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Formation and deformation of the $\psi(3770)$

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Introduction

Mysteries in the data

The vector meson $\psi(3770)$, reported in PDG with average parameters $M = 3773.13$ MeV and $\Gamma = 27.2 \pm 1.0$ MeV, has a deformed, i.e., non–Breit-Wigner line-shape.

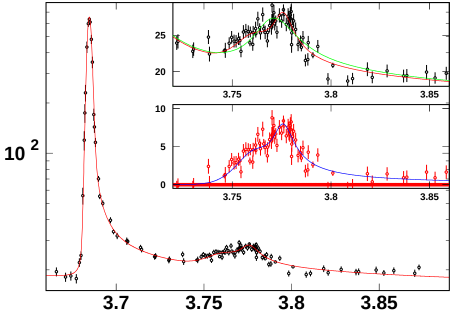
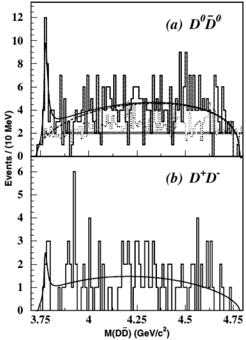


Figure: $\sigma = \sigma(E)$ in [nb, GeV]. PRL101,102004(2008) *BES*, $e^+e^- \to$ *hadrons*

Other data:

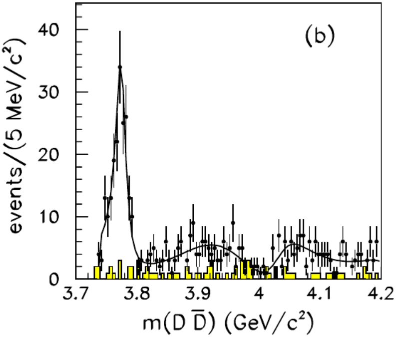
PRL93,051803(2004) Belle

$B^+ \to \psi(3770)K^+$



PRD76,111105(2007) BaBar

ISR



The Novosibirsk group: KEDR Collaboration, PLB711,292(2012).

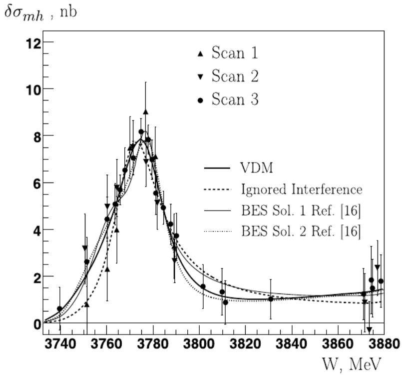


Figure: $e^+e^- \to D\bar{D}$

Analysis: interference between resonant and nonresonant part, where the nonresonant part is related to the nonresonant part of the form factor (use of vector dominance model). Interpretation with 1 resonance only !

Phenomenological Studies

Other analysis from Novosibirsk group

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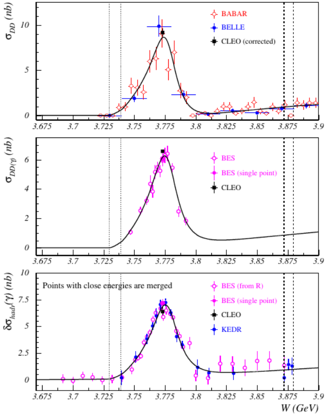
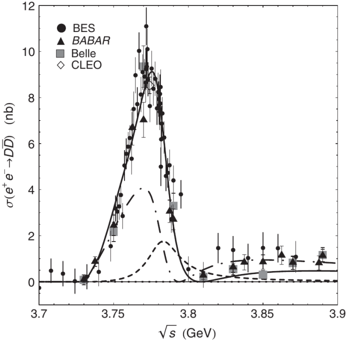


PRD87,057502(2013)



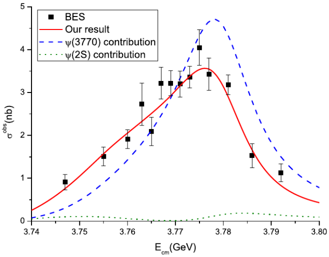
Interference between the $\psi(3770)$ and the tail of the $\psi(2S)$.

