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

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Overview

Introduction

Really Quick Overview

Goal: Describe $\psi(3770) \to D\overline{D}$ cross section as a function of energy

- Measure parameters of the $\psi(3770)$ such as mass and decay width
- Investigate branching fraction of non-$D\overline{D}$ decays from $\psi(3770)$

How is that actually done?

- Examine collisions of e^+e^- tuned to energies near $\psi(3770)$ mass
- Identify $D\overline{D}$ production by subtracting backgrounds from total
- Fit to cross section using formula based on $M^{\psi(3770)}$, $\Gamma^{\psi(3770)}$, ...
- Use results to determine $\psi(3770)$ parameters and explore non-$D\overline{D}$

Why does this need to be done? ($D\overline{D}$ Cross Section)

- Previous experiments have provided conflicting results
  - Largely did not include effects from interference

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

- Those including interference found it necessary to properly fit results
  - Statistics available were insufficient to fully resolve discrepancy
  - BESIII has much larger data sample available over this region
- Our analysis follows similarly to KEDR collaboration procedure
  - Include interference between $\psi(3770)$ and nearby $\psi(2S)$ in fit shape

Why does this need to be done? (Non-$D\overline{D}$)

- Previous experiments have provided very conflicting results

$\Gamma(\psi(3770) \to \text{non-}D\overline{D})$ (BESII)	$\Gamma(\psi(3770) \to \text{non-}D\overline{D})$ (CLEO-C)
$(15.1 \pm 5.6 \pm 1.8)\%$	$(-3.3 \pm 1.4^{+6.6}_{-4.8})\%$

- Impossible to directly determine $q\bar{q}$ (uds) contribution at $\psi(3770)$
  - Cannot reliably be separated from $D\overline{D}$ decays
- Use extrapolation from lower energy points (below $\psi(2S)$)
  - Assume $e^+e^- \to q\bar{q}$ scales as function of energy ($1/s$)

(Another) Really Quick Overview

- Must reconstruct D candidates from decays into other particles
  - (lifetime of D) vs. (available energy) $\rightarrow$ (very small displacement)
  - Use analysis software to look for proper combinations of particles
- Model particle decays with computer simulations: Monte Carlo (MC)
  - Analyze decays mistakable for $D\overline{D}$ production (e.g., $e^+e^- \rightarrow \tau^+\tau^-$)
  - Determine rate of correct identification in $D\overline{D}$ samples
- Process data/MC identically and subtract backgrounds to get signal
  - Compare rate of data collisions (luminosity: $\mathcal{L}$) to get cross section (σ)
- Acceleration of charged particles incurs radiative effects
  - Initial State Radiation (ISR) reduces total energy before collisions
  - Requires correction to accurately describe production cross section

Theoretical Background

Fundamental Forces

1) Electromagnetic (QED)

- Responsible for attracting / repelling electrically charged objects
- Mediated by the massless photon (γ)
- Very precisely calculable using perturbation theory

2) Weak

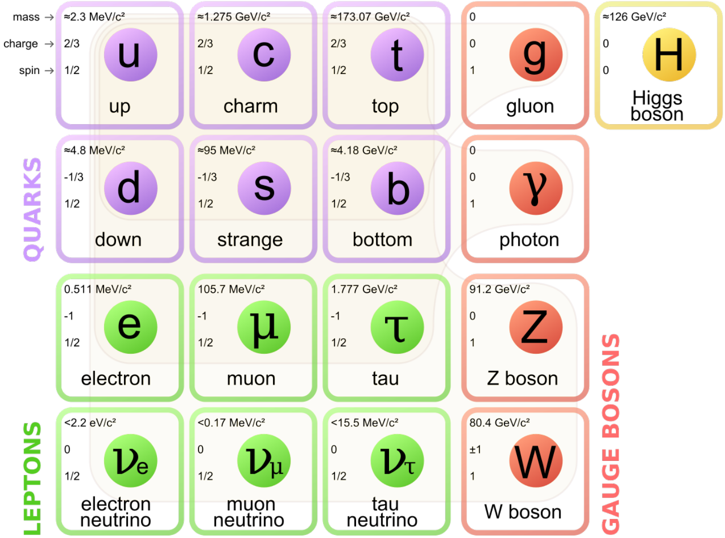
- Responsible for radioactive decays and flavor changes
- Mediated by the very heavy $W^{\pm}$ and Z
- Led to discovery of C and CP violation

3) Strong (QCD)

- Responsible for binding together hadrons
- Mediated by the massless gluon (g)
- Complicated calculations not described by perturbation theory

~~4) Gravity~~ *Negligible at this mass scale*

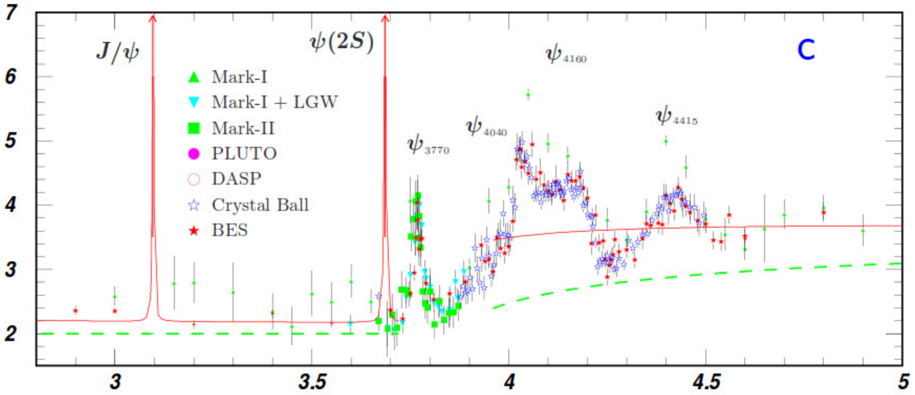
Standard Standard Model Slide



Charmonium

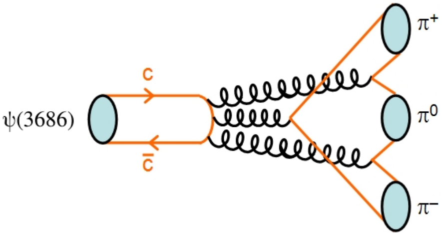
Resonances formed by a $c\bar{c}$ pair: J/ψ, $\psi(2S)$, $\psi(3770)$, ...

