Studies of $\psi(2S)$ and $\psi(3770)$ at KEDR

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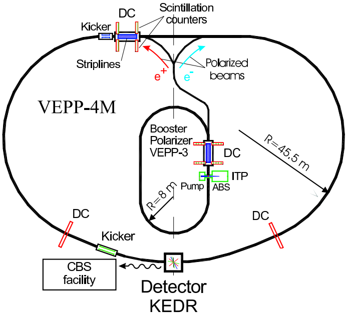
Outline

- VEPP-4M collider and KEDR detector
- Measurement of main parameters of the $\psi(2S)$ resonance
- Measurement of $\psi(3770)$ parameters
- Conclusion

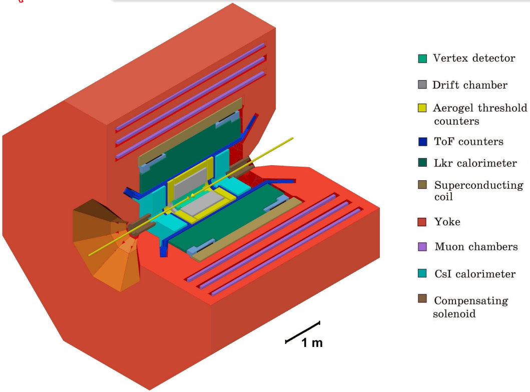
VEPP-4M and KEDR



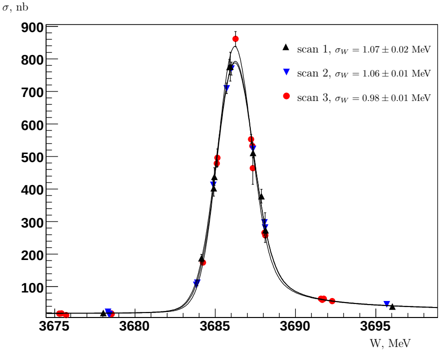
Beam energy	$1 \div 5$ GeV
Number of bunches	2×2
Luminosity at 1.8 GeV	1.5×10^{30} cm^{-2} s^{-1}

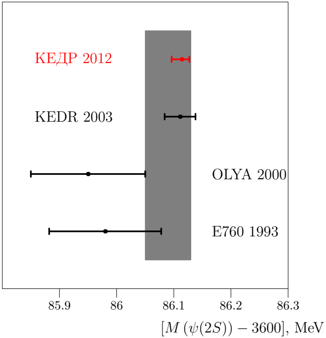
Energy determination uncertainty:

- Resonant depolarization technique $10 \div 30$ keV
- Infra-red light Compton backscattering ~ 100 keV



Measurement of $\psi(2S)$ parameters



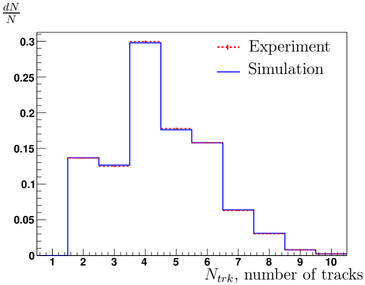


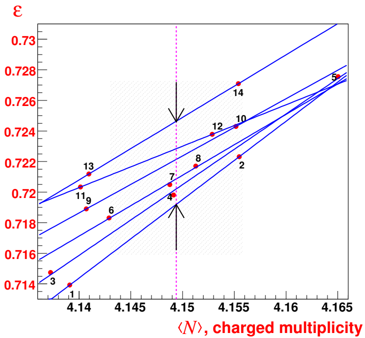
Scans 2004, 2006 $\int \mathcal{L}dt \simeq 0.6$ pb^{-1}

$$M = 3686.114 \pm 0.007(stat.) \pm 0.011(syst.)^{+0.002}_{-0.012}(model)\ \text{MeV}$$

The third uncertainty quoted is an estimate of the model dependence of the result due to assumptions on the interference effects.

