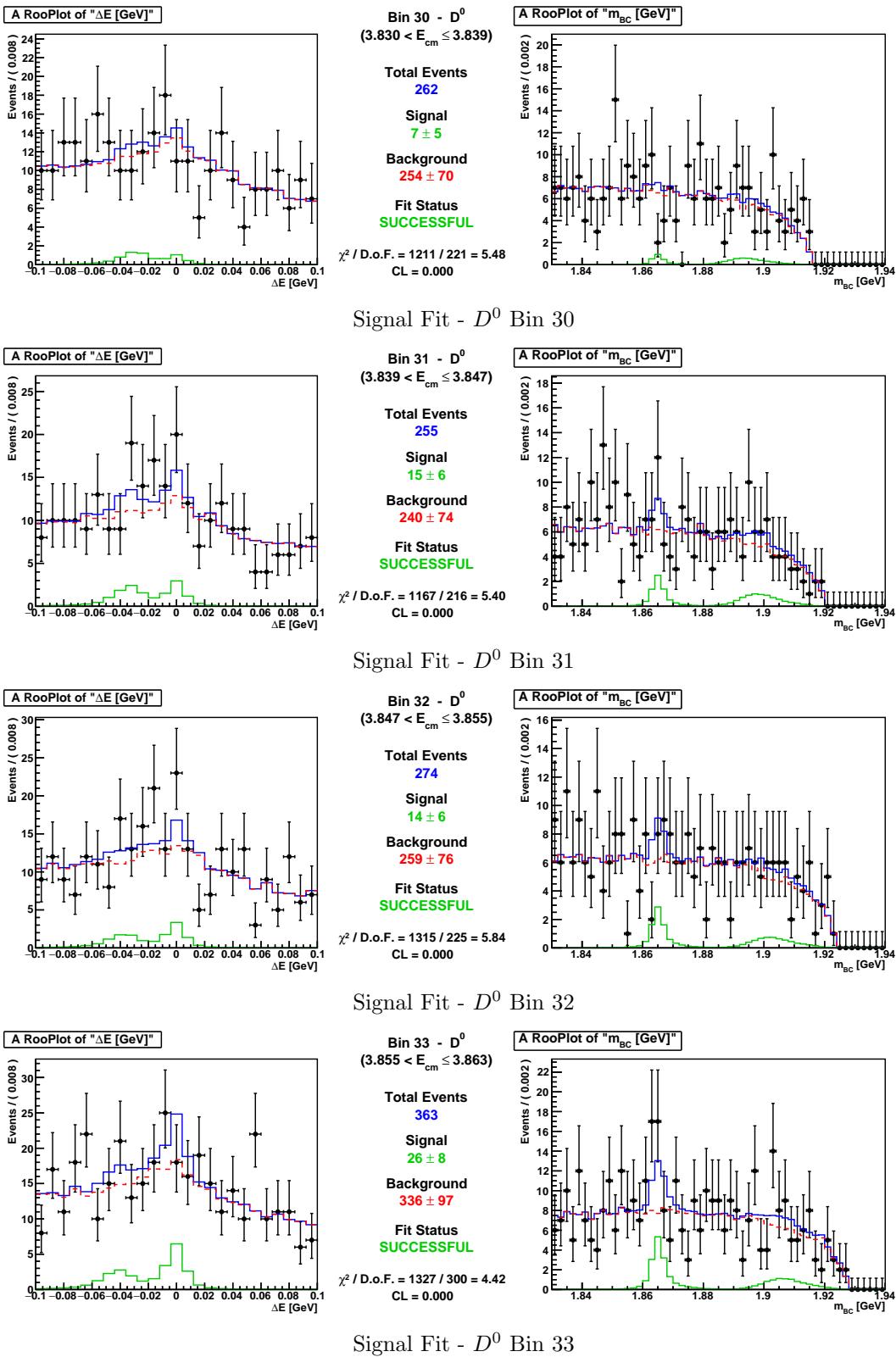
Figure B.4: Signal Fitting Plots for D^0 Bins 10 - 13.

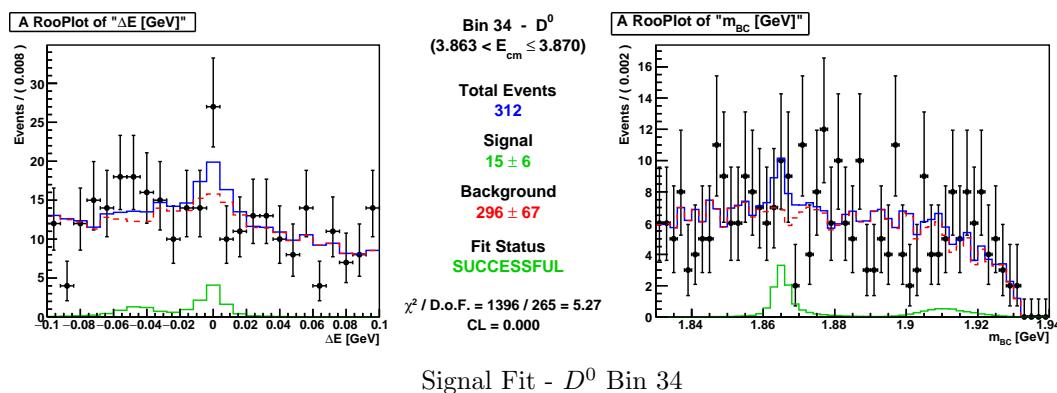
Figure B.5: Signal Fitting Plots for D^0 Bins 14 - 17.

Figure B.6: Signal Fitting Plots for D^0 Bins 18 - 21.

Figure B.7: Signal Fitting Plots for D^0 Bins 22 - 25.

Figure B.8: Signal Fitting Plots for D^0 Bins 26 - 29.

Figure B.9: Signal Fitting Plots for D^0 Bins 30 - 33.

Signal Fit - D^0 Bin 34Figure B.10: Signal Fitting Plots for D^0 Bin 34.

Appendix C

D^+ Signal Fits

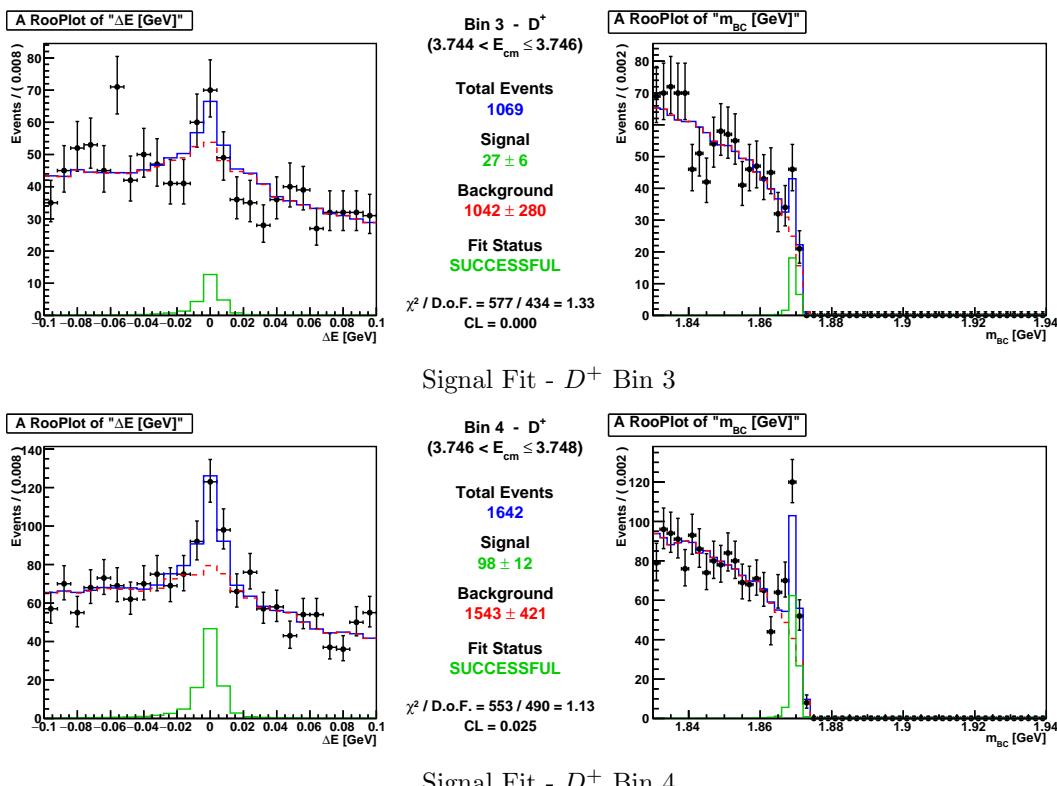
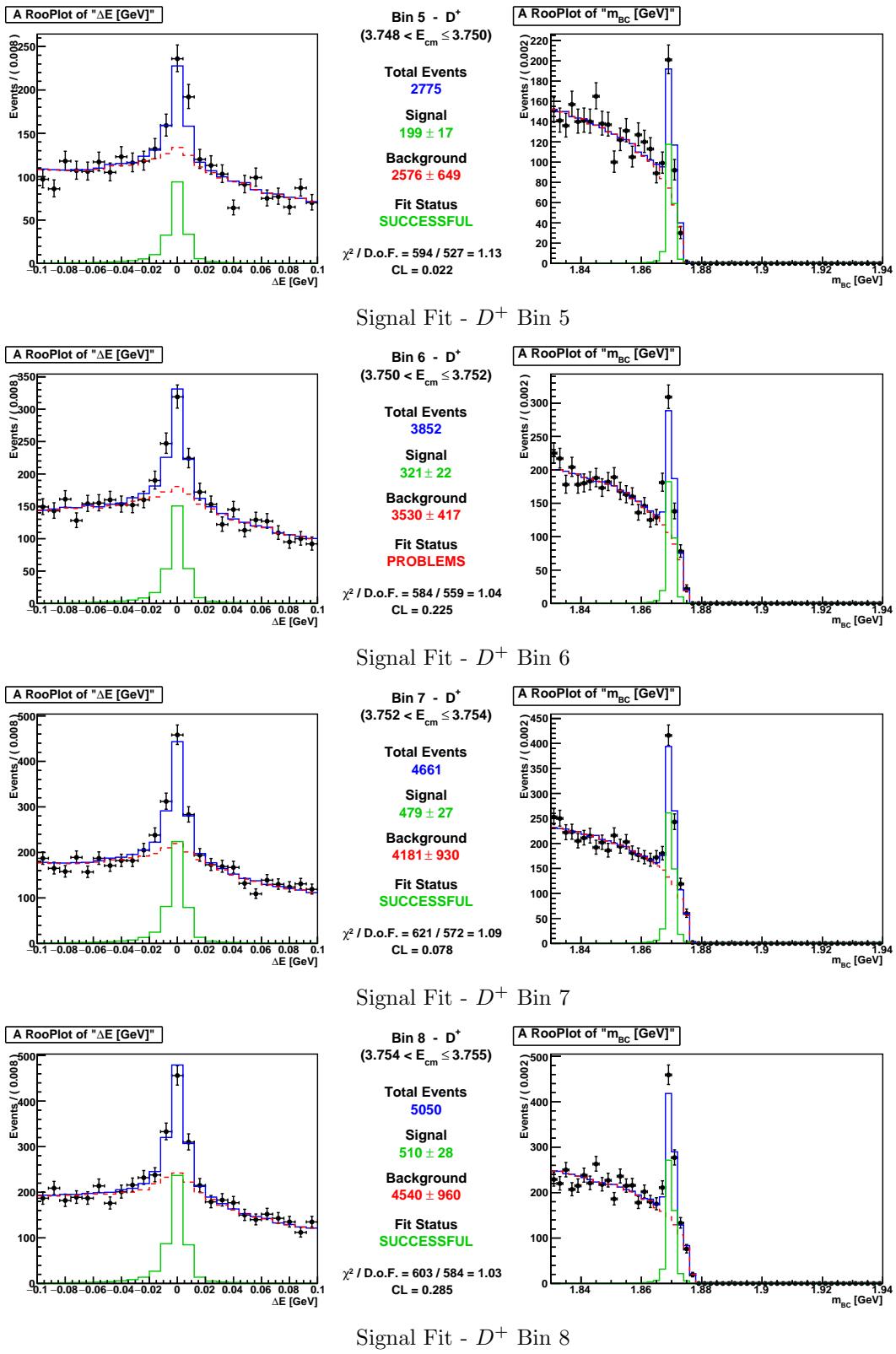
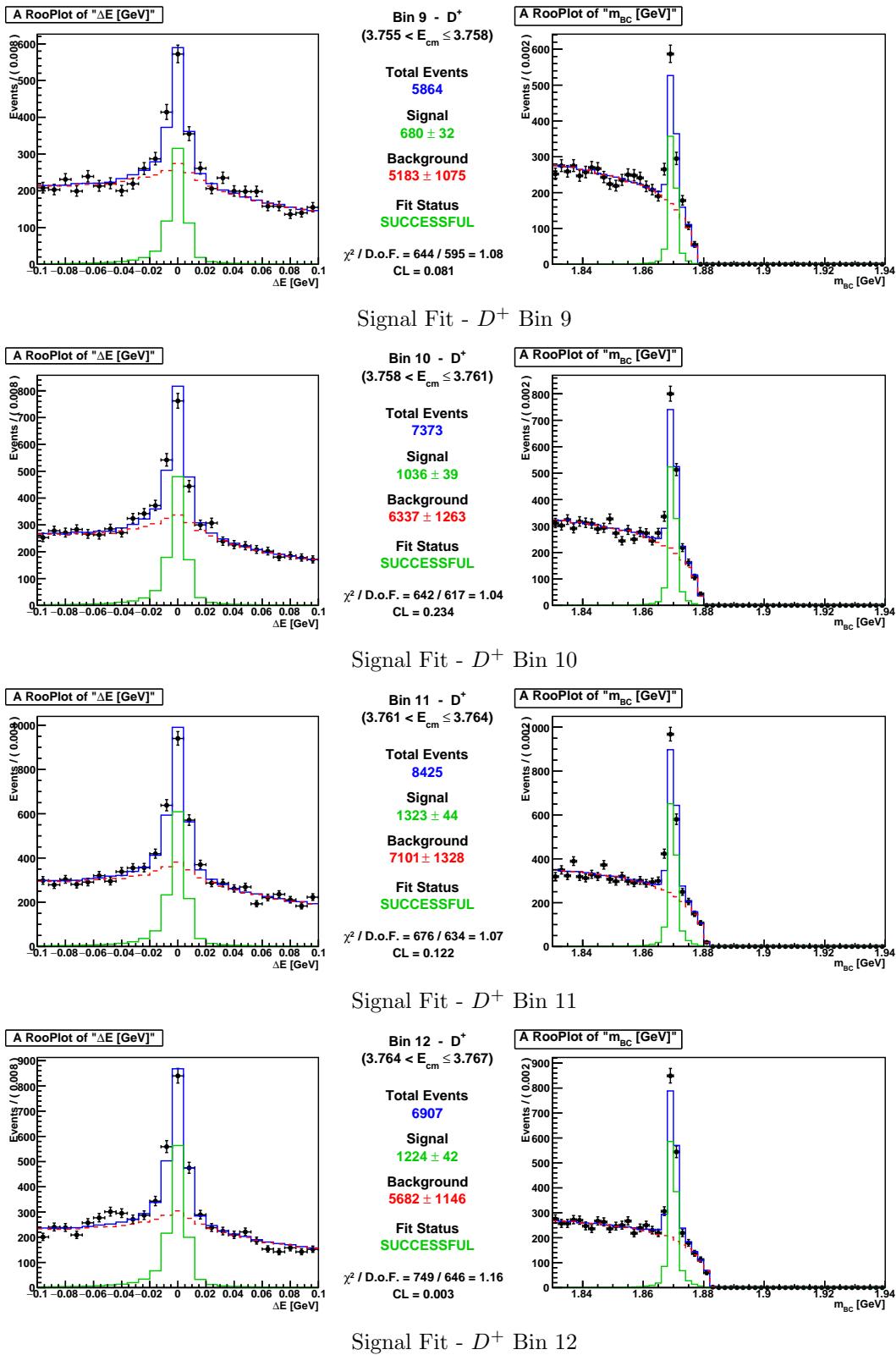
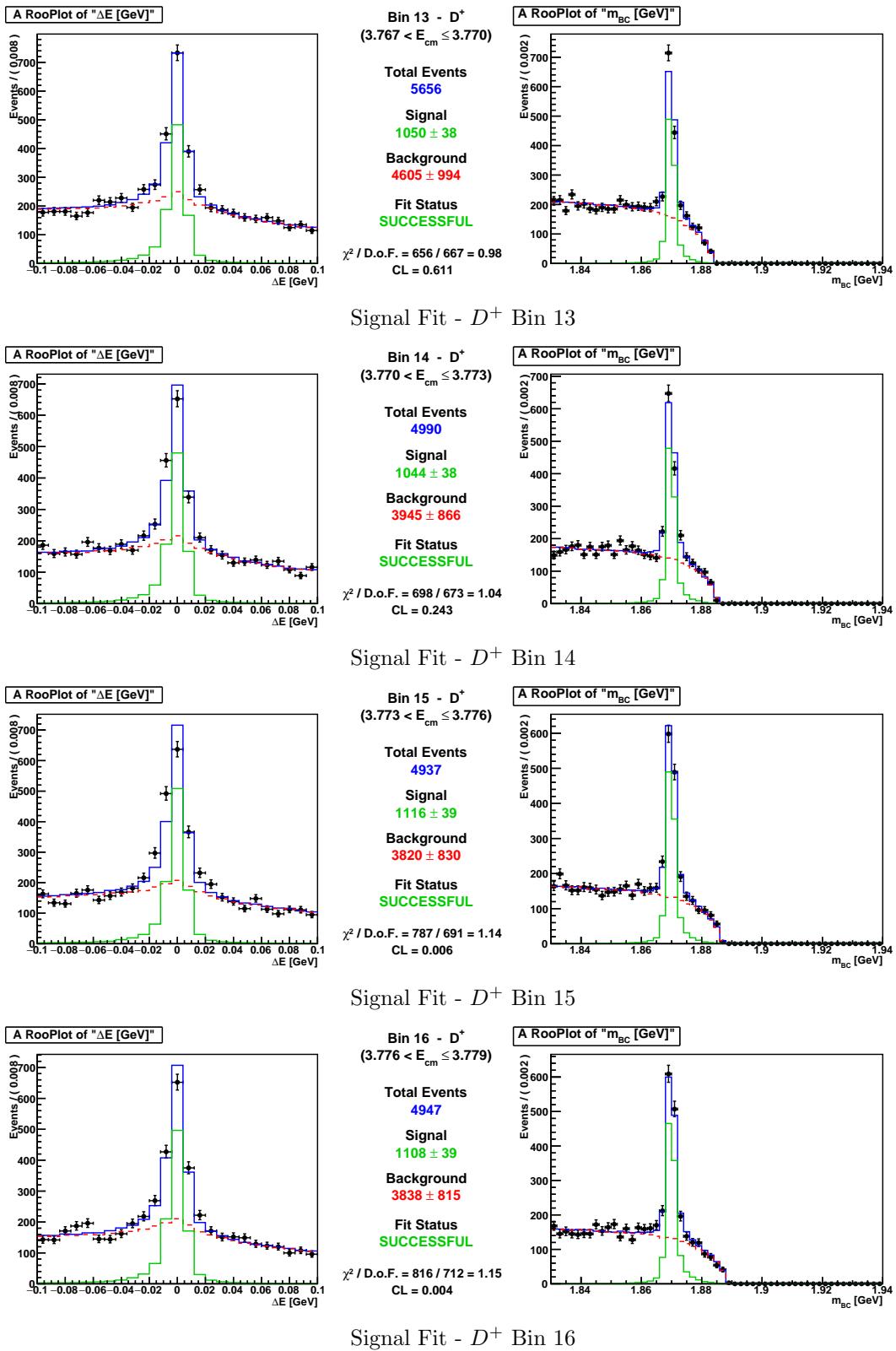
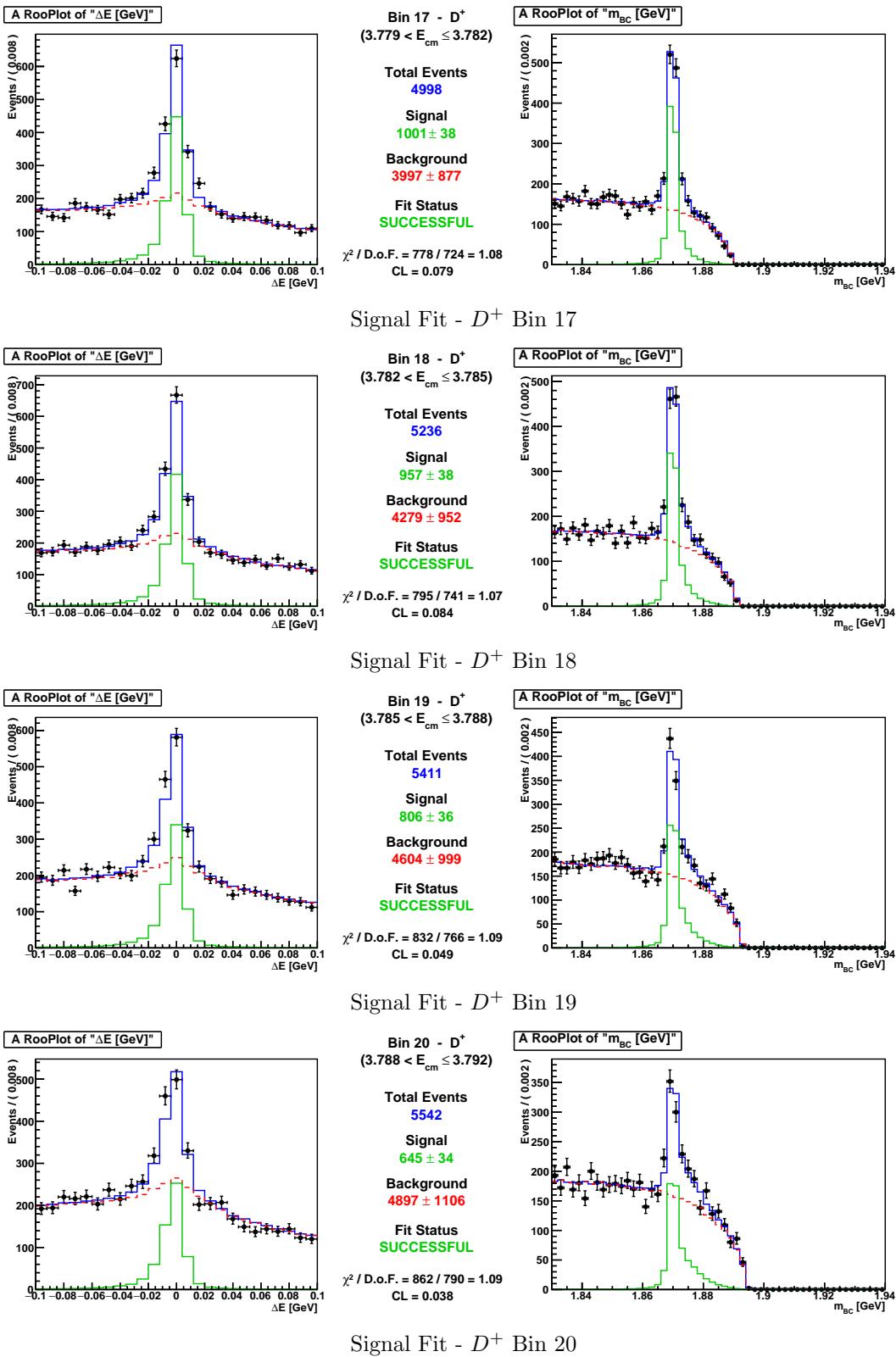


