Line shape and $D^{(*)}\bar{D}^{(*)}$ probabilities of $\psi(3770)$ from the $e^+e^- \to D\bar{D}$ reaction

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Overview

Introduction

The classical quark model

The quark model had achieved a huge success in explaining and predicting properties of spatial ground states of the flavor SU(3) vector meson nonet, baryon octet, and decuplet. However, it encounters serious problem when it comes to the lowest spatial excited states, in both meson and baryon sectors.

Problems...

1. In the constituent quark model, it fails to explain why the mass of $a_0(980)$ is degenerate with $f_0(980)$ instead of being close to the $f_0(500)$.
2. Similarly, in the baryon sector, where the lowest spatial excited baryon is expected to be a N^* with one quark in the $L = 1$ state according to the classical quark model. However, the experiments told us the spatial excited states is $\Lambda(1405)$ rather than $N(1535)$.

Introduction

On the other hand...

- Sophisticated analysis of meson-meson data by means of QCD and large N_c argument reached to the conclusion that low lying vector mesons are largely $q\bar{q}$ states.
- Meanwhile, the problem shown in the light quark sector can be easily understood from the perspective of tetraquark picture or the meson-meson interaction.

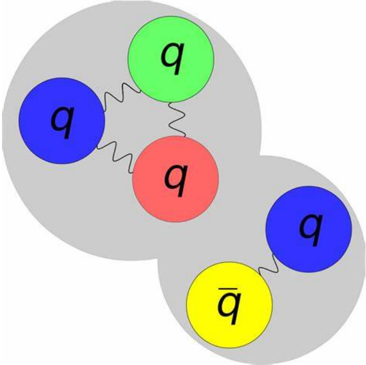
What we know...

1. The light quark sector dose not fit into the classical quark model very well, what about the charm and bottom sectors?
2. Some study was made within the quark model of the meson meson components of the charmonium vector states, and it pointed out that even the ground state J/ψ had **only as survival probability as a vector of about 0.69** when the meson meson components were considered.

Phys. Rev. C 77, 055206 (2008)

Question...

It brings us the question that whether higher excited vector charmonium states could have even smaller $q\bar{q}$ components or do not contain $q\bar{q}$ at all?



What we do here is...

- **We retake this issue for $\psi(3770)$ to calculate the percentage of $q\bar{q}$ components in this vector states.**
- **We make an elaborate study of the $D\bar{D}$, $D\bar{D}^*$, $D^*\bar{D}$, $D^*\bar{D}^*$ components of $\psi(3770)$ using the $^3P_0$ model for hadronization of $q\bar{q}$ into meson-meson components.**

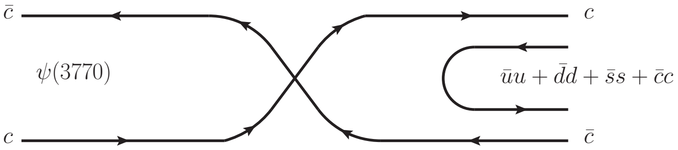
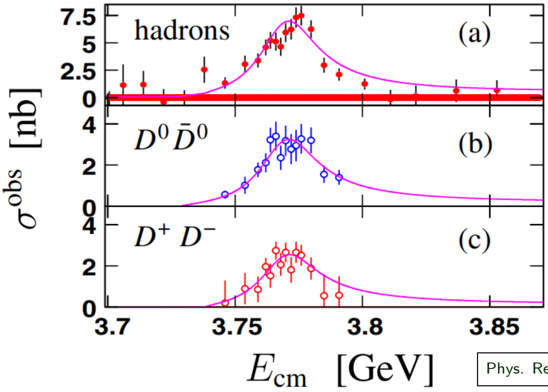


Figure: Hardronization process for $\psi(3770) \to D^{(*)}\bar{D}^{(*)}$

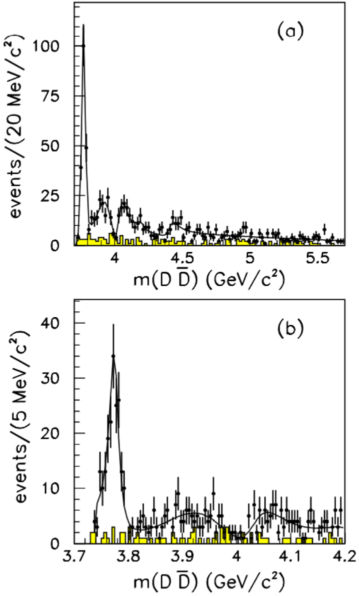
- **Using data of $e^+e^- \to D\bar{D}$ to determine the parameters so that we can evaluate the meson meson self-energy of $\psi(3770)$.**

