Anomalous line shapes of $\psi(3770)$ production & Inclusive decays for $\psi$'s $\rightarrow K^0/K^{*0} \ X$ from the BES-II

G. RONG

(For BES-II Collaboration)

Institute of High Energy of Physics, CAS, Beijing, China

Hadron 2009, FSU, Tallahassee, USA, 29 Nov.– 4 Dec., 2009
Outline

• Introduction

• Anomalous line shape of $\sigma_{e^+e^-\rightarrow hadrons}$

• Line shapes of $\sigma_{e^+e^-\rightarrow D\bar{D}}$

• Measurements of branching fractions for $J/\psi$, $\psi(3686)$ and $\psi(3770) \rightarrow K^0/K^{*0} X$

• Summary
What is the nature of $\psi(3770)$?

- **c\bar{c} bound state with S-D mixing**
  
  The charmonium model interprets $\psi(3770)$ as a $1^3D_1$ wave mixing with $2^3S_1$ wave. This is a popular interpretation.

- **Four quark states?**
  
  Some other models incorporate the $\psi(3770)$ as a p-wave resonance of 4-quark state.

- **How to identify the nature of $\psi(3770)$?**
  
  If $\psi(3770)$ is a pure c\bar{c} state, more than 98% of $\psi(3770)$ should decay to D\bar{D}, and the line shapes of cross sections for $e^+e^- \rightarrow$ hadron, $D^0\bar{D}^0$, $D^+D^-$, ... should be well described with one structure assumption.
Why so large $B[\psi(3770) \rightarrow \text{non-D}\overline{D}]$?

- BES-II measurements
  
  In assuming that there is only one simple $\psi(3770)$ structure in the range from 3.70 to 3.87 GeV, BES-II obtained:

  \[
  B[\psi(3770) \rightarrow D^+D^-]=(36.1\pm2.8)\% \\
  B[\psi(3770) \rightarrow D^0\overline{D}^0]=(48.7\pm3.2)\% \\
  B[\psi(3770) \rightarrow \text{non-D}\overline{D}]=(14.7\pm3.2)\% 
  \]

  This conflicts with theoretical prediction for the pure $c\bar{c}$ bound state!

- What does the large branching fraction indicate?
  1. More processes involved in $\psi(3770)$ decays
  2. $\psi(3770)$ is not a pure $c\bar{c}$ bound state
  3. Some new effects affect $\psi(3770)$ production and decay

- More precisely measuring line shapes for inclusive hadrons, inclusive any particle [$K^0, K^{*0}, \phi, \Lambda, J/\psi, \ldots$], and $D\overline{D}$ production can help understand the nature of $\psi(3770)$...
Inclusive decays for $\psi(3770) \rightarrow K^0/K^{*0} X$

- Measurements of the branching fractions for $\psi(3770) \rightarrow K^0/K^{*0} X$ can also help understand the nature of $\psi(3770)$

- By comparing $B[\psi(3770) \rightarrow K^0 X]$ with $B[D \rightarrow K^0 X]$, and the line shape for inclusive $K^0$ production and the one for inclusive hadron production, one can get some information about the nature of $\psi(3770)$

BES-II collaboration made some of these measurements with the data taken in the range from 3.65 to 3.89 GeV
BES-II/BEPC

BEPC

$E_{cm} \sim 2 - 5\ \text{GeV}$

$L_{peak} \sim 1 \times 10^{31}/\text{cm}^2\cdot\text{s}$

at $3.770\ \text{GeV}$

BEPC was shut down in 2004

The bird-view of Beijing Electron Positron Collider
Energy scan experiments

• **Scan in March 2003**
  \(~4 \text{ pb}^{-1}\) of energy scan data sample were taken at 49 energy points in the region between 3.65 GeV and 3.89 GeV

• **Scan in December 2003**
  \(~5 \text{ pb}^{-1}\) of energy scan data sample were taken at 67 energy points in the range from 3.665 to 3.878 GeV

• **Other data samples**
  Separated beam collision data at 3 energy points were collected to study beam associated background.
  
  Some J/\(\psi\) and \(\psi(2S)\) fast energy scan data samples were also collected to calibrate BEPC energy and determine \(\varepsilon_{\text{trg}}\)
Some data samples at BES-II

- about 17.3 pb⁻¹ data taken at 3.773 GeV
- about 6 pb⁻¹ data taken from 3.768 GeV to 3.778 GeV
- about 4 pb⁻¹ @ 3.665 to 3.878 GeV (Mar. 2003)
- about 5 pb⁻¹ @ 3.665 to 3.878 GeV (Dec. 2003)
  - about 6.5 pb⁻¹ data taken at 3.650 GeV
  - about 1 pb⁻¹ data taken at 3.665 GeV
  - about 1 pb⁻¹ data taken around 3.097 GeV
  - about 1 pb⁻¹ data taken around 3.686 GeV