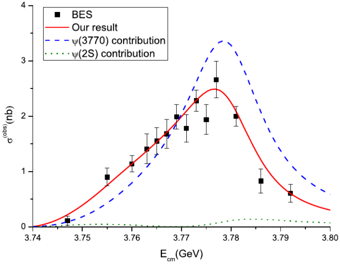
Some predictions concerning the $\psi(3770)$:

• In PRD88,014010(2013) contribution of off-shell PV channels

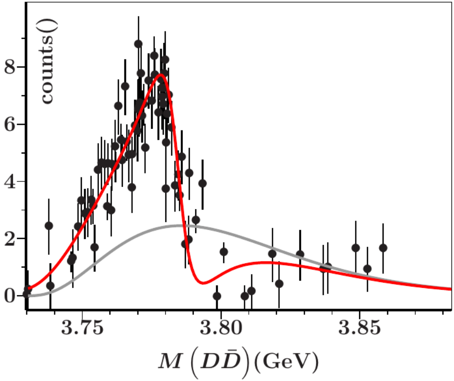
• PRD91,114022(2015), EPJC76,192(2016), and NPB888,271(2014) production through $p\bar{p}$ and baryonic contributions. Possibility to test at PANDA.

• PLB718,1369(2013) production $e^+e^- \to D\bar{D}$, including interference with nonresonant background due to $\psi(2S)$, and rescattering of final states:





- PRD80,074001(2009) E. van Beveren, G. Rupp



Interference with background due to $D\bar{D}$ threshold enhancement

Our plan:

Study the line-shape of the $\psi(3770)$ using an unitarized effective Lagrangian model.

Such model has been applied to some ligh-meson systems and, in some cases, an extra dynamically generated pole has been found.

- PRD93,014002(2016) Giacosa,Wolkanowski,Rischke: $a_0(980)$, $a_0(1450)$.
- NPB909,418(2016) Wolkanowski,Giacosa,Sołtysiak: $K_0^*(800)$, $K_0^*(1430)$.

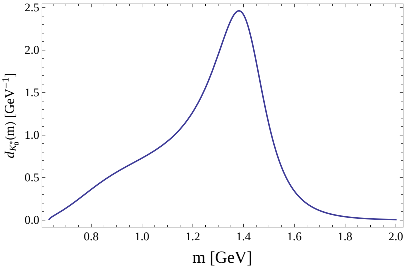


Figure: $K\pi$ channel

An Effective Lagrangian Model

Defining the Lagrangian

We consider the following decay of a vector to two pseudovectors:

$$\psi(3770) \to D^+ D^-$$

We define a Lagrangian density as

$$\mathcal{L} = \mathcal{L}_0 + \mathcal{L}_I$$

$$\mathcal{L}_0 = -\frac{1}{4}\Psi_{\mu\nu}\Psi^{\mu\nu} + \frac{1}{2}m_\psi^2\psi_\mu\psi^\mu + \frac{1}{2}\Big(\partial_\mu D^+ \partial^\mu D^- - m_D^2 D^+ D^-\Big)$$

$$\Psi_{\mu\nu} = \partial_\mu\psi_\nu - \partial_\nu\psi_\mu$$

$$\mathcal{L}_I = ig\psi_\mu\Big(\partial^\mu D^+ D^- - \partial^\mu D^- D^+\Big)$$

The 3-level decay width, for the spherically symmetric case, is given by

$$\Gamma(E) = \frac{g^2}{8\pi}\frac{p(E)}{s}|\mathcal{M}|^2.$$

The amplitude $|\mathcal{M}|^2$ is computed from the Lagrangian. It comes

$$|\mathcal{M}|^2 = \frac{1}{3}p^2(E)f(E),$$

where $f(E)$ is a cutoff function

$$f(E) = e^{-2p^2(E)/\Lambda^2}.$$

Free parameters:

g coupling for the vertex $\psi(3770)$ to D^+D^-

Λ cutoff parameter, $\Lambda \sim \frac{1}{\sqrt{<r^2>}}$

Propagator

The propagator for an unstable particle is given by

$$\Delta(E) = \frac{1}{E^2 - m_\psi^2 + \Sigma(E)}$$

where the loop-function, or self-energy, is

$$\Sigma(E) = \mathrm{Re}\ \Sigma(E) + i\mathrm{Im}\ \Sigma(E)$$

$$\mathrm{Im}\ \Sigma(E) = E\Gamma(E)$$

$$\mathrm{Re}\ \Sigma(E) = \Omega(E)$$

Dispersion relation, cauchy principal value

$$\Omega(E) = \frac{1}{\pi}\int_{th}^{\infty} \frac{\Gamma(q^2)}{E^2 - q^2} 2q\ dq$$

The introduction of $\Omega(E)$ in the propagator leads to a normalized spectral function (demonstration in PRD88,025010(2013)).