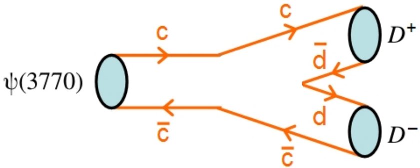
- $\psi(2S)$ and $\psi(3770)$ originally interpreted as excited states of J/ψ
- Evidence of mixed-states suggests more complicated picture



Decay Suppression (OZI Rule)

$\psi(2S)$ $\psi(3770)$





- Requires hard gluons for decay
- Very narrow decay width
  - $\Gamma_{\psi(2S)} = 0.286\,\mathrm{MeV}$

- Decays via open charm ($D\overline{D}$)
- Much wider decay width
  - $\Gamma_{\psi(3770)} = 27.5\,\mathrm{MeV}$

Addition of $D\overline{D}$ decays introduces drastically different behavior!

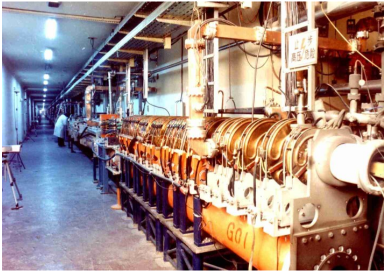
Accelerator and Detector

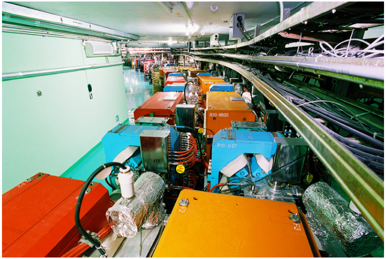
Institute of High Energy Physics (IHEP)

BESIII is hosted at the IHEP Campus located in Beijing, China

Accelerator - Beijing Electron-Positron Collider II (BEPCII)

1. Create positrons by firing electrons into stationary material
   - Generates high energy γs which interact with material to form e^+e^-
2. Separate newly created positrons magnetically
3. Accelerate positrons in linear accelerator and feed into storage ring
4. Accelerate electrons and feed into the oppositely circulating ring
   - Electrons readily available, so extraction from photons unnecessary
5. Focus each beam using magnets along storage rings until collision





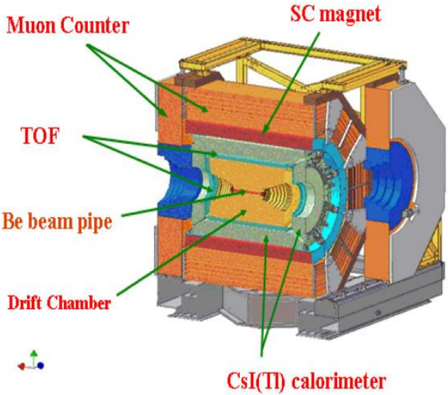
Detector - Beijing Spectrometer III (BESIII)

Collision of beams tuned to occur at central point of detector

- Beams angled during collision to improve integrated luminosity

Four main subdetector systems:

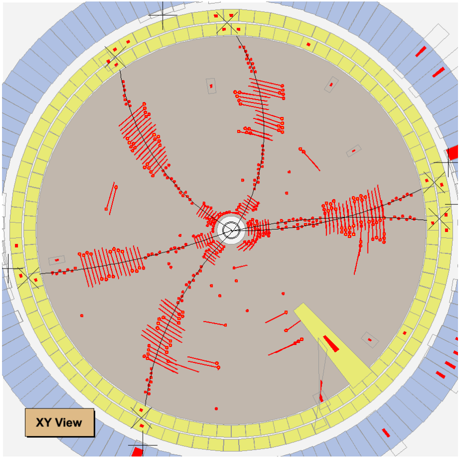
- Multi-Layer Drift Chamber
- Time-of-Flight
- Electromagnetic Calorimeter
- Muon Identifier



Multi-Layer Drift Chamber (MDC)

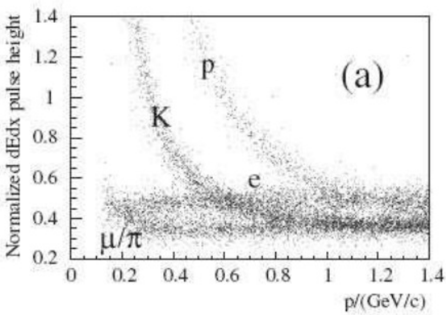
- Reconstruct charged tracks from interactions with sense wires (hits)
  - Wires surrounded by ionizable gas
  - Initial ionization due to particle triggers avalanche of electrons
  - High electric field near wires draws in released electrons to measure energy deposited
- Determine properties of particle from curvature in magnetic field
  - Radius determines momentum
  - Direction determines charge
- Energy deposition rate (dE/dx) helps determine particle candidate

BESIII Event Display

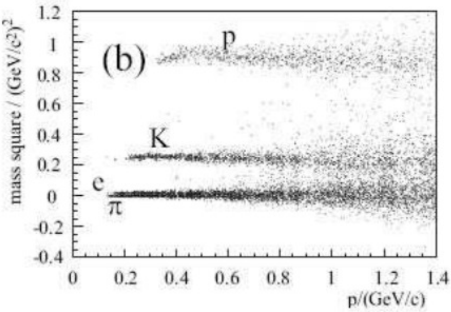


- Measure particle velocity using travel time after initial collision
  - Scintillator bands located at 0.81 m and 0.86 m from interaction point
  - Attached to photomultiplier tubes to measure light output
- Helps distinguish between $K^{\pm}$ and $\pi^{\pm}$ candidates at lower momenta
  - Combined with dE/dx measurements in MDC to set particle hypothesis

MDC Measurements

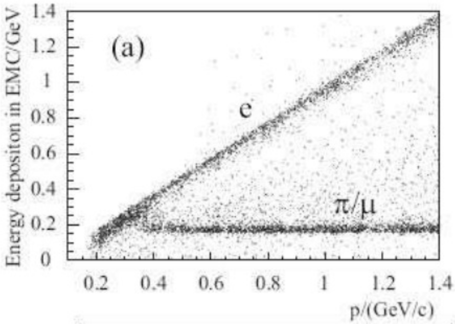


ToF Measurements



Electromagnetic Calorimeter (EMC)

- Measure energy deposited by electron and photon tracks
  - Other particles are generally relativistic and thereby minimum ionizing
    - These deposit relatively constant energy, independent of momenta
  - Use CsI(Tl) crystals attached to photodiodes to measure energy
    - Energy lost primarily in gaps of arrangement or out the back of crystals
- Allows reconstruction of purely neutral decays, such as $\pi^0 \to \gamma\gamma$