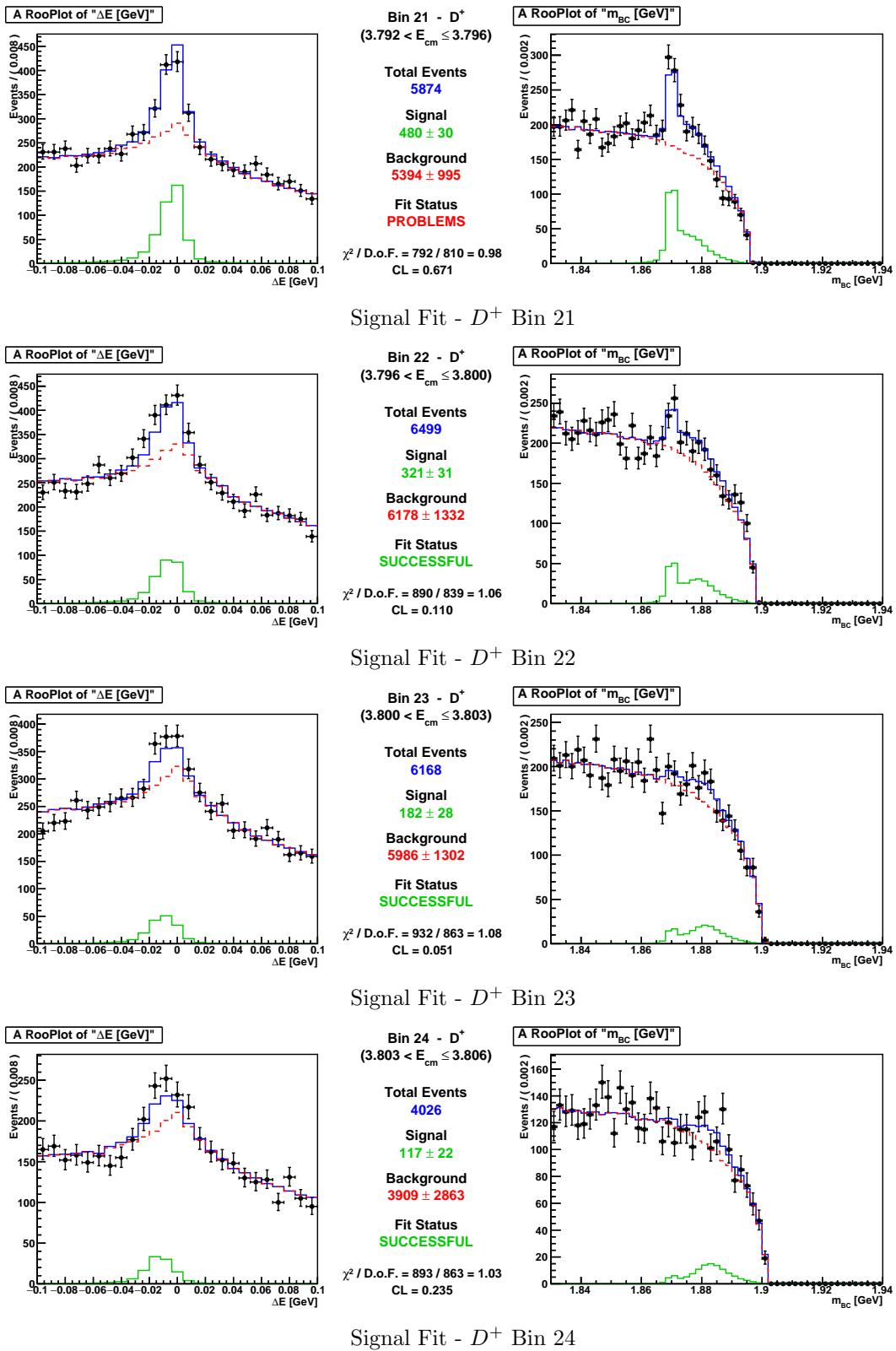
Figure C.1: Signal Fitting Plots for D^+ Bins 3 - 4.

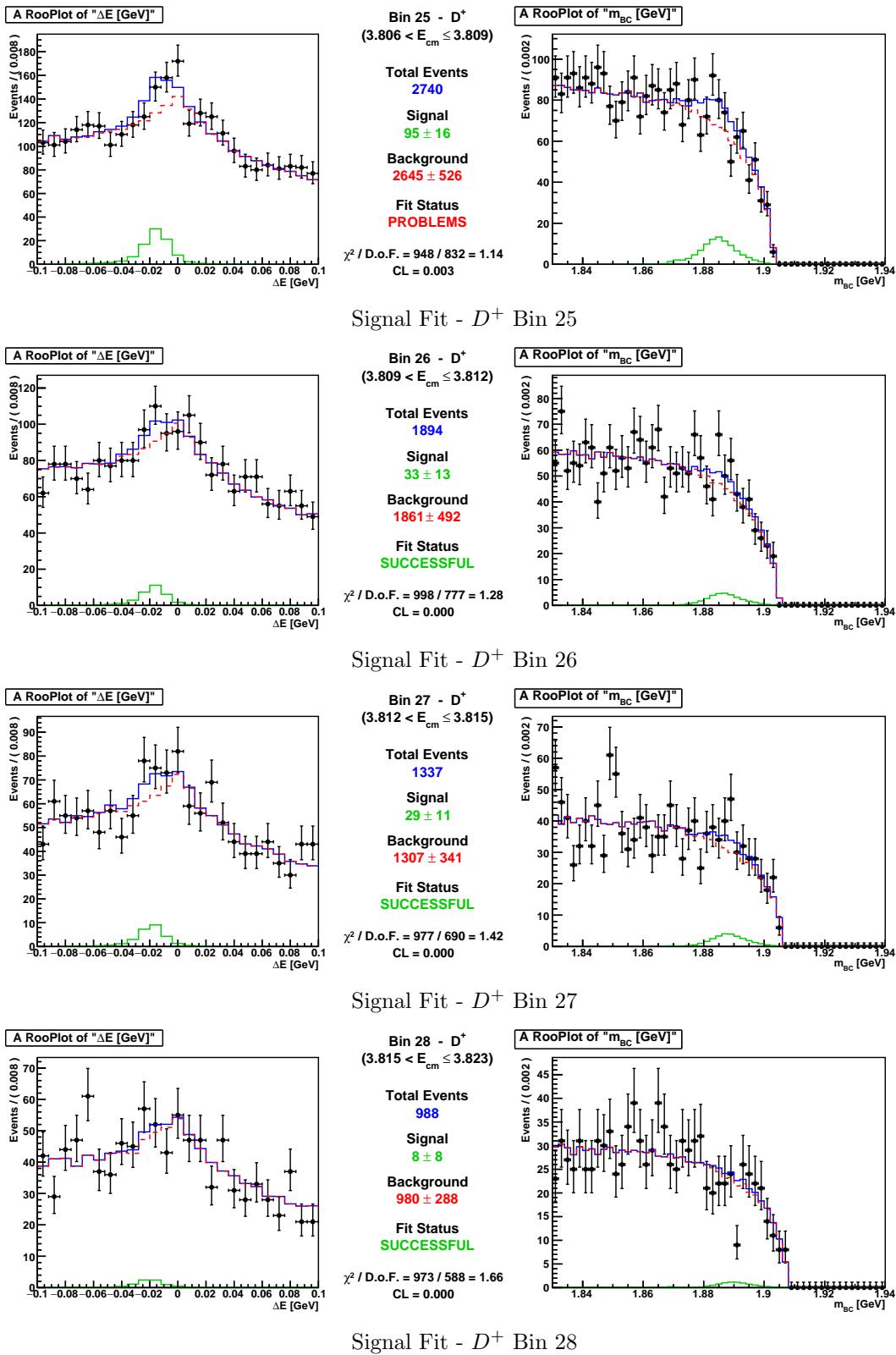
Figure C.2: Signal Fitting Plots for D^+ Bins 5 - 8.

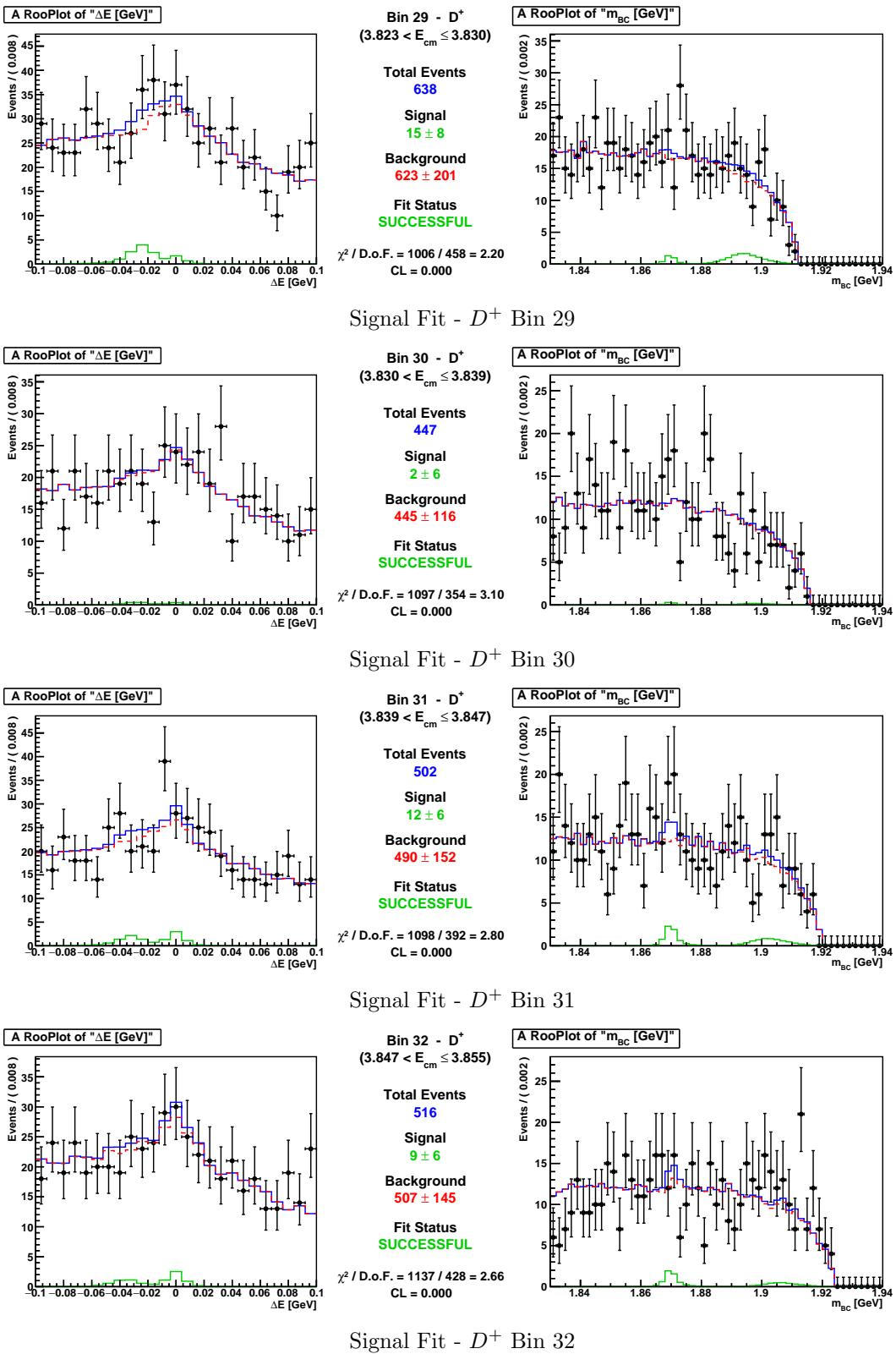
Figure C.3: Signal Fitting Plots for D^+ Bins 6 - 12.

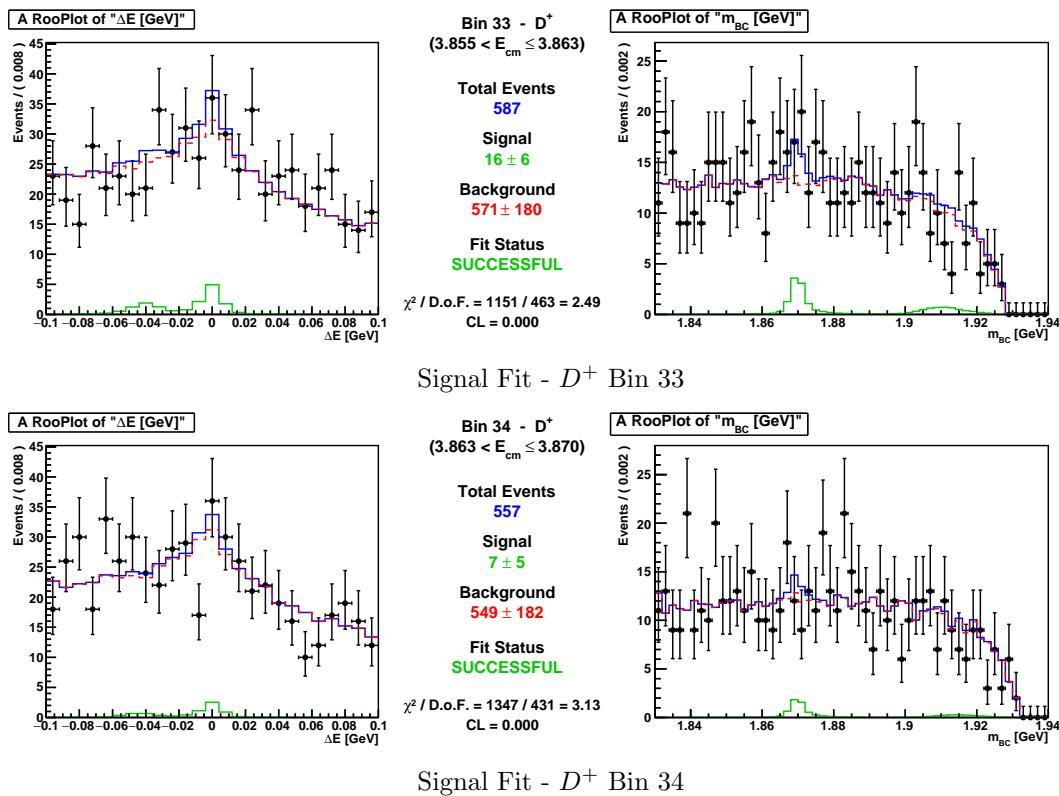
Figure C.4: Signal Fitting Plots for D^+ Bins 13 - 16.

Figure C.5: Signal Fitting Plots for D^+ Bins 17 - 20.

Figure C.6: Signal Fitting Plots for D^+ Bins 21 - 24.

Figure C.7: Signal Fitting Plots for D^+ Bins 25 - 28.

Figure C.8: Signal Fitting Plots for D^+ Bins 29 - 32.

Figure C.9: Signal Fitting Plots for D^+ Bins 33 - 34.

Appendix D

Scan Data Hadronic Counting Fits

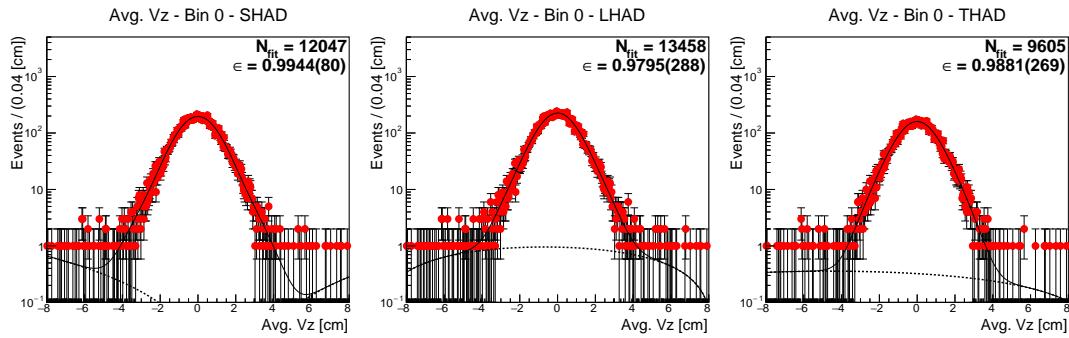


Figure D.1: The number of hadrons found in the 3734 (Scan) data sample. This includes results for SHAD (left), LHAD (middle), and THAD (right).

