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

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Overview

Introduction

Introduction

Describe basic meaning of $\psi(3770) \to D\overline{D}$ cross section

Previous Measurements

Show list of previous experimental results
Explain need for interference

Really Quick Overview

Describe need to measure decay products
Describe background subtraction
Describe getting counts to determine 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

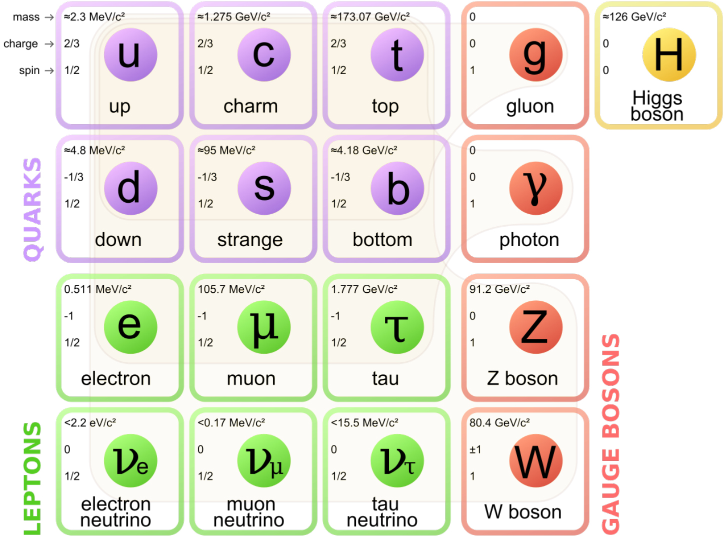
- Responsible for radioactive decays and flavor changes
- Mediated by the very heavy $W^{\pm}$ and Z
- Led to discovery of C and CP violation

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*

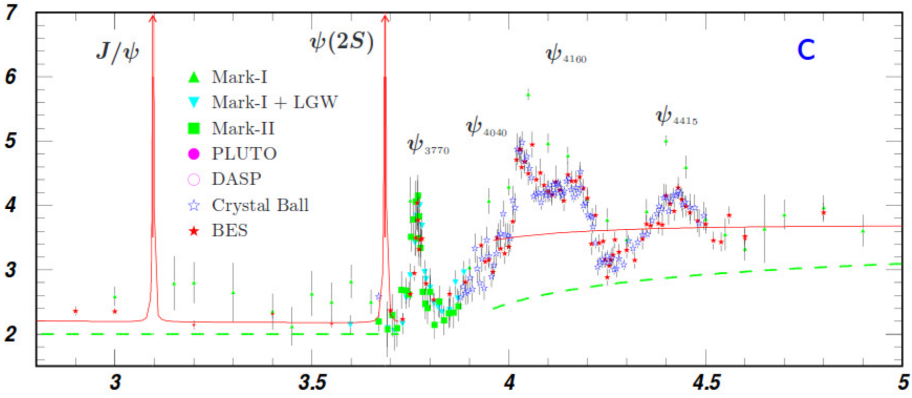
Standard Standard Model Slide



Charmonium

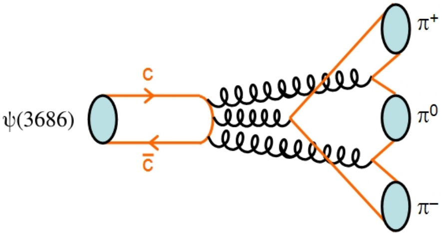
Resonances formed by a $c\bar{c}$ pair: J/ψ, $\psi(2S)$, $\psi(3770)$, ...

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

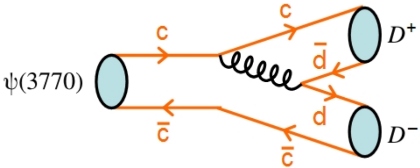


OZI Rule

$\psi(2S)$



$\psi(3770)$



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

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

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

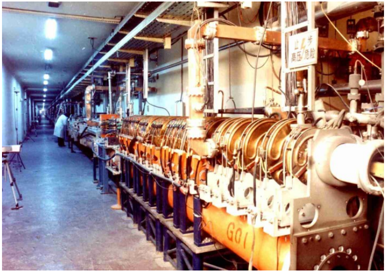
Accelerator and Detector

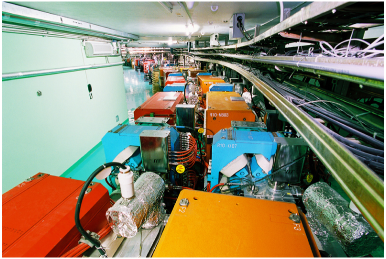
Institute of High Energy Physics (IHEP)