$\Gamma_{ee} \times \mathcal{B}_{hadrons}$ measurement





$\psi \to$ *hadrons* MC tuning

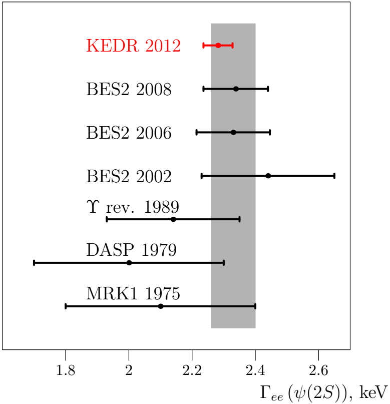
1. select a critical option or parameter and modify it using an educated guess
2. select a complementary parameter and modify it to find the value at which the observed charged multiplicity agrees with experiment
3. calculate the detection efficiency and compare it with previous results to estimate the uncertainty

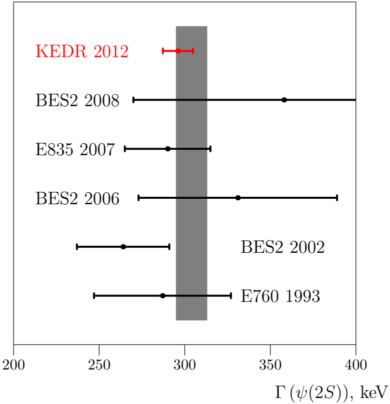
The main systematic uncertainties (simplified list)

Absolute luminosity measurement	$\sim 1.3\%$
$\psi(2S)$ decay simulation	$\sim 1.0\%$
Detector response	$\sim 0.5\%$
Accelerator related effects	$\sim 0.3\%$
Other uncertainties	$\sim 0.3\%$

$$\Gamma_{ee} \times \mathcal{B}_{hadrons} = 2.233 \pm 0.015 \pm 0.037 \pm 0.020\ \text{keV}$$

Results for $\psi(2S)$





Using $\mathcal{B}^{PDG}_{hadrons} = 0.9785 \pm 0.0013$ and $\mathcal{B}^{PDG}_{ee} = 0.00772 \pm 0.00017$

$$\Gamma_{ee} = 2.282 \pm 0.015 \pm 0.038 \pm 0.021\,\text{keV}$$

$$\Gamma = 296 \pm 2 \pm 8 \pm 3\,\text{keV}$$

Detailed analysis and $\psi(2S)$ results
Phys. Lett. B 711 (2012), 280-291

Incomplete compilation of results on $\psi(3770)$ mass

Analysis	M, MeV	Comments
MARK-I	3774.1 ± 3	$e^+e^- \to$ hadrons $^{(a)}$
DELCO	3772.1 ± 2	$e^+e^- \to$ hadrons $^{(a)}$
MARK-II	3766.1 ± 2	$e^+e^- \to$ hadrons $^{(a)}$
BELLE (2004)	$3778.4 \pm 3.0 \pm 1.3$	$B \to D^0\overline{D}^0K^+$ $^{(b)}$
BES-II (2006)	$3772.4 \pm 0.4 \pm 0.3$	$e^+e^- \to$ hadrons $^{(a)}$
BES-II (2008)	3772.0 ± 1.9	$e^+e^- \to$ hadrons
BELLE (2008)	$3776.0 \pm 5.0 \pm 4.0$	$B \to D^0\overline{D}^0K^+$
BABAR (2008)	$3775.5 \pm 2.4 \pm 0.5$	$B \to D\bar{D}K$
BABAR (2007)	$3778.8 \pm 1.9 \pm 0.9$	$e^+e^- \to D\overline{D}\gamma$ $^{(c)}$
Hai-Bo Li *et al.* 2009, data of BES+BELLE	$3776.0 \pm 1.0 \pm ?$	$e^+e^- \to D\overline{D}$ + $e^+e^- \to D\overline{D}\gamma$ $^{(c,d,e)}$
Yu.-Ji. Zhang *et al.* 2009, BES data	$3774.0 \pm 1.0 \pm ?$	$e^+e^- \to D\overline{D}\gamma$ $e^+e^- \to D\overline{D}$ $^{(c,d,e)}$

$^{(a)}$ — omitted in the latest PDG edition (2010)