For energy calibration

World ψ(3770) Samples

- pb⁻¹
- MARK-I DELCO MARK-II MARK-III BES-II CLEO-c

Cross section scan data

VC: \( \sigma_{xy} = 100 \, \mu m \) TOF: \( \sigma_T = 180 \, \text{ps} \) \( \mu \) counter: \( \sigma_{rb} = 3 \, \text{cm} \)
MDC: \( \sigma_{xy} = 220 \, \mu m \) BSC: \( \Delta E/\sqrt{E} = 22 \, \% \) \( \sigma_{ej} = 5.5 \, \text{cm} \)
\( \sigma_{dE/dx} = 8.5 \, \% \) \( \sigma_\phi = 7.9 \, \text{mr} \) B field: 0.4 T
\( \Delta p/p = 1.78\% \sqrt{1+p^2} \) \( \sigma_z = 3.1 \, \text{cm} \)
Monitoring of the energy

During the energy scan experiment in March 2003, the energy uncertainty of the BEPC is less than ±0.2 MeV.

During the energy scan experiment in December 2003, the uncertainty of the energy is less than ±0.4 MeV.

BEPC energy calibration
MC event generator & simulation

Full energy range ISR $e^+e^- \rightarrow \text{hadrons}$ Generator

Observed cross section for $e^+e^- \rightarrow$ hadrons

$$\sigma_{obs}^{had}(E_{cm}) = \frac{n_{had}}{L(E_{cm}) \varepsilon_{had}(E_{cm}) \varepsilon_{trg}}$$

Luminosities were measured by using large angle Bhabha scattering events.

Number of hadronic events were obtained by examining the distribution of the averaged $z$ of event vertex.

$N_b$ is physical background, which could be estimated based on the cross sections for different processes, luminosity and acceptance.
Expected cross sections for $e^+e^-\to\text{hadrons}$

$$\sigma_{\text{had}}^\text{expect}(s) = \int_0^{x_{\text{max}}} dx \ F(x,s) \ \sigma^B(s(1-x))$$

$\sigma^B(s)$ is Born order cross sections

$F(x,s)$ is sampling function

$$F(x,s) = \beta x^{\beta-1} \delta^{V+S} + \delta^H$$

$$\beta = \frac{2\alpha}{\pi} \left( \ln \frac{s}{m_c^2} - 1 \right)$$

$$\delta^{V+S} = 1 + \frac{3}{4} \beta + \frac{\alpha}{\pi} \left( \frac{\pi^2}{3} - \frac{1}{2} \right) - \frac{\beta^2}{24} \left( \frac{1}{3} \ln \frac{s}{m_c^2} + 2\pi^2 - \frac{37}{4} \right)$$

$$\delta^H = \delta_1^H + \delta_2^H$$

$$\delta_1^H = -\beta \left( 1 - \frac{x}{2} \right)$$

$$\delta_2^H = \frac{1}{8} \beta^2 \left[ 4(2-x) \ln \frac{1}{x} - \frac{1 + 3(1-x)^2}{x} \ln(1-x) - 6 - x \right]$$

Effective c.m. energy

Nominal c.m. energy

the electron equivalent radiator thickness

Kuraev & Fadin
Fit to the cross sections

The expected cross section for $e^+e^- \rightarrow$ hadrons:

$$\sigma_{\text{had}}^{\exp}(E_{\text{cm}}) = \sigma_{\text{Rs}(3770)}^{\exp}(E_{\text{cm}}) + \sigma_{J/\psi}^{\exp}(E_{\text{cm}}) + \sigma_{\psi(3686)}^{\exp}(E_{\text{cm}}) + \sigma_{\text{had}}^{\text{CTM}}(E_{\text{cm}})$$

$\text{Rs}(3770)$ means the full structure around 3.773 GeV, we use one or two pure P-wave Breit-Wigner amplitude with energy dependent total width to fit the data

$$\sigma_{\text{Rs}(3770)}^{\exp}(E_{\text{cm}}) = \left| A_1(E_{\text{cm}}) \right|^2 + \left| A_2(E_{\text{cm}}) \right|^2 \quad \text{solution 1}$$

$$\sigma_{\text{Rs}(3770)}^{\exp}(E_{\text{cm}}) = \left| A_1(E_{\text{cm}}) + e^{i\phi} A_2(E_{\text{cm}}) \right|^2 \quad \text{solution 2}$$

$$A_j(E_{\text{cm}}) = \frac{\sqrt{12\pi\Gamma^{ee}_j \Gamma^{\text{had}}_j}}{(E_{\text{cm}}^2 - M_j^2) + i\Gamma^{\text{tot}}_j(E_{\text{cm}})M_j} \quad j = 1, 2$$

$$\sigma_{\text{had}}^{\text{CTM}}(E_{\text{cm}}) = \sigma_{\text{LH}}^{\text{CTM}} + f \left[ \left( \frac{p_{D^0}}{E_{D^0}} \right)^3 \mathcal{G}_{00} + \left( \frac{p_{D^+}}{E_{D^+}} \right)^3 \mathcal{G}_{++} \right] \sigma_{\mu^+\mu^+}^{B}(E_{\text{cm}})$$
Anomalous line shape of cross sections

