

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

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11<sup>th</sup> International Workshop on Meson Production, Properties and Interaction (MESON 2010)

Kraków, June 2010



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# Contents

- 1 Experimental situation
- 2 Theoretical framework
- 3 The process  $e^+e^- \rightarrow D^0 D^- \pi^+$  through the  $D\bar{D}_2^*(2460)$  channel
- 4 The process  $e^+e^- \rightarrow D^0 D^{*-} \pi^+$  in the  $\psi(4415)$  energy region
- 5 Conclusions

# 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)*

*Subsequently,  $e^+e^-$  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)*

*Recently BES Collaboration reported new parameters 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  $e^+e^- \rightarrow D^0 D^- \pi^+$  and the first observation of  $\psi(4415) \rightarrow D\bar{D}_2^*(2460)$*
- *It represents a continuation of their studies of the exclusive open-charm production in the mass range where recently several charmoniumlike states were observed*

- Their measure

$$\sigma(e^+e^- \rightarrow \psi(4415)) \times \mathcal{B}(\psi(4415) \rightarrow D\bar{D}_2^*) \times \mathcal{B}(\bar{D}_2^* \rightarrow D\pi^+) = (0.74 \pm 0.17 \pm 0.08) \text{ nb}$$

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

- Final result

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

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

## 2.- Theoretical framework

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

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

$$L = \bar{\psi} (i\gamma^\mu \partial_\mu - MU\gamma^5) \psi \rightarrow U\gamma^5 = 1 + \frac{i}{f_\pi} \gamma^5 \lambda^a \pi^a - \frac{1}{2f_\pi^2} \pi^a \pi^a + \dots$$

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

- 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):

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

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

The process  $e^+e^- \rightarrow D^0 D^{*-} \pi^+$  through the  $DD_s^*(2460)$  channel

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

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

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

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

## 2.3.- $^3P_0$ model

### • Bibliography

- 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:

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

### • 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:

$$\begin{aligned} \Gamma &= 2\pi \sum_{JL} \int dk \delta(E_i - E_f) |\mathcal{M}_{A \rightarrow BC}^{JL}(k)|^2 \\ &= 2\pi \frac{E_B E_C}{k_0 M_A} \sum_{JL} |\mathcal{M}_{A \rightarrow BC}^{JL}(k_0)|^2 \end{aligned}$$

## 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

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

- and with the meaning of Braching ratios

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

- so our final expression is

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

The process  $e^+e^- \rightarrow D^0 D^{*-} \pi^+$  through the  $DD_s^*(2460)$  channel

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

## 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

- $Z_f = \rho P_f \Rightarrow \begin{cases} P_f \text{ decay momentum} \\ \rho \text{ order of the range interaction} \end{cases}$

- $B_L(Z_f)$

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

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

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

- Total width

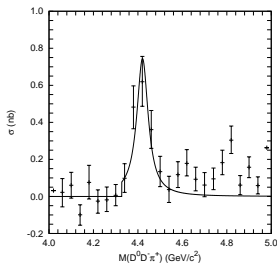
$$\Gamma_r^{\text{tot}}(\sqrt{S}) = \frac{2M_r}{M_r + \sqrt{S}} \sum_f \Gamma_r^f(\sqrt{S})$$

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

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

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

#### 3.1.- Experimental fit



- Set I

$$m_{\psi(4415)} = (4421 \pm 4) \text{ MeV}$$

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

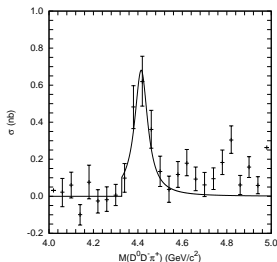
$$\Gamma_{tot} = (62 \pm 20) \text{ MeV}$$

