Charmonium resonances in e^+e^- annihilation cross sections around the $\psi(4415)$ region

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Contents

1.- Experimental situation

1.1.- Hystorical evolution

The heaviest well-established $J^{PC} = 1^{--}$ charmonium state, $\psi(4415)$, was first observed 30 years ago by Mark I and DASP Collaborations

- *J. Siegrist et al. (Mark I Collaboration), Phys. Rev. Lett.* **36**, *700 (1976)*
- *R. Brandelik et al. (DASP Collaboration), Phys. Lett. B* **76**, *361 (1978)*

e^+e^- annihilation cross section measurements in the region of the $\psi(4415)$ were reported by the Crystall Ball and BESII groups

- *A. Osterheld et al. (Crystall Ball Collaboration), SLAC-PUB-4160, 1986*
- *J. Z. Bai et al. (BES Collaboration), Phys. Rev. Lett.* **88**, *101802 (2002)*

No update of its parameters was done until 2005. Combined fit to the last data

- *K. K. Seth, Phys. Rev. D* **72**, *017501 (2005)*

BES Collaboration reported new parameter values for the $\psi(3770)$, $\psi(4040)$, $\psi(4160)$, $\psi(4415)$, resonances that are derived from a global fit to their cross sections measurements

1.2.- Study of the exclusive open charm-production in the mass range developed by Belle

- *Measurement of the exclusive cross section for the process $e^+e^- \to D^0D^-\pi^+$ and the first observation of $\psi(4415) \to D\bar{D}_2^*(2460)$*
- *It represents a continuation of their studies of the exclusive open-charm production in the mass range where recently several charmonium(-like) states were observed*

- Their measure

$$\sigma(e^+e^- \to \psi(4415))\times\mathcal{B}(\psi(4415) \to D\bar{D}_2^*)\times\mathcal{B}(\bar{D}_2^* \to D\pi^+) = (0.74\pm0.17\pm0.08)\text{ nb}$$

- Two sets
  - Set I
    $m_{\psi(4415)} = (4421 \pm 4)$ MeV
    $\Gamma_{ee} = (0.58 \pm 0.07)$ keV
    $\Gamma_{tot} = (62 \pm 20)$ MeV
  - Set II
    $m_{\psi(4415)} = (4415.1 \pm 7.9)$ MeV
    $\Gamma_{ee} = (0.35 \pm 0.12)$ keV
    $\Gamma_{tot} = (71.5 \pm 19.0)$ MeV
- Final result

$$\mathcal{B}(\psi(4415) \to D\bar{D}_2^*(2460)) \times \mathcal{B}(\bar{D}_2^*(2460) \to D\pi^+) = (10.5 \pm 2.4 \pm 3.8)\%$$

$$\mathcal{B}(\psi(4415) \to D\bar{D}_2^*(2460)) \times \mathcal{B}(\bar{D}_2^*(2460) \to D\pi^+) = (19.5 \pm 4.5 \pm 9.2)\%$$

2.- Theoretical framework

2.1.- Constituent quark model / J. Vijande *et* al., J. Phys. G: Nucl. Part. Phys. **31**, 481 (2005)

- Spontaneous chiral symmetry breaking (Goldstone-Bosons exchange):

$$L = \bar{\psi}\left(i\gamma^\mu \partial_\mu - M U^{\gamma_5}\right)\psi \to \quad U^{\gamma_5} = 1 + \frac{i}{f_\pi}\gamma^5 \lambda^a \pi^a - \frac{1}{2f_\pi^2}\pi^a \pi^a + \ldots$$

$$M(q^2) = m_q F\left(q^2\right) = m_q \left[\frac{\Lambda^2}{\Lambda^2 + q^2}\right]^{1/2}$$

