Measurement of ψ(3770) resonance parameters with KEDR detector at VEPP-4M

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KEDR collaboration

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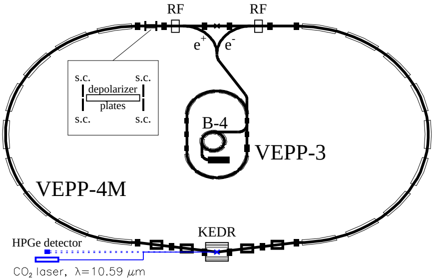
VEPP–4M collider

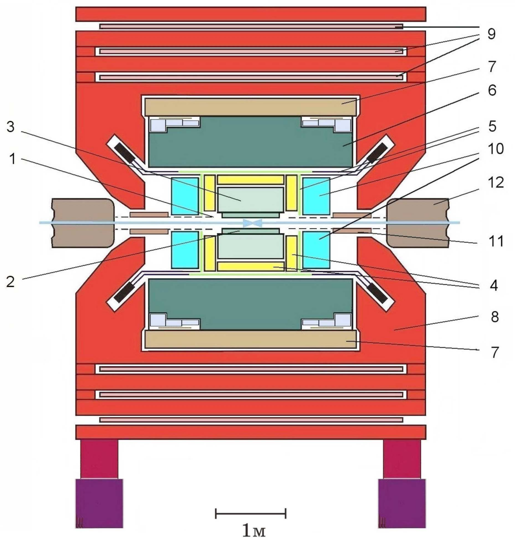


Beam energy	$1 \div 6$ GeV
Number of bunches	2×2
Beam current, $E = 1.8$ GeV	2.0 mA
Luminosity, $E = 1.8$ GeV	$1.5 \cdot 10^{30} \frac{1}{cm^2 \cdot s}$

- Resonant depolarization technique:
  Instant measurement accuracy $\simeq 1 \times 10^{-6}$
  Energy interpolation accuracy $(5 \div 15) \times 10^{-6}$ $(10 \div 30$ keV$)$

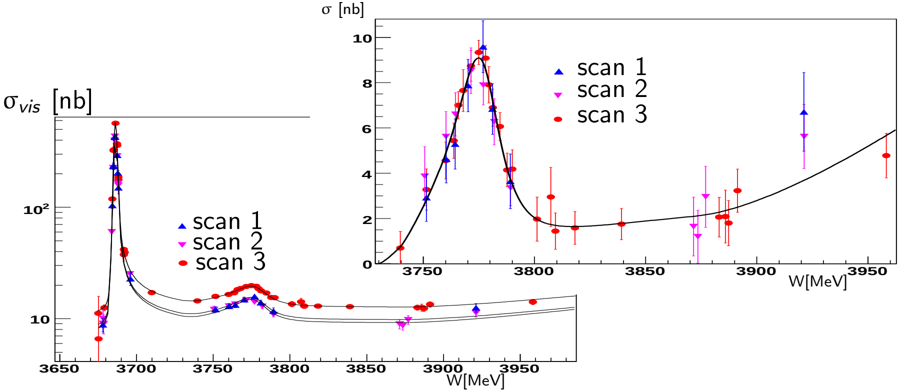
- Infra-red light Compton backscattering (2005):
  Statistical accuracy $\simeq 5 \times 10^{-5}$ / 30 minutes
  Systematic uncertainty $\simeq 3 \times 10^{-5}$ $(50 \div 70$ keV$)$

KEDR detector



1. Vacuum chamber
2. Vertex detector
3. Drift chamber
4. Aerogel counters
5. ToF–counters
6. LKr–calorimeter
7. Superconducting coil
8. Magnet yoke
9. Muon tubes
10. CsI-calorimeter
11. Compensation solenoid
12. VEPP–4M quadrupole

$\psi(2S) - \psi(3770)$ *scans*



Left: Visible cross section $e^+e^- \to hadrons$ vs. CM energy for the three scans(detection efficiencies are different)

Right: Cross section $e^+e^- \to hadrons$ after light quark etc. background subtraction.