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





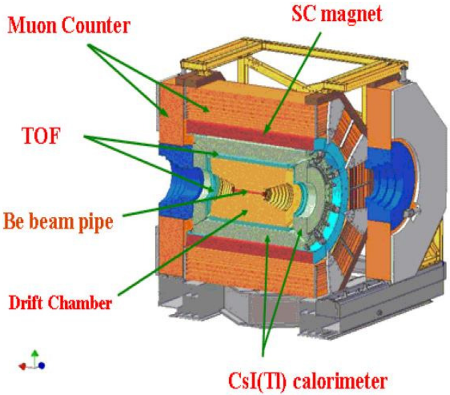
Detector - Beijing Spectrometer III (BESIII)

Collision of beams tuned to occur at central point of detector

- Beams angled during collision to improve integrated luminosity

Four main subdetector systems:

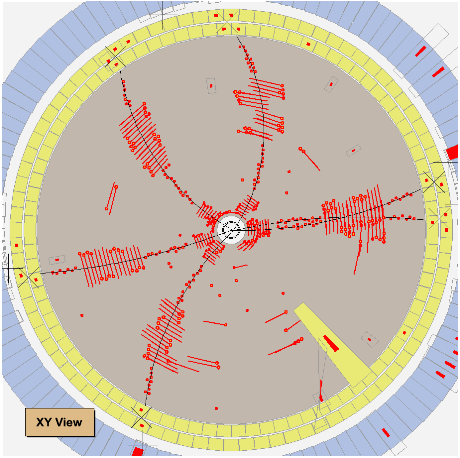
- Main Drift Chamber
- Time-of-Flight
- Electromagnetic Calorimeter
- Muon Identifier



Main 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

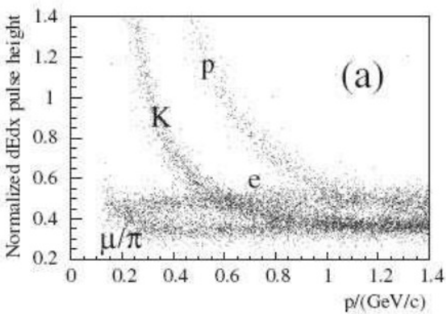
BESIII Event Display



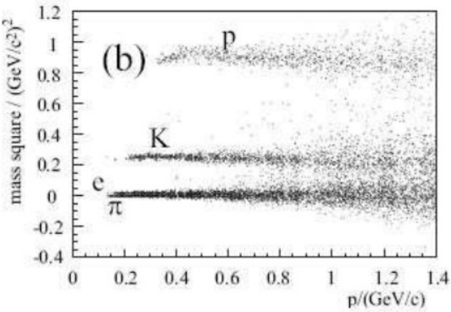
Time-of-Flight (ToF)

- 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

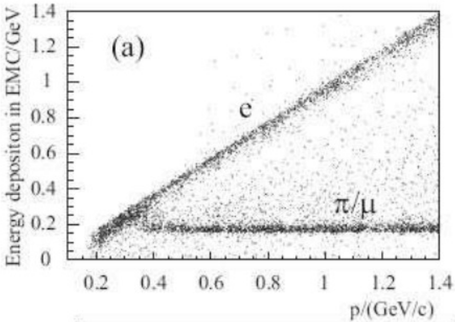


ToF Measurements



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 $p > 0.4\,\text{GeV}$ 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
  - Model material composition and detector arrangement in GEANT4
  - Simulate particle decay behavior using physics generators
  - Generate decays which could be mistaken as $D\overline{D}$ in reconstruction
    $$e^+e^- \to \tau^+\tau^-, \quad e^+e^- \to \gamma\psi(2S), \quad e^+e^- \to q\bar{q}, \quad \ldots$$
- Process samples using BESIII Offline Software System (BOSS)
  - Use information gathered by subdetectors to reconstruct events
  - Extract relevant physical parameters (ΔE, m_{BC}, $\ldots$) from each
- Identify contributions of generated background samples seen in data
  - Process both data and Monte Carlo (MC) samples identically
  - Subtract background components from data to determine signal events

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

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)
- Search through track combinations for those matching reconstructed modes
  - Take best set per mode based on
    $$\Delta E = |E_{\text{beam}} - E_{\text{tag}}|$$
    $$m_{\text{BC}} = \sqrt{E_{\text{beam}}^2 - |\vec{p_{\text{tag}}}|^2}$$
  - Allows multiple candidates per event