$^{(b)}$ — the result on $\mathcal{B}(B \to D^0\overline{D}^0K^+)$ is superseded by BELLE (2008)

$^{(c)}$ — interference between resonant and nonresonant $D\overline{D}$ production is taken into account

$^{(d)}$ — the authors analyze the published data, systematic uncertainties are not evaluated

$^{(e)}$ — electron width of $\psi(3770)$ is fixed at the world average value causing a negative bias in the mass

Description of the $\psi(3770)$ resonance lineshape

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 $D\overline{D}$ cross section $\sigma_{D\overline{D}} \propto q^3$ (point-like particles)
- **BES2 2006** – radiative correction added,
  nonstandard treatment of vacuum polarization
- **BES2 2008a** – combined fit with higher mass resonances
- **BES2 2008b** – double resonance $\psi(3770)$ lineshape

One can see the following problems

1. The resonance-continuum interference was ignored
2. Analyses assumed the simplest shape of nonresonant $D\overline{D}$ cross section similar to that for point-like pseudoscalars in QED

Conditions of analysis near of $\psi(3770)$ region

- Data analysis takes into account interference between the resonant and nonresonant $D\overline{D}$ production.

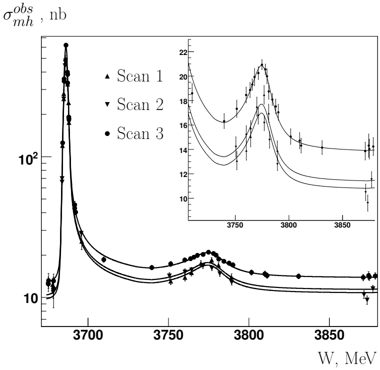
- The nonresonant form factor can be obtained with an application of the Vector Dominance Model (VDM) to charm production. In this work we employ VDM in a simplified form where

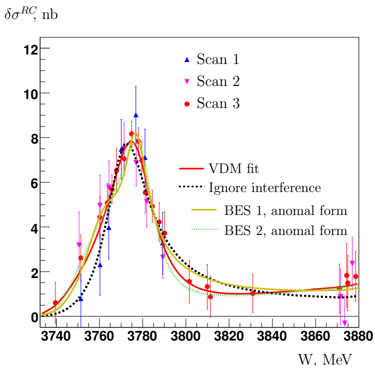
$$F_{D\overline{D}}^{nonresonant}(W) = F_{D\overline{D}}^{\psi(2S)}(W) + F_0$$

  where $F_{D\overline{D}}^{\psi(2S)}(W)$ is the main part of the form factor corresponding to the $\psi(2S)$ and F_0 is a real constant representing the contributions of the $\psi(4040)$ and higher ψ's.

- To evaluate the model dependence of the $\psi(3770)$ parameters we tried a few nonresonant form factor parameterizations, which do not assume VDM.

Measurement of $\psi(3770)$ parameters





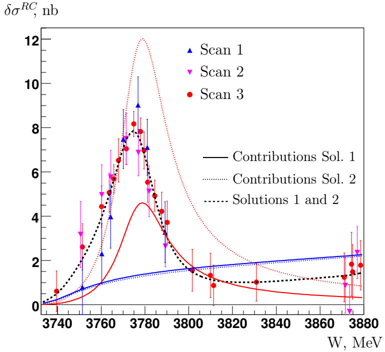
Scans 2004, 2006 $\int \mathcal{L}dt \sim 1.9\ \text{pb}^{-1}$. The observed multihadron cross section as a function of the c.m. energy for the three scans. The curves are the results of the vector dominance fit.