The lines are the result of a simultaneous fit. $\int \mathcal{L}\, dt \simeq 2.4$ pb^{-1}

The lineshape for ψ(3770)

$$\sigma_{vis}^{fit}(W) = \varepsilon_{D\bar{D}} \int \left(\left| BW^0_{\psi(3770)} + A_{D^0\bar{D}^0} e^{i\phi} \right|^2 + \left| BW^+_{\psi(3770)} + A_{D^+D^-} e^{i\phi} \right|^2 \right)$$
$$\times \mathcal{F}(x, W')\ G(W, W') dW' dx$$
$$+ \sigma_{D^*\bar{D}+\bar{D}^*D} + \sigma_{\psi(2S)}(W) + \varepsilon_{\tau\tau}\sigma_{\tau\tau}(W) + \sigma_{cont}(W)$$

$$BW^+_{\psi(3770)} = -\frac{\sqrt{12\pi\Gamma_{ee}\Gamma_{D^+D^-}(W)}}{W^2 - M^2 + i\Gamma(W_f)M}, \quad |A_{D^+D^-}|^2 \sim Z(W)\, q_+^3 \left(\frac{m_{D^+}}{W}\right)^5 F(q_+, W)$$

$$BW^0_{\psi(3770)} = -\frac{\sqrt{12\pi\Gamma_{ee}\Gamma_{D^0\bar{D}^0}(W)}}{W^2 - M^2 + i\Gamma(W_f)M}, \quad |A_{D^0\bar{D}^0}|^2 \sim q_0^3 \left(\frac{m_{D^0}}{W}\right)^5 F(q_0, W)$$

$\mathcal{F}(x, W')$ – radiative correction (E.A.Kuraev, V.S.Fadin Sov.J.Nucl.Phys.41(466-472)1985)
$G(W, W')$ – Gaussian distribution of CM energy
$Z(W)$ – Coulomb interaction factor
$\sigma_{D^*\bar{D}+\bar{D}^*D}$ – $D^*\bar{D}$ cross section above threshold
$F(q_0, W), F(q_+, W)$ – model form factor functions

Energy-dependent $\psi(3770)$ *total width*

$$\Gamma_{D^0\bar{D}^0}(W) = \Gamma_0 \frac{M}{W} \frac{\frac{\rho_0^3}{\rho_0^2+1}}{\frac{\rho_{0r}^3}{\rho_{0r}^2+1} + Z(M)\frac{\rho_{+r}^3}{\rho_{+r}^2+1}} \; ; \; \Gamma_{D^+D^-}(W) = \Gamma_0 \frac{M}{W} \frac{Z(W)\frac{\rho_+^3}{\rho_+^2+1}}{\frac{\rho_{0r}^3}{\rho_{0r}^2+1} + Z(M)\frac{\rho_{+r}^3}{\rho_{+r}^2+1}}$$

$\Gamma_0 = \Gamma(M)$ is nominal resonance width,
m_{D^0} and m_{D^+} are D meson masses,
$\rho_i = q_i R_0$, where R_0 is interaction radius and
$q_i (i = 0, +, 0r, +r)$ are the breakup momenta for $D\bar{D}$ pair at the given W and at the resonance peak:

$$q_0 = \sqrt{\frac{W^2}{4} - m_{D^0}^2}, \quad q_{0r} = \sqrt{\frac{M^2}{4} - m_{D^0}^2},$$
$$q_+ = \sqrt{\frac{W^2}{4} - m_{D^+}^2}, \quad q_{+r} = \sqrt{\frac{M^2}{4} - m_{D^+}^2}$$

The lineshape for $\psi(3770)$ *(short review)*

Description of the $\psi(3770)$ resonance lineshape in the experiments to study inclusive cross section:

- **MARK-I 1977, DELCO 1978, MARK-II 1980**
  $\psi(3770)$ shape is non-relativistic p-wave Breit-Wigner
  with energy-dependent total width.
  Nonresonant $D\bar{D}$ cross section $\sigma_{D\bar{D}} \propto q^3$