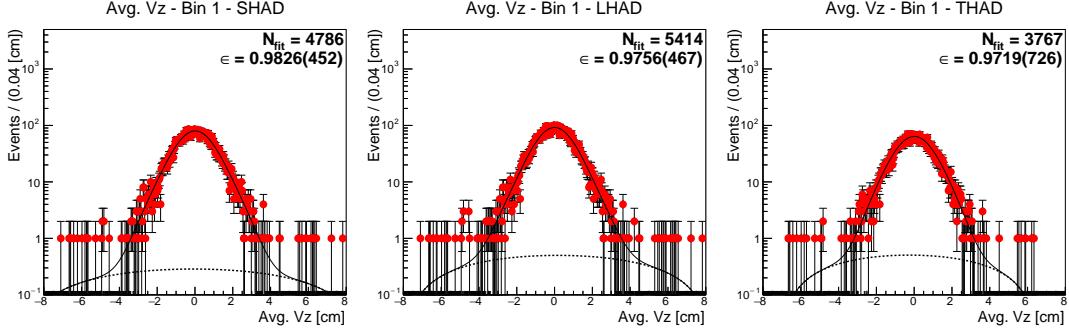


Figure D.2: The number of hadrons found in the 3736 (Scan) data sample. This includes results for SHAD (left), LHAD (middle), and THAD (right).

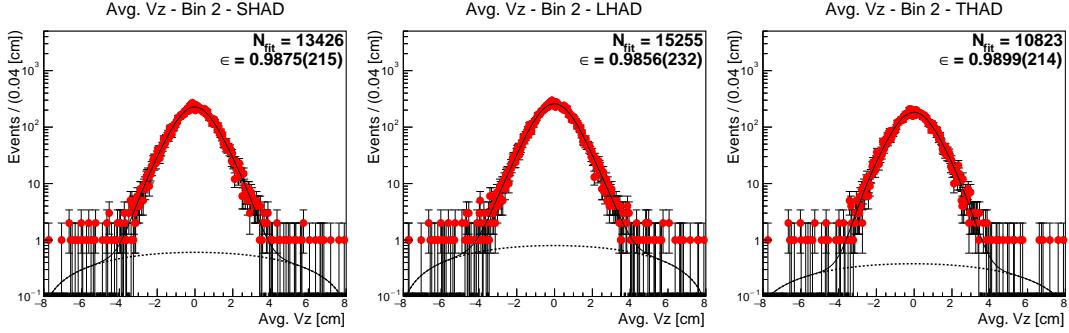


Figure D.3: The number of hadrons found in the 3744 (Scan) data sample. This includes results for SHAD (left), LHAD (middle), and THAD (right).

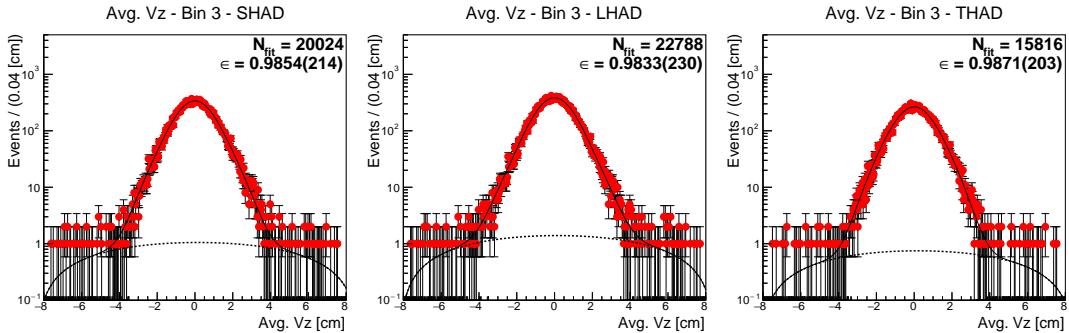


Figure D.4: The number of hadrons found in the 3748 (Scan) data sample. This includes results for SHAD (left), LHAD (middle), and THAD (right).

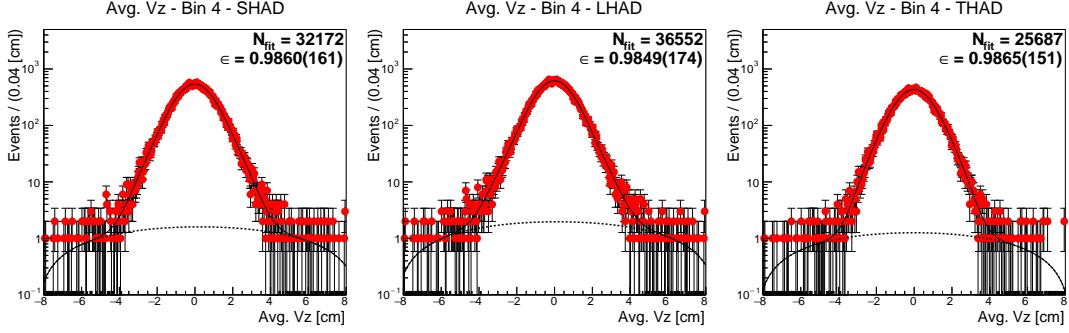


Figure D.5: The number of hadrons found in the 3750 (Scan) data sample. This includes results for SHAD (left), LHAD (middle), and THAD (right).

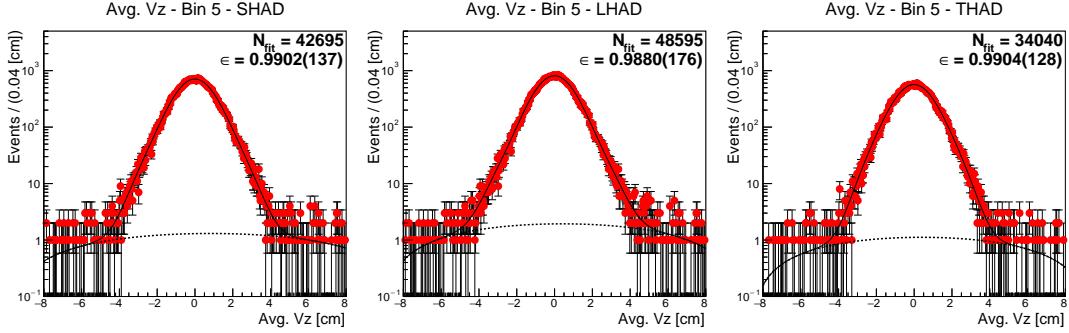


Figure D.6: The number of hadrons found in the 3751 (Scan) data sample. This includes results for SHAD (left), LHAD (middle), and THAD (right).

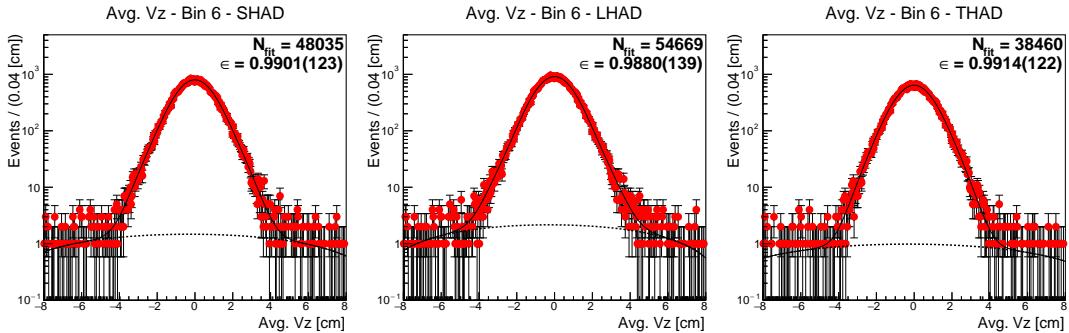


Figure D.7: The number of hadrons found in the 3753 (Scan) data sample. This includes results for SHAD (left), LHAD (middle), and THAD (right).

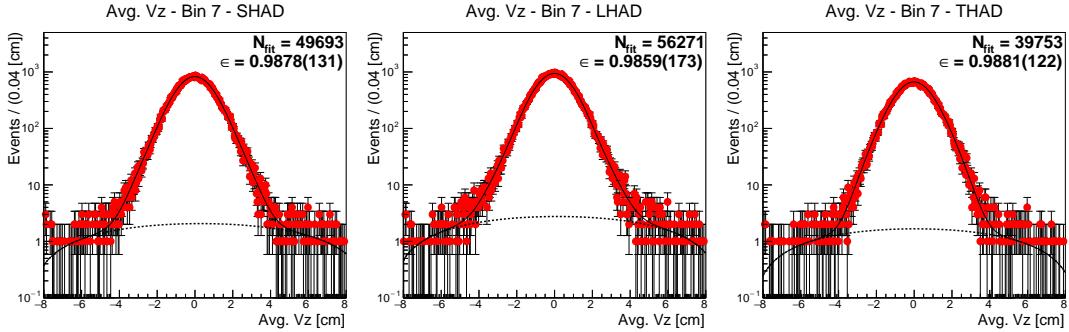


Figure D.8: The number of hadrons found in the 3755 (Scan) data sample. This includes results for SHAD (left), LHAD (middle), and THAD (right).

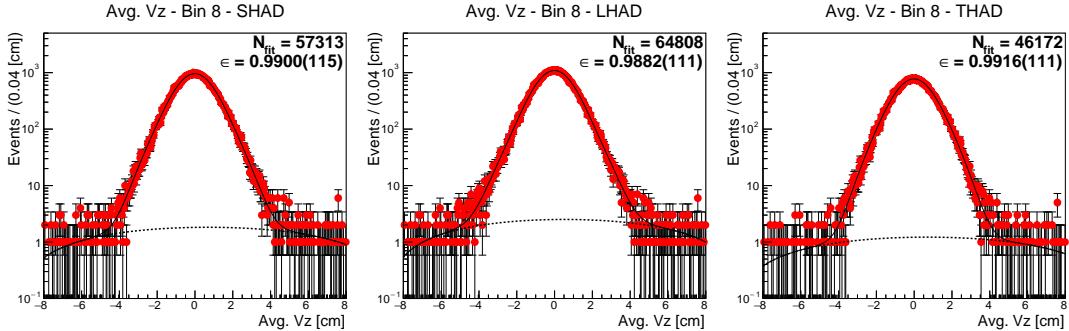


Figure D.9: The number of hadrons found in the 3756 (Scan) data sample. This includes results for SHAD (left), LHAD (middle), and THAD (right).

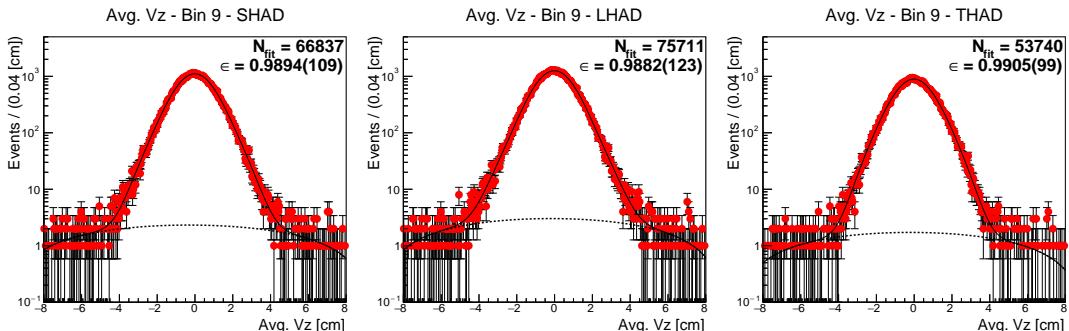


Figure D.10: The number of hadrons found in the 3759 (Scan) data sample. This includes results for SHAD (left), LHAD (middle), and THAD (right).

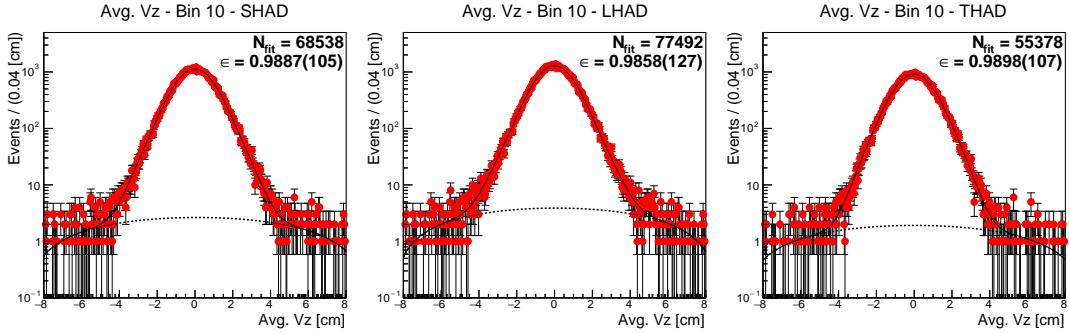


Figure D.11: The number of hadrons found in the 3762 (Scan) data sample. This includes results for SHAD (left), LHAD (middle), and THAD (right).

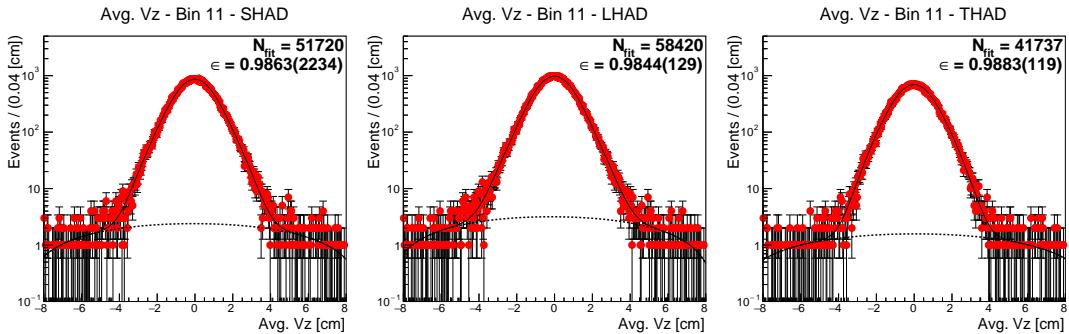


Figure D.12: The number of hadrons found in the 3765 (Scan) data sample. This includes results for SHAD (left), LHAD (middle), and THAD (right).

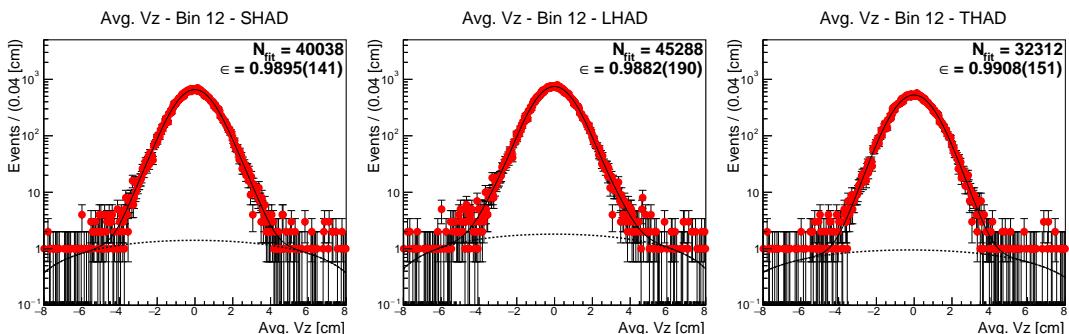


Figure D.13: The number of hadrons found in the 3767 (Scan) data sample. This includes results for SHAD (left), LHAD (middle), and THAD (right).

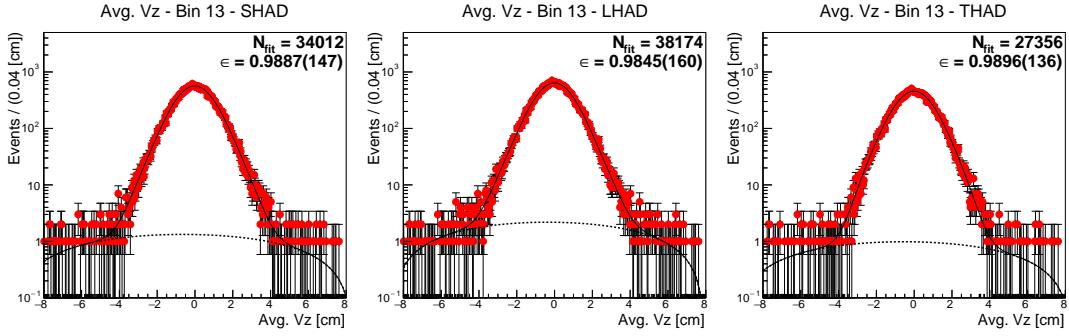


Figure D.14: The number of hadrons found in the 3771 (Scan) data sample. This includes results for SHAD (left), LHAD (middle), and THAD (right).

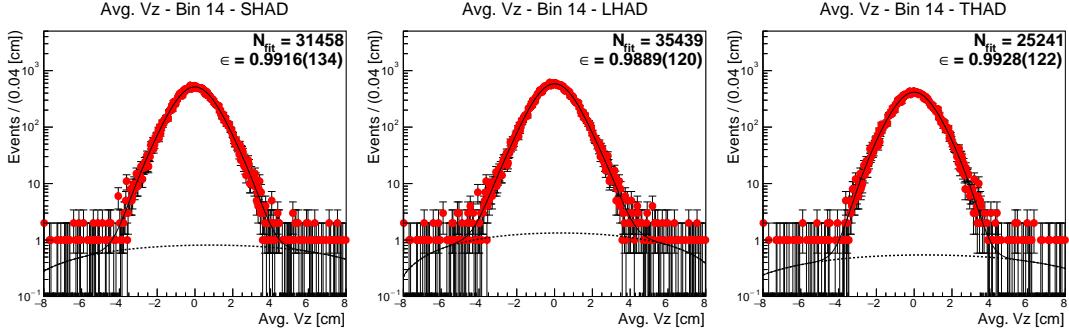


Figure D.15: The number of hadrons found in the 3774 (Scan) data sample. This includes results for SHAD (left), LHAD (middle), and THAD (right).

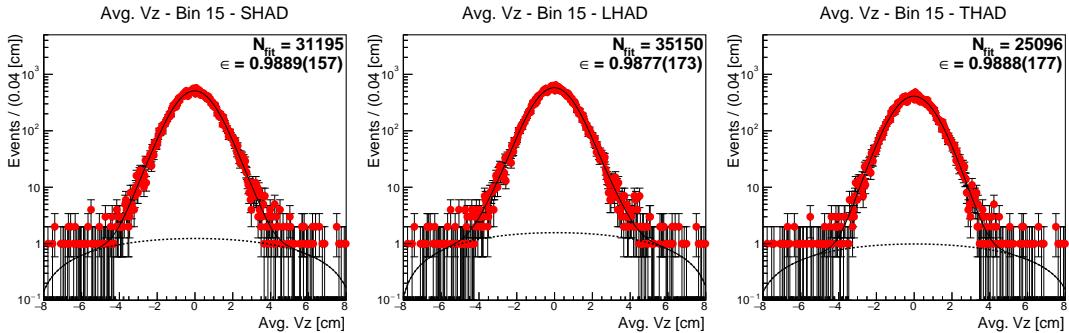


Figure D.16: The number of hadrons found in the 3777 (Scan) data sample. This includes results for SHAD (left), LHAD (middle), and THAD (right).