- QCD perturbative effects (One gluon exchange):

$$L = i\sqrt{4\pi\alpha_s}\,\bar{\psi}\gamma_\mu G^\mu \lambda^c \psi$$

- Confinement (screened potential):

$$V_{CON}^{C}(\vec{r}_{ij}) = \left[-a_c(1 - e^{-\mu_c r_{ij}}) + \Delta\right](\vec{\lambda}_i^c \cdot \vec{\lambda}_j^c)$$

$$\begin{cases} V_{CON}^{C}(\vec{r}_{ij}) = (-a_c \mu_c r_{ij} + \Delta)\,(\vec{\lambda}_i^c \cdot \vec{\lambda}_j^c) & r_{ij} \to 0 \\ V_{CON}^{C}(\vec{r}_{ij}) = (-a_c + \Delta)(\vec{\lambda}_i^c \cdot \vec{\lambda}_j^c) & r_{ij} \to \infty \end{cases}$$

2.2.- Prediction of our model in $J^{PC} = 1^{--}$ $c\bar{c}$ mesons

(nL)	States	M_{CQM}	M_{EXP}	$\Gamma^{e^+e^-}_{CQM}$	$\Gamma^{e^+e^-}_{EXP}$
(1S)	J/ψ	3096	3096.916 ± 0.011	3.93	5.55 ± 0.14
(2S)	$\psi(2S)$	3703	3686.09 ± 0.04	1.78	2.43 ± 0.05
(1D)	$\psi(3770)$	3796	3772 ± 1.1	0.22	0.22 ± 0.05
	$X(4008)$		4008 ± 40		
(3S)	$\psi(4040)$	4097	4039 ± 1	1.11	0.83 ± 0.20
(2D)	$\psi(4160)$	4153	4153 ± 3	0.30	0.48 ± 0.22
	$X(4260)$		4260 ± 10		
(4S)	$X(4360)$	4389	4361 ± 9	0.78	-
(3D)	$\psi(4415)$	4426	4421 ± 4	0.33	0.35 ± 0.12
$\begin{bmatrix}(5S)\\(4D)\end{bmatrix}$	$X(4660)$	$\begin{bmatrix}4614\\4641\end{bmatrix}$	4664 ± 11	$\begin{bmatrix}0.57\\0.31\end{bmatrix}$	-

J. Segovia, D. R. Entem and F. Fernández, Phys. Rev. D **78**, *114033 (2008)*

2.3.- $^3P_0$ model

- *Bibliograhy*
  - *L. Micu, Nucl. Phys. B* **10**, *521 (1969)*
  - *A. Le Yaouanc, L. Olivier, O. Pene, and J.C. Raynal, Phys. Rev. D***8**, *2223 (1973)*
  - *R. Bonnaz, and B. Silvestre-Brac, Few-Body Syst.* **27**, *163 (1999)*

- Phenomenological transition operator:

$$T = -3\gamma \sum_\mu \int d^3p d^3p' \, \delta^{(3)}(p+p') \left[\mathcal{Y}_1 \left(\frac{p-p'}{2} \right) b_\mu^\dagger(p) d_\nu^\dagger(p') \right]^{C=1,I=0,S=1,J=0}$$

- Defining the S-matrix as:

$$\langle f|S|i\rangle = I + i(2\pi)^4 \delta^4(p_f - p_i)\mathcal{M}$$

- So, the partial width is:

$$\Gamma = 2\pi \sum_{JL} \int dk \delta(E_i - E_f) \left|\mathcal{M}^{JL}_{A\to BC}(k)\right|^2$$
$$= 2\pi \frac{E_B E_C}{k_0 M_A} \sum_{JL} \left|\mathcal{M}^{JL}_{A\to BC}(k_0)\right|^2$$

2.4.- Cross section. Relativistic Breit-Wigner amplitude

- Breit-Wigner cross section

$$\sigma(S) = \frac{(2J+1)}{(2S_1+1)(2S_2+1)} \frac{4\pi}{k^2} |\sqrt{\mathcal{B}_{in}}\, \mathcal{A}(S)\, \sqrt{\mathcal{B}_{out}}|^2$$