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- **BES2 2008b** – double resonance $\psi(3770)$ lineshape

Extended vector-dominance model and alternatives

Mahiko Suzuki, Walter W. Wada, Phys.Rev.15, **3** *1977*

$$\sigma^{fit}_{vis}(W) = \varepsilon_{D\bar{D}} \int \left(\left| BW^0_{\psi(3770)} + BW^0_{\psi(2S)} e^{i\phi} + A_{D^0\bar{D}^0} e^{i\phi} \right|^2 + \left| BW^+_{\psi(3770)} + BW^+_{\psi(2S)} e^{i\phi} + A_{D^+D^-} e^{i\phi} \right|^2 \right) \times \mathcal{F}(x, W')\ G(W, W') dW' dx + \cdots$$

Fit of BaBar and Belle data by *Yuan-Jiang Zhang, Quiang Zhao* arxiv:0911.5641

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What are the alternatives ?

We checked a few possible form factor dependences on q and W:

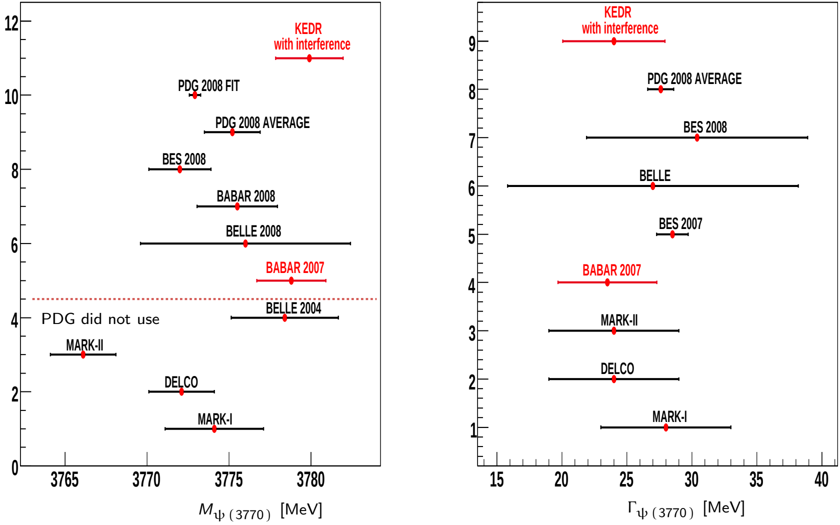
$$e^{-\frac{q^2}{a^2}} \; ; \; e^{-\frac{q^2}{a^2}} e^{ib(W-2\,m_{D^{0,+}})} \; ; \; \frac{1}{1+aq^b} \; ; \; \frac{e^{ib(W-2\,m_{D^{0,+}})}}{1+aq^4} \; ; \; \frac{1}{1+aq^2+bq^4} \; ;$$

$$\frac{1}{1+a(W-M_{\psi(2S)})+b(W-M_{\psi(2S)})^2} \; ; \; \frac{1}{(W-M_{\psi(2S)})^a} \; ; \; \frac{e^{ib(W-2\,m_{D^{0,+}})}}{(W-M_{\psi(2S)})^a}$$