- Set II

$$m_{\psi(4415)} = (4415.1 \pm 7.9) \text{ MeV}$$

$$\Gamma_{ee} = (0.35 \pm 0.12) \text{ keV}$$

$$\Gamma_{tot} = (71.5 \pm 19.0) \text{ MeV}$$



We can estimate from PDG the Branching for  $\bar{D}_2^* \rightarrow D\pi^+$  and obtain

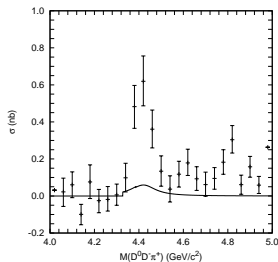
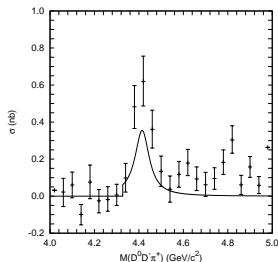
set I:  $\mathcal{B}(\psi(4415) \rightarrow D\bar{D}_2^*) = 0.47$

set II:  $\mathcal{B}(\psi(4415) \rightarrow D\bar{D}_2^*) = 0.86$

The process  $e^+e^- \rightarrow D^0 D_2^{*+} \pi^+$  through the  $DD_2^*(2460)$  channel

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

### 3.2.- 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)

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

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

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

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

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

T. Barnes:  $\mathcal{B}(\psi(4415) \rightarrow DD_2^*) = 0.30$

J. Segovia:  $\mathcal{B}(\psi(4415) \rightarrow DD_2^*) = 0.15$

The process  $e^+e^- \rightarrow D^0 D^{*-} \pi^+$  through the  $DD_s^*(2460)$  channel

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

### 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

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

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

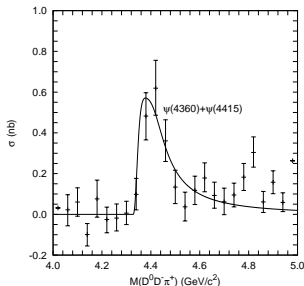
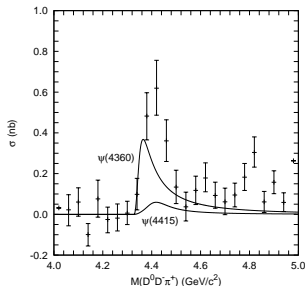
$$\Gamma_{ee} = 0.33 \text{ keV}$$

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

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

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

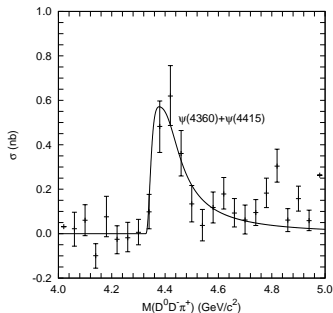
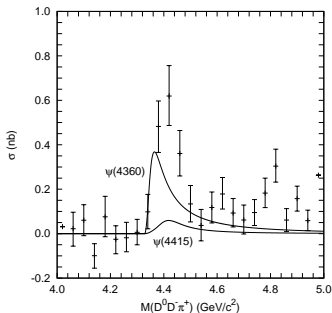
- Theoretical cross sections with the two resonances (BW are included)