- Relativistic Breit-Wigner amplitude

$$\mathcal{A}(S) = \frac{M\Gamma}{S - M^2 + iM\Gamma} e^{i\delta}$$

$$|\mathcal{A}(S)|^2 = \frac{M^2\Gamma^2}{(S-M^2)^2 + M^2\Gamma^2}$$

- Final expression

$$\sigma(S) = \mathcal{B}_{in}\mathcal{B}_{out} \frac{(2J+1)}{(2S_1+1)(2S_2+1)} \frac{4\pi}{k^2} \frac{M^2\Gamma^2}{(S-M^2)^2 + M^2\Gamma^2}$$

If there are more than one resonance in the energy range we will have

$$\sigma(S) = \frac{(2J+1)}{(2S_1+1)(2S_2+1)} \frac{4\pi}{k^2} \left| \sum_r \sqrt{\mathcal{B}_r^{in}} \frac{M_r \Gamma_r^{tot} e^{i\delta_r}}{S - M_r^2 + iM_r\Gamma_r^{tot}} \sqrt{\mathcal{B}_r^{out}} \right|^2$$

where k is the momentum in the CM system, $k = \frac{\sqrt{S}}{2}$

2.5.- Cross section. Blatt-Weiskhoff corrections

M. Ablikim et al. (BES Collaboration), Phys. Lett. B **660**, *315-319 (2008)*

- Our initial expression is

$$\sigma(S) = \frac{(2J+1)}{(2S_1+1)(2S_2+1)} \frac{4\pi}{k^2} \left| \sum_r \sqrt{\mathcal{B}_r^{in}} \frac{M_r \Gamma_r^{tot} e^{i\delta_r}}{S - M_r^2 + i M_r \Gamma_r^{tot}} \sqrt{\mathcal{B}_r^{out}} \right|^2$$

- and with the meaning of Braching ratios

$$\sigma(S) = \frac{(2J+1)}{(2S_1+1)(2S_2+1)} \frac{16\pi}{S} \left| \sum_r \frac{M_r \sqrt{\Gamma_r^{in}} \sqrt{\Gamma_r^{out}} e^{i\delta_r}}{S - M_r^2 + i M_r \Gamma_r^{tot}} \right|^2$$

- so our final expression is

$$\sigma(S) = \frac{(2J+1)}{(2S_1+1)(2S_2+1)} \frac{16\pi}{S} \left| \sum_r \frac{M_r \sqrt{\Gamma_r^{in}} \sqrt{\Gamma_r^{out}(\sqrt{S})} e^{i\delta_r}}{S - M_r^2 + i M_r \Gamma_r^{tot}(\sqrt{S})} \right|^2$$

2.5.- Cross section. Blatt-Weiskhoff corrections (Continuation)

- Partial width of the resonance for one channel

$$\Gamma_r^f(\sqrt{S}) = \hat{\Gamma}_r \sum_L \frac{Z_f^{2L+1}}{B_L}$$

  - Only one dominant L
  - $Z_f = \rho P_f \Rightarrow \begin{cases} P_f \text{ decay momentum} \\ \rho \text{ order of the range interaction} \end{cases}$
  - $B_L(Z_f)$

$$\begin{array}{ll} B_0 = 1 & B_2 = 9 + 3Z_f^2 + Z_f^4 \\ B_1 = 1 + Z_f^2 & B_3 = 225 + 45Z_f^2 + 6Z_f^4 + Z_f^6 \end{array}$$

  - $\hat{\Gamma}_r$ is a free parameter and it is fixed as

$$\Gamma_r^f(M_r) = \Gamma_0 = \hat{\Gamma}_r \frac{Z_f^{2L+1}(P_0)}{B_L(P_0)} \Rightarrow \hat{\Gamma}_r = \Gamma_0 \frac{B_L(P_0)}{Z_f^{2L+1}(P_0)}$$

- Final expression

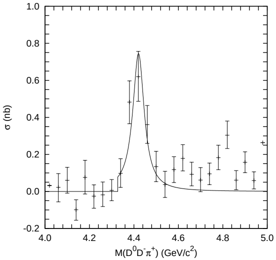
$$\Gamma_r^f(\sqrt{S}) = \Gamma_0 \frac{Z_f^{2L+1}(P_f)}{Z_f^{2L+1}(P_0)} \frac{B_L(P_0)}{B_L(P_f)}$$