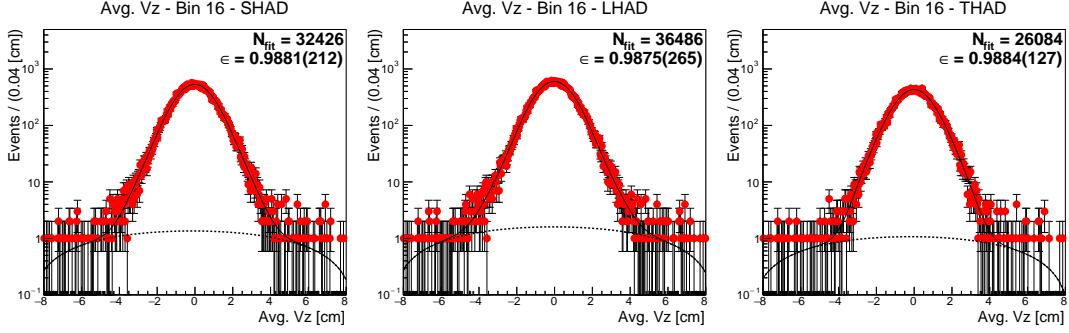


Figure D.17: The number of hadrons found in the 3780 (Scan) data sample. This includes results for SHAD (left), LHAD (middle), and THAD (right).

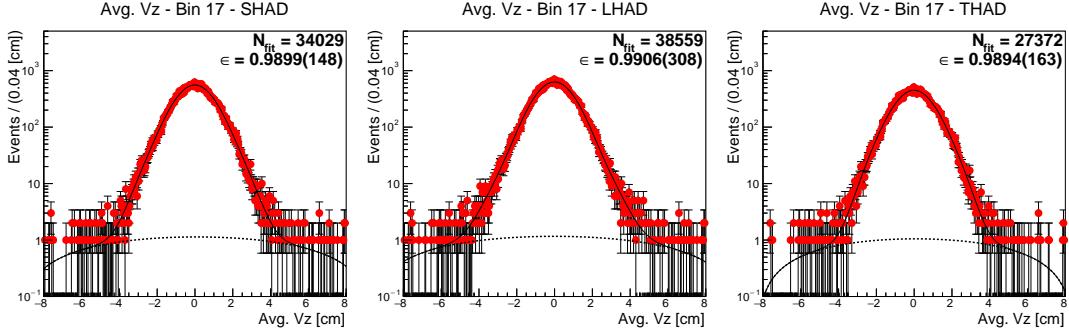


Figure D.18: The number of hadrons found in the 3782 (Scan) data sample. This includes results for SHAD (left), LHAD (middle), and THAD (right).

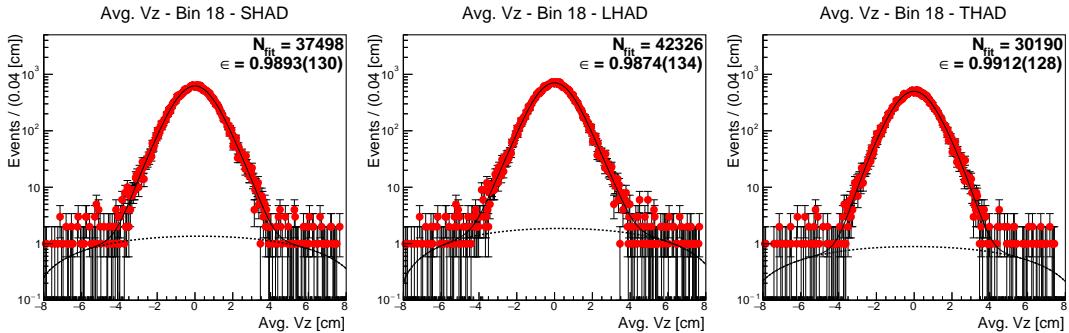


Figure D.19: The number of hadrons found in the 3786 (Scan) data sample. This includes results for SHAD (left), LHAD (middle), and THAD (right).

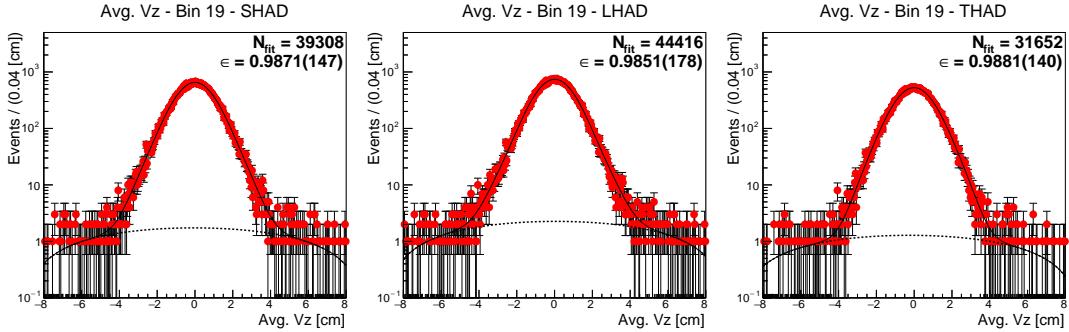


Figure D.20: The number of hadrons found in the 3789 (Scan) data sample. This includes results for SHAD (left), LHAD (middle), and THAD (right).

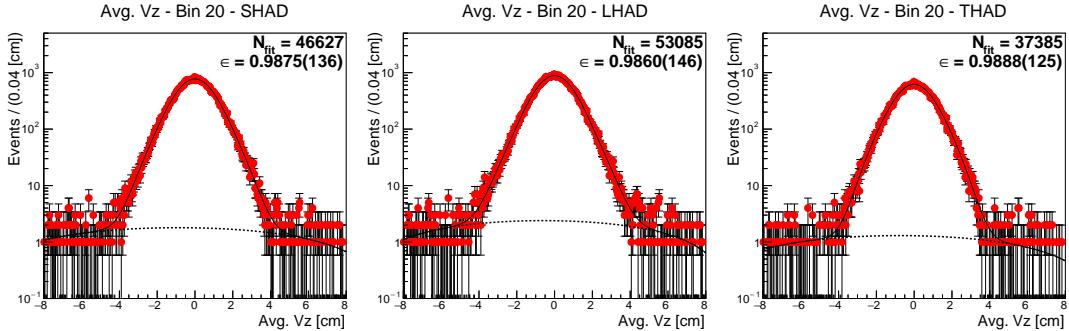


Figure D.21: The number of hadrons found in the 3792 (Scan) data sample. This includes results for SHAD (left), LHAD (middle), and THAD (right).

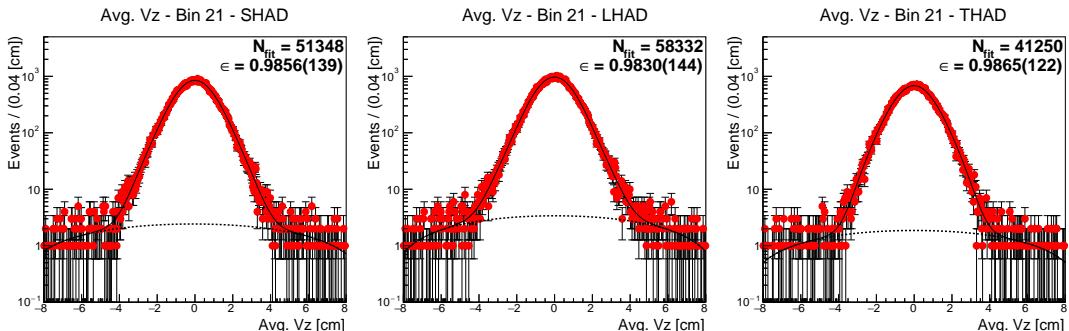


Figure D.22: The number of hadrons found in the 3797 (Scan) data sample. This includes results for SHAD (left), LHAD (middle), and THAD (right).

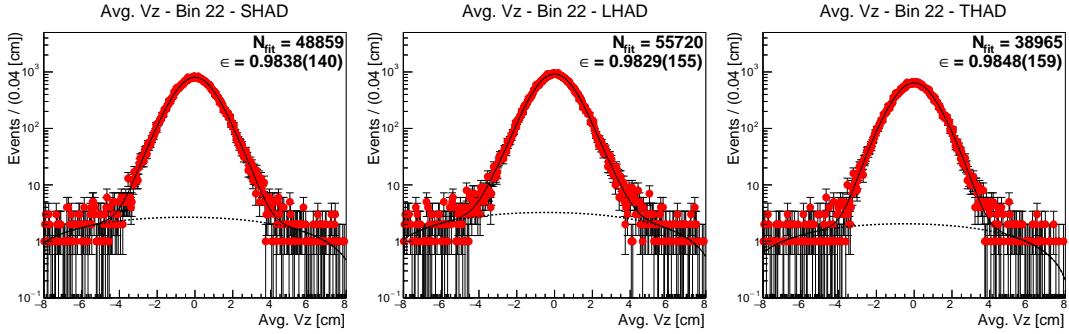


Figure D.23: The number of hadrons found in the 3800 (Scan) data sample. This includes results for SHAD (left), LHAD (middle), and THAD (right).

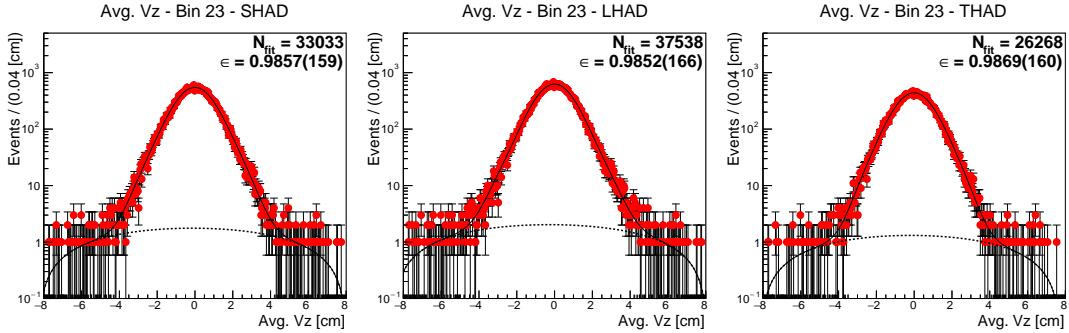


Figure D.24: The number of hadrons found in the 3802 (Scan) data sample. This includes results for SHAD (left), LHAD (middle), and THAD (right).

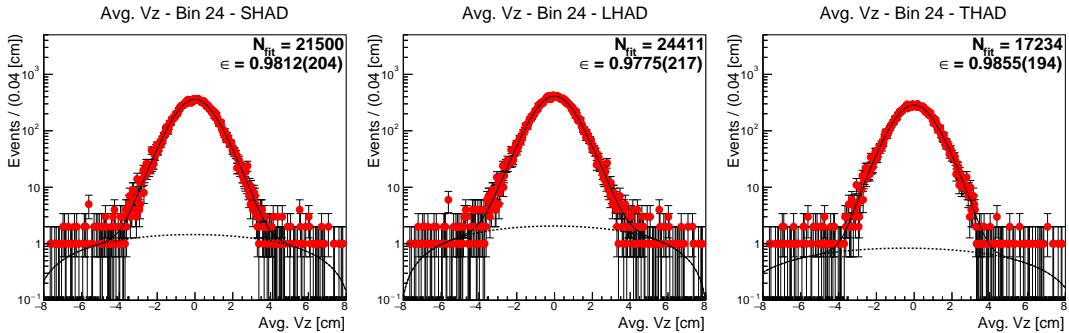


Figure D.25: The number of hadrons found in the 3807 (Scan) data sample. This includes results for SHAD (left), LHAD (middle), and THAD (right).

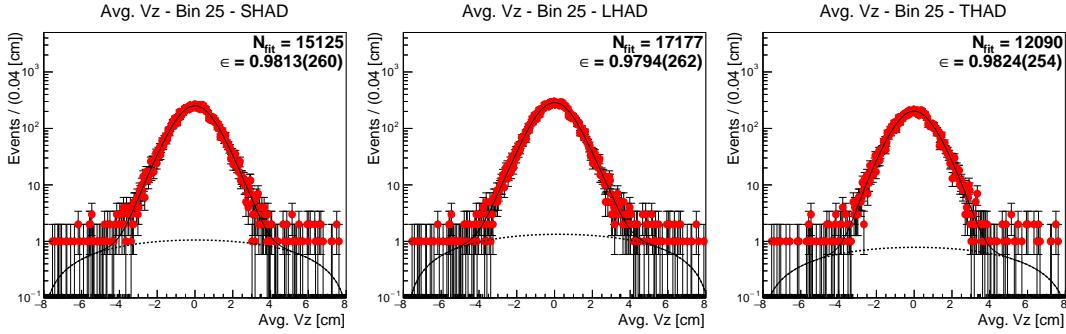


Figure D.26: The number of hadrons found in the 3809 (Scan) data sample. This includes results for SHAD (left), LHAD (middle), and THAD (right).

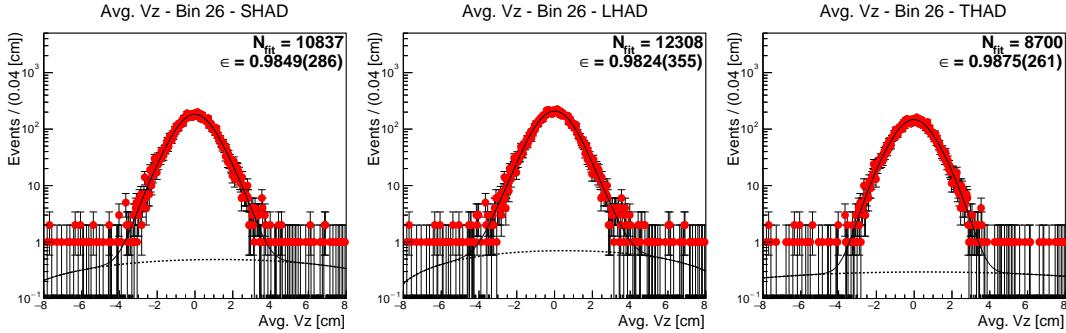


Figure D.27: The number of hadrons found in the 3813 (Scan) data sample. This includes results for SHAD (left), LHAD (middle), and THAD (right).

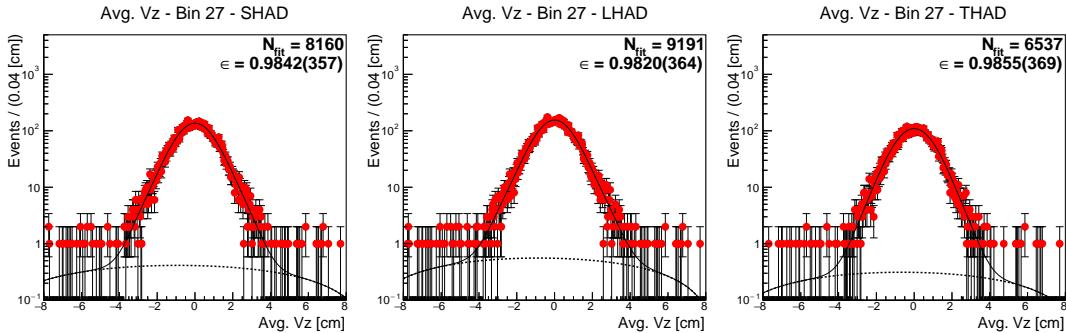


Figure D.28: The number of hadrons found in the 3815 (Scan) data sample. This includes results for SHAD (left), LHAD (middle), and THAD (right).

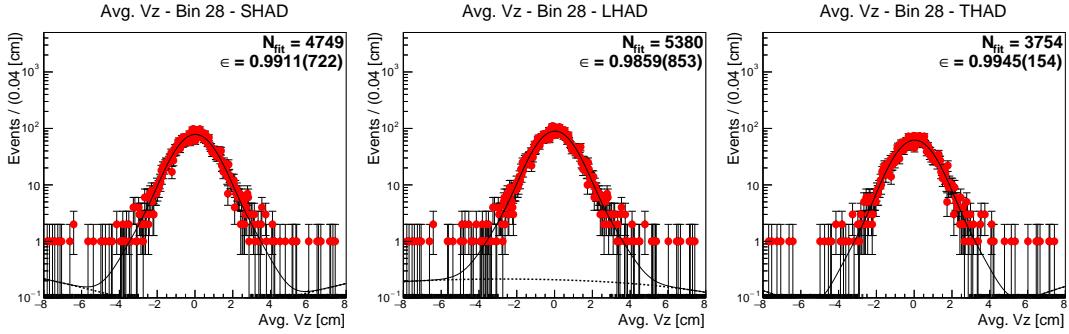


Figure D.29: The number of hadrons found in the 3822 (Scan) data sample. This includes results for SHAD (left), LHAD (middle), and THAD (right).

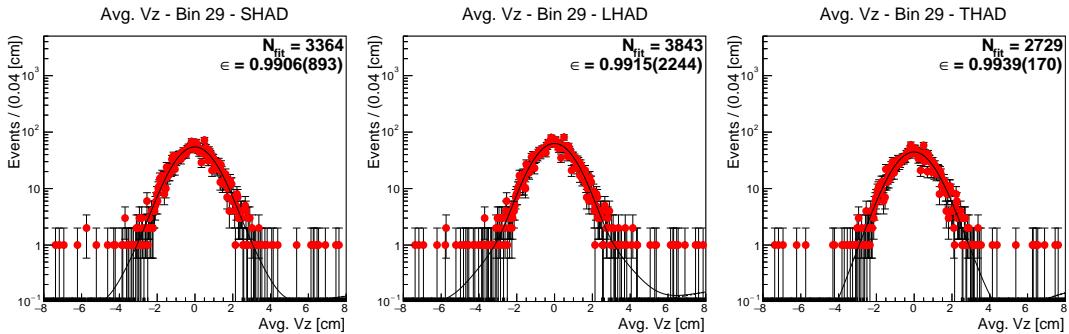


Figure D.30: The number of hadrons found in the 3832 (Scan) data sample. This includes results for SHAD (left), LHAD (middle), and THAD (right).

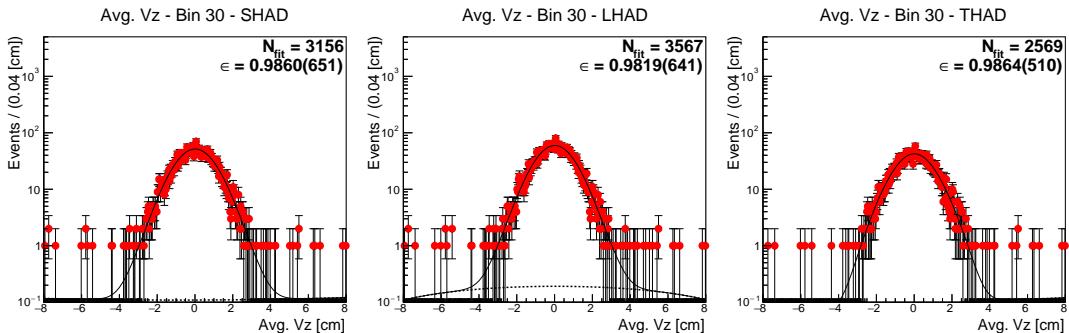


Figure D.31: The number of hadrons found in the 3839 (Scan) data sample. This includes results for SHAD (left), LHAD (middle), and THAD (right).

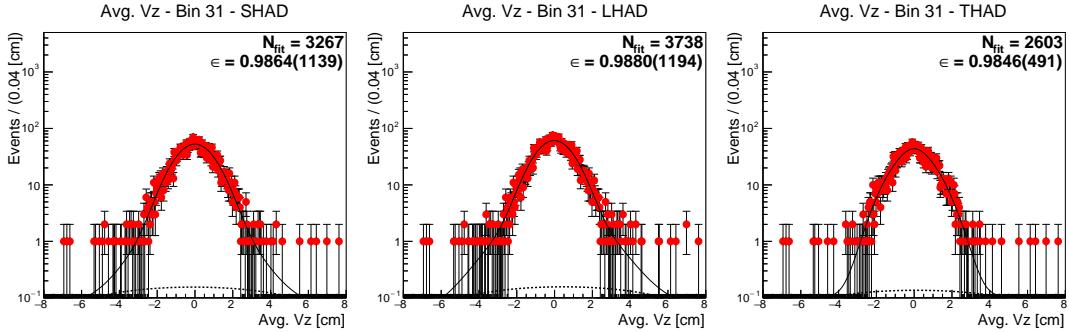


Figure D.32: The number of hadrons found in the 3849 (Scan) data sample. This includes results for SHAD (left), LHAD (middle), and THAD (right).