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

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

### 3.3.- Theoretical results with two resonances. Continuation

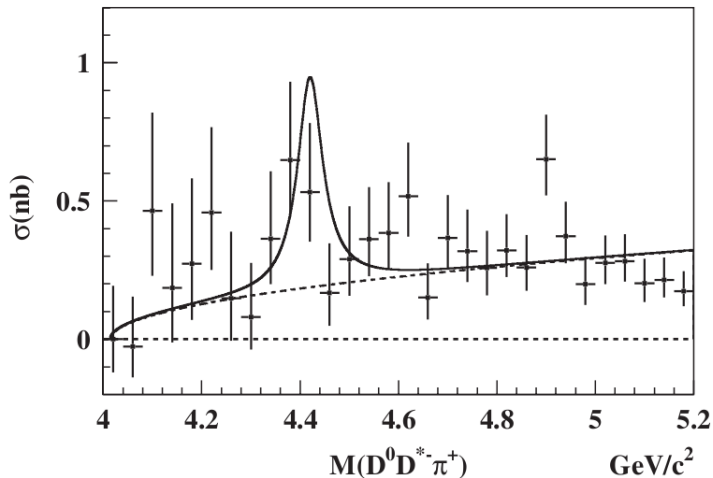


$$\begin{aligned} \sigma(e^+e^- \rightarrow \psi(4415)) \times \mathcal{B}(\psi(4415) \rightarrow D\bar{D}_2^*) \times \mathcal{B}(\bar{D}_2^* \rightarrow D\pi^+) &= \\ = \begin{cases} (0.74 \pm 0.17 \pm 0.08) \text{ nb} & \text{Experiment} \\ 0.48 \text{ nb} & \text{Theory} \end{cases} \end{aligned}$$

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

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

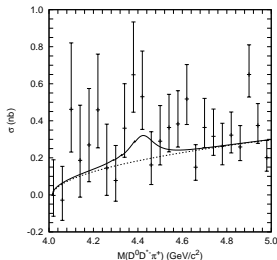
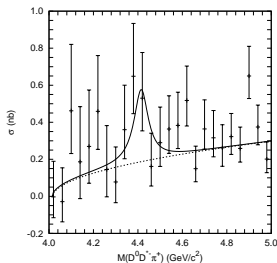
### 4.1.- Experimental fit



The process  $e^+e^- \rightarrow D^0 D^{*-} \pi^+$  through the  $DD_s^*(2460)$  channel

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

## 4.2.- Theoretical results with only one resonance



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

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

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

$$\Gamma_{tot} = 78 \text{ MeV}$$

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

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

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

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

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

*T. Barnes:*  $\mathcal{B}(\psi(4415) \rightarrow D^* D^*) = 0.21$

*J. Segovia:*  $\mathcal{B}(\psi(4415) \rightarrow D^* D^*) = 0.21$

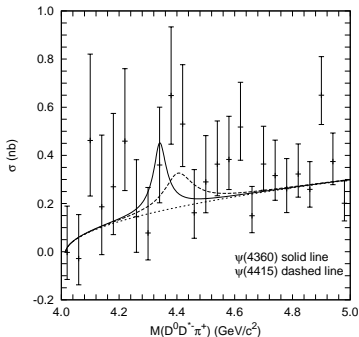
$$\mathcal{B}(\psi(4415) \rightarrow D^0 D^{*-} \pi^+) = \begin{cases} 7.04\% \text{ Th.} \\ < 11\% \text{ Ex.} \end{cases}$$



The process  $e^+e^- \rightarrow D^0 D^{*-} \pi^+$  through the  $DD_s^*$  (2460) channel

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

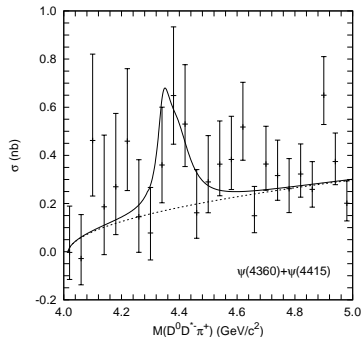
### 4.3.- Theoretical results with two resonances



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

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

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



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

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

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

## 5.- Conclusions

- The reaction  $e^+e^- \rightarrow D^0 D^- \pi^+$ 
  - 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  $\pm 100$  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 estimation for the  $B(\psi(4415) \rightarrow D\bar{D}_2^*(2460)) \times B(\bar{D}_2^*(2460) \rightarrow D\pi^+)$  branching products
- The reaction  $e^+e^- \rightarrow D^0 D^{*-} \pi^+$ 
  - 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  $\psi(4415)$  but not around it.
  - 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