Excess of the multihadron cross section in the $\psi(3770)$ region. The curves show relevant parts of the fits. All data are corrected for the detection efficiency which is different in the three scans.

$$M = 3779.2\ ^{+1.8}_{-1.7}\ ^{+0.5}_{-0.7}\ ^{+0.3}_{-0.3}\ \text{MeV}$$

$$\Gamma = 24.9\ ^{+4.6}_{-4.0}\ ^{+0.5}_{-0.6}\ ^{+0.2}_{-0.9}\ \text{MeV}$$

Ambiguity of $\psi(3770)$ resonance parameters



Excess of the multihadron cross section in the $\psi(3770)$ region. Solid and short-dashed curves correspond to two VDM solutions. Resonant and non-resonant parts are presented separately.

$$(1)\quad \Gamma_{ee} = 154\,^{+79}_{-58}\,^{+17}_{-9}\,^{+13}_{-25}\ \text{eV},\quad \sigma^{NR}_{D\bar{D}} = 1.4 \pm 0.7\,^{+0.1}_{-0.2}\,^{+0.3}_{-0.2}\ \text{nb}$$

$$(2)\quad \Gamma_{ee} = 414\,^{+72}_{-80}\,^{+24}_{-26}\,^{+90}_{-10}\ \text{eV},\quad \sigma^{NR}_{D\bar{D}} = 1.3 \pm 0.7\,^{+0.1}_{-0.2}\,^{+0.6}_{-0.2}\ \text{nb}$$

The phase shifts of the $\psi(3770)$ amplitude relative to the negative nonresonant amplitude are 171 ± 17 and 240 ± 9 degrees for solutions (1) and (2), respectively.

Detailed analysis published in
Phys. Lett. B 711 (2012), 292-300

Conclusion

Analysis of the $\psi(2S)$ resonance

A high-precision determination of the main parameters of the $\psi(2S)$ resonance has been performed.

$$M = 3686.114 \pm 0.007 \pm 0.011\ {}^{+0.002}_{-0.012}\ \text{MeV}$$

$$\Gamma_{ee} \times \mathcal{B}_{hadrons} = 2.233 \pm 0.015 \pm 0.037 \pm 0.020\,\text{keV}$$

Analysis of the $\psi(3770)$ resonance

Our results for the mass and total width of $\psi(3770)$ are

$$M = 3779.2\ {}^{+1.8}_{-1.7}\ {}^{+0.5}_{-0.7}\ {}^{+0.3}_{-0.3}\ \text{MeV},$$

$$\Gamma = 24.9\ {}^{+4.6}_{-4.0}\ {}^{+0.5}_{-0.6}\ {}^{+0.2}_{-0.9}\ \text{MeV}.$$

The result on the $\psi(3770)$ mass agrees with that by BaBar also taking into account interference. For the electron partial width two possible solutions have been found:

$$(1)\quad \Gamma_{ee} = 154\ {}^{+79}_{-58}\ {}^{+17}_{-9}\ {}^{+13}_{-25}\ \text{eV},\quad \sigma^{NR}_{D\overline{D}} = 1.4 \pm 0.7\ {}^{+0.1}_{-0.2}\ {}^{+0.3}_{-0.2}\ \text{nb},$$

$$(2)\quad \Gamma_{ee} = 414\ {}^{+72}_{-80}\ {}^{+24}_{-26}\ {}^{+90}_{-10}\ \text{eV},\quad \sigma^{NR}_{D\overline{D}} = 1.3 \pm 0.7\ {}^{+0.1}_{-0.2}\ {}^{+0.6}_{-0.2}\ \text{nb}.$$

Our statistics are insufficient to prefer one solution to another. The solution (2) mitigates the problem of non-$D\overline{D}$ decays but is disfavored by potential models.

BACKUP SLIDES

$\Gamma_{ee} \times \mathcal{B}$ systematic uncertainties

The dominating systematic uncertainties in the $\Gamma_{ee} \times \mathcal{B}$, product for three scans (%). The correlated parts of the uncertainties are also presented. The inaccuracy of about 0.9% due to possible interference phase correlation is not included.

