Measurement of $\psi(3770)$ resonance parameters with KEDR detector at VEPP-4M

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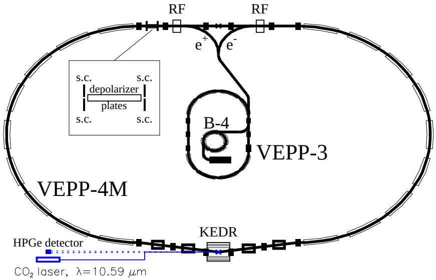
Outline

- VEPP-4M collider and KEDR detector
- Motivations to this work
- The multihadron cross section in the vicinity of $\psi(3770)$
- Results
- Conclusions

VEPP–4M collider

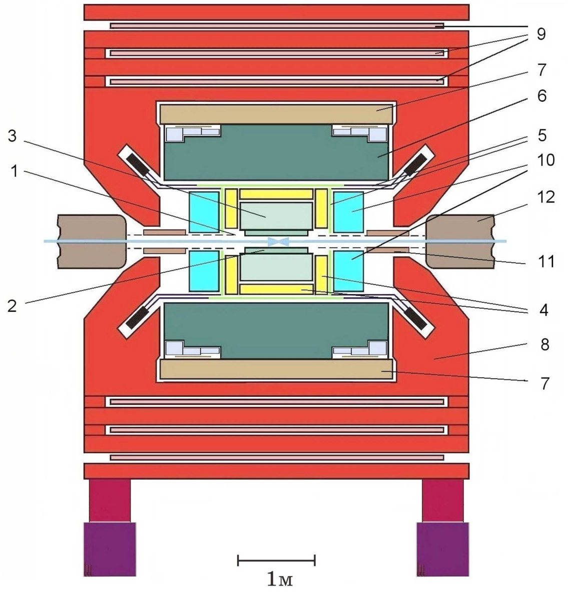


Beam energy	$1 \div 5.5$ GeV
Number of bunches	2×2
Beam current, $E = 1.8$ GeV	2.0 mA
Luminosity, $E = 1.8$ GeV	$1.5 \cdot 10^{30} \frac{1}{cm^2 \cdot s}$

- 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. Threshold aerogel counters
5. ToF–counters
6. Liquid krypton calorimeter
7. Superconducting coil
8. Magnet yoke
9. Muon tubes
10. CsI-calorimeter
11. Compensation solenoid
12. VEPP–4M quadrupole
13. Electron tagging system (is not shown here)

Experimental motivation

ψ(3770) mass and width are known with relatively large uncertainties. It seems that results depend on chosen assumption of non-resonant contribution.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
3772.92±0.35	**OUR FIT**	Error includes scale factor of 1.1.			
3775.2±1.7	**OUR AVERAGE**	Error includes scale factor of 1.4. See the ideogram.			
3772.0±1.9		[1] ABLIKIM	08D	BES2	$e^+e^- \to$ hadrons
3775.5±2.4±0.5	57	AUBERT	08B	BABR	$B \to D\overline{D}K$
3776±5±4	68	BRODZICKA	08	BELL	$B^+ \to D^0\overline{D}^0K^+$
3778.8±1.9±0.9		AUBERT	07BE	BABR	$e^+e^- \to D\overline{D}\gamma$
* * * We do not use the following data for averages, fits, limits, *etc.* * * *					
3778.4±3.0±1.3	34	CHISTOV	04	BELL	Sup. by BRODZICKA 2008

Theoretical motivation

- Theoretical description of $\psi(3770)$ is still questionable. Is it mixture

  $|\psi(3770)> = \cos\theta\ |1^3D_1> + \sin\theta\ |2^3S_1>$

  or there is another way to explain $\psi(3770)$ parameters ?

- $\psi(3770)$ mass predictions from potential models do not agree well with experimental data.

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 $\sigma_{D\bar{D}} \propto q^3$. Does not interfere with resonance term.