The line shape of $\psi(3770)$

- **We show the form factor is relevant to the meson-meson probabilities and is tied to the fall down of $e^+e^- \to D\bar{D}$ cross section above the $\psi(3770)$ peak.**
- **We retake the discussion on the asymmetry of the $\psi(3770)$ peak observed in the $e^+e^- \to D\bar{D}$ reactions.**



Phys. Rev. Lett. 97, 121801 (2006)



Phys. Rev. D 76, 111105 (2007)

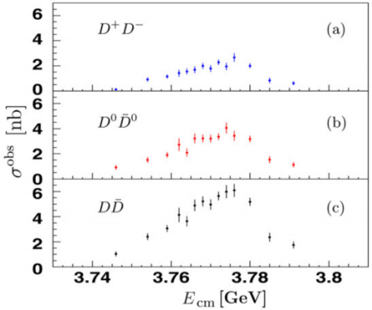
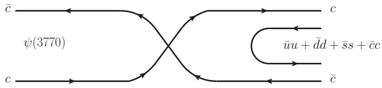


Fig. 5. The observed cross sections versus the nominal c.m. energies, where (a) is for $e^+e^- \to D^+D^-$, (b) is for $e^+e^- \to D^0\bar{D}^0$, and (c) is for $e^+e^- \to D\bar{D}$.

Phys. Lett. B 668, 263 (2008)

Formalism

- We start from the hadronization process where a $q\bar{q}$ pair with the quantum numbers of the vacuum is inserted between the quark constituents of $\psi(3770)$, $c\bar{c}$.



- The hadronization process proceeds as:

$$\psi \to c\bar{c} \to c(\bar{u}u + \bar{d}d + \bar{s}s + \bar{c}c)\bar{c} \to F, \tag{1}$$

with F

$$F = \sum_{i=1}^{4} c\bar{q}_i q_i \bar{c} = \sum_{i=1}^{4} M_{4,i} M_{i,4} = (M^2)_{4,4}, \tag{2}$$

where M corresponds to the following matrix

$$M = (q\bar{q}) = \begin{pmatrix} u\bar{u} & u\bar{d} & u\bar{s} & u\bar{c} \\ d\bar{u} & d\bar{d} & d\bar{s} & d\bar{c} \\ s\bar{u} & s\bar{d} & s\bar{s} & s\bar{c} \\ c\bar{u} & c\bar{d} & c\bar{s} & c\bar{c} \end{pmatrix}. \tag{3}$$

Formalism

- The $q\bar{q}$ in matrix M can be further written in the form of the ϕ matrix for pseudoscalar mesons and V matrix for vector mesons, as follows

$$\phi = \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{3}}\eta + \frac{1}{\sqrt{6}}\eta' & \pi^+ & K^+ & \bar{D}^0 \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{3}}\eta + \frac{1}{\sqrt{6}}\eta' & K^0 & D^- \\ K^- & \bar{K}^0 & -\frac{1}{\sqrt{3}}\eta + \sqrt{\frac{2}{3}}\eta' & D_s^- \\ D^0 & D^+ & D_s^+ & \eta_c \end{pmatrix}. \quad (4)$$

$$V = \begin{pmatrix} \frac{1}{\sqrt{2}}\rho^0 + \frac{1}{\sqrt{2}}\omega & \rho^+ & K^{*+} & \bar{D}^{*0} \\ \rho^- & -\frac{1}{\sqrt{2}}\rho^0 + \frac{1}{\sqrt{2}}\omega & K^{*0} & \bar{D}^{*-} \\ K^{*-} & \bar{K}^{*0} & \phi & D_s^{*-} \\ D^{*0} & D^{*+} & D_s^{*+} & J/\psi \end{pmatrix}. \quad (5)$$

- The matrix M in F could either be the pseudoscalar matrix (P) or the vector matrix (V), which leads to four different kinds of hadronization of the $\psi(3770)$. $\longrightarrow$ PP, PV, VP and VV.
- For example, we have the following hadronization when both M are pesudoscalar mesons

$$(M^2)_{4,4} \to (\phi\phi)_{4,4} = PP = D^0\bar{D}^0 + D^+D^- + D_s^+D_s^-, \quad (6)$$