Source	Scan 1	Scan 2	Scan 3	Common_{12}	Common_{123}
Absolute luminosity measurement	1.6	1.7	1.2	1.6	0.5
$\psi(2S)$decay simulation	1.0	1.0	1.1	1.0	1.0
Detector response					
Trigger efficiency	0.2	0.2	0.2	0.2	0.2
Nuclear interaction	0.2	0.2	0.3	0.2	0.2
Cross talks in VD	0.1	0.17	0.1	0.1	0.1
Variation of cuts	0.5	0.3	0.6	0.3	0.3
Accelerator related effects					
Beam energy determination	0.15	0.18	0.6	0.15	0.15
Non-Gaussian energy distribution	0.2	0.2	0.2	0.2	0.2
Residual background	$<$0.1	$<$0.1	$<$0.1	$<$0.1	$<$0.1
Other uncertainties	0.3	0.3	0.3	0.3	0.3
Sum in quadrature	$\approx$2.0	$\approx$2.1	$\approx$1.9	$\approx$2.0	$\approx$1.3

The main sources of systematic uncertainty in $\psi(3770)$ parameters

Systematic uncertainties on the $\psi(3770)$ mass, total width and electron partial width. For the latter the uncertainties of two solutions are presented where different. The uncertainty on the nonresonant $D\overline{D}$ cross section is also presented.

Source	M[MeV]	Γ[MeV]	Γ_{ee}[%]	$\sigma^{NR}_{D\overline{D}}$[%]
Theoretical uncertainties and external data precision				
$\mathcal{B}_{nD\overline{D}}$	${}^{+0.0}_{-0.5}$	${}^{+0.0}_{-0.2}$	${}^{+8.8}_{-0} / {}^{+0}_{-2.3}$	${}^{+0}_{-12.}$
R_0 value in $\Gamma(W)$	0.3	0.3	2.	1.5
$\Gamma_{D^0\overline{D}^0}/\Gamma_{D^+D^-}$	0.1	0.1	0.4	0.8
$D, \overline{D}$ masses	0.06	0.04	0.3	0.5
$D\overline{D}\pi$ cross section	0.15	0.05	1.	2.
Detector and accelerator related uncertainties				
Det. efficiency variation	0.03	0.04	2.4	5.
Hadronic event selection	0.3	0.3	3.	5.
Residual background	0.06	0.3	2.9	3.
Luminosity measurement	0.1	0.1	2.	2.
Beam energy	0.03	–	–	–
Sum in quadrature	${}^{+0.48}_{-0.69}$	${}^{+0.54}_{-0.58}$	${}^{+10.5}_{-5.7} / {}^{+5.7}_{-6.1}$	${}^{+8.}_{-14.}$

$\psi(3770)$ analysis

Detection efficiency for the processes of interest and its variation in the experiment energy range $\Delta W \approx 200$ MeV.

Process	ϵ_{2004}	ϵ_{2006}	$\Delta\epsilon/\epsilon$, %
D^+D^-	0.75 ± 0.02	0.84 ± 0.02	$+1.0 \pm 0.3$
$D^0\overline{D}^0$	0.74 ± 0.02	0.81 ± 0.02	$+1.0 \pm 0.3$
$\psi(2S)$	0.63 ± 0.01	0.72 ± 0.01	-0.1 ± 0.1
J/ψ	0.50 ± 0.02	0.60 ± 0.02	-0.2 ± 0.1
uds	0.55 ± 0.02	0.69 ± 0.02	$+2.1 \pm 0.5$

$\psi(3770)$ fit results for the vector dominance compared to the ignored-interference case.

Sol.	M, MeV	Γ, MeV	Γ_{ee}, eV	ϕ, degrees	$\Gamma^{\psi(2S)}_{D\overline{D}}$, MeV	F_0	$\sigma^{NR}_{D\overline{D}}$, nb	$P(\chi^2)$,%
1	$3779.3^{+1.8}_{-1.7}$	$25.3^{+4.4}_{-3.9}$	160^{+78}_{-58}	170.7 ± 16.7	$12.9^{+18.5}_{-11.8}$	$-4.8^{+3.0}_{-3.6}$	1.83 ± 0.96	35.7
2	$3779.3^{+1.8}_{-1.6}$	$25.3^{+4.6}_{-4.0}$	420^{+72}_{-80}	239.6 ± 8.6	$11.5^{+16.5}_{-10.5}$	$-4.9^{+3.3}_{-3.7}$	1.71 ± 0.86	35.7
i.i.	3773.3 ± 0.5	$23.3^{+2.5}_{-2.2}$	249^{+25}_{-22}	-	-	-	$0.07^{+0.09}_{-0.07}$	7.5
PDG2010	3772.9 ± 0.4	27.3 ± 1.0	265 ± 18	-	-	-	-	-