Muon Identifier (MUC)

- Identify tracks traversing through multiple layers as muons
  - Most particle types will be stopped before reaching the MUC
    - Electrons susceptible to Bremsstrahlung radiation
    - Kaons and pions susceptible to strong interactions
  - Requires muons with $p > 0.4\,\mathrm{GeV}$ for appropriate curvature

Triggering System

- Events filtered through two-step process
  - L1: Hardware - Extracts information from various subdetectors
    - MDC
      - Examines the number of superlayers each track passes through

        Superlayer: a collection of wires at same radial distance
      - Applies a cut on minimum transverse momentum for each
    - ToF
      - Examines number of hits in barrel and endcap regions
      - Checks for hits which are on opposite sides of the detector
    - EMC
      - Examines clustering of deposited energy around local maximum
  - L3: Software - Assembles information to decide if potentially relevant
- Quickly and efficiently removes non-physics background events
  - e.g., reduces beam-related backgrounds from $\sim$13 MHz to $\sim$1 kHz

Analysis Software

Monte Carlo Generation

- Create simulations of detector construction and particle interactions
  - Simulate material composition and detector response using GEANT4
  - Simulate particle decay behavior using physics generators
- Generate $D\overline{D}$ components to determine accuracy of reconstruction
  - Check how often generated decay matches reconstructed decay
- Generate decays which could be mistaken as $D\overline{D}$ in reconstruction
  $$e^+e^- \to \tau^+\tau^-, \quad e^+e^- \to \gamma\psi(2S), \quad e^+e^- \to q\bar{q}(uds), \quad \ldots$$
- Identify contributions of generated background samples seen in data
  - Subtract background components from data to estimate signal events

Data Processing

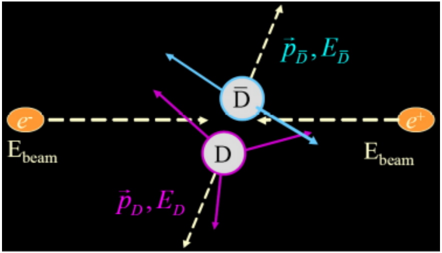
- Process samples using BESIII Offline Software System (BOSS)
  - Use information gathered by subdetectors to reconstruct events
  - Extract relevant physical parameters (E, p, $\ldots$) from each track
- Reconstruct D candidates using 'D-Tagging' process
  - Search over combinations of tracks to best match decay products
  - Take best set of tracks based on characteristics of tag

$$\Delta E = E_{\text{beam}} - E_{\text{tag}} \qquad m_{\text{BC}} = \sqrt{E_{\text{beam}}^2 - |\vec{p_{\text{tag}}}|^2}$$

- Treat both data and Monte Carlo (MC) samples identically

D-Tagging

- Reconstruct D candidates from decays
  $$D \to \{\pi^{\pm},\ K^{\pm},\ \pi^{0},\ K_S^{0}\}$$
- Modes selected based on reconstruction efficiency
  - High branching fractions
  - Manageable number of tracks (multiplicity)



Reconstructed Modes*	
(0)	$D^0 \to K^- \pi^+$
(1)	$D^0 \to K^- \pi^+ \pi^0$
(3)	$D^0 \to K^- \pi^+ \pi^+ \pi^-$
(200)	$D^+ \to K^- \pi^+ \pi^+$
(201)	$D^+ \to K^- \pi^+ \pi^+ \pi^0$
(202)	$D^+ \to K_S^0 \pi^+$
(203)	$D^+ \to K_S^0 \pi^+ \pi^0$
(204)	$D^+ \to K_S^0 \pi^+ \pi^+ \pi^-$
(205)	$D^+ \to K^+ K^- \pi^+$

*Charge conjugation implied

Measurement of the $D\overline{D}$ Cross Section

Overview for $D\overline{D}$ Cross Section

- Construct parametrization used to compare to measured data points
- List data samples with their luminosities / center-of-mass energies
- Describe signal and background component identification
- Show calculation of reconstruction efficiency for $D\overline{D}$ events
- Combine everything into cross section and discuss fitting procedure
- Assess systematic uncertainties from parameters used in analysis

Derivation of $\sigma(\psi(3770) \to D\overline{D})$

- Need to convert integral expression into measurable function
$$\sigma^{RC}_{D\overline{D}}(W) = \int z_{D\overline{D}}(W\sqrt{1-x})\,\sigma_{D\overline{D}}(W\sqrt{1-x})\,\mathcal{F}(x, W^2)\,dx$$
  - $z_{D\overline{D}}$: Coulomb interaction (D^+D^-) and mass constraints
  - $\sigma_{D\overline{D}}$: Born level (lowest order) cross section
  - $\mathcal{F}$: Initial State Radiation (ISR) correction [Kuraev and Fadin]
  - x: Fraction of energy radiated away
- Strategy: split into small intervals and numerically integrate
  - Treat $z_{D^+D^-}$ and $\sigma_{D\overline{D}}$ as constant in each interval
  - Integrate $\mathcal{F}(x, W^2) = \beta\, x^{\beta-1} F(W^2)$ over x
$$\beta = \frac{2\alpha}{\pi}(L-1), \qquad L = \log\left(\frac{W^2}{m_e^2}\right)$$
  - Obtain complicated, but calculable function for $D\overline{D}$ cross section

Form Factors

- Need to parameterize the form factor in the Born level cross section

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

- Comprised of resonant (R) and non-resonant (NR) components

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

- Resonant components parametrized by Breit-Wigner shape

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

- Non-resonant component has no definitive parametrization
  - Investigate two potential models for analysis
    - Exponential: generic form to approximate shape
    - Vector Dominance Model (VDM): physically based parameters

Form Factor Models

Exponential Model

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

- Fit Parameters
  - F_{NR}: Amplitude
  - a_{NR}: Width
- Used for systematic check

Vector Dominance Model

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

- Fit Parameters
  - $\Gamma^{\psi(2S)}$: Decay width for $\psi(2S)$*
  - F_0: Higher resonances ($\psi(4040)$)
- Used for final results
- Use $M^{\psi(3770)}$ in place of $M^{\psi(2S)}$
  - Avoid mass below $D\overline{D}$ threshold
  - *Unclear physical meaning