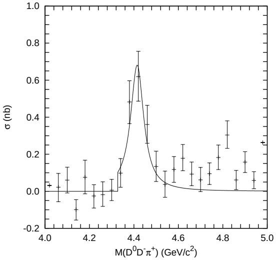
- Total width

$$\Gamma_r^{tot}(\sqrt{S}) = \frac{2M_r}{M_r + \sqrt{S}} \sum_f \Gamma_r^f(\sqrt{S})$$

3.- The process $e^+e^- \to D^0D^-\pi^+$ through the $D\bar{D}_2^*(2460)$ channel

3.1.- Experimental fit





- Set I

$$m_{\psi(4415)} = (4421 \pm 4)\text{ MeV}$$
$$\Gamma_{ee} = (0.58 \pm 0.07)\text{ keV}$$
$$\Gamma_{tot} = (62 \pm 20)\text{ MeV}$$

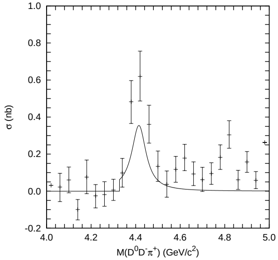
- Set II

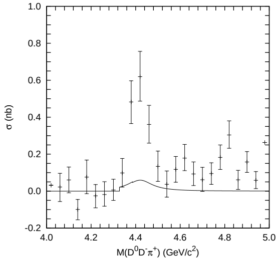
$$m_{\psi(4415)} = (4415.1 \pm 7.9)\text{ MeV}$$
$$\Gamma_{ee} = (0.35 \pm 0.12)\text{ keV}$$
$$\Gamma_{tot} = (71.5 \pm 19.0)\text{ MeV}$$

$$\mathcal{B}_{\psi(4415)\to D\bar{D}_2^*} \times \mathcal{B}_{\bar{D}_2^*\to D\pi^+} = (10.5 \pm 2.4 \pm 3.8)\%$$
$$\mathcal{B}_{\psi(4415)\to D\bar{D}_2^*} \times \mathcal{B}_{\bar{D}_2^*\to D\pi^+} = (19.5 \pm 4.5 \pm 9.2)\%$$

We can estimate from PDG the Braching for $\bar{D}_2^* \to D\pi^+$ and obtain
set I: $\mathcal{B}(\psi(4415) \to DD_2^*) = 0.47$
set II: $\mathcal{B}(\psi(4415) \to DD_2^*) = 0.86$

3.2.- Theoretical results with only one resonance





- T. Barnes *et* al., Phys. Rev. D **72**, 054026 (2005)

  $m_{\psi(4415)} = 4415$ MeV

  $\Gamma_{ee} = (0.58 \pm 0.07)$ keV (PDG)

  $\Gamma_{tot} = 78$ MeV

- J. Segovia *et* al, Phys. Rev. D **78**, 114033, (2008)

  $m_{\psi(4415)} = 4426$ MeV

  $\Gamma_{ee} = 0.33$ keV

  $\Gamma_{tot} = 133.1$ MeV

  $\mathcal{B}(D_2^{*+} \to D^0\pi^+) = 0.4295$ $(Exp. : 0.4368)$

  $\mathcal{B}(D_2^{*0} \to D^+\pi^-) = 0.4296$ $(Exp. : 0.4646)$

T. Barnes: $\mathcal{B}(\psi(4415) \to DD_2^*) = 0.30$
J. Segovia: $\mathcal{B}(\psi(4415) \to DD_2^*) = 0.15$

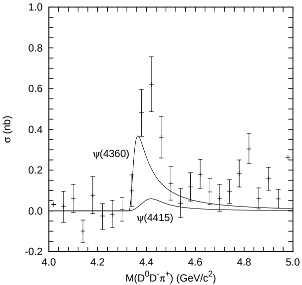
3.3.- Theoretical results with two resonances