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

Selection Cuts

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

Vertex (xy)	$V_{xy} < 1\,\text{cm}$
Vertex (z)	$\lvert Vz \rvert < 10\,\text{cm}$
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)	$E_{\text{EMC}} > 25\,\text{MeV}$	$(\lvert \cos\theta \rvert < 0.80)$
Min. Energy (Endcap)	$E_{\text{EMC}} > 50\,\text{MeV}$	$(0.84 < \lvert \cos\theta \rvert < 0.92)$
TDC Timing	$(0 \leq t \leq 14) \times 50\,\text{ns}$	

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

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

Procedure

Derive theoretical model used to describe cross section
List data samples used for measurement
Determine E_{cm} and $\mathcal{L}$ for each data point
Identify signal and background components
Measure efficiency of reconstruction
Combine everything to determine cross section
Assess systematic uncertainties

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

Show derivation of cross section

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

Show derivation of cross section

Form Factors

Explain form factor choices and describe necessary modifications

Data Samples

Show scan data and describe usage $\psi(3770)$, R-scan, and XYZ-scan samples

Center-of-Mass Energy

Describe measurement and correction process

Luminosity

Describe measurement process

Monte Carlo Generation

List included MC samples and explain KKMC modification

Signal Determination

Describe process of 2D fitting to ΔE and m_{BC}
Show example results plot near $\psi(3770)$

Born Level Event Contribution

Show splitting of Born / ISR events in m_{BC}

Efficiency Correction

Describe process of averaging efficiency over all decay modes

CP Violation Correction

Quickly list process of correcting for CP

Cross Section Fitting

Describe procedure of obtaining $\psi(3770)$ parameters

Exponential Results

Show Exponential results

Vector Dominance Model Results

Show VDM results

Results Overview

Describe quality of fit and interference implication

Systematic Uncertainties

Describe process of measuring systematics

Systematics

Luminosity
$\pi^{\pm}/K^{\pm}$ Tracking
π^{0} Tracking
K_S^0 Tracking
Single Tag Fitting
PDG Branching Fractions
Meson Radii
*MC Iteration
*MC ISR Generation
*Intermediate Resonances

Model Dependent Systematic

Form Factor assumption

Final Results

Show final results with systematics
Compare to KEDR and PDG

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

Procedure

Event Selection
Hadron Cut Methods
Signal Counting Fits
MC Background Subtraction
Efficiency Extrapolation
$D\overline{D}$ Multiplicity Correction
Examination of Results for $\psi(3770)$ Data
Background Investigation
Examination of Results for Scan Data

Data Samples

Show 3650 Data Sets

Mention energy measurement

Event Selection

Charged Track Selection
Neutral Track Selection
Background Rejection

Hadronic Selection

Show SHAD, LHAD, and THAD cut tables

Signal Counting

Show signal counting fits for data

Background Subtraction

List MC samples considered (and note those excluded)
Relate to total number of hadrons found for future extrapolation

Efficiency Extrapolation

Repeat procedure for new continuum data

Extrapolate efficiency based on E_{cm}

Show extrapolation plots for SHAD, LHAD, and THAD

Procedure for $\psi(3770)$ Data

Repeat procedure for $\psi(3770)$ data
Introduction of new backgrounds and $D\overline{D}$ component

$D\overline{D}$ Correction

Create multiplicity distributions from single-tag events
Obtain correction factors for R1 and R2 separately
Example plots for D^0 and D^+ of R1

Reconstruction Efficiencies

Show example backgrounds for SHAD
Describe correction used for $\gamma\psi(2S)$ events
Point out cross sections used by Derrick for $\psi(3770)$ data

Initial Attempt - $\psi(3770)$ Data

Show cross section / branching fractions
Point out likely high values due to $\psi(2S)$ shape

Background Investigation - Part I

Describe alternate estimation for $\psi(2S)$ events
Show branching fraction results with estimation

Background Investigation - Part II

Describe alternate estimation ignoring $\psi(2S)$ events
Show branching fraction results with estimation

Procedure for Scan Data

Using best information available from $\psi(3770)$ results
Show hadronic cross section over region

Results for Scan Data

Show non-$D\overline{D}$ cross section over region
Show non-$D\overline{D}$ branching fraction over region

Conclusion

Conclusion

Show overview of measurements for $D\overline{D}$ cross section and non-$D\overline{D}$ branching fraction
List results of parameters for $\psi(3770)$
List branching fraction range for non-$D\overline{D}$