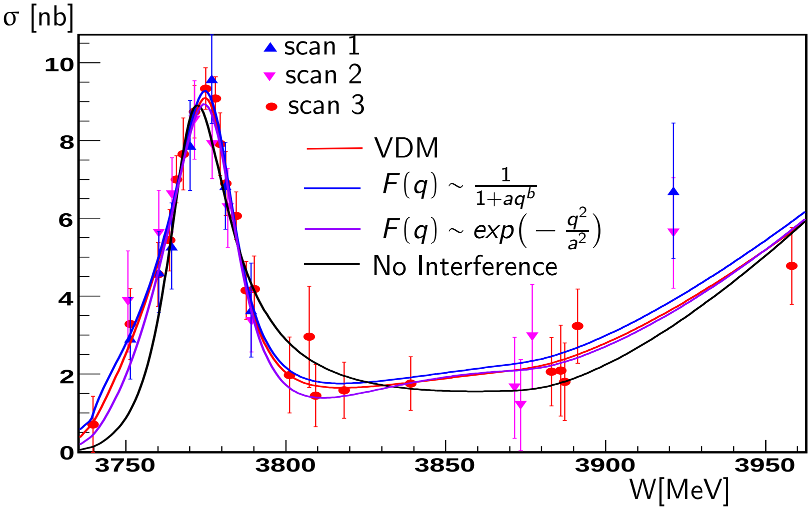
Fit results

Model,F(q)	$M_{\psi(3770)}$[MeV]	Γ_0 [MeV]	Γ_{ee}[eV]	$\sigma^{bg}_{D\bar{D}}(M)$[nb]	C.L.[%]
VDM	3779.9 ± 1.6	24.0 ± 3.6	166 ± 69	0.21 ± 0.21	91.1
No Interf.	3772.8 ± 0.5	23.3 ± 2.2	324 ± 28	0.23 ± 0.10	12.2
$e^{-\frac{q^2}{a^2}}$	3780.5 ± 2.1	27.9 ± 3.6	258 ± 81	3.67 ± 1.69	86.2
$\frac{1}{1+aq^b}$	3779.4 ± 1.5	24.0 ± 3.6	168 ± 62	3.38 ± 0.85	90.5
$\frac{1}{1+aq^2+bq^4}$	3779.5 ± 1.5	24.8 ± 3.3	184 ± 61	3.29 ± 0.39	90.3
$\frac{e^{ib(W-2m_{D^{0,+}})}}{1+aq^4}$	3778.7 ± 1.7	25.3 ± 3.3	477 ± 236	2.81 ± 0.94	91.2
$\frac{1}{(W-M_{\psi(2S)})^a}$	3780.4 ± 1.7	25.3 ± 3.8	185 ± 75	3.99 ± 1.25	89.8
$\frac{e^{ib(W-2m_{D^{0,+}})}}{(W-M_{\psi(2S)})^a}$	3780.1 ± 1.5	25.1 ± 3.8	322 ± 246	3.52 ± 1.10	90.0

Comparison of different experiments



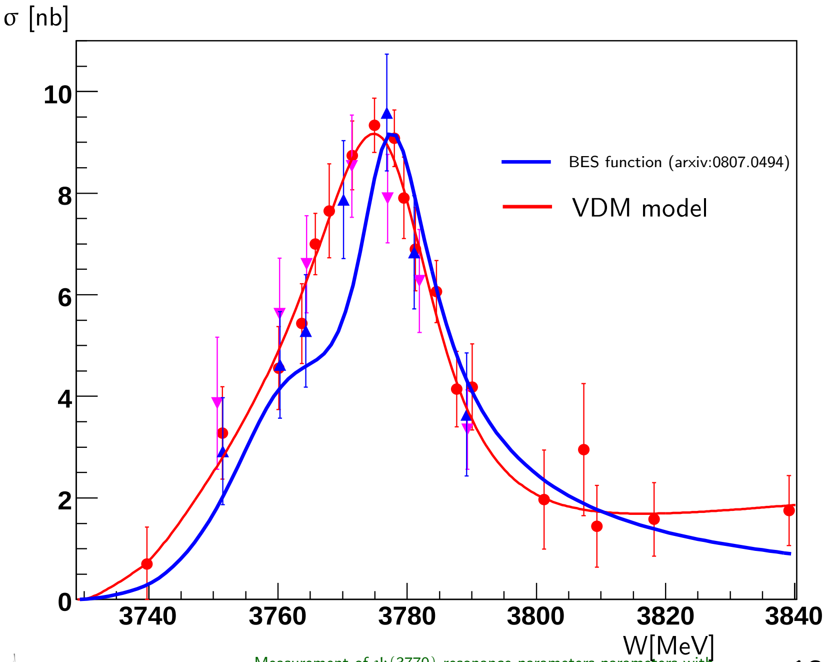
Fits curves for different models



Conclusions

- The parameters of $\psi(3770)$ are measured using the data collected by KEDR detector at VEPP-4M collider in 2004 and 2006.
- Model errors were underestimated at all previous works where total cross section was fitted.
- Correct resonance description should include interference and form factor.
- We did not observe two resonances near $\psi(3770)$ energy region.