Data Samples

- Use scan data to determine overall cross section shape
  - Taken over $3.735\,\text{GeV} \leq E_{\text{cm}} \leq 3.870\,\text{GeV}$ and split into 34 bins
  - Chosen to be above $D^0\overline{D^0}$ threshold and below $D^{*0}\overline{D^0}$ threshold
  - Includes two bins below D^+D^- threshold which have zero production
  - Luminosity measured using $e^+e^- \to e^+e^-(\gamma)$ events ($\mathcal{L} = 69.80\,\text{pb}^{-1}$)
- Use additional high statistics samples for comparison measurements

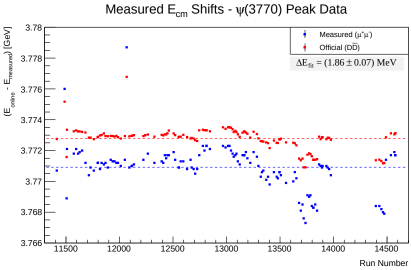
Name	E_{cm} [GeV]	$\mathcal{L}$
On-Peak $\psi(3770)^\dagger$	3.773	$2.93\,\text{fb}^{-1}$
XYZ-Scan	3.810	$50.54\,\text{pb}^{-1}$
R-Scan	3.850	$7.95\,\text{pb}^{-1}$

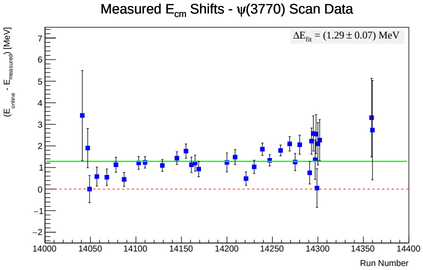
†Analysis of $D\overline{D}$ cross section performed independently

Center-of-Mass Energy

Accurate E_{cm} required for precise determination of $M^{\psi(3770)}$

- Measure E_{cm} using M_{inv} of 'On-Peak $\psi(3770)$' $e^+e^- \to \mu^+\mu^-$ events
- Compare results to separate, trustworthy procedure using $D\overline{D}$ events
  - Difference in average values determines correction to $\mu^+\mu^-$ procedure
- Measure E_{cm} for scan data using $\mu^+\mu^-$ procedure
  - Shift values by correction from $D\overline{D}$ procedure to get final results





Monte Carlo Generation

- Generate MC samples to help identify signal and background rates
  - Signal: $\psi(3770) \to D^0\overline{D^0}$, $\psi(3770) \to D^+D^-$
  - Background: $q\bar{q}$, $\tau^+\tau^-$, $\gamma J/\psi$, $\gamma\psi(2S)$
  - Events per sample of $\sim 10^6$-10^7 depending on decay type
  - Decays simulated using run-dependent E_{cm} and accelerator conditions

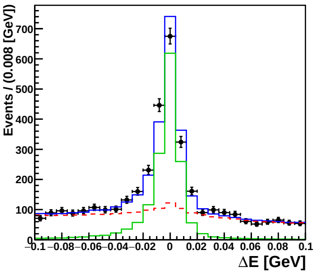
- Samples of $\psi(3770) \to D\overline{D}$ generated using our cross section results
  - Use Born cross section from final fit results to improve MC generator
  - Requires iteration of MC generation to properly reflect true shape
    - Performed five iterations of input shapes during analysis

Signal Determination

- Measure $D^0\overline{D^0}$ / D^+D^- yields separately with 2D fit
  - Extract ΔE and m_{BC} distributions and arrange MC samples into groups

    (1) Proper D-tags (3) $q\bar{q}$

    (2) Improper D-tags (4) $\tau^+\tau^- + \gamma J/\psi + \gamma\psi(2S)$
  - Float normalizations of each group to fit data distributions (χ^2)



Bin 14 - D^0
$3.774 \leq E_{cm}$ [GeV] < 3.777

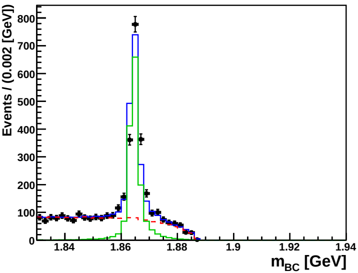
Total Events
3586

Signal
1569 ± 46

Background
2017 ± 302

Fit Status
SUCCESSFUL

χ^2 / D.o.F. = 818 / 643 = 1.27
CL = 0.000



Efficiency Correction

- Correct for D reconstruction efficiency to determine total production
  - Average MC candidate amounts (N_{prop} vs. N_{gen}) over decay modes

$$\epsilon_D = \sum_i \epsilon_{i\ \text{rec}}\, \mathcal{B}_i = \sum_i \left(\frac{N_{i\ \text{prop}}}{N_{i\ \text{gen}}} \right) \mathcal{B}_i$$

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

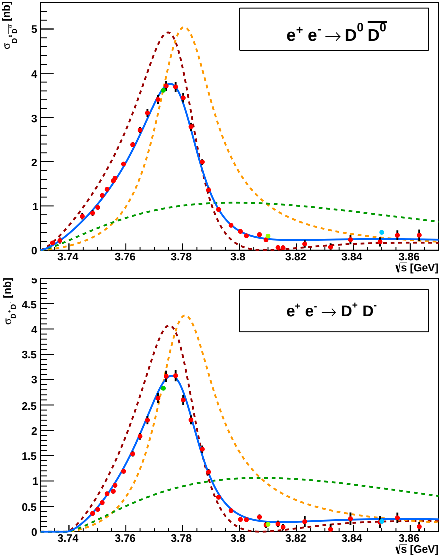
Cross Section Fitting

- Use signal amount, efficiency, and luminosity to find cross sections:
  - Include factor of 2 to correct for double counting (D vs. $D\overline{D}$)

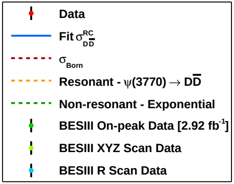
$$\sigma^{RC}_{D\overline{D}}(E_i) = \frac{N_D(E_i)}{2\,\epsilon_D(E_i)\,\mathcal{L}(E_i)}$$

- Fit to theoretical parametrization to determine $\psi(3770)$ parameters
  - $M^{\psi(3770)}$ $\Gamma^{\psi(3770)}$ $\Gamma_{ee}^{\psi(3770)\to D\overline{D}}$ $\phi^{\psi(3770)}$
  - Use $\Gamma_{ee}^{\psi(3770)\to D\overline{D}}$ in place of known $\mathcal{B}_{nD\overline{D}}$ or $\Gamma_{ee}^{\psi(3770)}$
- Two additional fit parameters depending on form factor choice
  - Exponential: F_{NR} a_{NR} VDM: $\Gamma^{\psi(2S)}$ F_0
- Minimize sum of χ^2 with simultaneous fit to D^0 and D^+