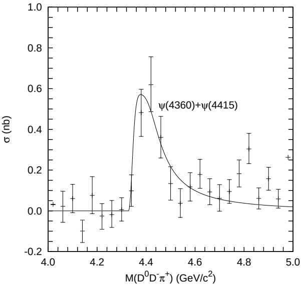
Experimental energy window around the mass of $\psi(4415)$ is $\pm 100 MeV$

- Our model predicts two resonances inside this energy region

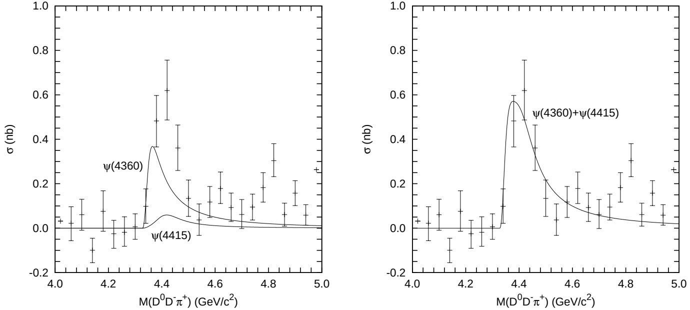
$$m_{\psi(4415)} = 4426\,\text{MeV} \qquad m_{\psi(4360)} = 4389\,\text{MeV}$$
$$\Gamma_{ee} = 0.33\,\text{keV} \qquad \Gamma_{ee} = 0.78\,\text{keV}$$
$$\Gamma_{tot} = 133.1\,\text{MeV} \qquad \Gamma_{tot} = 89.8\,\text{MeV}$$

- Theoretical cross sections with the two resonances (BW are included)





3.3.- Theoretical results with two resonances. Continuation

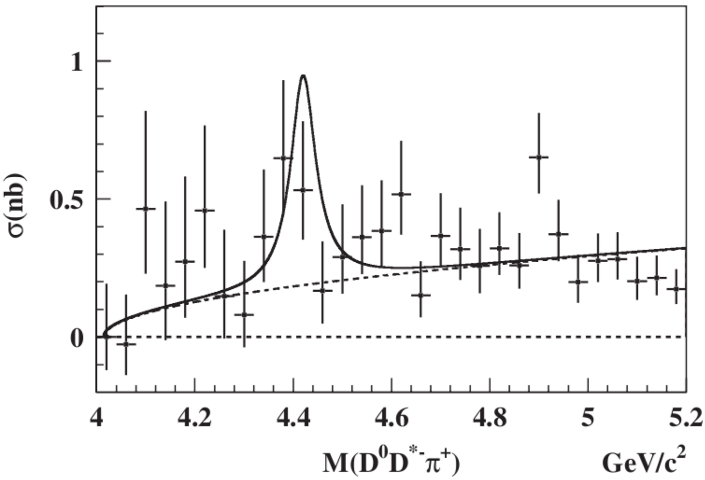


$$\sigma(e^+e^- \to \psi(4415)) \times \mathcal{B}(\psi(4415) \to D\bar{D}_2^*) \times \mathcal{B}(\bar{D}_2^* \to D\pi^+) =$$
$$= \begin{cases} (0.74 \pm 0.17 \pm 0.08)\ nb & Experiment \\ 0.48\ nb & Theory \end{cases}$$

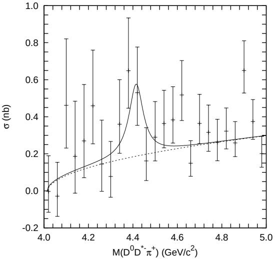
$\rightarrow$ *Experimental data point is* $(0.62^{+0.14}_{-0.13})$ *nb at* 4.20 *GeV*

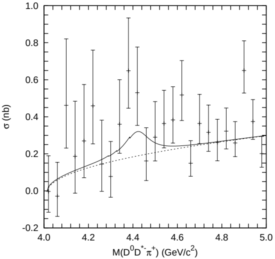
4.- The process $e^+e^- \to D^0 D^{*-} \pi^+$ in the $\psi(4415)$ energy region