Formalism

- Similarly, we can write the combinations coming from VP, PV and VV

$$(PV)_{4,4} = D^0\bar{D}^{*0} + D^+D^{*-} + D_s^+D_s^{*-}, \tag{7}$$

$$(VP)_{4,4} = D^{*0}\bar{D}^0 + D^{*+}D^- + D_s^{*+}D_s^-, \tag{8}$$

$$(VV)_{4,4} = D^{*0}\bar{D}^{*0} + D^{*+}D^{*-} + D_s^{*+}D_s^{*-}. \tag{9}$$

The line shape of $\psi(3770)$

For the interpretation of the line shape of $\psi(3770)$, we first follow the steps of previous studies. We consider the propagator of the vector meson $R \equiv \psi(3770)$

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$$G_{\mu\nu}(p) = \left(-g_{\mu\nu} + \frac{p_\mu p_\nu}{M_R^2}\right) G(p), \tag{10}$$

with $G(p) = \frac{1}{p^2 - M_R^2 + i\varepsilon}$.

- The fact that $\psi(3770)$ couples to PP, PV, VP, VV indicates that $\psi(3770)$ will get a self-energy $\Pi(p)$ coming from the meson-meson loop.

Formalism

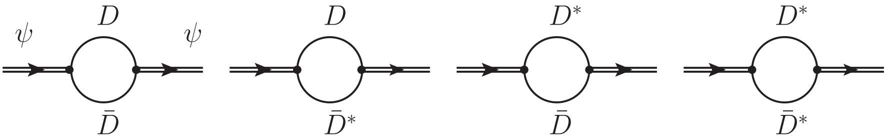


Figure: Contribution to the ψ selfenergy for the vector ψ propagator dressed with a meson-meson loop.

- In the loop one has $\Pi \sim \int d^4 q G(q) G(p-q)$ and the relevant part of it that enters the shape is $\mathrm{Im}\Pi$, where the two intermediate mesons are placed on shell.
- The reason is that the evaluation of the cross section for $e^+e^- \to D^+D^-$ will place the D, $\bar{D}$ on shell and the D momenta are about $250\,\mathrm{MeV}$. With this small momentum one can neglect the zero component of the ϵ^μ polarization vectors.

Line shape

- With the self-energy $\Pi(p)$, we can rewrite the $G(p)$ as the following form:

$$G(p) = \frac{1}{p^2 - M_R^2 - \Pi(p)}, \tag{11}$$

- The novelty in our propagator is that we include not only the PP component, but also the PV, VP, VV mesons in $\Pi(p)$.
- The $\mathrm{ImG(p)}$ that affects the line shape has the form:

$$ImG(p) = \frac{Im\Pi(p)}{(p^2 - M_R^2 - Re\Pi(p))^2 + (Im\Pi(p))^2}. \tag{12}$$

  The $\mathrm{Im\Pi}$ in the equation comes only from $D\bar{D}$, but $\mathrm{Re\Pi(p)}$ in the denominator comes from all channels.
- The evaluation of Π requires us to relate the strength of the PP, PV and VV couplings to the $\psi(3770)$. This we can do with $^3P_0$ model, which requires elaborate sums of many Clebsch-Gordan coefficients. We first present the couplings

PP	$\|C_1\|^2 = \frac{1}{12}$	D^+D^-, $D^0\bar{D}^0$, $D_s^+D_s^-$
PV, VP	$\|C_2\|^2 = \frac{1}{6} \times \frac{1}{4}$	$D^0\bar{D}^{*0}$, $D^{*0}\bar{D}^0$, $D^+\bar{D}^{*-}$, $D^{*+}D^-$, $D_s^{*+}D_s^-$, $D_s^+D_s^{*-}$
VV	$\|C_3\|^2 = \frac{1}{12} \times \frac{231}{30}$	$D^{*0}\bar{D}^{*0}$, $D^{*+}D^{*-}$, $D_s^{*+}D_s^{*-}$