Solution 1: two amplitudes without interference

\[ \sigma_{R_s(3770)}^{\text{exp}} (E_{cm}) = |A_1 (E_{cm})|^2 + |A_2 (E_{cm})|^2 \]

Slopes of the observed cross sections at the two sides of the peak are quite different!

Green line is the fit with one \( \psi(3770) \) hypothesis

Red line is the fit with two amplitudes

Circles with error bars in red are the measured net cross sections after subtracting \( J/\psi, \psi(3686) \) and continuum contribution.

PRL101 (2008) 102004
Anomalous line shape of cross sections

Solution 2: two amplitudes with complete interference

\[ \sigma_{Rs(3770)}^{\text{exp}}(E_{\text{cm}}) = \left| A_1(E_{\text{cm}}) + e^{i\phi} A_2(E_{\text{cm}}) \right|^2 \]

Green line is the fit with one \( \psi(3770) \) hypothesis

Red line is the fit with two amplitudes

Circles with error bars in red are the measured net cross sections after subtracting \( J/\psi, \psi(3686) \) and continuum contribution.

Slopes of the observed cross sections at the two sides of the peak are quite different!
Anomalous line shape of cross sections

Solution 3: $\psi(3770)$ amplitude + $G(3900)$, with interference


Red line: Solution 3
Blue line: one $\psi(3770)$
Yellow line: Solution 1
Green line: Solution 2

The ratio of the residual between the observed cross section and the fitted value for one $\psi(3770)$ amplitude to the error of the observed cross section

$$\text{Ratio} = \frac{\sigma_{\text{obs}} - \sigma_{\text{one } \psi(3770)}}{\Delta \sigma_{\text{obs}}}$$
If no other effect distort the pure D-wave Breit-Weigner shape of the cross sections, these results indicate that there is likely a new structure additional to $\psi(3770)$ resonance around 3.773 GeV.
The observed cross section

\[ \sigma_{D^0 \bar{D}^0 (\text{or} \; D^+D^-)}^{\text{obs}} = \frac{N_{D^0_{\text{tag}} (\text{or} \; N_{D^+_{\text{tag}}})}}{2 \times L \times B \times \epsilon} \]

PLB 668 (2008) 263
Line shapes of cross sections for D$\bar{D}$ production

**PLB 668 (2008) 263**

hep-ph/0402171 M. B. Voloshin

**BES-II 結果**
Measurements of branching fractions for $J/\psi \rightarrow K^0/K^{*0} X$

In the fits to the observed cross sections for the $K^0/K^{*0}$ production, we fixed the resonance parameters of $J/\psi$ at the PDG08 values.

$$B(J/\psi \rightarrow K^0 X) = (23.0 \pm 0.5 \pm 1.5)\%$$

These results are preliminary!
Measurements of branching fractions for $\psi(3686) \rightarrow K^0/K^{*0} X$

In the fits to the observed cross sections, we fixed the resonance parameters of $\psi(3686)$ and $J/\psi$ at the PDG08 values.

$B[\psi(3686) \rightarrow K^0 X] = (28.3 \pm 0.7 \pm 2.9)\%$ \hspace{1cm} $B[\psi(3686) \rightarrow K^{*0} X] = (16.6 \pm 0.7 \pm 0.5)\%$

These results are preliminary!
Measurements of branching fractions for \( \psi(3770) \to K^0/K^{*0} X \)

In the fits to the observed cross sections, we fixed all resonance parameters of \( \psi(3770) \), \( \psi(3686) \) and \( J/\psi \) at the PDG08 values.

\[
BF(\psi(3770) \to K^0X) = (71.3 \pm 3.5 \pm 8.4)\% \quad BF(\psi(3770) \to K^{*0}X) = (23.1 \pm 3.1 \pm 2.5)\% \quad BF(\psi(3770) \to K^0X_{\text{non-DD}}) = (11.5 \pm 6.9 \pm 1.5)\%
\]

These results are preliminary!
Comparison of the measured branching fraction with those from PDG08