Exponential Results



Exponential Fit Results



$M^{\psi(3770)}$ = (3.7821 ± 0.0003)

$\Gamma^{\psi(3770)}$ = $(2.6004 \pm 0.0597) \times 10^{-2}$

$\Gamma^{\psi(3770)}_{ee}$ = $(2.3313 \pm 0.1016) \times 10^{-7}$

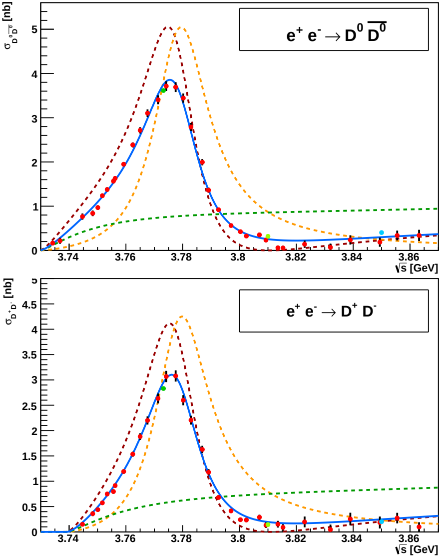
$\phi^{\psi(3770)}$ = (3.7455 ± 0.0388)

F_{NR} = $(2.0844 \pm 0.0752) \times 10$

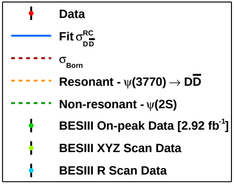
a_{NR} = $(4.2701 \pm 0.1336) \times 10^{-1}$

χ^2 / D.O.F. = 110 / 59 = 1.86

Vector Dominance Model Results



VDM Fit Results



$$M^{\psi(3770)} = (3.7808 \pm 0.0002)$$

$$\Gamma^{\psi(3770)} = (2.4098 \pm 0.0534) \times 10^{-2}$$

$$\Gamma^{\psi(3770)}_{ee} = (2.1583 \pm 0.0867) \times 10^{-7}$$

$$\phi^{\psi(3770)} = (3.6149 \pm 0.0435)$$

$$\Gamma^{\psi(2S)} = (1.1491 \pm 0.1236) \times 10^{-2}$$

$$F_0 = (-2.8845 \pm 0.4462)$$

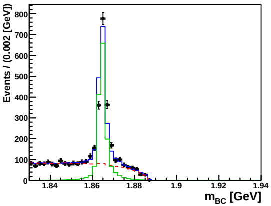
$$\chi^2 \text{ / D.O.F.} = 124 / 59 = 2.11$$

Results Overview

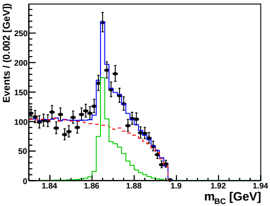
- Both form factor choices show generally good agreement
  - Excess in χ^2 largely due to two D^0 points just above 3.81 GeV
  - Could indicate need for improved model in higher energy region
- Values for $\psi(3770)$ parameters primarily dependent on peak region
  - Consistent shape in this region emphasizes quality of results
- Inteference related to behavior of Born level cross section
  - Reappearance of Born level events is strong indication of interference
  - Impossible to reproduce with two non-interfering Breit-Wigner shapes

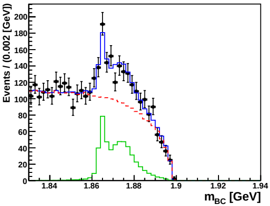
Born Level Event Contribution in m_{BC}

At $\psi(3770)$ Peak

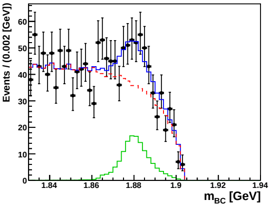


Approaching Born Minimum

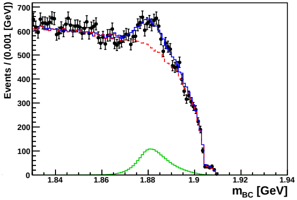




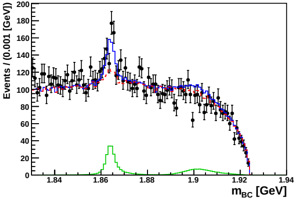
At Born Minimum



At (*XYZ*-Scan)

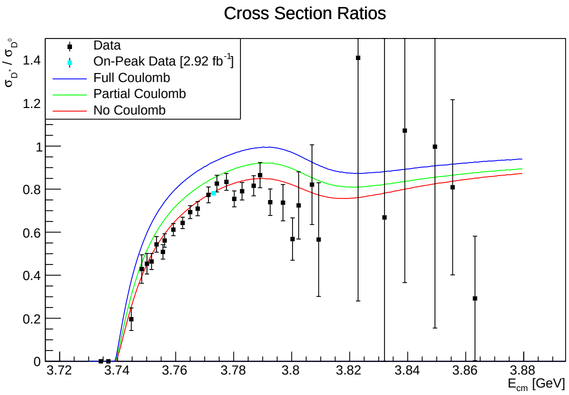


Above (*R*-Scan)



Coulomb Interaction

- Results shown previously use $z_{D^+D^-} = 1$ for calculations
  - Significantly worse results when including value for $z_{D^+D^-}$ $(\chi^2_r \approx 5)$
- Ratio of cross sections $(\sigma_{D^+}/\sigma_{D^0})$ prefers $z_{D^+D^-}$ value excluded
  - Unclear explanation for behavior, but consistent with $\Upsilon(4S) \to B\overline{B}$



Systematic Uncertainties

- Examine uncertainty from parameters involved throughout procedure
  - Individually increase / decrease value by the uncertainty of each
  - Re-fit cross section with altered values and take maximal variation
- Many uncertainties adjust overall scale of cross section normalization
  - Only affects the value of $\Gamma_{ee}^{\psi(3770)\to D\overline{D}}$

Name	Change	Description
Luminosity	$\mathcal{L}$	1.0 %
$\pi^{\pm}/K^{\pm}$ Tracking	$\epsilon_{i\ \mathrm{rec}}$	1.0 % per $\pi^{\pm}$ or $K^{\pm}$ in the mode
π^0 Tracking	$\epsilon_{i\ \mathrm{rec}}$	2.0 % per π^0 in the mode
K_S^0 Tracking	$\epsilon_{i\ \mathrm{rec}}$	1.5 % per K_S^0 in the mode
Single Tag Fits	N_D	Adjust by fit difference (small)
PDG Branching Fractions	$\epsilon_{i\ \mathrm{rec}}$	Adjust by PDG errors