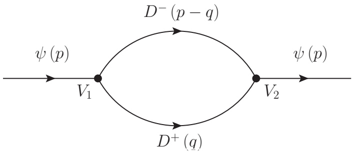
Vertex

In order to evaluate the self-energy $\Pi(p)$, we first need the vertex $V_{\psi,(MM)_i}$,

$$V_{\psi,(MM)_i} = g_{\psi,(MM)_i} \epsilon\, \mathbf{q}\, F(\mathbf{q}), \qquad (13)$$

with

$$g_{\psi,(MM)_i} = A\, C_i\, (i = 1, 2, 3), \qquad (14)$$



Evaluating $\Pi(p)$

$$-i\Pi(p) = \int \frac{d^4q}{(2\pi)^4}(-i)V_1(-i)V_2 \frac{i}{q^2 - m_{D^+}^2 + i\varepsilon} \frac{i}{(p-q)^2 - m_{D^-}^2 + i\varepsilon} F(\mathbf{q})^2, \qquad (15)$$

define

$$\Pi(p) = g_{\psi,D^+D^-}^2\, \tilde{G}(p^0), \qquad (16)$$

Here we obtain the final expression for the self-energy of $\psi(3770)$ which comes from the all the channels (*PP*, *VP*, *PV*, *VV*) we mentioned.

$$\Pi(p^0) = |A|^2 \Big\{ \frac{1}{12}\tilde{G}(p^0)\big|_{D^0\bar{D}^0} + \frac{1}{12}\tilde{G}(p^0)\big|_{D^+D^-} + \frac{1}{24}\tilde{G}(p^0)\big|_{D^0\bar{D}^{*0}} + \frac{1}{24}\tilde{G}(p^0)\big|_{D^{*0}\bar{D}^0} + \frac{1}{24}\tilde{G}(p^0)\big|_{D^+D^{*-}} + \frac{1}{24}\tilde{G}(p^0)\big|_{D^{*+}\bar{D}^-} + \frac{231}{360}\tilde{G}(p^0)\big|_{D^{*0}\bar{D}^{*0}} + \frac{231}{360}\tilde{G}(p^0)\big|_{D^{*+}D^{*-}} + \frac{1}{12}\tilde{G}(p^0)\big|_{D_s^+D_s^-} + \frac{1}{24}\tilde{G}(p^0)\big|_{D_s^+D_s^{*-}} + \frac{1}{24}\tilde{G}(p^0)\big|_{D_s^{*+}D_s^-} + \frac{231}{360}\tilde{G}(p^0)\big|_{D_s^{*+}D_s^{*-}} \Big\}. \tag{17}$$

where $\tilde{G}(p^0)$ has the form

$$\begin{aligned} \tilde{G}(p^0) &= \int \frac{d^3q}{(2\pi)^3} \frac{1}{2\omega_1(\mathbf{q})} \frac{1}{2\omega_2(\mathbf{q})} \mathbf{q}^2 \frac{2\omega_1(\mathbf{q}) + 2\omega_2(\mathbf{q})}{(p^0)^2 - (\omega_1(\mathbf{q}) + \omega_2(\mathbf{q}))^2 + i\varepsilon} F(\mathbf{q})^2 \\ &= \int \frac{dq}{(2\pi)^2} \frac{\omega_1(\mathbf{q}) + \omega_2(\mathbf{q})}{\omega_1(\mathbf{q})\omega_2(\mathbf{q})} \frac{\mathbf{q}^4}{(p^0)^2 - (\omega_1(\mathbf{q}) + \omega_2(\mathbf{q}))^2 + i\varepsilon} F(\mathbf{q})^2, \end{aligned} \tag{18}$$

with $\omega_1(\mathbf{q}) = \sqrt{\mathbf{q}^2 + m_{D^+}^2}$, $\omega_2(\mathbf{q}) = \sqrt{\mathbf{q}^2 + m_{D^-}^2}$.

Form factor $F(q)$

Rather than evaluating the form factor $F(q)$ with the quark wave function we take an empirical attitude here, and let the data determine this form factor from the shape of the $e^+e^- \to D\bar{D}$ cross section.

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$$\sigma = -g^2_{\psi e^+e^-} ImD(M_{inv}), \tag{19}$$

Here we separate σ into the contribution of the different channels $(D^+D^-, D^0\bar{D}^0)$.

$$\sigma_i = -g^2_{\psi e^+e^-} ImD_i(M_{inv}), \tag{20}$$

where

$$ImD_i = \frac{Im\Pi_i(p)}{(p^2 - M_R^2 - Re\Pi(p))^2 + (Im\Pi(p))^2}, \tag{21}$$

where $\Pi_i(p)$ is the contribution to $Im\Pi(p^2)$ from the D^+D^- or $D^0\bar{D}^0$ channel (see Eq. (17)). Note that in the denominator we have $\Pi(p)$, meaning that all channels are included here.