Spectral function with D^+D^- loop but no rescattering

Considering the once-subtracted dispersion relation

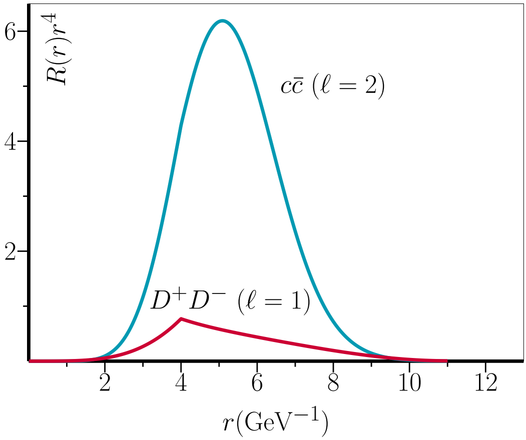
$$\Omega_{1S}(E) = \Omega(E) - \Omega(m_\psi)$$

$$\Sigma(E) = \Omega_{1S}(E) + i\Gamma(E)$$

$$\Delta(E) = \frac{1}{E^2 - m_\psi^2 + g^2\Omega_{1S}(E) + ig^2 E\Gamma(E)}$$

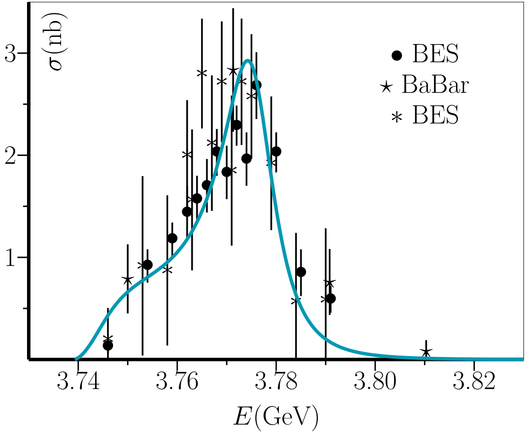
$$d_S(E) = \frac{2E}{\pi}\frac{Eg^2\Gamma(E)}{(E^2 - m_\psi^2)^2 + (g^2\Sigma(E))^2}$$

Estimating the cutoff through the wave-function of a system $c\bar{c}$ $(D - wave) -$ D^+D^- $(P - wave)$



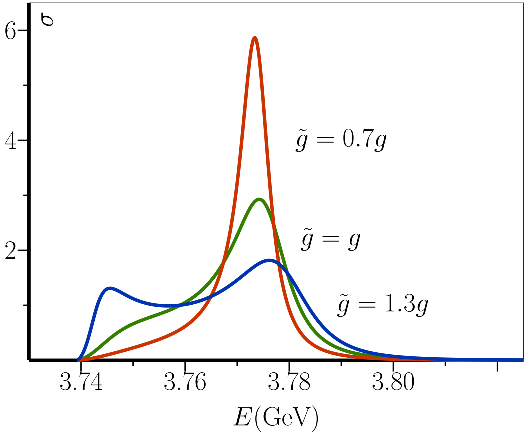
$\sqrt{< r^2 >} = 4.74\ \mathrm{GeV}^{-1} \sim 0.93$ fm.

Cutoff parameter: $\Lambda \sim \frac{1}{4.74\mathrm{GeV}^{-1}} = 211$ MeV



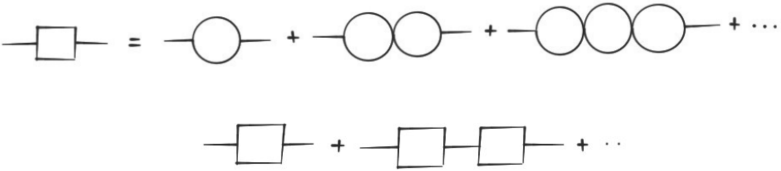
Two poles are found: $3744 - i11$ MeV and $3775 - i6$ MeV!