Systematic Uncertainties

- **Meson Radii**
  - Adjust values of $R_{\psi(2S)}$ and $R_{\psi(3770)}$ by 25 % (from KEDR)
  - Take max variation over all four combinations of up / down on each
  - Most significant source of systematic uncertainty
- **MC Iteration** (negligible)
  - Take difference in parameters before / after Born level modification
- **MC ISR Generation** (negligible)
  - Take difference in fit results with KKMC vs. ConExc generators
- **Intermediate Resonances** (negligible)
  - Examine effects of $\rho^0 \to \pi^+\pi^-$ in the mode $D^+ \to K^- \pi^+ \pi^+$
  - Take difference in $K\pi$ vs. $\pi\pi$ invariant mass splits using 'On-Peak' data

Systematic Uncertainties

- Uncertainties summed in quadrature (assumed independent)

Systematic	$M^{\psi(3770)}$ [%]	$\Gamma^{\psi(3770)}$ [%]	$\Gamma_{ee}^{\psi(3770)\to D\bar{D}}$ [%]	$\phi^{\psi(3770)}$ [%]
Luminosity	0.000	0.004	1.005	0.014
$K^{\pm}/\pi^{\pm}$ 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
Total [%]	0.016	2.411	5.389	1.479

- Total contribution similar to statistical error for most parameters
  - Value for $M^{\psi(3770)}$ is small, but has very small statistical error

	$M^{\psi(3770)}$	$\Gamma^{\psi(3770)}$	$\Gamma_{ee}^{\psi(3770)\to D\bar{D}}$	$\phi^{\psi(3770)}$
$\sigma_{\text{sys}}/\sigma_{\text{stat}}$	3.000	1.088	1.342	1.229

Form Factor Uncertainty

- Notable discrepancy between choices of non-resonant form factor
  - Both methods provide reasonably good fit with data
  - Use difference of Exponential and VDM fit values as uncertainty
  - Follow example of KEDR by treating as model-dependent uncertainty

Form Factor	$M^{\psi(3770)}$ [GeV]	$\Gamma^{\psi(3770)}$ [MeV]	$\Gamma_{ee}^{\psi(3770)\to D\overline{D}}$ [eV]	$\phi^{\psi(3770)}$ [°]
Exponential	3.7821	26.004	233.13	214.60
VDM	3.7808	24.098	215.83	207.12
Difference	0.0013	1.906	17.30	7.48

Final Results

- Results not limited by statistics, but by model-dependency

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

Errors are statistical, systematic, and model-dependent, respectively

- Results consistent with KEDR and very inconsistent with PDG

Method	$M^{\psi(3770)}$ [MeV]	$\Gamma^{\psi(3770)}$ [MeV]	$\Gamma_{ee}^{\psi(3770) \to D\overline{D}}$ [eV]
Exponential	$3782.1 \pm 0.3 \pm 0.6 \pm 1.3$	$26.0 \pm 0.6 \pm 0.7 \pm 1.9$	$233 \pm 10 \pm 13 \pm 17$
VDM	$3780.8 \pm 0.2 \pm 0.6 \pm 1.3$	$24.1 \pm 0.6 \pm 0.6 \pm 1.9$	$216 \pm 9 \pm 12 \pm 17$
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	$[262 \pm 18] \times \mathcal{B}_{D\overline{D}}$

Exploration of the Non-$D\overline{D}$ Branching Fraction

Overview for Non-$D\overline{D}$ Branching Fraction

- List data samples with their luminosities / center-of-mass energies
- Detail event selection criteria and group cut methods
- Show hadronic signal counting fits and background subtraction
- Describe efficiency extrapolation using lower energy data points
- Examine procedure for $\psi(3770)$ data with $D\overline{D}$ component
- Investigate alternative expressions for the $\psi(2S)$ cross section

Data Samples

- Use data from continuum (Old/New) and $\psi(3770)$ (R1/R2)
  - Begin with continuum data and use to extrapolate to $\psi(3770)$ data

- $E_{\rm cm}$ measured as before
  - 4-6 MeV shift in new continuum samples
  - No shift for old continuum samples

Sample Name	$E_{\rm cm}$ [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

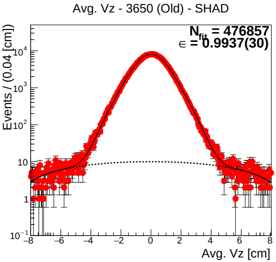
- Requires precise $E_{\rm cm}$ measurement for extrapolation procedure
  - Cross section of $\psi(2S)$ rapidly changes near its peak

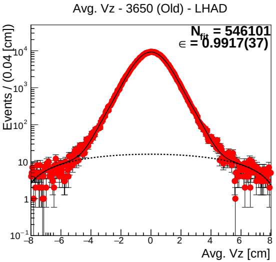
Event Selection Criteria

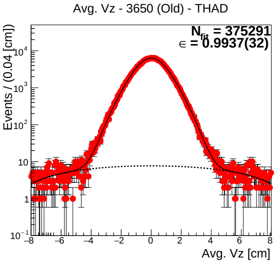
- Apply cuts on charged (neutral) tracks in the MDC (EMC)
- Apply cuts on highest energy / momentum
  - Removes $e^+e^- \to \{e^+e^-, \gamma\gamma\}$ backgrounds
- Apply groups of cuts to select multihadron events
  - Number of Tracks
  - Visible Energy
  - Visible Momentum (z-direction)
  - Max Shower Energy
  - Total Shower Energy
- Values for group cuts dependent on level of impact
  - Standard (SHAD), Loose (LHAD), Tight (THAD)

Signal Counting

- Identify events using average distance of closest approach in z (V_z)
  - Signal tracks will originate within few cm of vertex
  - Background tracks can originate away from collision point
- Fit with a double Gaussian (sig) + 2nd-order polynomial (bkg) shape







Background Subtraction

- Need to determine background contributions seen in data

$$N_{\text{had}} = \mathcal{L} \times \sigma \times \epsilon_{\text{MC}} = \mathcal{L} \times \sigma \times \left(\frac{N_{\text{rec}}}{N_{\text{gen}}} \right)$$