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  nonstandard treatment of vacuum polarization

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

The multihadron cross section in the vicinity of $\psi(3770)$

$$\sigma_{m.h.} = \sigma_{D^+D^-} + \sigma_{D^0\bar{D}^0} + \sigma_{bg}$$

let's consider $\sigma_{D^+D^-}$

$$\sigma_{D^+D^-} \propto \left| A_{\psi(3770)} + B \cdot e^{i\phi} \right|^2$$

where

$$A_{\psi(3770)} = -\frac{\sqrt{12\pi\Gamma_{ee}\Gamma_{D^+D^-}}}{W^2 - M^2 + i\Gamma M} \qquad |B|^2 \propto q_+^3 \cdot Z(W) \cdot F(q_+, W)$$

$$\Gamma_{D^+D^-} \propto \Gamma_0 \frac{M}{W} Z(W) \frac{\rho_+^3}{\rho_+^2 + 1} \qquad q_+ = \sqrt{\frac{W^2}{4} - m_{D^+}^2} \text{ (D momentum)}$$

$\rho_+ = q_+ R_0$ (R_0 is interaction radius), $Z(W)$ – Coulomb interaction factor
$\sigma_{D^0\bar{D}^0}$ analogously with $Z = 1$

Extended vector-dominance model and alternatives

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

$$B = A_{\psi(2S)} + A_0\,,\ \text{ with } A_{\psi(2S)} \text{ analogous to } A_{\psi(3770)}$$

$$\Gamma_{\psi(2S)} = \Gamma^0_{\psi(2S)} + \Gamma^{D\bar{D}}_{\psi(2S)}$$

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

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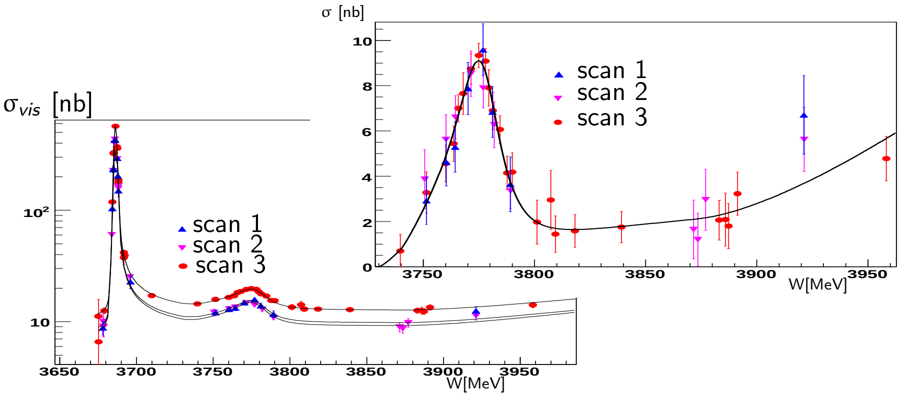
We checked a few possible B dependences on q and W:

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

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

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



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

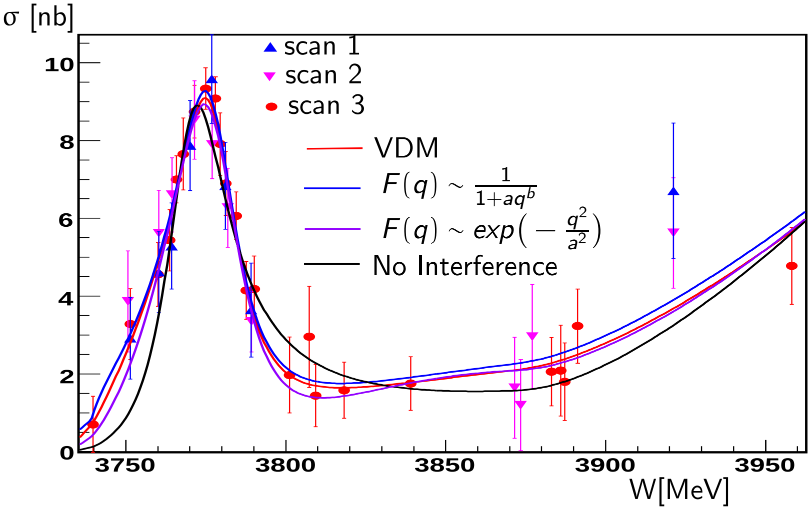
Right: Cross section $e^+e^- \to$ *hadrons* after light quark etc.
background subtraction.