$$M_{\psi(3770)} = 3779.9 \pm 1.6^{+0.6}_{-1.3}\ \text{MeV}$$
$$\Gamma_{\psi(3770)} = 24.0 \pm 3.6^{+1.3}_{-0.7}\ \text{MeV}$$


σ [nb]
10
8
6
4
2
0
3740
3760
3780
3800
3820
3840
W[MeV]
BES function (arxiv:0807.0494)
VDM model

Parametrization of $\psi(2S)$

$$\sigma_{\psi(2S)}(W) = \frac{12\pi}{W^2}\frac{\Gamma_{ee,\psi(2S)}\Gamma_{h,\psi(2S)}}{\Gamma_{\psi(2S)}M_{\psi(2S)}}\left[\left(1+\delta_{\rm sf}\right)\mathrm{Im}\, f - \left(1+\frac{11}{12}\beta\right)\frac{2\alpha\sqrt{R}\Gamma_{\psi(2S)}M_{\psi(2S)}}{3W\sqrt{\Gamma_{ee,\psi(2S)}\Gamma_{h,\psi(2S)}}}\lambda\ \mathrm{Re}\, f + \cdots\right],$$

Here α is the fine structure constant, $R = \sigma^{(h)}/\sigma^{(\mu\mu)}$,
$\lambda = 0.023 \pm 0.009$

$$\delta_{\rm sf} = \frac{3}{4}\beta + \frac{\alpha}{\pi}\left(\frac{\pi^2}{3}-\frac{1}{2}\right) + \beta^2\left(\frac{37}{96}-\frac{\pi^2}{12}-\frac{1}{36}\ln\frac{W}{m_e}\right)$$

$$\beta = \frac{4\alpha}{\pi}\left(\ln\frac{W}{m_e}-\frac{1}{2}\right)$$

$$f = \frac{\pi\beta}{\sin\pi\beta}\left(\frac{M^2_{\psi(2S)}}{W^2} - 1 - i\frac{\Gamma_{\psi(2S)}M_{\psi(2S)}}{W^2}\right)^{\beta-1}$$

$$\sigma^{\rm fit}_{\psi(2S)}(W) = \varepsilon_{\psi(2S)}\int \sigma_{\psi(2S)}(W')G(W,W')\,dW'$$

Event selection

2004

1. ≥ 3 charged tracks
2. ≥ 2 charged tracks from IP
3. Sphericity more than 0.05

Selection efficiency is about 66%

2006

1. ≥ 3 charged tracks
2. ≥ 1 charged tracks from IP and ≥ 5 clusters
   OR
   ≥ 2 charged tracks from IP and ≥ 4 clusters
   OR
   ≥ 3 charged tracks from IP and ≥ 3 clusters
3. An energy deposited in calorimeter ≥ 0.25 energy beam

Selection efficiency is about 78%

$\psi(3770)$ *mass systematic errors*

Source	Error [MeV]
Non-resonant cross section form	$^{+0.5}_{-1.2}$
Fitting form (R_0 variations)	0.3
Luminosity measurement	0.2
Detection efficiency instability	0.1
Event selection	0.1
Absolute energy determination	0.03
Sum in quadrature	$\approx ^{+0.6}_{-1.3}$ MeV

Table: The main systematic uncertainties in $\psi(3770)$ mass (MeV)

$\psi(3770)$ *total width systematic errors*

Source	Error [MeV]
Non-resonant cross section form	$^{+1.3}_{-0.7}$
Fitting form (R_0 variations)	0.2
Luminosity measurement	0.1
Event selection	0.1
Detection efficiency instability	0.1
Sum in quadrature	$\approx ^{+1.3}_{-0.7}$ MeV

Table: The main systematic uncertainties in $\psi(3770)$ width (MeV)