Meson-meson probabilities in the $\psi(3770)$ wave function

First, we rewrite $\Pi(p)$ using the once-subtracted dispersion relation, with the subtraction in point M_ψ.

$$\Pi'(p) = \Pi(p) - Re(\Pi(M_\psi)), \tag{22}$$

Furthermore, we can make an expansion around M_ψ and have

$$\begin{aligned} G(p) &= \frac{1}{p^2 - M_\psi^2 - Re(\Pi'(p)) - iIm\Pi(p)} \\ &= \frac{1}{p^2 - M_\psi^2 - [Re(\Pi'(p)) - Re(\Pi'(M_\psi))] - iIm\Pi(p)}, \end{aligned} \tag{23}$$

since $\mathrm{Re}\Pi'(\mathrm{M}_\psi) = 0$, hence

$$\begin{aligned} G(p) &\simeq \frac{1}{p^2 - M_\psi^2 - \frac{\partial Re\Pi}{\partial p^2}\Big|_{M_\psi^2}(p^2 - M_\psi^2) - iIm\Pi(p)} \\ &= \frac{1}{(p^2 - M_\psi^2)(1 - \frac{\partial Re\Pi}{\partial p^2}\Big|_{M_\psi^2}) - iIm\Pi(p)} \\ &= \frac{Z}{p^2 - M_\psi^2 - iZIm(p)}, \end{aligned} \tag{24}$$

where Z has the form

$$Z = \frac{1}{1 - \frac{\partial Re\Pi(p^2)}{\partial p^2}\Big|_{p^2=M_\psi^2}}. \tag{25}$$

1. **Z is interpreted as the probability to still have the original vector when it is dressed by the meson-meson components.**
2. **If $\frac{\partial Re\Pi}{\partial p^2}$ is reasonably smaller than 1, one can make an expansion to the above equation**

$$Z \simeq 1 + \frac{\partial Re\Pi}{\partial p^2}\Big|_{p^2=M_\psi^2}. \tag{26}$$

3. **Then $1 - Z$ will be the meson-meson probability of the dressed vector.**

$$1 - Z = -\frac{\partial Re\Pi}{\partial p^2}\Big|_{p^2=M_\psi^2}, \tag{27}$$

Which is to say the probability for different channel can be written as

$$\boxed{\mathbf{P_{(MM)i} \simeq -\frac{\partial Re\Pi_i(p^2)}{\partial p^2}\Big|_{p^2=M_\psi^2}},} \tag{28}$$

Interpretation of P as probabilities

- Assume that we have a potential V in momentum space which generates a bound state at energy E_α. The scattering matrix has a pole at $s_\alpha = E_\alpha^2$,

$$T = \frac{V}{1 - VG} = \frac{1}{V^{-1} - G} \simeq \frac{g^2}{s - s_\alpha}, \tag{29}$$

g^2 by means of L'Hôpital's rule as

$$g^2 = \lim_{s \to s_\alpha} \frac{s - s_\alpha}{V^{-1} - G} = -\frac{1}{\frac{\partial G}{\partial s}}, \tag{30}$$

Hence,

$$-g^2 \frac{\partial G}{\partial s} = 1 \rightarrow \sum_i (-1) g_i^2 \frac{\partial G_i}{\partial s} = 1, \tag{31}$$

- Since g_i can be complex and so is G_i for the open channels, the corresponding terms in Eq. (31) are complex but the sum is 1 which means there is an extra cancellation of the imaginary parts and then Eq. (31) becomes

Eur. Phys. J. A 50, 57 (2014)⟵

$$\sum_i (-1) \mathrm{Re} \left(g_i^2 \frac{\partial G_i}{\partial s} \right) = 1. \tag{32}$$

Interpretation of P as probabilities

- **The open channels can be taken into account by means of a Hamiltonian H which is no longer hermitian and its eigenstates are not orthogonal. One must introduce a biorthogonal basis of eigenstates of $H, |\lambda_n\rangle$ and of $H^+, |\bar{\lambda}_n\rangle$ and one has**

$$\langle\bar{\lambda}_n|\lambda_m\rangle = \delta_{nm}. \tag{33}$$

- **H is not Hermitian but is symmetric and then $|\bar{\lambda}_n\rangle = |\lambda_n^*\rangle$. This has a consequence that in the derivations of the sum rule we must substitute**

$$\langle\psi_i|\psi_i\rangle \to \langle\bar{\psi}_i|\psi_i\rangle = \int d^3p(\psi_i^*(p))^*\psi_i(p) = \int d^3p\psi_i^2(p), \tag{34}$$