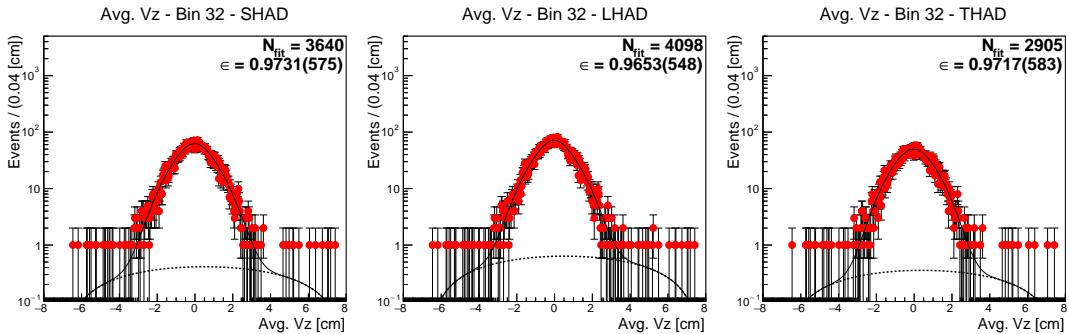


Figure D.33: The number of hadrons found in the 3855 (Scan) data sample. This includes results for SHAD (left), LHAD (middle), and THAD (right).

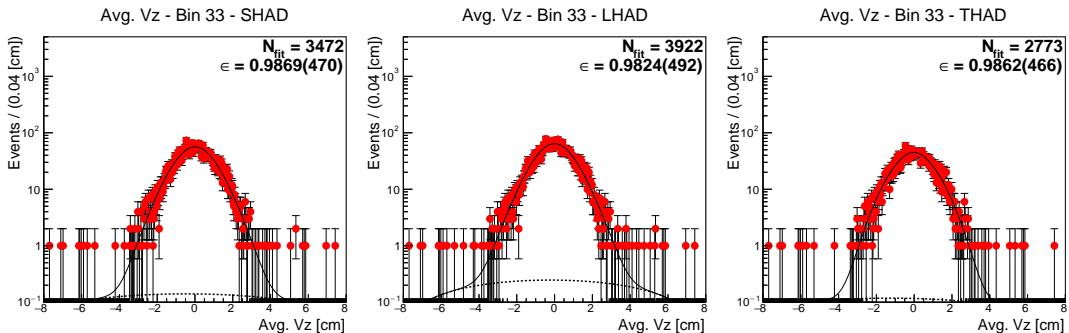


Figure D.34: The number of hadrons found in the 3863 (Scan) data sample. This includes results for SHAD (left), LHAD (middle), and THAD (right).

Appendix E

Scan Data Reconstruction Efficiency

| 3734 (Scan) Reconstruction | | | | |
|----------------------------|---------------|-----------------------------------|-----------------------------------|-----------------------------------|
| Sample | σ [nb] | ϵ_{MC} (SHAD) [%] | ϵ_{MC} (LHAD) [%] | ϵ_{MC} (THAD) [%] |
| $D^0\bar{D}^0$ | 0.164 | 0.7360 ± 0.0019 | 0.7956 ± 0.0020 | 0.6015 ± 0.0017 |
| D^+D^- | 0.000 | - | - | - |
| $\tau^-\tau^+$ | 2.467 | 0.1284 ± 0.0008 | 0.2834 ± 0.0012 | 0.0987 ± 0.0007 |
| $\gamma J/\psi$ | 1.060 | 0.4662 ± 0.0015 | 0.5625 ± 0.0017 | 0.3475 ± 0.0013 |
| $\gamma\psi(2S)$ | 5.359 | 0.6305 ± 0.0018 | 0.6967 ± 0.0019 | 0.5142 ± 0.0016 |

Table E.1: Reconstruction of background samples for the 3734 (Scan) data.

| 3736 (Scan) Reconstruction | | | | |
|----------------------------|---------------|-----------------------------------|-----------------------------------|-----------------------------------|
| Sample | σ [nb] | ϵ_{MC} (SHAD) [%] | ϵ_{MC} (LHAD) [%] | ϵ_{MC} (THAD) [%] |
| $D^0\bar{D}^0$ | 0.218 | 0.7348 ± 0.0027 | 0.7951 ± 0.0028 | 0.5995 ± 0.0024 |
| D^+D^- | 0.000 | - | - | - |
| $\tau^-\tau^+$ | 2.475 | 0.1281 ± 0.0011 | 0.2815 ± 0.0017 | 0.0984 ± 0.0010 |
| $\gamma J/\psi$ | 1.055 | 0.4640 ± 0.0022 | 0.5597 ± 0.0024 | 0.3429 ± 0.0019 |
| $\gamma\psi(2S)$ | 5.094 | 0.6334 ± 0.0025 | 0.6995 ± 0.0026 | 0.5148 ± 0.0023 |

Table E.2: Reconstruction of background samples for the 3736 (Scan) data.

| 3744 (Scan) Reconstruction | | | | |
|----------------------------|---------------|-----------------------------------|-----------------------------------|-----------------------------------|
| Sample | σ [nb] | ϵ_{MC} (SHAD) [%] | ϵ_{MC} (LHAD) [%] | ϵ_{MC} (THAD) [%] |
| $D^0\bar{D}^0$ | 0.765 | 0.7304 ± 0.0019 | 0.7932 ± 0.0020 | 0.5959 ± 0.0017 |
| D^+D^- | 0.150 | 0.6071 ± 0.0017 | 0.6838 ± 0.0018 | 0.4871 ± 0.0016 |
| $\tau^-\tau^+$ | 2.514 | 0.1270 ± 0.0008 | 0.2812 ± 0.0012 | 0.0983 ± 0.0007 |
| $\gamma J/\psi$ | 1.039 | 0.4626 ± 0.0015 | 0.5613 ± 0.0017 | 0.3431 ± 0.0013 |
| $\gamma\psi(2S)$ | 4.428 | 0.6259 ± 0.0018 | 0.6938 ± 0.0019 | 0.5101 ± 0.0016 |

Table E.3: Reconstruction of background samples for the 3744 (Scan) data.

| 3748 (Scan) Reconstruction | | | | |
|----------------------------|---------------|-----------------------------------|-----------------------------------|-----------------------------------|
| Sample | σ [nb] | ϵ_{MC} (SHAD) [%] | ϵ_{MC} (LHAD) [%] | ϵ_{MC} (THAD) [%] |
| $D^0\bar{D}^0$ | 0.838 | 0.7276 ± 0.0016 | 0.7906 ± 0.0016 | 0.5907 ± 0.0014 |
| D^+D^- | 0.360 | 0.6037 ± 0.0014 | 0.6800 ± 0.0015 | 0.4820 ± 0.0013 |
| $\tau^-\tau^+$ | 2.522 | 0.1262 ± 0.0006 | 0.2781 ± 0.0010 | 0.0970 ± 0.0006 |
| $\gamma J/\psi$ | 1.032 | 0.4609 ± 0.0012 | 0.5588 ± 0.0014 | 0.3427 ± 0.0011 |
| $\gamma\psi(2S)$ | 4.180 | 0.6252 ± 0.0014 | 0.6928 ± 0.0015 | 0.5080 ± 0.0013 |

Table E.4: Reconstruction of background samples for the 3748 (Scan) data.

| 3750 (Scan) Reconstruction | | | | |
|----------------------------|---------------|-----------------------------------|-----------------------------------|-----------------------------------|
| Sample | σ [nb] | ϵ_{MC} (SHAD) [%] | ϵ_{MC} (LHAD) [%] | ϵ_{MC} (THAD) [%] |
| $D^0\bar{D}^0$ | 0.968 | 0.7351 ± 0.0012 | 0.7960 ± 0.0013 | 0.5996 ± 0.0011 |
| D^+D^- | 0.439 | 0.6130 ± 0.0011 | 0.6879 ± 0.0012 | 0.4921 ± 0.0010 |
| $\tau^-\tau^+$ | 2.533 | 0.1283 ± 0.0005 | 0.2812 ± 0.0007 | 0.0993 ± 0.0004 |
| $\gamma J/\psi$ | 1.029 | 0.4661 ± 0.0010 | 0.5633 ± 0.0011 | 0.3470 ± 0.0008 |
| $\gamma\psi(2S)$ | 4.065 | 0.6322 ± 0.0011 | 0.6986 ± 0.0012 | 0.5162 ± 0.0010 |

Table E.5: Reconstruction of background samples for the 3750 (Scan) data.

| 3751 (Scan) Reconstruction | | | | |
|----------------------------|---------------|-----------------------------------|-----------------------------------|-----------------------------------|
| Sample | σ [nb] | ϵ_{MC} (SHAD) [%] | ϵ_{MC} (LHAD) [%] | ϵ_{MC} (THAD) [%] |
| $D^0\bar{D}^0$ | 1.237 | 0.7316 ± 0.0009 | 0.7935 ± 0.0009 | 0.5950 ± 0.0008 |
| D^+D^- | 0.574 | 0.6084 ± 0.0008 | 0.6841 ± 0.0009 | 0.4872 ± 0.0007 |
| $\tau^-\tau^+$ | 2.542 | 0.1274 ± 0.0004 | 0.2805 ± 0.0006 | 0.0983 ± 0.0003 |
| $\gamma J/\psi$ | 1.025 | 0.4629 ± 0.0007 | 0.5606 ± 0.0008 | 0.3439 ± 0.0006 |
| $\gamma\psi(2S)$ | 3.969 | 0.6279 ± 0.0008 | 0.6959 ± 0.0009 | 0.5098 ± 0.0008 |

Table E.6: Reconstruction of background samples for the 3751 (Scan) data.

| 3753 (Scan) Reconstruction | | | | |
|----------------------------|---------------|-----------------------------------|-----------------------------------|-----------------------------------|
| Sample | σ [nb] | ϵ_{MC} (SHAD) [%] | ϵ_{MC} (LHAD) [%] | ϵ_{MC} (THAD) [%] |
| $D^0\bar{D}^0$ | 1.377 | 0.7342 ± 0.0010 | 0.7955 ± 0.0010 | 0.5973 ± 0.0009 |
| D^+D^- | 0.748 | 0.6103 ± 0.0009 | 0.6855 ± 0.0009 | 0.4888 ± 0.0008 |
| $\tau^-\tau^+$ | 2.553 | 0.1267 ± 0.0004 | 0.2798 ± 0.0006 | 0.0976 ± 0.0003 |
| $\gamma J/\psi$ | 1.022 | 0.4636 ± 0.0008 | 0.5606 ± 0.0008 | 0.3443 ± 0.0007 |
| $\gamma\psi(2S)$ | 3.871 | 0.6290 ± 0.0009 | 0.6964 ± 0.0009 | 0.5112 ± 0.0008 |

Table E.7: Reconstruction of background samples for the 3753 (Scan) data.

| 3755 (Scan) Reconstruction | | | | |
|----------------------------|---------------|-----------------------------------|-----------------------------------|-----------------------------------|
| Sample | σ [nb] | ϵ_{MC} (SHAD) [%] | ϵ_{MC} (LHAD) [%] | ϵ_{MC} (THAD) [%] |
| $D^0\bar{D}^0$ | 1.566 | 0.7322 ± 0.0009 | 0.7931 ± 0.0009 | 0.5961 ± 0.0008 |
| D^+D^- | 0.797 | 0.6080 ± 0.0008 | 0.6832 ± 0.0009 | 0.4883 ± 0.0007 |
| $\tau^-\tau^+$ | 2.562 | 0.1276 ± 0.0004 | 0.2808 ± 0.0006 | 0.0986 ± 0.0003 |
| $\gamma J/\psi$ | 1.018 | 0.4632 ± 0.0007 | 0.5603 ± 0.0008 | 0.3450 ± 0.0006 |
| $\gamma\psi(2S)$ | 3.752 | 0.6272 ± 0.0008 | 0.6946 ± 0.0009 | 0.5104 ± 0.0008 |

Table E.8: Reconstruction of background samples for the 3755 (Scan) data.

| 3756 (Scan) Reconstruction | | | | |
|----------------------------|---------------|-----------------------------------|-----------------------------------|-----------------------------------|
| Sample | σ [nb] | ϵ_{MC} (SHAD) [%] | ϵ_{MC} (LHAD) [%] | ϵ_{MC} (THAD) [%] |
| $D^0\bar{D}^0$ | 1.629 | 0.7410 ± 0.0010 | 0.7995 ± 0.0011 | 0.6067 ± 0.0009 |
| D^+D^- | 0.914 | 0.6150 ± 0.0009 | 0.6889 ± 0.0010 | 0.4960 ± 0.0008 |
| $\tau^-\tau^+$ | 2.573 | 0.1293 ± 0.0004 | 0.2821 ± 0.0006 | 0.1002 ± 0.0004 |
| $\gamma J/\psi$ | 1.017 | 0.4686 ± 0.0008 | 0.5645 ± 0.0009 | 0.3507 ± 0.0007 |
| $\gamma\psi(2S)$ | 3.721 | 0.6347 ± 0.0010 | 0.7011 ± 0.0010 | 0.5184 ± 0.0009 |

Table E.9: Reconstruction of background samples for the 3756 (Scan) data.

| 3759 (Scan) Reconstruction | | | | |
|----------------------------|---------------|-----------------------------------|-----------------------------------|-----------------------------------|
| Sample | σ [nb] | ϵ_{MC} (SHAD) [%] | ϵ_{MC} (LHAD) [%] | ϵ_{MC} (THAD) [%] |
| $D^0\bar{D}^0$ | 1.948 | 0.7415 ± 0.0009 | 0.8000 ± 0.0009 | 0.6076 ± 0.0008 |
| D^+D^- | 1.192 | 0.6162 ± 0.0008 | 0.6894 ± 0.0008 | 0.4967 ± 0.0007 |
| $\tau^-\tau^+$ | 2.584 | 0.1286 ± 0.0004 | 0.2826 ± 0.0005 | 0.0999 ± 0.0003 |
| $\gamma J/\psi$ | 1.011 | 0.4688 ± 0.0007 | 0.5652 ± 0.0008 | 0.3507 ± 0.0006 |
| $\gamma\psi(2S)$ | 3.572 | 0.6351 ± 0.0008 | 0.7010 ± 0.0008 | 0.5194 ± 0.0007 |

Table E.10: Reconstruction of background samples for the 3759 (Scan) data.

| 3762 (Scan) Reconstruction | | | | |
|----------------------------|---------------|-----------------------------------|-----------------------------------|-----------------------------------|
| Sample | σ [nb] | ϵ_{MC} (SHAD) [%] | ϵ_{MC} (LHAD) [%] | ϵ_{MC} (THAD) [%] |
| $D^0\bar{D}^0$ | 2.385 | 0.7420 ± 0.0008 | 0.8004 ± 0.0009 | 0.6078 ± 0.0007 |
| D^+D^- | 1.534 | 0.6154 ± 0.0007 | 0.6891 ± 0.0008 | 0.4964 ± 0.0007 |
| $\tau^-\tau^+$ | 2.598 | 0.1285 ± 0.0003 | 0.2819 ± 0.0005 | 0.0998 ± 0.0003 |
| $\gamma J/\psi$ | 1.005 | 0.4680 ± 0.0007 | 0.5642 ± 0.0007 | 0.3496 ± 0.0006 |
| $\gamma\psi(2S)$ | 3.426 | 0.6359 ± 0.0008 | 0.7017 ± 0.0008 | 0.5199 ± 0.0007 |

Table E.11: Reconstruction of background samples for the 3762 (Scan) data.

| 3765 (Scan) Reconstruction | | | | |
|----------------------------|---------------|-----------------------------------|-----------------------------------|-----------------------------------|
| Sample | σ [nb] | ϵ_{MC} (SHAD) [%] | ϵ_{MC} (LHAD) [%] | ϵ_{MC} (THAD) [%] |
| $D^0\bar{D}^0$ | 2.715 | 0.7425 ± 0.0010 | 0.8006 ± 0.0011 | 0.6085 ± 0.0009 |
| D^+D^- | 1.882 | 0.6168 ± 0.0009 | 0.6905 ± 0.0010 | 0.4978 ± 0.0008 |
| $\tau^-\tau^+$ | 2.613 | 0.1281 ± 0.0004 | 0.2819 ± 0.0006 | 0.0997 ± 0.0004 |
| $\gamma J/\psi$ | 1.000 | 0.4693 ± 0.0008 | 0.5649 ± 0.0009 | 0.3519 ± 0.0007 |
| $\gamma\psi(2S)$ | 3.315 | 0.6376 ± 0.0010 | 0.7035 ± 0.0010 | 0.5219 ± 0.0009 |

Table E.12: Reconstruction of background samples for the 3765 (Scan) data.

| 3767 (Scan) Reconstruction | | | | |
|----------------------------|---------------|-----------------------------------|-----------------------------------|-----------------------------------|
| Sample | σ [nb] | ϵ_{MC} (SHAD) [%] | ϵ_{MC} (LHAD) [%] | ϵ_{MC} (THAD) [%] |
| $D^0\bar{D}^0$ | 3.102 | 0.7432 ± 0.0011 | 0.8008 ± 0.0012 | 0.6090 ± 0.0010 |
| D^+D^- | 2.200 | 0.6171 ± 0.0010 | 0.6908 ± 0.0011 | 0.4978 ± 0.0009 |
| $\tau^-\tau^+$ | 2.627 | 0.1286 ± 0.0005 | 0.2818 ± 0.0007 | 0.0999 ± 0.0004 |
| $\gamma J/\psi$ | 0.995 | 0.4693 ± 0.0009 | 0.5653 ± 0.0010 | 0.3511 ± 0.0008 |
| $\gamma\psi(2S)$ | 3.212 | 0.6369 ± 0.0010 | 0.7025 ± 0.0011 | 0.5214 ± 0.0009 |

Table E.13: Reconstruction of background samples for the 3767 (Scan) data.

| 3771 (Scan) Reconstruction | | | | |
|----------------------------|---------------|-----------------------------------|-----------------------------------|-----------------------------------|
| Sample | σ [nb] | ϵ_{MC} (SHAD) [%] | ϵ_{MC} (LHAD) [%] | ϵ_{MC} (THAD) [%] |
| $D^0\bar{D}^0$ | 3.406 | 0.7440 ± 0.0014 | 0.8021 ± 0.0014 | 0.6098 ± 0.0012 |
| D^+D^- | 2.634 | 0.6179 ± 0.0012 | 0.6913 ± 0.0013 | 0.4987 ± 0.0011 |
| $\tau^-\tau^+$ | 2.641 | 0.1284 ± 0.0006 | 0.2821 ± 0.0008 | 0.1003 ± 0.0005 |
| $\gamma J/\psi$ | 0.989 | 0.4700 ± 0.0011 | 0.5661 ± 0.0012 | 0.3528 ± 0.0009 |
| $\gamma\psi(2S)$ | 3.075 | 0.6356 ± 0.0013 | 0.7020 ± 0.0013 | 0.5206 ± 0.0011 |

Table E.14: Reconstruction of background samples for the 3771 (Scan) data.