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

†Contribution from $\psi(2S)$ assumes standard Breit-Wigner shape

Background Subtraction

- Subtract backgrounds from total data events to get signal hadrons
  - Ignore negligible samples for extrapolation $\{e^+e^-, \mu^+\mu^-, \gamma\gamma\}$

3650 (Old) Results

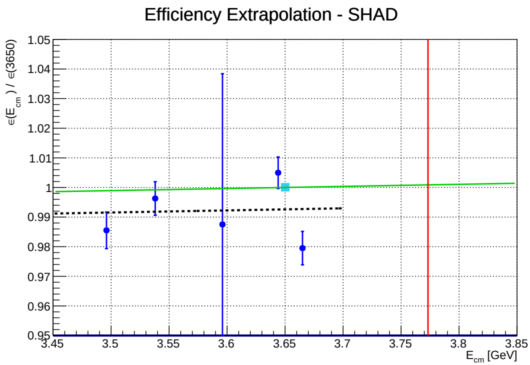
Sample	N_{had} (SHAD)	N_{had} (LHAD)	N_{had} (THAD)
Data	477001 ± 691	546546 ± 739	375380 ± 613
e^+e^{-*}	149 ± 43	187 ± 48	12 ± 12
$\mu^+\mu^{-*}$	8 ± 1	11 ± 1	7 ± 1
$\tau^+\tau^-$	10490 ± 30	23514 ± 59	8122 ± 25
$\gamma J/\psi$	25658 ± 60	30826 ± 71	19067 ± 46
$\gamma\gamma^*$	9 ± 2	10 ± 2	4 ± 1
2γ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

†Contribution from $\psi(2S)$ assumes standard Breit-Wigner shape

Efficiency Extrapolation

- Contribution of $q\bar{q}$ events above $D\overline{D}$ threshold not well modeled
  - Repeat procedure for new continuum data to extrapolate

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



Procedure for $\psi(3770)$ Data

- Repeat procedure for $\psi(3770)$ data samples
  - Use extrapolation to determine $q\bar{q}$ background contribution
- Modify included backgrounds to account for $D\overline{D}$ threshold
  - Use measurement of $\psi(3770) \to D\overline{D}$ cross section for $D\overline{D}$ component
    - Use measurement from 'On-Peak' sample for initial exploration
  - Switch direct contribution from $\psi(2S)$ to radiative decays $(\gamma\psi(2S))$
    - Use measurements from CLEO-c and BESIII for cross section value
  - Neglect 2γ events due to minimal contribution in this region
- Need data-driven procedure to correctly determine $D\overline{D}$ efficiencies
  - MC samples unreliable at modeling track multiplicities
  - Re-weight MC samples based off differences seen in data
    - Scale by track multiplicity ratios for data / MC

$D\overline{D}$ Efficiency Correction

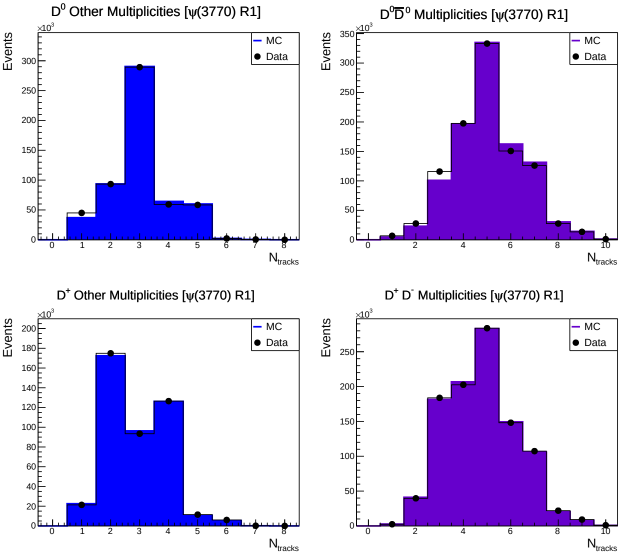
Group	Multiplicity
SHAD	$N_{\text{tracks}} > 2$
LHAD	$N_{\text{tracks}} > 1$
THAD	$N_{\text{tracks}} > 3$

$\psi(3770)$ R1 - D^0

Group	$(\epsilon_{\text{Data}}/\epsilon_{\text{MC}})$
SHAD	0.9751
LHAD	0.9930
THAD	0.9662

$\psi(3770)$ R1 - D^+

Group	$(\epsilon_{\text{Data}}/\epsilon_{\text{MC}})$
SHAD	0.9992
LHAD	1.0018
THAD	1.0064



Hadronic Counts - $\psi(3770)$ (R1)

$\psi(3770)$ (R1) Reconstruction

Sample	σ [nb]	ϵ_{MC} (SHAD) [%]	ϵ_{MC} (LHAD) [%]	ϵ_{MC} (THAD) [%]
$D^0\overline{D^0}$	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

$\psi(3770)$ (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
$D^0\overline{D^0}$	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

Initial Exploration of $\psi(3770)$ Data

- Convert hadronic signal to non-$D\overline{D}$ cross section
  - Assume efficiency is similar to that for $\gamma\psi(2S)$ decays

$$\sigma(\psi(3770) \to \text{non-}D\overline{D}) = \frac{N_{\text{non-}D\overline{D}}}{\epsilon_{\text{non-}D\overline{D}} \times \mathcal{L}}$$

Sample	$\sigma_{\text{non-}D\overline{D}}$ (SHAD)	$\sigma_{\text{non-}D\overline{D}}$ (LHAD)	$\sigma_{\text{non-}D\overline{D}}$ (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

- Likely overestimated due to assumption of Breit-Wigner for $\psi(2S)$

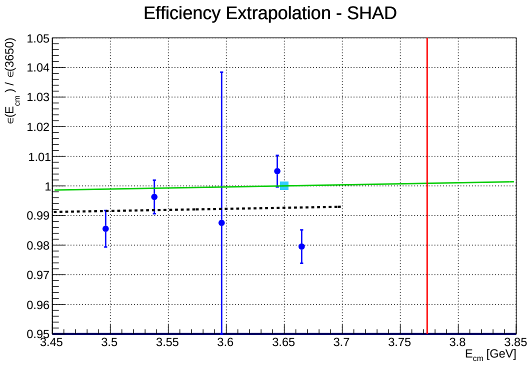
- Convert cross section to branching fraction using $D\overline{D}$ measurements

$$\Gamma(\psi(3770) \to \text{non-}D\overline{D}) = \frac{\sigma(\psi(3770)\to\text{non-}D\overline{D})}{\sigma(\psi(3770)\to D\overline{D}) + \sigma(\psi(3770)\to\text{non-}D\overline{D})}$$