- **Furthermore, we find that with an appropriate prescription for the global phase of the wave function (which makes the wave function real in the case of a bound state)**

$$\langle\bar{\psi}_i|\psi_i\rangle = -g_i^2\frac{\partial G_i}{\partial s}. \tag{35}$$

- **Hence, the term $\mathrm{Re}(g_i^2\frac{\partial G_i}{\partial s})$ in Eq. (32) has to be interpreted as**

$$\mathrm{Re}(g_i^2\frac{\partial G_i}{\partial s}) \simeq \mathrm{Re}\int d^3p\psi_i^2(p). \tag{36}$$

It is clear that Eq. (36) provides a measure of the strength of the wave function in the region of the interaction before the mesons become free propagating particles. In the evaluation of physical processes only the interaction region would be relevant and hence $\mathrm{Re}(g_i^2 \frac{\partial G}{\partial s})$ provides us with a measure of the "weight" or "strength" of this component, not a probability in the strict sense which would be infinite.

- We have so far assumed that the states we obtain are fully composite states. In the real world there can be some genuine component, like in the case we investigate, where the genuine components would be a vector state and the meson-meson components are those we evaluated.

$$\sum_i (-1)\mathrm{Re}(g_i^2 \frac{\partial G}{\partial s}) = 1 - Z, \tag{37}$$

where Z is the probability of the genuine component.

Form factors

- First, we use the same form factor as the one employed in the reference (**Nucl. Phys. A981, 38 (2019)**)

$$f_\Lambda(\xi) = e^{-\xi/(4\Lambda^2)}\, e^{(m_{D^0}^2 + m_{D^+}^2)/(2\Lambda^2)}, \tag{38}$$

with $\xi = 4(\mathbf{q}^2 + m^2)$, we get similar results using this form factor, the parameter Λ appearing in the equation was fitted to the $e^+e^- \to D\bar{D}$ data

- In addition, we use two form factors:

$$F(\mathbf{q})^2 = \frac{1 + (R\, q_{on})^2}{1 + (R\, q)^2}, \tag{39}$$

and

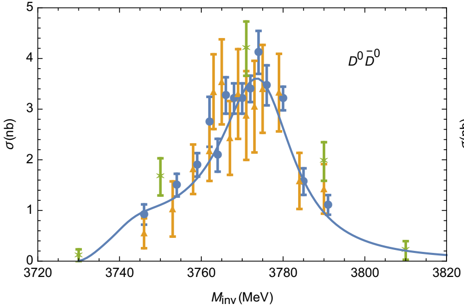
$$F(\mathbf{q})^2 = \frac{1 + (R\, q_{on})^4}{1 + (R\, q)^4}, \tag{40}$$

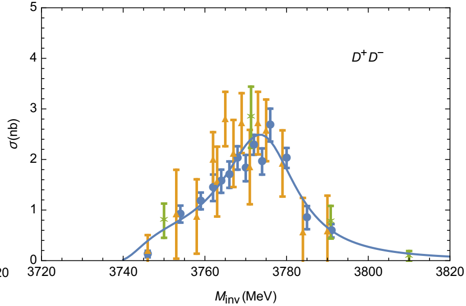
with q_{on} the following form for $D\bar{D}$

$$q_{on} = \frac{\lambda^{1/2}(M_\psi^2, m_D^2, m_{\bar{D}}^2)}{2M_\psi}, \tag{41}$$

Results and discussion

We use the form factor in Eq. (40) in the fitting the data.





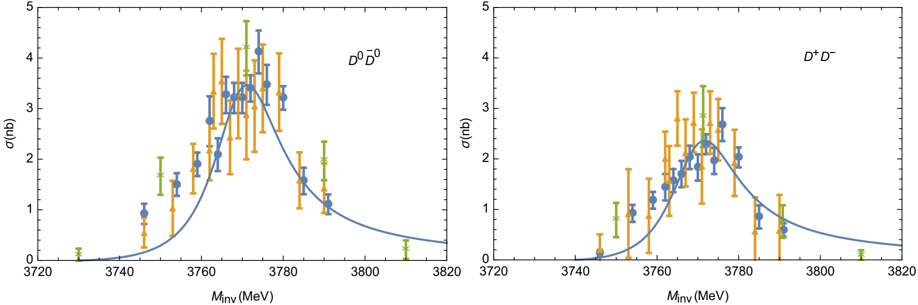
•Phys.Lett.B 668, 263 (2008); ▲Phys.Rev.Lett. 97, 121801 (2006); ⋆Phys.Rev.D 76, 111105 (2007).