| 3774 (Scan) Reconstruction | | | | |
|----------------------------|---------------|-----------------------------------|-----------------------------------|-----------------------------------|
| Sample | σ [nb] | ϵ_{MC} (SHAD) [%] | ϵ_{MC} (LHAD) [%] | ϵ_{MC} (THAD) [%] |
| $D^0\bar{D}^0$ | 3.714 | 0.7429 ± 0.0014 | 0.8009 ± 0.0014 | 0.6084 ± 0.0012 |
| D^+D^- | 3.067 | 0.6172 ± 0.0012 | 0.6903 ± 0.0013 | 0.4975 ± 0.0011 |
| $\tau^-\tau^+$ | 2.656 | 0.1286 ± 0.0006 | 0.2819 ± 0.0008 | 0.0996 ± 0.0005 |
| $\gamma J/\psi$ | 0.983 | 0.4695 ± 0.0011 | 0.5657 ± 0.0012 | 0.3509 ± 0.0009 |
| $\gamma\psi(2S)$ | 2.975 | 0.6365 ± 0.0013 | 0.7028 ± 0.0013 | 0.5194 ± 0.0011 |

Table E.15: Reconstruction of background samples for the 3774 (Scan) data.

| 3777 (Scan) Reconstruction | | | | |
|----------------------------|---------------|-----------------------------------|-----------------------------------|-----------------------------------|
| Sample | σ [nb] | ϵ_{MC} (SHAD) [%] | ϵ_{MC} (LHAD) [%] | ϵ_{MC} (THAD) [%] |
| $D^0\bar{D}^0$ | 3.692 | 0.7436 ± 0.0016 | 0.8016 ± 0.0016 | 0.6090 ± 0.0014 |
| D^+D^- | 3.078 | 0.6171 ± 0.0014 | 0.6904 ± 0.0015 | 0.4978 ± 0.0013 |
| $\tau^-\tau^+$ | 2.669 | 0.1299 ± 0.0007 | 0.2837 ± 0.0010 | 0.1012 ± 0.0006 |
| $\gamma J/\psi$ | 0.978 | 0.4702 ± 0.0013 | 0.5662 ± 0.0014 | 0.3537 ± 0.0011 |
| $\gamma\psi(2S)$ | 2.870 | 0.6362 ± 0.0015 | 0.7024 ± 0.0015 | 0.5204 ± 0.0013 |

Table E.16: Reconstruction of background samples for the 3777 (Scan) data.

| 3780 (Scan) Reconstruction | | | | |
|----------------------------|---------------|-----------------------------------|-----------------------------------|-----------------------------------|
| Sample | σ [nb] | ϵ_{MC} (SHAD) [%] | ϵ_{MC} (LHAD) [%] | ϵ_{MC} (THAD) [%] |
| $D^0\bar{D}^0$ | 3.444 | 0.7460 ± 0.0014 | 0.8036 ± 0.0014 | 0.6126 ± 0.0012 |
| D^+D^- | 2.599 | 0.6194 ± 0.0012 | 0.6925 ± 0.0013 | 0.5003 ± 0.0011 |
| $\tau^-\tau^+$ | 2.683 | 0.1285 ± 0.0006 | 0.2824 ± 0.0008 | 0.1000 ± 0.0005 |
| $\gamma J/\psi$ | 0.973 | 0.4703 ± 0.0011 | 0.5665 ± 0.0012 | 0.3530 ± 0.0009 |
| $\gamma\psi(2S)$ | 2.788 | 0.6380 ± 0.0013 | 0.7043 ± 0.0013 | 0.5228 ± 0.0011 |

Table E.17: Reconstruction of background samples for the 3780 (Scan) data.

| 3782 (Scan) Reconstruction | | | | |
|----------------------------|---------------|-----------------------------------|-----------------------------------|-----------------------------------|
| Sample | σ [nb] | ϵ_{MC} (SHAD) [%] | ϵ_{MC} (LHAD) [%] | ϵ_{MC} (THAD) [%] |
| $D^0\bar{D}^0$ | 2.791 | 0.7441 ± 0.0012 | 0.8019 ± 0.0013 | 0.6101 ± 0.0011 |
| D^+D^- | 2.206 | 0.6195 ± 0.0011 | 0.6923 ± 0.0012 | 0.5004 ± 0.0010 |
| $\tau^-\tau^+$ | 2.696 | 0.1281 ± 0.0005 | 0.2814 ± 0.0008 | 0.0995 ± 0.0004 |
| $\gamma J/\psi$ | 0.968 | 0.4706 ± 0.0010 | 0.5663 ± 0.0011 | 0.3531 ± 0.0008 |
| $\gamma\psi(2S)$ | 2.712 | 0.6377 ± 0.0011 | 0.7046 ± 0.0012 | 0.5210 ± 0.0010 |

Table E.18: Reconstruction of background samples for the 3782 (Scan) data.

| 3786 (Scan) Reconstruction | | | | |
|----------------------------|---------------|-----------------------------------|-----------------------------------|-----------------------------------|
| Sample | σ [nb] | ϵ_{MC} (SHAD) [%] | ϵ_{MC} (LHAD) [%] | ϵ_{MC} (THAD) [%] |
| $D^0\bar{D}^0$ | 1.995 | 0.7460 ± 0.0012 | 0.8037 ± 0.0013 | 0.6122 ± 0.0011 |
| D^+D^- | 1.627 | 0.6194 ± 0.0011 | 0.6923 ± 0.0012 | 0.5013 ± 0.0010 |
| $\tau^-\tau^+$ | 2.709 | 0.1289 ± 0.0005 | 0.2810 ± 0.0007 | 0.1007 ± 0.0004 |
| $\gamma J/\psi$ | 0.961 | 0.4698 ± 0.0010 | 0.5652 ± 0.0011 | 0.3524 ± 0.0008 |
| $\gamma\psi(2S)$ | 2.605 | 0.6380 ± 0.0011 | 0.7044 ± 0.0012 | 0.5223 ± 0.0010 |

Table E.19: Reconstruction of background samples for the 3786 (Scan) data.

| 3789 (Scan) Reconstruction | | | | |
|----------------------------|---------------|-----------------------------------|-----------------------------------|-----------------------------------|
| Sample | σ [nb] | ϵ_{MC} (SHAD) [%] | ϵ_{MC} (LHAD) [%] | ϵ_{MC} (THAD) [%] |
| $D^0\bar{D}^0$ | 1.361 | 0.7457 ± 0.0010 | 0.8035 ± 0.0011 | 0.6118 ± 0.0009 |
| D^+D^- | 1.178 | 0.6188 ± 0.0009 | 0.6918 ± 0.0010 | 0.5002 ± 0.0008 |
| $\tau^-\tau^+$ | 2.722 | 0.1284 ± 0.0004 | 0.2805 ± 0.0006 | 0.1003 ± 0.0004 |
| $\gamma J/\psi$ | 0.957 | 0.4700 ± 0.0008 | 0.5655 ± 0.0009 | 0.3526 ± 0.0007 |
| $\gamma\psi(2S)$ | 2.550 | 0.6379 ± 0.0010 | 0.7040 ± 0.0010 | 0.5225 ± 0.0009 |

Table E.20: Reconstruction of background samples for the 3789 (Scan) data.

| 3792 (Scan) Reconstruction | | | | |
|----------------------------|---------------|-----------------------------------|-----------------------------------|-----------------------------------|
| Sample | σ [nb] | ϵ_{MC} (SHAD) [%] | ϵ_{MC} (LHAD) [%] | ϵ_{MC} (THAD) [%] |
| $D^0\bar{D}^0$ | 0.920 | 0.7440 ± 0.0010 | 0.8019 ± 0.0011 | 0.6094 ± 0.0009 |
| D^+D^- | 0.680 | 0.6176 ± 0.0009 | 0.6905 ± 0.0010 | 0.4989 ± 0.0008 |
| $\tau^-\tau^+$ | 2.739 | 0.1286 ± 0.0004 | 0.2800 ± 0.0006 | 0.0998 ± 0.0004 |
| $\gamma J/\psi$ | 0.951 | 0.4677 ± 0.0008 | 0.5637 ± 0.0009 | 0.3498 ± 0.0007 |
| $\gamma\psi(2S)$ | 2.467 | 0.6364 ± 0.0010 | 0.7027 ± 0.0010 | 0.5196 ± 0.0009 |

Table E.21: Reconstruction of background samples for the 3792 (Scan) data.

| 3797 (Scan) Reconstruction | | | | |
|----------------------------|---------------|-----------------------------------|-----------------------------------|-----------------------------------|
| Sample | σ [nb] | ϵ_{MC} (SHAD) [%] | ϵ_{MC} (LHAD) [%] | ϵ_{MC} (THAD) [%] |
| $D^0\bar{D}^0$ | 0.562 | 0.7444 ± 0.0010 | 0.8025 ± 0.0010 | 0.6102 ± 0.0009 |
| D^+D^- | 0.414 | 0.6183 ± 0.0009 | 0.6916 ± 0.0009 | 0.4998 ± 0.0008 |
| $\tau^-\tau^+$ | 2.755 | 0.1280 ± 0.0004 | 0.2796 ± 0.0006 | 0.0998 ± 0.0004 |
| $\gamma J/\psi$ | 0.944 | 0.4688 ± 0.0008 | 0.5646 ± 0.0008 | 0.3512 ± 0.0007 |
| $\gamma\psi(2S)$ | 2.370 | 0.6380 ± 0.0009 | 0.7042 ± 0.0009 | 0.5218 ± 0.0008 |

Table E.22: Reconstruction of background samples for the 3797 (Scan) data.

| 3800 (Scan) Reconstruction | | | | |
|----------------------------|---------------|-----------------------------------|-----------------------------------|-----------------------------------|
| Sample | σ [nb] | ϵ_{MC} (SHAD) [%] | ϵ_{MC} (LHAD) [%] | ϵ_{MC} (THAD) [%] |
| $D^0\bar{D}^0$ | 0.424 | 0.7417 ± 0.0009 | 0.8004 ± 0.0009 | 0.6068 ± 0.0008 |
| D^+D^- | 0.241 | 0.6161 ± 0.0008 | 0.6894 ± 0.0009 | 0.4965 ± 0.0007 |
| $\tau^-\tau^+$ | 2.771 | 0.1281 ± 0.0004 | 0.2803 ± 0.0006 | 0.0994 ± 0.0003 |
| $\gamma J/\psi$ | 0.938 | 0.4671 ± 0.0007 | 0.5633 ± 0.0008 | 0.3492 ± 0.0006 |
| $\gamma\psi(2S)$ | 2.301 | 0.6358 ± 0.0008 | 0.7029 ± 0.0009 | 0.5183 ± 0.0008 |

Table E.23: Reconstruction of background samples for the 3800 (Scan) data.

| 3802 (Scan) Reconstruction | | | | |
|----------------------------|---------------|-----------------------------------|-----------------------------------|-----------------------------------|
| Sample | σ [nb] | ϵ_{MC} (SHAD) [%] | ϵ_{MC} (LHAD) [%] | ϵ_{MC} (THAD) [%] |
| $D^0\bar{D}^0$ | 0.325 | 0.7421 ± 0.0011 | 0.8008 ± 0.0012 | 0.6075 ± 0.0010 |
| D^+D^- | 0.236 | 0.6157 ± 0.0010 | 0.6892 ± 0.0011 | 0.4959 ± 0.0009 |
| $\tau^-\tau^+$ | 2.784 | 0.1285 ± 0.0005 | 0.2806 ± 0.0007 | 0.0995 ± 0.0004 |
| $\gamma J/\psi$ | 0.935 | 0.4676 ± 0.0009 | 0.5635 ± 0.0010 | 0.3496 ± 0.0008 |
| $\gamma\psi(2S)$ | 2.260 | 0.6362 ± 0.0010 | 0.7034 ± 0.0011 | 0.5195 ± 0.0009 |

Table E.24: Reconstruction of background samples for the 3802 (Scan) data.

| 3807 (Scan) Reconstruction | | | | |
|----------------------------|---------------|-----------------------------------|-----------------------------------|-----------------------------------|
| Sample | σ [nb] | ϵ_{MC} (SHAD) [%] | ϵ_{MC} (LHAD) [%] | ϵ_{MC} (THAD) [%] |
| $D^0\bar{D}^0$ | 0.352 | 0.7407 ± 0.0012 | 0.8000 ± 0.0013 | 0.6049 ± 0.0011 |
| D^+D^- | 0.289 | 0.6132 ± 0.0011 | 0.6876 ± 0.0012 | 0.4941 ± 0.0010 |
| $\tau^-\tau^+$ | 2.795 | 0.1286 ± 0.0005 | 0.2800 ± 0.0007 | 0.0995 ± 0.0004 |
| $\gamma J/\psi$ | 0.927 | 0.4666 ± 0.0010 | 0.5628 ± 0.0011 | 0.3480 ± 0.0008 |
| $\gamma\psi(2S)$ | 2.174 | 0.6344 ± 0.0011 | 0.7024 ± 0.0012 | 0.5175 ± 0.0010 |

Table E.25: Reconstruction of background samples for the 3807 (Scan) data.

| 3809 (Scan) Reconstruction | | | | |
|----------------------------|---------------|-----------------------------------|-----------------------------------|-----------------------------------|
| Sample | σ [nb] | ϵ_{MC} (SHAD) [%] | ϵ_{MC} (LHAD) [%] | ϵ_{MC} (THAD) [%] |
| $D^0\bar{D}^0$ | 0.233 | 0.7430 ± 0.0016 | 0.8019 ± 0.0016 | 0.6092 ± 0.0014 |
| D^+D^- | 0.132 | 0.6170 ± 0.0014 | 0.6907 ± 0.0015 | 0.4977 ± 0.0013 |
| $\tau^-\tau^+$ | 2.807 | 0.1281 ± 0.0007 | 0.2803 ± 0.0010 | 0.0998 ± 0.0006 |
| $\gamma J/\psi$ | 0.923 | 0.4676 ± 0.0012 | 0.5632 ± 0.0014 | 0.3511 ± 0.0011 |
| $\gamma\psi(2S)$ | 2.133 | 0.6375 ± 0.0015 | 0.7046 ± 0.0015 | 0.5216 ± 0.0013 |

Table E.26: Reconstruction of background samples for the 3809 (Scan) data.

| 3813 (Scan) Reconstruction | | | | |
|----------------------------|---------------|-----------------------------------|-----------------------------------|-----------------------------------|
| Sample | σ [nb] | ϵ_{MC} (SHAD) [%] | ϵ_{MC} (LHAD) [%] | ϵ_{MC} (THAD) [%] |
| $D^0\bar{D}^0$ | 0.060 | 0.7393 ± 0.0019 | 0.7994 ± 0.0020 | 0.6045 ± 0.0017 |
| D^+D^- | 0.153 | 0.6128 ± 0.0018 | 0.6879 ± 0.0019 | 0.4923 ± 0.0016 |
| $\tau^-\tau^+$ | 2.819 | 0.1272 ± 0.0008 | 0.2783 ± 0.0012 | 0.0980 ± 0.0007 |
| $\gamma J/\psi$ | 0.917 | 0.4679 ± 0.0015 | 0.5634 ± 0.0017 | 0.3488 ± 0.0013 |
| $\gamma\psi(2S)$ | 2.063 | 0.6341 ± 0.0018 | 0.7020 ± 0.0019 | 0.5160 ± 0.0016 |

Table E.27: Reconstruction of background samples for the 3813 (Scan) data.

| 3815 (Scan) Reconstruction | | | | |
|----------------------------|---------------|-----------------------------------|-----------------------------------|-----------------------------------|
| Sample | σ [nb] | ϵ_{MC} (SHAD) [%] | ϵ_{MC} (LHAD) [%] | ϵ_{MC} (THAD) [%] |
| $D^0\bar{D}^0$ | 0.056 | 0.7424 ± 0.0019 | 0.8022 ± 0.0020 | 0.6068 ± 0.0017 |
| D^+D^- | 0.089 | 0.6157 ± 0.0018 | 0.6887 ± 0.0019 | 0.4969 ± 0.0016 |
| $\tau^-\tau^+$ | 2.829 | 0.1287 ± 0.0008 | 0.2809 ± 0.0012 | 0.0999 ± 0.0007 |
| $\gamma J/\psi$ | 0.914 | 0.4675 ± 0.0015 | 0.5635 ± 0.0017 | 0.3494 ± 0.0013 |
| $\gamma\psi(2S)$ | 2.034 | 0.6381 ± 0.0018 | 0.7048 ± 0.0019 | 0.5202 ± 0.0016 |

Table E.28: Reconstruction of background samples for the 3815 (Scan) data.

| 3822 (Scan) Reconstruction | | | | |
|----------------------------|---------------|-----------------------------------|-----------------------------------|-----------------------------------|
| Sample | σ [nb] | ϵ_{MC} (SHAD) [%] | ϵ_{MC} (LHAD) [%] | ϵ_{MC} (THAD) [%] |
| $D^0\bar{D}^0$ | 0.140 | 0.7442 ± 0.0019 | 0.8038 ± 0.0020 | 0.6097 ± 0.0017 |
| D^+D^- | 0.197 | 0.6176 ± 0.0018 | 0.6919 ± 0.0019 | 0.4992 ± 0.0016 |
| $\tau^-\tau^+$ | 2.859 | 0.1295 ± 0.0008 | 0.2813 ± 0.0012 | 0.1003 ± 0.0007 |
| $\gamma J/\psi$ | 0.902 | 0.4676 ± 0.0015 | 0.5651 ± 0.0017 | 0.3497 ± 0.0013 |
| $\gamma\psi(2S)$ | 1.920 | 0.6401 ± 0.0018 | 0.7064 ± 0.0019 | 0.5234 ± 0.0016 |

Table E.29: Reconstruction of background samples for the 3822 (Scan) data.

| 3832 (Scan) Reconstruction | | | | |
|----------------------------|---------------|-----------------------------------|-----------------------------------|-----------------------------------|
| Sample | σ [nb] | ϵ_{MC} (SHAD) [%] | ϵ_{MC} (LHAD) [%] | ϵ_{MC} (THAD) [%] |
| $D^0\bar{D}^0$ | 0.069 | 0.7469 ± 0.0027 | 0.8037 ± 0.0028 | 0.6122 ± 0.0025 |
| D^+D^- | 0.046 | 0.6209 ± 0.0025 | 0.6924 ± 0.0026 | 0.5009 ± 0.0022 |
| $\tau^-\tau^+$ | 2.887 | 0.1290 ± 0.0011 | 0.2796 ± 0.0017 | 0.1003 ± 0.0010 |
| $\gamma J/\psi$ | 0.888 | 0.4678 ± 0.0022 | 0.5634 ± 0.0024 | 0.3500 ± 0.0019 |
| $\gamma\psi(2S)$ | 1.799 | 0.6366 ± 0.0025 | 0.7046 ± 0.0027 | 0.5206 ± 0.0023 |

Table E.30: Reconstruction of background samples for the 3832 (Scan) data.

| 3839 (Scan) Reconstruction | | | | |
|----------------------------|---------------|-----------------------------------|-----------------------------------|-----------------------------------|
| Sample | σ [nb] | ϵ_{MC} (SHAD) [%] | ϵ_{MC} (LHAD) [%] | ϵ_{MC} (THAD) [%] |
| $D^0\bar{D}^0$ | 0.237 | 0.7435 ± 0.0027 | 0.8017 ± 0.0028 | 0.6102 ± 0.0025 |
| D^+D^- | 0.254 | 0.6168 ± 0.0025 | 0.6902 ± 0.0026 | 0.4991 ± 0.0022 |
| $\tau^-\tau^+$ | 2.914 | 0.1270 ± 0.0011 | 0.2759 ± 0.0017 | 0.0983 ± 0.0010 |
| $\gamma J/\psi$ | 0.877 | 0.4676 ± 0.0022 | 0.5631 ± 0.0024 | 0.3502 ± 0.0019 |
| $\gamma\psi(2S)$ | 1.716 | 0.6374 ± 0.0025 | 0.7059 ± 0.0027 | 0.5231 ± 0.0023 |

Table E.31: Reconstruction of background samples for the 3839 (Scan) data.