<table>
<thead>
<tr>
<th></th>
<th>BES-II (%)</th>
<th>PDG08 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi \to K^0X$</td>
<td>23.0 ± 0.5 ± 1.5</td>
<td>&lt; 10</td>
</tr>
<tr>
<td>$J/\psi \to K^{*0}X$</td>
<td>8.7 ± 0.5 ± 0.5</td>
<td></td>
</tr>
<tr>
<td>$\psi(3686) \to K^0X$</td>
<td>28.3 ± 0.7 ± 2.9</td>
<td>&lt; 7</td>
</tr>
<tr>
<td>$\psi(3686) \to K^{*0}X$</td>
<td>10.6 ± 0.7 ± 0.5</td>
<td></td>
</tr>
<tr>
<td>$\psi(3770) \to K^0X$</td>
<td>71.3 ± 2.5 ± 8.4</td>
<td>N/A</td>
</tr>
<tr>
<td>$\psi(3770) \to K^{*0}X$</td>
<td>23.1 ± 3.1 ± 2.5</td>
<td>N/A</td>
</tr>
<tr>
<td>$\psi(3770) \to K^0X</td>
<td>_{\text{non-}D\bar{D}}$</td>
<td>11.5 ± 6.9 ± 1.5</td>
</tr>
</tbody>
</table>

The values of PDG08 are the sum of the branching fractions for all exclusive decay modes of the resonance listed in PDG08.

BES-II results are preliminary!

$B[\psi(3770) \to D\bar{D}] \times B[D\bar{D} \to K^0X] = (65.7 \pm 5.1)\%$ (based on PDG08)

There are more rooms for searching for the modes of $J/\psi$ and $\psi(3686)$ decays containing $K^0/K^{*0}$ in final states.
Summary

- BES observed an anomalous line shape of $\sigma_{e^+e^-\rightarrow\text{hadrons}}$ in the range from 3.70 to 3.89 GeV, which indicates that
  1) either the conventional theories describing $\psi(3770)$ decays need to be improved
  2) or there are some new structure or new dynamics distorting the line shape of $\sigma_{e^+e^-\rightarrow\text{hadrons}}$.

- BES made the first measurements of the line shapes for $D^0\bar{D}^0$, $D^+D^-$, $D\bar{D}$ production in the range from 3.73 to 3.89 GeV

- BES made the first measurements of the branching fractions for $J/\psi$, $\psi(3686)$ and $\psi(3770) \rightarrow K^0X$ and $K^{*0}X$ after these were discovered for more than 32 years.
Thank You
Observation of a Resonance in $e^+ e^-$ Annihilation Just above Charm Threshold


Stanford Linear Accelerator Center and Department of Physics, Stanford University, Stanford, California 94305, and Lawrence Berkeley Laboratory and Department of Physics, University of California 94720, and Department of Physics and Astronomy, University of Illinois 60801, and Department of Physics and Astronomy, University of Hawaii, Honolulu, Hawaii 96822 (Received 27 June 1977)

We observe a resonance in the total cross section for hadron annihilation at a mass of $3772 \pm 6$ MeV/c$^2$ having a total width of $59 \pm 9$ MeV and a partial width to electron pairs of $370 \pm 90$ eV/c$^2$.

However, by mixing with an S state, it is normally assumed that the $^3D_1$ mixes primarily with the $^2S_1$, which is identified with the $\psi$. In the approximation in which only these two states mix, one can calculate from the data in Table I that the mixing angle is $23 \pm 3^\circ$.

Other explanations for the $\psi(3772)$, such as its being a four-quark state,$^{11}$ are conceivable, but are not required by the present data.

Reference

Anomalous Line Shape of Cross Sections

- initial state radiation
- DD production threshold
- the energy dependence of the DD scattering amplitudes due to the Blatt-Weisskopf barrier

One simple resonance hypothesis is quite questionable to fit the current data.
The Line Shapes of Cross Sections

Normal line shape

![Graph of Normal line shape]

Anomalous line shape

![Graph of Anomalous line shape]
Fit to the expectations

\[ \chi^2 = \sum_{i=1}^{N} \left( \frac{\sigma_{\text{obs}}^i - \sigma_{\text{expect}}^i}{\Delta \sigma_{\text{obs}}^i} \right)^2 \]

\[ \sigma_{e^+e^- \to K^0X}(E_{\text{cm}}) = \sigma_{J/\psi \to K^0X}(E_{\text{cm}}) + \sigma_{\psi(3686) \to K^0X}(E_{\text{cm}}) + \sigma_{\psi(3770) \to K^0X}(E_{\text{cm}}) + \sigma_{K^0X \text{continuum}}(E_{\text{cm}}) \]

\[ \sigma_{\psi}(s) = \int_{0}^{x_{\text{max}}} dx \ F(x,s) \ \sigma_{B}^\psi(s(1-x)) \]

\[ \sigma_{\psi \to K^0X}^B(s') = \frac{12 \pi \Gamma_{ee}^{K^0X}}{(s'^{-M^{-2}})^2 + (\Gamma_{\text{tot}}^M)^2} \]

\[ \Gamma_{K^0X} = \Gamma_{\text{tot}}^\times BF[\psi \to K^0X] \]