M_R	3773 MeV
$g^2_{\psi e^+e^-}$	1.40×10^{-6}
R	$0.0070\ \mathrm{MeV}^{-1}$
$\lvert A\rvert^2$	1750

- M_R is of course very close to the nominal mass of the $\psi(3770)$.
- $g_{\psi e^+e^-}$ determines the strength of the cross section.
- A is related to the width of the resonance.
- R determines the fall down of the resonance shape above the resonance peak.

Results and discussion

Using form factor of Eq. (39) in the fitting the data.



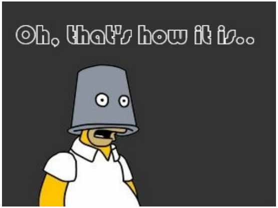
M_R	3773 MeV
$g^2_{\psi e^+ e^-}$	1.55×10^{-6}
R	0.0030 MeV^{-1}
$\lvert A\rvert^2$	2756

- Observing a good fit in the region above the peak, but not as good as before below it, although still comparable with the bulk of the data.
- **Actually, it is interesting to note that the low part of the spectrum could as well be filled by the contribution of the $\psi(2686)$**

Phys. Rev. D 81, 034011 (2010); Phys. Lett. B 718, 1369 (2013)

About the fitting...

We should note that the description of the data is a result of the parametrization, and in particular the fall down of the distribution above the peak is related to the parameter R.



The asymmetries in this fitting

There is nothing fundamental in this interpretation of the asymmetry. However, the data and particularly the fall down above the threshold determine the range of the form factor, and this is important to make the integral $\tilde{G}(p)$ convergent, such that the probabilities that we obtain are a consequence of the peculiar shape of the $e^+e^- \to D\bar{D}$ data. In this sense, the probabilities that we obtain are a prediction based on the $e^+e^- \to D\bar{D}$ data.

Evaluation of the vector and meson-meson probabilities

Table: Meson-meson probabilities in the $\psi(3770)$ wave function with the form factor of Eq. (40).

Channels	$-\frac{\partial\Pi}{\partial p^2}\Big\|_{p^2=M_\psi^2}$	$P_{(MM)}$	Z
$D^0\bar{D}^0$	$-0.0555-0.0406i$	-0.0555	1.059
D^+D^-	$-0.0879-0.0444i$	-0.0879	1.096
$D^0\bar{D}^{*0}+c.c$	0.0083	0.0083	0.992
$D^+\bar{D}^{*-}+c.c$	0.0074	0.0074	0.993
$D^{*0}\bar{D}^{*0}$	0.0164	0.0164	0.984
$D^{*+}D^{*-}$	0.0156	0.0156	0.985
$D_s^+D_s^-$	0.0040	0.0040	0.996
$D_s^+D_s^{*-}+c.c$	0.0014	0.0014	0.999
$D_s^{*+}D_s^{*-}$	0.0054	0.0054	0.995
Total	$-0.0850-0.0846i$	-0.0850	1.093

- The $D^+D^{*-}+c.c$ or $D^0D^{*0}+c.c$ are practically zero.
- There is the unpleasant feature that $-\frac{\partial\Pi_{D\bar{D}}}{\partial p^2}\Big|_{p^2=M_\psi^2}$ is complex, and $(P_{(MM)})$ is negative.

In view of the problem appearing in the former calculation, we use a form factor more in agreement with phenomenology, which is Eq. (39).

- This form factor induces a correction to the width

$$\Gamma(s) \to \Gamma_0 \frac{1+(R\, q_{on})^2}{1+(R\, \bar{q})^2} \quad \text{with} \quad \bar{q} = \frac{\lambda^{1/2}(s, m_D^2, m_{\bar{D}}^2)}{2\sqrt{s}}, \tag{42}$$

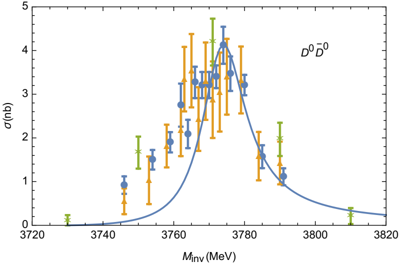
- This factor is the Blatt-Weisskopf barrier penetration factor, commonly used to write the width in usual Breit-Wigner amplitudes.