Dependence of the spectral function on the coupling g



$3741 - i20$ & $3774 - i3$ | $3744 - i11$ & $3775 - i6$ | $3743 - i4$ & $3778 - i9$

Spectral function with D^+D^- loop and rescattering of final states



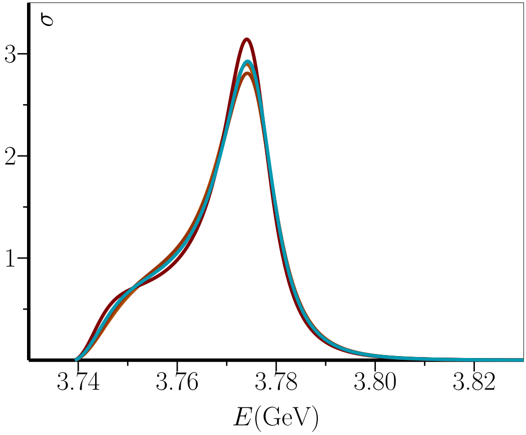
Redefining the loop function

$$\Sigma'(E) = g^2\Sigma + g^2\Sigma\lambda\Sigma + \cdots = g^2\Sigma\sum_{n=0}(\lambda\Sigma)^n = g^2\frac{\Sigma}{1-\lambda\Sigma}$$

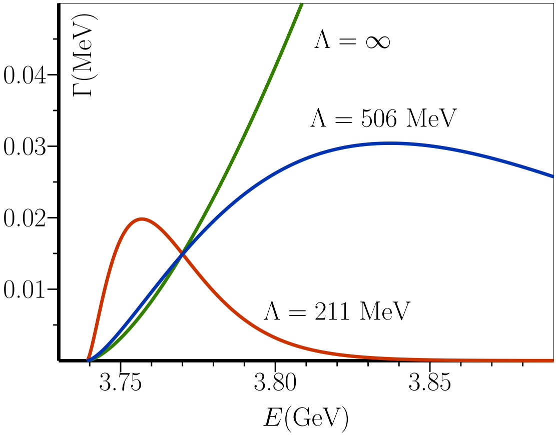
$$\Delta(E) = \frac{1}{E^2 - m_\psi^2 + g^2(\Sigma'(E) - \mathrm{Re}\ \Sigma(m_\psi))}$$

a new parameter λ is introduced (rescattering coupling)

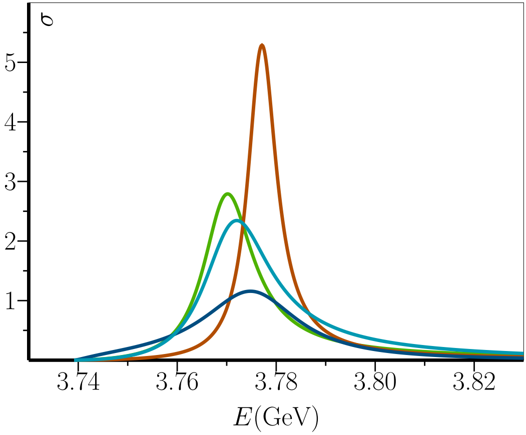
Influence of the rescattering over the spectral function, for $\Lambda = 211$ MeV



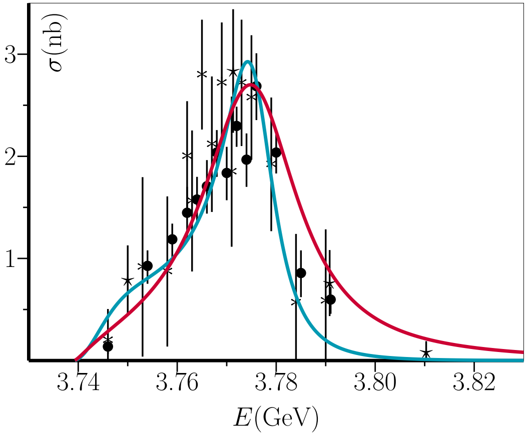
Width dependence on the cutoff



Influence of the rescattering over the spectral function, for $\Lambda = 506$ MeV



Fit with rescattering: channel D^+D^-



$\Lambda = 211$ MeV	$\Lambda = 506$ MeV
$3775 - i6$, $3744 - i11$	$3774 - i3$, $3742 - i13$

Summary and Perspectives

⧫ Given the increasing number of XYZ states, and the existence of many thresholds in the charmonium energy region, correct analysis of data are very important to understand the signals.

⧫ We are employing an effective Lagrangian approach to study the line-shape of the $\psi(3770)$. Independently of the final state rescattering, we find two poles associated with the cross section fitted to data.

Further studies:

- Production to leptons
- Include coupled-channels and/or other poles
- Compute phase-shifts

$\therefore$