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

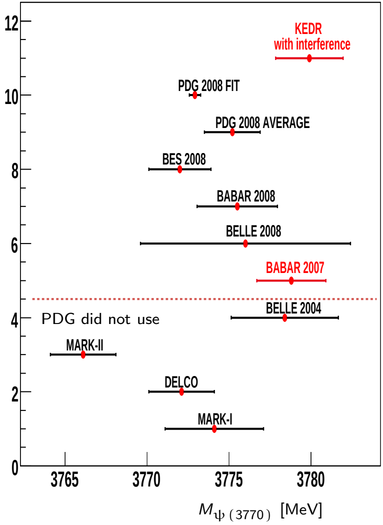
Fit results

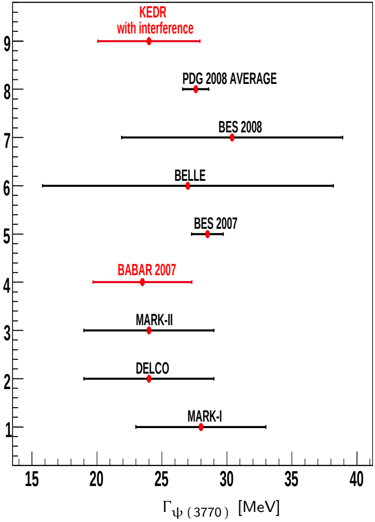
Model,F(q)	$M_{\psi(3770)}$[MeV]	Γ_0 [MeV]	Γ_{ee}[eV]	$\sigma^{D\bar{D}}_{n.r.}(M)$[nb]	C.L.[%]
VDM	3779.9 ± 1.6	24.0 ± 3.6	166 ± 69	3.20 ± 0.95	91.1
No Interf.	3772.8 ± 0.5	23.3 ± 2.2	324 ± 28	0.23 ± 0.10	12.2
$e^{-\frac{q^2}{a^2}}$	3780.5 ± 2.1	27.9 ± 3.6	258 ± 81	3.67 ± 1.69	86.2
$\frac{1}{1+aq^b}$	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

Fits curves for different models



Comparison of different experiments





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

Source	Error [MeV]
Non-resonant cross section shape	${}^{+0.5}_{-1.2}$
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)

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 in 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.

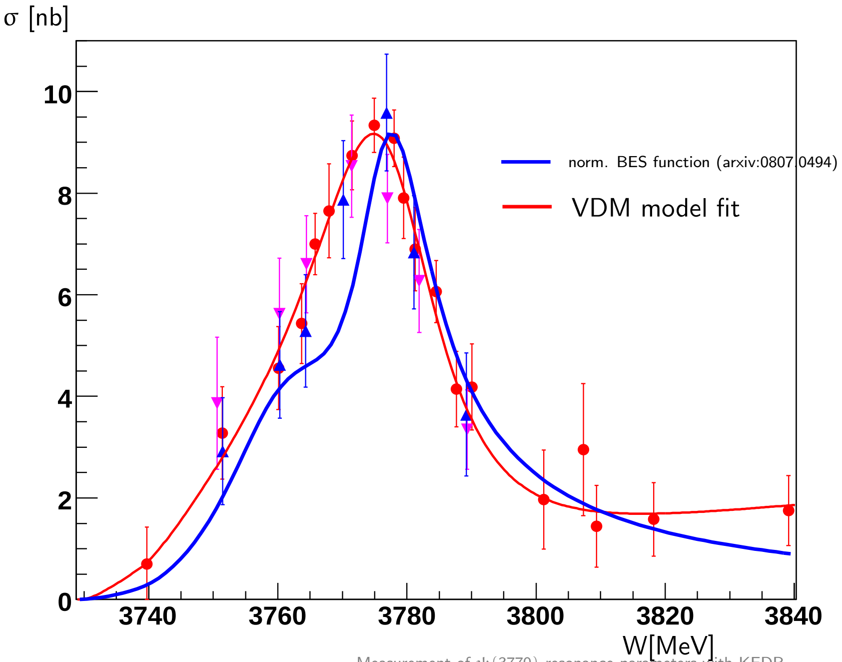
$$M_{\psi(3770)} = 3779.9 \pm 1.6^{+0.6}_{-1.3}\ \text{MeV}$$
$$\Gamma_{\psi(3770)} = 24.0 \pm 3.6^{+1.3}_{-0.7}\ \text{MeV}$$

BACKUP

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

Source	Error [MeV]
Non-resonant cross section shape	$^{+1.3}_{-0.7}$
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)


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

The lineshape for $\psi(3770)$ *in detail*

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

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

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

$\mathcal{F}(x, W')$ – 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 in detail

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

$\Gamma_0 = \Gamma(M)$ 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:

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

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

Event selection

2004

1. $\geq$ 4 charged tracks
2. $\geq$ 2 charged tracks from IP
3. Sphericity more than 0.05

Selection efficiency is about 64%

2006

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

Selection efficiency is about 78%