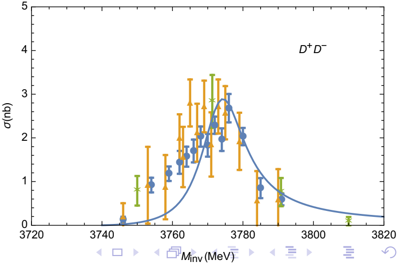
Table: Meson-meson probabilities in the $\psi(3770)$ wave function with the form factor of Eq. (39).

Channels	$-\frac{\partial \Pi}{\partial p^2}\big\|_{p^2=M_\psi^2}$	$P_{(MM)}$	Z
$D^0\bar{D}^0$	$0.0019 + 0.1814i$	0.0019	0.998
D^+D^-	$0.0295 + 0.1862i$	0.0295	0.971
$D^0\bar{D}^{*0} + c.c$	$0.0264 + 0.0003i$	0.0264	0.974
$D^+\bar{D}^{*-} + c.c$	$0.0244 + 0.0002i$	0.0244	0.976
$D^{*0}\bar{D}^{*0}$	$0.0708 + 0.0004i$	0.0708	0.934
$D^{*+}D^{*-}$	$0.0681 + 0.0004i$	0.0681	0.936
$D_s^+D_s^-$	$0.0152 + 0.0001i$	0.0152	0.985
$D_s^+D_s^{*-} + c.c$	0.0065	0.0065	0.994
$D_s^{*+}D_s^{*-}$	0.0268	0.0268	0.974
Total	$0.2696 + 0.3690i$	0.2696	0.787

- **With a different form factor, we can see that all the probabilities are positive and Z probability is smaller than one.**
- **The results indicate small meson-meson probabilities in $\psi(3770)$.**
- **A total probability for Z to have still a vector component is about 80%.**

- Although, as we have seen that the line shapes evaluated with the form factor of Eq. (39) exhibit a smaller slope of the cross section above the peak as compared to the line shapes evaluated with the form factor of Eq. (40), we choose the form factor which are more in agreement with phenomenology as mentioned before.
- With the form factor of Eq. (39) we choose a different set of parameters that make the slope above the peak more similar in all cases, at the cost of not having such a good agreement at low energies.





- The parameters used for the fitting are shown in the table on the right side.
- In this case, we find $Z \sim 0.854$.
- In view of the results for the former fit, we can settle the value of Z within $0.80 - 0.85$.

M_R	$3775\ \mathrm{MeV}$
$g^2_{\psi e^+ e^-}$	1.25×10^{-6}
R	$0.0029\ \mathrm{MeV}^{-1}$
$\|A\|^2$	1700

- **An elaborate study combining elements of QCD, large N_c limits and phenomenology concludes that while low lying scalar mesons, like the σ, $f_0(980)$, $\cdots$ are completely off the $q\bar{q}$ picture, the vector mesons are largely $q\bar{q}$ states.**
- Our result comes handy when some calculations could make us lose confidence in this picture.
- For example, in reference (Phys. Rev. C 77, 055206 (2008)) where a calculation within a quark model was done to assess the relevance of the meson-meson components in the vector mesons, even the J/ψ was found to have a Z probability of only **65%**, implying that more massive ψ vectors could have an even smaller Z probability.
- **The result of the present paper incorporating the features of the $\psi(3770)$ shape in the $e^+e^- \to D\bar{D}$ reactions, demanded the presence of a form factor that has a consequence the small meson-meson probabilities and the large Z value.**

Summary

1. **We have performed an evaluation of the meson-meson components in the $\psi(3770)$ wave function, considering PP, PV, VP and VV components.**
2. **We found that the determination of such probabilities was much tied to the shape of the $e^+e^- \to D\bar{D}$ reaction.**
3. **Within uncertainties we found that the Z probability of a vector component in the $\psi(3770)$ is of order of $80\% - 85\%$ and the individual meson-meson components are small.**
4. **We can conclude the dominant weight of the vector component in the $\psi(3770)$.**
5. **The same methods can be applied to some higher excited states in the future, and further experiments shall tell us more about the nature of these higher excited states.**

The End