| 3849 (Scan) Reconstruction | | | | |
|----------------------------|---------------|-----------------------------------|-----------------------------------|-----------------------------------|
| Sample | σ [nb] | ϵ_{MC} (SHAD) [%] | ϵ_{MC} (LHAD) [%] | ϵ_{MC} (THAD) [%] |
| $D^0\bar{D}^0$ | 0.186 | 0.7440 ± 0.0027 | 0.8028 ± 0.0028 | 0.6087 ± 0.0025 |
| D^+D^- | 0.186 | 0.6195 ± 0.0025 | 0.6921 ± 0.0026 | 0.5007 ± 0.0022 |
| $\tau^-\tau^+$ | 2.939 | 0.1289 ± 0.0011 | 0.2773 ± 0.0017 | 0.1001 ± 0.0010 |
| $\gamma J/\psi$ | 0.862 | 0.4679 ± 0.0022 | 0.5612 ± 0.0024 | 0.3496 ± 0.0019 |
| $\gamma\psi(2S)$ | 1.604 | 0.6357 ± 0.0025 | 0.7041 ± 0.0027 | 0.5206 ± 0.0023 |

Table E.32: Reconstruction of background samples for the 3849 (Scan) data.

| 3855 (Scan) Reconstruction | | | | |
|----------------------------|---------------|-----------------------------------|-----------------------------------|-----------------------------------|
| Sample | σ [nb] | ϵ_{MC} (SHAD) [%] | ϵ_{MC} (LHAD) [%] | ϵ_{MC} (THAD) [%] |
| $D^0\bar{D}^0$ | 0.337 | 0.7467 ± 0.0019 | 0.8046 ± 0.0020 | 0.6116 ± 0.0017 |
| D^+D^- | 0.273 | 0.6188 ± 0.0018 | 0.6917 ± 0.0019 | 0.5006 ± 0.0016 |
| $\tau^-\tau^+$ | 2.967 | 0.1290 ± 0.0008 | 0.2785 ± 0.0012 | 0.1000 ± 0.0007 |
| $\gamma J/\psi$ | 0.853 | 0.4676 ± 0.0015 | 0.5621 ± 0.0017 | 0.3498 ± 0.0013 |
| $\gamma\psi(2S)$ | 1.545 | 0.6374 ± 0.0018 | 0.7049 ± 0.0019 | 0.5207 ± 0.0016 |

Table E.33: Reconstruction of background samples for the 3855 (Scan) data.

| 3863 (Scan) Reconstruction | | | | |
|----------------------------|---------------|-----------------------------------|-----------------------------------|-----------------------------------|
| Sample | σ [nb] | ϵ_{MC} (SHAD) [%] | ϵ_{MC} (LHAD) [%] | ϵ_{MC} (THAD) [%] |
| $D^0\bar{D}^0$ | 0.340 | 0.7476 ± 0.0019 | 0.8040 ± 0.0020 | 0.6123 ± 0.0017 |
| D^+D^- | 0.099 | 0.6191 ± 0.0018 | 0.6916 ± 0.0019 | 0.5006 ± 0.0016 |
| $\tau^-\tau^+$ | 2.988 | 0.1280 ± 0.0008 | 0.2763 ± 0.0012 | 0.1001 ± 0.0007 |
| $\gamma J/\psi$ | 0.843 | 0.4667 ± 0.0015 | 0.5620 ± 0.0017 | 0.3499 ± 0.0013 |
| $\gamma\psi(2S)$ | 1.476 | 0.6370 ± 0.0018 | 0.7054 ± 0.0019 | 0.5210 ± 0.0016 |

Table E.34: Reconstruction of background samples for the 3863 (Scan) data.

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Appendix F

Scan Data Signal Counts

| 3734 (Scan) Results | | | |
|---------------------|-------------------------|-------------------------|-------------------------|
| Sample | N_{had} (SHAD) | N_{had} (LHAD) | N_{had} (THAD) |
| Data | 12047 ± 109 | 13458 ± 116 | 9605 ± 98 |
| $q\bar{q}$ | 7942 ± 62 | 8743 ± 66 | 6314 ± 52 |
| $D^0\overline{D^0}$ | 100 ± 1 | 108 ± 1 | 81 ± 1 |
| D^+D^- | 0 ± 0 | 0 ± 0 | 0 ± 0 |
| $\tau^-\tau^+$ | 262 ± 1 | 579 ± 3 | 201 ± 1 |
| $\gamma J/\psi$ | 409 ± 2 | 494 ± 2 | 305 ± 1 |
| $\gamma\psi(2S)$ | 2802 ± 12 | 3096 ± 13 | 2285 ± 10 |
| Hadrons | 529 ± 126 | 435 ± 134 | 416 ± 111 |

Table F.1: Hadronic events selected in the 3734 (Scan) data.

| 3736 (Scan) Results | | | |
|---------------------|-------------------------|-------------------------|-------------------------|
| Sample | N_{had} (SHAD) | N_{had} (LHAD) | N_{had} (THAD) |
| Data | 4786 ± 69 | 5413 ± 73 | 3767 ± 61 |
| $q\bar{q}$ | 3144 ± 28 | 3460 ± 30 | 2500 ± 23 |
| $D^0\overline{D^0}$ | 52 ± 1 | 56 ± 1 | 42 ± 1 |
| D^+D^- | 0 ± 0 | 0 ± 0 | 0 ± 0 |
| $\tau^-\tau^+$ | 104 ± 1 | 229 ± 1 | 80 ± 1 |
| $\gamma J/\psi$ | 160 ± 1 | 194 ± 1 | 118 ± 1 |
| $\gamma\psi(2S)$ | 1060 ± 7 | 1171 ± 8 | 861 ± 6 |
| Hadrons | 263 ± 75 | 301 ± 80 | 162 ± 66 |

Table F.2: Hadronic events selected in the 3736 (Scan) data.

| 3744 (Scan) Results | | | |
|---------------------|-------------------------|-------------------------|-------------------------|
| Sample | N_{had} (SHAD) | N_{had} (LHAD) | N_{had} (THAD) |
| Data | 13426 ± 115 | 15255 ± 123 | 10823 ± 104 |
| $q\bar{q}$ | 9082 ± 72 | 9984 ± 78 | 7226 ± 61 |
| $D^0\bar{D}^0$ | 532 ± 2 | 577 ± 2 | 434 ± 1 |
| D^+D^- | 86 ± 1 | 97 ± 1 | 69 ± 1 |
| $\tau^-\tau^+$ | 304 ± 2 | 673 ± 3 | 235 ± 1 |
| $\gamma J/\psi$ | 457 ± 2 | 555 ± 2 | 339 ± 1 |
| $\gamma\psi(2S)$ | 2639 ± 11 | 2925 ± 12 | 2151 ± 9 |
| Hadrons | 322 ± 137 | 440 ± 146 | 366 ± 121 |

Table F.3: Hadronic events selected in the 3744 (Scan) data.

| 3748 (Scan) Results | | | |
|---------------------|-------------------------|-------------------------|-------------------------|
| Sample | N_{had} (SHAD) | N_{had} (LHAD) | N_{had} (THAD) |
| Data | 20024 ± 141 | 22788 ± 150 | 15815 ± 125 |
| $q\bar{q}$ | 13384 ± 105 | 14706 ± 113 | 10651 ± 90 |
| $D^0\bar{D}^0$ | 857 ± 3 | 931 ± 3 | 695 ± 2 |
| D^+D^- | 305 ± 1 | 344 ± 1 | 243 ± 1 |
| $\tau^-\tau^+$ | 447 ± 2 | 985 ± 4 | 343 ± 2 |
| $\gamma J/\psi$ | 668 ± 2 | 810 ± 2 | 497 ± 2 |
| $\gamma\psi(2S)$ | 3672 ± 13 | 4069 ± 14 | 2984 ± 11 |
| Hadrons | 688 ± 177 | 940 ± 189 | 398 ± 155 |

Table F.4: Hadronic events selected in the 3748 (Scan) data.

| 3750 (Scan) Results | | | |
|---------------------|-------------------------|-------------------------|-------------------------|
| Sample | N_{had} (SHAD) | N_{had} (LHAD) | N_{had} (THAD) |
| Data | 32171 ± 179 | 36551 ± 191 | 25686 ± 160 |
| $q\bar{q}$ | 21617 ± 168 | 23746 ± 180 | 17205 ± 144 |
| $D^0\bar{D}^0$ | 1616 ± 4 | 1750 ± 4 | 1318 ± 3 |
| D^+D^- | 611 ± 1 | 686 ± 1 | 490 ± 1 |
| $\tau^-\tau^+$ | 738 ± 3 | 1618 ± 5 | 571 ± 2 |
| $\gamma J/\psi$ | 1089 ± 3 | 1316 ± 3 | 810 ± 2 |
| $\gamma\psi(2S)$ | 5838 ± 16 | 6451 ± 17 | 4767 ± 14 |
| Hadrons | 659 ± 246 | 982 ± 263 | 522 ± 216 |

Table F.5: Hadronic events selected in the 3750 (Scan) data.

| 3751 (Scan) Results | | | |
|---------------------|-------------------------|-------------------------|-------------------------|
| Sample | N_{had} (SHAD) | N_{had} (LHAD) | N_{had} (THAD) |
| Data | 42694 ± 206 | 48594 ± 220 | 34040 ± 184 |
| $q\bar{q}$ | 28246 ± 219 | 31021 ± 234 | 22483 ± 188 |
| $D^0\bar{D}^0$ | 2687 ± 6 | 2915 ± 6 | 2186 ± 5 |
| D^+D^- | 1037 ± 2 | 1166 ± 2 | 830 ± 2 |
| $\tau^-\tau^+$ | 961 ± 3 | 2117 ± 5 | 742 ± 2 |
| $\gamma J/\psi$ | 1409 ± 3 | 1707 ± 4 | 1047 ± 2 |
| $\gamma\psi(2S)$ | 7401 ± 17 | 8204 ± 18 | 6010 ± 14 |
| Hadrons | 948 ± 301 | 1461 ± 322 | 739 ± 264 |

Table F.6: Hadronic events selected in the 3751 (Scan) data.

| 3753 (Scan) Results | | | |
|---------------------|-------------------------|-------------------------|-------------------------|
| Sample | N_{had} (SHAD) | N_{had} (LHAD) | N_{had} (THAD) |
| Data | 48035 ± 219 | 54668 ± 233 | 38460 ± 196 |
| $q\bar{q}$ | 31437 ± 244 | 34517 ± 262 | 25027 ± 210 |
| $D^0\bar{D}^0$ | 3344 ± 7 | 3623 ± 7 | 2720 ± 6 |
| D^+D^- | 1510 ± 3 | 1696 ± 3 | 1209 ± 2 |
| $\tau^-\tau^+$ | 1069 ± 3 | 2363 ± 6 | 824 ± 3 |
| $\gamma J/\psi$ | 1567 ± 3 | 1895 ± 4 | 1164 ± 3 |
| $\gamma\psi(2S)$ | 8055 ± 18 | 8918 ± 20 | 6547 ± 15 |
| Hadrons | 1049 ± 329 | 1652 ± 352 | 967 ± 288 |

Table F.7: Hadronic events selected in the 3753 (Scan) data.

| 3755 (Scan) Results | | | |
|---------------------|-------------------------|-------------------------|-------------------------|
| Sample | N_{had} (SHAD) | N_{had} (LHAD) | N_{had} (THAD) |
| Data | 49692 ± 222 | 56270 ± 237 | 39753 ± 199 |
| $q\bar{q}$ | 32437 ± 254 | 35604 ± 272 | 25826 ± 219 |
| $D^0\bar{D}^0$ | 3917 ± 8 | 4242 ± 9 | 3188 ± 7 |
| D^+D^- | 1655 ± 3 | 1860 ± 4 | 1329 ± 3 |
| $\tau^-\tau^+$ | 1116 ± 3 | 2457 ± 6 | 862 ± 3 |
| $\gamma J/\psi$ | 1610 ± 3 | 1948 ± 4 | 1199 ± 3 |
| $\gamma\psi(2S)$ | 8039 ± 17 | 8903 ± 19 | 6541 ± 15 |
| Hadrons | 915 ± 339 | 1253 ± 362 | 803 ± 296 |

Table F.8: Hadronic events selected in the 3755 (Scan) data.

| 3756 (Scan) Results | | | |
|---------------------|-------------------------|-------------------------|-------------------------|
| Sample | N_{had} (SHAD) | N_{had} (LHAD) | N_{had} (THAD) |
| Data | 57313 ± 239 | 64807 ± 254 | 46172 ± 214 |
| $q\bar{q}$ | 36748 ± 288 | 40333 ± 309 | 29261 ± 248 |
| $D^0\bar{D}^0$ | 4672 ± 10 | 5042 ± 10 | 3825 ± 8 |
| D^+D^- | 2176 ± 4 | 2437 ± 5 | 1754 ± 4 |
| $\tau^-\tau^+$ | 1287 ± 4 | 2809 ± 7 | 997 ± 4 |
| $\gamma J/\psi$ | 1844 ± 4 | 2222 ± 5 | 1380 ± 3 |
| $\gamma\psi(2S)$ | 9141 ± 20 | 10098 ± 22 | 7466 ± 17 |
| Hadrons | 1441 ± 375 | 1863 ± 401 | 1485 ± 328 |

Table F.9: Hadronic events selected in the 3756 (Scan) data.

| 3759 (Scan) Results | | | |
|---------------------|-------------------------|-------------------------|-------------------------|
| Sample | N_{had} (SHAD) | N_{had} (LHAD) | N_{had} (THAD) |
| Data | 66837 ± 258 | 75711 ± 275 | 53739 ± 231 |
| $q\bar{q}$ | 42080 ± 333 | 46166 ± 357 | 33513 ± 287 |
| $D^0\bar{D}^0$ | 6410 ± 12 | 6916 ± 13 | 5253 ± 10 |
| D^+D^- | 3260 ± 6 | 3647 ± 7 | 2627 ± 5 |
| $\tau^-\tau^+$ | 1474 ± 4 | 3241 ± 7 | 1145 ± 4 |
| $\gamma J/\psi$ | 2103 ± 4 | 2536 ± 5 | 1573 ± 3 |
| $\gamma\psi(2S)$ | 10067 ± 20 | 11112 ± 21 | 8234 ± 17 |
| Hadrons | 1439 ± 422 | 2090 ± 451 | 1391 ± 369 |

Table F.10: Hadronic events selected in the 3759 (Scan) data.

| 3762 (Scan) Results | | | |
|---------------------|-------------------------|-------------------------|-------------------------|
| Sample | N_{had} (SHAD) | N_{had} (LHAD) | N_{had} (THAD) |
| Data | 68538 ± 261 | 77492 ± 278 | 55377 ± 235 |
| $q\bar{q}$ | 42513 ± 341 | 46621 ± 365 | 33866 ± 294 |
| $D^0\bar{D}^0$ | 7945 ± 15 | 8570 ± 16 | 6508 ± 12 |
| D^+D^- | 4238 ± 8 | 4746 ± 9 | 3418 ± 7 |
| $\tau^-\tau^+$ | 1499 ± 4 | 3288 ± 7 | 1164 ± 3 |
| $\gamma J/\psi$ | 2111 ± 4 | 2545 ± 5 | 1577 ± 3 |
| $\gamma\psi(2S)$ | 9779 ± 19 | 10791 ± 20 | 7995 ± 16 |
| Hadrons | 449 ± 431 | 927 ± 460 | 846 ± 377 |

Table F.11: Hadronic events selected in the 3762 (Scan) data.

| 3765 (Scan) Results | | | |
|---------------------|-------------------------|-------------------------|-------------------------|
| Sample | N_{had} (SHAD) | N_{had} (LHAD) | N_{had} (THAD) |
| Data | 51719 ± 227 | 58419 ± 241 | 41736 ± 204 |
| $q\bar{q}$ | 31053 ± 253 | 34042 ± 272 | 24741 ± 218 |
| $D^0\bar{D}^0$ | 6617 ± 15 | 7135 ± 16 | 5423 ± 12 |
| D^+D^- | 3810 ± 9 | 4265 ± 9 | 3075 ± 7 |
| $\tau^-\tau^+$ | 1098 ± 4 | 2417 ± 7 | 854 ± 3 |
| $\gamma J/\psi$ | 1540 ± 3 | 1854 ± 4 | 1155 ± 3 |
| $\gamma\psi(2S)$ | 6939 ± 16 | 7656 ± 17 | 5679 ± 14 |
| Hadrons | 657 ± 341 | 1046 ± 364 | 804 ± 299 |

Table F.12: Hadronic events selected in the 3765 (Scan) data.

| 3767 (Scan) Results | | | |
|---------------------|-------------------------|-------------------------|-------------------------|
| Sample | N_{had} (SHAD) | N_{had} (LHAD) | N_{had} (THAD) |
| Data | 40038 ± 200 | 45288 ± 212 | 32311 ± 179 |
| $q\bar{q}$ | 23074 ± 192 | 25285 ± 206 | 18387 ± 165 |
| $D^0\bar{D}^0$ | 5629 ± 14 | 6065 ± 15 | 4613 ± 12 |
| D^+D^- | 3314 ± 8 | 3711 ± 9 | 2673 ± 7 |
| $\tau^-\tau^+$ | 825 ± 3 | 1808 ± 5 | 640 ± 2 |
| $\gamma J/\psi$ | 1140 ± 3 | 1374 ± 3 | 853 ± 2 |
| $\gamma\psi(2S)$ | 4994 ± 13 | 5509 ± 14 | 4088 ± 11 |
| Hadrons | 1058 ± 278 | 1534 ± 297 | 1053 ± 244 |

Table F.13: Hadronic events selected in the 3767 (Scan) data.

| 3771 (Scan) Results | | | |
|---------------------|-------------------------|-------------------------|-------------------------|
| Sample | N_{had} (SHAD) | N_{had} (LHAD) | N_{had} (THAD) |
| Data | 34012 ± 184 | 38173 ± 195 | 27356 ± 165 |
| $q\bar{q}$ | 19014 ± 161 | 20825 ± 173 | 15156 ± 138 |
| $D^0\bar{D}^0$ | 5106 ± 15 | 5504 ± 16 | 4185 ± 12 |
| D^+D^- | 3279 ± 10 | 3668 ± 11 | 2647 ± 8 |
| $\tau^-\tau^+$ | 683 ± 3 | 1501 ± 5 | 533 ± 2 |
| $\gamma J/\psi$ | 936 ± 3 | 1127 ± 3 | 702 ± 2 |
| $\gamma\psi(2S)$ | 3938 ± 12 | 4349 ± 13 | 3225 ± 10 |
| Hadrons | 1053 ± 246 | 1194 ± 262 | 904 ± 216 |

Table F.14: Hadronic events selected in the 3771 (Scan) data.

| 3774 (Scan) Results | | | |
|---------------------|-------------------------|-------------------------|-------------------------|
| Sample | N_{had} (SHAD) | N_{had} (LHAD) | N_{had} (THAD) |
| Data | 31457 ± 177 | 35438 ± 188 | 25241 ± 158 |
| $q\bar{q}$ | 17211 ± 148 | 18843 ± 159 | 13721 ± 127 |
| $D^0\bar{D}^0$ | 5038 ± 15 | 5431 ± 16 | 4126 ± 13 |
| D^+D^- | 3456 ± 10 | 3865 ± 12 | 2786 ± 9 |
| $\tau^-\tau^+$ | 623 ± 3 | 1367 ± 5 | 483 ± 2 |
| $\gamma J/\psi$ | 843 ± 2 | 1015 ± 3 | 630 ± 2 |
| $\gamma\psi(2S)$ | 3458 ± 10 | 3818 ± 11 | 2822 ± 9 |
| Hadrons | 825 ± 232 | 1095 ± 247 | 671 ± 204 |

Table F.15: Hadronic events selected in the 3774 (Scan) data.