4.1.- Experimental fit



4.2.- Theoretical results with only one resonance





- T. Barnes *et* al., Phys. Rev. D **72**, 054026 (2005)

$$m_{\psi(4415)} = 4415 \text{ MeV}$$
$$\Gamma_{ee} = (0.58 \pm 0.07) \text{ keV (PDG)}$$
$$\Gamma_{tot} = 78 \text{ MeV}$$

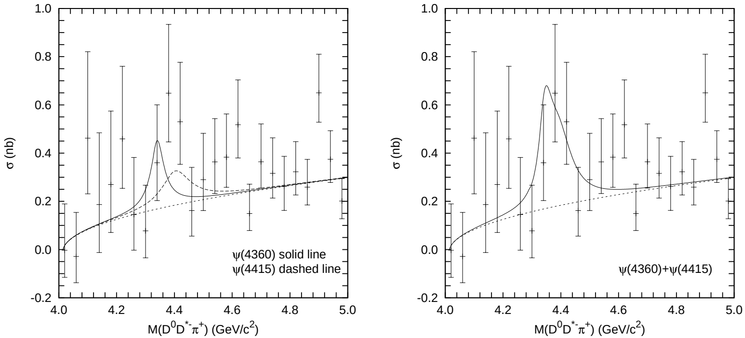
- J. Segovia *et* al, Phys. Rev. D **78**, 114033, (2008)

$$m_{\psi(4415)} = 4426 \text{ MeV}$$
$$\Gamma_{ee} = 0.33 \text{ keV}$$
$$\Gamma_{tot} = 133.1 \text{ MeV}$$

$$\mathcal{B}(D^+ \to D^0\pi^+) = 0.6870 \; (Exp. : 0.677 \pm 0.006)$$

$$\textit{T. Barnes: } \mathcal{B}(\psi(4415) \to D^* D^*) = 0.21$$
$$\textit{J. Segovia: } \mathcal{B}(\psi(4415) \to D^* D^*) = 0.21$$
$$\mathcal{B}(\psi(4415) \to D^0 D^{*-}\pi^+) = \begin{cases} 7.04\% \; Th. \\ < 11\% \; Ex. \end{cases}$$

4.3.- Theoretical results with two resonances



$m_{\psi(4360)} = 4389\,\text{MeV}$

$\Gamma_{ee} = 0.78\,\text{keV}$

$\Gamma_{tot} = 89.8\,\text{MeV}$

$m_{\psi(4415)} = 4426\,\text{MeV}$

$\Gamma_{ee} = 0.33\,\text{keV}$

$\Gamma_{tot} = 133.1\,\text{MeV}$

5.- Conclusions

- The reaction $e^+e^- \to D^0D^-\pi^+$
  - Only the resonance $\psi(4415)$ as intermediate state
    - We are not able to reproduce the experimental data
    - A similar results is obtained if we use a different model for the description of the $c\bar{c}$ system (T. Barnes et al.)
  - Mass window around the nominal $\psi(4415)$ mass in the experiment is of ± 100 MeV:
    - We introduce in the calculation the resonance $X(4360)$ assigned as a 1^{--} $c\bar{c}$ meson in our model
    - The inclusion of this second resonance produces a remarkable agreement with the experimental data
    - We provide a new estimate for the $B(\psi(4415) \to D\bar{D}_2^*(2460))\times$ $\times B(\bar{D}_2^*(2460) \to D\pi^+)$ branching product
- The reaction $e^+e^- \to D^0D^{*-}\pi^+$
  - Only the resonance $\psi(4415)$ as intermediate state
    - We are not able to reproduce the experimental data
    - However in this case, Barnes *et al.* manage to explain the experimental data in the mass of $\psi(4415)$
  - We introduce in the calculation the resonance $X(4360)$ assigned as a 1^{--} $c\bar{c}$ meson in our model
    - The inclusion of this second resonance produces a remarkable agreement with the experimental data