Begin exploratory analysis - NOT OFFICIAL MEASUREMENTS

Investigation I: Standard Breit-Wigner for $\psi(2S)$

- $\psi(2S)$ calculated as standard Breit-Wigner
- Significant drop in last point of efficiency ratio
- Upper bound for branching fraction



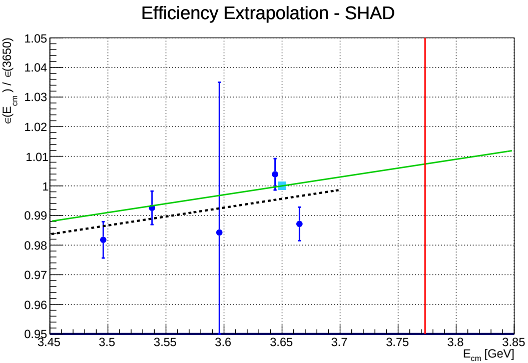
Sample	$BF_{\text{non-}D\overline{D}}$ (SHAD)	$BF_{\text{non-}D\overline{D}}$ (LHAD)	$BF_{\text{non-}D\overline{D}}$ (THAD)
$\psi(3770)$ (R1)	0.1331 ± 0.0183	0.1534 ± 0.0185	0.1334 ± 0.0190
$\psi(3770)$ (R2)	0.1444 ± 0.0186	0.1671 ± 0.0189	0.1474 ± 0.0193
Lum. Weighted	0.1408 ± 0.0185	0.1627 ± 0.0187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

Investigation II: Continuum Ratio Estimation

- $\psi(2S)$ approximated by

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

- Use $\sigma_{\psi(2S)}$ from BESIII
  - $\delta_{E_{\text{cm}}} \approx 1.5\,\text{MeV}$
- Estimated value for branching fraction



Sample	$BF_{\text{non-}D\overline{D}}$ (SHAD)	$BF_{\text{non-}D\overline{D}}$ (LHAD)	$BF_{\text{non-}D\overline{D}}$ (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

Investigation III: No $\psi(2S)$ Contribution

- $\psi(2S)$ ignored
- Inaccurate assumption
- Lower bound for branching fraction

Sample	$BF_{\text{non-}D\overline{D}}$ (SHAD)	$BF_{\text{non-}D\overline{D}}$ (LHAD)	$BF_{\text{non-}D\overline{D}}$ (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

Conclusion

Conclusion

Result: Described $\psi(3770) \to D\overline{D}$ **cross section shape near** $\psi(3770)$

- Measured $\psi(3770)$ parameters more precisely than ever before
  - Form factor model choice still major source of uncertainty
- Found clear indication for needing interference (Born level shape)
  - Reappearance above minimum impossible for non-interfering shapes
  - Splitting of m_{BC} peaks further validates behavior seen
- Explored progress on non-$D\overline{D}$ branching fraction (no official results)
  - Determined rough bounds on value through simple assumptions
  - Precise $\psi(2S)$ cross section allows for quickly updated measurement
  - Data taking near $\psi(2S)$ planned by BESIII for next year

Backup Slides

Monte Carlo Generators

- KKMC
  - Used to model electroweak interactions: $e^+e^- \to f\bar{f} + (n)\gamma$
    $f = \{\mu^-,\ \tau^-,\ u,\ d,\ s,\ c,\ b\}$ and $(n)\gamma =$ (additional photons)
  - Decays $f\bar{f}$ pair based on involved fermions (TAUOLA, PYTHIA)
  - Takes into account initial- and final-state radiation (ISR / FSR)
    - For resonances, only handles ISR, then passes off γ^* to BesEvtGen
- BesEvtGen
  - Handles resonance decay as well as radiative effects
    - Reduced E_{cm} such that only lower mass resonances can be produced
- Babayaga
  - Used to model QED processes: $e^+e^- \to \{e^+e^-,\ \mu^+\mu^-,\ \gamma\gamma\}$
  - Very accurate results; estimated theoretical uncertainty of 0.1 %
    - High precision required for determination of integrated luminosity

Selection Cuts

$\pi^{\pm}$ and $K^{\pm}$ Selection

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

γ Selection

Min. Energy (Barrel)	$E_{\mathrm{EMC}} > 25\,\mathrm{MeV}$	$(\lvert\cos\theta\rvert < 0.80)$
Min. Energy (Endcap)	$E_{\mathrm{EMC}} > 50\,\mathrm{MeV}$	$(0.84 < \lvert\cos\theta\rvert < 0.92)$
TDC Timing	$(0 \leq t \leq 14) \times 50\,\mathrm{ns}$	

	$\pi^0 \to \gamma\gamma$ Selection	$K^0_S \to \pi^+\pi^-$ Selection
Nominal Mass	$115 < m_{\pi^0}[\mathrm{MeV}] < 150$	$487 < m_{K^0_S}[\mathrm{MeV}] < 511$
Fit Quality	$\chi^2 < 200$, Converged	$\chi^2 < 100$, Converged

Hadronic Selection Event Cuts

Vertex (xy)	$V_{xy} < 1\,\mathrm{cm}$
Vertex (z)	$\lvert Vz \rvert < 10\,\mathrm{cm}$
MDC Angle	$\lvert \cos\theta \rvert < 0.93$

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

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

Hadronic Selection Group Cuts (SHAD)

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	$0.25 < (E_{\text{EMC}}^{\text{tot}}/E_{\text{cm}}) < 0.75$ $0.15 < (E_{\text{EMC}}^{\text{tot}}/E_{\text{cm}}) < 0.75$	$(N_{\text{tracks}} = 3)$ $(N_{\text{tracks}} = 4)$

Hadronic Selection Group Cuts (LHAD)

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	$0.25 < (E_{\text{EMC}}^{\text{tot}}/E_{\text{cm}}) < 0.75$	$(N_{\text{tracks}} = 2, 3)$
	$0.15 < (E_{\text{EMC}}^{\text{tot}}/E_{\text{cm}}) < 0.75$	$(N_{\text{tracks}} = 4)$

Hadronic Selection Group Cuts (THAD)

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	$0.15 < (E_{\text{EMC}}^{\text{tot}}/E_{\text{cm}}) < 0.75$ $0.00 < (E_{\text{EMC}}^{\text{tot}}/E_{\text{cm}}) < 0.75$	$(N_{\text{tracks}} = 4)$ $(N_{\text{tracks}} = 5)$