| 3777 (Scan) Results | | | |
|---------------------|-------------------------|-------------------------|-------------------------|
| Sample | N_{had} (SHAD) | N_{had} (LHAD) | N_{had} (THAD) |
| Data | 31195 ± 176 | 35150 ± 187 | 25095 ± 158 |
| $q\bar{q}$ | 17165 ± 150 | 18785 ± 161 | 13688 ± 129 |
| $D^0\bar{D}^0$ | 5006 ± 16 | 5397 ± 17 | 4100 ± 13 |
| D^+D^- | 3464 ± 11 | 3875 ± 12 | 2794 ± 9 |
| $\tau^-\tau^+$ | 632 ± 3 | 1380 ± 5 | 492 ± 3 |
| $\gamma J/\psi$ | 838 ± 3 | 1009 ± 3 | 630 ± 2 |
| $\gamma\psi(2S)$ | 3329 ± 11 | 3675 ± 12 | 2723 ± 9 |
| Hadrons | 758 ± 233 | 1026 ± 248 | 665 ± 205 |

Table F.16: Hadronic events selected in the 3777 (Scan) data.

| 3780 (Scan) Results | | | |
|---------------------|-------------------------|-------------------------|-------------------------|
| Sample | N_{had} (SHAD) | N_{had} (LHAD) | N_{had} (THAD) |
| Data | 32426 ± 180 | 36485 ± 191 | 26084 ± 161 |
| $q\bar{q}$ | 18339 ± 161 | 20062 ± 173 | 14627 ± 138 |
| $D^0\bar{D}^0$ | 5011 ± 14 | 5398 ± 15 | 4114 ± 12 |
| D^+D^- | 3139 ± 9 | 3510 ± 10 | 2536 ± 8 |
| $\tau^-\tau^+$ | 672 ± 3 | 1477 ± 5 | 523 ± 2 |
| $\gamma J/\psi$ | 892 ± 2 | 1074 ± 3 | 669 ± 2 |
| $\gamma\psi(2S)$ | 3469 ± 10 | 3830 ± 11 | 2843 ± 9 |
| Hadrons | 900 ± 242 | 1130 ± 258 | 768 ± 213 |

Table F.17: Hadronic events selected in the 3780 (Scan) data.

| 3782 (Scan) Results | | | |
|---------------------|-------------------------|-------------------------|-------------------------|
| Sample | N_{had} (SHAD) | N_{had} (LHAD) | N_{had} (THAD) |
| Data | 34028 ± 184 | 38558 ± 196 | 27372 ± 165 |
| $q\bar{q}$ | 20194 ± 179 | 22082 ± 192 | 16109 ± 154 |
| $D^0\bar{D}^0$ | 4464 ± 12 | 4812 ± 13 | 3660 ± 10 |
| D^+D^- | 2938 ± 8 | 3283 ± 9 | 2373 ± 7 |
| $\tau^-\tau^+$ | 742 ± 3 | 1631 ± 5 | 576 ± 2 |
| $\gamma J/\psi$ | 979 ± 3 | 1178 ± 3 | 734 ± 2 |
| $\gamma\psi(2S)$ | 3717 ± 10 | 4107 ± 11 | 3037 ± 9 |
| Hadrons | 991 ± 258 | 1462 ± 275 | 878 ± 226 |

Table F.18: Hadronic events selected in the 3782 (Scan) data.

| 3786 (Scan) Results | | | |
|---------------------|-------------------------|-------------------------|-------------------------|
| Sample | N_{had} (SHAD) | N_{had} (LHAD) | N_{had} (THAD) |
| Data | 37498 ± 193 | 42325 ± 205 | 30190 ± 173 |
| $q\bar{q}$ | 23901 ± 214 | 26122 ± 229 | 19072 ± 184 |
| $D^0\bar{D}^0$ | 3793 ± 10 | 4086 ± 10 | 3112 ± 8 |
| D^+D^- | 2568 ± 7 | 2870 ± 7 | 2078 ± 5 |
| $\tau^-\tau^+$ | 890 ± 3 | 1940 ± 6 | 695 ± 3 |
| $\gamma J/\psi$ | 1150 ± 3 | 1384 ± 3 | 863 ± 2 |
| $\gamma\psi(2S)$ | 4236 ± 11 | 4677 ± 12 | 3468 ± 9 |
| Hadrons | 957 ± 289 | 1241 ± 309 | 898 ± 253 |

Table F.19: Hadronic events selected in the 3786 (Scan) data.

| 3789 (Scan) Results | | | |
|---------------------|-------------------------|-------------------------|-------------------------|
| Sample | N_{had} (SHAD) | N_{had} (LHAD) | N_{had} (THAD) |
| Data | 39308 ± 198 | 44415 ± 210 | 31651 ± 177 |
| $q\bar{q}$ | 26534 ± 239 | 28991 ± 256 | 21176 ± 206 |
| $D^0\bar{D}^0$ | 2874 ± 6 | 3096 ± 7 | 2358 ± 5 |
| D^+D^- | 2064 ± 5 | 2308 ± 5 | 1668 ± 4 |
| $\tau^-\tau^+$ | 989 ± 3 | 2162 ± 6 | 773 ± 3 |
| $\gamma J/\psi$ | 1273 ± 3 | 1532 ± 3 | 955 ± 2 |
| $\gamma\psi(2S)$ | 4607 ± 11 | 5084 ± 12 | 3773 ± 9 |
| Hadrons | 964 ± 311 | 1238 ± 332 | 944 ± 272 |

Table F.20: Hadronic events selected in the 3789 (Scan) data.

| 3792 (Scan) Results | | | |
|---------------------|-------------------------|-------------------------|-------------------------|
| Sample | N_{had} (SHAD) | N_{had} (LHAD) | N_{had} (THAD) |
| Data | 46626 ± 215 | 53085 ± 230 | 37384 ± 193 |
| $q\bar{q}$ | 33038 ± 300 | 36079 ± 322 | 26373 ± 259 |
| $D^0\bar{D}^0$ | 2416 ± 5 | 2604 ± 5 | 1979 ± 4 |
| D^+D^- | 1482 ± 3 | 1657 ± 3 | 1197 ± 2 |
| $\tau^-\tau^+$ | 1243 ± 4 | 2707 ± 7 | 964 ± 4 |
| $\gamma J/\psi$ | 1570 ± 3 | 1893 ± 4 | 1174 ± 3 |
| $\gamma\psi(2S)$ | 5543 ± 12 | 6120 ± 13 | 4526 ± 11 |
| Hadrons | 1330 ± 370 | 2020 ± 396 | 1166 ± 323 |

Table F.21: Hadronic events selected in the 3792 (Scan) data.

| 3797 (Scan) Results | | | |
|---------------------|-------------------------|-------------------------|-------------------------|
| Sample | N_{had} (SHAD) | N_{had} (LHAD) | N_{had} (THAD) |
| Data | 51348 ± 226 | 58331 ± 241 | 41249 ± 203 |
| $q\bar{q}$ | 37808 ± 349 | 41264 ± 373 | 30191 ± 300 |
| $D^0\bar{D}^0$ | 1693 ± 3 | 1825 ± 3 | 1388 ± 3 |
| D^+D^- | 1036 ± 2 | 1158 ± 2 | 837 ± 1 |
| $\tau^-\tau^+$ | 1427 ± 5 | 3118 ± 8 | 1112 ± 4 |
| $\gamma J/\psi$ | 1790 ± 4 | 2156 ± 4 | 1341 ± 3 |
| $\gamma\psi(2S)$ | 6119 ± 13 | 6755 ± 14 | 5005 ± 11 |
| Hadrons | 1471 ± 416 | 2050 ± 445 | 1372 ± 363 |

Table F.22: Hadronic events selected in the 3797 (Scan) data.

| 3800 (Scan) Results | | | |
|---------------------|-------------------------|-------------------------|-------------------------|
| Sample | N_{had} (SHAD) | N_{had} (LHAD) | N_{had} (THAD) |
| Data | 48859 ± 221 | 55719 ± 236 | 38965 ± 197 |
| $q\bar{q}$ | 36644 ± 342 | 39976 ± 367 | 29268 ± 295 |
| $D^0\bar{D}^0$ | 1235 ± 2 | 1333 ± 2 | 1010 ± 2 |
| D^+D^- | 583 ± 1 | 652 ± 1 | 470 ± 1 |
| $\tau^-\tau^+$ | 1395 ± 4 | 3051 ± 7 | 1081 ± 4 |
| $\gamma J/\psi$ | 1721 ± 3 | 2076 ± 4 | 1286 ± 3 |
| $\gamma\psi(2S)$ | 5748 ± 12 | 6354 ± 13 | 4686 ± 10 |
| Hadrons | 1530 ± 408 | 2273 ± 436 | 1160 ± 355 |

Table F.23: Hadronic events selected in the 3800 (Scan) data.

| 3802 (Scan) Results | | | |
|---------------------|-------------------------|-------------------------|-------------------------|
| Sample | N_{had} (SHAD) | N_{had} (LHAD) | N_{had} (THAD) |
| Data | 33032 ± 181 | 37538 ± 193 | 26268 ± 162 |
| $q\bar{q}$ | 25099 ± 238 | 27373 ± 255 | 20050 ± 205 |
| $D^0\bar{D}^0$ | 649 ± 1 | 700 ± 1 | 531 ± 1 |
| D^+D^- | 391 ± 1 | 438 ± 1 | 315 ± 1 |
| $\tau^-\tau^+$ | 963 ± 3 | 2103 ± 6 | 746 ± 3 |
| $\gamma J/\psi$ | 1177 ± 3 | 1418 ± 3 | 880 ± 2 |
| $\gamma\psi(2S)$ | 3871 ± 10 | 4280 ± 10 | 3161 ± 8 |
| Hadrons | 880 ± 300 | 1223 ± 320 | 582 ± 261 |

Table F.24: Hadronic events selected in the 3802 (Scan) data.

| 3807 (Scan) Results | | | |
|---------------------|-------------------------|-------------------------|-------------------------|
| Sample | N_{had} (SHAD) | N_{had} (LHAD) | N_{had} (THAD) |
| Data | 21499 ± 146 | 24410 ± 156 | 17234 ± 131 |
| $q\bar{q}$ | 16378 ± 159 | 17850 ± 171 | 13087 ± 137 |
| $D^0\bar{D}^0$ | 459 ± 1 | 495 ± 1 | 374 ± 1 |
| D^+D^- | 311 ± 1 | 349 ± 1 | 251 ± 1 |
| $\tau^-\tau^+$ | 632 ± 2 | 1377 ± 5 | 489 ± 2 |
| $\gamma J/\psi$ | 761 ± 2 | 918 ± 2 | 567 ± 1 |
| $\gamma\psi(2S)$ | 2427 ± 7 | 2688 ± 8 | 1980 ± 6 |
| Hadrons | 527 ± 217 | 729 ± 232 | 482 ± 190 |

Table F.25: Hadronic events selected in the 3807 (Scan) data.

| 3809 (Scan) Results | | | |
|---------------------|-------------------------|-------------------------|-------------------------|
| Sample | N_{had} (SHAD) | N_{had} (LHAD) | N_{had} (THAD) |
| Data | 15124 ± 122 | 17177 ± 131 | 12089 ± 109 |
| $q\bar{q}$ | 11655 ± 116 | 12699 ± 124 | 9315 ± 99 |
| $D^0\bar{D}^0$ | 217 ± 1 | 234 ± 1 | 177 ± 1 |
| D^+D^- | 102 ± 1 | 114 ± 1 | 82 ± 1 |
| $\tau^-\tau^+$ | 450 ± 2 | 986 ± 4 | 351 ± 2 |
| $\gamma J/\psi$ | 541 ± 2 | 652 ± 2 | 406 ± 1 |
| $\gamma\psi(2S)$ | 1705 ± 6 | 1885 ± 7 | 1395 ± 5 |
| Hadrons | 451 ± 169 | 605 ± 181 | 360 ± 148 |

Table F.26: Hadronic events selected in the 3809 (Scan) data.

| 3813 (Scan) Results | | | |
|---------------------|-------------------------|-------------------------|-------------------------|
| Sample | N_{had} (SHAD) | N_{had} (LHAD) | N_{had} (THAD) |
| Data | 10836 ± 104 | 12308 ± 110 | 8700 ± 93 |
| $q\bar{q}$ | 8323 ± 85 | 9063 ± 91 | 6653 ± 73 |
| $D^0\overline{D}^0$ | 39 ± 1 | 43 ± 1 | 32 ± 1 |
| D^+D^- | 84 ± 1 | 94 ± 1 | 67 ± 1 |
| $\tau^-\tau^+$ | 321 ± 2 | 703 ± 3 | 247 ± 1 |
| $\gamma J/\psi$ | 384 ± 1 | 463 ± 2 | 286 ± 1 |
| $\gamma\psi(2S)$ | 1173 ± 5 | 1298 ± 5 | 954 ± 4 |
| Hadrons | 509 ± 135 | 641 ± 144 | 456 ± 118 |

Table F.27: Hadronic events selected in the 3813 (Scan) data.

| 3815 (Scan) Results | | | |
|---------------------|-------------------------|-------------------------|-------------------------|
| Sample | N_{had} (SHAD) | N_{had} (LHAD) | N_{had} (THAD) |
| Data | 8159 ± 90 | 9190 ± 95 | 6536 ± 80 |
| $q\bar{q}$ | 6308 ± 66 | 6868 ± 71 | 5044 ± 56 |
| $D^0\overline{D}^0$ | 28 ± 1 | 30 ± 1 | 23 ± 1 |
| D^+D^- | 37 ± 1 | 41 ± 1 | 30 ± 1 |
| $\tau^-\tau^+$ | 247 ± 1 | 540 ± 3 | 192 ± 1 |
| $\gamma J/\psi$ | 290 ± 1 | 350 ± 1 | 217 ± 1 |
| $\gamma\psi(2S)$ | 883 ± 4 | 975 ± 4 | 719 ± 3 |
| Hadrons | 363 ± 112 | 383 ± 119 | 309 ± 99 |

Table F.28: Hadronic events selected in the 3815 (Scan) data.

| 3822 (Scan) Results | | | |
|---------------------|-------------------------|-------------------------|-------------------------|
| Sample | N_{had} (SHAD) | N_{had} (LHAD) | N_{had} (THAD) |
| Data | 4748 ± 68 | 5379 ± 73 | 3754 ± 61 |
| $q\bar{q}$ | 3695 ± 41 | 4019 ± 44 | 2956 ± 35 |
| $D^0\overline{D}^0$ | 41 ± 1 | 44 ± 1 | 34 ± 1 |
| D^+D^- | 48 ± 1 | 54 ± 1 | 39 ± 1 |
| $\tau^-\tau^+$ | 147 ± 1 | 321 ± 2 | 114 ± 1 |
| $\gamma J/\psi$ | 168 ± 1 | 203 ± 1 | 126 ± 1 |
| $\gamma\psi(2S)$ | 491 ± 2 | 542 ± 3 | 401 ± 2 |
| Hadrons | 154 ± 80 | 193 ± 86 | 81 ± 70 |

Table F.29: Hadronic events selected in the 3822 (Scan) data.

| 3832 (Scan) Results | | | |
|---------------------|-------------------------|-------------------------|-------------------------|
| Sample | N_{had} (SHAD) | N_{had} (LHAD) | N_{had} (THAD) |
| Data | 3364 ± 58 | 3842 ± 61 | 2729 ± 52 |
| $q\bar{q}$ | 2622 ± 31 | 2848 ± 34 | 2098 ± 26 |
| $D^0\overline{D}^0$ | 14 ± 1 | 15 ± 1 | 12 ± 1 |
| D^+D^- | 8 ± 1 | 9 ± 1 | 6 ± 1 |
| $\tau^-\tau^+$ | 105 ± 1 | 229 ± 1 | 82 ± 1 |
| $\gamma J/\psi$ | 118 ± 1 | 142 ± 1 | 88 ± 1 |
| $\gamma\psi(2S)$ | 326 ± 2 | 360 ± 2 | 266 ± 2 |
| Hadrons | 168 ± 66 | 236 ± 70 | 174 ± 58 |

Table F.30: Hadronic events selected in the 3832 (Scan) data.

| 3839 (Scan) Results | | | |
|---------------------|-------------------------|-------------------------|-------------------------|
| Sample | N_{had} (SHAD) | N_{had} (LHAD) | N_{had} (THAD) |
| Data | 3156 ± 56 | 3567 ± 59 | 2569 ± 50 |
| $q\bar{q}$ | 2574 ± 31 | 2793 ± 34 | 2061 ± 27 |
| $D^0\overline{D}^0$ | 49 ± 1 | 53 ± 1 | 40 ± 1 |
| D^+D^- | 43 ± 1 | 49 ± 1 | 35 ± 1 |
| $\tau^-\tau^+$ | 103 ± 1 | 225 ± 1 | 80 ± 1 |
| $\gamma J/\psi$ | 114 ± 1 | 138 ± 1 | 86 ± 1 |
| $\gamma\psi(2S)$ | 306 ± 2 | 339 ± 2 | 251 ± 1 |
| Hadrons | -36 ± 64 | -32 ± 68 | 13 ± 57 |

Table F.31: Hadronic events selected in the 3839 (Scan) data.

| 3849 (Scan) Results | | | |
|---------------------|-------------------------|-------------------------|-------------------------|
| Sample | N_{had} (SHAD) | N_{had} (LHAD) | N_{had} (THAD) |
| Data | 3266 ± 57 | 3738 ± 61 | 2603 ± 51 |
| $q\bar{q}$ | 2529 ± 32 | 2740 ± 34 | 2027 ± 27 |
| $D^0\overline{D}^0$ | 38 ± 1 | 41 ± 1 | 31 ± 1 |
| D^+D^- | 31 ± 1 | 35 ± 1 | 25 ± 1 |
| $\tau^-\tau^+$ | 104 ± 1 | 225 ± 1 | 81 ± 1 |
| $\gamma J/\psi$ | 111 ± 1 | 133 ± 1 | 83 ± 1 |
| $\gamma\psi(2S)$ | 281 ± 2 | 312 ± 2 | 230 ± 1 |
| Hadrons | 168 ± 65 | 249 ± 70 | 123 ± 57 |

Table F.32: Hadronic events selected in the 3849 (Scan) data.

| 3855 (Scan) Results | | | |
|---------------------|-------------------------|-------------------------|-------------------------|
| Sample | N_{had} (SHAD) | N_{had} (LHAD) | N_{had} (THAD) |
| Data | 3640 ± 60 | 4097 ± 64 | 2905 ± 53 |
| $q\bar{q}$ | 2910 ± 36 | 3151 ± 39 | 2333 ± 31 |
| $D^0\overline{D^0}$ | 80 ± 1 | 86 ± 1 | 65 ± 1 |
| D^+D^- | 53 ± 1 | 60 ± 1 | 43 ± 1 |
| $\tau^-\tau^+$ | 122 ± 1 | 263 ± 1 | 94 ± 1 |
| $\gamma J/\psi$ | 127 ± 1 | 152 ± 1 | 95 ± 1 |
| $\gamma\psi(2S)$ | 314 ± 2 | 347 ± 2 | 256 ± 1 |
| Hadrons | 32 ± 70 | 35 ± 75 | 16 ± 62 |

Table F.33: Hadronic events selected in the 3855 (Scan) data.

| 3863 (Scan) Results | | | |
|---------------------|-------------------------|-------------------------|-------------------------|
| Sample | N_{had} (SHAD) | N_{had} (LHAD) | N_{had} (THAD) |
| Data | 3472 ± 58 | 3921 ± 62 | 2773 ± 52 |
| $q\bar{q}$ | 2732 ± 35 | 2955 ± 38 | 2191 ± 30 |
| $D^0\overline{D^0}$ | 76 ± 1 | 82 ± 1 | 62 ± 1 |
| D^+D^- | 18 ± 1 | 20 ± 1 | 14 ± 1 |
| $\tau^-\tau^+$ | 114 ± 1 | 247 ± 1 | 89 ± 1 |
| $\gamma J/\psi$ | 118 ± 1 | 142 ± 1 | 88 ± 1 |
| $\gamma\psi(2S)$ | 282 ± 1 | 312 ± 2 | 230 ± 1 |
| Hadrons | 129 ± 68 | 160 ± 73 | 94 ± 60 |

Table F.34: Hadronic events selected in the 3863 (Scan) data.

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