The nonresonant part of the form factor can be written as

$$F^{nonresonant}_{D\overline{D}}(W) = \frac{1}{|1 - \Pi_0(W)|} f_D(W) \qquad (1)$$

with $f_D(W) = 1$ for point-like particles. We used

$$f_D = -\frac{g_q}{(1 + a_q\, q_D^2 + b_q\, q_D^4)^n} \qquad (n = 0.5, 1). \qquad (2)$$

The minus sign is chosen to match the $\psi(2S)$ dominance expectations. Alternatively, the dependence on $W - m_D$

$$f_D = -\frac{g_W}{1 + a_W(W - 2m_D) + b_W(W - 2m_D)^2} \qquad (3)$$

and combined dependences

$$f_D = -\frac{g_{qW}}{(1 + a_{qW}\,(W - 2m_D) + b_{qW}\, q_D^2)^n}, \qquad (4)$$

$$f_D = \frac{g_m}{a_m - W}\left(1 + \frac{i\, b_m\, \beta_D^n}{a_m - W}\right) \qquad (n = 0, 1, 3)\,. \qquad (5)$$

Model	Mass, total width and $P(\chi^2)$			Solution 1 (smaller ϕ)			Solution 2 (larger ϕ)		
Equation	M, MeV	Γ, MeV	$P(\chi^2)$,%	ϕ, degrees	Γ_{ee} , eV	$\sigma^{NR}_{D\overline{D}}$, nb	ϕ, degrees	Γ_{ee} , eV	$\sigma^{NR}_{D\overline{D}}$, nb
(2) n=1	$3779.1^{+2.0}_{-1.6}$	$24.4^{+5.0}_{-3.6}$	32.7	167.6 ± 16.0	146^{+66}_{-48}	1.82 ± 0.76	243.1 ± 9.5	417^{+75}_{-65}	1.76 ± 0.73
(2) n=0.5	$3779.0^{+1.7}_{-1.6}$	$25.5^{+3.0}_{-3.5}$	33.1	172.2 ± 17.3	172^{+241}_{-66}	1.59 ± 0.86	241.0 ± 15.6	418^{+76}_{-65}	1.55 ± 0.66
(3)	$3779.0^{+2.1}_{-1.9}$	$24.4^{+5.1}_{-3.7}$	32.7	167.5 ± 21.3	145^{+83}_{-49}	2.09 ± 0.87	243.1 ± 9.5	418^{+76}_{-74}	2.02 ± 0.86
(4) n=1	$3779.0^{+2.0}_{-1.7}$	$24.4^{+5.1}_{-3.7}$	32.7	167.4 ± 20.4	145^{+68}_{-49}	2.14 ± 0.88	243.0 ± 9.6	422^{+75}_{-74}	2.07 ± 0.86
(4) n=0.5	$3779.0^{+1.7}_{-1.6}$	$25.2^{+4.2}_{-2.8}$	33.1	172.2 ± 21.6	171^{+68}_{-65}	1.81 ± 0.88	241.3 ± 11.9	419^{+75}_{-68}	1.76 ± 0.85
(5) n=0	3779.6 ± 2.0	25.3 ± 6.6	31.9	200.4 ± 14.7	137 ± 87	2.20 ± 0.93	230.3 ± 33.0	461 ± 73	2.47 ± 1.37
(5) n=1	3779.6 ± 1.9	25.3 ± 6.3	31.8	176.1 ± 16.6	154 ± 113	2.14 ± 0.91	239.4 ± 14.7	433 ± 74	1.96 ± 0.96
(5) n=3	3779.1 ± 1.7	25.2 ± 4.4	32.9	126.0 ± 15.8	139 ± 88	1.89 ± 0.90	282.0 ± 16.9	501 ± 89	2.54 ± 0.91